Differential interferometry of the Broad Line Region of Quasars

Innermost structure of quasars using optical interferometry and reverberation mapping

Presented and defended by

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Interférométrie Différentielle des régions à raies larges (BLR) des quasars

Région centrale des quasars en combinant interférométrie optique et cartographie des échos lumineux.

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- Walter Jaffe, Professeur, U. Leiden, Leiden
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Abstract

Active Galactic Nuclei (AGNs) and the subclass quasars are powered by the accretion of matter onto a super massive black hole (SMBH) surrounded by an accretion disk, which is surrounded by the broad line region (BLR) where clouds are orbiting around the SMBH with high velocity. The study of the BLR is crucial to understand geometry and kinematics of the central engine, accretion mechanism, SMBH mass estimate and distance measurement across cosmic time. Reverberation mapping (RM) estimates BH masses using virial relation, which relies on a poorly known scale factor that depends on geometry and kinematic of the BLR. Optical interferometry (OI) with its high angular resolution can constrain the geometry, estimate scale factor, and calibrate the BH mass-luminosity relation obtained by RM.

Using “blind mode observation” at AMBER/VLTI, for the first time it has been possible to resolve the BLR of the quasar 3C273 in Paα. The first result shows a drop in differential visibility indicating an extended BLR much larger than RM prediction. I developed a three-dimensional geometrical and kinematical model that simultaneously predicts all RM and OI signals, showing that differential measures can provide strong constraints on the BLR. A Bayesian model fit of the simulated OI data sets show BH mass can be constrained with an uncertainty less than 0.15 dex, which can further be reduced by combining OI data with RM data. A global fit to the 3C273 data shows that the Paα BLR is extended beyond the dust inner rim, inclined close to face-on and has a spherical structure, where Keplerian rotation and macroturbulent velocities have similar contribution. The mass of the SMBH in 3C273 is found to be about $5 \times 10^8 M_\odot$.

Comparing to the RM virial mass, this provides the value of scale factor to be about 3. To use BLRs as standard candles, I investigated the BLR parallax method from simulated RM and OI data finding an accuracy better than 20% on the distance estimation. I performed an evaluation of the potential of second-generation VLTI instruments such as GRAVITY, MATISSE, and possible instruments dedicated to BLR work (OASIS, OASIS+ and OASIS+fringe tracker). This suggests VLTI at its full potential with a next generation fringe tracker could allow us to observe 60 targets on a large range of
luminosity, sufficient to attempt a big unification from the study of BLR model parameters as a function of luminosity. The combination of RM, OI and spectro-astrometry could transform quasars in a decisive cosmological tool.
Résumé

Les noyaux actifs de galaxies (AGN), dont les quasars sont une sous classe, sont animées par l’accrétion de matière autour d’un trou noir super massif (SMBH). Le disque d’accrétion est entouré par des nuages de gaz qui se déplacent à grande vitesse et produisent des raies d’émission très larges et constituent la Broad Line Region ou BLR. L’étude des BLRs est cruciale pour comprendre la géométrie et la cinématique du moteur central des AGNs, contraindre le mécanisme d’accrétion et mesurer la masse du trou noir. Elle peut être utilisée pour mesurer la distance des quasars à des échelles cosmologiques. La technique de cartographie des échos lumineux, ou Reverberation Mapping (RM) permet d’estimer la masse du SMBH à partir d’une relation virielle qui est affectée d’un facteur de projection mal connu et très dépendant de la géométrie de la BLR. L’interférométrie optique (IO) peut contraindre cette géométrie et donc ce facteur d’échelle et permet donc de calibrer la relation masse-luminosité des quasars fournie par RM.

Une nouvelle technique d’observation en aveugle avec l’instrument AMBER du VLTI a permis de résoudre pour la première fois la BLR du quasar 3C273 dans la raie. Les premiers résultats ont été une chute de la visibilité différentielle dans la raie d’émission ce qui indique une BLR très étendue, bien plus grande que la prédiction du RM pour cette source. Une analyse soignée de nos données interférométriques et des données de RM a permis de confirmer ce résultat. Nous avons mis au point un modèle tridimensionnel de la géométrie et de la cinématique des BLRs qui permet d’estimer simultanément les mesures de RM et d’IO. Il nous a permis de montrer que l’IO contraint fortement des BLRs malgré la résolution insuffisante du VLTI. Un ajustement de modèle Bayésien de données simulées montre que l’IO seule permet des mesures de masse avec une précision de 0.15 dex, qui peut être améliorée en combinant IO et RM. Ce modèle a été utilisé pour interpréter les observations de 3C273 et nous obtenons une BLR presque deux fois plus étendue que le bord interne du tore de poussière, observé pratiquement de face et avec une structure sphérique avec une des vitesses de macroturbulence et de rotation globale à peu près équivalentes. La masse du SMBH est de , ce qui correspond à un facteur de projection.

Nous avons évalué une méthode de mesure des distances, appelée BLR parallax à partir de la combinaison des mesures linéaires du RM et angulaire de l’IO. Nous montrons des précisions de distance typique de 20 % à 500 Mpc et nous donnons des pistes pour améliorer ce potentiel. Nous avons analysé le potentiel du VLTI avec ses instruments de seconde génération GRAVITY et MATISSE ainsi qu’avec des instruments optimisés pour
l'observation à moyenne résolution de BLR, comme OASIS et OASIS+, éventuellement combinées à un suiveur de frange de nouvelle génération. Nous montrons que le VLTI pleinement exploité permettrait de résoudre plus de 60 BLR avec une large gamme de luminosités, suffisante pour tenter une grande unification des modèles de BLR fondées sur l'étude de leurs paramètres en fonction de la luminosité et de leur spectre d'émission. La combinaison de l'IO et du RM, puis de la spectro-astrométrie transformerait alors les quasars en sondes cosmologiques majeures.
Acknowledgments

In 2012, when I arrived in Nice, I was very much excited about the new place, about the work and about the life here. First month in Nice was a bit difficult for me mainly because of the language, a different way of life and food, but things become perfect after some time. The first person I met in Nice was my supervisor Romain Petrov. My sincere and deepest gratitude to him for his kind and friendly behavior that made me very comfortable to discuss any kind of topic. He was always supportive and showed me the right direction to complete my work. He is the person who introduced optical interferometry to me and guided me to complete my PhD thesis work. I thank Stephane Lagarde for his initial help in modeling interferometric data and more useful discussions. I am very grateful to Anthony Meilland for his help to develop me code and discussions in many science topic. His friendly behaviors made me comfortable to discuss any kind of problems. I express my heartiest gratitude to Florentin Millour for teaching me AMBER+ data reduction and Martin Vennier for his help in data reduction. My deepest gratitude goes to Eric Fossat for sharing his ideas about time series analysis. I will always be grateful to Sebastian Hoenig for his advice and help during the last year of my PhD. I am thankful to many others like Hum Chand, Bruno Lopez, Farrokh Vakili for many useful discussions during these years.

Three years is a long time and would not have completed happily without the help of many people. It was possible due to the constant support and love of some persons who will be always in my heart. During that time, my parents Jaba Rakshit and Sunil Rakshit were always supporting me from India, encouraging me for my work and teaching me how to cook Indian food in which I had zero experience. Neha’s supports and encouragements were with me since I started my thesis. She helped me to tackle all the problems that I faced during my PhD. She made my life easier by notifying me many small mistakes errors in my papers and manuscripts. I will be always grateful to my Didi Lipika, Jijaji Chandi and little Chandrima for their support during these years. I want to thank them all for being with me all the time.
We often say “Har ek friend jaruri hota hai” (every friend is mandatory). In last years, I got many friends with whom I shared my problems about work and life, and spent time happily. Specially I will never forget the supports and the encouragements that I have received from Mamadou, who is not only a friend but also a brother of mine. I will be always thankful to Narges, Zeinab, Samir, Husne, Arwa, Onelda, Sibila, Alvaro, Alkis, Srivatsan, Gaetan, Judit and many other friends for their support and the wonderful times that we spent together. I also thank Abhishek, Archana, Piyush and Subhajeet for their support from India. I express my gratitude to Parikshit, Veenth and Disha for their help. I am grateful to many other friends who will be always in my heart.

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My deepest gratitude to all the jury members for spending their valuable time to review my thesis and for coming to attend my thesis defense. Their comments and suggestions helped me to improve this thesis.

Finally, I must acknowledge the “power” which kept me strong enough to overcome all the difficulties that I faced during these years.

Thanks to all for helping me to make my dream successful.
“So many things on the night sky
very different from each other
there must be reasons
finding them must be fascinating”

–suvendu
Dedicated to
Ma, Baba and Didi
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## Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AGN</td>
<td>Active Galactic Nucleus</td>
</tr>
<tr>
<td>BH</td>
<td>Black Hole</td>
</tr>
<tr>
<td>BLR</td>
<td>Broad Line Region</td>
</tr>
<tr>
<td>DI</td>
<td>Differential Interferometry</td>
</tr>
<tr>
<td>HR</td>
<td>High Resolution</td>
</tr>
<tr>
<td>MCMC</td>
<td>Markov chain Monte Carlo</td>
</tr>
<tr>
<td>MR</td>
<td>Medium Resolution</td>
</tr>
<tr>
<td>OI</td>
<td>Optical Interferometry</td>
</tr>
<tr>
<td>QSO</td>
<td>Quasi Stellar Object</td>
</tr>
<tr>
<td>RM</td>
<td>Reverberation Mapping</td>
</tr>
<tr>
<td>SMBH</td>
<td>Super Massive Black Hole</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>VLTI</td>
<td>Very Large Telescope Interferometer</td>
</tr>
<tr>
<td>2DFT</td>
<td>2D Fourier Transform</td>
</tr>
</tbody>
</table>
Physical Constants

Speed of Light \[ c = 3 \times 10^8 \text{ ms}^{-1} \]
Gravitational constant \[ G = 6.67 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2} \]
Solar mass \[ M_\odot = 1.989 \times 10^{30} \text{ kg} \]
Solar luminosity \[ L_\odot = 3.8 \times 10^{26} \text{ w} \]
Chapter 1

Introduction

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1.1 This thesis

1.1.1 Goal of this thesis

Active Galactic Nuclei (AGNs) are extremely powerful objects in the night sky emitting 1/5 of the total power in the universe. They are powered by the accretion of matter onto a central super massive black hole (SMBH) surrounded by an accretion disk. The clouds in the broad line region (BLR), situated at a distance of a few light days to a few hundred light days away from the center, orbiting around the SMBH with velocity of a few thousands km/s, emit broad emission lines.

Depending on the emission properties, AGNs are classified into different categories, but according to the “unified model” they have same internal structure. The reason of these differences are due to the different viewing angles. The bright members of an AGN subclass look star-like due to their large distances. These objects are called quasars, which show very broad emission lines at large redshift.
Study of these objects can explain the evolution of AGNs, and the co-evolution of BHs and their hosts at cosmological distances. Moreover, formation and evolution of BHs and distribution of mass in the universe can be explained by observing high-redshift AGNs. In this context, the BLR has particular importance as it provides mass estimates of the SMBH and accretion mechanism, and can be used as standard candle. However, this needs better understanding of geometry and kinematics of the BLR. Reverberation mapping (RM) provides BH mass estimates but is affected by unknown geometry and kinematics.

Thus, the main goal of this thesis is to take advantage of high angular resolution near-infrared interferometry to show how OI can contribute to the understanding of BLR geometry and kinematics, in spite of the fact that all BLRs are expected to be unresolved or only partially resolved. I will combine optical interferometric (OI) observations with RM to constrain the BLR morphology. I will describe a three-dimensional BLR model to predict simultaneously both the OI and RM measurements. I will explain effects of different model parameters on both OI and RM data. I will present and discuss the first OI observation of 3C273 and a global model fit of the data. SNR analysis will be performed to evaluate the full potential of the current and upcoming interferometric instruments to see the feasibility of BLR observation within next few years. Since quasars can be found at redshift up to 7, they can be used to study the early universe. Thus, a method to measure directly the distance of high-redshift quasars is needed to constrain the expansion rate of the universe and prove dark matter. Hence, I will estimate angular distance to quasars using a geometrical method, “BLR parallax”, to use them as standard cosmological candle.

1.1.2 Structure of this thesis

This thesis is structured in the following way. A general introduction of AGNs, its key components, unification model and its role in cosmology are described in section 1.2. Since roughly half of this thesis work is related to reverberation mapping, its basic concepts are summarized in chapter 2 with its key results and main limitations, which are important for this thesis. In chapter 3, I discussed the basic concept of optical interferometry including an overview of VLTI and AMBER instrument and data reduction process that I used to reduce raw data obtained from faint sources like quasars. A detailed description of a geometrical and kinematical model of BLR is presented in chapter 4, which also explains different observables of both RM and OI techniques including a direct model fitting approach using Bayesian framework. First interferometric observation of the BLR of 3C273 using AMBER at VLTI is presented in chapter 5 with a detailed description of the observation and data reduction process including the result of the Bayesian model fitting to the data. To see the full potential of the VLTI in observing the BLR of quasars, the result of a feasibility study of different second-generation instruments of VLTI is presented in chapter 6. Feasibility of quasar parallax method to estimate angular distance using BLR is presented in chapter 7 including the result of the simulation estimating distance accuracy from the mock interferometric and reverberation mapping data. Finally, the conclusion of this thesis and my future perspectives are written down in chapter 8.
Note that in the following chapters “we” represents all the collaborators associated with me in these projects. However, this does not mean that the statements have been endorsed by all of them.

1.2 Introduction to Active galactic nuclei

1.2.1 A brief history

In 1908, Edward A. Fath observed the nucleus of NGC 1068, the brightest AGN (Fath, 1908). He obtained six emission lines along with Hβ, which were re-observed by V.M. Slipher in 1917. In 1926, emission line spectra of three more objects were observed by Edwin Hubble, and two decades later, Carl K. Seyfert published the historical paper in which he stated that the nuclei of a small fraction of galaxies show high-ionization emission lines, which are broader than the absorption lines in normal galaxies (Seyfert, 1943). He, furthermore, noted that these lines were originating from a compact bright nucleus with a range of ionization parameter (see section 1.2.4.3). Then this new class of objects were named Seyfert galaxies. They are defined by a spiral structure with bright nucleus and emission lines. They represent about 3-5% of all galaxies.

After the advances of radio astronomy, many bright radio sources were detected and thought to be star-like objects in the optical (Hazard et al., 1963). Some of them are brighter than Seyfert galaxies by factor of 100 or more, and show strong broad emission lines at unexpected wavelength. These are known as quasi-stellar radio sources or quasars, which are the most distant and bright objects in the sky. In the 1960’s, Maarten Schmidt discovered the first quasar 3C273 and measured its redshift from its optical spectrum (Schmidt, 1963). The large redshift of the objects implied an extremely high luminosity ($\simeq 10^{12} - 10^{14} L_\odot$). After this first success, many such objects were detected in night sky. Later, it was found that many of those do not emit radio waves and termed as quasi-stellar objects or QSOs. Even if only about 1% of QSO-like objects in the optical domain have detectable radio emission, the radio-quiet objects (most of the QSOs) are nowadays also termed quasars since the underlying physics is the same for both. The 2dF* QSO redshift survey produced a sample of over 40,000 QSOs (Boyle et al., 2000), whereas the Sloan Digital Sky Survey data release 10† (SDSS DR 10) produced a catalog consisting 166,583 quasars. Note that Seyfert galaxies and quasars are the two largest subclasses of “active galactic nucleus”, or AGN, the most luminous sources in the universe with a very compact nucleus, and much brighter than normal galaxy.

*http://www.2dfquasar.org/
†http://www.sdss.org/
Table 1.1: Different types of AGN and their observed emission

<table>
<thead>
<tr>
<th>AGN Types</th>
<th>Narrow lines</th>
<th>Broad lines</th>
<th>X-rays</th>
<th>UV excess</th>
<th>far-IR excess</th>
<th>Radio loud</th>
<th>variable</th>
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<tr>
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Figure 1.1: A Cartoon to explain different components of AGN based on Urry and Padovani (1995). Central black hole, broad line region, dusty torus and narrow line region are shown in white labels. Different types of AGN are shown in green labels explaining the unified model of AGNs. It says the differences are due to the observer viewing angle (green arrows). Credit: Pierre Auger Observatory.

1.2.2 AGN types

AGNs are divided in many categories depending on luminosity, presence of broad and narrow lines, variability etc. However, the major division comes from the presence of strong radio emission, which divided AGNs into two main classes: “radio loud” and “radio quiet” (if the ratio between radio flux in 5 GHz to optical flux in B band is greater than 10 then the object is radio loud otherwise it is called radio quiet). Radio loud objects exhibit strong radio emission, which originates from the jet, but radio quiet objects show weak radio contribution, but their emissions dominate in other wavelength. These objects are further classified into many different categories depending on observed emission profile such as the presence of narrow and broad lines, X-ray, UV and far IR excess, and variabilities. Table 1.1 summarizes different categories and the reason of this classification.

Antonucci (1993) in his unification model stated that all AGNs have similar structure, and the differences in their emission profile are due to observer line of sight
to the object (figure 1.1). Thus depending on the orientation of object relative
to the observer line of sight, different classes of AGN are formed: optically vio-
lent variable (OVV; jet points directly), Blazar (jet points towards), Seyfert 1 or
Quasar (jet points away but central structure still visible) and Seyfert 2 (edge-on
view and central structure is blocked by obscuring dust torus).

1.2.3 Unified models of AGN

The aim of the unified models is to find simple explanation for all the apparent
properties of different classes of AGNs as noted before. The first simple unification
idea was proposed by Antonucci and Miller (1985), who found that the spectrum
of Seyfert 2 galaxy NGC 1068 in polarized light shows signature of Seyfert 1 galaxy
due to scattering of light from the BLR clouds, thus confirming the presence of the
BLR, obscured by the dusty torus and not directly viewed due to its inclination
with respect to the observer. This suggests that the inclination plays a crucial role
to determine the observed properties. Thus galaxies, which show broad emission
lines, are defined as type 1 and those with obscured broad emission lines are type
2.

It is also interesting to note that, many but not all Seyfert 2 show hidden BLRs in
the polarized light. The absence of BLR signature in some Seyfert 2 observations
in polarized light could be due to weak BLR emission compared to the underlying
continuum, as well as, absence of strong emission from the central engine to illu-
minate the BLR. However, adding luminosity as a parameter could explain some
of these properties. As a result, unification models now concentrate on unifying
AGNs within the same class adding different parameters such as mass, Eddington
ratio, luminosity with inclination. Unification of different classes of radio-loud
AGN has been explain by Urry and Padovani (1995).

The unification model indeed provides very simple explanation of the observed
differences in AGN including Seyfert galaxy. Our long term goal is to obtain a
broad unification based on the relation between BH mass and other properties of
AGNs such as luminosity, inclination, vertical height of the BLR and dust torus.

1.2.4 Components of AGN

The main components of AGN are as follows:

- A super massive black hole with $10^6 M_\odot < M < 10^{10} M_\odot$. Size of the event
  horizon $\sim 0.01 – 10$ AU.
- An accretion disk, major power house, surrounding the SMBH of size $< 1000$AU. Matter attracted by the gravity of black hole spirals in and forms
disk. The disk is made of hot ($10^4 – 10^6$ K) and optically thick plasma.
- A broad line region (BLR) of size $0.01 – 1$ pc, made of gas clouds orbiting arround the SMBH with velocities of a few thousand km/s. The gas is ionized
by the continuum radiation and emits lines which are very broad because of
high Doppler shifts. BLR will be discussed in more detail later.
• A dusty torus of size $1 - 10$ pc. The torus is “optically thick”. Inner rim of the torus which is at temperature $\sim 1500$ K dominates the $K$ band emission.

• At large distance ($\sim 10 - 1000$ pc), there is another region where low density clouds are moving less rapidly ($\sim$ few $100$ km/s). This is the narrow line region (NLR), which emits permitted and forbidden narrow emission line.

• About $10\%$ of AGNs have jets, perpendicular to the accretion disk, which extend from $0.01 - 10^6$ pc. Material inside the jets moves at relativistic velocity.

1.2.4.1 The Black Hole

In 1963, Hoyle and Fowler pointed out that the energy source of AGNs and Quasars could arise from the gravitational collapse of massive object. The existence of such a massive object, which is named as super massive black hole (SMBH), at the center of an AGN is very common (Lynden-Bell, 1969). Some of these sources are accreting matter at a very high rate (see later). Black holes (BH) with mass of $\sim 10^{10} M_\odot$ were detected at $z > 6$ (Wu et al., 2015) suggesting that the evolution of BHs have been linked with their parent galaxies since at the early universe. It was also suggested that SMBH grew faster than their host galaxy in the early universe (Wang et al., 2010). Interestingly, a tight correlation can be found between SMBH growth and the evolution of the host galaxy. Both quiescent and active galaxies show similar correlation between SMBH and the bulge of the host galaxy, such as the relation between BH mass and the bulge velocity dispersion ($M_{BH} - \sigma_*$), and BH mass with bulge luminosity ($M_{BH} - L_{bol}$) (Ferrarese and Merritt, 2000; Gebhardt et al., 2000a; Bentz et al., 2009a). In order to study growth of SMBH and evolution of galaxy, we need to have a better relation between BH mass and luminosity of AGN.

Reverberation mapping is a powerful tool to successfully provide such a relation (Blandford and McKee, 1982). However, the RM virial masses have large scatter due to the unknown geometry and kinematics (see chapter 2). Calibration of such relation is one of the goals of this thesis.

1.2.4.2 Accretion disk

Accretion of matter onto a SMBH is the major power source of AGN. Surrounding the central black hole, a structure of diffused material called accretion disk is present. As far away material with subsonic velocity is attracted by the central object and becomes supersonic as its Mach number increases toward the center. Because of friction in the accretion disk, material is heated up producing enormous amount of radiation across the electro magnetic spectrum. Matter spirals inward and loses angular momentum, which has to be balanced by the angular momentum gain of matter far away from the central source. Depending on the accretion rate, in-falling matter forms radiatively efficient thin accretion disk (Shakura and Sunyaev, 1973) or radiatively inefficient thick disk, which cooled by advection (ADAF; Narayan and Yi, 1994). Luminosity of the object depends on the accretion rate, $L_{acc} = \epsilon \dot{M} c^2$, where $\epsilon$ is the radiative efficiency, $\dot{M}$ is the accretion rate and $c$ is
the speed of light. Considering spherical symmetry, a theoretical limit for luminosity was defined, called the Eddington luminosity $L_E$, which is the maximum luminosity of the object with a balance between radiation force acting outward and gravitational force of the black hole acting inward:

$$L_{\text{acc}} \leq L_E = 3.2 \times 10^4 \frac{M_{\text{bh}}}{M_\odot} L_\odot$$

For very luminous accretion disks, whose luminosity exceeds the Eddington luminosity, a slim-disk model has been proposed by Abramowicz et al. (1988), a disk with low viscosity, optically thick, radiatively very inefficient and cooled by advection. In the context, SS 434 is a well-known galactic object with a super-Eddington accretion disk (Okuda et al., 2009).

### 1.2.4.3 Broad line region

The broad line region (BLR), a region of gas clouds surrounding the accretion disk orbiting with velocity up to 20000 km/s and emitting broad emission lines in the observed spectrum. The study of BLR is particularly important since it can provide details about the central black hole because of the virial relation, its growth history at a cosmic time scale. However, the apparent size is so small that even in the nearest AGNs resolving BLR clouds is a challenge for astronomers.

Since this thesis is based on the study of the broad line region (BLR), a detailed discussion about some of the important properties of the BLR is presented in this chapter, and in chapter 2.

**Cloud properties:** The assumption that clouds are the basic line emitting entity in the BLR of AGN, comes from the observational evidence of condensation in galactic HII regions and the interstellar medium. Moreover, clouds are needed for line intensity consideration, mainly the typical observed line width, which is very similar between low- and high-ionization lines, roughly within a factor 2. An ensemble of small thick clouds, where each of them produces many emission lines with a large range of ionization, can explain the observed line profile, and is consistent with the stratification and virial prediction (a detailed discussion can be found in Netzer, 2013). As an alternative, it was considered that broad emission is coming from extended envelope of the stars, and thus BLR is associated with stars, but in that case the mass of the stars in the BLR becomes too large, which is problematic since the total of the line emitting clouds is about $10^3 - 10^4 M_\odot$ (Baldwin et al., 2003). How many clouds are in the BLR? The number of clouds can be estimated from the line profile shape. The number of estimated clouds required to produce smooth high resolution emission line profile for given gas velocity is very large $\sim 10^{6-8}$, considering individual clouds have typical line width $\sim 10$ km/s (Arav et al., 1997, 1998).

Clouds could survive over many dynamical times\footnote{Dynamical time scale of the BLR can be defined by the time that a line emitting cloud would take to cross the BLR, $\tau_{\text{dyn}} \simeq R/\Delta V_{\text{FWHM}}$, where R is the size of the region and $\Delta V_{\text{FWHM}}$ is the typical velocity width. For a Seyfert galaxy, this corresponds to 3-5 years.} due to either confinement, magnetic or relativistic High Intercloud Medium (HIM), or because they are the part...
of self gravitating bodies like stars. The required magnetic field for magnetic confinement is small ($\sim 1$ G). Confinement due to HIM is problematic as it would smear the central source variation and the wings of the broad emission lines.

**Broad line spectrum:** AGN spectra show a wide variety of line strengths and profiles (see Table 1.1 in Peterson, 1997). The width of the emission lines range from 500 km/s to more than $10^4$ km/s, which is the result of Doppler broadening. They also show a large variety in shape, from a “logarithmic”, i.e the flux at radial velocity $\Delta V$ from the line center $F_\lambda(\Delta V) \propto -\ln \Delta V$, to a more complicated profile which is variable in time. Different lines in the same spectrum can have very different morphologies. AGN spectra often show several strong broad emission lines such Ly$\alpha$ ($\lambda 1216$)+ Nv ($\lambda 1240$), CIV ($\lambda 1549$), Mg II ($\lambda 2798$), H$\beta$ ($\lambda 4861$) as well as many other emission lines including Paschen series lines in IR. Due to large Doppler broadening spectral lines are often blended such as CIV doublets and helium line. Figure 1.2 shows a mean spectrum of 700 QSOs with several prominent emission lines.

Some of the quantities that are often used to describe the BLR physical condition are summarized below.

**Covering factor:** Covering factor is defined as the fraction of sky covered by the BLR clouds as seen from the center. It is estimated from the fraction of ionized continuum photons absorbed by the BLR clouds and reprocessed emission lines. It is estimated to be of the order of 10 % from the equivalent width of the emission line, such as Ly $\alpha$ (Baldwin and Netzer, 1978).

**Column density:** The neutral hydrogen column density along any line-of-sight is defined as $\eta_H = \int N_H(l) dl$, where $N_H$ is the number of neutral hydrogen atoms per cm$^3$. The estimated number, for which the emitted spectra in not sensitive to the column density, is between $10^{22} - 10^{24}$ cm$^{-2}$, where the lower limit is set by
the appearance of low excitation lines of Mg II and Fe II in AGN spectra, and the upper limit is set by observation of Ca II in some AGN spectra.

**Filling factor:** This indicates how much of the emitting volume actually contain line-emitting material, where rest of the volume can be assumed to be vacuum. Filling factor in quasar BLR is very low about $10^{-4}$ calculated from the observed intensity of emission lines.

**Photoionization of the BLR:** The emission line flux varies with time and follow the variation of the continuum flux. This correlated variation suggests that the BLR is photo-ionized by the radiation from the central continuum source. Photoionization models have been extensively used in the past to understand the emission from gaseous nebulae and many of the emission lines usually found in gaseous nebula are seen in AGN spectra as noted by Seyfert (1943). Our knowledge about the BLR physical condition and hence photoionization modeling have been improved due to the observational evidences such as higher spectral resolution and increased sensitivity in AGN spectra have revealed more complex BLR dynamics than previously thought. The ionization parameter is defined by the ratio of photon number density to particle density at the ionized face of the cloud

$$U = \frac{Q(H)}{4\pi r^2 n_H c} = \frac{\Phi(H)}{n_H c},$$

where $Q(H) = \int \frac{L}{m_v} dv$, the number of hydrogen ionizing photons per second, depends on the specific luminosity ($L_\nu$) of the central source, $\Phi(H) [\text{cm}^{-2}\text{s}^{-1}]$ is the surface flux of the ionizing photon, $r$ is the distance of the cloud from the central source, $n_H$ is the hydrogen number density and $c$ is the velocity of light.

The photoionization models thus depend on the shape of the ionizing continuum SED, the element abundances (usually solar or cosmic), particle density, column density and the ionization parameter or the ionizing photon flux. Incident continuum strikes the front face of the clouds, producing high-ionized zone and emitting strongly in the high ionization lines like Ly$\alpha$ and CIV. However, the back side of the cloud, which is partially ionized due to heating from penetrating x-rays, strongly emits in the low ionization line such as Mg II and Fe II. Typical values of ionizing parameter and density are \(\log_{10} U \simeq -1.5\) and \(n_H \sim 4 \times 10^9 \text{cm}^{-3}\) for the BLR. The limit on the gas density comes from the width and the presence or absence of forbidden and/or semiforbidden lines. The small value of covering factor ($\sim 10\%$) and a very small filling factor ($10^{-4}$) as well smooth emission line profile indicates that the BLR consists of a large number of line emitting clouds, which occupy small parts of the total volume and intercept small fraction of the total ionizing continuum.

The success of early reverberation mapping observations improved our understanding about BLR, however, these findings initially imposed a number of problems. The estimated time lag through photo-ionized modeling is an order of magnitude larger than measured from the RM observations. This suggests that the line emission originates closer to the central source and gas density is denser than previously believed. Models with standard BLR parameters produce large intensity ratios between different Balmer lines (Ly$\alpha$/H$\beta \sim 50$, H$\alpha$/H$\beta \sim 10$) but the observed values are far lower (Ly$\alpha$/H$\beta \sim 3$, H$\alpha$/H$\beta \sim 4$). Moreover, different
emission lines exhibit very different lag times. For instance CIV has lower lag than Hβ suggesting that the BLR is stratified. Clouds with various density are distributed around the central source, and the emission comes from the clouds only when the optimal conditions (density and photon flux) are satisfied for that line Baldwin et al. (1995). This is further explained by figure 1.3, which shows that the NLR, molecular torus, and BLR are just due to the different atomic and molecular physics, spanning several orders of magnitude in $n_H$ and radiation field intensity (see Ferland et al., 2013).

**Correlation between line and continuum emission:** AGN emission lines are strongly correlated with the continuum properties. Radiation from the central source hits the gas clouds photoionizing them (see chapter 2). Line intensity is directly proportional to the continuum intensity but depends on shape of the incident continuum, exact label of ionization, gas kinematics etc. This correlation allows us to understand the physics of accretion mechanism and the BLR, and this is the basis of reverberation mapping technique, which will be discussed in detail in chapter 2. There are some other observationally well established correlations, such as Hβ line width, X-ray continuum slope, and Eddington ratio ($\lambda_E = L/L_E$). A relationship known as “Baldwin effect”, between the equivalent width (EW) of CIV λ1549 and the continuum luminosity measured near the line wavelength, was discovered by Baldwin (1977), and later found to be followed by several other lines. But, some lines like Hα and Hβ show very weak correlation with continuum luminosity. There is strong evidence showing better correlation with $\lambda_E$ than continuum luminosity, indicating the possibility that line EW is related to the accretion rate. The correlation between EW and $M_{BH}$ was also found weaker than $M_{BH}$ and $L$. 

![Figure 1.3: Physical and thermodynamical limits (in white) and different regions in AGNs (in yellow) are shown in annotated version for illustration. A wide range of densities, and various energy-density temperatures of the $10^6$ K blackbody, are shown. Taken from Ferland et al. (2013).](image-url)
A schematic diagram of AGN central engine is presented in figure 1.4 showing that BLR clouds are surrounding the central objects. They absorb the continuum photons and re-emit them as emission line photons allowing us to study the geometry and kinematics of the central engine, the accretion mechanism, and the central black hole growth history.

### 1.2.4.4 Dusty torus

A dusty region surrounding the central part of AGNs, located at a distance of few parsec, made of molecular gas as well as warm dust at $T \sim 1500$ K are emitting at near-IR, and cooler dust $T \sim 300$ K emitting at mid-IR. This was thought to be the outer boundary of the BLR. A combination of silicate and graphite grains of few nm to $\mu$m size is the key ingredient of this dust. The silicate absorption feature indicate AGN dust is very different than normal interstellar dust. Torus in AGN is important since it alters the spectral energy distribution (SED). Spectropolarimetric observations of Seyfert 2 galaxies by Antonucci and Miller (1985) show strong signature of the broad lines in the polarized light but invisible in total light. This suggests a dust obscuration effect where broad line emission is overwhelmed by the unpolarized continuum. If the object is viewed face on, central engine is visible and unobscured by torus, whereas its emission is blocked for edge-on view due to dust obscuration. The overall picture, a “bird nest” structure, of the BLR and dust torus is shown in figure 1.4 as suggested by Gaskell (2009).

The resolution needed to resolve the torus is beyond the capability of a single-dish telescope and hence no direct evidence was available, until Jaffe et al. (2004) resolved NGC 1068 with Very large telescope interferometer (VLTI). Since then, many AGNs have been successfully observed in the $N$ and $K$ bands. This allowed to constrain the size of the innermost dust torus structure and revealed its complexity. Burtscher et al. (2013) rejects the existence of a simple size-luminosity relation in AGNs, because the $L^{0.5}$ scaling of bright sources fails to represent properly fainter sources, and there are clearly several components, with at least
a cooler more equatorial structure and a hotter more polar one. Both the Keck interferometer (KI) and the VLTI measurements, summarized in Kishimoto et al. (2012), show that in the $K$-band, the dust torus inner rim size is fairly close to a $R_{\text{rim}} \propto L^{0.5}$ size as first indicated by the infrared RM observations of Suganuma et al. (2006) and Koshida et al. (2014), with a size excess with regard to $\propto L^{0.5}$ that increases as $L$ decreases but remains small in the $K$-band (more discussion can be found in section 2.4). Later, we will use this infrared RM dust size as a lower limit of the inner rim size to estimate the feasibility of interferometric observations of BLR.

1.2.4.5 Narrow line region

At a distance of the order of 100 pc, there is a photo-ionized region, called narrow line region (NLR), where the gas clouds have velocity less than 1000 km/s and produce “narrow” lines. As this region is far away from the central source, it is unaffected by the possible presence of absorbing material. The presence of forbidden lines in the NLR suggests a small density about $10^4 \text{cm}^{-3}$ and column density about $10^{20-21} \text{cm}^{-2}$. NLR has a covering factor of the order of 0.01, which is obtained from the luminosity of entire NLR dividing the luminosity of the continuum. NLR can be resolved in many objects suggesting a double cone geometry, called the “ionization cone”. Recent high-resolution maps of NLR from modern integral field unit (IFU) instruments reveal complex geometry with nonuniform gas distribution, which is attributed to anisotropic illumination of the gas due to central obscuring torus (Storchi Bergmann, 2015). Velocity field of this region is also complex indicating presence of outflow plus rotation components.

1.2.4.6 The Jet

Relativistic Jets are commonly seen in radio-loud AGNs. The jet originates at a location where optical-UV and X-ray continuum originates. The exact mechanism behind the production of jet is yet unknown. According to the present understanding, the magnetic field lines in the inner accretion disk warp around and get locked in double helix configuration, and, as a consequence the charged particles
accelerate at a highly relativistic speed. Radio image taken with very large array (VLA) from radio galaxy Cygnus A is shown in figure 1.5 showing 50 Kpc jet extended out of the central bright core (bright spot).

The jet emission is highly beamed and often appeared to be very bright. Very low luminosity AGNs (like M87) as well as the very high luminosity quasars (like 3C273) show highly coliminated radio and optical jets. A wide range of apparent velocities can be found in radio jets and usually a Lorentz factor $\Gamma = (1 - \beta^2)^{-1/2}$ is used to quantify them (where $\beta = v/c$). Radio loud objects with jets often show broad, nonthermal continuum contribution due to synchrotron radiation from the charged particles in the jet.

In the context of this thesis, jet is relevant because of

- Its contribution in the near-IR SED,
- Its position angle can be used to constrain the orientation of the central structure since jet emits perpendicular to accretion disk. Jet position angles have been obtained for many AGNs from VLBA observation (Lister et al., 2009). Thus, we will use the position angle constraint derived from the observed radio-jet orientation. However, note that, interferometric observation could also constrain position angle, if observations are available at many different angles.
- observer viewing/inclination angle can also be constrained from apparent jet speed by following simple equation.

$$\beta_{\text{obs}} = \frac{\beta \sin \theta}{1 - \beta \cos \theta},$$

which is maximum of $\Gamma \beta c$ when $\sin \theta = 1/\Gamma$. For example, inclination of 3C120 is $i < 20^\circ$ constrained by its superluminal jet (Marscher et al., 2002). Note observed emission line profile provides strong constraint on the inclination angle (see chapter 4).

1.2.5 Spectral energy distribution of AGN

AGN continuum is spread over the entire electromagnetic spectrum from radio to gamma ray. The spectrum is relatively flat and nonthermal as shown in figure 1.6. It consists of many complex structures: the broad and narrow emission lines, broad thermal excess components in IR and optical UV bands, and pseudocontinuum structure such as the small blue bump which is comprised of the line emission from iron and from the H-Balmer series (Elvis et al., 1994).

In the X-ray region, the continuum consists of several components, a power-law continuum, a “soft excess” with X-ray energy bellow 1 KeV (Arnaud et al., 1985), and a “reflection bump” in hard X-ray band with energy 10 to 30 KeV (George and Fabian, 1991). For many objects, the soft excess is due to emission that exceeds the extrapolation from the observed hard X-ray power-law continuum, however least understood in AGN continuum. This spectrum is non-thermal in
nature and believed to be due to Compton scattering of optical/UV photons by hot or nonthermal electrons in the hot corona above the accretion disk (Liang, 1979). At 6.6 KeV, there is a Fe K-alpha broad emission line. Both Fe K-alpha and “reflection bump” is thought to be due to fluorescence and reflection from “cold” material, possibly from the accretion disk.

The Big Blue Bump (BBB) continuum component in AGNs ranges from 10 to 400 nm, and sometime down to soft X-ray side. This thermal radiation emits at temperature $10^4$ to $10^5$ K. Although the exact origin is unclear, it probably arises from the accretion disk due to black body radiation from optically thick gas or due to free-free emission from optically thin gas. This spectral window emits half of the bolometric luminosity for an unobscured AGN.

The broad infrared bump extends from $\sim 1$ to $\sim 300 \mu$m, separated from BBB by a deep minimum at 1 $\mu$m. This infrared bump is thought to be emitted from reprocessing of the BBB emission by the dust of dusty torus with temperature $\leq 1800$ K and various distance from the central UV source (Barvainis, 1987). Infrared bump is due to thermal emission in the case of radio-quiet AGNs, while this bump in the case of radio-loud AGNs is due to both thermal and non-thermal components, though often only one component is dominant (Haas et al., 1998).

For this thesis, the SED features in the UV and near-IR are very important, since near-IR continuum originates from the inner rim of dust torus. We will use the SED shape to interpret $K$ band interferometry measurements or the scaling of angular size of torus with temperature. Moreover, the emission line features in the $K$ band can be constrained by our work. This will help to do modeling of the UV/optical variability of AGN to predict emission line light curve. The flux at different bands, such as $V$, $K$, $L$ etc can also be obtained from the SED profile, which will be used in chapter 6.
Chapter 1. Introduction

1.3 AGN evolution and cosmology

AGNs have been observed over a distance range of few Mpc to redshift (z) beyond 7. More than 40 of those have been found with redshift larger than 6. The population of these quasars peaks at redshift $1.5 < z < 2.0$ suggesting that at earlier times in the Universe there have been many more quasars per unit volume than today. The study of BH evolution suggests that the most massive BHs grew first while the less massive BH started their growth much later time and are still growing at a fast rate. On the other hand, the existence of BHs with mass about $10^{10}M_\odot$ at the early universe suggests that massive BH must have been common at the very early universe.

The reason “why BH mass measurement is important?” is that the formation and evolution of BH in the universe is unclear. A powerful tool to study AGN evolution with time is to study their redshift-dependent luminosity function (LF). Combination of such LF with BH masses, can provide mass function of BH, vital to study distribution of masses across the cosmic time. The relations between BH masses with luminosity and Eddington ratio of AGN have been found, but those masses are highly scattered, measured by RM virial relation that depends on the unknown $f$ factor. Moreover, BH mass estimates provide constraints on the evolution of host galaxy. High accretion rate and fast growth of the BH is thought to be due to galaxy interactions and merging since cold gas away from the center of galaxy can not reach close to the BH due to high angular momentum, and gravitational interaction with a nearby galaxy can distort the morphology of the parent galaxy allowing the gas to reach the SMBH. To study the formation history of galaxy, it is thus necessary to have better relation connecting BH masses with host galaxy luminosity as well as velocity dispersion. The continuum variability which could be due to the instability in the accretion disk or variable accretion rate is also related to the BH masses (see chapter 2). Thus, having accurate BH mass measurements will allow us to improve our understanding of the accretion mechanism. Better constraints on the variability of AGN light curves will thus provide better distance measurements using parallax method which could constrain cosmological constant and prove dark energy and modified gravity theories (see chapter 7).

A tight correlation has been found between accreting SMBH mass and some properties of the host galaxy, such as stellar velocity dispersion, bulge luminosity, and the bulge mass (Ferrarese and Merritt, 2000; Gebhardt et al., 2000a; Bentz et al., 2009a). Considering only galaxy with secure BH detection, Marconi and Hunt (2003) showed that all the correlation have similar intrinsic dispersion of 0.3 in $\log(M_{bh})$ at a given $L_{bul}$, $M_{bul}$ or $\sigma^*$. Moreover, applying the correlations between $M_{bh}$ and host galaxy properties, it is possible to estimate black hole mass function or total mass density in the local universe (Salucci et al., 1999), and hence accretion efficiency, Eddington ratio ($L/L_E$) and the average lifetime of BHs (Marconi et al., 2004).

In general, the correlations indicate a bridge between galaxy formation and the evolution and growth of BH in the universe. Such correlations suggest that SMBHs are affected and influenced the evolution of their hosts. The ratio of BH to the
bulge mass is a powerful tool to understand this co-evolution of BH and their host. In the local universe, this ratio found to be dependent on the BH mass, but smaller dependency was found in the case of galaxy that host massive BH. However, this is not clear in high-redshift galaxy, where the estimation of BH mass comes from reverberation mapping virial relation but in that case the measurement of stellar mass is highly uncertain due to much fainter stellar light then high luminous non-stellar continuum. Some evidence suggest that the ratio of stellar mass to BH mass was larger in the past than today. The existence of quasar at high redshift provides insight on the early universe, throughout much of the subsequent cosmic evolution, and thus the formation of the discrete structure in the universe from the primordial gas can be studied.
Chapter 2

Reverberation mapping

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Variability is one of the main characteristic of AGNs. A significant magnitude variation (≥ 0.1 mag) over a time scale as short as day can be found in their light curve. Such a rapid variability indicates a compact continuum emitting region, which must be of the order of a few light days from the source coherence argument. This variation can be found at all wavelengths in electromagnetic spectra. However, the physical origin of the variation is highly debated. Accretion disk instabilities such as magnetohydrodynamics instabilities, variable accretion rate and obscuration of the nuclear source, or micro-lensing due to star could be the possible origins of the variability. Similarly, broad emission lines often vary in flux and in profile shape with a time scale of months to years. The variability in longer time scale is dramatic but in shorter time scale the variation is more subtle (a detailed review in this topic can be found in Peterson, 2001).

Variability was thought to be a powerful tool to study the geometry and kinematics of AGNs since the early 1980s. Since then, many multi-years monitoring were conducted to obtain Ultraviolet (UV) or optical continuum and emission lines variations in Seyfert 1 galaxies. UV spectra obtained by IUE monitoring on NGC 4151 showed close coupling in UV and optical continuum variation (Ulrich et al., 1991). Interestingly, this revealed that emission line variations are correlated with continuum variations. However response of different emission lines are vary different, in amplitude as well as in time scale (Antonucci and Cohen, 1983; Bentz et al., 2010a). Spectroscopic monitoring of NGC 4151 led to remarkable findings,
2.1 Reverberation mapping theory

2.1.1 Basic principle

Observing the response of the emission lines to the continuum variation, it is possible to estimate the geometry and kinematics of the BLR. Emission line responds to the continuum after a time delay, which is due to the light travel time within BLR, suggesting that emission line “reverberate” the changes in continuum. Hence, this technique of observing line and continuum variability to infer the BLR size is termed as “reverberation mapping” after Blandford and McKee (1982).
The idea is easy to understand if one thinks of the BLR as a collection of discrete clouds, each small with regard to the overall BLR, with a definite position and velocity. The variations of the continuum produced in the compact central accretion disk will be echoed in the emission line with a delay related to its position and a Doppler shift given by its radial velocity. For the purpose of illustration, the response of clouds orbiting in a clockwise thin spherical shell of radius $R$ is shown in figure 2.1. The continuum pulse originating from the center propagate outward with the speed of light. It will then be absorbed and reprocessed by the BLR clouds located at a distance $r = c\tau$ producing the emission line photons. A distant observer will simultaneously record both continuum pulse and emission line response from the front side of the shell. However, the emission line response that is coming from another part of the shell will be delayed in time, which is due to the extra path traveled by the light from the continuum source to the BLR cloud and then to the observer. This delay can be written as

$$\tau = \frac{r}{c}(1 + \cos \theta)$$  \hspace{1cm} \text{(2.1)}$$

where $0 \leq \theta \leq 2\pi$. After a given time delay $\tau$, observer will see the emission line photons that lie along a surface of constant delay called “isodelay surface”. The corresponding Doppler velocities of this clouds are $\pm v_{\text{orb}} \sin \theta$. If we project the circular orbit along velocity and time delay axes, the projected map becomes an ellipse centered at $(0, r/c)$ with axes equal to $2v_{\text{orb}}$ and $2r/c$ as shown in the lower panel of figure 2.1. The projected maps will change depending upon the inclination of the orbit or with other model parameters. Construction of response function of a BLR in the context of such a simple case is quite straightforward. The surface area of a thin spherical shell is $2\pi r^2 \sin \theta d\theta$, and if we consider a constant line response per unit area ($\eta$) of the BLR clouds, the emission line response of the ring can be written as

$$\Psi(\theta) = 2\pi \eta r^2 \sin \theta d\theta.$$  \hspace{1cm} \text{(2.2)}$$

From Eq.2.1, a fixed infinitesimal unit of lag can be written as

$$\frac{d\tau}{d\theta} = -\frac{r}{c} \sin \theta.$$  \hspace{1cm} \text{(2.3)}$$

The line response can be written in terms of time delay

$$\Psi(\tau) d\tau = \Psi(\theta) \left| \frac{d\theta}{d\tau} \right| d\tau = 2\pi \eta r c d\tau,$$  \hspace{1cm} \text{(2.4)}$$

where $\Psi(\tau)$ is called 1-D response function or transfer function. Eventually, the transfer function of a thin spherical shell is constant between $\tau = 0$ ($\theta = 2\pi$ for clouds lies along the observer line of sights) and $\tau = 2r/c$ ($\theta = 0$ for the clouds far side of the BLR). Such a transfer function is shown in figure 2.2, more model RM transfer functions are shown in the figure 2.2.
2.1.2 Method and observables

The main goal of reverberation mapping study is to recover the transfer function by studying the continuum and line flux variability. The main assumptions of reverberation mapping are: 1) The continuum emitting region is very small compared to the BLR and can be considered as point source, 2) Emission line clouds respond instantaneously to the changes in the continuum and the BLR is stationary during the reverberation monitoring campaign, and 3) The relationship between the observed line flux and continuum flux is simple, though not necessarily linear (see for a review Peterson, 2001).

The relationship between continuum and line emission can be written in terms of “transfer equation”

\[ L(v, t) = \int_{-\infty}^{\infty} \Psi(v, \tau) C(t - \tau) d\tau \]  

(2.6)

where \( L(v, t) \) is the emission line flux at line of sight velocity \( v \) and time \( t \), \( C(t) \) is the continuum light curve, and \( \Psi(v, \tau) \) is the RM “transfer function” at \( v \) and time lag \( \tau \). The transfer function is basically the emission line response to a \( \delta \)-function continuum pulse. The goal of the reverberation mapping is to recover the transfer function from the continuum and line light curve. However, due to noisy and sparse data, most reverberation mapping is focused on recovering velocity integrated 1-D response function \( \Psi(\tau) \) from velocity integrated line light curve \( L(t) \)

\[ L(t) = \int_{-\infty}^{\infty} \Psi(\tau) C(t - \tau) d\tau \]  

(2.7)

and use in combination of line profile i.e. \( \Psi(v) = \int \Psi(v, \tau) d\tau \).

Because of poor quality data, the most common technique to estimate the BLR size is to perform simple cross-correlation between line and continuum light curve.

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*This “transfer function” terminology is traditional in RM papers. It is different from the transfer function definition in standard signal processing as well as in optical interferometry.
to obtain the temporal shift that maximizes the correlation. The cross-correlation function is defined by

$$\text{CCF}(\tau) = \int_{-\infty}^{\infty} L(t)C(t - \tau)dt. \quad (2.8)$$

After simple calculation one can find that the cross-correlation function is simply the convolution of transfer function with continuum auto-correlation function (see Peterson, 2001). The centroid of the CCF is defined by

$$\tau_{\text{cent}}^* = \frac{\int \tau \text{CCF}(\tau) d\tau}{\int \text{CCF}(\tau) d\tau} \quad (2.9)$$

and is related to the mean response time or the centroid of the transfer function

$$\tau_{\text{cent}} = \frac{\int \tau \Psi(\tau) d\tau}{\int \Psi(\tau) d\tau} \quad (2.10)$$

Note that these two quantities are same only if we have an infinite and well sampled time series. Thus, a key problem in RM is to find the true $\tau_{\text{cent}}$ in spite of time window and sampling problems. Thus, much work is going on for the best possible interpolation of the observed light curves (see Zu et al., 2011).

### 2.2 Model response function

In this section, I will provide some examples of transfer function considering different types of BLR geometry where the clouds are orbiting with Keplerian velocity: 1) face-on ring, 2) face-on extended thin disk, 3) inclined disk and 4) shell geometry.

The geometry of a **face-on ring** BLR is shown in of figure 2.3-1a. The clouds are orbiting with Keplerian velocity $V_r = \sqrt{GM_{\text{bh}}/r}$. The line of sight velocity and time lag can be written as

$$V_z = \pm V(r) \sin \theta \sin i \quad (2.11)$$

and

$$\tau = \frac{r}{c} (1 + \cos \theta \sin i). \quad (2.12)$$

Since, the BLR is face-on ($i = 0$), the line of sight velocity component is zero. Time lag is also zero except at the location of the BLR cloud and subsequently shows a spike at time $r_{\text{blr}}/c$. As a result, in figure 2.3-1b, the 2D velocity-lag diagram a point appears at the location $(0, r_{\text{blr}}/c)$. The sum of 2D velocity-lag diagram along velocity axis gives the 1D response function of BLR shown in figure 2.3-1c, and sum along time delay axis gives the line profile shown in figure 2.3-1d.
The 1D response function is a delta function at the location of BLR radius, while line profile shows a spike at zero velocity. Note that response functions and line profiles are normalized by their maximum intensity.

A face-on extended thin disk BLR geometry is shown in figure 2.3-2a. Since the clouds are spatially extended, the response comes from various radii of the BLR, and hence the response function is no longer flat but extended according to the distribution of the clouds as shown figure 2.3-2b, which is very similar to figure 2.3-1b, except the line response (figure 2.3-2c) extends up to $2r_{\text{blr}}$. Line profile (figure 2.3-2d) shows a spike at zero, which is due to face-on view.
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The response function of an inclined disk geometry can be calculated by summing the response over different circular orbits. Such an inclined disk with an extended BLR is shown in figure 2.3-3a. As the orbits are inclined, line of sight velocity is no-longer zero, changing the line profile from a delta function ($i = 0^\circ$) to a double peaked profile (figure 2.3-3b). The 2nd response function clearly shows the total response from all different orbits of the disk, and due to large number of orbits, the 2D response function shows a smoothed profile. The extended clouds distribution results in a very extended response function (figure 2.3-3c), which is more than two times than before. The wings of the line profile (figure 2.3-3d) is extended from $-V_r(r_{\text{min}})\sin i$ to $+V_r(r_{\text{min}})\sin i$, where $r_{\text{min}}$ is the inner radius.

A shell geometry, such as one shown in figure 2.3-4a, can be constructed from randomly oriented thin circular orbits with inclination ranging between 0 to $2\pi$. As inclination decreases from $i = 90^\circ$ to $0^\circ$, the projected line of sight velocity decreases from $\pm V_r$ to 0. Similarly, the time lag decreases from $[0, 2r_{\text{blr}}/c]$ to $[r_{\text{blr}}(1-\sin i)/c, r_{\text{blr}}(1-\sin i)/c]$. For $i = 0$, the geometry becomes a ring. Since the BLR orbits are randomly oriented, the projected velocity-time delay diagram appears to be filled up with the response from all the orbits whose size decreases down to zero with decreasing inclination (figure 2.3-4b). Note that, in this case, the 1D response function (figure 2.3-4c) and line profile (figure 2.3-4d) are rectangular functions due to the equal response from all the clouds. Response functions for more complex geometries, in the context of a geometrical and kinematical model, will be discussed in chapter 4.

2.3 Mean and rms spectrum

The BLR size derived from reverberation mapping can be used to determine virial mass of the central black hole knowing its velocity field. Information regarding the dynamics of BLR is encoded in the line profile, which is used to estimate two quantities; the Full Width at Half Maximum (FWHM) and velocity dispersion ($\sigma_l$). Combining width of the spectrum ($\Delta V$) with BLR size, one could infer the virial mass using the following equation:

$$M = f r \Delta v^2 / G,$$

where $f$ is a scale factor that depends on the geometry and kinematics of the BLR.

One concern in the reverberation mapping BH mass estimation using Eq.2.13 is to determine which line-width estimator gives the best mass measurement. Since the ratio of these two measurements (FWHM and $\sigma_l$) varies on object to object as well as on spectral properties. A general tendency is to take all spectra of an object, obtained during the whole monitoring campaign, and estimate their “mean” and “root-mean-square” spectrum (thereafter mean and rms spectrum†). An example of such mean and rms spectrum is shown in figure 2.4 from Peterson (2001). The top panel shows the mean spectrum of NGC 5548 computed from

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†mean spectrum is the average spectrum of all the spectra obtained during the campaign, whereas rms spectrum is based on the variation around this mean.
34 HST spectra whereas the lower panel shows the rms spectrum of the same data. The rms spectrum clearly isolates the constant features or slowly varying components, such as narrow emission line and the host galaxy contribution of the spectrum. However, the variability amplitude of the rms spectrum is low and often too noisy. Collin et al. (2006) showed that both FWHM and $\sigma_l$ measured from rms spectrum have higher uncertainty than the mean spectrum since the former tend to be more noisy. However, they found that for both line width estimators, the width of H$\beta$ line in the mean and the rms spectrum are correlated, though mean spectrum is typically 20% broader than rms spectrum. This suggest that if the narrow line contribution and other contamination features can be taken into account, the line width inferred from mean spectrum is consistence with rms spectrum. Thus care should be taken when dealing with single epoch spectra to estimate BH mass via virial relation since the variable part of the emission line can not be isolated.

Collin et al. (2006) suggested that $\sigma_l$ (second order moment of the line profile is equal to the standard deviation for a Gaussian profile) is a less biased mass estimator, and virial mass calculated using $\sigma_l$ is more consistent than FWHM, since virial mass calculated using $\sigma_l$ is insensitive to the line profile, line ratios, inclination etc., but virial mass estimated using FWHM is affected by the above factors. Hence the use of FWHM and a constant scale factor in virial relation will underestimate or overestimate the masses of the central object. The reason why FWHM is more sensitive to inclination than $\sigma_l$ is that the former is sensitive to the line core that arises in a Keplerian disk component whereas the later is more sensitive to the line wings arising in Disk wind component.
2.4 Size-luminosity relation

Much efforts were made to estimate BLR size from the continuum and the line variability. Several highly sampled multi-wavelength reverberation mapping campaigns were undertaken that successfully recovered time lag of around 50 AGNs but mostly with Hβ line except for few AGNs where multiple emission lines lag were measured. After the success of first better sampled multi-wavelength reverberation mapping, International AGN watch program, during 1988-89 (Peterson et al., 1991), new campaigns were focused on better quality light curve. Kaspi et al. (2000) observed 17 PG quasars with a time span of 7 years for different Balmer lines providing a size-luminosity relationship. In this context, a homogeneous decent sampled data can be found in Peterson et al. (2004). Recent reverberation mapping campaigns such as Lick AGN Monitoring program (LAMP; see Bentz et al., 2009b) are focused on obtaining highly sampled light curve to constrain the BLR, and estimate better time lag and BH mass. Result of a similar recent high quality reverberation mapping program is presented in Bentz et al. (2006) and Grier et al. (2012). Direct model fitting of the LAMP data successfully estimated BLR size and BH mass without virial scale factor providing its detailed geometry and kinematics (Brewer et al., 2011; Pancoast et al., 2012, 2014a). However, this was done only for few very low luminous AGNs, and even with the better quality RM data, parameter degeneracy remains (see chapter 4 and 7). Few attempts were also made to find the size-luminosity relation for high redshift (2 ≤ z ≤ 3.2) and high luminous quasars using CIVλ1550 broad emission line (Kaspi et al., 2007). These observations suggest that

- Different emission lines come from different regions of BLR and arise only when the combination of emissivity and responsivity optimized for that emission line, suggesting ionization stratification of the BLR: higher-ionization lines have shorter time lag and originate closer to the Black Hole than the lower-ionization line.

- Studies of rms spectrum also suggest that BLR is virialized, which means the higher-ionization lines are broader than lower-ionization line ($\tau \propto \Delta V^{-2}$).

- BLR size is related to the AGN luminosity $L$ via a simple relationship, which is approximately $R \propto L^{1/2}$.

Prior to the advance in reverberation mapping, photo-ionization modeling predicted the existence of such size-luminosity relationship (Ferland and Mushotzky, 1982), which was searched even with the first undersampled reverberation mapping observation (Koratkar and Gaskell, 1991), but Kaspi et al. (2000) found a well defined version of this relation, which is $R \propto L^{0.7}$ by studying few PG quasars over a time span of 7 years. However, after several improvements such as better light curve sampling (Bentz et al., 2009b), improved light curve interpolation technique to remove the gaps between different epochs (Zu et al., 2011) and measuring AGN luminosity subtracting the host galaxy contribution (Bentz et al., 2009c), the final relationship looks like $R \propto L^{0.54}$, which is quite close to photo-ionization model prediction. This recent $R - L$ relation, which is obtained for Hβ broad emission line, is shown in figure 2.5. The intrinsic scatter of this relation is 0.13 dex. This
suggested, with an accurate host corrected AGN luminosity, $R - L$ relation in H$\beta$ would allow to obtain BLR size as good as best individual reverberation mapping lag measurements (which is accurate to 0.09 dex). Although $R - L$ relation is well-calibrated only in H$\beta$, some observations indicate similar relation also holds for CIV and UV continuum, however, much efforts are needed to actually have a well-calibrated one (Kaspi et al., 2007).

Current reverberation mapping campaigns however focus on getting highly sampled light curves to estimate accurate time lag, but are mainly limited to the low to intermediate luminosity region and very low redshift $z < 0.2$ because the targets are selected for their apparent brightness, known variability or favorable position in the sky. Certainly, there is a need to expand the reverberation mapping population to calibrate $R - L$ relation for high redshift objects as well. The problem is that the BLR size increases with luminosity and also with redshift as $R \propto (1 + z)^{0.5}$, hence at large redshift, objects are having longer time lag, which means long duration reverberation mapping campaigns, and sufficient sampling is needed to estimate time lag with good accuracy (see Horne et al. (2004) and chapter 5). Another problem is that the line center shifted with redshift as $(1 + z)$, and hence for high redshift objects one needs to observe high ionization lines that are coming closer to the central source and hence CIV line is potentially more important than H$\beta$.

**Outer boundary of the BLR**

The outer boundary of BLR is the most important parameter in the photoionization model since it determines the actual BLR size, gas velocities as well as line ratio of different lines. Recent reverberation mapping observations suggest that the dust sublimation radius is a factor of 4-5 larger than the mean H$\beta$ BLR size.
Figure 2.6: Size-luminosity relation of BLR and dust obtained from RM and OI observations. Radius of innermost dust torus from RM (red filled circle), $K$-band interferometric observation (purple open square), H$_\beta$ BLR radius from RM (blue cross) and location of the hot-dust clouds obtained from the spectral energy distribution (green dot) is plotted against $V$-band luminosity. The lines represent the best fits of the different data sets. This plot is taken from Koshida et al. (2014), a detailed description can be found there.

(Koshida et al., 2014). This suggests that the existence of dust grains beyond the sublimation radius may be a natural boundary of the dust-free BLR. Two independent techniques support this hypothesis.

Monitoring of several AGNs in dust reverberation mapping campaign clearly shows time lag between $K$-band, which is interpreted as the emission from the innermost dust torus, and $V$-band, which is due to the central source (Suganuma et al., 2006; Koshida et al., 2014). In the case of dust reverberation mapping, the $V$-band continuum is absorbed by the innermost dust and re-emitted in $K$-band and hence dust time lag provides size of dust sublimation radius. On the other hand, optical interferometry in near-IR $K$-band successfully resolved the emission from inner rim of dust torus at different temperatures for a handful number of AGNs (Kishimoto et al., 2009a, 2011a,b). These interferometric observations also provided an independent size-luminosity relation of dust in $K$-band. However, the dust reverberation radius is smaller by a factor of two compared to the interferometric radius of the innermost dust torus. This apparent difference between interferometric and reverberation mapping radius observed in the same band could be due to the fact that the former is a flux weighted radius and the latter is response-weighted (Kishimoto et al., 2011b). Since dust temperature decreases with radius, the flux-weighted radius would be larger at large distance than inner boundary of dust, due to flux contribution from lower temperature dust at larger radii. On the other hand, reverberation mapping radius is weighted on a larger amplitude of flux variation and thus coming from a compact emitting region or at smaller radii in the dust torus. The radius of the innermost dust torus as obtained from dust reverberation mapping (red filled circle) and $K$-band interferometric observation
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Figure 2.7: The $M_{bh} - \sigma_*$ relationship of quiescent galaxy (black) and AGNs (blue) as shown in Woo et al. (2010).

Figure 2.8: BH mass - luminosity relation for a sample of 35 reverberation mapping AGNs. The open circles represent NLS1s. From Peterson et al. (2004).

(purple open square), and the H$\beta$ BLR radius (blue cross) as well as the locations of the hot dust clouds (green dot) from spectral energy distribution (SED) fitting of type-1 AGNs are plotted against optical V-band luminosity in figure 2.6, including the best-fit lines for dust and BLR reverberation mapping, showing clear differences in radii of different regions (for a detailed discussion see Koshida et al., 2014).
2.5 Mass-luminosity relation

As noted earlier, study of multiple emission lines suggests that the lines with shorter lag tend to be broader than those with longer lag, and consistent with “virial relation” (Peterson et al., 2004; Peterson and Wandel, 1999). SMBH masses estimated using Eq.2.13 depends on $f$, which is determined by measuring BH mass with other technique.

Since there is no other direct technique to estimate BH mass, a common practice is to use the relationship between BH mass and host-galaxy bulge velocity dispersion, $M_{\text{bh}} - \sigma_*$, It has been seen that the $M_{\text{bh}} - \sigma_*$ relation for quiescent galaxies (Ferrarese and Merritt, 2000) is consistence with the AGNs (Gebhardt et al., 2000b; Onken et al., 2004), although host-galaxy bulge velocity dispersion in AGN is difficult to measure due to its bright nucleus and distant position. However, the assumption allowed to compute a statistical average value of the scale factor, which is $< f > = 5.5$ (Onken et al., 2004). The $M_{\text{bh}} - \sigma_*$ relations for quiescent galaxy (black) and AGNs (blue) are shown in figure 2.7 from Woo et al. (2010) with an average scale factor $< f >= 5.25$. The scatter in scale factor is 0.4 dex, which is the main source of uncertainty in the BH mass measurement. The BH mass and luminosity relation is shown in figure 2.8, which shows a scatter around 30 % (Peterson et al., 2004).

To reduce the uncertainty in BH mass estimate, a compulsory step is to reduce the scatter in scale factor, and thus it is necessary to constrain the BLR geometry and kinematics. Although reverberation mapping is a direct mass estimator where spatial resolution is replaced by time resolution, the dependence on another method, $M_{\text{bh}} - \sigma_*$ relation, makes it a secondary mass estimation method. Very recently few attempts have been made to directly model high quality reverberation mapping data keeping BH mass along with other BLR geometry and kinematics parameters as free (Pancoast et al., 2014a). This study shows very different scale factor for individual objects ranging from 0.7 (0.2) for NGC 6814 to 42.6 (6.1) for Mrk 1310 measured using rms (mean) profile. This suggests that $f$ depends strongly on geometry and kinematics of the individual object. An alternative technique is needed to estimate the black hole mass independent from the virial scale factor constraining the geometry and kinematics of the BLR, and hence calibrating mass-luminosity relation. Such a technique is optical interferometry, which has the potential to spatially resolve the BLR clouds. In the following chapters, I will discuss how optical interferometry can directly estimate BH mass and constrain the BLR geometry and kinematics.

2.6 Summary

Reverberation mapping is a powerful tool, which uses variability to study the BLR of quasar and successfully provided a size-luminosity and mass-luminosity relation. The size-luminosity relation, if properly calibrated, can be used for cosmological distance estimation. The main uncertainty in size-luminosity relation is due to inaccurate time lag estimation, which is due to poor light curve sampling, and
inaccurate luminosity measurement. Recently, many steps have been taken to obtain better quality light curve and host galaxy corrected luminosity measurements. However more efforts are needed to reduce the scatter. The main limitation is that all reverberation mapping targets are highly selective and limited to low redshift. Thus, it is necessary to expand the target list to higher redshift and luminosity as well as for different emission lines, to use the size-luminosity relation as standard candles. The mass-luminosity relation, on the other hand, suffers from the unknown scale factor problem. However, other technique such as interferometry, could solve this scale factor problem by constraining BLR geometry and kinematics, and estimating BH masses directly. This could also allow to estimate distances using “quasar parallax” method combining reverberation mapping data (Elvis and Karovska, 2002).
Chapter 3

Optical interferometry

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3.1 Observing at High resolution

From the time of William Herschel, it was clear that the sharpness of an image is limited by atmosphere rather than the optics of the telescope. Reaching the diffraction limit of a single-dish was a big challenge in the past. A remarkable technique was proposed by Fizeau to overcome the diffraction limit of a single telescope by observing through a pair of holes. Following this, various methods have been proposed to overcome the diffraction limit of a telescope such as Speckle interferometry by Labeyrie (1970), Adaptive optics (Babcock, 1953; Beckers, 1993) and Aperture masking (Baldwin et al., 1986). Although, with the help of all the above techniques, it was not possible to resolve the central structure of AGNs.

Multi-telescopes optical interferometry (OI) is intended to provide very high angular resolution information, and ideally images, with resolution $\lambda/B$ where $\lambda$ is the observation wavelength and $B$ is the interferometer baseline, i.e., the maximum distance between two apertures. After a long period of pioneering instrumental
results, the 2000 decade has seen an explosion of the number of science papers produced by optical interferometry, mainly triggered by the the interferometric mode of the VLT, called the VLTI (Glindeham et al., 2000), and its AMBER and MIDI instruments, followed in number of papers by the US interferometers CHARA, PTI, IOATA, NPOI and KI. A recent review of OI science results can be found in Jankov (2011). The major OI instruments in operation are spectro-interferometers, which means that the interferometric measures are obtained in several spectral channels simultaneously with resolutions ranging from 30-40 (LR for low resolution) to 300-1500, often called medium resolution or MR, and 12000-30000, which is the high resolution (HR) domain. The cross analysis of interferogram, simultaneously obtained in different spectral channels, allows high accuracy differential interferometric observations, which give access to high dynamical features or to very unresolved objects with small signature (“differential interferometry” Petrov, 1989). The different spectro-interferometric measurements and their uses are presented later in this chapter in the context of the VLTI near infrared spectro-interferometric instrument AMBER (Petrov et al., 2007).

### 3.2 Basics of interferometry

Present OI is somehow a modification of the famous Young’s double slit experiment, which was done in nineteenth century by Thomas Young, who used a screen with two holes and another screen as a detector for interferometric pattern as shown in figure 3.1. The former is now replaced by two individual telescopes separated by a distance that is usually referred as the baseline of the interferometer, whereas an interferometric beam combiner is used in place of the second screen. The light beams from two telescopes are then carefully combined and fringe pattern is produced due to interference of the light beams and provide information.
about the source with a resolution $\theta \propto \lambda/B$, where $\lambda$ is the observing wavelength. The observed intensity at the image plane is simply the modulus squared of the summation of the electric field arriving from two slits. If, we consider them as $E_1$ and $E_2$ respectively, then the observed intensity

$$I = \langle (E_1 + E_2) \times (E_1 + E_2) \rangle$$

$$= \langle |E_1|^2 \rangle + \langle |E_2|^2 \rangle + 2 \langle |E_1||E_2|\cos(\phi) \rangle,$$

where $\phi$ is the phase difference between two electric fields, and the first two terms define the mean intensity of the fringes, while the third term refers to the visibility function.

We are mainly interested in measuring two quantities of the fringes, its amplitude and its phase. Fringe amplitude or contrast is the measure of the “Michelson visibility”, which is related to the maximum and minimum intensities of the fringe pattern by

$$V_M = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}.$$  (3.3)

On the other hand, fringe phase gives the position of the fringe center with respect to the zero optical-path-difference (OPD) position (for a review, see Haniff, 2007).

An interferometer with baseline $B$ yields the complex visibility of the source, i.e. the normalized Fourier Transform $\hat{O}(\mathbf{u}, \lambda)$ of the source brightness distribution $O(\mathbf{r}, \lambda)$ at the spatial frequency $\mathbf{u} = B/\lambda$. According to the van Cittert Zernike theorem

$$\hat{O}(\mathbf{u}, \lambda) = \frac{\iint O(\mathbf{r}, \lambda)e^{-2\pi i \mathbf{u} \cdot \mathbf{r}} d^2 \mathbf{r}}{\iint O(\mathbf{r}, \lambda) d^2 \mathbf{r}} = V_s(\lambda)e^{i\phi_s(\lambda)}.$$  (3.4)

The modulus $V_s(\lambda)$ of $\hat{O}(\mathbf{u}, \lambda)$ is given by the contrast of the fringes and called the source absolute visibility. The relative position of the fringes yields the phase $\phi_s(\lambda)$ of the source complex visibility.

A schematic diagram of a two telescopes interferometer is shown in figure 3.2, which mainly consists of five different sections, each of which plays crucial role such as:

- Two collectors collecting the photons from the source we are looking at.
- A beam transport system to carry the signal from the telescope to the central laboratory where the beams can be combined. The distances between collector and beam combiner are $d_1$ and $d_2$ for two different telescopes.
- A delay line system to adjust the additional path travel by one beam compared to the other before combination.
- A beam combiner.
- A detector to store the signals obtained from beam combination.

Since the atmosphere constantly changes, the refractive index $n(\lambda)$ and hence the OPD also change. To overcome this, it is either necessary to make short exposures and extract the piston (OPD difference) from monochromatic delay before
Figure 3.2: A simple cartoon to illustrate a two telescopes interferometer. Different parts play different role explained in the main text.
computing the differential phase (see later), or to use an adaptive system called a fringe tracker that freezes the OPD (with $\lambda/u$) and allows to use less exposures. The variation of OPD during the frame is a major reason for instrumental contrast change, and hence loss of visibility accuracy. Thus a fringe tracker increases substantially the measurement accuracy. Fringe tracker can be the instrument itself, or a specialized device operating at a different wavelength or different beam combination architecture (see Petrov et al., 2014).

The monochromatic electric field, at the beam combiner, for two different apertures, can be defined as a function time $t$ by

$$\Psi_1 = A_1 \exp (ik \hat{s} \cdot \mathbf{B} + d_1) \exp(i\omega t) \tag{3.5}$$

$$\Psi_2 = A_2 \exp (ikd_2) \exp(i\omega t), \tag{3.6}$$

where, $A_1$ and $A_2$ are proportional to the collecting area of the telescope. If they are equally sensitive then $A_1 = A_2 = A$. The resulting intensity after the combination, can be written as

$$I = < |\Psi_1 + \Psi_2|^2 > \propto 2 + 2\cos (ik \hat{s} \cdot \mathbf{B} + d_1 - d_2) \propto 2 + 2\cos(kD), \tag{3.7}$$

where the quantity $D = [\hat{s} \cdot \mathbf{B} + d_1 - d_2]$ is often called the delay or the optical path difference (OPD) between two beams and $k = 2\pi/\lambda$. In reality $D$ includes an atmospheric delay term that makes difficult to obtain the phase information in a two telescopes interferometer.

The projected baseline $\mathbf{B}$, i.e. the separation between two telescopes as seen from the source, can be defined as $\mathbf{B} = B_X \hat{i} + B_Y \hat{j} = \lambda (u \hat{i} + v \hat{j})$, where $B_X$ and $B_Y$ are the baseline components along $x$ and $y$ axis respectively. The spatial frequencies $u$ and $v$ are defined as

$$u = B_X \cos h - B_Y \sin \phi \sin h \tag{3.9}$$

$$v = B_X \sin \delta \sin h + B_Y (\sin \phi \sin \delta + \cos \phi \cos \delta), \tag{3.10}$$

where $h$ is the hour angle, $\delta$ is the declination and $\phi$ is the latitude of the interferometer.

Since, at any given wavelength ($\lambda_0$), the detector has a finite bandpass ($\Delta \lambda$), the above monochromatic treatment is not applicable, and hence we need to consider the polychromatic case by integrating Eq.3.8 for uniform bandpass:

$$I \propto \int_{\lambda_0 - \Delta \lambda/2}^{\lambda_0 + \Delta \lambda/2} 2[1 + \cos(2\pi D/\lambda)]d\lambda \propto \Delta \lambda \left[ 1 + \frac{\sin(\pi D)\lambda_0^2}{(\pi D)^2}\cos(k_0 D) \right] \tag{3.11}$$

$$\propto \Delta \lambda \left[ 1 + \frac{\sin(\pi D/L_{\text{coh}})}{(\pi D/L_{\text{coh}})}\cos(k_0 D) \right], \tag{3.12}$$

$$\propto \Delta \lambda \left[ 1 + \frac{\sin(\pi D/L_{\text{coh}})}{(\pi D/L_{\text{coh}})}\cos(k_0 D) \right], \tag{3.13}$$
where the quantity $\Lambda_{\text{coh}} = \frac{\lambda_0^2}{\Delta \lambda}$ is called the coherence length and $k_0 = \frac{2\pi}{\lambda_0}$.

Thus, the response of polychromatic detector is a modulation of the fringes by a sinc function, which is so-called “coherence envelope”.

The resulting fringe pattern for a two telescopes interferometer as a function of optical path difference (OPD) is shown in figure 3.3. Fringe contrast is modulated by coherence envelope. Thus, delay lines are needed to match the optical path better than $\Lambda_{\text{coh}}$, otherwise the measured fringe visibility will not be the source coherence function. As the fringe contrast is reduced by the coherence envelop, the OPD should be $<< \Lambda_{\text{coh}}$.

### 3.3 Spectro-interferometric measurements

A spectro-interferometric instrument such as AMBER (Petrov et al., 2007) provides several observables, in each spectral channel, absolute visibility, differential visibility, differential phase and closure phase (a detail discussion about these can be found in Petrov et al., 2007; Petrov, 2012). In this section, first, I will give equations related to spectro-interferometric measurements and then briefly discuss them.

Although the basic equation of optical interferometry is given by Eq.3.4, in reality what we measure is the Fourier interferogram $\hat{I}(u, \lambda)$ from the Fourier Transform (FT) of the fringe intensity distribution $I(u, \lambda)$. In multi-axial instruments with $n_T$ telescopes, like AMBER ($n_T = 3$), we have a single interferogram where the
three baselines are separated in frequency space.

\[
\hat{I}(u, \lambda) = \hat{F}(u, \lambda) \sum_{i=1}^{n_T} p_{si}(\lambda) + \sum_{i,j>i}^{n_T} \hat{F}(u - u_{ij}, \lambda) \sqrt{p_{si}(\lambda)p_{sj}(\lambda)} \times V_{sij}(\lambda)V_{ij}(\lambda)e^{j[\phi_{sij}(\lambda)+\phi_{ij}(\lambda)]},
\]  

(3.14)

where \(p_{si}(\lambda)\) is the contribution of telescope \(i\) to the source flux collected in the interferometric channel; \(\hat{F}(u, \lambda)\) is a fixed instrumental function (product of the individual aperture transfer function by an instrument window transfer function); \(V_{sij}(\lambda)\) and \(\phi_{sij}(\lambda)\) are the source visibility and phase at the spatial frequency \(u_{ij} = B_{ij}/\lambda\) where \(B_{ij}\) is the baseline length between apertures \(i\) and \(j\); \(V_{ij}(\lambda)\) and \(\phi_{ij}(\lambda)\) are the instrumental visibility and phase terms respectively. After the correction of photometry and coherent flux (see chapter 5), the (average) Fourier interferogram at the spatial frequency \(u_{ij}\) yields an estimate of the complex visibility

\[
C_{Mij}(\lambda) = V_{sij}(\lambda)V_{ij}(\lambda)e^{j[\phi_{sij}(\lambda)+\phi_{ij}(\lambda)]}.
\]

(3.15)

We have to calibrate \(V_{ij}(\lambda)\) and \(\phi_{ij}(\lambda)\) to obtain the source information \(V_{sij}(\lambda)\) and \(\phi_{sij}(\lambda)\). The instrumental contrast \(V_{ij}(\lambda)\) is calibrated by the observation of a reference source with known \(V_{sij}(\lambda)\) (ideally \(V_{sij}(\lambda) = 1\) for a fully unresolved source). The calibration procedure assumes that \(V_{ij}(\lambda)\) is constant in time, which is seldom the case. In practice the changes in instrumental contrast limit the accuracy on the absolute visibility \(V_{sij}(\lambda)\) to 0.05, or 0.03 in the best case (Petrov et al., 2007; Petrov, 2012).

However, the wavelength dependent \(V_{ij}(\lambda)\) is often very stable, particularly for MR observation where we look at a small wavelength range. This explains the interest to use the differential visibility

\[
V_{dij}(\lambda) = \frac{|C_{Mij}(\lambda)|}{C_{Mij}(\lambda_{ref})} = \frac{V_{sij}(\lambda)}{V_{sij}(\lambda_{ref})}.
\]

(3.16)

For simplicity, we assumed that the instrument differential visibility \(\frac{V_{ij}(\lambda)}{V_{ij}(\lambda_{ref})} = 1\).

The measured phase \(\phi_{sij}(\lambda)\) is affected by the instrumental achromatic differential piston \(\delta_{ij}\) and instantaneous atmospheric piston. The phase introduced by the achromatic piston is \(\phi_{ij}(\lambda) = 2\pi\delta^{ij}(\sigma)\), where \(\sigma = 1/\lambda\). There are two ways to obtain phase information from the source complex visibility. The first one is the closure phase between triplets of baseline, for instruments with at least 3 telescopes:

\[
\Psi_{ijk}(\lambda) = \arg[C_{Mij}(\lambda)C_{Mjk}(\lambda)C_{Mij}^*(\lambda)] = \phi_{sij}(\lambda) + \phi_{sjk}(\lambda) - \phi_{sk}(\lambda)
\]

(3.17)

because the instrumental closure phase \(\Psi_{ijk}(\lambda) = \phi_{ij}(\lambda) + \phi_{jk}(\lambda) - \phi_{ik}(\lambda) = 0\) as discovered by radio astronomers more than 50 years ago. The second one is to use the differential phase. The phase of the reference channel can be well known in MR, continuum channel, where the source phase is supposed to be constant. Thus, we first fit the measured phase with a linear function of \(\sigma\) allowing us to
correct the residual piston

\[
\phi_{\text{d}ij}(\lambda) = \arg[C_{Mij}(\lambda)C_{Mij}(\lambda_{\text{ref}})] = \phi_{\text{s}ij}(\lambda) - \phi_{\text{s}ij}(\lambda_{\text{ref}}).
\] (3.18)

Note that reference channel can be defined in many ways and must be accounted in model fitting process.

Thus, spectro-interferometric measurements can be summarized as follows:

- **Spectrum:** Spectrum of the emission line is an important observable that contains informations on the physical conditions, chemistry and kinematics of the object. Each individual beam from each telescope provides one spectrum in the observing spectral window. It is necessary to calibrate the spectrum in the amplitude and wavelength, and averaging them in one spectrum. Thus a calibrator with known continuum and spectral features, and magnitude and position close to the science target has to be used. The spectrum is used to constrain kinematics of many objects (see for example Meilland et al., 2007).

- **Absolute visibility:** Absolute visibility is obtained from the fringe contrast, and it is the modulus of the source complex visibility (Eq.3.4). It gives information on the size of the source in the direction of observed baseline (if the source is centro-symmetric then absolute visibility should be same in all directions). However, note that, absolute visibility, obtained from any interferometer, depends on the instrument and atmospheric parameters, hence it has to be calibrated prior to use to constrain source morphology. Usually, a source with known visibility, known as “calibrator”, is used to correct the “instrumental visibility” considering that both the calibrator and science target are observed in the same condition, which makes the calibration process difficult.

- **Differential visibility:** An accurate measurement of the visibility can be obtained from the Differential visibility, by self calibrating the absolute visibility with respect to the visibility of the reference channel or the broad band visibility defined in Eq.3.16. Our recent AMBER observation of 3C273 shows that the accuracy on the differential visibility can be as good as 1%, though the accuracy on absolute visibility is of the order of 5% (Petrov et al., 2012). The reason is that the differential visibility is free from the systemic effects that are present in absolute visibility, and also insensitive to the variation of the “piston”, which is the average of the wavefront OPD, over a limited wavelength range. Moreover, differential visibility does not require a calibrator star to eliminate the instrument effects.

- **Differential phase:** Source absolute phase refers to the phase of the complex visibility (Eq.3.4). However, measuring absolute phase is not possible, since OPD changes with atmosphere. Because of this, an off-axis reference source is needed, which is however often not available. Moreover, a complicated system is needed to get rid of instrument and atmospheric effects. One way is to measure the differential phase as written in Eq.3.18. In order to calculate the differential phase we subtract first average slope and then average phase.
• **Closure phase:** The closure phase, which is a combination of phases measured on three baselines, as defined by Eq.3.17, is free from optical path affecting individual beams. Closure phase combined with accurate visibility can be used to reconstruct image of the astronomical source and to obtain detailed information about it (Lawson et al., 2006). However, note that, closure phase is difficult to measure and often difficult to interpret.

### 3.3.1 Differential interferometry of non-resolved sources

A non-resolved source has a global angular size $\Lambda$ smaller than the interferometer resolution limit $\lambda/B$. In Eq.3.4, this implies that $o(r, \lambda)$ is different from 0 only for values of $r < \lambda/B = 1/u$, i.e. the integral in Eq.3.4 can be limited to values $ur < 1$. Since Petrov (1989), we know that the interferometric phase for such a source is given by

$$\phi_{ij}(\lambda) = 2\pi u_{ij} \cdot \epsilon_{ij}(\lambda), \quad (3.19)$$

where,

$$\epsilon_{ij}(\lambda) = \int\int o(r, \lambda) d^2 r \int\int o(r, \lambda) d^2 r \quad (3.20)$$

is the photocenter of the source. This result has been obtained from a first order limited development of the complex visibility $\tilde{O}(u, \lambda)$. Extending this development to higher terms (Rakshit and Petrov, 2014) shows that the source visibility $V_{ij}$ is given by

$$V_{ij} = 1 - \alpha^2_{ij} \quad \text{where} \quad \alpha = \frac{\pi \Lambda}{\sqrt{2} \left( \frac{\lambda}{B} \right)}, \quad (3.21)$$

and the closure phase decreases as $\alpha^3$. However, photocenter decreases only like $\frac{RB}{\lambda}$ between the source size, $R \propto \epsilon(\lambda)$, and the interferometric resolution $(\lambda/B)$, while $1-V(\lambda)$ decreases like $(\frac{RB}{\lambda})^2$. Hence photocenter displacement can easily be measured for unresolved sources. Its application to unresolved sources had been proposed first for differential speckle interferometry by Beckers (1982) and extended to the long baseline interferometry by Petrov (1989).

### 3.4 Modeling visibility

As already mentioned in the previous section, modeling interferometric measurements provide the source brightness distribution though Eq.3.4, and hence in this section I will discuss some simple models and show how their visibility functions look like. This will help to understand how visibility changes with baseline length for different simple geometries. Various complex models that can be fitted to the observed data to better constrain the geometry and dynamics, will be discussed in the following chapters in the context of model fitting.

Intensity distribution and the corresponding visibility function is plotted in figure 3.4 for different simple geometries; point source, binary source, Gaussian and uniform disk.
Figure 3.4: Examples of the visibility functions for various simple source surface brightness distributions are plotted. From top to bottom the models are point source, binary source, Gaussian and uniform disk. The surface brightness is plotted on the left while on the right corresponding visibility functions are plotted. Colors on the left panels corresponds to the right panels.
Point source:

Intensity distribution of a point source can be written in terms of a Dirac $\delta$-function as shown in upper-left panel of figure 3.4:

$$I(r) = I_0 \delta(r - r_0), \quad (3.22)$$

where, $r = \sqrt{x^2 + y^2}$ is the radial coordinate and $r_0$ is the position of the source.

The Fourier transform of a point source gives a complex visibility whose amplitude is 1. Thus, the absolute visibility is always constant and is equal to 1 as shown in upper-right panel figure 3.4:

$$V(u) = 1, \quad (3.23)$$

where $u = B/\lambda$ is the spatial frequency as noted earlier. This shows that visibility of a point source is independent of spatial frequency or the length of baseline and always remain unresolved. If we have source phase information, which in this case is $e^{-2\pi u r_0}$, we will have the information about its position, since source phase varies linearly with spatial frequency ($u$) with a slope of $r_0$.

Binary:

A binary system consists of two point sources or two Dirac-$\delta$ functions separated by distance $d$. The intensity distribution can be written in terms of radial coordinate as

$$I(r) = I_1 \delta(r - \frac{d}{2}) + I_2 \delta(r + \frac{d}{2}). \quad (3.24)$$

The fluxes of two sources are represented by $I_1$ and $I_2$ ($I_1 + I_2 = 1$) respectively. Note that visibility of a binary strongly depends on the projected baseline, and if the baseline is perpendicular to the binary, visibility function will be constant, $V(u) = 1$, as interferometer will see only one point source. The visibility function for a binary can be written as

$$V(u) = \sqrt{\frac{1 + f^2 + 2f \cos(2\pi ud)}{1 + f}}, \quad (3.25)$$

where $f = I_1/I_2$ is the intensity ratio of two point sources. The intensity distribution and corresponding visibility for two different binaries with different flux ratios are plotted in 2nd row of figure 3.4. Thus, flux ratio has a strong effect on visibility signature.

Gaussian:

Gaussian function often used to model source brightness distribution since a complex source at low resolution can be represented by a simple Gaussian, which can be defined with zero mean and standard deviation $\sigma$ as

$$I(r) = e^{-\frac{r^2}{2\sigma^2}}. \quad (3.26)$$

Its visibility function

$$V(u) = e^{-2(\pi \sigma u)^2}, \quad (3.27)$$
is also a Gaussian function as shown in 3rd row of figure 3.4. Note that, in Fourier space, source size is inversely proportional to the source size of real space i.e., an extended source in real space (for example green Gaussian) appears compact in the Fourier space.

**Uniform disk:**

Stellar surfaces are often described by a uniform disk. Its intensity distribution can simply be written as

\[
I(r) = \begin{cases} 
I_0 & \text{for } |d| \leq d/2 \\
0 & \text{else.}
\end{cases}
\]

(3.28)

(3.29)

Its absolute visibility is given by

\[
V(u) = \left| \frac{2J_1(\pi ud)}{\pi ud} \right|,
\]

(3.30)

where \( J_1 \) is the Bessel function of the first kind of the order 1. Intensity distribution and corresponding visibility for a uniform disk are shown in lower panel of figure 3.4.

### 3.5 The VLTI

To observe faint targets such as AGN, it is necessary to use interferometers with large apertures (8-10 m) to collect a large number of photons. Thus, only two interferometers: Very Large Telescope Interferometer (VLTI) and Keck Interferometer (KI), have the capability to observe AGNs (Glindemann et al., 2000). Unfortunately, KI is no longer in operation. Other interferometers such CHARA, NPOI etc. have longer baselines, but consist of smaller telescopes and hence are mainly focused to study stars. As a consequence, present optical interferometric observation of AGNs only depends on VLTI. It offers several beam combiners such as MIDI working on mid-IR and AMBER working on near-IR. Mid-IR emission originates from warm dust \( (T \sim 300 \text{ K}) \), and hence it was extensively used to study the dust structure, while AMBER works in near-IR K-band, where emission originates from hot dust and gas \( (T \sim 1500 \text{ K}) \), and hence is used to study inner structure of the dust torus and the BLR emission line in MR.
The VLTI is located at 24°40′S, 70°25′W at the top of Cerro Paranal in the Atacama desert at altitude of 2635 m. The unique location in the driest desert provides a great observation conditions; many clear nights with good stable seeing. Its remote location ensures minimum light pollution by human. These conditions allow infrared wave band to be transparent and thus a great advantage for high spatial resolution observation all over the year.

VLTI consists of four 8.0 m unit telescopes (UTs) located at fixed position and four movable 1.8 m auxiliary telescopes (ATs) as shown in figure 3.5. The maximum ground separation or baseline length of the UTs is 130 m, which is the distance between UT1-UT4, providing milli-arcsecond spatial resolution. We can combine three telescopes using AMBER (Petrov et al., 2007) offering simultaneous observation using three telescopes ($N_b = \frac{N_{tel}(N_{tel}-1)}{2}$) in near-IR and four telescopes using PIONIER (see section 3.5.2).

3.5.1 Light transportation and delay line

The most complicated system in VLTI is hidden underneath the UT platform and used to transport and combine the light beams, which is first received by individual telescope and then transferred via Nasmyth focus to the Coude room located underneath the platform. The wavefronts are then corrected from the atmospheric distortion by the adaptive optics (AO) system Multi-Application Curvature Adaptive Optics (MACAO; Arsenault et al., 2003). In near-IR or shorter wavelength, MACAO is very useful to correct wavefronts of the individual telescopes. In addition, another fringe tracking instrument, FINITO (Fringe-tracking Instrument of NICE and TOrino), a three-beams fringe tracker that operates in the $H$ band, is used at VLTI to measure the relative phase difference between the light beams.

After the AO correction the light is transported to the delay lines, which consists of retro-reflector carriages on a movable rail as shown in figure 3.6. The complicated delay line system is thus used to adjust the optical path between the light beams, which was discussed before. Several variable curvature mirrors (VCMs) maintain the VLTI pupil fixed in the focal lab while the delay line moves by adjusting their curvature. An Infrared Image Sensor (IRIS) is used here to correct the additional delay introduced by the air in the VLTI delay line tunnel and is not corrected by the MACAO or FINITO. After optical delay adjustment, light is guided to the interferometric laboratory to combine different light beams. Beam compressors are also used to compress the light beam to obtain equal diameter beams before sending them to the beam-combiners.

VLTI provides unique opportunity to connect many UTs or ATs in near and mid-IR in interferometric mode. However, its complicated light transportation system, i.e., light has to go through several reflections, limits the sensitivity of the interferometer. Only about 15% of light received by the telescopes can thus reach the interferometric beam-combiners (Puech et al., 2006), and the global VLTI plus instrument plus detector efficiency is of the order of 10%.
3.5.2 VLTI instruments

Several instruments are dedicated to the interferometric observations at VLTI.

- **MIDI**: A two beams combiner works at the mid-IR wavelength (8 – 13µm, Leinert et al., 2003). It has two spectral resolution mode 230 and 30. It was used extensively in the case of AGN to study mid-IR emission from the dust torus. MIDI has recently been decommissioned.

- **AMBER**: A three beams combiner working on near-IR (1 – 2.5 µm) in J, H and K bands (Petrov et al., 2007). It has 3 spectral resolution mode; 12000, 1500, 30. This is the only instrument allowing to study BLR of AGN with resolution 1500 in K band and hence will be discussed later in detail.

- **PIONIER**: A four beams combiner in H band (Le Bouquin et al., 2011). It allows mainly imaging at low spectral resolution and not useful in studying AGNs so far (very faint in H band).

VLTI future instruments or the next generation instruments are

- **MATISSE**: A four beams combiner in L, M and N bands (Lopez et al., 2006). This will be very useful to study AGN dust torus geometry.

- **GRAVITY**: Four beams combiner in K band, with spectroscopic, fringe tracking and astrometric capabilities (Eisenhauer et al., 2008). Gravity would allow to observe BLR of AGNs. These applications will be discussed in chapter 6.
3.5.3 The AMBER instrument

Astronomical Multi-BEam combinerR (AMBER) is the first-generation general-user near-infrared (\(J\), \(H\), and \(K\) bands) interferometric beam combiner of the VLTI (A general description about AMBER can be found in Petrov et al. (2007), and its data reduction process has been explained in Tatulli et al. (2007)). Figure 3.7 shows a photograph of AMBER instrument with its different components. It combines light beams coming from three different telescopes. It is in operation at VLTI since 2004. AMBER fringes are spectrally dispersed and it provides interferometric observation at three different spectral resolutions: \(R \sim 30\) i.e. low, \(R \sim 1500\) i.e. medium, and, \(R \sim 12000\) i.e. high resolution. It was designed to obtain milli-arcsecond resolution to study the astrophysical objects like young and evolved stars as well as AGNs, and to possibly detect exoplanet signal. AMBER uses optical fibers and a dispersed fringe combiner using spatial coding.

Initially, AMBER and FINITO were expected to reach \(K > 10\) and hence to study some AGNs. Mainly because of VLTI problems, the limiting magnitude of both systems was limited to about \(8 - 9\) (AMBER in LR in \(K\) band) and FINITO limited to \(8 - 8.5\) for MR observations. This is because both need an SNR \(> 1\) for each short exposure and channel. In 2011, we implemented AMBER+, that can work in “blind mode” and for SNR \(< < 1\) per frame and spectral channel (see section 3.6.1). This allowed LR as well as MR observations in \(K = 10 - 11\) range. With some recent VLTI improvements this limit might be up to \(K > 11\). This will be discussed in more detail in chapters 5 and 6.

The basic concept of AMBER design is shown in figure 3.8. It works in three steps. First, a single mode fiber (at the left) is used to filter beams coming from three telescopes to convert the phase fluctuation of the corrugated wavefront to intensity fluctuation. The amount of light entering the filter depends on the Strehl ratio\(^*\). The beams are then compressed into one dimensional elongated beams by a pair of conjugated cylindrical mirrors and guided to the entrance slit of the spectrograph. One part of the light is then separated from each beam using beam-splitters and

\(^*\)It is the ratio of peak diffraction intensities of an aberrated vs. perfect wavefront.
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**Figure 3.8:** Basic layout of AMBER. The beams, from three telescopes, enter to the spatial filter (left) and then passing through complicated setup reach to the detector (right) where photometric and one interferometric data are recorded. See the text for detail. Right panel shows an example of AMBER reconstituted image from the raw data of HD135382 obtain in medium resolution. Each column in detector shows dark region (DK), three photometric regions (P1, P2 and P3), and one interferogram (IF). Image from Tatulli et al. (2007)

Different tilt is applied to each beam to put them in different location on the detector, and as a result we obtain three photometric channels corresponding to each incoming beam. While the other part of light of the three beams are allowed to superimpose on the detector image plane obtaining interference fringes. A spectral dispersing element (prism or gratings) is used to disperse the beams in the pupil plane and hence all three photometric regions and one interferogram are spectrally dispersed allowing to record all observables on the detector.

AMBER has Rockwell/HAWAII detector with readout noise $11e^-$, cooled by liquid nitrogen at a temperature of 78 K, covering a spectral window of $0.8 - 2.5 \mu m$ (see Petrov et al., 2007; Tatulli et al., 2007). It consists of $512 \times 512$ pixel array in which first 20 pixels are masked and used to estimate read-out noise and bias during an exposure. These pixels are noted as “DK” in the figure 3.8, while the photometric outputs, noted as “P1”, “P2” and “P3”, are 32 pixels wide. The interferometric output, which stores interference fringes, is using $N_{\text{pix}} = 32$ pixels.

Additionally, a calibration and alignment unit (CAU) is used to provide well defined artificial fringes for the interferometric calibration process, and a polarization corrector is used to eliminate one of the polarization of the incoming beams but losing 50% of the incoming photons. This polarization correction is necessary since single-mode fibers, which are used in AMBER, introduces a variable OPD between two polarizations and can destroy the instrumental contrast.

In an interferometer with multi-axial recombination mode, such as AMBER, there is a linear relationship between pixels of the interferogram and the instantaneous complex visibilities. This concept is known as Pixel to Visibility Matrix (thereafter P2VM; Tatulli et al., 2007; Chelli et al., 2009). In P2VM data processing (Tatulli et al., 2007), the shape of unresolved source fringe and calibrated giving a Visibility to Pixel Matrix (V2PM). Thus, we fit the best source complex visibilities on the 3 baselines that match the observed interferogram and photometric measurements. This is obtained through a geometrical inversion of V2PM that is the P2VM.
This procedure works only if individual phase can be obtained in each frame, that assumes an SNR per frame is greater than 1.

### 3.6 Observing with AMBER

AGN observations with AMBER are performed in “visitor mode” allowing the observer to be present at the VLTI operating room during observation along with ESO astronomer, unlike the “service mode” in which observations are performed only by ESO astronomers without the presence of observers. Observers can guide the astronomer on the strategies that need to be followed during the observation. This is particularly important as AGNs are observed in the non-standard AMBER+ “blind mode”.

To ask for observing time, a proposal must be written and submitted to ESO. Several cares should be taken to write the proposal such as information about source, its visibilities and suitable calibrators, selection of the baselines, list of backup targets in case of problem to observe desired target etc. Once the proposal is selected, observer in “visitor mode” is invited to go to the site. Prior to the observing night, different blocks of observations, depending on the strategies, are created using standard tool “Phase 2 Preparation Package” (P2PP), which are then used to perform observation through VLT control system. These blocks include information regarding templates, instrument setup, pointing interferometer...

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2. A detail description can be found here: [http://www.eso.org/sci/observing/phase2/SMGuidelines/Documentation/P2PPTutorialAMBER.html](http://www.eso.org/sci/observing/phase2/SMGuidelines/Documentation/P2PPTutorialAMBER.html)
to the target, optimizing beam injection in AMBER, fringe search to obtain the exact zero OPD (ZOPD), and finally acquiring observation data. When fringes have been found and tracking of fringes is done, actual integration starts to record data (a photograph of VLTI/AMBER control room is shown in figure 3.9, which was taken before our observation).

Using P2PP, an observer can change some of the parameters such as wavelength range, spectral dispersion, or detector integration time (DIT). Night astronomer can use Breaker of Observing Blocks (BOB) to successfully execute the observation and can abort or redo some part if necessary.

### 3.6.1 Blind mode observation

A different approach was developed by our group to observe faint targets like QSOs with AMBER since to study the BLR emission line we need to resolve the emission line spectrally. Spectral resolution greater than 500 would give access more than 10 velocity bins allowing to constrain the global velocity field. A resolution around 200 would give access to the size and position of the BLR. However, to obtain such a resolution in near-IR, a traditional point of view is to have a fringe tracker to stabilize the fringes. It allows exposure times longer than the piston coherence time, and this is necessary to get out of the detector noise regime. Our first proposal for differential interferometric observation of BLR with AMBER/VLTI assumed fringe tracking, and an expected photocenter accuracy of 2\(\mu\)m for one hour of observation on a \(K = 10\) magnitude object. This implied that two dozens of target could be observed using our observation technique (Marconi et al., 2003).

The limiting magnitude of the fringe tracker poses a problem for BLR observations. As per ESO call for proposal\(^8\), medium resolution observation with AMBER/VLTI allows fringe tracking up to \(K = 7.5\) with UTs, and at maximum \(K = 8.5\) in very close conditions.

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\(^8\)http://www.eso.org/sci/observing/phase1.html
good weather condition since the current fringe trackers need a sufficient SNR in extremely short exposures, to be able to freeze the piston at a fraction of wavelength. As a result, it is difficult to have fringe tracker to observe AGN in medium resolution. This makes observation of BLR very difficult.

Due to above problems, we have developed a new observing technique called “Blind mode observation” keeping in mind that it is not necessary to detect fringes in each individual frame. With the medium spectral resolution of AMBER, the coherence length in the $K$ band is of about 3 mm. The atmospheric piston jitter has a RMS amplitude of typically a few tens of microns and the delay line model errors and drift are below 100 $\mu$m/mn. So, after centering the fringes on a bright calibrator, we have at least half an hour to observe a faint target with the guarantee that the fringes are present in the data, even if each individual frame looks just as detector noise. This is why it is called “blind mode” as no fringes can be seen on the detector nor by the Fourier transform. We still need to make exposures short enough to have a good fringe contrast. We must integrate values which are not sensitive to the piston value but still contain information about the source visibility, differential phase and closure phase.

The Blind mode technique can be summarized as:

- First, we find the fringes on a bright calibrator and we know that they will remain within the coherence length of MR observations (3 mm in $K$) for at least 10 minutes.

- Then, we observe the faint target, without detecting any fringes in individual frames (i.e. P2VM is useless) and we accumulate incoherently the 2-Dimensional Fourier Transform (2DFT) of the $x-\lambda$ interferograms similar to the REGAIN/GI2T and VEGA/CHARA data accumulation technique (Berio et al., 1999). The 2DFT data processing is discussed in the following section.

- Then data is processed (see section 3.6.2 and Petrov et al., 2012), and the fringe peaks appear in a few seconds in the average $|2\text{DFT}|^2$, showing the average piston. This average piston value is communicated to the operator, with typically half a minute delay, and allows him to correct for slow OPD drift. In MR observation, such corrections are useful typically in every 10 minutes, to keep the fringe peaks in a correct position (within 100 $\mu$m). A correct position is defined by fringe peaks well separated in the piston (i.e. $\lambda$ direction). This is necessary because we cannot use the P2VM fit to separate the contribution of partially overlapping fringe peaks.

- The final data processing, described in Petrov et al. (2012), allows extracting unbiased visibility, differential visibility and differential phase from each 1 minute exposure of data.

This principle is further illustrated by figure 3.10, in which, on the left, three $x-\lambda$ interferograms have been shown with an image at the rightmost panel that shows 10' average of 2D Fourier transform of the $x-\lambda$ interferogram. Among the three interferograms, the figure 3.10a (left) is for a bright star with $K = 4$ showing clearly
three well-separated fringes, while the figure 3.10b (middle) is for a faint source of $K = 8.5$. This is the limit of the P2VM operation, where fringes are quite hard to see, but frame-by-frame data processing detects fringes and measures a piston in at least in some frames. Figure 3.10c (right) shows interferogram with $K = 9.7$, in which fringes are invisible and any frame-by-frame processing fails. However, the 2D Fourier transform (2DFT) processing of this $x - \lambda$ interferogram of $K = 9.7$ yields the average power spectrum displayed in figure 3.10d with 3 clear fringe peaks. Piston offsets have been introduced to clearly separate the fringe peaks. The peak blurring corresponds to the piston drift in 10 minutes. We see here that it is smaller than $50 \mu m$.

The position of the fringe peak in the 2DFT modulus can be used to evaluate and correct the piston value. Figure 3.11 displays the cuts of figure 3.10d in the piston direction at the frequency of each baseline, as they evolve in time. The position of the fringe peak yields the absolute piston (group delay) evolution with time.

In blind mode technique, we use a 2D Fourier transform of $x - \lambda$ interferograms, similar to the one used in REGAIN/G12T and VEGA/CHARA (Berio et al., 1999). This particularly helps a straightforward and unambiguous detection of the average group delay after some integration time and as a result it is easy to use as a low frequency coherencing sensor correcting slow drifts of the OPD. Similar tools were used to analyze the dark current and sky images on detector (Li Causi et al., 2008).

Let us consider $i_m(x, \lambda)$ is the $x - \lambda$ interferogram of AMBER as shown in figure 3.10. First, we resample the data along $\lambda$ direction to obtain equally spaced interferinge corresponding to the average wavelength ($\bar{\lambda} = 1/\bar{\sigma}$). Thus, in the new interferogram $i(x, \sigma)$, spectral channels are equally spaced in wavenumber $\sigma = 1/\lambda$, achieved by a bilinear interpolation to obtain an $x - \sigma$ image. If frames
Chapter 3. Optical interferometry

are oversampled in both \( x \) and \( \lambda \) directions, then it is expected to have little impact on the quality of the data, and the information is present in the fringes as before. Then, we perform Fourier transform of the \( i(x, \sigma) \) images in each spectral channels yielding 1D Fourier interferogram \( I(u, \sigma) \), which is:

\[
I(u, \sigma) = \mathcal{F}_x [i(x, \sigma)] = n(\sigma)F(u, \sigma) \sum_i n_i + \sum_{i,j>i} \sqrt{n_i n_j} \Omega(u, \sigma)e^{2\pi\sigma p^{ij}_a},
\]

(3.31)

where \( n(\sigma) \) is the source spectrum as seen by the instrument, \( F(u, \sigma) \) is the Fourier transform of the resampled window, \( n_i \) denotes the total contribution of telescope \( i \) to the photon in the interferogram, \( \Omega(u, \sigma) \) is the Fourier transform of the source as seen by the instrument, and \( p^{ij}_a \) is the achromatic part of the piston difference in the baseline \( i - j \). The quantity \( \Omega(u, \sigma) \) can be written as:

\[
\Omega(u, \sigma) = n(\sigma)V_i(u, \sigma)V_s(u, \sigma)e^{[\phi_i(u, \sigma)+i\phi_s(u, \sigma)+2\pi\sigma p^{ij}_c(\sigma)]}F(u, \sigma),
\]

(3.32)

where \( V_i(u, \sigma) \) and \( \phi_i(u, \sigma) \) represent the instrument visibility and phase respectively, while \( V_s(u, \sigma) \) and \( \phi_s(u, \sigma) \) are the source visibility and phase at the spatial frequency \( u \) and wavenumber \( \sigma \). \( p^{ij}_c(\sigma) \) is the chromatic part of the piston difference:

\[
p^{ij}(\sigma) = p_i(\sigma) - p_j(\sigma) = p^{ij}_a + p^{ij}_c(\sigma),
\]

(3.33)

where the achromatic OPD difference \( p^{ij}_a \) corresponds to OPD or “piston” difference between two beams, and \( p^{ij}_c(\sigma) \) contains all the wavelength dependent terms in the OPD that are dominated by the dispersion in the VLTI tunnels. The former varies rapidly with time but the latter is dominated by the terms evolving more slowly as the source zenith distance changes. For simplicity, we will consider that the window function \( f(x, \sigma) \) is flat and with constant size and hence \( F(u, \sigma) = \delta(u) \).

A Fourier transform of the interferogram in Eq.3.6.1 in the wavenumber direction yields the 2D Fourier transform:

\[
\hat{I}(u, \nu) = \mathcal{F}_\nu [i(u, \sigma)] = \hat{n}(\sigma) \hat{F}(u, \nu) \sum_i n_i + \sum_{i,j>i} \sqrt{n_i n_j} \Omega(u, \nu) \delta(\nu - p^{ij}_a),
\]

(3.34)

and the average power spectrum:

\[
D(u, \nu) = \langle |\hat{I}(u, \nu)|^2 \rangle = |\hat{n}(\nu) \hat{F}(u, \nu)|^2 \sum_i n_i + \sum_{i,j>i} \sqrt{n_i n_j} |\Omega(u, \nu)|^2 < \delta(\nu - p^{ij}_a) >,
\]

(3.35)

\( D(u, \nu) \) shows a low frequency peak and one fringe peak for each baseline at the position \( u = B_{ij}\sigma \) and \( \nu = p^{ij}_a \) as illustrated in figure 3.10d. The typical size of the fringe peak is given by the spectral coverage of the initial interferogram. For AMBER, in medium resolution, this is between \( \lambda_1 = 2 \mu m \) and \( \lambda_2 = 2.3 \mu m \) yielding a fringe peak width of \( \lambda_1\lambda_2/(\lambda_2 - \lambda_1) = \lambda^2/\Delta\lambda = 15 \mu m \). Under standard conditions, it takes at least a few seconds for the piston to drift by that value, and this sets a limit of the blind-mode technique: we can observe sources producing a
fringe peak of sufficient SNR in a few seconds to allow a piston measurement and correction. If the classical limit of the instrument is set by the necessity to detect SNR = 3 fringes in say 100 ms and we consider that blind observation can manage the same SNR = 3 criteria over say 10 s, then we can afford a fringe peak SNR per frame of 0.3. In detector noise regime, this corresponds to a source 10 times fainter and hence a gain of 2.5 magnitudes. The gain is even more important with regard to a fringe tracker that must reach an SNR of the order of 3 in a much shorter frame time. The SNR gain of the AMBER+ mode is discussed in more detail in chapter 6.

### 3.6.2 2DFT data processing

During the blind mode observation, we introduce piston offsets, as shown in figure 3.10, so that fringe peaks are well separated in the piston direction and do not overlap allowing us to get rid of the cross-talk problem, which is very common to AMBER and other all-in-one multi-axial beam combiners. The separations of the piston as shown in figure 3.11 are about $100^{-200} \mu m$, which are very small compared to the coherence length of 3 mm. As the fringe peaks are well separated, we can go ahead by processing them individually. This means solving only the part of Eq.3.6.1 and Eq.3.6.1 that is connected to the baselines. Thus the new interferogram associated to each baseline $ij$ is

$$I_{ij}(\sigma) = \sqrt{n_i n_j} \tilde{\Omega}_{ij} e^{2i\pi \sigma p_{ij}^a}$$

(3.36)

where

$$\Omega(\sigma) = \Omega(u = B_{ij} \hat{\sigma}, \sigma) = n(\sigma)V_i(\sigma)V_j(\sigma)e^{[\phi_i(\sigma) + i\phi_j(\sigma) + 2i\sigma p_{ij}^a(\sigma)]}.$$ 

(3.37)

We then compute differential cross spectra (DCS) $W_{ij}(\sigma)$ at each $\sigma$ to calculate differential measurements at the frequency $u_{ij}$. DCS is computed between a 2D interferogram forcing all of its channels to be zero except the channel $\sigma$ and a 2D interferogram in which only $\sigma$ channel have been forced to zero:

$$W_{\sigma}^{ij}(\nu) = \mathcal{F}_r[I_{ij}(\sigma') \delta(\sigma' - \sigma)] \times \mathcal{F}_r[I_{ij}(\sigma') \left(1 - \delta(\sigma' - \sigma)\right)]^*$$

(3.38)

$$= n_i n_j \tilde{\Omega}^{ij}(\nu - p_{ij}^a) - \Omega^{ij}(\sigma) e^{-2i\pi \sigma(\nu - p_{ij}^a)}.$$ 

(3.39)

If we know the exact achromatic piston $p_{ij}^a$ from the 2DFT power spectrum then the above equation could be simplified to

$$W_{\sigma}^{ij}(\nu = p_{ij}^a) = n_i n_j \Omega^{ij}(\sigma) \left[\tilde{\Omega}^{ij}(0) - \Omega^{ij}(\sigma)\right]$$

(3.40)

$$= n_i n_j \Omega^{ij}(\sigma) \left[\int \Omega^{ij}(\sigma') d\sigma' - \Omega^{ij}(\sigma)\right]$$

(3.41)

$$= n_i n_j \Omega^{ij}(\sigma) R(\sigma),$$

(3.42)

*It makes sure that DCS has no power spectrum terms affected by a quadratic bias.*
where the quantity \( R(\sigma) \) is nearly constant. For simplicity, we will consider \( R(\sigma) \approx R \), even though we use the actual value of \( R(\sigma) \) during practical data processing. If we further assume that individual telescope collect equal number of photons i.e. \( n_i = n_j = n \) and \( V^{ij}_I(\sigma) = V_I \), we have \( |W^{ij}_\sigma(p^{ij}_\sigma)| \approx n(\sigma)V^{ij}_I(\sigma)n^2V^2_I \), which means that the DCS is proportional to the square of the flux and the square of the visibility but its variations with \( \sigma \) are proportional to the source differential visibility.

If we further assume that individual telescope collect equal number of photons i.e. \( n_i = n_j = n \) and \( V^{ij}_I(\sigma) = V_I \), we have

\[
|W^{ij}_\sigma(\sigma)| \approx n(\sigma)V^{ij}_I(\sigma)n^2V^2_I,
\]

which means that the DCS is proportional to the square of the flux and the square of the visibility but its variations with \( \sigma \) are proportional to the source differential visibility.

If we do further calculation, we can find a calibrated measures \( E^{ij}(\sigma) \) from the information of the spectrum \( n(\sigma) \), the fluxes \( n_i \) and \( n_j \) and from the DCS on the science and the reference source:

\[
E^{ij}(\sigma) = \frac{W^{ij}_\sigma(p^{ij}_\sigma)}{n(\sigma)n_i n_j} = \frac{\Omega^{ij}_s(\sigma)R_s}{\Omega^{ij}_{\text{cal}}(\sigma)R_{\text{cal}}}, \tag{3.43}
\]

where the subscript “*” refers to science target and “cal” refers to calibrator related to the science target. If we further assume that the instrumental visibility and phases are same for science and the calibrator, then we can simplify the above equation to:

\[
E^{ij}(\sigma) = V^{ij}_s(\sigma) \exp \left( i\phi^{ij}_s(\sigma) + 2\pi\sigma[p^{ij}_s(\sigma) - p^{ij}_{\text{cal}}(\sigma)] \right) \frac{R_s}{R_{\text{cal}}}, \tag{3.44}
\]

Finally, to get the differential visibility and phase, we divide \( E^{ij}(\sigma) \) by its average over \( \sigma \). This allows us to avoid errors in the calibration of the ratio \( R_s/R_{\text{cal}} \), for example from the changes in the instrument visibility. Thus, the estimator of the differential visibility is

\[
\phi^{ij}_{d*}(\sigma) = \arg \left( \frac{E^{ij}(\sigma)}{<E^{ij}(\sigma)>_\sigma} \right) = \phi^{ij}_s(\sigma) + 2\pi\sigma\Delta p_{\text{c}}(\sigma), \tag{3.45}
\]

and the differential visibility is:

\[
V^{ij}_{d*}(\sigma) = \frac{\Re \left[ E^{ij}(\sigma) \exp (-i\phi^{ij}_{d*}(\sigma)) \right]}{<\Re \left[ E^{ij}(\sigma) \exp (-i\phi^{ij}_{d*}(\sigma)) \right>_{\sigma}} = \frac{V^{ij}_s(\sigma)}{<V^{ij}_s(\sigma)>_\sigma}. \tag{3.46}
\]

The term \( 2\pi\sigma\Delta p_{\text{c}}(\sigma) \) is due to change in the chromatic dispersion between science and calibrator. This dispersion can be minimized by a correction of the computed chromatic OPD. One simple way is to fit the differential phase variation outside the line since differential phase is expected to have a sharp variation through line. We thus use a polynomial fit of the chromatic OPD and the phase offset for all the spectral channels outside the line. More about the data processing and calibration will be discussed in chapter 5.
## Chapter 4

**Geometrical and kinematical model of BLR**

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### 4.1 Introduction

Despite more than 40 years of intense study, the geometry and kinematics of the BLR are quite unknown. Intensive reverberation mapping spectrophotometric variability studies have been successfully provided some insights about the physics of BLR. The observational evidences indeed suggest that the BLR is photo-ionized,
since high ionized lines come closer to the central source than low ionized lines. However, it is not clear that the BLR has a thin geometry or a thick one, dominated by rotational motion or by random turbulence component. A summetry of various simple but possible BLR models can be found in Collin et al. (2006).

There are strong evidences that suggest the existence of disk like geometry with radial velocity field in the BLR but mainly applicable in the case of radio-loud AGNs. A fraction of AGNs shows double peaks in their Balmer line profile that usually associated with the disk like structure. In the case of super-luminous object, Rokaki et al. (2003) found that equivalent width of Hα line is anti-correlated with various beaming indicators, which could be associated with a disc-like BLR co-rotating with the accretion disc. Moreover, a sample of 12 double peaked Hα line profiles by Eracleous and Halpern (1994) suggests the presence of disk like emitting region. These emission lines are well fitted with a simple relativistic disk model. On the other hand, radio-quiet objects show few evidence in favor of thin disk BLR geometry. For example, polarization across Hα, which can be seen in significant fraction of Type 1 AGNs, can be explained as a presence of thin line emitting region surrounding the accretion disk (Smith et al., 2005). Since the BLR clouds must absorb significant fraction of the continuum in order to produce its large equivalent width and hence it should have significant width or opening. Large quasar spectroscopic survey indicates that the C IV and Mg II lines have small dispersion in the distribution of line widths which implies that BLR can not be flat disk (Fine et al., 2008, 2010). Various authors proposed BLR models where line emitting gas spans from the outer accretion disk to the inner dust torus and the scale height increases with radial distance (Gaskell, 2009; Goad et al., 2012). The above evidences suggest that BLR structure is neither flat nor spherical and hence to understand the underlaying physics we need to constrain BLR geometry and kinematics by high quality datasets.

Recent high quality reverberation mapping data starts exploring the previously unknown BLR geometry and kinematics. For example, recent Lick observatory reverberation mapping data successfully provided velocity-delay map of few AGNs providing some signatures of Keplerian and inflow velocity profiles (Grier et al., 2013). On the other hand, dynamical modeling of reverberation mapping data using Bayesian approach started constraining the geometry and kinematics of the BLR (Pancoast et al., 2011, 2014b). Direct modeling of data allows to estimate BH mass which does not depend on the scale factor. Dynamical modeling of Lick reverberation mapping data of 5 Sy1 AGNs suggests that the BLR kinematics are consistence with inflow motion or elliptical orbit or the combination of both (Pancoast et al., 2014a). Even if advanced RM model fitting can constrain many parameters of a complex model, degeneracies between these parameters remain, as we will illustrate on simple cases in further chapters. We therefore need to complement RM with another technique.

In this chapter we describe a BLR model intended to constrain BLR geometry and kinematics. We are interested not only to fit reverberation mapping data but also to fit interferometric data. For this purpose we will first introduce a geometrical and kinematical model in section 4.2 to predict both the interferometric and reverberation mapping observables and then explain in section 4.3 how the key BLR model parameters can be constrained from differential interferometric and RM
Chapter 4. Geometrical and kinematical model of BLR

signature. In section 4.4, we estimated expected uncertainty on key parameters from simulated OI data. Finally, this chapter is concluded in section 4.5.

4.2 BLR model

To make a geometrical and kinematical model of the BLR we first proceed to define its geometry i.e. the spatial distribution of clouds, and then added kinematics to it i.e. the velocity of clouds.

4.2.1 Geometrical model

Our geometrical model includes cloud spatial distribution function and an angular distribution. Cloud distribution is flexible enough to reproduce varieties of radial distribution. We then add an opening angle which allows us to go from a flat geometry to a spherical one. We also define an inclination angle to describe the disk orientation with respect to the observer. Furthermore, a position angle is introduced to take care the position of the observer in the azimuthal direction. Thus, using few model parameters we can create various BLR geometries.

4.2.1.1 Radial distribution of Clouds

The radial distribution of clouds is defined by a function \( R_d(r) \) which is defined here as a list of points randomly distributed according to a normal distribution of standard deviation \( \sigma_{\text{blr}} \) limited by an inner radius \( R_{\text{in}} \) below which we exclude the presence of clouds. This is the inner limit to have atomic lines due to the radiation from the central source. As a first application of our model, we used a truncated Gaussian distribution whose probability distribution is defined by

\[
P(l < r < l + dl) = \frac{1}{\sigma_{\text{blr}} \sqrt{(2\pi)}} \exp \left( -\frac{l^2}{2\sigma_{\text{blr}}^2} \right) \quad \text{for } r \geq R_{\text{in}}.
\]  

(4.1)

Later, as in chapter 7, we will use other distributions.

4.2.1.2 Opening, inclination and position angles

Once we have radial distribution of the clouds, we distributed them in x-y plane by assigning random positions where the azimuthal angle \( \phi \) is randomly taken between 0 to \( 2\pi \). Then we apply a random rotation to the clouds by opening angle \( \omega \) to pull up a 3D configuration in \((x, y, z)\) from the 2D configuration. The opening angle allows to make a thick geometry out of a thin geometry. The zero opening corresponds to the flat geometry whereas 90° opening produces a spherical geometry. In doing so, we found the concentration of cloud near the +y and -y axis and it causes non-axisymmetric distribution. To restore the axisymmetry of the cloud distribution we applied a random rotation between 0 to \( 2\pi \).
After creating a 3D configuration, we applied a rotation about y-axis with angle $i$ defined as inclination angle. $i=0$ refers to a “face on” (observer seeing along z axis) and $i=90^\circ$ is for “edge on” view. We further rotate the clouds with an angle $\Theta$ to take into account the position angle of the system, which is along North to East. Position angle $\Theta = 0^\circ$ means the semi-major axis is along North. Note that position angle is important for interferometric observation, but it has no effect on the RM signal. Figure 4.1 shows different geometries, when observer is seeing edge-on (left panel, observer along y axis) and face-on (right panel, observer along z axis). In figure 4.1A, the BLR has a disk like geometry for $\omega = 0$, and as $i = 0$ for edge-on view the observer only sees the surface of a ring (left panel), while for a face-on view the geometry looks like a disk. However, for $\omega = 90^\circ$, the geometry becomes spherical (see 4.1B), and both face-on and edge-on view look identical. For a thin inclined disk (4.1C), the geometry becomes ellipse in face-on view.

4.2.1.3 Anisotropy

The cloud’s apparent brightness can be affected by a geometrical effect related to its optical thickness and to its position, named “anisotropy” (Goad et al., 2012;
Figure 4.2: Effect of anisotropy parameter for a thin disk at $i = 40^\circ$. Optically thin clouds ($F_{\text{anis}} = 0$) contribute equally (left panel), while in the case of optically thick clouds ($F_{\text{anis}} = 1$), contribution is more from the surface facing the observer (right panel).

O’Brien et al., 1994). If the cloud is optically thick, then the observer sees only the fraction of its surface that is facing towards him. If the cloud is optically thin, then all points of the cloud contribute to its intensity in all directions. This effect, similar to a “moon phase”, is described as

$$I(\phi) = (1 - F_{\text{anis}} \cos \phi \sin i),$$

where the anisotropy factor $F_{\text{anis}}$ goes from 0 for optically thin clouds to 1 for optically thick clouds. The effect of anisotropy is shown in figure 4.2 for no anisotropy case ($F_{\text{anis}} = 0$) on the left panel and full anisotropy case ($F_{\text{anis}} = 1$) on the right panel. All clouds contribute equally in the former case, while in the latter case contribution is more from the clouds which is facing the observer.

4.2.2 Kinematical model

Each cloud is emitting a line with profile $L_{XYZ}(\lambda)$ depending from the local physical conditions and hence from the cloud position. This profile is convolved by the instrument spectral PSF $P_I(\lambda)$. If we observe at relatively low spectral resolution, from 200 to 1500, we can consider that $P_I(\lambda)$ is much broader than $L_{XYZ}(\lambda)$ and, as a first approximation, we can consider that the line shape details are lost in the convolution. Each cloud is emitting the same line profile $L(\lambda)$, but for its intensity, which can be included in the radial intensity distribution $R_d(r)$:

$$L_{XYZ}(\lambda) P_I(\lambda) \simeq R_d(r) L(\lambda)$$

$$L(\lambda) = N(\lambda - \lambda_0, \sigma_0),$$

as we choose to represent the local line profile by a Gaussian function centered at the emission line wavelength $\lambda_0$ and with standard deviation $\sigma_0$ that is a parameter of the model. When $\sigma_{\text{OS}}$ is describing the source line width, it refers to the local contributions in the cloud (thermal broadening, micro turbulence etc). If $\sigma_{\text{OS}}$ refers to the source and $\sigma_{\text{OI}}$ to the instrument, and both profiles are Gaussian,
then

\[ \sigma_0^2 = \sigma_{OS}^2 + \sigma_{OI}^2. \]  

(4.5)

In practice, \( \sigma_{OS} \simeq 10 \text{ km/s} \ll \sigma_{OI} \) and \( \sigma_0 \) (except if we use and enhance \( \sigma_{OS} \) to represent an enhanced local turbulent velocity field as in section 4.3.3.)

### 4.2.2.1 Tangential and radial velocity components

From the position of the cloud in this \( r, \theta, \phi \) spherical referential we can define its local velocity considering several possible components:

**a)** An orbital component, tangential to the circle:

\[ V_{\text{orb}} = V_a \left( \frac{R_{\text{in}}}{r} \right)^\beta, \]  

(4.6)

The parameter \( \beta \) defines different orbital velocity laws (Stee, 1996). For Keplerian motion \( \beta = 0 \) and amplitude \( V_a = \sqrt{\frac{GM_{bh}}{R_{\text{in}}}} \), where \( M_{bh} \) is the BH mass.

**b)** A radial component (inflow or outflow):

\[ V_{\text{rad}} = V_c \left( \frac{R_{\text{in}}}{r} \right)^\gamma, \]  

(4.7)

where \( \gamma \) is the power law index of this radial velocity. Freefall corresponds to \( \gamma = 0.5 \) and \( V_c = \sqrt{\frac{2GM_{bh}}{R_{\text{in}}}} \). \( \gamma = -1 \) is an outflow case with outflow velocity amplitude \( V_c \) set at the inner radius \( R_{\text{in}} \) of the BLR (Welsh and Horne, 1991).

In source \( x - y \) coordinate, the components of velocity vector can be defined as:

\[ V_x = V_{\text{orb}} \sin \phi + V_{\text{rad}} \cos \phi \]  

(4.8)

\[ V_y = -V_{\text{orb}} \cos \phi + V_{\text{rad}} \sin \phi, \]  

(4.9)

where \( 0 < \phi < 2\pi \) is the azimuthal angle. Rotations are then applied with \( \omega \) and \( i \) to obtain observer line of sight velocity components in 3D. The composition of these orbital and radial velocity laws constitute the global velocity field of the BLR.

### 4.2.2.2 Macroturbulent velocity

We have also considered a local macroturbulent velocity component of amplitude \( V_{\text{turb}} \). Note that the direction of macroturbulence velocity is random and thus it is independent of inclination angle. Several authors Collin et al. (2006); Goad et al. (2012) relate the amplitude \( V_{\text{turb}} \) to the thickness \( H(r) \) of the BLR at the radius \( r \)

\[ |V_{\text{turb}}| = V_{\text{orb}} P_{\text{turb}} H(r). \]  

(4.10)
Since, in our model \( r \sin \omega \) is typical thickness at radius \( r \), hence we set \( H(r) = r \sin \omega \). The multiplicative parameter \( P_{\text{turb}} \) tunes the amplitude of the turbulence velocity. Hence, in our model, the macroturbulence can be turned off both for a flat disk (\( \omega = 0 \)) and for \( P_{\text{turb}} = 0 \).

### 4.2.3 Intensity map

For each cloud, the line is Doppler shifted by the projected velocity component \( V_z \) and the contribution of each cloud to the BLR intensity is:

\[
I_{\text{blr}}(i, \lambda) = R_d(i) N \left[ \lambda - \lambda_0 \left( 1 + \frac{V_z(i)}{c} \right) , \sigma_0 \right],
\]

where \( i \) refers to the contribution of \( i \)-th cloud. To get a BLR intensity map \( I_{\text{blr}}(X, Y, Z, \lambda) \) we add the contribution of all the clouds located in \((X, X+\text{d}X, Y, Y+\text{d}Y, Z, Z+\text{d}Z)\) box at each \( \lambda \). From this 4D intensity map, we calculated 3D map, \( I_{\text{blr}}(X, Y, Z, \lambda) \), by summing along \( Z \) direction and then normalizing it to have the maximum intensity of 1.

In Figure 4.3, we show scatter plot of clouds. The upper panel shows a flat Keplerian disk (\( \omega = 0 \), \( \beta = 0.5 \), \( V_{\text{rad}} = 0 \), \( i = 30^\circ \), \( R_{\text{in}} = 1000R_g \), \( \sigma_{\text{blr}} = 0.1 \text{ mas} \)) with flat Keplerian disk geometry \( \omega = 0^\circ \) (upper plot) and spherical geometry \( \omega = 90^\circ \) (lower plot). The colors represent the velocity in the direction of the observer. Note
Table 4.1: Model parameters and the observables.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Ref. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH mass</td>
<td>$M_{bh}$</td>
<td>$1 \times 8 M_{\text{sun}}$</td>
</tr>
<tr>
<td>BLR inner radius</td>
<td>$R_{\text{in}}$</td>
<td>$200 R_g$</td>
</tr>
<tr>
<td>BLR width</td>
<td>$\sigma_{\text{blr}}$</td>
<td>0.4 mas</td>
</tr>
<tr>
<td>Inclination</td>
<td>$i$</td>
<td>$30^\circ$</td>
</tr>
<tr>
<td>Opening angle</td>
<td>$\omega$</td>
<td>0$^\circ$</td>
</tr>
<tr>
<td>Rest line width</td>
<td>$\sigma_0$</td>
<td>85 km/s</td>
</tr>
<tr>
<td>Macroturbulence</td>
<td>$P_{\text{turb}}$</td>
<td>0</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>$F_{\text{anis}}$</td>
<td>0</td>
</tr>
<tr>
<td>Continuum size</td>
<td>$R_{\text{rim}}$</td>
<td>0.25 mas</td>
</tr>
<tr>
<td>Disk position angle</td>
<td>$\Theta$</td>
<td>90$^\circ$</td>
</tr>
<tr>
<td>Object Redshift</td>
<td>$z$</td>
<td>0.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measure</th>
<th>Symbol</th>
<th>Observing Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute visibility</td>
<td>$V_{\text{abs}}(\lambda)$</td>
<td>OI</td>
</tr>
<tr>
<td>Differential visibility</td>
<td>$V_{\text{diff}}(\lambda)$</td>
<td>OI</td>
</tr>
<tr>
<td>Differential phase</td>
<td>$\phi_{\text{diff}}(\lambda)$</td>
<td>OI</td>
</tr>
<tr>
<td>Spectrum</td>
<td>$s(\lambda)$</td>
<td>RM or OI</td>
</tr>
<tr>
<td>2D Response function</td>
<td>$\psi(v, \tau)$</td>
<td>RM</td>
</tr>
<tr>
<td>1D Response function</td>
<td>$\psi(\tau)$</td>
<td>RM</td>
</tr>
</tbody>
</table>

that the velocity range in the spherical case is twice as large for the same central mass and BLR size.

4.2.4 Continuum model

In the $K$-band, the continuum emission is strongly dominated by the hot dust near the sublimation radius $R_{\text{rim}}$ (Kishimoto et al., 2007, 2009b). As this structure remains unresolved both for the VLTI and the KI, we have access only to its equivalent radius. We choose to represent it by a narrow ring whose radius ($R_{\text{rim}}$) will give the right visibility observed in the continuum, when such a measurement is available, or proportional to $L^{0.5}$ with a proportionality constant deduced from Suganuma et al. (2006). For most of this thesis, we consider that the ring is uniform and we do not introduce any skewing related to the inclination, although such a function is easy to introduce in a parametric form. A skewing of the continuum image, with a “face on” side brighter than the “back on” side will introduce a measurable phase effect that is briefly discussed in section 6.4.1. The continuum brightness distribution $I_{\text{con}}(X, Y)$ is normalized to have $\int \int I_{\text{con}}(X, Y) dX dY = 1$.

4.2.5 Model parameters and observables

The global intensity is obtained by adding the BLR and continuum intensities

$$I(X, Y, \lambda) = I_{\text{con}}(X, Y) + F I_{\text{blr}}(X, Y, \lambda), \quad (4.12)$$
Figure 4.4: Line intensity map (upper panel) across the emission line for a flat Keplerian velocity field for seven different spectral channels (top panel). Emission line profile is shown in lower-left panel. Photocenter displacement (lower-middle) and visibility (lower-right) in parallel to the rotation axis (green) and perpendicular to the rotation axis (blue) with spectral resolution $R = 1500$. This model is computed considering a thin Keplerian disk $\sigma_{\text{blr}} = 0.4$ and $i = 30^\circ$.

where $F$ is the maximum emission line flux, for a measured spectrum $S_M(\lambda_c)=1$ in the continuum. A Fourier transform of the intensity distribution $I(X,Y,\lambda)$ via Eq.3.4 yields the complex visibility and its modulus and phase, with the subsequent absolute and differential visibility and differential phase as mentioned in chapter 3.

### 4.2.5.1 Reverberation mapping response function

The time delay, between continuum and emission line echo, is a function of clouds position and defined by

$$\tau(r, Z) = \frac{r - Z_c}{c}. \quad (4.13)$$

A normalized histogram of the time delays $\tau$ and velocities in the observer direction $V_z$ yields the 2D echo diagram $\Psi(v, \tau)$ and the subsequent 1D line profile $\Psi(v)$ whose FWHM gives the equivalent velocity range $\Delta V$, and 1D response function $\Psi(\tau)$, whose centroid gives the equivalent time lag $\tau_{\text{cent}}$. Table 1 summarizes the parameters used in our geometrical model as well as some typical values used in this chapter.
4.2.5.2 Spectro-interferometric observables

For a flat Keplerian disk model narrow-band line images (continuum is removed in plot) are plotted in the upper panel of figure 4.4 for different spectral channels. As we enter the line at maximum redshift, a line image appears in addition to the continuum. Emission line profile (lower-right panel) shows a double peaked profile. Line intensity shows maxima (B and F channels) related to the inclination and the equivalent outer edge of the BLR. The photocenter (lower-middle panel) shifting perpendicular to the rotation axis, goes through a extrema around channels B and C, then cancels in channel D in the center of line, where the image is symmetric. The blue wing images (E to G) mirror the red wing ones and the photocenter is shifted in the opposite direction. We see that the images in channels B and F show maximum intensity and extension in the direction \( \perp \) to the axis and this corresponds to local minima in the visibility (lower-right) in \( \perp \) baseline\(^*\) (blue), while the maximum intensity and extension in the \( \parallel \) direction is in channel D yielding the local visibility minima in \( \parallel \) baseline (green). Different special cases with RM response function will be discussed in section 4.3.1, and different kinematic models will be discussed in section 4.3.4.

4.3 Observable signatures of the model parameters

In this section, we illustrate the effect of the main model parameters on the OI and RM observables. We have tried to analyze the parameters in an order that allows to partially separate their observable effect and makes it therefore easier to illustrate typical spectro-interferometric signatures. We will discuss first the measurement of the equivalent angular sizes of the BLR that depends mostly from the global amplitude of visibility measures. Then we will examine how differential visibility and phase can solve the major BLR model ambiguity that is the degeneracy between inclination \( (i) \), thickness \( (\omega) \) and the balance between local and global velocity field \( (\sigma_0) \). Then, we will show how the components of the global velocity field can be separated by differential phase measurements and we will also examine the signatures of other physical phenomena such as the clouds optical thickness and the macroturbulent component of the local velocity field.

\(^*\) \( \perp \) baseline means perpendicular to the rotation axis and \( \parallel \) baseline means parallel to the rotation axis.
4.3.1 Interferometric BLR size

An estimation of the angular size of the BLR is critical to constrain the \( r_{\text{blr}} - L \) and the \( M_{\text{bh}} - L \) relations. Combined with the RM linear size measurement it can yield a direct distance (Elvis and Karovska, 2002). This angular size can be constrained by broad-band absolute visibility measured in the continuum combined with a relatively low spectral resolution differential visibility measurement with only one or a very few points in the emission line.

The left panel of figure 4.5 displays the average continuum absolute visibility amplitude as a function of \( R_{\text{rim}} \). With the typical visibility accuracy of current VLTI instruments, \( \sigma_{\text{avis}} \simeq 0.03 \) (see chapter 6), we see that the smallest \( R_{\text{rim}} \) that can be estimated in the \( K \)-band with the VLTI baselines is \( R_{\text{rim}} \simeq 0.15 \) mas. A fringe tracker, such as the one built-in in GRAVITY, should allow to reduce the absolute visibility error down to \( \sigma_{\text{avis}} \simeq 0.005 \) and to access \( R_{\text{rim}} \lesssim 0.06 \) mas. If the absolute visibility error can be reduced, the accuracy on the “dust parallax distance” can be improved as discussed in chapter 7.

The right panel in figure 4.5 displays the differential visibility (visibility divided by the average continuum absolute visibility) as a function of the ratio of \( \sigma_{\text{blr}} / R_{\text{rim}} \). It has a very good accuracy, \( \sigma_{\text{dvis}} \lesssim 0.001 \), limited only by fundamental noises, but it cannot yield the relative sizes \( \sigma_{\text{blr}} / R_{\text{rim}} \) when \( |V_{\text{diff}} - 1| < 0.001 \), if \( R_{\text{rim}} \lesssim 0.1 \) mas at the VLTI i.e. \( (\lambda/B) / R_{\text{rim}} \gtrsim 35 \). That sets an upper limit for the super-resolution factor that can be expected from visibility measurements. The uncertainty on the angular size of the BLR will be dominated by the absolute visibility accuracy that is therefore a key specification for BLR size estimates.

Note that figure 4.5 confirms the prediction of Eq. 3.21 and sets the equivalence between the size parameters \( R_{\text{rim}} \) and \( \sigma_{\text{blr}} \): a flat Keplerian BLR model produces the same visibility than a thin ring when \( \sigma_{\text{blr}} / R_{\text{rim}} \simeq 0.7 \).
If we have differential visibilities for two different baselines (with $(\lambda/B)/R_{\text{rim}} \gtrsim 35$ for the shortest baseline) we can obtain $\sigma_{\text{blr}}$ and $R_{\text{rim}}$ without absolute visibility measures, but the accuracy of this method has not been evaluated yet.

### 4.3.2 Interferometric and Reverberation Mapping BLR sizes

The different parts of the source contribute to the interferometric and RM sizes with different weights. To illustrate this we considered different flat geometries with different combinations of $R_{\text{in}}$ and $\sigma_{\text{blr}}$ that produce the same equivalent time lag $\tau_{\text{cent}}$, from a hollow thin torus (large $R_{\text{in}}$ and small $\sigma_{\text{blr}}$, black line in figure 4.6) to an extended BLR with almost no central hole (small $R_{\text{in}}$ and large $\sigma_{\text{blr}}$, pink line in figure 4.6). Figure 4.6 shows that these combinations produce very different visibilities. The peak of $\Psi(\tau)$ grows with $R_{\text{in}}$ but the centroid $\tau_{\text{cent}}$ remains constant. The shape of the $V_{\text{diff}}(\lambda)$ remains constant, a “v” and “w” for $\parallel$ and $\perp$ baselines respectively, but its amplitude is almost proportional to $\sigma_{\text{blr}}$. Measuring QSO distances from a combination of OI with RM requires a calibration of this effect, that will also influence the size-luminosity relation. This will be discussed in chapter 7.

![Figure 4.6: RM 1D Response function (upper panel) and visibility in two baselines $\parallel$ (lower-left panel) and $\perp$ (lower-right panel) for different BLR geometries that produce same $\tau_{\text{cent}}$ but different visibilities.](image)

### 4.3.3 Fundamental geometrical and kinematical parameters

After estimating the angular size of the BLR we will constrain three key parameters to understand the global BLR structure: $i$, $\omega$ and $\sigma_0$. Goad et al. (2012), Collin et al. (2006) and Fine et al. (2010) have shown that these parameters dominate
the RM scale factor \( f \) and hence the virial BH mass estimate. This is illustrated by figure 4.7 where the measured BH mass (left panel) and the scale factor \( f \) (right panel) are plotted as a function of \( i \) for various values of \( \omega \). These values result from the root mean square dispersion, \( \sigma_l \) of the variable line profile and the \( \tau_{\text{cent}} \) obtained from our model with a fixed input mass and each value of \( i \) and \( \omega \). \( f \) is the ratio of model input mass and the \( M_{\text{out}} = c \tau_{\text{cent}} \sigma_{l}^{2}/G \). Figure 4.7 shows that changes in \( i \) and \( \omega \) can introduce more than a factor 10 error on the mass estimate and shows how important it is to constrain these parameters.

**Figure 4.7:** The simulated measured mass (left panel) and the scale factor (right panel) as a function of inclination for different opening angles \( \omega = 0^\circ \) (red), \( 30^\circ \) (green) and \( 60^\circ \) (blue). The input mass of this simulation is \( 10^8 M_{\odot} \). We see that an error on \( i \) or \( \omega \) can result in a very large mass error.

**Figure 4.8:** Spectrum (left panel) and 1D response function \( \Psi(\tau) \) (right panel) for different inclination and opening angle. Green curves in each plot obtained with \( \sigma_0=85 \) km/s whereas the red curves are for different \( \sigma_0 \) as mentioned in the left panel.

Figure 4.8 shows the RM observables for a grid of \( i - \omega \) with different line width \( \sigma_0 \) considering a fixed BLR size \( \sigma_{\text{blr}} = 0.4 \) mas. Here \( \sigma_0 \) is used to represent various local turbulent velocity fields as discussed in section 4.2.2 (see also in section 4.3.5).
The spectra are in the left panel and the 1D response functions in the right panel. The green curves show the spectra obtained with a fixed $\sigma_0 = 85$ km/s. The width of that spectrum is sensitive to inclination and opening angle. For small $\omega$, an increasing $i$ shows more and more clearly the typical double peaked line profile of a Keplerian thin disk. Increasing $\omega$ broadens the line profile and blurs the double peaks until a flat top line profile independent of $i$ as we approach a spherical structure with large $\omega$. The red curves represents line profiles broadened by a change in $\sigma_0$ in order to obtain an equivalent global line width $\Delta V = 3300$ km/s in all cases. The corresponding $\sigma_0$ is indicated in each picture. The $\sigma_0$ broadening blurs all line details, but for the largest opening angles. The 1D delay transfer function $\Psi(\tau)$ is independent of $\sigma_0$. Its exact shape very slightly changes with $i$, which shifts its maximum, and $\omega$ that makes the drop sharper for small delays, but the RM BLR size $c\tau_{\text{cent}}$ is not constrained by these parameters. The overall conclusion of this figure is that RM alone cannot separate $i$, $\omega$ and $\sigma_0$ from $\Delta V$ and $\tau_{\text{cent}}$ measures only. However, a detail line profile analysis could discriminate these parameters up to a certain accuracy.

![Figure 4.9: Differential phase in degree (left panel) and differential visibility (right panel) for the same grid as in figure 4.8 with || (dotted) and ⊥ (solid) baselines.](image)

To show the effect of $i$, $\omega$ and $\sigma_0$ on OI observables we plotted differential phase (left panel) and differential visibility (right panel) in figure 4.9 for || (dotted) and ⊥ (solid) baselines. The photocenter shift between the line emitting region and the continuum source increases with $i$, which increase the line of sight velocities. It globally decreases with $\omega$ that makes the iso-radial velocity regions more and more symmetric. Differential phase for large opening angle shows sharp turns whereas the high local velocity case shape is much smoother and with reduced amplitude. An increase in $\sigma_0$, which blurs the iso-velocity zones, is another case for a decrease in the differential phase amplitude, but for an identical amplitude, the $\phi_{\text{diff}}(\lambda)$ function shows much sharper angles for high $\omega$ than for high $\sigma_0$.

---

†This value of $\sigma_0 = 85$ km/s is used here considering AMBER MR ($R = 1500$) observation, which implies $\Delta V = 200$ km/s. The value of $\tau_{\text{cent}} = 150$ days is a typical value as can be found in Kaspi et al. (2000). This values are used only for illustration.
Chapter 4. Geometrical and kinematical model of BLR

Figure 4.10: Spectrum (left), differential visibility (left-middle), differential phase (middle), 2D response function (middle-right), 1D response function (middle-middle). OI observables are computed using baselines U1 (red), U2 (cyan), U3 (blue), and U4 (green).
Differential visibility is an even sharper marker of the different models, if we have a sufficient spectral resolution, i.e. sufficient SNR. In low spectral resolution, differential visibility is of little help. However, the fine shape of the differential visibility spectacularly differs in the different cases. Large opening angles yield a “w” shape that is independent from the direction of the baseline, while flat structures yield differential visibilities very sensitive to the baseline orientation, as it could be expected from figure 4.4, showing that the global size of the individual spectral bins is strongly different in the rotation axis and in the perpendicular direction. This baseline direction dependence is removed by a large local velocity field, but this changes the curve shape and width.

4.3.4 Kinematics of the global velocity field

Understanding the global kinematics of BLR has been a long standing problem as the sparsely sampled RM data was usually not enough to recover emission line as a function of velocity. However recently various authors have found signatures of rotation, inflow or outflow in the BLR, analyzing high quality RM data and recovering $\Psi(v, \tau)$ (Pancoast et al., 2012; Grier et al., 2013; Bentz et al., 2010b). On the other hand OI has been successful to provide signatures of rotation and expansion velocity in circum-stellar disks (Meilland et al., 2007; Stee, 1996; Meilland et al., 2012). To find the constrains that OI can provide on the kinematics of BLR we simulated OI as well as RM observables.

Figure 4.10, shows the spectrum, interferometric differential visibility and differential phase together with RM 2D and 1D response function for Keplerian rotation and free fall kinematics models in a thin disk (for detail about echo functions see Welsh and Horne, 1991). We considered VLTI baselines with different position angles: U1 ($B = 130$ m, $PA = 0^\circ$), U2 ($B = 130$ m, $PA = 90^\circ$), U3 ($B = 80$ m, $PA = 0^\circ$) and U4 ($B = 80$ m, $PA = 90^\circ$).

For a Keplerian rotation law, as strongly suggested by figure 4.4, we see that for a baseline perpendicular to the rotation axis (baseline with $PA = 90^\circ$) the difference between the line and the continuum photocenter grow as we enter the line, cancels in the line center and reverses in the second half of the line. This gives a typical “S” shaped differential phase with an amplitude proportional to the resolution factor $\alpha$ defined by Eq. 3.21. In the direction of the rotation axis (baseline with $PA = 0^\circ$), the photocenter displacement and the differential phase are 0. The differential visibility globally displays a “w” shape in $\bot$ direction and a “v” shape in $\parallel$ direction, with an amplitude depending from $\alpha$ and going from a peak over the continuum visibility (BLR smaller than the inner dust rim) to a visibility droop with a depth growing with $\alpha$. For an inflow, the velocity amplitudes are larger for the same BH mass, as shown by the line profile and the 2D echo diagram, but this can be compensated by a mass change and hence introduces a mass uncertainty. The general shape of the curves are similar but $\parallel$ and $\bot$ directions are exchanged. The photocenter shift is now $\parallel$ to the rotation axis. The same exchange between $\parallel$ and $\bot$ direction can be observed on the differential visibility. The 2D echo diagram is different but this difference can be seen only on very high quality data.
The decisive capacity of differential measures from OI to discriminate between rotation and inflow/outflow is further illustrated by figure 4.11 that show the rotation of the global photocenter track with $\lambda$ as the ratio between rotation and expansion changes, as first illustrated by Chalabaev (1992) for circumstellar disks. Here $y$ direction is defined by the projected axis of symmetry i.e. position angle of the disk $\Theta = 90^\circ$, which can be measured from the jet orientation or the OI broad-band observation. In this context, Stee (1996) has shown that the trajectory of the photocenter displacement vector $\vec{\epsilon}(\lambda)$ yields the strongest constraint on the velocity law index $\beta$ and Meilland et al. (2007, 2012) showed that the equatorial disk of Be stars is strongly dominated by a Keplerian rotation ($\beta = 0.5$). The same approach can be applied to disk BLRs.

### 4.3.5 Macroturbulence

Several authors have suggested models where the cloud motions are dominated by random macroturbulence (Collin et al., 2006; Fine et al., 2008, 2010; Goad et al., 2012). Macroturbulence in the BLR can provide the internal pressure required to support the disk vertical extent (Shakura and Sunyaev, 1973). Collin et al. (2006) suggested various disk geometries and implemented turbulence velocity that depends on the scale height of disk. Goad et al. (2012) showed that for low inclination object macroturbulence dominates the Keplerian velocity and hence can produce significant broadening.

We used a similar approach, as defined in Eq. 4.10, to introduce a macroturbulent velocity component in our model. Figure 4.12 shows the effect of macroturbulence...
on spectrum (upper), differential phase (middle) and differential visibility (lower) in the $\perp$ baseline, for different opening angle $\omega$ and turbulence parameter $P_{\text{turb}}$. On the line profile, macroturbulence broadens the line and particularly enhances the response of the line wings (also discussed in 5.3). From the general shape of all other observables, it is impossible to discriminate between the effects of an increase of the local line width $\sigma_0$ and this of an increased macroturbulence. However, even if we cannot know if the local velocity field is dominated by $\sigma_0$ or by macroturbulence, we can separate it from the global velocity field and therefore obtain all the global geometric and kinematic parameters.

The main specific effect of the macroturbulence is to change the weight of the line wings. The ratio between the line FWHM and its standard dispersion $\sigma_l$ increases when $\omega$ increases or $i$ decreases (upper panel of figure 4.12). For known $i$ and $\omega$, this ratio $\text{FWHM}/\sigma_l$ could be used to constrain the relative contributions to the local velocity field, but as this ratio can also be sensitive to geometrical parameters such as the radial distribution of clouds as well as to their exact spectral response‡, a fine analysis needs a physical modeling of the cloud response that could be done in future.

‡at large radius the clouds have a stronger response with a Lorentzian line profile according to Goad et al. (2012)
4.3.6 Anisotropy

The emission line optical depth of each cloud determines the anisotropy of the re-emitted light, from an isotropic emission for an optically thin cloud to a maximum anisotropy, with dark and bright sides, for a thick cloud. O’Brien et al. (1994) computed this for different strong emission lines and suggested that lines with large ionization parameter emitted anisotropically at some radii. Goad and Wanders (1996) and O’Brien et al. (1994) showed that anisotropy increase the time lag almost without changing the line profile, which can be a cause for mass estimate error.

To compute the effect on anisotropy we used Eq. 4.2 and its effect on the differential phase is shown in figure 4.14. We see a strong effect in the direction of the rotation axis and no effect in the \( ⊥ \) direction. This is because the inclusion of anisotropy reduces the emission on the nearest side of the observer and increases to the furthest side, enhances its brightness and shifts the photocenter towards its direction. The photocenter along the \( \parallel \) direction changes rapidly while the
photocenter in $\perp$ direction remain unchanged. Differential phase is therefore a good marker of anisotropy, particularly if we have a priori information on the axis position angle.

### 4.4 Parameter uncertainty from simulated optical interferometric data

In section 4.3 we described the observables signatures of the main BLR parameters. Eventually the BLR model parameters will be estimated from a global model fit of RM and OI observables. In this section we give a first estimate of the accuracy of some parameters after a global fit of OI observables with the SNR of a few typical observations. However, the main goal of this section is to illustrate a methodology. A detail analysis of the accuracy can be performed in the future.

#### 4.4.1 Simulated datasets

To estimate uncertainty of the parameters from optical interferometry data, we created mock data sets using the values mentioned in Table 4.2a and Table 4.3a, considering Gaussian noise on all the spectro interferometric observables. We considered AMBER+ and GRAVITY with absolute visibility accuracy of 3% and 0.5% respectively. For AMBER+ we considered $\sigma_{\phi_D} = 0.01$ radian and $\sigma_{\nu_D} = \sqrt{2} \times \sigma_{\phi_D}$. For GRAVITY we took $\sigma_{\phi_D} \approx 0.002$ radian. We considered 0.2% uncertainty on the line flux measurement. A justification of the typical values as well as a discussion of their sensitivity to observing conditions and source magnitude can be found in chapter 6.

#### Table 4.2: Simulated data with fixed $\sigma_0 = 85$ km/s

<table>
<thead>
<tr>
<th>Data sets</th>
<th>instrument</th>
<th>$\sigma_{\text{blr}}$ (mas)</th>
<th>log($M_{\text{bh}}/M_{\odot}$)</th>
<th>$i(\degree)$</th>
<th>$\omega(\degree)$</th>
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<tbody>
<tr>
<td>A</td>
<td>AMBER+</td>
<td>0.4</td>
<td>8</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>B</td>
<td>GRAVITY</td>
<td>0.4</td>
<td>8</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>C</td>
<td>AMBER+</td>
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<td>8</td>
<td>15</td>
<td>60</td>
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<th>$i(\degree)$</th>
<th>$\omega(\degree)$</th>
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<tbody>
<tr>
<td>A</td>
<td>$0.378^{+0.015}_{-0.010}$</td>
<td>$8.059^{+0.126}_{-0.123}$</td>
<td>$24.8^{+5.4}_{-3.5}$</td>
<td>$39.2^{+9.0}_{-7.0}$</td>
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<td>B</td>
<td>$0.379^{+0.017}_{-0.015}$</td>
<td>$8.020^{+0.085}_{-0.056}$</td>
<td>$28.5^{+2.0}_{-2.8}$</td>
<td>$37.2^{+4.7}_{-4.7}$</td>
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<td>C</td>
<td>$0.386^{+0.026}_{-0.024}$</td>
<td>$7.997^{+0.106}_{-0.076}$</td>
<td>$15.7^{+4.4}_{-3.2}$</td>
<td>$58.7^{+6.9}_{-9.4}$</td>
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Table 4.3: Simulated data with fixed $\sigma_{\text{blr}} = 0.4$ mas

<table>
<thead>
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<tr>
<td>Data sets</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>F</td>
</tr>
</tbody>
</table>

Recovered parameters

<table>
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<th>$\log(M_{\text{bh}}/M_{\odot})$</th>
<th>$i(^\circ)$</th>
<th>$\omega(^\circ)$</th>
<th>$\Delta v_0(2.35 \sigma_0)$ km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>8.008$^{+0.088}_{-0.059}$</td>
<td>28.3$^{+3.0}_{-2.8}$</td>
<td>36.6$^{+4.9}_{-1.2}$</td>
<td>684.5$^{+86.8}_{-137.8}$</td>
</tr>
<tr>
<td>E</td>
<td>8.138$^{+0.060}_{-0.065}$</td>
<td>20.8$^{+5.4}_{-2.4}$</td>
<td>40.9$^{+5.3}_{-6.6}$</td>
<td>1324.2$^{+172.4}_{-169.7}$</td>
</tr>
<tr>
<td>F</td>
<td>8.004$^{+0.134}_{-0.085}$</td>
<td>18.5$^{+9.3}_{-5.5}$</td>
<td>58.0$^{+8.8}_{-18.4}$</td>
<td>1481.2$^{+81.4}_{-171.5}$</td>
</tr>
</tbody>
</table>

4.4.2 Recovering parameters from Simulated datasets

In order to recover the parameters of the data sets and their associated uncertainties, we optimized the likelihood function that we considered to be Gaussian assuming that the errors on the measurements are Gaussian, and defined by

$$p(\text{data}|\text{model}) = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi \sigma_i^2}} \exp \left[ -\frac{(\text{data}_i - \text{model}_i)^2}{2\sigma_i^2} \right], \quad (4.14)$$

where $\sigma_i$ is the uncertainty on data$_i$. Maximizing the likelihood is identical to minimizing the $\chi^2$. We considered all OI observables i.e. spectrum, differential visibility, differential phase and absolute visibility are the part of our data sets and minimized the global $\chi^2$. According to the Bayes’ theorem, the posterior probability distribution $p(\text{model}|\text{data})$ is linked with the prior function $p(\text{model})$ which includes any previous knowledge about the parameters:

$$p(\text{model}|\text{data}) \propto p(\text{model}) \times p(\text{data}|\text{model}). \quad (4.15)$$

We assigned uniform prior to all the parameters except black hole mass for which we used log uniform prior. All the parameters are sampled from a large range: $\log_{10}(M_{\text{bh}}/M_{\odot})$ ranges from 6.5 to 10, $\sigma_{\text{blr}}$ ranges from 0.05 to 1.5, $i$ and $\omega$ range from 0$^\circ$ to 90$^\circ$.

To sample the parameters efficiently we used EMCEE package, developed by Foreman-Mackey et al. (2013), which is Python implementation of Affine Invariant Markov Chain Monte Carlo (MCMC) ensemble sampler by Goodman and Weare (2010). EMCEE explores the full posterior distribution using set of random points (thereafter “walkers”) in each step. This means selecting randomly a set of values from the range of each parameter. The result of the walkers of the current step is used for the next step in order to optimize the maximum likelihood. The

$^8$See http://ned.ipac.caltech.edu/level5/Stetson/Stetson3_2.html for a discussion about non-Gaussian error distribution.
walkers climb up towards the maximum likelihood in each steps. If the walkers are stucked in local minimum, then it would be necessary to use more walkers. To sample a highly multi-modal problem, one possibility is to run multiple MCMC simultaneously, which will be discussed in chapter 7.

In our simulations, we run EMCEE with 200 walkers and 200 steps. Thus we have 200 values on each parameters at each iteration, and this process is continued for 200 iterations. After few steps the parameters converge i.e. the width of the probability distribution of parameters stabilizes and does not change with further iterations. In figure 4.15, we plotted the mean and standard deviation of the probability distribution of all the parameters at each iteration for data set B showing that after few steps the mean and standard deviation do not change and remain almost constant. The steps before which it happens are called the “burn-in” steps. The probability distribution of the parameters is then calculated from the post burn-in samples. In all our data set, we consider 150 steps as “burn-in” phase since parameters remain stable after 100 iterations. Rest of the samples are considered as post burn-in phase and used to estimate the parameters and their uncertainties.

![Figure 4.15](image_url)

**Figure 4.15:** Mean (blue) and standard deviation (green) of the probability distribution of each parameters are plotted as a function of number of iteration during EMCEE run. After few iterations mean and standard deviation become fixed.

An example of the post burn distribution of samples is shown in figure 4.16, which is obtained for data set B. The scatter plots show the 2D distribution of samples with one $\sigma$ ellipse representing the covariance matrix whereas the histograms show 1D cut of the samples. The direction of semi-major axis of the ellipse shows the correlation or anti-correlation between two parameters, while eccentricity of
the ellipse shows qualitative information on the dependency of two parameters (for example circle means the parameters are independent). In our plot ellipses indicate anti-correlation or degeneracy of the parameters $M_{bh} - i$ and $M_{bh} - \omega$, which globally underline the critical sensitivity to the inclination $i$. For all datasets, the recovered parameters and their one $\sigma$ uncertainties are given in Table 4.2 and Table 4.3. Most of the parameters are recovered within one $\sigma$ uncertainty. The maximum uncertainty in $\sigma_{\text{blr}}$ is obtained in the case of dataset C, which is $0.386^{+0.026}_{-0.024}$ mas. Due to slight degeneracy between $\sigma_{\text{blr}} - M_{bh}$, $\sigma_{\text{blr}}$ tends to be underestimated even if the result is within $1\sigma$ of the input value. This is important for distance measurement using “BLR parallax” as discussed in chapter 7. Inclination has maximum uncertainty in the case of dataset A, $i = 24.8^{+5.4}_{-3.5}$. Opening angle is constrained well in all data sets and one $\sigma$ uncertainty is less than $10^\circ$. Although, $M_{bh}$, $i$ and $\omega$ are coupled in BLR differential measures, but the overall uncertainty remains quite good.

As discussed in section 4.3.1, OI can estimate the BLR size that can also be deduced from the RM typical time lag. Thus we can concentrate on the degeneracy between $i$, $\omega$ and $\sigma_0$ that impacts on the mass measurement. The results of a model fit with a fixed $\sigma_{\text{blr}}$ are given in Table 4.3.

From a fit of the OI data only we obtain good constrains on all the parameters with AMBER+ quality level, with a mass accuracy of about $0.08-0.13$ dex. The largest uncertainty is obtained for a quite low $15^\circ$ inclination. This uncertainty is quite similar to that achieved by Pancoast et al. (2011) with simulated RM data. However, when Pancoast et al. (2012) fit the real RM data of Mrk 50, they found a much larger uncertainty that they attribute to the modeling error. Remember that the statistical uncertainty of 0.15 dex obtained in traditional RM result (e.g., Bentz et al., 2009c; Denney et al., 2010) neglects the scatter of 0.44 dex in the RM scale factor $f$ (Woo et al., 2010; Greene et al., 2010). In that context, our $0.08-0.13$ dex results dealing specifically with the major causes of $f$ dispersion are very encouraging, even if it is a minimum value because this first global fit of OI data uses a very simplified model and a quite limited number of parameters. More accurate measurements of GRAVITY will bring very substantial improvement, as already indicated by data set B. A global fit of OI and RM data will further improve accuracy of the parameters.

4.5 Conclusion

We have developed a 3D BLR model to estimate both OI and RM observables. We have restricted ourselves to a limited set of parameters, as our first goal was to understand the typical OI signatures of the BLR features and to evaluate the potential of the QSO BLR observations with the VLTI. However, in future work our model can be very easily updated by changing the properties of the list of clouds making up the BLR, for example with a different radial distribution or by forcing the clouds to be located on a specific surface such as in bowl shaped BLR models.
Chapter 4. Geometrical and kinematical model of BLR

Input parameters
\( \sigma_{\text{blr}} \): 0.4 mas
\( \log_{10} (M_{\text{bh}}/M_{\text{sun}}) \): 8.0
inclination: 30 degree
opening: 40 degree

Recovered parameters
\( \sigma_{\text{blr}} \): 0.379\(^{+0.017}_{-0.015}\) mas
\( \log_{10} (M_{\text{bh}}/M_{\text{sun}}) \): 8.020\(^{+0.085}_{-0.056}\)
inclination: 28.5\(^{+2.0}_{-2.8}\) degree
opening: 37.2\(^{+4.7}_{-4.7}\) degree

Figure 4.16: EMCMC post-burn distributions for dataset B. The red line shows actual input parameters of this data set. The scatter plots show the projected two-dimensional distributions and green ellipses represents the one \( \sigma \) regions of the projected covariance matrix. The histograms show the projected one-dimensional distributions with dotted green lines representing mean and the one \( \sigma \) uncertainties. From top-to-bottom and left-to-right, the panels show BLR width \( \sigma_{\text{blr}} \), \( \log_{10} (M_{\text{bh}}/M_{\text{sun}}) \), inclination \( i \) and opening angle \( \omega \).
We show that OI, with a spectral resolution of the order of 1000, will remove the degeneracies between the inclination $i$, the opening angle $\omega$ and the local velocity field contribution $\sigma_0$ that are the main cause for the dispersion of mass estimates from RM using only the equivalent time lag and width of the emission lines. Monte Carlo Markov Chain (MCMC) with the EMCEE package model fitting of differential visibility and phase confirmed that OI alone can measure the BH mass, $i$, $\omega$ and $\sigma_0$, if we have a good estimate of the BLR angular size. The resulting mass estimate accuracy will be of the order or better than 0.15 dex with AMBER+, (except at inclinations lower than 10°), and will be further improved with GRAVITY. This is much better than the standard mass dispersion of 0.30 to 0.44 dex that includes the effect of $f$ dispersion (Bentz et al., 2009c; Woo et al., 2010). It is similar to the best advanced model fits of RM data by Pancoast et al. (2011, 2014b). Combining OI and RM will increase the number of usable equations and therefore the number of parameters that can be fitted and will decrease the number of a priori model assumptions.

We have underlined the importance of high accuracy absolute visibility measurements. A key condition is the possibility to use a fringe tracker (FT) that stabilizes the OI transfer function and reduces its calibration errors. However, there are many targets where absolute visibility measurements will not be accurate enough while we will still have accurate differential visibilities and phases. Then it will be necessary to obtain the size information from RM measurements, but this assumes that we can compute the scaling factor between OI and RM sizes discussed in paragraph 4.3.1 as well as the scaling factor between OI and RM observations made in different emission lines (see section 7.5 for a discussion).

When the global angular size of the BLR has been estimated, either from direct OI observables or from properly scaled RM observables, differential visibilities and phases, or even differential phases alone, are sufficient for accurate mass estimates, if the interferometric observations feature a sufficient SNR. In addition to $i$, $\omega$ and $\sigma_0$, these observables constrain the other BLR characteristics such as the nature of the global velocity field (rotation and inflow-outflow velocity laws) or the cloud optical thickness.
5

Broad Line Region of 3C273

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5.1 Introduction to 3C273

3C273 is the brightest quasar, located in the constellation Virgo, with \( z = 0.158 \) corresponds to angular size distance of about 540 Mpc\(^*\) (at this distance 1 mas=2.617 pc), and \( K \) magnitude of 9.7 (figure 5.1). It is redshifted enough for the Pa\( \alpha \) line to be fall in the \( K \) band making it particularly suited for observing with AMBER because Pa\( \alpha \) is two times brighter than Br\( \gamma \). Previously estimated width of the Pa\( \alpha \) emission line is about 3400 km/s, centered at 2.17 \( \mu \)m.

Kaspi et al. (2000) estimated time lag of 514\( ^{+65}_{-64} \), 382\( ^{+117}_{-96} \) and 307\( ^{+57}_{-86} \) light days (lds) between UV continuum (B band) to H\( \alpha \), H\( \beta \) and H\( \gamma \) emission lines, respectively, from the reverberation mapping (RM) variability study. This corresponds to a BLR size of 387\( ^{+58}_{-50} \) lds.

On the other hand, the estimated absolute visibility of the inner rim dust torus in \( K \) band with KI is 0.979\( \pm \)0.017 corresponding to a size of 0.296\( \pm \)0.124 mas at the distance of 3C273, implying a torus inner rim radius of 0.81\( \pm \)0.34 pc (Kishimoto\(^*\))

\(^*\)\( H_0 = 73.0 \text{ km s}^{-1}\text{Mpc}^{-1}, \Omega_m = 0.3 \text{ and } \Omega_\Lambda = 0.7 \)
Thus, it is expected that $\text{Pa}_\alpha$ BLR size to be between $\text{H}_\alpha$ and inner rim size.

3C273 has a kilo-parsec jet, visible across the electromagnetic spectrum, shown in figure 5.2, having two distinct components: a small scale jet, which shows superluminal motion and observed with VLBI techniques, and a long jet visible at radio, optical and X-ray. Recent optical and radio data as well as polarization study suggest that the long jet has a position angle of $222.2^\circ$ (Conway et al., 1993).

Several authors estimated inclination of 3C273, however, the results are very different in each case. Based on VLBI observation and jet beaming argument Unwin et al. (1985) estimated an inclination between $10^\circ$ and $20^\circ$ depending on its bulk Lorentz factor. However, Kundt and Gopal-Krishna (1986) estimated an inclination of $20^\circ \pm 10^\circ$ from the width of the lobes in the Jet. A limit on inclination $i = 8.5^\circ$ was given by Lister et al. (2009) from the super-luminal motion of the inner jet. On the other hand, the orientation of the larger-scale jet in 3C273 differs from the orientation of inner small-scale jet by about $20^\circ$, for example Conway and Davis (1994) found an inclination between $30^\circ$ to $35^\circ$ and similarly Mikhailova et al. (2010) estimated inclination between $29^\circ$ to $33^\circ$. However, this difference most probably due to apparent bend of the flow occurring between 8 and 20 mas from the core (see Conway and Davis, 1994; Stawarz, 2004).

Analyzing the variability of 3C273 in UV and optical light curve, Paltani et al. (1998) found two variable components that contributing to the blue-bump of 3C273, one of which shows short term variation associated to the geometrically thick accretion disk model, and another shows long term variation associated to the inner jet. In the infrared, a change in the variability by a factor of 2 has been detected on a timescale as short as one day in this object (Courvoisier et al., 1988), showing flux density has a power-law spectrum with spectral index 1.2 i.e. $f_\nu \sim \nu^{-1.2}$. 
Figure 5.2: Jet of 3C273 visible across the electromagnetic spectrum is that in 3C273. Images obtained with HST (left) and MERLIN 18cm (right). Credit: Bahcall et al. (1995).

Figure 5.3: Differential visibility and phase is plotted for three different baselines of AMBER with a compact BLR of size $\sigma_{\text{blr}} = 0.1$ mas, $i = 30^\circ$, $\omega = 0^\circ$ and a SMBH of mass $M_{\text{bh}} = 5 \times 10^8 M_\odot$. 
Chapter 5. Broad Line Region of 3C273

Figure 5.4: Model line profile of the same model as above.

Though, the above studies give very useful insight about 3C273 BLR, the geometry and kinematics of the central engine remain unknown, mainly due to the resolution needed to observe the BLR. We thus looked at the brightest QSO 3C273 with AMBER at VLT1. In this chapter, we will present the result of our first detection of a spectrally and spatially resolved emission line of 3C273. If we consider Paα BLR of 3C273 is very compact (similar to the RM BLR size), with a flat-thin disk geometry (zero opening) inclined at 30° having a central BH of mass $5 \times 10^8 M_\odot$, from figure 5.3 we find that differential visibility has a rise at the top of the continuum visibility of about 2%, and differential phase is up to 2°, if jet direction is along the rotation axis. Differential visibility appears to be double peaked while differential phase profile is “s” shaped. On the other hand, the Paα emission line profile (figure 5.4) appears to be double peaked in contrast to the observed line profile with SINFONI spectrograph (PI: A. Marconi).

This chapter is presented as follows. In section 5.2, we described our interferometric observation and data reduction process. In section 5.3, we presented Bayesian model fitting of 3C273 BLR. A detailed analysis of previous visible RM data is performed in section 5.4. Finally, we discussed our result in section 5.5.

5.2 Observation and Data reduction

5.2.1 Observation

We observed the quasar 3C273 in May 2011 with AMBER in medium resolution using the UTs 1, 2 and 4. We used the “blind” mode observation technique as described in section 3.6 allowing us to increase the limiting magnitude of medium resolution (MR) observation. During observation, we first found the fringes on a bright calibrator and we knew that they will remain within the coherence length of MR observations (3 mm in K band) for several tens of minutes. Then, we observed the 3C273, without detecting any fringes in individual frame (i.e. P2VM is useless) and we accumulated incoherently the $|2DFT|^2$ of the $x - \lambda$ interferograms. The incoherent integration is done when the SNR is lower than 1 because
Figure 5.5: Differential visibility measured on a calibrator. Left (a): calibrator spectrum $n(\sigma)$. Center (b): calibrator DCS $|W_{ij}(p_{ij}^\sigma)| \approx n(\sigma)V_{ij}^2(\sigma)$. Right (c): calibrator differential visibility $V_{ij}^2(\sigma)$. All functions are divided by its average over $\sigma$. The curves are shifted for visualization. The wavelength range is from 1.99 $\mu$m to 2.33 $\mu$m. The black curves around 1 represent the time average while from top to bottom, the curves are obtained from four different calibrators of magnitude $K = 6.6$ (green), $K = 9$ (red), $K = 8.2$ (blue) and $K = 9$ in the longest baseline UT1-UT4=125 m.

in that case it is impossible to average the complex coherent flux ($C$) as the randomly variable phase will rapidly kill the amplitude of the average. Then, one incoherently integrates a phase independent quantity such as $|C|^2$.

The data was processed of the line in real time using AMBER+ advanced data reduction pipeline developed by F. Millour. The fringe peaks appear in a few seconds, showing the average piston that was then informed to the operator (an ESO astronomer who performs the observation), with typically half a minute delay, allowing him to correct for slow OPD drift. In MR observation, such corrections are useful typically after every 10 minutes, to keep the fringe peaks in correct position (within 100 $\mu$m), which is defined by the fringe peaks well separated in the piston direction (i.e. $\lambda$ direction). This is necessary because we cannot use the P2VM fit to separate the contribution of partially overlapping fringe peaks.

We used frame times of 300 ms, and collected about 200 photons per channel and per frame. This represents about 3 photons per pixel and is well below the detector read out noise of $11e^-$. The seeing conditions were very good, from 0.5 to 0.8 arcseconds, stable between 0.6 and 0.7 most of the time. During the half observing night presented here, we collected 47 exposures on 3C273, each with 200 frames of 300 ms, i.e. 1 hour and 20 minutes of open shutter time on 3C273 but only 47 minutes of actual integration. In addition, we recorded a collection of calibrators of different magnitudes. In spite of the fairly long DIT, the VLTI/AMBER visibility was between 0.2 and 0.4, depending on the baseline and the conditions.

5.2.2 Data reduction

We reduced the full data set using AMBER+, a FFT-based data reduction software for AMBER, developed by F. Millour, and modifying some of the functions (Petrov et al., 2012). The equations relevant to the data reduction has been written in
Figure 5.6: Differential cross spectrum and differential visibility on the 3C273. Left (a): 3C273 spectrum. Middle (b) and right (c): differential cross spectrum (thin color curves) and differential visibility (thick black) for 50m UT1-2 baseline (middle) and 125m UT1-4 baseline (right).

section 3.6. Figure 5.5 illustrates the data processing on a set of calibrators: figure 5.5a shows the measured spectrum $n(\sigma)$, figure 5.5b shows the measured cross spectrum $W_{ij}^\sigma(p_{ij}^\sigma)$ and figure 5.5c shows the calibrator differential visibility. We used 4 calibrators of magnitudes $K = 6.6$, $K = 9$, $K = 8.2$ and $K = 9$. The behavior of the differential visibility is very stable and can be calibrated with an accuracy better than 1% on the $K = 9$ target. We find differential visibility is bent, which mainly due to the effect of chromatic OPD that has not been corrected in this first data processing. The spectral 508 channels obtained in the AMBER medium resolution observations have been binned by groups of 16 for SNR reasons (on the science target), thus we now have 0.009 $\mu$m per channel, corresponding to a resolution $R = 240$.

The result obtained from 3C273 observations is shown in figure 5.6. Figure 5.6a shows the spectrum of 3C273. We note the same telluric and instrumental lines as for the calibrators, at 2.01 and 2.06 $\mu$m and the Pa$\alpha$ emission line red-shifted at 2.17 $\mu$m. Figure 5.6b and 5.6c show the differential cross spectrum and the differential visibility for a 50 m (5.6b) and 125 m (5.6c) baselines. The emission line appears very clearly in the DCS in figure 5.6b while it is quite erased in the DCS in figure 5.6c. This indicates a differential visibility decrease in the line when the baseline increases, which can be seen in the differential visibility plots. However, figure 5.6 also shows a flux dependent bias of the DCS, which strongly affects the differential visibility in the telluric lines and casts suspicion on the variation in the emission line. In addition, the general shape of the differential visibility in the continuum is far from 1 and changes with the baseline. A bias analysis is needed before confirming the differential visibility measurement in the line.

Figure 5.7 shows the differential phases obtained on the calibrators and on the 3C273. On the calibrators, the differential phase displays the expected differential chromatic OPD. The 3C273 differential phases are always flat. The 3C273 observations were affected by the same chromatic OPDs, since 3C273 and all calibrators were less than 2$^\circ$ apart, and they were interlaced in time. This reveals a bias on the differential phase at the faintest magnitudes.
Figure 5.7: Differential phase of 3C273 (lower curves) as shown in Figure 5.6 and calibrator (upper curves) as shown in 5.5 in radian. All curves are at 0 average and shifted for visualization. The thick black line represents the average differential phase on 3C273. The color codes in 3C273 and in the calibrators are matched in time: we obtained first the black curves on 3C273, then the black curves on a calibrator, then the blue curves on the science followed by the blue curves on a calibrator and so on.

It is necessary to mention that there is a big time gap between the publication of preliminary result of this observation in Petrov et al. (2012) and current results. Thus, it will be better to summarize the history. The data was processed using an AMBER+ data reduction package mainly developed by Florentin Millour in 2011. It is an adaption of the GI2T 2DFT data processing to AMBER. The basic equations are given in chapter 3 and in Petrov et al. (2012). In a first step, AMBER+ computes the piston in each frame, from a block of frames temporally centered on it. In this block of frame, we compute the average $|2DFT|^2$ as explained in chapter 3, and use the fringe peak position to estimate the piston.

In a second step, we use this estimated piston to compute the differential visibility, coherent flux, and phase, in each frame and spectral channel. This assumes that for each frame, we compute $n_\lambda$ 2DFT cross-spectra as explained by section 3.6.2. To have flexibility in the time averaging, F. Millour has chosen to manipulate a 4D data hypercube of size $n_x \times n_\lambda \times n_\lambda \times n_{frame}$, where $n_x$ is the number of pixels in the interferogram, $n_\lambda$ the number of spectral channels and $n_{frame}$ is the number of frame in an exposure. This data cube is huge, more than 12 GB, at full resolution, which resulted in a software that is difficult to handle. In addition, AMBER+ is based on the “amdlib” standard AMBER software and uses the P2VM to estimate the photometric contribution of each beam and to find the fringe peak position.

In early 2012, we obtained the results presented in figure 5.6. It immediately appeared that the BLR seemed substantially more resolved than the inner dust rim that dominates the continuum interferomgram, which was in strong contradiction with RM expectations. But we also detected many problems that raised doubts about the validity of the results:

1. In the coherent flux, we see an obvious bias in the telluric lines at 2.01 and 2.06 $\mu$m, a strong drop in flux produces an apparent increase in coherent flux. Thus one could suspect that an increase in flux (like in the emission
lines), could result in an artificial decrease in the coherent flux and hence in the differential visibility.

2. The differential phase behavior on all calibrators is coherent with the expected chromatic dispersion in the air of the tunnels, while on 3C273 all phases appeared to be “flat”, as shown in figure 5.7.

These two facts, and other minor problems, raised serious doubts on our surprising result.

In addition, as we were obliged to bin the spectral channels by group of 16 to get a decent SNR, our final resolution was poor (only \( R = 240 \)) and our visibility drop, even if confirmed, could be created by the contamination of the field by large scale structure, such as some NLR clouds. We therefore needed to

- make a very complete bias analysis, to confirm and if possible improve our visibility and phase measurements
- reduce the data again, with a smaller spectral bin, and therefore a higher spectral resolution, to eliminate possible NLR contaminations (that should be much less extended in velocity)
- if possible, check and improve the data reduction software

For a minimum second data reduction with a reduced spectral bin and a reduced spectral window, we had to wait up to 2014 i.e. three years after the first data reduction in 2012 due to the data reduction software problem, which was beyond the control of the author of this thesis. We had therefore to perform the bias analysis and the calibration using the data as it has been reduced.

### 5.2.3 Bias analysis

Both the differential visibility and phase show biases on the 3C273 that do not appear or appear only marginally on the faintest calibrators. The differential cross-spectral measurements are not affected by the “quadratic noise bias” that appears in the power spectra containing terms of square of zero mean noise.

On the 3C273, the DCS is overestimated in the lowest parts of the telluric lines. A careful look at the calibrator plots shows that some of the exposures on the faintest calibrators are slightly biased in the bottom of the line. The \( K = 9 \) calibrator is fainter in this line than 3C273 in the continuum around the emission line and in first approximation we should say that the 3C273 measurements are not biased around the emission line. We have used an estimate of this bias as a function of the correlated flux made in all available channels outside the emission line. It reduces, but does not cancel the bias in the telluric lines and does not change much the visibility variation in the emission line. This does not really correct the general shape of the differential visibility and differential phase of 3C273 in the continuum, which is mainly due to the “piston error” bias analyzed below.
5.2.3.1 Piston error bias

Differential phase estimated using Eq.3.40 assumes an accurate estimation of the achromatic piston $p^a_{ij}$. If we make an error of $\Delta p$ on the estimation of the piston, the differential cross spectrum becomes

$$W_{ij}^\sigma = n_i n_j \Omega^{ij}(\sigma) \left[ \Omega^{ij}(\Delta p) - \Omega^{ij}(\sigma) \right] e^{-2i\pi\sigma(\Delta p)} >$$

and our measurements are affected by a bias term

$$B(\sigma) = \left[ \Omega^{ij}(\Delta p) - \Omega^{ij}(\sigma) \right] e^{-2i\pi\sigma(\Delta p)} >$$

This term cannot be corrected using calibrators, since the piston error depends on the source magnitude and on the observation conditions. $B(\sigma)$ depends on the source visibility, on the variations of instrument visibility with $\sigma$ and on the chromatic OPD, since all these effects will change $\Omega(\Delta p)$. In particular, the biases on the DCS detected in the telluric lines will behave like strong and random variations of $V^{ij}_I(\sigma)$ and hence of $\hat{\Omega}^{ij}(\Delta p)$. Figure 5.8 displays a Monte Carlo simulation of the effect of $B(\sigma)$ on the differential visibility and phase. We have simulated a target with a flat visibility but a sharp local variation of 10% at the position of the emission line, and a zero differential phase but a sharp local variation of 0.05 radians. The object is affected by window and gain table correction errors, which bent the overall differential visibility, and by variable local biases that mimic the behavior of the DCS of the telluric lines. The differential phase is affected by a variation of the chromatic OPD similar to the one observed on the calibrators through the 3C273 observations.

Figure 5.8a displays the evolution of the real differential visibility and phase through the observations. To evaluate the bias term, we have generated one random piston error per frame, with a standard deviation of 5 $\mu$m in figure 5.8b (good calibrator case) and of 50 $\mu$m in figure 5.8c (worst 3C273 case). Each plot in figure...
5.8b and 5.8c represents an exposure of 200 frames. We see that with a small piston error, the bias has almost no effect on the differential measures. This is coherent with the good measurements on the calibrators. With a strong piston error, both the differential visibility and phase are severely biased, and their error bars are increased. The average broadband visibility is substantially modified. However the sharp variations in the line are very well maintained for the differential visibility and somehow maintained for the differential phase. The global curvature of the differential phase is strongly affected, which looks similar to what we observe on the differential phase of 3C273. However, even when we simulate with exaggerated parameters, it seems that we are unable to kill a sharp differential phase feature of more than typically 3°. The simulation legitimates corrections of the smooth curvatures in the differential visibility and phase by a polynomial fit outside the emission line and outside the telluric lines. The simulation also shows that when the source is flat, i.e. when all chromatic OPD, window and detector biases are corrected from models in each frame before computing the 2DFTs, the tolerance to piston errors is much higher.

5.2.3.2 Photometric bias

To examine biases on photometry we plotted, in figure 5.9, the measured flux as function of an estimation of the true flux. The true flux was estimated by multiplying the average shape of the spectrum (avg=1 on spectral channels 14 to 28) computed on the 1/3 of the best exposures, with the average flux computed per exposure on spectral channels 14 to 28. A small bias is appeared in figure 5.9a at the bottom of the weakest atmospheric line. However, the bias disappears after eliminating the weakest channels (figure 5.9b), i.e. the first atmospheric bands at spectral bins 3 to 5. Thus we can ignore the bias on the photometry everywhere on 3C273, except in the deepest instrument-atmosphere absorption line.

![Figure 5.9: Bias on photometry. Left: Plots with all spectral channels. Right: Some channels are removed. See text for explanation.](image-url)
Figure 5.10: Coherent flux as a function of measured flux in a log-log scale. The flux scale has been converted in K magnitude. The global slope is an indication of the visibility and the ratio between coherent flux and measured flux. The points correspond to the different observations of 3C273 as well as 3 calibrators: BD+032657 (K = 8.7, observed twice), BD+022546 (K = 8.1) and TYC282-174-1 (K = 6.7).

5.2.3.3 Coherent flux bias

Figure 5.10 shows the bias in coherent flux (CF), \( \sqrt{W_{ij}} \propto f(\lambda)V_I\sqrt{V_{ij}^2}(\lambda) \), as a function of measured flux (F) \( f(\lambda) \propto \sqrt{n_i n_j n(\lambda)} \) on the ij baseline. If the differential visibility is constant (true for a calibrator after the correction of the chromatic OPD effects), the slope of the function yields the instrumental visibility. The ratio of CF and F gives the estimation of differential visibility and phase as discussed before. The measurement is therefore unbiased by flux fluctuations until CF remains proportional to F. In figure 5.10, these two quantities are plotted in log scales, which was matched with the source magnitude. The points correspond to three calibrators, BD+032657 (K = 8.7, observed twice), BD+022546 (K = 8.1) and TYC282-174-1 (K = 6.7), and the 3C273 (K = 9.8, observed 5 times). We see that the slope of CF/F is constant except for few aberrant points appeared at the lowest flux (inside the circle), in the bottom of the instrument plus atmosphere absorption line at 2.06 microns. This effect disappears after removing the spectral channels corresponding to the atmospheric lines. It can also be seen in figure 5.11,
Figure 5.11: Bias on coherent flux in linear scale. Left panel: plot with all spectral channels. Right panel: After removing the atmospheric lines.

which is in linear scale. In the left panel, all spectral channels have been used. We see a clear bending of the CF as a function of the measured flux. This is illustrated by the dark points representing the average of the CF measured in a given bin of flux. We can use this curvature to correct our data. When we remove the points of the atmospheric lines from the plot (right panel), we see the function (CF/F) is straight (dark points) within the noise dispersion. Thus CF proportional to F is a correct approximation if the weakest channels are removed. This however sets the magnitude limit between $K = 10.5$ and $K = 11$ for practical data processing considering 2 hours of observations.

The conclusion of the bias analysis:

1. The photometric bias does not exist if we remove the telluric line channels in the faintest exposures of the 3C273 data
2. The piston error bias gives an explanation for the flatness of 3C273 differential phase in the 2012 processing
3. The piston error bias is strongly reduced if we eliminate the telluric line channels from the 2DFT analysis. The residual can be properly treated by a polynomial fit of the signal in the continuum outside the emission line.
4. After elimination of the telluric lines, the coherent flux become marginal and can be corrected by a simple fit, which also removes the bent of the continuum and the line.

Therefore, we re-reduced our 3C273 data after eliminating the telluric line. This time we binned the spectral channel by groups of 8 corresponding to a spectral resolution of $R=480$. After correcting from the coherent flux residual bias, we obtained differential visibility as shown in figure 5.12. We did a polynomial fitting to remove the chromatic OPD shown by blue-solid line. The raw-spectrum is also
Chapter 5. Broad Line Region of 3C273

Figure 5.12: Visibility of 3C273 after correcting from the coherent flux residual bias. Continuum outside the emission line is fitted with a simple polynomial function (blue line). The emission line profile is over plotted to show its position in the spectral window (red-dashed line).

Figure 5.13: 3C273 result obtained after the final reduction and continuum subtraction. Plot shows differential visibility (upper panel) and phase (lower panel) for 50 m (left), 80 m (middle) and 125 m (right) baselines. The error bars in the plots are estimated from the temporal dispersion over the 47 exposures.

After removing the continuum slope, we get our final differential visibility and phase as shown in figure 5.13. This improves the accuracy on the differential visibility, which is $\leq 0.01$ per channel. It drops on all baselines and drops increase with the baseline length. On the largest baseline (UT1-4), we achieved an SNR=10. Interestingly, differential visibility drop extends over the line. In the case of differential phase, no signature has been found larger than 1°.
5.3 Bayesian model fitting

5.3.1 Model of 3C273

To interpret our 3C273 interferometric observation, we used our geometrical and kinematical model as described in chapter 4 and also presented in Rakshit et al. (2015). The model parameters that we wanted to constrain are $\sigma_{\text{blr}}$ that defines the width of the BLR, central BH mass $M_{\text{bh}}$, inclination angle $i$, opening angle $\omega$ and macro-turbulence parameter $P_{\text{turb}}$ since these are the main geometrical and kinematical parameters. Some of the parameters are kept fixed at the values obtained from literatures; $R_{\text{rim}} = 0.25$ mas (Kishimoto et al., 2011a), $F = 0.58$ (from 3C273 spectra) and $\Theta = 222.2^\circ$ (from jet position angle).

5.3.2 Model fitting

As a first step, for visual inspection, we run two models with $i = 20^\circ$, $\sigma_{\text{blr}} = 0.5$ mas, $w = 20^\circ$ and local velocity $\sigma_0 = 500$ km/s and with two different masses $M_{\text{bh}} = 5 \times 10^8 M_\odot$ and $M_{\text{bh}} = 50 \times 10^8 M_\odot$. The results are shown in figure 5.14. The corresponding fits of the spectrum is shown in figure 5.15. Both models provide a bad fit to the data. For model with low mass, figure 5.14, the line of sight velocity is very low making visibility signal very sharp although differential phase fits within error bar except the 80 m baseline (middle panel). The drop of the visibility although suggests an extended BLR. However, the line profile, shown in figure 5.15a, suggests that low inclination and low mass can not explain the result. If we increase mass then fits improve, shown in figure 5.14, however differential phase shows strong “S” shape signature. The line profile is broader than the observed one. This implies the BLR of 3C273 is not a flat disk, and central BH is not more massive than $M_{\text{bh}} = 50 \times 10^8 M_\odot$. Also interesting to note that if the inclination is very small then we either need a very thick geometry close to spherical or a large contribution from micro- or macro-turbulence to explain the width of the emission line and the visibility curve.

In order to find a global solution, we need to explore the parameter space. Thus, we adapted Bayesian model fitting approach, described in section 4.4.2, and maximize the likelihood $p(\text{data}|\text{model})$, which is equivalent to minimizing the $\chi^2(\text{data}|\text{model})$. We used EMCEE package, developed by Foreman-Mackey et al. (2013), which is a Python implementation of Affine Invariant Markov Chain Monte Carlo (MCMC) ensemble sampler by Goodman and Weare (2010). We showed in section 4.4.2 that EMCEE is very efficient in sampling the parameter space and it can be run in parallel using many CPUs. Each MCMC simulations runs for 300 iterations and for 200 walkers. After few iterations, called “burn-in” iterations, we found that the width of the probability distribution of the samples become stable i.e., no variation of width of sample distribution ensuring the convergence of the model. We remove the burn-in iterations, and calculated best fit value and its 1 $\sigma$ uncertainty of all free parameters from the rest of the samples.

We used four main key parameters $\sigma_{\text{blr}}$, $M_{\text{bh}}$, $i$ and $w$ as free parameters for global fitting keeping $P_{\text{turb}}$ fixed. We also repeated MCMC fitting for different $P_{\text{turb}}$ to
**Figure 5.14:** Comparison of the data (red points with blue error bars) and model (green line). Observed line profile is over plotted (solid-dashed line) showing the position of the line. The parameters of the model are same in both cases: $i = 20^\circ$, $\sigma_{blr} = 0.5$ mas, $\omega = 20^\circ$, $dv = 500$ km/s except the mass, which is $M_{bh} = 5 \times 10^8 M_\odot$ for the first model as shown in upper panels (a) and $M_{bh} = 50 \times 10^8 M_\odot$ for the second model as shown in lower panels (b).
find its best value that fits the data. Once we have data and model, we just need prior on the parameters defining any previous knowledge about them. In our case, $M_{bh}$ spans few order in magnitude thus, we used uniform prior in log on $M_{bh}$ where $\log_{10}(M_{bh}/M_\odot)$ ranges from 6.0 to 10.0. For all other parameters, we used uniform prior, where $\sigma_{blr}$ varies between 0.05 to 1.5 mas, $i$ between 5° to 90° (considering radio jet) and $\omega$ between 0° to 90°.

The mean and standard deviation of the sample distribution in each step during MCMC runs are plotted in figure 5.16. It shows that $\sigma_{blr}$ and $M_{bh}$ become stable after few iterations and have low standard deviation, except inclination and opening angle since these two parameters have opposite effects. Figure 5.17 shows the probability distribution of the parameters. The 2D scatter plot with
Figure 5.17: Parameters probability distribution obtained from MCMC fitting with $P_{turb} = 1$. The scatter plots show the projected two-dimensional distributions and green ellipses represents the 1σ regions of the projected covariance matrix. The histograms show the projected 1D distributions with dotted green lines representing mean and the 1σ uncertainties. From top-to-bottom and left-to-right, the panels show BLR width $\sigma_{\text{blr}}$, $\log_{10} (M_{\text{bh}}/M_\odot)$, inclination $i$ and opening angle $\omega$.

green ellipses of 1σ regions of the projected covariance matrix is shown. The histograms represent 1D probability distribution of the samples with its mean and 1σ uncertainties (green lines) for $\sigma_{\text{blr}}$, $\log_{10} (M_{\text{bh}}/M_\odot)$, inclination $i$ and opening angle $\omega$. The mean and 1σ uncertainties of the parameters (see Table 5.1) are $\sigma_{\text{blr}} = 0.585^{+0.011}_{-0.012}$ (mas), $\log_{10} (M_{\text{bh}}/M_\odot) = 8.682^{+0.017}_{-0.018}$, $i = 8.4^{+3.7}_{-2.2}$ (deg) and $\omega = 88.6^{+1.0}_{-1.5}$ (deg). Note that we neglected error on $R_{\text{rim}}$ measurement in the fitting process. This could increase the uncertainties on the parameters.

The fits of the differential phase and visibility (green line) using the mean value of the model parameters are shown in figure 5.18, and the corresponding fitted Paα emission line profile observed with SINFONI (blue) is shown in figure 5.19a. In all baselines, model fits all the spectro-interferometric measurements within the error
bars. We see that both the model emission line and visibility profile are narrower in the wings. As discussed in chapter 4, this can be due to a high turbulence that enhance the line wings, or due to a different radial intensity profile (more curvy than a Gaussian) that could increase the line wings by adding more “fast” material near the center of the object. However, a spherical geometry with the presence of turbulence gives a better representation of the data. The best fit model is plotted in figure 5.20 for edge-on (left) and face-on (right) views. Note that in the plots, size of the clouds increases with the time lag. Both the images appear to be similar as the geometry of the BLR is close to spherical, and since the inclination is close to face-on plots appear to be circular.

**Figure 5.18:** Global fit of the data from the best fit model obtained from MCMC fitting.

**Figure 5.19:** Global fit of the emission line profile.
5.4 Reverberation mapping window problem

The result of our most clean 3C273 OI data result is that the angular size of the BLR is substantially larger than the inner dust rim, and much larger than visible RM estimates. Kaspi et al. (2000) have spectro-photometrically monitored 28 Palomar-Green quasars including QSO 3C273 to obtain relationships between BLR size and central BH mass with quasar luminosity. Spectrophotometric monitoring was performed for 7.5 years with 20-70 observing epochs per object. During the observation, both continuum and emission line flux variation was found.

We have collected the RM data of 3C273 from Kaspi et al. (2000). The light curves are very sparsely sampled, consists of 39 spectroscopic epochs in 7.5 years. With
simple cross-correlation analysis, the estimated mean BLR size of Hα and Hβ line emitting regions is $387^{+58}_{-50}$ lds. Our interferometric data suggests an extended BLR that has the centroid of the response function at $\tau_{\text{cent}^*} = 1514$ days, as shown in figure 5.21. With a 7.5 years of observation, it is not possible to constrain such a large BLR size. Hence, we decided to analysis in depth the RM data. We first undertook analysis of the biases in RM data resulting from the time window and sampling problem, with E. Fossat who is an expert of similar problems in the analysis of the time series of spectra in astroseismology. After some interesting results, we decided to use the most recent RM methods to treat this problem and reanalyze the 3C273 RM data.

![Figure 5.22: Interpolation of the 3C273 continuum light curve observed by Kaspi et al. (2000). The solid line is the best fit light curve and the filled region represents the 1σ uncertainty region.](image)

In RM, time window and sampling problems are treated by optimum interpolation procedure described in Zu et al. (2011). We thus make use of the software, which is Python code “Javelin” developed by Zu et al. (2011) for continuum light curve interpolation. Javelin allows simultaneous fitting of continuum and different emission lines light curves. It uses a damped random walk model, which is described in section 7.2. The fitted continuum light curve is shown in figure 5.22. Once we have a continuum light curve at all time, we can create an emission line light curve convolving a simple top-hat response function of centroid $\tau_{\text{cent}^*}$. After cross-correlating the continuum and emission line light curves, we calculated the centroid ($\tau_{\text{cent}}$) of the cross-correlation function (CCF). This step has been repeated for various $\tau_{\text{cent}^*}$, allowing us to plot centroid of response vs centroid of CCF, as shown in figure 5.23.

As discussed in chapter 2, $\tau_{\text{cent}^*}$ is equal to $\tau_{\text{cent}}$ if light curves extend up to infinity. From figure 5.23, we see that the time-lags are unbiased until $\tau_{\text{cent}} \simeq 600$ lds and then they remain bijectively related to the true input values up to $\tau_{\text{cent}} \simeq 800$ lds, after which any input $\tau_{\text{cent}^*}$ results in a measured $\tau_{\text{cent}}$ randomly placed between 200 to 400 lds. This occurs mainly due to 7.5 years of time window. Hence, to detect a distinct peak in CCF for 3C273 Paα line, we need much longer duration monitoring campaign since our estimated Paα line emitting region is much larger than Hβ. According to the above simulation, the duration of the light curve or monitoring campaign should be more than 3 times of the maximum time lag ($2R_{\text{blr}}/c$) to estimate accurately the mean response of the BLR. Similar suggestion
was also given by Horne et al. (2004). Note that, to detect peak in CCF for high-ionization line like CIV, a shorter than 7.5 years monitoring should be sufficient, and thus for low-luminous objects much shorter campaign will be fine.

5.5 Discussion and conclusion

We successfully resolved the Pa\(\alpha\) emission line of the quasar 3C273 using a “Blind mode” observing technique with AMBER instrument at VLTI. An AMBER+2DFT data reduction algorithm was used to reduce the data as standard AMBER data reduction software can not be used at that faint magnitude. Emission line signature in few spectral channels has been detected. Differential visibility shows a drop that increases with baseline length showing a larger BLR than continuum dust sublimation radius. Moreover, we obtained differential phase of 0 ± 1° in all baselines.

We used a geometrical and kinematical model to interpret our 3C273 observation, which is very flexible and can account various geometrical and kinematical models (see chapter 4). In order to sample the parameters space, we employed a MCMC simulation, and calculated probability distribution of each model free parameters. We found that 3C273 has a larger BLR, a Gaussian of standard deviation \(\sigma_{\text{blr}} = 0.585^{+0.012}_{-0.011}\) mas = \(1823^{+57}_{-34}\) lds or HWHM_{blr} = \(2142^{+43}_{-39}\) lds, extended beyond the dust sublimation radius. Its response function has a centroid at about 1514 days (figure 5.21), which is about 4 times larger than H\(\beta\) emission line size obtained via cross-correlation by Kaspi et al. (2000).

This suggests that emission line gas clouds is extended beyond sublimation radius, and present in and above the inner rim dust torus. When the clouds are directly illuminated by the central source, they emit emission line photons. Heavily shielded clouds (dust) produce very weak lines, and contribute in the near-IR continuum. This result supports the recently proposed “Bowl shaped” BLR model by Goad et al. (2012), where the authors suggested that the clouds can be present on the surface of the dusty torus forming a “Bowl shaped” where height of the clouds

![Figure 5.23: Centroid of the CCF is plotted against the centroid of response function. The time lag can not be measured if the centroid of CCF is greater than 800 days for a 7.5 years observing campaign.](image-url)
increases with its distance from the central source, and emits only when they are illuminated by the radiation of the central source. Note that the large BLR radius is also estimated recently by Landt et al. (2014) from recent near-IR spectroscopic study, suggesting that the BLR has an outer radius, and for 3C273 this is 15,551 light-days obtained from Pa$\beta$ emission line spectroscopy.

One possible reason for this bigger BLR size measured by OI than RM is that the OI visibility depends on a flux weighted radius. Actually the impact of a given cloud on the visibility profile increases as the square of its angular radius (see chapter 4). Thus, it is weighted to the flux contribution from larger radius. On the other hand, the RM size is a response-weighted radius, weighted to the larger amplitude of flux variation, which comes from the compact emitting region or smaller radius. Kishimoto et al. (2011b) and Koshida et al. (2014) discussed the difference between RM and OI estimates in near-IR in the apparent size of the inner rim. OI estimated size of the inner rim is a factor of $1.5 - 2.5$ larger than RM (see figure 2.6). Since Pa$\alpha$ is a lower ionization line than H$\beta$ or H$\alpha$, the expected RM size of Pa$\alpha$ emitting region could be 1.2 to 2 times larger than H$\beta$ (Alessandro Marconi in private communication, and also see Goad, 1995). Moreover, OI size could be two times larger than RM size. Thus, our estimated Pa$\alpha$ size, about 4 times larger than RM H$\beta$ size, is not in much contradiction with RM H$\beta$ (or H$\alpha$) result. However, the BLR larger than dust inner-rim remains a surprise.

The differential phase estimates of $0 \pm 1^\circ$ suggest that the BLR of the 3C273 has a roughly spherical geometry, which is inclined at a very low inclination towards observer. High inclination and flat geometry will produce strong phase signature as shown in figure 5.14. Note that our estimated inclination is similar to the values obtained by Unwin et al. (1985) and Lister et al. (2009) from the observation of radio-jet. Due to the low inclination, a large opening of the BLR is needed to match the width of the emission line profile as well as the broadening of differential visibility shape. Our Pa$\alpha$ emission line shows a Lorentzian profile, which is due to the emission from an extended region. It has been suggested that a Lorentzian profile could be due to the presence of turbulence (Goad et al., 2012). We also found the presence of macro-turbulence in 3C273 BLR broadening the emission lines and making it Lorentzian shape. Note that very large turbulence can also fit the line profile and differential phase without the need of a large opening angle, but then it would be difficult to explain the origin of such large turbulence velocity.

Our geometrical and kinematical model provides an estimate of the 3C273 BH mass $4.80^{+0.20}_{-0.17} \times 10^8 M_\odot$ (neglecting the error on $R_{\text{rim}}$ measurement), which is similar to the mass obtained by RM mapping data by Kaspi et al. (2000), but an order of magnitude lower than Paltani and Türler (2005). The higher mass estimated by Paltani and Türler (2005) could be due to the problem of line width measurement. After a re-analysis of Kaspi et al. (2000) data, Peterson et al. (2004) found a virial product of $1.61 \pm 0.34 \times 10^8 M_\odot$. However, using a virial scale factor $f = 5.5$, they estimated a BH mass $8.86 \pm 1.87 \times 10^8 M_\odot$ of 3C273. Since, our measurement provides BH mass, which is independent of unknown virial factor ($f$), we estimate $f \approx 3$ comparing with virial product of 3C273 estimated by Peterson et al. (2004). This $f$ value is within the value of $f = 2.8$ obtained by Graham et al. (2011) from the scaling of $M_{\text{bh}} - \sigma$ relation (see chapter 2) and $f = 4.3$ obtained by Grier et al. (2013) using high quality RM data to recover velocity-delay map. This value
is also close to the $< f > = 4.7$ obtained from recent dynamical model of RM high quality LAMP data by Pancoast et al. (2014a) although the dispersion around this mean is very larger of the order of 5, showing individual object have very different $f$. Our estimation of the virial factor suggests that BH masses estimated from RM data using $f = 5.5$ is overestimated by a factor of about 1.8. A handful number of objects can indeed allow to estimate a mean $f$ value from interferometric data and calibrate the BH masses estimated using virial relation in RM technique.
6

Feasibility of BLR observation

6.1 Introduction

Signal-to-noise ratio (often abbreviated as SNR or S/N) is defined as the ratio of signal amplitude to the noise RMS (root mean square), and it predicts the feasibility of an observation and allows to anticipate the accuracy on the recovered mode fitting parameters. To understand the feasibility of BLR observation with the IR instruments at VLTI, we did an SNR analysis. The aim is to estimate the number of objects that could be accessible with the current, upcoming and possible spectro-interferometric instruments in the near-infrared (near-IR) at VLTI to set the possibility of having a large unification scheme, which assumes that we can analyse enough sources to study correlations between the main morphological parameters and the luminosity for example.

Since the end of KI operation, the VLTI with Unit Telescopes (UTs) is the single interferometer with an IR SNR potentially sufficient for MR ($R = 500 - 1500$) observation in the $K$ band. We have seen in chapter 4 that a spectral resolution of the order of $R = 1000$ is necessary to discriminate between some BLR models. Moreover, we believe that the 8 m UTs, due to their large collecting area, are
a key feature for an AGN program with such spectral resolution as other interferometric facilities, such as CHARA or NPOI, are equipped with substantially smaller telescopes and for the time being, these are far from the necessary limiting sensitivity.

In the case of each VLTI instrument we examine the possibility to observe a target, i.e. to detect and maintain the fringes on the target itself, and the accuracy of the absolute and differential visibility and phase that can be obtained on each target.

### 6.2 Current, incoming, and possible VLTI instruments

The VLTI is the interferometric mode of the very large telescope situated at Mount Paranal in Chile and installed by European Southern Observatory (ESO). It consists of four 8 m UTs and four 1.8 m auxiliary telescopes (ATs) offering high sensitive and high angular resolution observation. The UTs are fixed while ATs can be moved to 30 different locations, that would provide maximum baseline separation of 200 m, but currently offering a maximum baseline of 139 m between UT1 and UT4 (see figure 3.5).

**AMBER+:** AMBER is a first-generation near-IR spectro-interferometric VLTI instrument (Petrov et al., 2007). With its standard frame-by-frame processing, it cannot observe AGNs in medium resolution (MR) as the current VLTI fringe tracker (FT), used to stabilize fringes, is limited to about $K < 9$. However, AMBER can already operate in an alternative mode, called AMBER+ (Petrov et al., 2012), where the full dispersed fringe image is processed, in a way equivalent to a coherent integration of all spectral channels, whatever the SNR per channel is. It allowed observing successfully the quasar 3C273 in MR (R=1500). The fringes were detected with a SNR=3 in typically 1 s. To obtain differential visibility and phase with a sufficient accuracy (respectively 0.02 to 0.03 and $1^\circ$ to $2^\circ$), it was necessary to bin the spectral channels down to a resolution 250. The results achieved with AMBER+ on 3C273 have been used to validate and calibrate our SNR computations.

**OASIS:** OASIS (“Optimizing AMBER for Spectro-Interferometry and Sensitivity”), minor AMBER modification proposed by Petrov et al. (2014), could be installed in a few months as soon as ESO accepts it to include in the VLTI planning. It uses spectral encoding to separate the fringe peaks, allowing to code the interferogram on 4 pixels instead of 32 pixels currently needed for AMBER. Moreover, the spatial filters with fibers would be bypassed by optimized optics which yields a gain in transmission of about 7 with regard to the current AMBER instrument. For MR differential observations, theses spatial filters are not necessary, as they basically improve the accuracy on the absolute visibility. However, as we have seen from chapter 4 that absolute visibility accuracy in the continuum is important, the idea is to combine OASIS MR observations with GRAVITY or PIONIER LR observation that will allow accurate absolute visibility than their spatial filtering and stability obtained with very compact integrated optics.

**OASIS+:** OASIS+ would be a major improvement of AMBER. It could be developed as a visitor instrument in the 1 M€ range. The current AMBER detector
would be replaced with a new SELEX detector and the spectrograph which is optimized for BLRs, with a fixed spectral resolution, i.e. $R \approx 500$. We note that OASIS+, or any other successor of the 2nd generation VLTI instruments, is not in the current ESO plans, but it gives an idea of what could be ultimate VLTI performance for AGNs.

**GRAVITY**: GRAVITY is the 2nd generation 4 telescopes beam combiner VLTI near-IR spectro-interferometric instrument that will be commissioned in 2016 (Eisenhauer et al., 2008). It is expected to provide astrometry accuracy of 10 µas and phase-referenced imaging with 4 mas resolution. It will have three spectral resolution mode 30, 450 and 1500. Gravity will provide all the interferometric measurements that presently AMBER does, but with 6 baselines observation. Visibility phase between the reference star and science object in all spectral channels as well as differential phase between two objects can be obtained from GRAVITY observations. Using these information it will be possible to obtain images exploring the complex visibilities, and for astrometry using the differential phase and group delay. Its main characteristic of interest for a BLR program is that it has an internal FT that should allow cophased observations up to $K = 10.5$. This allows much longer individual frame times, a higher instrumental visibility and a more stable one. The current GRAVITY plans do not foresee using without its fringe tracker. The GRAVITY internal FT will boost the accuracy of all measures on source bright enough to allow using FT (or with a nearby reference source bright enough for off-axis FT). The GRAVITY FT will have two effects:

1. It will improve the fundamental SNR but allowing much longer frame times, and hence differential visibility and phase SNR will be improved.

2. It will stabilize the VLTI/GRAVITY instrumental contrast and therefore will allow more accurate absolute visibility measurements.

The main drawback of the current GRAVITY FT is that it is optimized for accuracy rather than for absolute sensitivity, and should therefore hardly allow observations fainter than $K \approx 10.5$.

**OASIS+FT**: It refers to the use of OASIS+ with a second-generation FT, with a limiting sensitivity larger than $K = 10.5$. Such a FT would allow increasing the accuracy of the measurements just like the one in GRAVITY, and it would also extend the possibilities of GRAVITY. Currently proposed designs show that FT magnitudes higher than 13 in $K$-band should be achievable (Petrov et al., 2014; Meisner et al., 2012). I have participated in the study of a concept of “Hierarchical Fringe Tracking (HFT)”, which is described in Petrov et al. (2014), where this kind of magnitude gain could be obtained:

1. Instead of dividing the flux of each telescope between the number of telescope pairs like the pairwise GRAVITY FT, all the flux of a telescope is used to cophase it with the one in the local pair. In the HFT, when two telescopes are cophased all the flux is transmitted as coming from a single telescope and use to cophase a pair of pairs.
2. In the central component of the HFT, which is a “Two telescopes Spatial Filter”, the piston is measured using only 3 to 5 pixels that analyze the broad band signal in both polarizations, instead of using 4 pixels per spectral channel (5 in the GRAVITY FT) and polarization.

The estimated magnitude gain, with the same detector and control algorithms is between 2.5 to 3.5.

MATISSE: MATISSE is another 2nd generation 4 telescopes beam combiner VLTI instrument that will offer an extremely large spectral coverage, from 3 to 13 μm (covering 3 spectral bands L, M and N) with a spectral resolution ranging from 30 to 4500. MATISSE offers several possibilities to study AGNs:

1. It will give much better constraints on the dust torus morphology than MIDI or the K band instruments. This can allow more reliable absolute visibility estimate and thus better models of the torus than the ring model used in most of this thesis.

2. In MR in the L band, we will be able to observe BLR in Brγ emission line for low redshift targets.

### 6.3 Interferometric signal and noise

From a general formalism described in Petrov et al. (1986) and updated in Vannier et al. (2006), it is easy to show that the noise on the coherent flux computed from each interferogram is given by:

\[
\sigma_c = \sqrt{n_T n_\ast t_{\text{DIT}}} + n_p \sigma_{\text{RON}}^2 + n_T n_{\text{th}} t_{\text{DIT}}, \tag{6.1}
\]

where \(n_\ast\) is the source flux per spectral channel, frame and second, \(n_T\) is the number of telescopes, \(t_{\text{DIT}}\) the frame exposure time, \(n_p\) is the number of pixels (for multi-axial instruments up to \(n_T = 4\) we have \(n_p = 4n_T(n_T - 1)/2\)), \(\sigma_{\text{RON}}^2\) is the variance of the detector read-out noise and \(n_{\text{th}}\) is the background flux per spectral channel, frame and second. \(t_{\text{DIT}}\) must be short enough to freeze the turbulence. In good seeing conditions, it is possible to use \(t_{\text{DIT}} = 200\) ms. In K-band this value is much smaller than the detector noise and hence can be neglected for short exposures. However for long exposures such as in cophased mode \(n_{\text{th}}\) should be taken into account. In K-band, \(n_{\text{th}} = 1.07\) photons s\(^{-1}\)cm\(^{-2}\)A\(^{-1}\) (In the \(\lambda^2\) solid angle of a single mode spatial filter). For a pair-wise instrument like GRAVITY, the same formula applies with \(n_p = 4\) and the flux of each telescope has to be divided by \((n_T - 1)\) that is the number of pairs each aperture is involved in.

The classical SNR on the coherent flux, per spectral channel and per frame (Vannier et al., 2006; Lagarde et al., 2012) is then given by:

\[
\text{SNR}_0 = \frac{C}{\sigma_c} \approx \frac{n_\ast t_{\text{DIT}} V_{\text{inst}}}{\sigma_c}, \tag{6.2}
\]
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and

\[ \sigma_\phi \simeq \frac{\sigma_c}{C\sqrt{2}}, \quad (6.3) \]

where \( V_{\text{inst}} \) is the instrument visibility.

The source flux per spectral channel per frame and per second is given by:

\[ n_* = n_0 AST \delta \lambda 10^{-0.4 K_{\text{mag}}}, \quad (6.4) \]

where \( n_0 \) is the number of photons \( s^{-1} \text{cm}^{-2} \mu \text{m}^{-1} \) from a star with \( K_{\text{mag}} = 0 \), outside earth atmosphere, \( n_0 = 45 \times 10^4 \) photons \( s^{-1} \text{cm}^{-2} \mu \text{m}^{-1} \), \( A \) is the collecting area of telescope, \( S \) is the Strehl ratio with the VLTI adaptive optics system MACAO, \( T \) is the overall transmission of the atmosphere, the VLTI and the instrument, and \( \delta \lambda \) is the spectral band-width equal to \( \lambda_0/R \), where \( R \) is the resolution.

### 6.3.1 Standard processing

In the classical AMBER data processing (the P2VM approach described in Tatulli et al., 2007), the coherent fluxes measured in each frame are added coherently. This assumes that we have been able to measure the atmospheric piston in each frame with a sufficient accuracy of at least \( \lambda/2\pi \). At best the piston is estimated from all the independent phase differences that can be extracted from the \( n_\lambda \) spectral channels.

\[ p = \frac{\Delta \phi}{2\pi} \frac{1}{\Delta \sigma} > n_\lambda/2 \quad (6.5) \]

\[ = \frac{\Delta \phi}{2\pi} \frac{2R \lambda}{n_\lambda} > n_\lambda/2 \quad (6.6) \]

and

\[ \sigma_p \simeq \sigma_\phi \sqrt{2} 2R \lambda \frac{1}{n_\lambda} \sqrt{n_\lambda/2} \quad (6.7) \]

and the condition \( \sigma_p < \frac{\lambda}{2\pi} \) yields \( \sigma_\phi < \frac{n_\lambda^{3/2}}{4R} \) at AMBER MR mode (\( R = 1500 \), \( n_\lambda = 256 \)) this yields \( \sigma_\phi < 0.7 \text{ rad} \). The condition for coherent processing is that the \( \text{SNR}_0 = \frac{1}{\sigma_\phi \sqrt{2}} \simeq 1 \). This limits the MR mode of AMBER without FT, i.e. with short exposure to \( K \sim 8 \).

An alternative is the so called incoherent addition, when we arrange the modulus of the coherent flux that is insensitive to phase errors. From Jaffe 2014 (private communication) we know that the \( \text{SNR}_Q \) on \( |C|^2 \) is

\[ \text{SNR}_Q = \frac{\text{SNR}_0^2}{\sqrt{1 + 2\text{SNR}_0^2}}\sqrt{N_{\text{EXP}}n_\lambda}, \quad (6.8) \]

where \( n_\lambda \) is the number of spectral channels and \( N_{\text{EXP}} = \frac{t_{\text{EXP}}}{t_{\text{DIT}}} \) is the total number of \( t_{\text{DIT}} \) frames processed in the \( t_{\text{EXP}} \) total time. If \( \text{SNR}_0 \ll 1 \); \( \text{SNR}_Q \simeq \text{SNR}_0^2\sqrt{N_{\text{EXP}}n_\lambda} \) and this mode is a very poor way to increase the sensitivity.
6.3.2 AMBER+ processing

We have developed a new approach where the full-dispersed fringe image is processed, in a way equivalent to a coherent integration of all spectral channels, whatever the SNR\textsubscript{0} per channel is. This data processing is inspired by the GI2T and VEGA/CHARA (Berio et al., 1999), and explained in chapter 3 and 5. Then we still have to make a quadratic average on the frames and the SNR of this processing is given by

$$SNR_+ = n_\lambda \frac{SNR^2_0}{\sqrt{1 + 2n_\lambda SNR^2_0}} \sqrt{N_{\text{EXP}}}.$$  \hspace{1cm} (6.9)

In this case, SNR\textsubscript{+} is directly the fringe peak detection SNR\textsubscript{c} as shown in figure 3.10d. SNR\textsubscript{+} > 3 yields SNR\textsubscript{0} \simeq 0.05 for 20 s observations ($n_\lambda = 256$, $N_{\text{EXP}} = 50$). The magnitude gain with regard to the standard mode is about 3, as we are in the detector noise regime with SNR\textsubscript{0} \propto n_\lambda.

The phase is estimated from the average coherent flux and its accuracy is given by

$$\sigma_\phi = \frac{<C>}{\sigma_c \sqrt{2n_b} \sqrt{N_{\text{EXP}}}} = \frac{1}{SNR_0 \sqrt{2n_b} \sqrt{N_{\text{EXP}}}}$$ \hspace{1cm} (6.10)

with $N_{\text{EXP}} = 36000$ for 2 hours of observations and $n_b$ is the number of binning.

In AMBER+, a SNR analysis (Petrov et al., 2014) shows that

$$\sigma_\phi^+ = \sigma_\phi \sqrt{\frac{2\sigma_\phi^2}{n_\lambda} + \frac{1 + n_\lambda}{n_\lambda}}.$$ \hspace{1cm} (6.11)

6.4 Fringe detection limit

In figure 6.1 we plotted the fringe detection limit $\log_{10} (\text{SNR})$ as a function of $K_{\text{mag}}$ using Eq. 6.8 and Eq. 6.9 for different instruments like standard AMBER performance with 0.2 s per frame, AMBER+ performance with incoherent 2DFT processing (see chapter 3), OASIS module and OASIS+ module. The parameters used for the calculation are presented in Table 6.1. We found AMBER+ could reach up to $K_{\text{mag}} \sim 10.5$ and the potential limit of the new OASIS and OASIS+ is greater than 13.

We note that fringe detection limit for GRAVITY is not included in this plot as GRAVITY will use an internal FT working up to $K_{\text{mag}} = 10.5$. Nevertheless, it should be possible to use GRAVITY without the internal FT in a mode similar to AMBER+ mode, allowing to observe targets fainter than $K_{\text{mag}} = 10.5$ with performances intermediate between AMBER+ and OASIS.
Figure 6.1: Fringe detection limits (log10(SNR)) for different VLTI instruments: from left to right: standard AMBER performance with 0.2 s frames (blue), current AMBER+ measured performance with incoherent 2DFT processing (green), OASIS module (red) and OASIS+ module (cyan). The AMBER+ curve (given here for a maximum of 20 s) is compatible with our experimental result of fringe detection with SNR=3 in 1 s. The horizontal dotted black line shows the threshold fringe detection limit of SNR=3 in 1 s and 20 s. The vertical dotted black line corresponds to \( K_{\text{mag}} = 10 \).
Table 6.1: Parameters for fringe detection limit$^a$ and differential observation of BLR$^b$ plot.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>$n_T$</th>
<th>$t_{DIT}$ (sec)</th>
<th>$n_p$</th>
<th>$\sigma_{RON}$</th>
<th>$V_{inst}$</th>
<th>$n_{\lambda}$</th>
<th>$N_{EXP}$</th>
<th>$n_0$$^c$</th>
<th>$A$ (cm$^2$)</th>
<th>$S$</th>
<th>$T$</th>
<th>$R$ $^d$</th>
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<tbody>
<tr>
<td>AMBER</td>
<td>3</td>
<td>0.2</td>
<td>32</td>
<td>11</td>
<td>1.07</td>
<td>0.25</td>
<td>512</td>
<td>100$^a$, 36000$^b$</td>
<td>45</td>
<td>497628</td>
<td>0.5</td>
<td>0.01</td>
</tr>
<tr>
<td>AMBER+</td>
<td>3</td>
<td>0.2</td>
<td>32</td>
<td>11</td>
<td>1.07</td>
<td>0.25</td>
<td>512</td>
<td>100$^a$, 36000$^b$</td>
<td>45</td>
<td>497628</td>
<td>0.5</td>
<td>0.01</td>
</tr>
<tr>
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<td>4</td>
<td>11</td>
<td>1.07</td>
<td>0.25</td>
<td>512</td>
<td>100$^a$, 36000$^b$</td>
<td>45</td>
<td>497628</td>
<td>0.5</td>
<td>0.01 $\times$ 7</td>
</tr>
<tr>
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<td>4</td>
<td>3</td>
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<td>0.5</td>
<td>512</td>
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<td>0.5</td>
<td>0.01 $\times$ 7</td>
</tr>
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<td>4$^c$</td>
<td>11</td>
<td>1.07</td>
<td>0.75</td>
<td>512</td>
<td>120$^b$</td>
<td>45</td>
<td>497628</td>
<td>0.5</td>
<td>0.01</td>
</tr>
<tr>
<td>OASIS+FT</td>
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<td>4$^c$</td>
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<td>512</td>
<td>120$^b$</td>
<td>45</td>
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<td>0.5</td>
<td>0.01 $\times$ 7</td>
</tr>
<tr>
<td>MATISSE</td>
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<td>15</td>
<td>1.67 $\times$ 10$^3$</td>
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<td>512</td>
<td>36000$^b$</td>
<td>45</td>
<td>497628</td>
<td>0.5</td>
<td>0.01</td>
</tr>
<tr>
<td>VISIBLE$^g$ with UTs</td>
<td>4</td>
<td>0.02</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>461$^h$</td>
<td>50$^a$, 360000$^b$</td>
<td>1000</td>
<td>497628</td>
<td>0.1</td>
<td>0.02</td>
</tr>
<tr>
<td>VISIBLE with ATs</td>
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<td>4</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>461$^h$</td>
<td>500$^a$, 360000$^b$</td>
<td>1000</td>
<td>$\pi \times (180)^2$</td>
<td>0.5</td>
<td>0.02</td>
</tr>
</tbody>
</table>

$^a$unit is in photon s$^{-1}$ cm$^{-2}$ A

$^b$Resolution per spectral pixel. The actual spectroscopic resolution is typically $R/2$.

$^c$GRAVITY has a pair wise beam combiner and must be analyzed as a 2T interferometer, with 1/3 of the flux in each aperture.

$^d$0.1s for MATISSE without FT and 10s with FT

$^e$only photon noise

$^f$Considering wavelength range of 5500 – 7500 Å and spectral resolution $R = 1500$. 

6.4.1 Signal estimation

In the following, we estimate three interferometric quantities: the absolute visibility in the continuum \( V_c \), the amplitude of the differential visibility \( \Delta V_{\text{diff}} \) and differential phase \( \Delta \phi_{\text{diff}} \) variations in the line.

To estimate the absolute visibility signal we used the Eq. 3.21. The amplitude of the differential visibility variation in the line is given by:

\[
\Delta V_{\text{diff}} = 1 - V_s/V_c = \frac{V_c F_c + V_l F_l}{V_c F_c + F_l},
\]

(6.12)

where \( V_s \) is the source visibility, \( V_l \) the source visibility averaged over the line, \( V_c \) the visibility in the nearby continuum and \( F_l \) and \( F_c = 1 \) are the line and continuum flux, respectively.

We consider two extreme cases for the differential visibility signal: \( R_{\text{blr}} < R_{\text{rim}} \) and \( R_{\text{blr}} = 2 R_{\text{rim}} \). In the first case, we assume that the BLR is fully unresolved by the interferometer, i.e., \( V_{\text{blr}} = 1 \). Thus, using Eq. 6.12 for the unresolved BLR (i.e. \( V_l = 1 \)) we obtain:

\[
\Delta V_{\text{diff}} = \frac{-F_l}{1 + F_l} \frac{\alpha_c^2}{1 - \alpha_c^2},
\]

(6.13)

where \( \alpha_c = 2 \frac{R_{\text{rim}}}{\lambda/B} \).

For the large BLR case, the line visibility can be written as \( V_l = 1 - 2(2\alpha_c)^2 \), consequently:

\[
\Delta V_{\text{diff}} = 3 \frac{F_l}{1 + F_l} \frac{\alpha_c^2}{1 - \alpha_c^2},
\]

(6.14)

Finally, the typical differential phase amplitude for the BLR is given by

\[
\Delta \phi_{\text{diff}} = \pi \frac{F_l}{1 + F_l} \alpha_l \cos \omega,
\]

(6.15)

where \( \alpha_l = 2 \frac{R_{\text{blr}}}{\lambda/B} \). If the inner rim of the dust torus is inclined and skewed, differential interferometry will also be sensitive to the difference between the global line and the continuum apparent photocenter with maximum amplitude of

\[
\Delta \phi_{\text{diff}} \approx \frac{\pi}{2} \frac{F_l}{1 + F_l} \frac{\alpha_c}{\sqrt{2}}.
\]

(6.16)

Thus, maximum photocenter of skewed rim depends on the flux ratio of line and continuum.
Figure 6.2: Feasibility of BLR observation with 135 m baseline using differential phase (upper panel) and absolute and differential visibility (lower panel) measurements. The solid lines represent the differential phase (up) and differential visibility (down) for AMBER+ (green), OASIS (red), OASIS+ (cyan) and GRAVITY (black) for $n_b = 2$. Note that the black dotted line represents the observing limit of GRAVITY internal fringe-tracker (i.e. $K=10.5$). Each symbol represents one Sy1 AGN observable at Paranal. On the upper panel, the amplitudes of the differential-phase variation are computed either using the $R_{blr}$ estimated from visible RM (red circles) or assuming the skewness of the dust inner rim (green squares). The red polygon marked by 3C273 is obtained considering explicit 3C273 error, taking into account the binning of 16, while rest of the plot is made with $R = 1500$ and no binning. On the lower panel, the differential and absolute visibility for each object are plotted as blue stars and black polygons, respectively.
6.4.2 Selection of targets

We collected a list of all Sy1 and QSOs observable with the VLTI found in the SIMBAD catalog with search criteria $K_{\text{mag}} < 13$, $V_{\text{mag}} < 15$ and $\text{dec} < 15^\circ$. For each source we estimate the inner rim radius from its magnitude thanks to an extrapolation of Suganuma et al. (2006) known measurements. From this rim radius we evaluate the possible values of the continuum visibility, differential visibility and phase. These values are compared to the SNR estimates deduced from the source estimated $K$ magnitude. We use the CMB corrected redshift for each target from NED and $K$ magnitude from 2MASS point source catalog. We collected the list of objects from Bentz et al. (2013) that have classical RM BLR size. Then we fitted the radius with their $K$ magnitude and extrapolate for the objects that do not have the RM BLR size.

For each target, we use the strongest emission line in the $K$-band given the actual redshift of the target. To compute the interferometric observables we used the following values for the normalized line flux $F_l$.

- $F_l = 0.6$ when $\text{Pa}\alpha$ is in the $K$-band ($0.08 \leq z < 0.25$)
- $F_l = 0.3$ when $\text{Pa}\beta$ is in the $K$-band ($0.4 \leq z < 0.87$)
- $F_l = 0.06$ when $\text{Br}\gamma$ is in the $K$-band ($z < 0.08$)
- $F_l = 0.12$ when $\text{Pa}\gamma$ is in the $K$-band ($z \geq 0.87$)

These mean values are deduced from the IR line intensity measurements in Landt et al. (2008). The dispersion of line strengths is very large. For example the $\text{Br}\gamma$ line flux goes from 0.01 to 0.18 with a 0.07 mean. This limited dataset does not allow good statistics but we used it to estimate that about one third of the targets where $\text{Br}\gamma$ must be used, will eventually be impossible to observe ($F_l < 0.02$) while our signal estimates are actually pessimistic for half of the targets where $F_l$ is larger than the mean values used here.
Figure 6.3: Feasibility of observation of BLR with MATISSE. The points represent the same things as in figure 6.2. The solid lines represent differential phase accuracy (upper panel) and differential visibility accuracy (lower panel) as a function of $L$ magnitude for MATISSE without FT (red) and with FT (black).
Chapter 6. Feasibility of BLR observation

6.4.3 Feasibility of observation

6.4.3.1 K band observation

Figure 6.2 summarizes the feasibility of observation of BLRs with current, upcoming, and possible VLTI instruments. We found that AMBER+ would observe at most a few sources whereas GRAVITY will provide high quality differential measurements on 10 to 15 sources for which it would also give decisive absolute visibility measurement. On the other hand, OASIS would at least double the number of differential phase measurement (with respect to GRAVITY). Moreover, OASIS+ would again double this accessible number of targets then the OASIS number. A next generation FT would boost the GRAVITY list of targets. The ultimate VLTI performance would be obtained with the new generation FT and OASIS+. Remember that an instrument accessing more targets also gives much better results on the brighter targets. OASIS+FT would allow to access targets with four decades of luminosity range, critical for an unification model based on key parameters with luminosity.

6.4.3.2 L band observation

In figure 6.3, we plotted differential phase (upper panel) and visibility variation (lower panel) as a function of $L$ band magnitude for MATISSE without (red) or with (black) external FT. Each point represents one Sy1 AGN, labeled by name, which has an emission line in $L$ band, and limited to the $K = 10.5$, so that they can also be observed using GRAVITY as FT. Although it will be possible to estimate differential visibility (blue star) only for few objects, absolute visibility can be estimated for many objects up to $L = 15$ using MATISSE. We see that for a few objects, which have redshift such that the best line is in the $L$ band, MATISSE can observe emission lines. This will specially help to compare the emission line sizes at different wavelengths to constrain the geometry of the BLR and dust. Note that MATISSE is mandatory to constrain the equivalent dust torus sizes (i.e. the absolute visibilities in the continuum) necessary to properly calibrate the emission lines differential measures. Measuring $L$ band interferometric size combined with $L$ band reverberation mapping will allow to measure distances using “Dust parallax” (Hönig et al., 2014) as discussed in chapter 7.

6.4.3.3 Visible observation

The first goal of an OI operating in the visible would be to obtain BLR actual image thanks to the higher spatial resolution. However, even for the largest known BLR such an image requires a full resolution of at least 0.1 mas and this implies multi-kilometric baselines (1.5 km at 0.7 $\mu$m) that are not available at any current interferometer with large aperture. Thus, we should use the improved angular resolution and much stronger emission lines in the visible to perform the kind of differential observations discussed in this thesis, but possibly with much better accuracy.
Hence, we studied the feasibility of BLR observations in the visible mode at the VLTI. We considered both UTs and ATs. The parameters are listed in table 6.1. We calculated SNR with $V$ magnitude for UTs and ATs as shown in figure 6.4. SNR obtained with UTs of Strehl ratio 0.1 and $N_{\text{EXP}} = 50$ (1 sec observation) is shown by green line. This shows that with UTs we can reach up to $V = 15$ if we have adaptive optics (AO) providing a Strehl ratio of 0.1 in the visible which is challenging but feasible. The red curve represents the SNR obtained with ATs of Strehl ratio 0.5 with $N_{\text{EXP}} = 3500$ (70 seconds observation), while the blue curve is obtained with $N_{\text{EXP}} = 500$ (10 seconds observation). ATs with Strehl ratio 0.5 will be helpful but quite long exposures are needed to reach up to $V = 15$ with SNR > 3. Such Strehl ratio at 0.7 $\mu$m on a 1.8 m telescope is quite feasible, but will be out of reach of the currently planned AO for the ATs.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure6.4.png}
\caption{Plot of log10(SNR) as a function of $V$ magnitude. SNR for UTs with Strehl ratio 0.1 with $N_{\text{EXP}} = 50$ (1 second observation; green curve), and ATs with Strehl ratio 0.5 with $N_{\text{EXP}} = 3500$ (70 seconds observation; red curve), and with $N_{\text{EXP}} = 500$ (10 seconds observation; blue curve) for $t_{\text{DIT}} = 0.02$ are shown. The dotted black line shows the fringe detection limit of SNR=3.}
\end{figure}

Differential phase (up) and visibility accuracy (down) are plotted as a function of $V$ magnitude in figure 6.5. In this case, we considered 2 hours of observation i.e. 360000 exposures with UTs (green) and ATs (blue). Each individual source represents Sy1 target observable from Paranal as described in section 6.4.2 and used in section 6.4.3.1. However, in this case we considered that H$\alpha$ lines can be detected for all the sources. Since H$\alpha$ line is up to 10 times brighter than Pa$\alpha$ (see Landt et al., 2008), we gain in flux, and as a result, we see that differential phase can be measured for all the 134 objects up to $V = 15$ with UTs in visible, while ATs can also provide access to objects up to $V = 14$. It could be possible to estimate differential visibility as well as absolute visibility for a few objects using UTs or ATs. Having both differential visibility and phase, it will be possible
to fully constrain BLR models. Differential phase alone will be also helpful to constrain the kinematics of the BLR and hence could be used to estimate angular diameter distance using parallax with a much better accuracy than in the $K$ band as the gain in differential phase accuracy is of the order of 190 if $K = V$ and of the order of 60 if $K - V = 2.5$.

Figure 6.5: Feasibility of BLR observation with a visible mode of VLTI (considering Hα line). The solid curves represent differential phase (up) and differential visibility (down) for a visible mode with UTs (green) and ATs (blue) corresponding to figure 6.4. Rest of the symbols are as noted in figure 6.2.
6.5 Conclusion

To evaluate the potential of OI to observe BLR of quasars with the current and near future VLTI instruments, we have computed the expected accuracy for absolute visibility, differential visibility and phase with current (AMBER+), near future (GRAVITY) and possible (OASIS, OASIS+ and OASIS+FT) VLTI instruments. This SNR analysis has been checked on our real 3C273 data from AMBER+ and the values for the other instruments are deduced from elementary cross-multiplications based on the known changes in detector noise, number of measures, transmission and exposure time of the new instruments. We have considered the possible SNR for all QSOs and Seyfert 1 observable at Paranal brighter than $K = 15$ that is the potential limit for VLTI observations with OASIS+.

Even if all these BLRs remain unresolved with the VLTI in the $K$-band, we see that measures are possible on many targets. GRAVITY, limited by its internal FT at $K = 10.5$, will give a full data set on half a dozen sources. For about fifteen sources it will have only absolute visibility and differential phase that still allows to fit all parameters. OASIS will allow a small increase in the number of targets while OASIS+ will reach more than 50 targets. A FT working fainter than $K = 10.5$ would allow a major breakthrough by extending the number of GRAVITY targets to about 30 and of OASIS+ targets to more than 50, if it can be operated up to $K = 13$, which seems well within the reach of the currently proposed designs (Petrov et al., 2014; Meisner et al., 2012). As the main contribution of OI will come from differential measures, study of the innermost part of the torus that can constrain the continuum measures in $K$-band, will be performed in $L$-band by the VLTI second generation instrument MATISSE (Lopez et al., 2012) that can also do some BLR observations in lines in the $L$-band.

A visible mode of VLTI can access more than 130 targets up to $V = 15$ providing differential phase signature, helpful to constrain BLR kinematics and to obtain more accurate BLR parallax measures. This could also provide differential visibility measurements for few targets, which is along with differential phase, could provide strong constrain on the BLR models. This indeed will help to calibrate the RM $R - L$ and $M - L$ relations obtained using H$\beta$ lines. Combining RM data with interferometric measurements, parallax distances could be measured for many objects.

Such a large sample of targets would allow a general unification of BLR model by studying for example the key parameters such as the projection factor $f$, the BLR thickness $\omega$, the local velocity field parameter $\sigma_0$ or the ratio of rotation and inflow as a function of the luminosity (see chapter 4). The VLTI, with its full potential, could allow exploring four to five decades of luminosity range. Full imaging of BLRs requires the improvement of the angular resolution by a factor of at least ten that requires a major breakthrough on sensitivity of OI in the visible, on CHARA for example, or the construction of a new interferometer with much larger baselines (such as recently proposed Planet Formation Imager in near/mid-IR, Monnier et al., 2014). These are long term goals, while differential interferometry of quasars with the VLTI has already started, will substantially expand very soon
with GRAVITY and can reach its full potential with a new generation FT and a specialized light instrument like OASIS+ in less than 5 years.
Distance measurement using BLR parallax

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Figure 7.1: Measuring geometrical distance. a) Parallax distance to a star and b) Distance to a quasar using Broad line region. Image from Elvis and Karovska (2002).
Chapter 7. Distance measurement using BLR parallax

7.1 Introduction

One of the fundamental challenges in modern astronomy remains the distance measurement of astronomical objects. It can constrain the time evolution of the cosmic scale factor that represents relative expansion of the universe. One hypothesis is that although the universe contains a significant amount of ordinary matter ($\Omega_m$), which de-accelerates the universe, a significant amount of possible energy in the vacuum ($\Omega_\Lambda$), known as Einstein “cosmological constant”, would accelerate the universe putting a negative pressure (Carroll et al., 1992). Distance measurement using Type-I supernova led to the remarkable discovery of acceleration of the universe having a non-zero cosmological constant, and the dark energy (Riess et al., 1998; Perlmutter et al., 1999). Type-I supernovae are extensively used to estimate distances, however they are limited to $z \sim 1.7$ (Riess et al., 2001), beyond which an alternative technique is needed to estimate reliable distances. This is crucial in order to constrain cosmological model and the nature of dark energy.

Quasars, a high luminous class of AGNs, can be easily found up to $z \sim 7$, offer a possibility to use them as standard “candles”. Several methods were proposed to estimate distances such as using quasars BLR (Haas et al., 2011; Watson et al., 2011; Czerny et al., 2013), using well-established R-L relationship (Kaspi et al., 2000; Bentz et al., 2013) as well as using hot dust emission (Kobayashi et al., 1998; Oknyanskij, 1999; Yoshii et al.; Hönig, 2014). A simple and model independent method using parallax was proposed for both the BLR (Elvis and Karovska, 2002) and the dust (Hönig et al., 2014). This method as proposed by Elvis and Karovska (2002) involves a combination of RM variability study of the BLR or of the dust to estimate a linear size, $\mu(\text{ld}) = c\tau(\text{days})$ with interferometric observation to measure equivalent angular size, $\rho(\text{mas})$ (figure 7.1). The angular distance can be written as

$$D_A(\text{Mpc}) = 0.173 \times \frac{\tau(\text{days})}{\rho(\text{mas})(1 + z)}$$  \hspace{1cm} (7.1)

where $z$ is the redshift and the factor 0.173 is just a geometrical conversion factor. Note that Eq.7.1 assumes both $\rho$ and $\mu$ refer to the same physical size, however both the sizes depend on geometry of the object and weighting on different measurements.

Recently Hönig et al. (2014) applied this method to the dust, thereafter, “dust parallax”, in which they used dust photometric RM to measure linear size of the inner-rim dust torus, and interferometry to measure the equivalent angular size. Using dust parallax, they estimated angular distance to NGC 4151 with an accuracy of 13.5 % showing the capability of simple parallax method using AGNs to estimate distances. Hönig et al. (2014) also showed that the different parameters in the model multiply both RM size $\mu$ and OI size $\rho$ by the same factor. Both RM and OI observation of inner dust were performed successfully for a handful number of objects (Koshida et al., 2014; Kishimoto et al., 2011a), hence this method is very feasible. However the dust reverberation observation needs longer monitoring and especially costly for high luminous objects since dust inner radius is scaled with $L^{0.5}$. On the other hand, observing BLR with OI has been started when Petrov et al. (2012) successfully resolved the emission line of bright quasar 3C273...
for the first time, and as shown in chapter 6, OI could observe a large number of BLR with upcoming instruments. Thus, both the BLR and dust parallax seem to be a good distance measurement method. The variation of angular distance as a function of redshift is plotted in figure 7.2 for different cosmologies. Quasars could provide angular distances beyond redshift $z = 1.7$ allowing to constrain cosmological parameters and the distribution of dark energy.

Hence, in this chapter, we will use the quasar-parallax method on the BLR to estimate the accuracy on the angular distances using both simulated RM and OI data. We will present simulations showing the feasibility of this method. Structure of this chapter is as follows. We described continuum modeling approach in section 7.2. An improved BLR model is presented in section 7.3. Test to estimate distances using parallax method from simulated RM and OI data is presented in section 7.4. Result of the simulations is discussed in section 7.5 with a conclusion and future perspective in section 7.6.

### 7.2 Modeling continuum light curve

We adopt the approach of Kelly et al. (2009) to model the continuum light curve, which is a damped random walk model (Zu et al., 2011; Kelly et al., 2009; MacLeod et al., 2010). The model is a white noise process with two parameters; an amplitude of variability parameter ($\sigma_d$) and a variability time scale parameter ($\tau_d$) that decreases exponentially. It was shown that the damped random walk (DRW) model can properly represent the variability of quasars continuum light curve. We generated the light curve from the following equations (for more detail, see Kelly et al., 2009)

$$x_i = Ax_{i-1} + \epsilon_i,$$

(7.2)
where $\epsilon_i$ is a normally distributed random variable with zero mean and variance $s^2$, and the data $x_i$ are observed at regular time interval. The variance can be written as

$$s^2 = \frac{\tau_d \sigma_d^2}{2} \left( 1 - e^{-\frac{2\Delta t}{\tau_d}} \right)$$

(7.3)

and $A = e^{-\Delta t/\tau_d}$, is usually constrained as $|A| < 1$ in order to ensure stationarity; a time series is said to be stationary when its mean and covariance do not vary with time. The case $A = 1$ corresponds to a random walk.

Thus, we have two parameters in this model, the relaxation time or damping time scale, $\tau_d$, that can be interpreted as the time required for the time series to become roughly uncorrelated, and $\sigma_d$ describing the variability of the time series on timescales short compared to $\tau_d$. Kelly et al. (2009) suggested that $\tau_d$ can be associated to a characteristic timescale, such as the time required to smooth out local accretion rate perturbations. On the other hand, $\sigma_d$ represents the variability resulting from local random deviations in the accretion disk structure, such as caused by turbulence and other random magneto-hydrodynamic effects. Interestingly, Kelly et al. (2009) and Li et al. (2013) found that $\sigma_d$ and $\tau_d$ are related to some of the key parameters of the AGN, such as $M_{bh}$, $L$, $\lambda_e$ etc. According to Kelly et al. (2009)

$$\log \sigma_d^2 = (-3.83 \pm 0.17) - (0.09 \pm 0.19) \log \left( \frac{\lambda L_\lambda}{10^{45} \text{ergs}^{-1}} \right) - (-0.25 \pm 0.24) \log \left( \frac{M_{bh}}{10^8 M_\odot} \right) [R \text{mag}^2 \text{day}^{-1}],$$

(7.4)
and

\[
\tau_d = (80.4^{+66.9}_{-35.8}) \left( \frac{\lambda L_\lambda}{10^{45}\text{ergs}^{-1}} \right)^{-0.42^{+0.28}_{-0.28}} \times \left( \frac{M_{\text{bh}}}{10^8 M_\odot} \right)^{1.03^{+0.38}_{-0.38}} \text{[days].} \quad (7.5)
\]

These relations indicate the importance of the accurate mass estimates discussed in chapter 4 and others. Figure 7.3 shows continuum light curve created with different central black hole masses and luminosities. It is assumed that light curves are observed once every 10 days over a duration of more than 8 years and have the uncertainty of 1% of the flux value. Note that, the variability is stochastic, it can not be repeated.

Once we have a continuum light curve, we just need to have a model response function of the BLR to obtain line light curve. The response function as well as all interferometric data can be simulated from a given geometrical and kinematical model.

### 7.3 Geometrical and kinematical model of BLR

In order to simulate both OI and RM data, we need to have a geometrical and kinematical model that self-consistently estimate all the observables. In chapter 4, we have described a 3D geometrical and kinematical model, which calculates all interferometric observables as well as reverberation mapping response function and line profile. Once we get emission line response function \(\Psi(\tau)\) from our model (chapter 4), we can obtain emission line light curve by convolving a continuum light curve with it using Eq.2.7. Thus, we will have all the observables for a given model.

In this work, we have used the same model, described in chapter 4, except modifying the radial distribution of the clouds so that it can take any shape from very narrow Gaussian to a power law distribution, as used recently by Pancoast et al. (2014a,b) for modeling the RM data. The distribution is taken from a shifted gamma distribution whose probability density function is

\[
P(x|\kappa, \theta) \sim x^{\kappa-1}\exp(-\frac{x}{\theta}),
\]

where \(\kappa\) is the shape parameter and \(\theta\) is the scale parameter of the distribution. After the change of variables, we represent the distribution considering three parameters; the mean radius \(\mu\) (refers to linear size of the BLR), the shape parameter of the shifted gamma distribution \(\beta\) and a parameter \(F\) that is the fraction of \(\mu\) at which gamma distribution starts. The radial position of cloud is now taken randomly from

\[
r = R_s + \mu F + \mu\beta^2(1 - F) \times \Gamma(\beta^{-2}, 1),
\]

where \(R_s = 2GM_{\text{bh}}/c^2\) is the Schwarzschild radius of the central BH of mass \(M_{\text{bh}}\) providing the hard limit on the radius, and \(\Gamma(\beta^{-2}, 1)\) is the gamma distribution with scale 1. The width of the BLR can be written as \(\sigma_r = \mu\beta(1 - F)\). Radial distributions obtained from different set of parameters \((\mu, \beta, F)\) are shown in figure 7.4.
Chapter 7. Distance measurement using BLR parallax

Table 7.1: Simulated data: Input parameters of the model

<table>
<thead>
<tr>
<th>set</th>
<th>redshift</th>
<th>$D_A$ (pc)</th>
<th>$L$ ($\text{ergs}^{-1}$)</th>
<th>$\log_{10}(M_{bh}/M_\odot)$</th>
<th>$\mu$ (ld)</th>
<th>$R_{\text{rim}}$ (mas)</th>
<th>$\iota$ (°)</th>
<th>$\omega$ (°)</th>
<th>noise and sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1324</td>
<td>467.0</td>
<td>45.05</td>
<td>8.45</td>
<td>244.5</td>
<td>0.28</td>
<td>39.3</td>
<td>22.2</td>
<td>1.0%, 1.5%, 10 days^a</td>
</tr>
<tr>
<td>B^b</td>
<td>0.1324</td>
<td>467.0</td>
<td>45.05</td>
<td>8.45</td>
<td>244.5</td>
<td>0.28</td>
<td>39.3</td>
<td>22.2</td>
<td>0.5%, 0.5%, 5 days</td>
</tr>
<tr>
<td>C</td>
<td>0.0887</td>
<td>328.5</td>
<td>44.38</td>
<td>8.28</td>
<td>98.5</td>
<td>0.18</td>
<td>30.7</td>
<td>20.9</td>
<td>0.5%, 0.5%, 5 days</td>
</tr>
</tbody>
</table>

^aThe numbers represent flux uncertainty in continuum and emission line light curve, and observing night interval for reverberation mapping.

^bNote that even with same continuum model parameters, continuum variability pattern is different than set A.

Figure 7.4: Probability distribution of shifted gamma function. Distributions are plotted for different values of shape parameter $\beta = 0.1$ (cyan), $\beta = 0.5$ (blue), $\beta = 1$ (green) and $\beta = 1.5$ (red) keeping $\mu = 10$ and $F = 0$ fixed.

After defining the radial distribution we built the rest of the model as already described in chapter 4, and we calculated all differential interferometric measures as well as RM measures for a given continuum light curve needed for angular distance measurement using Eq.7.1.

7.4 Simulation setup

In this chapter, our goal was to recover $D_A$ and its uncertainty from simulated datasets. For this work, first mock RM (continuum and emission line light curves) and OI (spectrum, differential visibility and differential phase) datasets were created for few simulated objects, and then recovered those parameters by fitting the data sets.
Chapter 7. Distance measurement using BLR parallax

7.4.1 Simulated datasets

We simulated data for objects, which were defined by their redshift \( z \), BH mass \( M_{\text{bh}} \), luminosity \( L \), angular distance \( D_A \), BLR radial distribution parameters \( \mu, \beta \) and \( F \), inner rim radius \( R_{\text{rim}} \), inclination \( i \) and opening angle \( \omega \). All the parameters were randomly picked up except \( \beta \) and \( F \), which for simplicity were fixed at 0.5 and 0 respectively (represented by blue color in figure 7.4). We proceed as follows:

First, redshift of the object was picked up randomly from a \((1 + z)^3\) distribution, where \( z \) lies between 0 to 0.2, considering local universe. BH mass was then taken randomly from \( \log_{10}(M_{\text{bh}}/M_\odot) = 6.5 \) to 9.5, and an Eddington ratio was assigned, where \( \log_{10}(\lambda_e) \) was taken from a Gaussian distribution of mean -1.5 and standard deviation 0.3. This allowed to calculate luminosity for a given mass and an Eddington ratio using \( L(\text{ergs/s}) = M_{\text{bh}}[M_\odot] \times 1.26 \times 10^{38} \times \lambda_e \) (Nobuta et al., 2012). Having luminosity and BH mass of the object, we created a continuum light curve as described in section 7.2.

To create mock RM emission light curves as well as interferometric data, mean radius of the BLR and the inner rim radius of torus were drawn from object luminosity following Bentz et al. (2013) and Kishimoto et al. (2011a, b) respectively. BLR radius was then scaled by a factor of 2 since near-IR emission line sizes at K-band could be larger than H\( \beta \) BLR size. Inclination \( i \) and opening angle \( \omega \) were chosen randomly.

Since, our aim was to calculate the accuracy on the angular distance, we used an input angular distance \( D_A \), calculated from redshift of the simulated object considering a standard cosmology with \( H_0 = 73 \text{ km/s/Mpc} \), \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \). With this angular distance, we calculated angular size \( \rho \approx \mu/D_A \) of the BLR, using Eq.7.1 for the given linear size \( \mu \), needed to create interferometric data. The main parameters that we used to simulate the data are shown in table 7.1. Here we are presenting only result of 3 simulations to see the feasibility of this method.

We created OI data for 4 baselines of length 80 m and 130 m with baseline orientation parallel and perpendicular to rotation axis. We added realistic noise in all datasets. We consider noise based on the upcoming interferometric instrument GRAVITY, i.e. uncertainty on differential phase \( \sigma_{\phi_D} \approx 0.002 \) radian and differential visibility \( \sigma_{V_D} = \sqrt{2} \times \sigma_{\phi_D} \) as discussed in chapter 4 as well as in Rakshit and Petrov (2014) and Rakshit et al. (2015). We considered a monitoring campaign of 8 years and line light curves starts 500 days after the first continuum monitoring. A long duration RM campaign was considered since our luminosity range is very wide, and size of the BLR scales as \( L^{0.533} \). Hence to detect distinct peak in the cross-correlation function we need very long duration observation campaign, more than 3 times longer than the time-lag corresponding to the BLR size (see section 5.4).
7.4.2 Recovering model parameters

We used a Bayesian sampling algorithm and maximize the likelihood as described in chapter 4, where we wrote that the posterior probability distribution $p(\text{model}|\text{data})$ includes the prior function $p(\text{model})$ containing knowledge about the parameters:

$$p(\text{model}|\text{data}) \propto p(\text{model}) \times p(\text{data}|\text{model}).$$  \hspace{1cm} (7.8)

For efficient sampling of the entire parameter space, we used EMCEE package, developed by Foreman-Mackey et al. (2013), which is a Python implementation of Affine Invariant Markov Chain Monte Carlo (MCMC) ensemble sampler by Goodman and Weare (2010) backed by Parallel Tempering (thereafter, PTMCMC), which allows to run N number of Markov chains at different temperatures $(T)$ in parallel ensuring that Markov Chain is not being stuck in a local maximum and accelerate the process to converge to a globally optimized solution. Since, the parameter space is usually big and quite possible to have multiple modes, thus PTMCMC is a good option to find the global maximum. In PTMCMC, each parallel chain is sampled from a modified distribution $p(\text{model}|\text{data})^\frac{1}{T}$ depending on its temperature. For example, if N chains are used than n-th chain of temperature $T_n$ is sampled from $p(\text{model}|\text{data})^\frac{1}{T_n}$. A sequence of temperatures, called the “temperature ladder”, is formed with $T_1 < T_2 < ... < T_N$ corresponds to different
chains (1, 2...N). In PTMCMC, a parameter $\beta \equiv 1/T$ is used to set a temperature ladder (see Earl and Deem, 2005). Each chain exchange its result after some iterations and climb towards higher likelihood. For a chain at high temperature, known as “hot chain”, the likelihood is flatter and broader, and more easily explore the parameter space, while a low temperature chain, known as “cold chain”, which gives the optimized result, explores the peak of the likelihood by jumping between nodes found by the hotter chains. This process increases the convergence rate for multiple modes problem but computationally expensive since we need to run few MCMC chains in parallel.

We run the sampling for many iterations and look at the variation of width of the distribution as a function of iteration. We remove the “burn-in” steps, which are necessary to stabilize the parameters as already discussed in section 4.4.2, and took rest of the samples to calculate uncertainties on the fitted parameters.

The model fitting process is shown graphically in figure 7.5. It calculates OI and RM measurements and then used Bayesian model fitting approach to fit the data, and finally estimates the parameters and its uncertainties. The fitting is done in two steps:

A) We fit only RM data i.e. continuum and emission line light curves and emission line profile. In this case, we have a total of 6 free parameters, which include 4 BLR parameters i.e. $\mu$, $M_{bh}$, $i$ and $\omega$, and 2 continuum model parameters i.e. $\sigma_d$ and $\tau_d$. We assign uniform priors in log to $\mu$ and $M_{bh}$ as they span few order in magnitude. Fitting of RM data allow us to recover linear size of the BLR with its uncertainty (in unit of light-days) along with rest of the parameters. Note that for continuum model we directly use $\sigma_d$ and $\tau_d$ to fit instead of $M_{bh}$ and $L$ that were used only to create mock continuum data.

B) We fit OI data i.e. differential visibility and phase as well as emission line profile keeping four free parameters, $\rho$, $M_{bh}$, $i$ and $\omega$. However, in this case, we assign priors on $M_{bh}$, $i$ and $\omega$ looking at the probability distribution of the parameters obtained from RM data fitting. We also assign uniform prior in log for angular size since it spans few order in magnitude. Fitting of OI data thus allows us to obtain angular size (in mas) as well as other parameters.

---

**Table 7.2: Simulated data: Recovered parameters**

<table>
<thead>
<tr>
<th>set</th>
<th>$\mu$ (ld)</th>
<th>$D_A$ (Mpc)</th>
<th>$\log_{10}(M_{bh}/M_\odot)$</th>
<th>$i$ (°)</th>
<th>$\omega$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>212.5$^{+30.0}_{-29.2}(244.5)^a$</td>
<td>499.2$^{+74.5}_{-65.3}(467.0)$</td>
<td>8.29$^{+0.22}_{-0.22}(8.45)$</td>
<td>39.2$^{+1.8}_{-1.8}(39.3)$</td>
<td>24.9$^{+10.8}_{-0.9}(22.2)$</td>
</tr>
<tr>
<td>B</td>
<td>218.6$^{+20.4}_{-18.8}(244.5)$</td>
<td>416.0$^{+62.5}_{-52.2}(467.0)$</td>
<td>8.40$^{+0.27}_{-0.27}(8.45)$</td>
<td>41.2$^{+18.7}_{-10.4}(39.3)$</td>
<td>27.3$^{+10.8}_{-0.9}(22.2)$</td>
</tr>
<tr>
<td>C</td>
<td>87.7$^{+12.1}_{-16.1}(98.5)$</td>
<td>288.3$^{+61.0}_{-58.5}(328.5)$</td>
<td>8.31$^{+0.38}_{-0.38}(8.28)$</td>
<td>26.5$^{+11.4}_{-9.1}(30.7)$</td>
<td>25.0$^{+12.5}_{-12.4}(20.9)$</td>
</tr>
</tbody>
</table>

*aTrue input values are in the bracket.*
7.5 Result and discussion

Figure 7.6 shows the probability distribution of different parameters with its mean value (red dotted line) recovered from dataset A. The recovered parameters and their 1σ uncertainties are $\mu(\text{ld}) = 212.5^{+40.0}_{-29.2}$, $\log_{10}(M_{\text{bh}}/M_\odot) = 8.29^{+0.25}_{-0.18}$, $i = 39.2^{+11.8}_{-10.9}$ degree and $\omega = 24.9^{+10.8}_{-9.9}$ degree (see Table 7.2). For each dataset, the output parameters are recovered within 1σ uncertainty. We see that with better sampling and lower noise in the light curves, $\mu$ is recovered with lower uncertainty compare to dataset A. Figure 7.7 shows the fit of the model to the RM continuum (top) and emission line (middle) light curves as well as emission line profile (bottom) using best fit model parameters for dataset A. The fits are indeed good.
Figure 7.7: Fit of the RM data with the best fit parameters for dataset A. From top to bottom, the panels are continuum light curve, emission line light curve and spectrum. The blue points with errorbars are the data whereas the solid-red line represents the best fit model.
Fig. 7.8: Fit of OI data with the best fit parameters for dataset A. Differential visibility (left) and differential phase (right) are plotted for four different baselines. From top to bottom: 80 m in parallel (first) and perpendicular (second) baselines, and 130 m in parallel (third) and perpendicular (fourth) baselines. The blue points with error bars are the data whereas the solid-red line represents the best fit model.
The accuracy on the parameters can further be improved with high quality data, which were obtained from recent high quality RM campaign aiming to constrain BLR geometry and kinematics (Bentz et al., 2010a; Barth et al., 2015). Some of these recent campaigns successfully provided 2D velocity-delay diagrams of few BLRs and thus enabled to constrain the BLR geometry and kinematics (e.g. Grier et al., 2013). Using direct model fitting approach to these highly sampled data, several authors have been successfully constrained many BLR model parameters with good accuracy (Brewer et al., 2011; Pancoast et al., 2012, 2014a). However, these campaigns are very selective to low-luminous object whose time delay is less than a month. Thus, with full spectral data, the parameters including the time delay, which is the most important for distance measurement, could be constrained with higher accuracy.

Model fitting of the OI data for dataset A is shown in figure 7.8 where we showed the fitting of differential visibility (left) and phase (right) with the best fit parameters for four different baselines: 80 m in parallel (first panel), and perpendicular (second panel), and 130 m in parallel (third panel) and perpendicular (fourth panel) baselines. The recovered angular size from the probability distribution of the samples is $\rho (\text{mas}) = 0.090^{+0.007}_{-0.008}$. In all cases, the fitting is good. Note that when baselines are parallel to the rotation axis, we do not have any phase signature, however a strong “W” shaped visibility signature appeared at the top of the continuum (1st and 3rd panel) since the disk is relatively thin ($\omega = 22.2^{\circ}$) and has relatively high inclination angle ($i = 39.3^{\circ}$). This has already been discussed in chapter 4. The baselines perpendicular to the rotation axis (2nd and 4th panel) show “S” shaped differential phase profile as also shown in figure 4.9. This strong differential phase signature helped significantly to constrain the geometry as in all the baselines, except the 3rd one, differential visibility has no strong signature to constrain the model parameters. Thus, differential phase or photocenter displacement is very much needed to constrain the BLR geometry and kinematics.

We showed a 2D scatter plot of linear size vs angular size in the upper-left panel of figure 7.9 with a cut of angular size in upper-right panel as obtained from the fits of OI data and a cut of linear size in lower-left panel as obtained from the fits of RM data. These histograms via Eq.7.1 give an angular distance measurement of $409.2^{+73.9}_{-65.3}$ Mpc with uncertainty about 16%. Although the mean of the histograms is far from the input value, it is within 1 $\sigma$ uncertainty of the input $D_A$. This uncertainty is due to the week constraint on the $\mu$ from RM data. The parameters space with $M_{\text{bh}}, i, \omega$ is highly degenerate. As can be seen in the left panel of figure 7.10, $\mu$ is constrained better with increased sampling rate and less noisy data. However, due to uncertainty on the OI data, we gain not much in distance accuracy (see Table 7.2). Note that since we fit a single-epoch spectrum instead of full spectral data, we are affected by the degeneracy of the parameters. However, this degeneracy could be removed up to some extent and the uncertainty on the recovered parameters from the RM data could be decreased by simultaneously fitting spectrum of each epoch observed during RM monitoring as shown in Pancoast et al. (2014a,b). This will provide better estimation of $M_{\text{bh}}, i, \omega$ and hence better measurement of $\rho$ from spectro-interferometric data. Thus, we could measure both the linear and angular sizes with less uncertainty. This will allow to gain the distance accuracy, which we would like to check in future.
Chapter 7. Distance measurement using BLR parallax

Figure 7.9: Angular distance from dataset A. Figure shows a scatter plot of linear size vs angular size of the BLR (upper-left), probability distribution of $\rho$ (upper-right), $\mu$ (lower-left) and $D_A$ (lower-right). The dotted red line in all the panels shows the true input parameter value.

Note that BLR parallax method will work only if we observe same emission line with RM and OI. Presently, there is no IR RM observation is available in the emission line, and interferometric observations are limited only to near- and mid-IR. Thus, it would be necessary to start near-IR RM campaign and for this, Pa$\alpha$ and Pa$\beta$ seem to be the best candidates as they are strong lines and unblended. Moreover, near-IR lines have some advantages compare to visible such as less dust extinction and weak host galaxy contamination (Landt et al., 2008, 2013). Hence, it would be desirable to observe at least few AGNs BLR in near-IR to find the time lag ratio between Pa$\alpha$ and Pa$\beta$ to H$\beta$. Photo-ionization calculations using “CLOUDY” code suggest that this lag ratio strongly depends on the geometry and can be larger than H$\beta$ by a factor of 2 (see for example Goad, 1995). If VLTI observations with GRAVITY and MATISSE allow to constrain geometrical parameters as a function of luminosity, then CLOUDY could easily predict time lag ratios for different emission lines. Having that for few AGNs, we would use visible RM observation multiplying the lag ratio with near-IR interferometric observation.
Chapter 7. Distance measurement using BLR parallax

On the other hand, since OI is limited to the near-IR, a visible/UV extension will allow to use this parallax method directly to use visible RM data (see discussion in chapter 6).

Another point is to determine which line is best for this technique to work on. A detailed discussion can be found in Elvis and Karovska (2002) about it. The size of the BLR increases with luminosity and it also increases with redshift. At a given redshift, high luminous objects are easier to resolve by OI and thus better target for interferometric observation, but problematic for RM observation as it needs long duration observation campaign. The line center also shifts with redshift as $(1 + z)$, which means lines with shorter wavelength are better for RM. Few attempts have been made to find the BLR size of few high luminous and intermediate redshift ($z = 2.2 – 3.2$) objects observing CIV emission line variability in RM campaign (Kaspi et al., 2007; Trevese et al., 2014), which can be applied for many objects. Shorter wavelengths are better also for OI due to increase in the angular resolution ($\lambda/B$). OI in the visible is thus highly desirable. As shown in section 6.4.3.3, UTs (8.2 m telescopes) at VLTI with Strehl ratio of the order of 0.1 could allow to observe 130 targets in the visible reaching up to V band magnitude of 15. This could allow full modeling of the BLR and direct distance measurement using BLR parallax with RM data. The ATs (1.8 m telescopes) with Strehl ratio of the order of 0.5 could reach up to V magnitude 15, allowing to observe about few dozen targets with better SNR on differential visibility than the K band with UTs. This could allow much better constrains on geometrical parameters of BLR model.
On the other hand, instrument like upcoming E-ELT could provide angular size of many BLRs by measuring the photocenter displacement using spectro-astrometric technique with resolution 1500 as recently described by Stern et al. (2015). This can be obtained for several lines depending on redshift. Thus, photocenter displacement could be used to estimate angular size of the BLR and combining with RM data, it could allow to estimate distance measurement up to $z = 3$. However, as already discussed in chapter 4, photocenter displacement gives the differential phase signature for unresolved object and this is very useful to constrain the geometry, but would not be sufficient in some case, for example where the kinematics is dominated by turbulence, and geometry is spherical, or disk is close to face-on. Then, differential visibility signature would be necessary to estimate the angular size as already discussed in detail in chapter 4.

### 7.6 Conclusion and future perspective

We simulated RM and OI datasets to estimate the accuracy on the distance measurement using BLR parallax method. In the Bayesian framework, we fit the RM data, which allows us to calculate mean radius as well as other parameters like $M_{bh}$, $i$, $\omega$ etc. Model fitting of OI data allows us to calculate angular size. Then using Eq.7.1, we recovered angular distance with uncertainty less than 20%, which is slightly larger than the uncertainty estimated in dust parallax distance (13.5%) by Hönig et al. (2014). The reason of this higher uncertainty is mainly due to the degeneracy of the parameter space and the quality of RM and OI data. Fitting individual emission line profile of different epochs obtained during RM monitoring could allow to reduce this uncertainty, which can be further reduced from better quality RM and OI data. Another improvement will be to fit first RM data and use the parameters probability distribution as prior for OI data fitting with only unknown parameter angular size. This will further reduce the uncertainty in angular size estimates.

BLR parallax method can be applied to the objects for which both OI and RM observations are possible in the same emission line. As shown in chapter 6, next generation GRAVITY instrument could allow to observe a dozen of object providing BLR angular size estimation including different model parameters. This will be a major step forward for distance measurement. Moreover, MATISSE instrument will allow to estimate rim size in $L$ band and will be particularly useful for dust parallax. OASIS with next generation fringe tracker could allow to observe BLR of about 50 objects with redshift up to 1 and four decades in luminosity, and allow to measure distances using BLR parallax. To apply this method as a tool for cosmic distance indicator, a desirable step is to have VLTI working in the visible (Hönig et al., 2014; Elvis, 2014). Adaptive optics on UTs with Strehl ratio about 0.1 could allow to estimate distances of about 100 objects using BLR parallax in visible. Spectro-astrometry with E-ELT could allow to estimate angular size of the BLR up to $z = 3$. For this, RM from the space would be very useful, a first step of which has already started (De Rosa et al., 2015).
8.1 Conclusion

We have investigated the application of optical interferometry to the study of AGN BLRs in order to discuss

- geometry and kinematics of the central engine by constraining morphology of BLRs
- SMBH mass measurement in quasars
- the use of quasars as standard candles

We developed a geometrical and kinematical model of BLR of quasar to predict simultaneously RM and OI signals. We showed that OI signals, such as differential visibility and phase, can provide strong constrain on BH mass, BLR size, radial distribution of BLR, velocity field, anisotropy, inclination and thickness. We created mock OI datasets using few key model parameters such as BH mass, BLR
size, inclination and thickness of BLR. All parameters are typical for quasar (see Li et al., 2013) except the angular size was taken from Petrov et al. (2012). We added realistic noises to properly simulate OI data. The aim was to find accuracy of those parameters from OI data. We employed a MCMC model fitting algorithm, and using Bayesian statistics we sampled the parameter space.

We found that OI data alone can constrain BH mass with uncertainty less than 0.15 dex. Virial mass estimated by traditional cross-correlation analysis has uncertainty of 0.30 to 0.44, which includes the dispersion of unknown scale factor $f$ (Woo et al., 2010). If $f$ can be constrained then uncertainty on the BH mass estimation using virial relation can be reduced highly. Our model has confirmed that the geometry strongly constrain the effect of $f$ factor, and OI measurements can constrain it since OI provides BH mass measurement independent of $f$. Direct model fitting of high quality RM data also provides constrain on the geometry and kinematics, and BH mass measurement with uncertainty comparable to our estimation, but parameters degeneracy remain. However, we have qualitatively illustrated the potential of the combination of RM and OI data that improve the overall constrain on the BLR geometry and kinematics and estimate BH masses with higher accuracy, but the full accuracy gain still have to be investigated.

As a first application of OI to BLR, we resolved Pa$_\alpha$ emission line region of a bright QSO 3C273. Its redshift of 0.158 and $K$ band magnitude of 9.7 make it particularly suitable to observe with VLTI AMBER instrument. We detected a drop in the differential visibility in all baselines. This shows that the BLR is more extended than the inner rim of dust torus. However, differential phase has been found to be $0 \pm 1^{\circ}$. Combined with this very large BLR size deduced from the visibility drop, the very small differential phase implies a geometry very far from a flat disk with global Keplerian or radial velocity field. We applied our 3D geometrical and kinematical model to interpret the data. In the framework of Bayesian statistics, using a MCMC algorithm, we sampled the parameter space to fit the model globally to the data. We found that 3C273 has an extended BLR, much larger than the RM H$\beta$ emission line size.

We discussed two ways to explain the difference between our interferometric size in Pa$_\alpha$ and the RM size in Balmer lines.

1. The RM data can not measure properly size larger than about 700 ld, and after 800 ld systematically converges around a value between 200 and 400 ld.

2. The Pa$_\alpha$ size of 2142 ld could actually be compatible with the H$\alpha$ size of about 500 ld, as there might be up to a factor 2 difference between H$\alpha$ and Pa$_\alpha$ due to photoionization of BLR, and multiplied by a factor of about 2 between RM size and OI size that resulted from different weighting in RM and OI (see Koshida et al., 2014; Kishimoto et al., 2011b).

We found that the 3C273 has a roughly face-on ($i = 10^{\circ}$) and spherical BLR. The clouds in the BLR are rotating in Keplerian orbit, but a significant contribution of turbulence velocity is present. Furthermore, we estimated a BH mass of 3C273 to be $5.30^{+0.24}_{-0.21} \times 10^{8}M_{\odot}$, similar to the mass obtained by Kaspi et al. (2000). Comparing our directly estimated BH mass to the RM virial mass, we estimated
the RM scale factor to be \( f \approx 3 \), which is close to the value obtained by Grier et al. (2013). Measurement of scale factor independently will help to calibrate BH masses that are estimated using virial relation. With more OI source resolved by OI and RM, we could calibrate \( f \) as a function of luminosity and probably with other parameters.

Motivated by our 3C273 result, we did a feasibility test to find the number of AGNs that can be observed with different instruments such as AMBER, GRAVITY, OASIS and OASIS+ (possible instruments) at VLTI with its full potential. We also obtain the accuracy on the absolute and different visibility and differential phase that can be obtained from different instruments. We found that next generation VLTI instrument GRAVITY could allow to observe a dozen of objects. For about 15 objects we will get absolute visibility and differential phase, still allowing us to constrain BLR geometry up to some extent. With OASIS and OASIS+, this target list could increase up to 40. Having an external FT, GRAVITY and OASIS+ number of targets could increase up to 30 and 50 respectively. Moreover, MATISSE in \( L \) band could observe emission lines of about 10 objects, and for many objects it will provide absolute visibility measurement, which is necessary to constrain dust torus geometry. VLTI in its visible mode with UTs of Strehl ratio 0.1 could provide differential visibility measurements of about 130 objects up to \( V = 15 \), for some of which we will have absolute visibility measurement. Differential phase with or without visibility measurement will be a key to estimate angular size for distance measurement using parallax. ATs with Strehl ratio 0.5 could also reach up to \( V = 14 \). In visible we will not only have the advantage of higher angular resolution but also will have the access to the bright Balmer lines. Thus, a visible mode at VLTI is highly desirable. VLTI with its full potential could allow to establish an independent \( r_{\text{blr}} - L \) and \( M_{\text{bh}} - L \) other than RM, and probably \( i - L \) and \( \omega - L \) relation.

A simply method, “Quasar parallax” was proposed by Elvis and Karovska (2002) to estimate distances using quasars based on the ratio of the linear size given by RM and the angular size given by OI, with a correction factor depending on the geometry of the source. Recently Hönig et al. (2014) applied this method to the dust torus of NGC 4151 estimating first direct distances using dust parallax with 13.5% uncertainty. With a very simple “ring” like geometry of the inner rim of the dust, they showed that model parameter have very little influences on distance measurements since they have similar influence on both RM and OI measurements. After our first successful observation of the BLR of the 3C273, we made a preliminary investigation of the BLR parallax method. We created mock RM continuum and line light curves, and OI data adding realistic noises. Fitting the mock data, we found a potential accuracy on the angular distance better than 20%. This uncertainty could be reduced with high quality RM data as model parameters can be better constrained in that case, which was shown recently by Pancoast et al. (2014a). The full dependence of BLR parallax method still needs to be estimated from a large sample of targets. On 3C273, our doubts about the actual RM size in Pa\( \alpha \) prevented so far an attempt to measure distance of 3C273 using this method. The full model including photo-ionization code CLOUDY could allow to estimate the lag ratio of Pa\( \alpha \) to H\( \alpha \), which should be feasible as we have strong constrain on the BLR geometry. This could be applied to all the targets.
that could be observed with VLTI to estimate angular diameter and its accuracy. The result will have remarkable significance as distance measurement with quasars at $z > 0.8$ would allow to constrain different cosmologies.

### 8.2 Ongoing work

#### 8.2.1 3C273 data reduction and modeling

There are a few works that are ongoing about 3C273. Calibration of 3C273 data is not finished yet. This can be done very soon. In future we will also try to investigate the possibility to fit simultaneously visible RM data of (Kaspi et al., 2000) with our Pa$\alpha$ emission line data, but this needs an estimation of lag-ratios between different line emitting regions. It can be calculated from our improved modeling after including photo-ionization physics.

#### 8.2.2 Parallax distance

The work presented in chapter 7 is not finished yet. We really believe that the accuracy on linear size estimation can be improved by simultaneous fitting of multi-epoch spectra. It will also help to better constrain other BLR model parameters whose probability distribution can be supplemented to the OI data fitting and thus we can have better constrain on the angular size. This work is in process. We also want to test the feasibility of this method with spectro-astrometry of E-ELT. Recently Stern et al. (2015) proposed that E-ELT can spatially resolve 100$\mu$as BLRs, thus expected to provide constrain on the angular size of many objects with large redshift range. Thus, we will estimate the accuracy on the angular distance that can be obtain with spectro-astrometry of E-ELT and RM data.

#### 8.2.3 Model development

We showed that our BLR model is capable to predict simultaneously OI and RM signals for various geometries and kinematics. Moreover, this can be easily improved considering elliptical orbits and non-linear response of BLR clouds on the incident continuum (Pancoast et al., 2014b; Li et al., 2013). This will be needed for fitting high quality RM data since current OI data is not accurate enough to fit many free parameters in model fitting. One important development is to include “photo-ionization” physics inside the model. With a precomputed grid of hydrogen density ($n_H$) and photon flux ($\phi_H$), we have computed radial emissivity of different emission lines. Having done that we could apply simultaneous model fitting of several emission lines data and constrain the photo-ionization model parameters. Again, this can be done with RM data since we have highly sampled light curves in several emission lines for many objects. For modeling OI data, we can use the precomputed radial emissivity in the model. Similarly anisotropy can also be computed from the same $n_H - \phi_H$ grid following Goad et al. (2012).
8.3 Future perspective

8.3.1 VLTI 2nd generation instruments

As discussed in chapter 6, VLTI next generation instruments like GRAVITY and MATISSE can combine all four unit-telescopes and provide simultaneously 6 baselines observation. They will also provide good quality data, and eventually will allow to constrain many more model parameters. GRAVITY is expected to start operation from 2017. This could provide very good differential phase measurement of a dozen of objects. Moreover, much better absolute visibility can be obtained from GRAVITY observations. This will be a major boost in MR observation of BLR. MATISSE on the other hand is expected to provide data from 2016. It could allow to provide images of the inner dust torus for a couple of objects. It will also provide dust size as a function of temperature by observing in $L$, $M$ and $N$ bands for all the GRAVITY objects. Thus, combining GRAVITY with MATISSE observations, we could develop a luminosity dependent model of BLR and dust (both depending from latitude distributions of luminosity).

8.3.2 Photometric reverberation mapping

Indeed emission line RM is the most powerful tool till now to estimate BH masses in AGN and to constrain the BLR geometry. However, due to sparsely sampled RM light curves, the scatter in these relations is still large. Moreover, emission line RM is observationally very expensive, since the reverberation spectra usually require observations with at least a 2 m-class telescope, need monitoring of objects from few months to several years to match distinct echo features, and are also prohibited at higher redshift.

As an alternative technique Haas et al. (2011) suggested photometric RM (PRM) in optical using a combination of narrow and broad band filters. In brief, the principle is that the narrow band filter plays crucial role to measure the flux of emission line, while broad band filter can be used to estimate the continuum. Narrow and broad band light curves can be used to get the time delay between continuum and emission line flux, leading to the BLR radius (Pozo Nuñez et al. (2012, 2014)). Since the photometric monitoring can be obtained more quickly than spectroscopic monitoring and that also using small telescope, so it opens a possibility of carrying out the RM study for larger sample of nearby AGNs, with reasonable telescope time. PRM will provide highly sampled light curves enabling us to constrain the geometry and kinematic of BLR as well to estimate accurate BLR size and BH mass, and hence improved $R - L$ and $M - L$ relations.

Thus, we are carrying out photometric reverberation mapping of 6 nearby AGNs, with V-band magnitude brighter than 15.0 using Aryabhatta research institute of observation sciences (ARIES) 1.3 m DFOT. This brightness criteria ensures that photometry can be carried out even on bright nights, with 1-2 m class telescope. The redshift range of members is chosen such that their H-β and H-α emission line respectively fall in the region of OIII and SII narrow band filter of ARIES 1.3 m DFOT. For continuum flux we wish to use the broad B and V-band observation.
The typical BLR size expected for our sample is at the most about 20 light days, which can be constrain very well by monitoring campaign of about 60-70 days. For three of our sources we are using OIII filter to cover H-β emission line, while for another three we are using SII filter to cover the H-α emission line.

### 8.3.3 Emission line reverberation mapping

Reverberation has been a powerful tool to estimate BH masses of AGNs. Recent high quality RM data enables to recover velocity-delay map providing kinematics signatures. Dynamical modeling of these data enables to constrain geometry and kinematics of the BLR and BH masses independent of virial factor. However, this has been done only for few objects. There is an immediate need to increase the sample size extending to high-luminosity and high redshift objects.

Therefore, with a group of ARIES, I am planning a 3 years RM campaign of a handful number of AGNs with recently installed 3.6 m Devasthal telescope. In early 2016 ADFOSC (ARIES Devasthal Faint object spectrograph) will be available for such spectroscopic RM observations. For some low luminous objects, we will do intensive variability monitoring to obtain highly sampled light curves not only to recover velocity-delay map by linear inversion with maximum entropy method but also to constrain their geometry and kinematics by direct modeling of BLR and Bayesian inversion technique. For few high luminous objects, we will monitor them once or twice per 2 weeks to estimate their BLR size via cross-correlation technique and Javeline fitting. This will allow to extend $R-L$ relation to the high luminosity region. Additionally, it would be interesting to measure emission line lag ratios for optical and near-IR lines, since no near-IR emission line RM data is available, and OI with AMBER or GRAVITY is limited to the near-IR. Thus, this will allow to estimate lag ratios between Hβ, Hα to Paβ and Paα. An extrapolation of these lag ratios could be used for high luminous object like 3C273 to find the difference between near-IR RM size vs OI size, and constrain the BLR and dust structure.

### 8.3.4 Observation with GAIA

GAIA will measure photometric and spectro-photometric variability of few hundred of thousand of QSOs but with a poor and irregular time sampling that depends on the source position (Proft and Wambsganss, 2015). It might be worth investigating if the time sampling of some of GAIA targets could be enough to constrain inner structure and physical process in BLR.

### 8.3.5 Spectro-astrometry

If we have a model (and the differential phase is not zero on other BLRs like in 3C273) spectro-astrometry with E-ELT could resolve the μas BLR providing its angular size measurement up to redshift more than 4 (Stern et al., 2015). This
measurements, accurate at the 1/1000 pixel level, would allow BLR parallax measurement up to redshift $z = 3$ for high-luminosity and $z = 2$ for low-luminosity objects, which is a preliminary result from Petrov et al. (2012) and will be investigated through our ongoing work on BLR parallax.
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