The Ergosphere and Dyadosphere of Black Holes

A chapter in D.L. Wiltshire, M. Visser and S.M. Scott editors, The Kerr Spacetime: Rotating Black Holes in General Relativity, (Cambridge University Press, 2009)

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1 Introduction

On most days I seem to use Roy Kerr's name ten times or more, primarily because the empty Einstein space constructed by him in Kerr (1963) is so important to relativistic field theories. This should not come as a surprise. If one looks on Google for "Kerr AND metric OR space" one will find at least 1.33×10^6 citations!

Sometimes this arises during the experimental verification of Einstein's theory using advanced space technologies. For instance, I recently had great pleasure seeing the launch of NASA's Gravity Probe B Mission. This is directly related to the Kerr solution, (see e.g. Fairbank et al., 1988). For the relation of gyroscope motion to the Kerr solution, (see e.g. Ohanian & Ruffini, 1994; Ruffini & Sigismondi, 2003, and references therein). This work also appears in explanations of the electrodynamical aspects of accretion disks for binary X–ray sources, extragalactic jets from active galactic nuclei and microquasars in our galaxy, (see e.g. Giacconi, 2002; Giacconi & Ruffini, 1978; Punsly, 2001).

For us Kerr space–time was visualized by numerically integrating the trajectories of five test particles leading to a splendid new image. This became the logo of our Centers for Relativistic Astrophysics, ICRA and ICRANet (see Figure 1.1 and Johnston & Ruffini, 1974), and a beautiful sculpted version is given triennially to the recipients of the Marcel Grossmann Awards, see `http://www.icra.it/MG/awards/`.

I will try to give a few examples of each of these applications in my talk. They can all be taken as examples of the following principle: *Humans have always been too conservative in their imagination. They have never been able to reach by imagination alone the realities discovered by logic and scientific endeavour based on the necessary mathematical formalism*[1]. This may be the reason why new ideas are not always easily accepted by the scientific establishment. There may be much strife before the previously inconceivable becomes the universally accepted.

[1]Examples of two theoretical predictions that could not have been imagined are those by Maxwell of electromagnetic waves, (see e.g., Maxwell (1986)) and Dirac of antimatter simply from their celebrated equations. Dirac himself remarked in one of his talks that his equation was more intelligent than its author (see, e.g., http://physics.indiana.edu/~sg/p622/lecture1quotes.html). Similarly, the concept of a critical mass for gravitational collapse, constructed by Oppenheimer from Einstein equations, was a complete surprise to John Archibald Wheeler (see "Discussion of Wheeler's report" in Institut International de Physique Solvay, 1958, pp. 147–148) and even Einstein himself (Einstein, 1939). Both were dubious at first but changed their minds later.

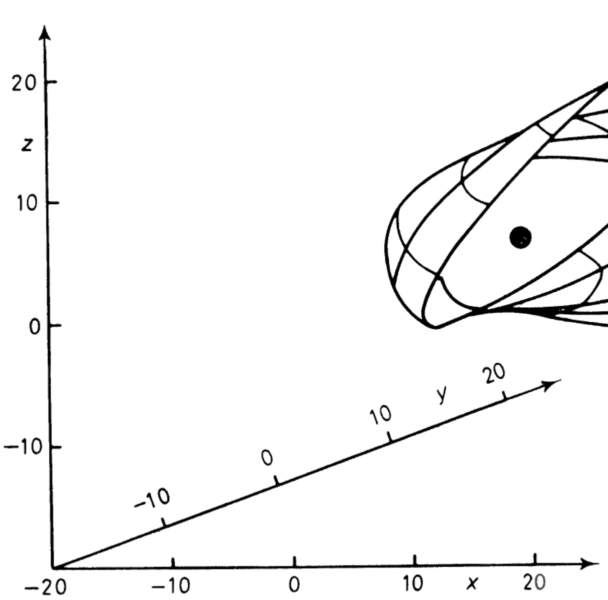


Figure 1.1: Motion of uncharged cloud of particles corotating about an extreme spinning charged black hole. The orbits are stable. The vertical lines indicate isochronous points (as seen from infinity). Details in Johnston & Ruffini (1974).

S. Chandrasekhar and I had many discussions where we compared the difficulties we had getting his ideas on White Dwarfs and mine on black holes accepted. The observational properties of White Dwarfs were well known before Chandrasekhar (1935) explained them by applying degenerate Fermi statistics to stars (see Chandrasekhar, 1939). This theory was forcefully rejected in Eddington (1935), a paper that was published in the same journal and even immediately preceding that of Chandrasekhar!

The situation has been even more difficult for black holes. We had to struggle against the preconceived notions of two quite independent groups, theoretical physicists and observational astronomers. Firstly, there was the resistance of some physicists against accepting certain properties of these new objects, *e.g.*, their horizons, their mass-energy formulae and the amazing power being generated by them. Secondly, astronomers were unable to explain the huge amounts of energy being released by the newly observed binary X-ray sources, but they still did not recognize the need for radically new ideas. Nuclear forces had been used for decades to explain the energy from stars, but were clearly unable to explain the X-ray emission from these binaries, since the energy released was both too sudden and too great (see below). The radically new idea of the conversion of gravitational energy by accretion processes around a gravitationally collapsed star was needed for this (see e.g. Giacconi & Ruffini, 1978, and references therein).

The Kerr metric has been crucial in this long debate. Although Roy's discovery was initially ignored by astrophysicists, the almost simultaneous discovery of quasars triggered the interest of a small minority in gravitational collapse (see e.g. Schild, Schücking & Robinson, 1965). This solution has become an essential mathematical tool, creating the theoretical framework needed to interpret the flood of observations from the newly built X-ray and γ-ray detectors in space, as well as from the corresponding optical and radio ones on the Earth's surface. The first major triumph for the new theories was the identification of Cygnus-X1 as a black hole inside our galaxy, see Giacconi & Ruffini (1978) and Giacconi (2002).

Even bigger challenges have confronted relativistic astrophysics in the last thirty years. These have included how to test the black hole mass-energy formula which predicts that up to 29% (50%) of its energy can be rotational (electromagnetic) and how to show that this energy, in principle extractable, could fuel the most ultra-relativistic and energetic phenomena ever observed in nature, Gamma-Ray Bursts (GRBs). The difficulties in bridging the communication gap between these new concepts and the traditional ones of the physical, astronomical and astrophysical communities have been simply enormous, much bigger than the corresponding ones for white dwarfs and binary X-ray sources. We will mention three of these major challenges.

The first has been for astronomers. They had successfully understood astronomical systems by observing their evolution over periods of many years. It was difficult for them to accept that significant observations in GRBs can occur over periods as short as a fraction of a millisecond because of the rate at which the source evolved. An almost instantaneous spectrum changing on such a short time–scale is no surprise to a physicist but it was to astronomers. They tend to associate a fixed and constant spectral characteristic to any given source, not an instantaneously changing one.

The second challenge has been for physicists. They needed to understand the properties of the extreme gravitational field around black holes and also some of the latest developments of relativistic quantum field theory. The concept of dyadosphere (see below) has not been accepted easily. It needs simultaneously detailed knowledge of Kerr–Newman geometry as well as of quantum field theory as developed in recent decades through the study of heavy ion collisions and high powered laser sources.

The last challenge has been for both groups. These systems move ultra–relativistically with a Lorentz γ-factor starting as high as 500 and then dropping all the way down to 1. The observed arrival times of the emitted photons are not what matters, just the corresponding rates of emission at the source, and to calculate these the entire past world–line of the source and its gravitational potential must be known (Ruffini et al., 2001a)!

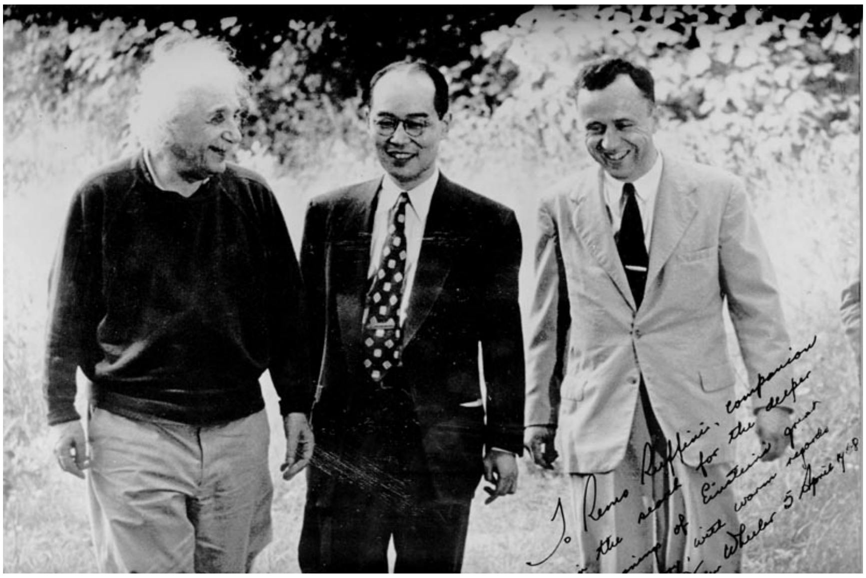


Figure 1.2: Albert Einstein, Hideki Yukawa and John Archibald Wheeler, with the dedication of John Wheeler on April, 5^{th}, 1968.

2 The maximum binding energy in Kerr geometry

After a period spent with Pasqual Jordan in Hamburg, I was invited to Princeton as a postdoctoral fellow by John Archibald Wheeler[1], starting September 1^{st}, 1967. Those were very active days for the astrophysical community. Pulsars had just been discovered by Jocelyn Bell and Tony Hewish (1967), and many theorists were actively trying to explain them as rotating neutron stars (see Gold, 1968, 1969; Pacini, 1968; Finzi & Wolf, 1968). These had already been predicted by George Gamow using Newtonian physics (Gamow, 1938) and by Robert Julius Oppenheimer and students using general relativity (Oppenheimer & Serber, 1938; Oppenheimer & Volkoff, 1939; Oppenheimer & Snyder, 1939). The crucial evidence confirming that pulsars were neutron stars came when their energetics was understood (Finzi & Wolf, 1968). The following relation was established from the observed pulsar period P and its positive first derivative dP/dt:

$$\left(\frac{dE}{dt}\right)_{obs} \simeq 4\pi^2 \frac{I_{NS}}{P^3}\frac{dP}{dt}\,, \tag{2.0.1}$$

where $\left(\frac{dE}{dt}\right)_{obs}$ is the observed pulsar bolometric luminosity and I_{NS} is its moment of inertia derived from the neutron star theory. This has to be related to the observed pulsar period. This equation not only identifies the role of neutron stars in explaining the nature of pulsars, but clearly indicates that the neutron star's rotational energy is the pulsar energy source. This success exemplifies how to understand any astrophysical system we must first explain its energetics. We will return to this point later.

Wheeler decided to change the focus of his group from the physics of neutron stars, which had already been the subject of a celebrated book by him and coworkers (Harrison et al., 1965), to the total gravitational collapse of a star with a mass larger than the critical neutron star mass and at the endpoint of its thermonuclear evolution. This far more extreme general relativistic system had already been conceived by Robert Oppenheimer and his students. It was frozen in both time and temperature due to its gravitational redshift becoming infinite at the corresponding Schwarzschild horizon. We did not like the name "frozen star" given to it by our Soviet colleagues, and instead

[1] Or Johnny, as the members of our group called him (see Figure 1.2).

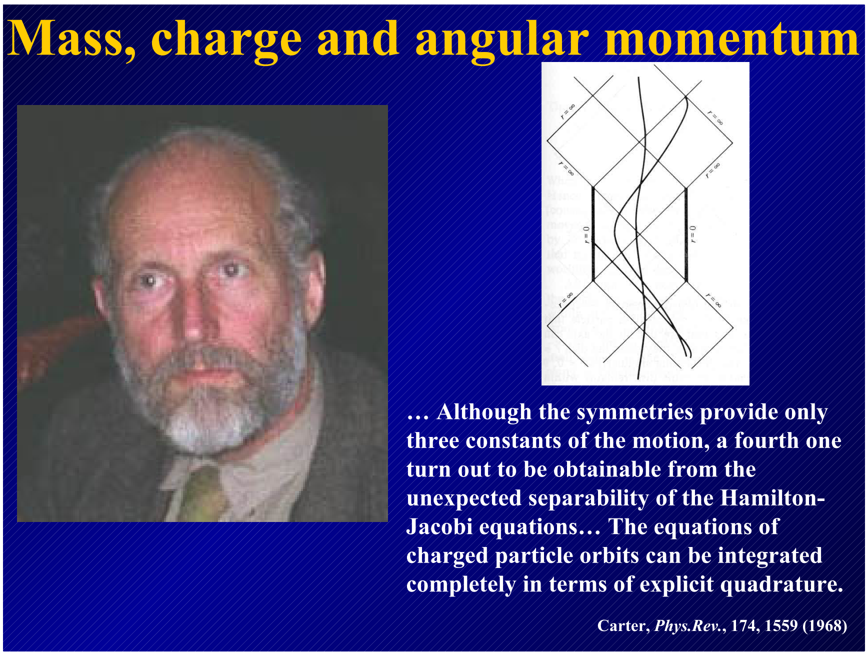


Figure 2.1: Brandon Carter and the introduction of his famous fourth constant of the motion.

decided to follow Wheeler's suggestion and call it a "black hole" (Ruffini & Wheeler, 1971a). This emphasized its two most extreme characteristics, the infinite gravitational red shift at its event horizon and its inevitable gravitational collapse.

At that time Princeton had a very pleasant scientific ambiance because of the fortunate interaction between its bright students and the outstanding scientists at both the Institute for Advanced Study and the University. These included Kurt Gödel, Eugene Wigner, Freeman Dyson, Martin Schwarzschild, David Wilkinson and Tullio Regge. In the following years, as a Member of the Institute for Advanced Study and an instructor and later assistant professor at Princeton University, I enjoyed many discussions with them and learned from their experiences and their understanding of physics.

Johnny Wheeler and Tullio Regge had developed a powerful mathematical physics technique (Regge & Wheeler, 1957) and we used this formalism, as later completed by the seminal work of Frank Zerilli (Zerilli, 1970, 1974), to describe the physical processes in a Schwarzschild solution. Our group studied a variety of problems on the emission of gravitational radiation in these highly relativistic regimes, using the Regge-Wheeler-Zerilli tensorial harmonics techniques.

My first encounter with the Kerr solution occurred in Princeton when Brandon Carter visited our group. He had just published a most remarkable paper (Carter, 1968, see Figure 2.1) on the separability of the Hamilton-Jacobi equations for the trajectories of charged test particles in Kerr–Newman spaces.

This classic work is a mandatory text for all students in my course on theoretical physics at "La Sapienza", the University of Rome. In this paper Brandon sets the mathematical foundations for the new physics in the spacetime described by the Kerr solution and its electromagnetic generalization. It was Johnny's idea that instead of attempting to integrate the first order equations derived by Brandon we should apply a well established effective potential technique to them. The simplest version of this technique has been well known since the classic works of Jacobi in classical mechanics (see Jacobi, 1997) and its use in discussions of the radially separated Schrödinger equation in quantum mechanics (see e.g. Landau & Lifshitz, 1981). It had also been extended to the more complex classical motion of charged particles in the Earth's magnetosphere by Carl Størmer (see Størmer, 1934, and references therein). It proved to be just as useful for the Kerr spacetime, even though the physical conditions there were very different from those in the original applications. I still remember Johnny's suggestion that we draw the effective potential on the largest possible diagram, thereby minimizing the imperfections in the final printed version. Unlike today when diagrams can be almost instantly constructed and plotted by a computer, back then each value had to be calculated using stacks of punched cards on a computer, and then plotted on the final diagram. This was particularly impressive for our case - the diagram measured three by two meters (see Figure 2.2)! A byproduct of preparing such a meticulous diagram was the time it gave us to think about the underlying physical process. It was during this numerical work that we realized that co-rotating orbits in the Kerr solution were much more tightly bound than counter-rotating ones. It was very gratifying when my good friend Evgeny Lifshitz found these results so important that he mentioned the Kerr solution extensively in the text of the last edition of the Landau and Lifshitz treatise, together with both Brandon's work and the results of Wheeler and myself as named problems for bright students!

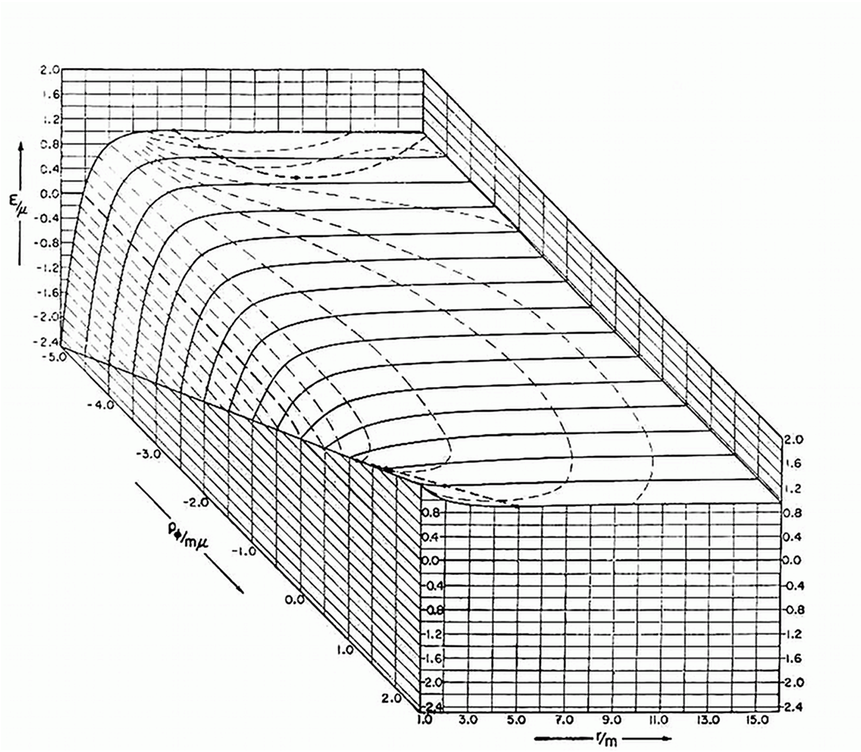


Figure 2.2: Effective potential experienced by a test particle moving in the equatorial plane of an extreme Kerr black hole. For corotating orbits, with positive values of the angular momentum, the maximum binding of 42.35% of the rest mass of the test particle is reached at the horizon.

3 The significance and magnitude of binding energy

One of the greatest feats of twentieth century science was understanding the nuclear binding energy of the elements. The precise value of the mass defect was calculated as a function of the atomic number for all known elements (see Figure 3.1). This has generated some of the most striking conceptual, technological, and cultural changes in the history of mankind. The life cycle of our solar system and even life on our planet depend essentially on the nuclear binding energy released when elements are transformed. Fusion processes occur when elements lighter than iron are converted to heavier ones with a larger nuclear binding energy per nucleon. Conversely, fission processes occur when atoms heavier than iron split into smaller constituents, again with more binding energy per nucleon.

Jean Perrin (1920) and Arthur Eddington (1920) were the first to point out, independently, that the fusion of four hydrogen nuclei into one helium nucleus could explain the energy production in stars. This idea was put on a solid theoretical base by Robert Atkinson and Fritz Houtermans (1929a,b) using George Gamow's quantum theory of barrier penetration (Gamow & Houtermans, 1928) and was further developed by C.F. von Weizsäcker (1937, 1938). The monumental theoretical work by Hans Bethe (1939), and later by Burbidge et al. (1957), completed the understanding of the basic role of fusion processes in the stars. Together with Fermi (1949), they realized that the relative abundances of the elements in our entire solar system, including the planets, depend universally on nuclear burning. The presence of heavy elements also proved that these processes had already occurred in a previous generation of stars. All forms of energy which make life on our planet possible are derived from the sun, an enormous but relatively simple nuclear fusion reactor dominated by less than one hundred different nuclear reactions.

Fermi's work also lead to our understanding of the fundamental role of fission and to the first chain reaction in Chicago (Fermi et al., 1942). A significant fraction of electric power on our planet is now generated by fission reactors, and progress is been made to design a viable controlled fusion process to generate an alternative and secure energy source. The latter may prove to be essential if we are to maintain our desired quality of life. It is well known that both fission and fusion processes have been used in military research, and that some of the people who have contributed to the development of rel-

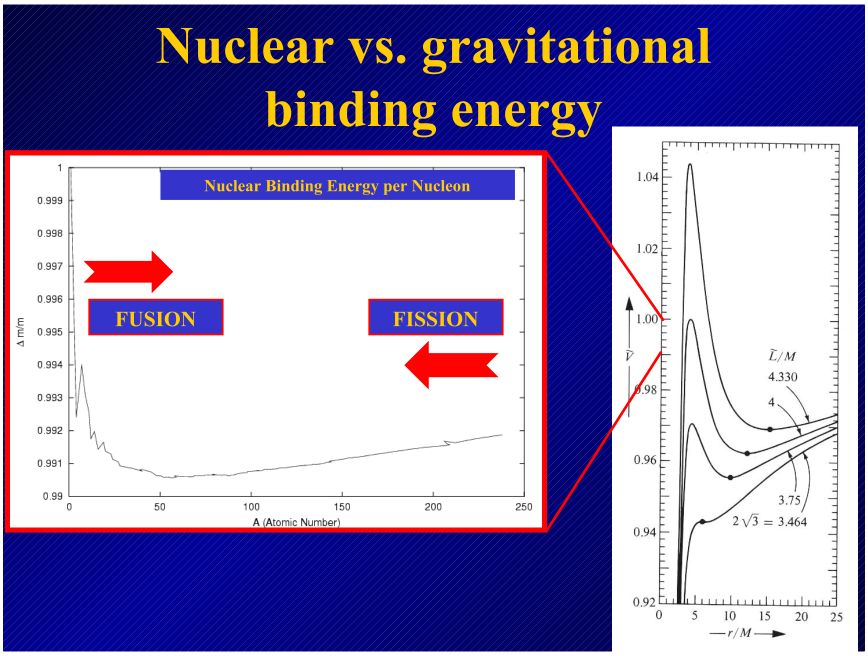


Figure 3.1: Nuclear vs. gravitational binding energy in a Schwarzschild black hole compared and contrasted. The gravitational binding energy in a Kerr metric is even bigger (see Figure 2.2).

ativistic astrophysics, *e.g.*, John Archibald Wheeler, Ya. B. Zel'dovich and A. Sakharov, had also previously made significant contributions to this field.

The huge difference between the sizes of mass defects due to nuclear binding energy and the mass defects of particles around a black hole due to its gravitational binding energy (see Figure 3.1) shows that the energy generation processes are far larger in the general relativistic scenario.

A major step in proving the importance of such deep gravitational fields in astrophysical systems came with the identification of the first known black hole in our galaxy, Cygnus-X1 (Giacconi & Ruffini, 1978). A further step was made by the introduction of the blackholic energy and the possibility of thereby explaining some of the most energetic processes in our Universe.

4 The ergosphere of a Kerr spacetime

The central tools used in our research into the new physics of the Kerr spacetime were the separability of the associated Hamilton-Jacobi equation, discovered by Brandon Carter, and the effective potential technique. Achille Papapetrou had written to Johnny Wheeler, telling him of a sixteen year old high school student, Demetrios Christodoulou from Athens, who appeared to be specially gifted in physics and general relativity. When Wheeler examined him in Paris he was so impressed that he used Princeton University's freedom as a private institution to enroll him immediately as an undergraduate. Demetrios was not allowed to return to Athens where he had been quarreling with his high school teachers. Instead he compressed a 4-year undergraduate program into a single year. He was then enrolled in graduate school at the age of 17. Wheeler was officially his Thesis Advisor and assigned him the study of the collapse of a spherically symmetric massless scalar field, which later became chapter 1 of his Thesis. I started by investigating with him the capture of test particles, both charged and uncharged, in a Kerr–Newman spacetime using the effective potential technique I had developed with Johnny (see Fig. 2.2), which became the remaining chapter of his Thesis.

In 1969 I was attending the first meeting of the European Physical Society in Florence. In those days the universities in Europe and elsewhere were in a very agitated state and so I was not surprised when this meeting was disrupted. I found myself sitting on the steps of the Palazzo della Signoria with Roger Penrose, discussing some aspects of a provocative talk he had just presented. In this he considered the possibility of an advanced civilization extracting energy from a Kerr spacetime by lowering tethered particles toward the singularity (see Figure 4.1). He also considered a ballistic method: an object splitting into two pieces, one crossing the horizon and the other escaping with more mass-energy than the original body. However, there were many aspects of his lecture which were not clear to me, and which were not cleared up by our discussion.

Returning to Princeton, Johnny and I began examining the details of particle decay around a black hole. We showed that, as claimed by Penrose, energy could indeed be extracted. A particle with positive energy and positive angular momentum in a Kerr spacetime could come from infinity with a finite impact parameter and then split into two separate particles. One,

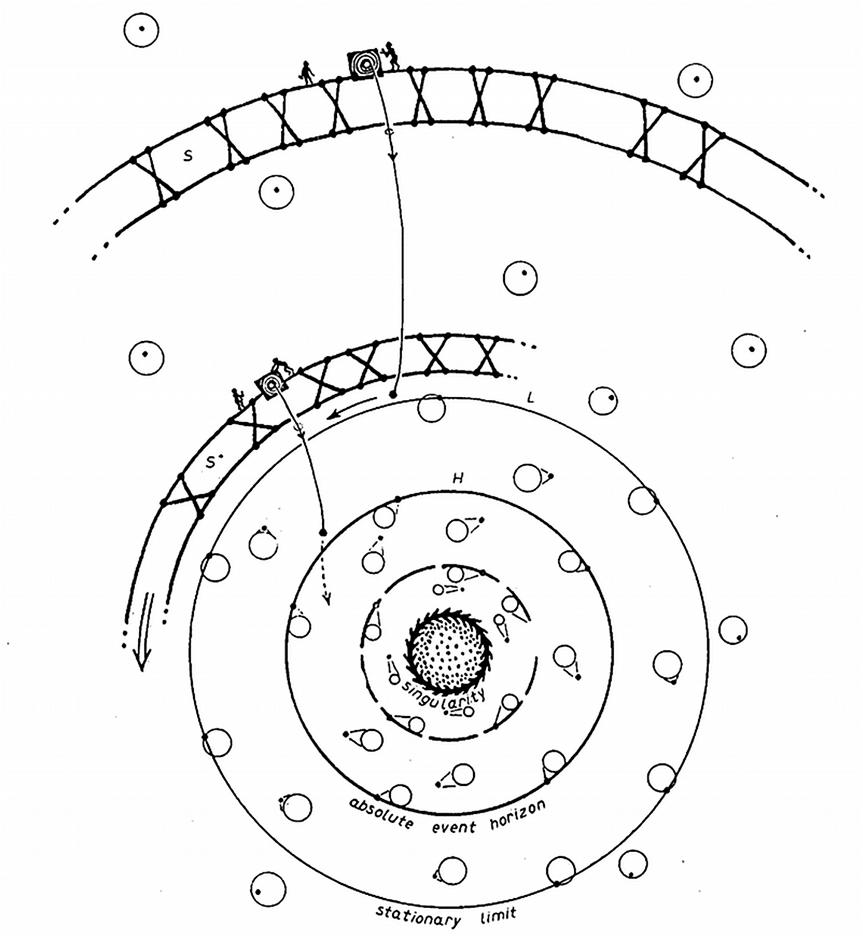
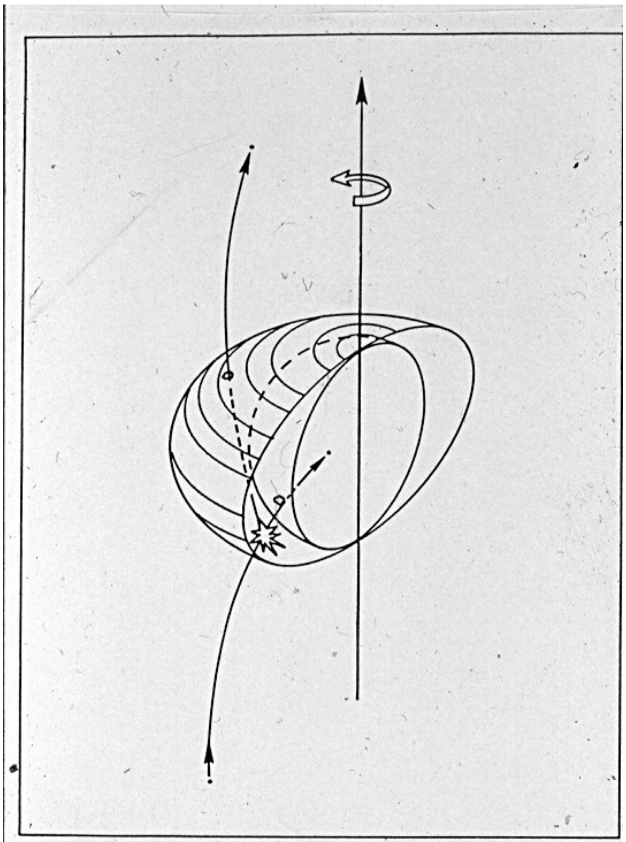


Figure 4.1: Extraterrestrial civilization as idealized by Penrose (1969).



Ergosphere of a rotating black hole. The region between the surface of infinite redshift (outer) and the event horizon (inner), here shown in a cutaway view, is called the "ergosphere." When a particle disintegrates in this region and one of the fragments falls into the black hole, the other fragment can escape to infinity with more rest plus kinetic energy than the original particle. Figure 5

Figure 4.2: The ergosphere. Reproduced from Ruffini & Wheeler (1971a).

counter-rotating and in a negative energy state as seen from infinity, would be captured by the horizon. The other, co-rotating and more energetic than the initial particle, would escape to infinity. We also identified the region in which such a process could occur as that between the horizon and the infinite redshift surface. I decided to call this the "energosphere" since energy extraction processes could exist there. Johnny said that this name was too clumsy, and that it should have a shorter more concise name. He suggested "ergosphere". After thinking a moment and recalling that the word *ergon* exists in Greek and means work, I agreed with him. This name has since become very popular. Originally I had mixed feelings toward this energy extraction process, was intrigued by its construction, and thought that proving its viability conceptually would be very interesting. However, the rest masses of the particles had to be reduced very significantly in the process making it hardly achievable from a physical point of view (see Figure 4.2).

5 The mass formula of a black hole

While this exercise of looking at the decay of a particle in the ergosphere was continuing, Demetrios and I started a systematic analysis of all possible trajectories for test particles near a Kerr black hole. The solution for circular orbits had previously proved to be very elegant, depending on certain old theorems on the algebraic solvability of some special polynomials of sixth degree. We were fortunate to find these in the treatise of Paolo Ruffini (1803), a copy of which was contained in the main library at Princeton.

These polynomials had some rather fortunate nonphysical factors and they could therefore be reduced to fourth order ones with classic algebraic solutions. In doing this analysis we became aware of a very particular subset of trajectories corresponding to a limiting capture process. These occurred on the horizon, had zero radial kinetic energies and very specific angular momenta. A peculiarity of these paths is that the energy for counter-rotating particles is negative when seen from an observer at infinity. The corresponding capture process, with zero radial kinetic energy on the horizon, leads to a decrease of the total energy and angular momentum of the black hole. The same capture process for a particle with the same rest mass but with the opposite value for the angular momentum (*i.e.*, co-rotating) leads to a positive contribution to both the total energy and angular velocity of the black hole. Most remarkably, the capture of the two particles with equal and opposite angular momenta leads to a black hole with its original total angular momentum. What was truly unexpected was that the total energy of the black hole was unchanged by the succession of two of these capture processes. We called these very special pairs of limiting transformations the reversible transformations of a black hole. All the other capture processes, with non-zero kinetic energy or occurring off the horizon, lead to irreversible transformations where the total mass energy of the black hole must increase.

In those days Johnny was very involved with other members of the physics department in what he considered a far more fundamental problem, the Teichmüller space of what he called “superspace”. Such Teichmüller spaces, with their Riemannian non-Finslerian metrics, were meaningless to me from a physical standpoint. Nevertheless, we were able to talk to him about those thermodynamical analogies which were surfacing from the physics of black holes. It was clear to me that we were dealing with a very new situation in which the rotational energy of the Kerr black hole could be increased or decreased at will. There had to be some new and underlying quantity characterizing the black hole. I was convinced that it should be possible to split its

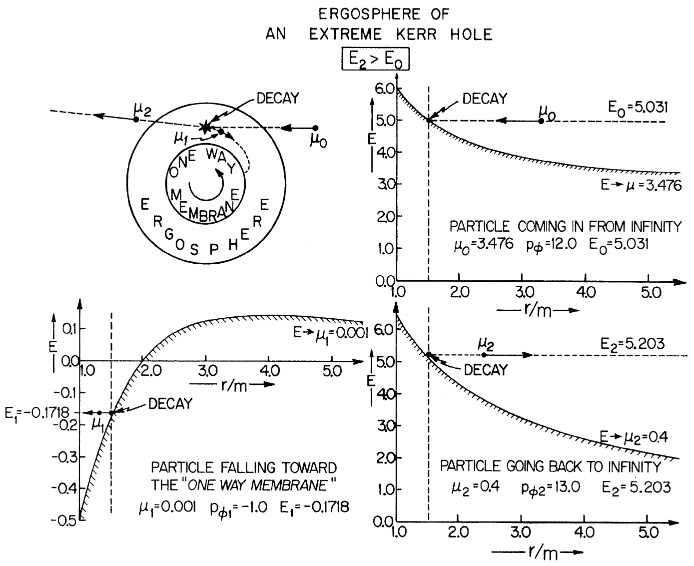


FIG. 2. (Reproduced from Ruffini and Wheeler, Ref. 4, with their kind permission.) Decay of a particle of rest-plus-kinetic energy E_0 into a particle which is captured into the black hole with positive energy as judged locally, but negative energy E_1 as judged from infinity, together with a particle of rest-plus-kinetic energy $E_2 > E_0$ which escapes to infinity. The cross-hatched curves give the effective potential (gravitational plus centrifugal) defined by the solution E of Eq. (2) for constant values of p_φ and μ.

Figure 5.1: The particle decay process in the field of a black hole as reproduced by Christodoulou (1970).

total energy into rotational and Coulomb energy. I suggested this problem to Demetrios. He was indeed able to express the infinitesimal limit on the horizon of the capture process I has examined with Wheeler and to integrate the corresponding differential equations. Next morning he came in smiling and visibly satisfied, saying "It is true. As you expected the rotational energy contribution to the Kerr solution can be split from its total energy by integrating our reversible transformations. There is a formula which relates these quantities to the non-rotating rest mass of the black hole". I gave the name "irreducible mass" (m_{ir})[1] to this black hole rest mass, since it can never decrease: it is left unchanged by reversible transformations and increases monotonically for all irreversible ones,

$$\Delta m_{ir} \geq 0 \,. \tag{5.0.1}$$

The same evening Johnny and I were walking back to the Institute through the woods bordering the golf course and swimming pool of the Institute. He had been very busy all day on certain fundamental issues of superspace. When I told him the result that Demetrios and I had just obtained, Johnny said that it was very important. It was then sent for publication to Physical Review Letters. I insisted that the sole author of the letter should be

[1] From the Italian word "irriducibile"

Copy made by Penrose for Wheeler 19 Dec 1970
Sent to Nature ~ 10 Dec 1970
Penrose said he will revise to refer to

Extraction of Rotational Energy from a "Black Hole"

Christodoulou's 30 nov 1970 Phys Rev Letter
on "Reversible and Irreversible Transformations in Black Hole Physics"

In recent years there has been considerable interest in the question of the gravitational collapse of a massive body and of possible astrophysical consequences of the existence of the "black hole" which general relativity predicts should sometimes be the result of such a collapse. In particular, the question has arisen whether the mass-energy content of a black hole could, in principle, be a source of available energy under suitable circumstances. In this note we consider the question of the extraction of rotational energy from a black hole. This has some interest particularly because it is to be expected that the rotational energy (defined appropriately) of a black hole should, in general, be comparable with its total mass-energy.

Later Penrose could not revise for strike of Nature
RR.

Figure 5.2: First page of a preprint by Floyd and Penrose with handwriting of Johnny and myself (see Floyd & Penrose, 1971).

Demetrios since it was he who had solved the mathematical equations. At the same time Johnny was delaying the publication of our results on both the ergosphere and the decay process and I therefore decided to insert in the letter a figure which included both the definition of the ergosphere and the details of the computations carried out with Johnny (see Figure 5.1). These had been clearly propaedeutic to the Demetrios result. The Editor objected to having our unpublished material in such a short letter when we were not coauthors. I promptly asked him if this objection would stand if the two authors of the figure would volunteer to ask him in writing to accept the Demetrios letter in that format. Finally, he accepted it and the results were published on 30 November, 1970 (Christodoulou, 1970). This letter recorded our propaedeutical analysis on the ergosphere, the decay process and the mass energy formula for a Kerr black hole.

A few months later Johnny sent me a copy of a preprint by Penrose and Floyd giving an example of energy extraction from a spinning black hole[2], but we were not interested in assessing priorities for such a contrived gedanken experiment. I was particularly concerned by the necessary reduction of the rest mass of the particles in such a decay process and we were working with

[2]See Figure 5.2 with the handwriting of Wheeler and myself.

Demetrios toward a more general formula for a Kerr–Newman black hole[3]. The mass formula was finally reached in July 1971 by Demetrios and myself (Christodoulou & Ruffini, 1971):

$$m^2 = \left(m_{ir} + \frac{e^2}{4m_{ir}}\right)^2 + \frac{L^2}{4m_{ir}^2}, \tag{5.0.2}$$

$$S = 16\pi m_{ir}^2, \tag{5.0.3}$$

$$\frac{L^2}{4m_{ir}^4} + \frac{e^4}{16m_{ir}^4} \leq 1, \tag{5.0.4}$$

where m is the total mass-energy of the black hole, m_{ir} the irreducible mass, S the surface area and e and L are the black hole charge and angular momentum. The inequality in Eq. (5.0.4) gives the maximum possible values consistent with the existence of an horizon. This implies that up to 29% (50%) of the total black hole mass-energy could be in principle extracted using reversible transformations to reduce its rotational (Coulomb) energy. From Eq. (5.0.3) and Eq. (5.0.1) it then follows that the surface area of the Kerr–Newman black hole must necessarily increase in any capture process:

$$\delta S = 32\pi m_{ir}\delta m_{ir} \geq 0\,. \tag{5.0.5}$$

In the meantime, S. Hawking (1971) had also derived this inequality from a different and possibly more general viewpoint, limited to the Kerr case. Demetrios finally defended his Ph.D. thesis at the age of 19, answering a splendid set of questions by the "external examiners": Eugene Wigner for the theory and David Wilkinson for the experiments (see Fig. 5.3).

In front of us there was now a vast horizon to be explored dealing with the energetics of the black holes. This will be outlined in the next chapters.

[3]Brandon Carter and Werner Israel had conjectured this to be the most general black hole, and were attempting to prove the uniqueness of its geometry.

Figure 5.3: Demetrios Christodoulou being addressed by Eugene Wigner during his Ph.D. thesis defense. Sitting, from left to right, David Wilkinson, myself, Johnny Wheeler and Eugene Wigner.

6 Introducing the black hole

Hermann Bondi, who was then Director General of the European Space Research Organization, had in the meantime invited Francis Everitt, Martin Rees, Leonard Schiff, Johnny, myself and a few others to Interlaken Switzerland to discuss the possibilities for fundamental research from space platforms.

Some of the seminal ideas discussed in Interlaken were expanded into an extended report by Wheeler and myself (Ruffini & Wheeler, 1971b) and used as the first ten chapters of our book with Martin Rees (Rees, Ruffini & Wheeler, 1976) and also in Misner, Thorne & Wheeler (1973). Our book with Martin and Johnny was considerably delayed in publication, and I therefore decided to add certain later results as appendices (see e.g. the important contribution by Shvartsman, 1971), while leaving the spirit of the earlier work unchanged. When writing this report, Johnny and I became convinced that the field had finally come of age. The study of black holes had moved from being a topic of research in formal general relativity with hypotheses assumed for purely mathematical convenience to being a field of profound physical significance. We therefore decided to write an article addressing the physics community at large. The editor of Physics Today accepted this and was especially helpful. He not only gave us the cover of Physics Today but also commissioning Helmuth Wimmer, an artist working at the Heiden Planetarium in New York, to find an appropriate representation of a black hole.

I recall explaining our research to Helmuth in a two hour session at the Physics Today office in New York. He told me later that he left the discussion totally confused and with a terrible headache. He woke up at 4am the following morning with a mental image that he immediately recorded in a painting. In his words, "This must be what they are talking about". He called me back at 9am. I rushed to New York that same morning and found the drawing to be quite beautiful. I asked Helmuth to change the sequence of colors in the spectrum but to leave the rest alone. The final picture was perfect and the article created a very favorable reaction in the scientific community (see Figure 6.1). Helmut was very happy and kindly offered me the painting in recognition of my explanation of our work to him (and also to increase his annual tax deductions due to the donation!). In the end we decided to donate the original to Princeton University, where it still hangs in the mathematical physics library in Jadwin Hall, and I accepted for myself the first proofs of the cover of physics today, signed by Helmuth Wimmer.

In the article, Johnny and I decided to emphasize one of the most profound

Figure 6.1: Introducing the black hole. From Ruffini & Wheeler (1971a).

aspects of the physics of black holes, namely that they can be characterized completely by their mass, charge and angular momentum.[1] This was becoming highly important to physics in view of the existence of the mass-energy formula for black holes. New domains of physics were being opened up, showing how nature might extract enormous power from black holes.

We also emphasized the vast number of papers written in the Soviet Union (see e.g. Zel'dovich & Guseynov, 1965; Shklovsky, 1967). They proposed certain methods for detecting black holes in binary star systems. In those days Saturn was passing in front of the sun so we added a significant sentence: "Of all objects that one can conceive to be traveling through empty space, few offer poorer prospects of detection than a solitary black hole of solar mass. No light comes directly from it. It can not be seen by its lens action or other effect on a more distant star. It is difficult enough to see Venus, 12000 km in diameter, swimming across the disk of the sun; looking for a 15-km object moving across a far-off stellar light source would be unimaginably difficult". The message was clear: in order to succeed we had to capitalize on binary star systems with a black hole as one of their members.

This brings us to the fundamental work of Riccardo Giacconi and his group. Before doing this I recall a result obtained in Princeton with my second graduate student Clifford Rhoades. Our determination of the absolute upper limit to a neutron star's mass was essential for formulating the paradigm for the

[1]Many have been working on the mathematical proofs of the "uniqueness theorem" of Carter and Israel (see Robinson's contribution in this volume).

identification of the first black hole in our galaxy.

7 On the maximum mass of a neutron star

With the help of some exceptional students in Princeton we were able to pursue our research much further. Although Johnny's main research interest was still superspace, he was also very interested in the thermodynamics of black holes started by Demetrios and myself with the introduction of reversible and irreversible transformations. He guided Jacob Bekenstein during his Ph.D. thesis on the topic of a seemingly absurd analogy: to identify the surface area of the black hole with a generalized entropy. He also suggested that the problem of dimensionality could be overcome by expressing the black hole surface area in units of the Plank mass squared. This is a pure number like any entropy should be! As Jacob recalls in his recent book (Bekenstein, 2006), I found this proposed identification noncontradictory but also possibly unnecessary.

I decided to concentrate myself on the astrophysical applications of our results with Demetrios, setting the goal to find a place in the Universe where the extraction of energy from a black hole could be observed.

Clifford Rhoades and I achieved a relevant intermediate step. Chandrasekhar (1930) and Landau (1932) had shown clearly and independently that a critical mass of $\sim 1.5 M_{\odot}$ exists for white dwarfs. Any potential white dwarf with a larger mass must collapse gravitationally. The existence of this was traceable back to the extreme special relativistic regimes encountered in the degenerate electron gas responsible for the equilibrium configuration of white dwarfs.

Newtonian gravity had been used in their analysis, the electron gas had been assumed neutral on average and the detailed electromagnetic interactions with each nucleus within the white dwarf had been neglected. The corrections to this basic treatment were found to be negligible to the first approximation (Ruffini, 2001a). There was still a critical mass, although it was slightly smaller. Similarly, if one compares and contrasts the results of the computations performed in Newtonian theory with those in General Relativity the lowest order differences are also negligible.

Neutron stars were introduced by George Gamow (1938) and by Robert Oppenheimer and his students (Oppenheimer & Serber, 1938; Oppenheimer & Volkoff, 1939). It quickly became clear that the treatment developed for white dwarfs could be applied to a system of self-gravitating neutrons. The concept of critical mass can be applied to neutron stars for the same physical reasons as for white dwarfs. The reason for this is traceable back to the extreme special relativistic regimes encountered in the degenerate neutron gas responsible for the equilibrium configuration of neutron stars. The neutron gas was still described as a free gas of fermions in that paper. The general relativistic corrections proved much larger for neutron stars than for white dwarfs. Finally, Oppenheimer estimated the critical mass to be $0.7M_{\odot}$.

It was evident that neutron stars are far more complex than white dwarfs. For the later the electrons composing the Fermion gas supporting the star are subject only to electromagnetic and gravitational interactions. The electromagnetic interactions can be precisely computed within the framework of Maxwell theory, possibly the best tested theory in physics. However, the critical mass for neutron stars occurs at supranuclear densities, and so the strong interactions among nuclei cannot be neglected. Unlike for white dwarfs where Maxwell theory is sufficient, neither field equations nor a theoretical description of bulk matter exist for such large densities. Moreover, there is no hope in the near future for laboratory experiments at these pressures. Various phenomenological attempts to estimate the neutron star mass have shown that this could be quite sensitive to strong interactions. If a factor 2 could easily exist, why not a factor 10 or even larger? The formation of a black hole would be avoided by masses less than some critical mass, but the value for this was unknown.

For this reason Clifford Rhoades and I (Rhoades & Ruffini, 1971) used an alternative approach to determine from first principles an absolute upper limit to the neutron star mass. We adopted three criteria: the correctness of general relativity; the existence of a fiducial density up to which a reliable equation of state maximizing the critical mass could exist; and non-violation of causality. For supranuclear densities we assumed an equation of state consistent with causality and the Le Chatelier principle. The proof involved the introduction of a variety of extremization techniques. Particularly helpful was the concept of the *domain of dependence* for the values of the critical mass as a function of the chosen fiducial density as introduced in my Les Houches lectures (see page R29 in Ruffini, 1973). The absolute upper limit to the neutron star critical mass was found to be $3.2M_{\odot}$. All observed neutron star masses until today are well within this limit.

Also in my Les Houches lectures, I introduced the concepts of alive black holes and dead black holes, differentiating the ones with charge and angular momentum from the ones uniquely characterized by their irreducible mass.[1]

[1]The Les Houches school represented a moment of great scientific tension and in fact signaled a division in black hole research. My work on alive black holes encountered strong resistance by Kip Thorne and his group, and also Jacob Bekenstein, presenting a report on his recently discussed Ph.D. thesis in an informal seminar, received strong criticisms from Stephen Hawking, although he was later to change his mind (Bekenstein, 2006).

8 The UHURU satellite

The launch of the UHURU satellite in 1971 by the group directed by Riccardo Giacconi meant that the universe could be examined for the first time in the X-ray band of the electromagnetic spectrum. It was a fundamental leap forward, creating a tremendous surge in relativistic astrophysics. Simultaneous observations of astrophysical objects could now be made in X-ray wavelengths by UHURU in space and in optical and radio wavelengths by ground based observatories. This unprecedentedly large collaboration generated high quality data on those binary systems where a normal star is stripped of matter by a compact massive companion star, either a neutron star or a black hole.

We had just published our article in Physics Today when Gloria Lubkin, its editor, told me at a Washington meeting of the American Physical Society; "You should listen to Riccardo Giacconi's talk. He claims to have observed some of the phenomena forecast by Wheeler and yourself in your article"[1].

I still recall how our almost daily discussions on the Uhuru observations strongly motivated me to find a method to discriminate between neutron stars and black holes as binary X-ray sources. Following the work with Clifford Rhoades, we were ready to establish the basic paradigm for distinguishing between them.

The observations by Riccardo and his team clearly gave the first unambiguous evidence for the discovery of neutron stars accreting matter from stars evolved out of the main sequence (see Figure 8.1). Soon after, important contributions on the accretion were presented by Shakura (1972a,b). The two X-ray pulsating sources Hercules-X1 and Centaurus-X3 were typical examples of this phenomenon. All the characteristic parameters of these binary sources could be derived from the data (see R. Giacconi, pages 17–42, in Giacconi & Ruffini, 1978). ¿From the binary period and the Doppler velocities of the main sequence star and from the pulsed X-ray emission of the neutron star it was possible to calculate the neutron star masses for the first time. These proved to be systematically lower than our absolute upper limit of $3.2M_{\odot}$. Hercules-X1 and Centaurus-X3 were crucial in differentiating these binary systems from pulsars. Unlike pulsars with their monotonically increasing

[1] That was the first time I met Riccardo. I did not know until years later that he was born in Italy and that he got his doctorate at the University of Milan, and for some years I did not realise that he knew Italian. It was only through a rather unorthodox New Year greeting that I found out that he did indeed speak the language. By that time, our collaboration with him and Herbert Gursky, a member of his group, had become very intense.

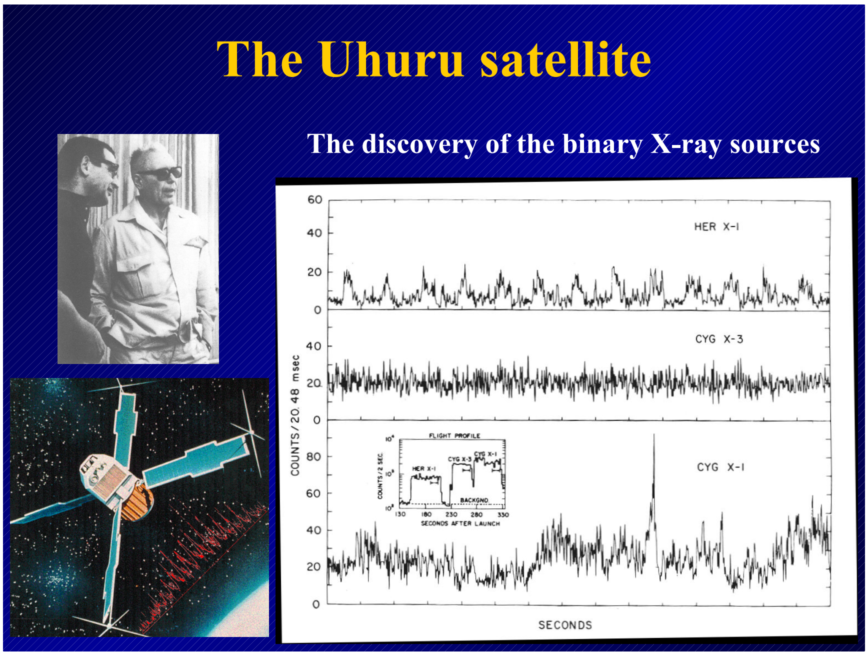


Figure 8.1: On the left side, Riccardo Giacconi and Luigi Broglio (above) at the launch of the Uhuru satellite (below) from the S. Marco platform. On the right side, the time variability of Hercules-X1 compared and contrasted with Cygnus-X1.

pulsation periods, these sources had fluctuating ones (see e.g. Gursky & Schreier, pages 175–220, and Figure 10 in Gursky & Ruffini, 1975). It was clear that the rotational energy, used previously as an explanation of the energetics of pulsars, could not be significant for these systems. The source of the very large X-ray luminosity, up to 10^{37} erg/s (i.e. 10^4 solar luminosity), had to be accretion in the deep gravitational well of a neutron star. For the first time we were witnessing direct evidence for the role of gravitation as the energy source of an extremely energetic astrophysical system!

We were then ready to establish the paradigm for the identification of Cygnus-X1 as the first "black hole". This was observed to be (see Figure 8.1) a nonpulsating source with significant time structure as short as a few milliseconds. I identified three essential steps to strengthen this identification:

1. The "black hole uniqueness theorem" implies axial symmetry and the absence of regular pulsations from black holes. However, although this is true for a black hole, it is also true for a neutron star provided that its magnetic field, if any, is aligned with its rotation axis.

2. The "effective potential technique", see Figure 2.2, shows that the percentage of the body's rest energy released by accretion is at most 1% for neutron stars but as much as 42% for an extreme Kerr black hole. This

clearly proves the importance of gravitational energy as a generator for binary X-ray sources. Again, this is equally true for either neutron stars or black holes; only the efficiency factor is different. The accretion observed in all binary systems can therefore adequately explain their X-ray emissions.

3. The "upper limit on the maximum mass of a neutron star" was indeed the crucial discriminating factor between non-magnetized neutron stars and black holes. If the gravitationally collapsed star in a binary X-ray source is non-pulsating, emits X-rays by accretion, and has a mass larger than 3.2 solar masses, then it must be a black hole.

These results were announced in a widely attended session chaired by John Wheeler at the 1972 Texas Symposium in New York. The evidence for Cygnus-X1 being a black hole was presented and was extensively reported in the New York Times[2]. The New York Academy of Sciences, which hosted the Texas Symposium, had just awarded me their Cressy Morrison Award for my work on neutron stars and black holes. Much to their dismay I did not submit a paper for the proceedings of this conference, the reason being that the substance of my talk at the Texas Symposium was recorded in a Letter that had just been submitted to Ap.J. with Robert Leach, a Princeton undergraduate (see Figure 8.2 and Leach & Ruffini, 1973).

The formulation of this paradigm did not come easily but slowly matured after innumerable discussions with R. Giacconi and H. Gursky, both face to face and over the phone. I still remember an irate professor of the Physics Department at Princeton pointing out at a faculty meeting my outrageous phone bill of $274 for one month, a scandalous amount for those times. Its size was largely due to my frequent calls to the Smithsonian. Fortunately, the department chairman, Murph Goldberg, had a much more relaxed and sympathetic attitude about this situation.

The results were summarized in my talk at the Sixteenth Solvay Conference on Astrophysics and Gravitation, held at the University of Bruxelles in 1974, and were expanded in the 1975 Enrico Fermi Varenna Summer school directed by Riccardo Giacconi and myself. The title of the school was "On the Physics and Astrophysics of Neutron Stars and Black Holes". The proceedings were published in both hardcover and paperback, and are to be reprinted soon. The conclusion of the story of this great scientific adventure was well told by Riccardo in his Nobel lecture in Stockholm (see Giacconi, 2002 and also Giacconi, 2005).

[2]The acceptance of our paradigm was far from unanimous at this time. Some astrophysicists who were initially amongst my strongest and most irate public objectors later became fervent supporters of my ideas. However, not all of them remembered to quote my results later!

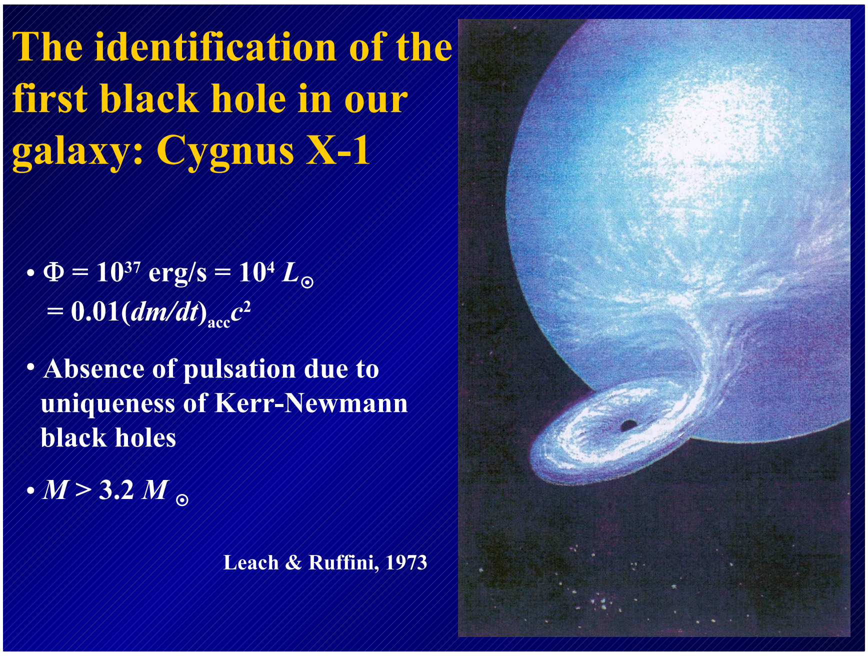


Figure 8.2: The identification paradigm for Cygnus-X1 vs. a pictorial representation of Cygnus-X1 and the companion star HDE-226868, whose binary nature was precisely pointed out by Webster & Murdin (1972); Bolton (1972a,b).

Black holes have played an essential though passive role in these accretion processes, providing the deep potential well used to release the observed X-ray flux. We had to find a different astrophysical system where black holes could play an active role if we were to extract energy from them. This has been my main goal in recent years as I will explain shortly.

9 Astrophysical "Tokomak" machines

Much attention was still being given in those days to the analogy I have already mentioned between black hole physics and the usual laws of thermodynamics. Following Bekenstein (1973, 1974), Stephen Hawking went a step further (Hawking, 1974, 1975, 1976). He proposed that a black hole radiates with a black body spectrum whose temperature T is defined as the surface gravity a the horizon multiplied by the Planck length squared and divided by 2π. The Hawking idea was of great conceptual interest. As Jacob recalls in his recent book (Bekenstein, 2006), I was concerned about the initial formulation of this program of research[1].

Anyway, I was not personally very much interested in these processes since they were of marginal interest in relativistic astrophysics. I summarized this point of view in my Varenna lectures (see R. Ruffini, pp. 324–325 in Giacconi & Ruffini, 1978) and, more recently, in Table 1 at p. 788 of Ruffini (2001b). I then turned to the physical processes which might use black holes as realistic sources of energy for astrophysical processes by using their extractable rotational or electromagnetic energy, what we call today the "Blackholic" energy[2]. We first focused on processes which use predominantly the rotational energy. This process can provide as much as 29% of the mass energy of an extreme Kerr black hole (see Eq. (5.0.2),(5.0.4)). Together with Jim Wilson, we gave a simple analytic example of a Kerr black hole accreting magnetized plasma (see Figure 9.1 and Ruffini & Wilson, 1975). We studied the entire electrodynamical system of currents for such an astrophysical circuit (see Figure 9.2) as well as the general conditions for stability of an accreting plasma in the field of a black hole (Damour et al., 1978). Particularly important were the contributions, motivated by our work, on the torque and momentum transfer in accreting black holes (Damour, 1975), which introduced the lines of currents reproduced in Figure 9.2. Further results, fundamental for the black hole thermodynamics, were presented by Thibault on the black hole eddy currents (Damour, 1978) and on the surface effects in black hole physics (Damour, 1982).

Our paper with Jim was soon followed by a similar paper by Blandford &

[1] Recently, I have been reconsidering some aspects by integrating the equations of a specific example (Ruffini & Vitagliano, 2003).

[2] This word is the English translation for the Italian word *energia buconerale*, suggested by Iacopo Ruffini, unhappy to hear continuously the wording "extractable energy from black

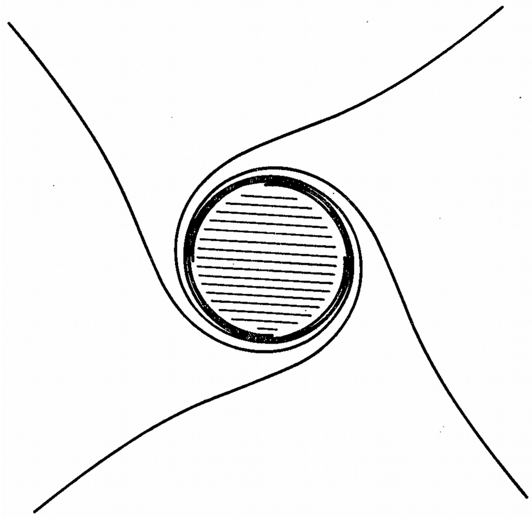


Figure 9.1: Magnetic lines of force in the equatorial plane of a maximally rotating Kerr black hole accreting magnetized plasma. The winding of the lines of force is due to the dragging of inertial frames. Details in Ruffini & Wilson (1975).

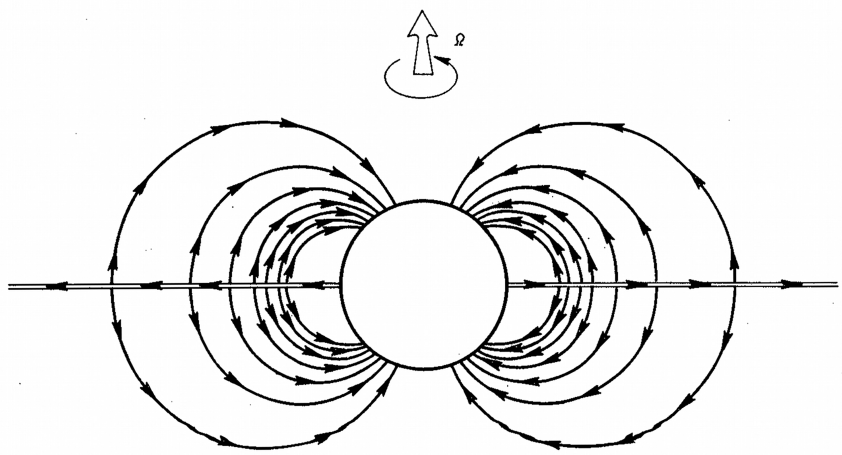


Figure 9.2: Lines of currents for the magnetosphere showed in Figure 9.1. Details in Giacconi & Ruffini (1978), pages 338 and following.

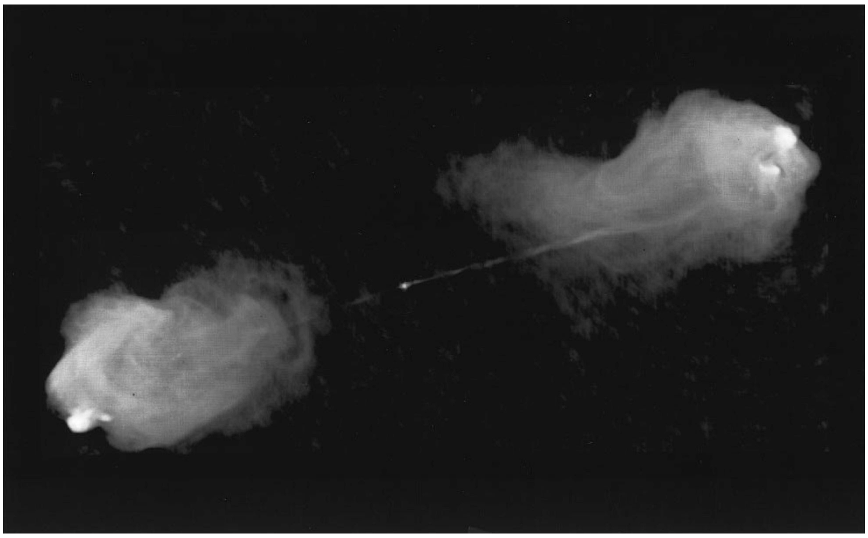


Figure 9.3: A greyscale representation of the image of Cygnus A at 5 GHz with 0.4 in. resolution made with the Very Large Array in Socorro, NM. The full source extent is 120 arc sec = 120 kpc. North is at the top and west is to the right. Reproduced from Carilli et al. (1998).

Znajek (1977) and later by another series of articles by Punsly, and by Punsly and collaborators (see e.g. Punsly, 2001, and references therein). These works promised to help explain extragalactic radio jets. The characteristic time scale for this energy extraction process is typically millions of years (see Figure 9.3) as can be deduced from the size of the radio lobes and jets in extragalactic radio sources. It is most interesting that recent radio observations made by the Westerbork Synthesis Radio Telescope on Cygnus-X1 have evidenced the existence of a jet in such a system (see Figures 9.4, 9.5, details in Gallo et al., 2005). The lifetime of such a jet has been estimated to be $\sim$ 0.02–0.32 Myr, which is comparable with the estimated age of the progenitor of the black hole in Cygnus-X1 (see Mirabel & Rodrigues, 2003). The total power dissipated by the jets of Cygnus-X1 in the form of kinetic energy has been estimated to be as high as the bolometric X-ray luminosity of the system (Gallo et al., 2005). It is then fair to say that Cygnus-X1 is even more interesting than what we understood in 1974. It is, beyond any doubt, a Kerr black hole, since we see an active process of rotational energy extraction by the jets, as given by Eq. (5.0.2).

We looked then to the extraction of electromagnetic energy. This process can provide as much as 50% of the mass energy of an extreme Kerr–Newman black hole (see Eq. (5.0.2), (5.0.4)). What is even more important is that this electromagnetic energy can be released in a very short time, of the order of a second. This clearly contrasts with the rotational energy extraction process

holes".

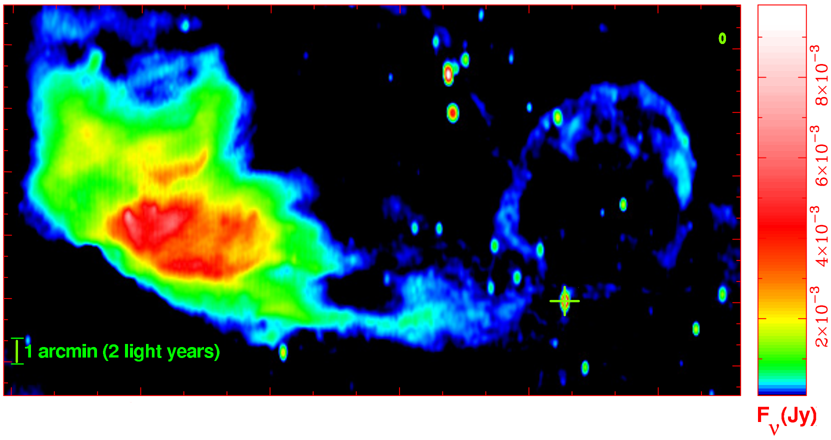


Figure 9.4: The cross marks the location of the black hole Cygnus-X1 in this radio image. The bright region to the left (east) of the black hole is a dense cloud of gas existing in the space between the stars, the interstellar medium. The action of the jet from Cygnus-X1 has 'blown a bubble' in this gas cloud, extending to the north and west (right) of the black hole. Reproduced from Gallo et al. (2005).

which, as we have shown in the jets in galactic and extragalactic sources, systematically occurs on time scales on the order of millions of years. The electromagnetic blackholic energy release leads to unprecedented power and luminosity in astrophysics, second only to the Big Bang. As we show in the next chapter, this is fundamental for the explanation of GRBs.

It is very likely that GRBs would never have been detected without an outrageous idea put forward by Yakov Borisovich Zel'dovich. We had been close friends since September 1968, and I knew his very important contributions as inventor of the Katiuscia rockets and his later work with Andrei Sakharov on the Soviet A and H Bomb projects. I enjoyed many interesting and provocative discussions on relativistic astrophysics with Lifshitz, Ginzburg and him while visiting Moscow. His unpredictability and even irrationality had often surprised me (see Fig. 9.6). However, his proposal in the late fifties (see e.g. Foresta Martin, 1999) to show the clear dominance of the Soviet Union in space by having a rocket carry an atomic bomb to the moon and explode it on the lunar surface, was beyond belief! This would have been visible to a very large part of the world's population, all those facing the moon when the bomb went off. Fortunately, the proposal was not accepted, but it is very likely that it served as additional motivation for the United States of America to put a set of four Vela Satellites into orbit, 150,000 miles above the Earth. They were top-secret omnidirectional detectors using atomic clocks to precisely record the arrival times of both X-rays and γ-rays (see Figure 9.7). The direction of the source of the signals could then be calculated by triangulation. When they

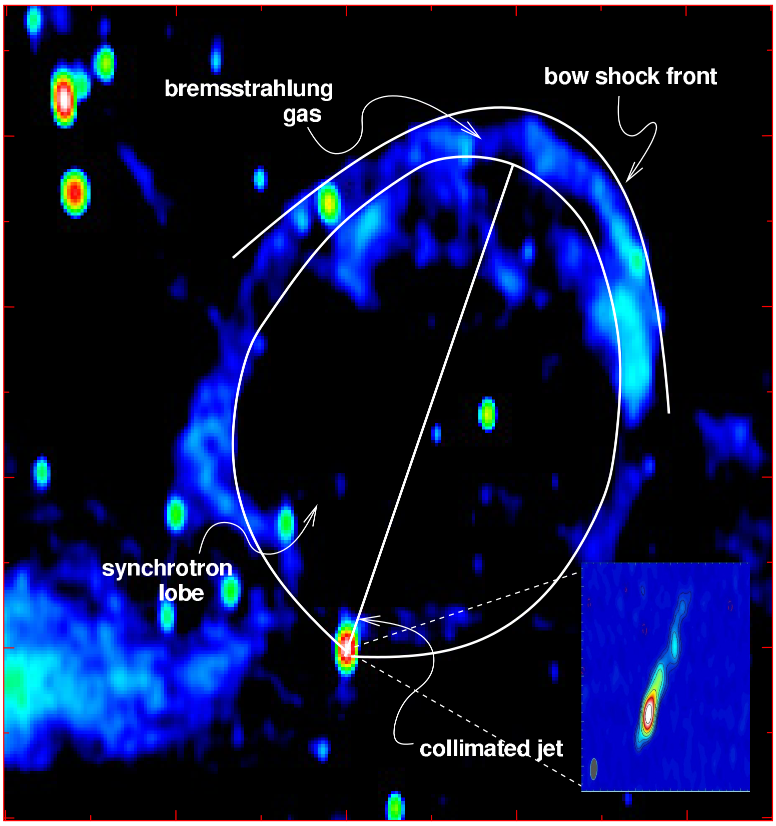


Figure 9.5: A model of how the black hole created the bubble. The black hole's powerful jet (seen separately in the inset) has been pushing on interstellar gas for about a million years. At the edges of the shell the interstellar medium is heated as the bubble rapidly expands. Reproduced from Gallo et al. (2005).

Figure 9.6: After approaching Pope John Paul II with an unidentified object concealed beneath his jacket, Zel'dovich produced a book of his collected papers, which he donated to the Pope. "Thanks" the Pope replied, to which Zel'dovich loudly responded "Not just 'thanks'! These are fifty years of my work!". The Pope kept Zel'dovich's collected papers (Zel'dovich, 1985) under his arm during the entire rest of the audience.

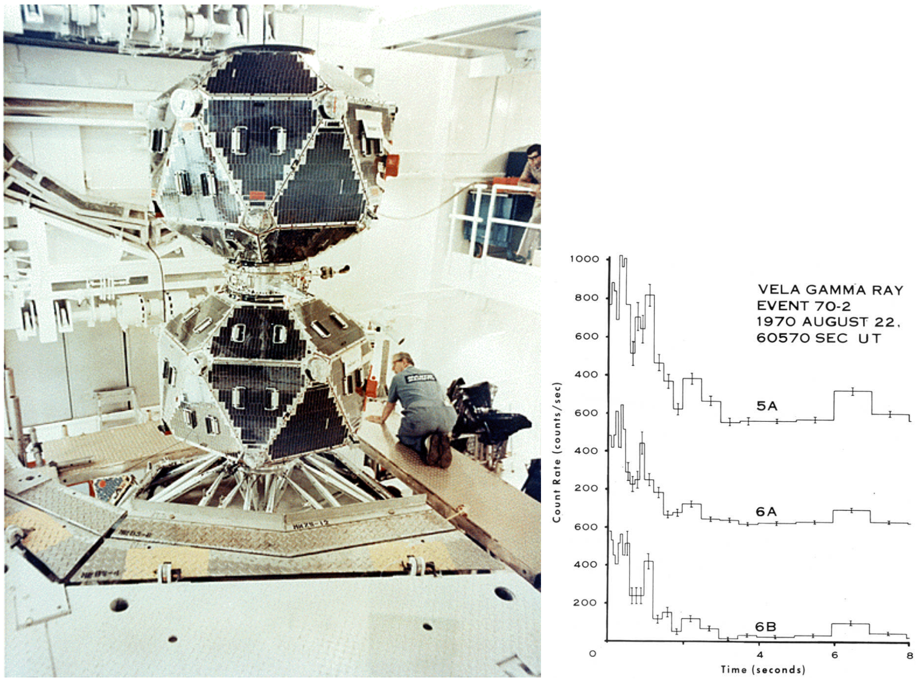


Figure 9.7: On the left the Vela 5A and 5B satellites and, on the right side, a typical event as recorded by three of the Vela satellites. Details in I. Strong in Gursky & Ruffini (1975).

were made operational they immediately produced results. It was thought at first that the signals originated from nuclear bomb explosions on the earth but they were much too frequent, one per day! A systematic analysis by the military showed that they had not originated on the earth, nor even the solar system. These Vela satellites had discovered GRBs! The first public announcement of this came at the AAAS meeting in San Francisco in a special session on neutron stars, black holes and binary X-ray sources, organized by Herb Gursky and myself (Gursky & Ruffini, 1975).

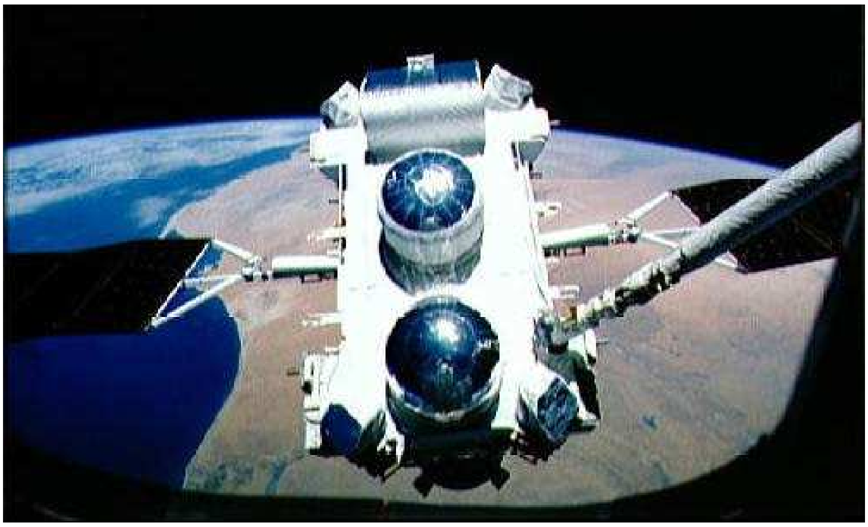
A few months later, Thibault Damour and I published a theoretical framework for GRBs based on the vacuum polarization process in the field of a Kerr–Newman black hole (Damour & Ruffini, 1975). We showed how the pair creation predicted by the Heisenberg–Euler–Schwinger theory (Heisenberg & Euler, 1935; Schwinger, 1951) would lead to a transformation of the black hole, asymptotically close to reversibility. The electron–positron pairs created by this process were generated by what we now call the blackholic energy. In that paper we concluded that this "naturally leads to a very simple model for the explanation of the recently discovered GRBs". Our theory had two very clear signatures. It could only operate for black holes with mass M_{BH} in the range 3.2–10^6 $M_\odot$ and the energy released had a characteristic

value of
$$E = 1.8 \times 10^{54} \frac{M_{BH}}{M_{\odot}} \text{ ergs} . \tag{9.0.1}$$
Since nothing was then known about the location and the energetics of these sources we stopped working in the field, waiting for a clarification of the astrophysical scenario. As Rashid Sunyaev mentioned to me at that time, "There are too many models for γ-ray bursts". I reproduced a limited list of them later (see Figure 11, page 787 in Ruffini, 2001b).

The mystery of these sources became even more profound as the observations of the BATSE instrument on board the Compton Gamma Ray Observatory Satellite (CGRO) proved the isotropy of these sources in the sky (see Figure 9.8). In addition to this data the CGRO satellite found an unprecedented number of GRBs and provided detailed information on their temporal structure and spectral properties (see Figure 9.9). All this was encoded in the fourth BATSE catalog (Paciesas et al., 1999). From the analysis there it soon became clear that there were two distinct families of GRBs; the short bursts lasting less than one second and harder in spectra, and the long bursts lasting more than one second and softer in spectra (see Figure 9.10).

The situation changed drastically with the discovery of the "afterglow" of GRBs (Costa et al., 1997) by the joint Italian-Dutch satellite BeppoSAX (see Figure 9.11). This X-ray emission lasted for months after the "prompt" emission of a few seconds duration and allowed the GRB sources to be identified much more accurately. This then led to the optical identification of the GRBs by the largest telescopes in the world. These had just become operative and included the Hubble Space Telescope, the KECK telescope in Hawaii and the VLT in Chile. Also, the very large array in Socorro made radio identification possible. We have recalled how the interplay between the X- and γ-ray satellites in space and the optical and radio observatories on the ground had been a major factor in the study of binary X-ray sources. This collaboration occurs now on a much larger scale for GRBs, thanks to the use of Space observatories like Chandra and XMM, dedicated space missions such as HETE and Swift and the unprecedented facilities on the ground. The first distance measurement for a GRB was made in 1997 for GRB970228 and the truly enormous energy of this was determined to be 10^{54} ergs per burst. This proved the existence of a single astrophysical system emitting as much energy during its short lifetime as that emitted in the same time by all other stars of all galaxies in the Universe![3]. It is interesting that this "quantum" of astrophysical energy coincided with the one Thibault Damour and I had already predicted, see Eq. (9.0.1). We clearly imagined much stronger opposition to the concepts of this model from the establishment, possibly even stronger than that already encountered for the identification of Cygnus-X1 as a black hole. Once again,

[3]Luminosity of average star = 10^{33} erg/s, Stars per galaxy = 10^{12}, Number of galaxies = 10^{9}. Finally, $33 + 12 + 9 = 54$!



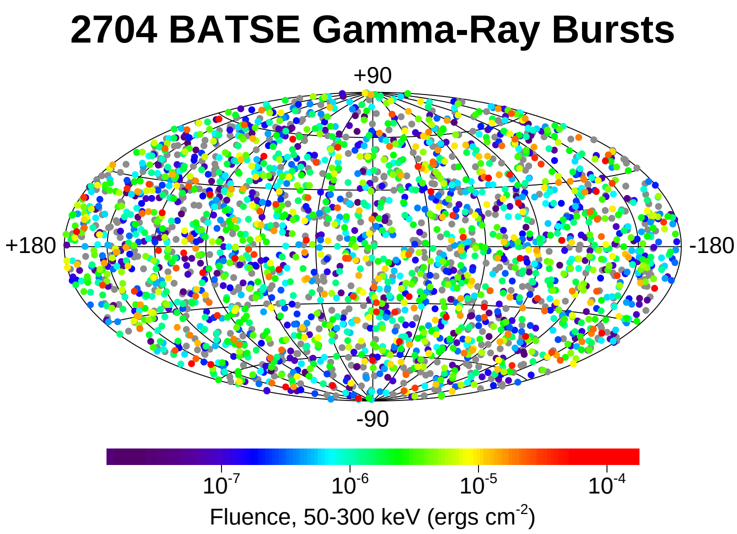


Figure 9.8: The CGRO satellite and the position in the sky of the observed GRBs in galactic coordinate. Different colors correspond to different intensities at the detector. There is almost perfect isotropy, both in the spatial and in the energetic distribution.

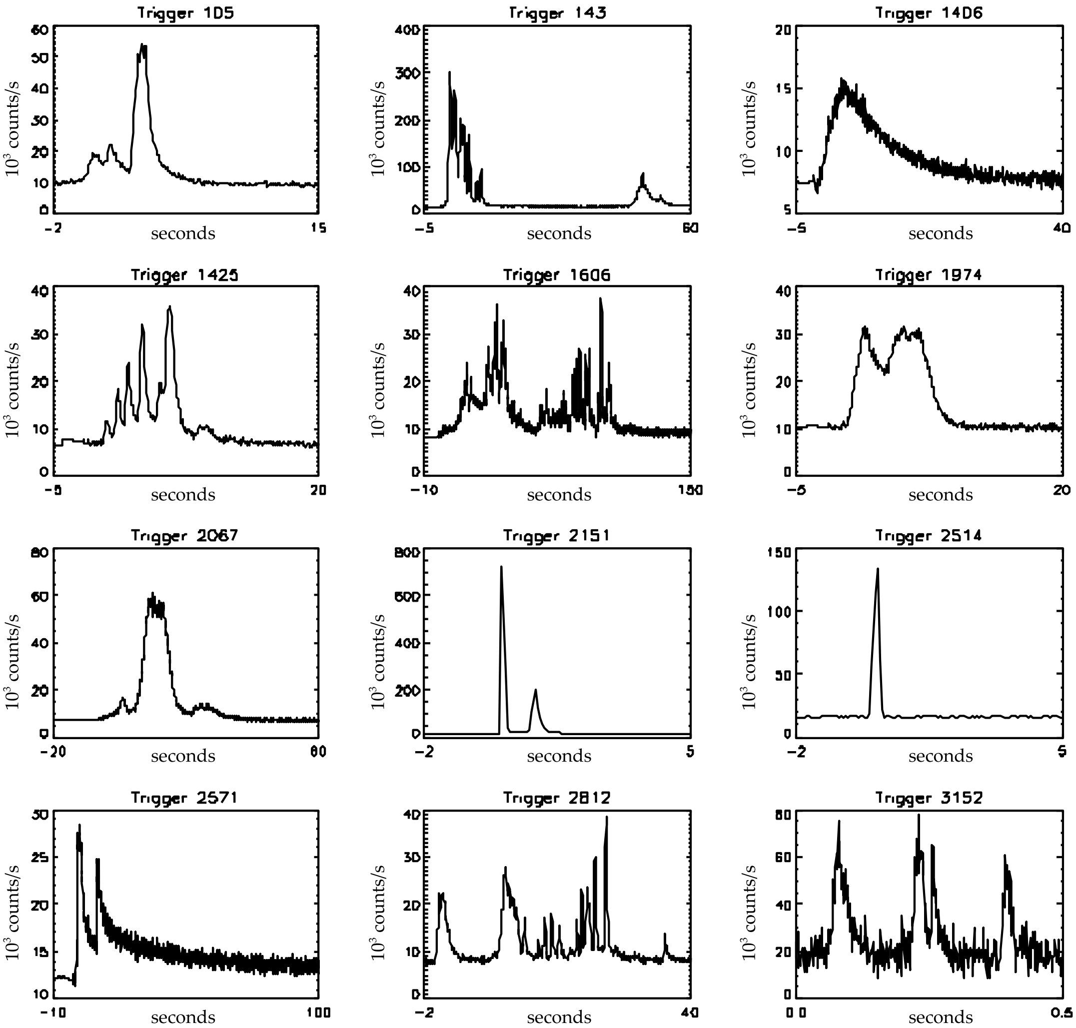


Figure 9.9: Some GRB light curves observed by the BATSE instrument on board of the CGRO satellite.

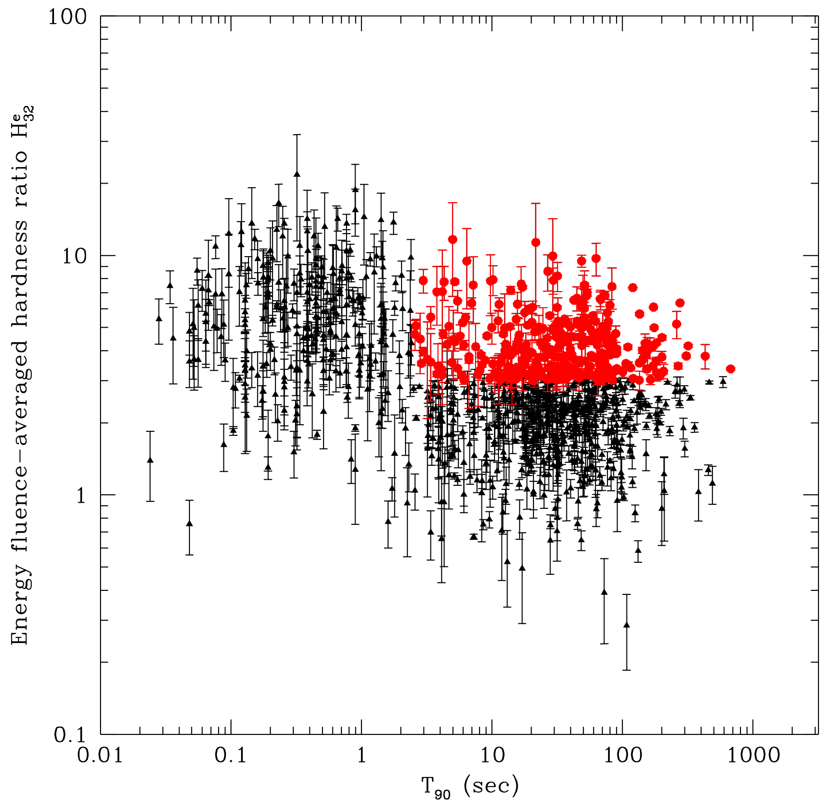


Figure 9.10: The energy fluence-averaged hardness ratio for short ($T < 1$ s) and long ($T > 1$ s) GRBs are represented. Reproduced, by his kind permission, from Tavani Tavani (1998) where the details are given.

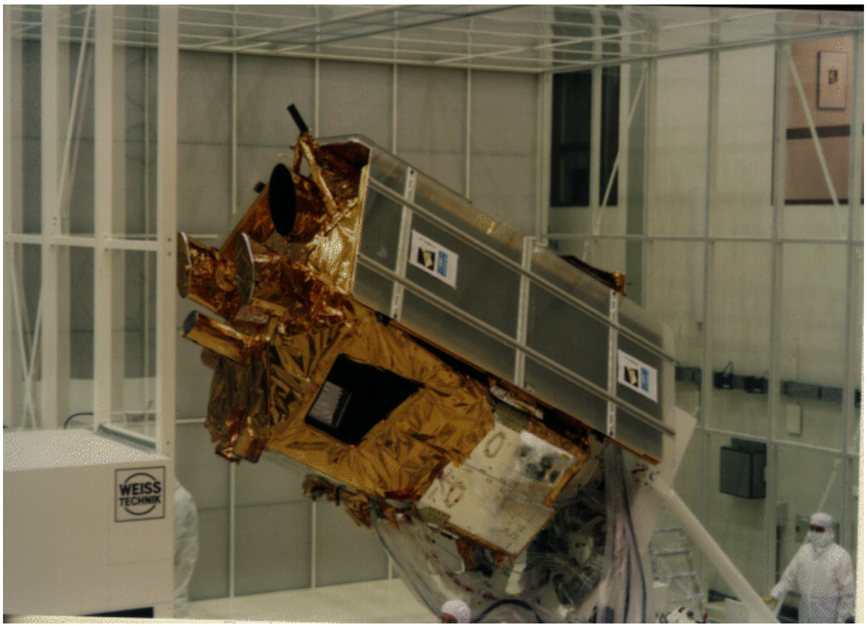


Figure 9.11: The Italian-Dutch satellite BeppoSAX (here represented) encountered enormous financial difficulties. In spite of this, BeppoSAX was ultimately a success, and achieved one of the most important discoveries ever in the field of astrophysics: the discovery of the GRB afterglow.

our imaginations have been too conservative.

10 Physics versus astrophysics

Among the many crucial advances made in physics, relativistic field theories and astrophysics that the 20^{th} century has been rich with, two fruitful contributions will be remembered for their manifold consequences: the Dirac theory of the electron and the Kerr–Newman geometry. There are some analogies between these two discoveries.

The Dirac theory:

1. introduced for the first time the concept of the spin of an elementary particle in Minkowski space, gave the mathematical tools for developing such a study, and produced an enormous set of predictions and experimental verifications in the field of atomic physics;

2. predicted the matter–antimatter solutions which were splendidly confirmed by the discovery of the positron (Anderson, 1933); and

3. together with the works of Heisenberg & Euler (1935) and Schwinger (1951), lead to the concepts of vacuum polarization and the creation of electron–positron pairs in extreme electromagnetic fields. These have still not been observed, in spite of more than fifty years of repeated attempts in the leading high energy physics laboratories worldwide (Ruffini, Vitagliano & Xue, 2007).

The Kerr–Newman solution:

1. is the exact mathematical solution corresponding to a spinning black hole satisfying the Einstein-Maxwell equations, generalizes to curved spacetimes the concepts of matter–antimatter solutions (see e.g. Deruelle, 1977; Damour, 1977) and has the same gyromagnetic ratio as the electron (Carter, 1968);

2. has been observationally verified with the discovery of Cygnus-X1 (see e.g. Giacconi & Ruffini, 1978); and

3. provides a field around an incipient black hole in which the vacuum polarization process generates electron–positron pairs. This extracts the blackholic energy, thereby emitting an enormous number of electron–positron pairs during the final collapse to the black hole. Such emission appears to be the natural explanation for GRBs (Damour & Ruffini, 1975).

Physicists had previously explored the new physical regimes predicted by the Dirac theory and compared their conclusions with the results of especially conceived experiments in high-energy laboratories on the ground. In such an approach, when the theoretical predictions are confirmed by a comprehensive set of experiments the great moment of discovery has occurred.

In astrophysics the situation is apparently different from that in particle physics. We cannot reproduce the experimental conditions in a laboratory because of the size of the systems involved. We have to use the entire universe instead by selecting among the billions of events those specific ones where the process we are interested in occur, and then compare these with the theoretical predictions. When these agree that most exciting moment of discovery occurs again. All this is no different from an experiment done in the laboratory. In both cases there is a selection of the natural phenomena to be observed.

There is another difference between the approaches of physicists and some astrophysicists. The latter have purported to examine and justify the origins of the theory itself, instead of looking at the predictions of the theory and their verification by experiment or observations. Such an epistemological approach may appear to be tautological. If one were to take seriously such an approach by asking how an electron is born or why the Dirac equations apply one would need a unified field theory and possibly all its fundamental interactions. Such a theory, in turn, would be inconceivable without the knowledge gained by the theoretical studies of the Dirac equation and its experimental verification. Fortunately such an approach was never considered by those pragmatic physicists who have received the deserved rewards of their many fundamental discoveries (Dirac himself, Dyson, Feynman, Fermi, Lamb, Segré, etc.).

Paradoxically such an approach is gaining some proselytes in the astrophysical community. Our group, which initially included Natalie Deruelle and Thibault Damour, studied the Kerr–Newman metric using an approach similar to that in theoretical physics. We trusted the predictions of the equations more than the qualitative feelings of imagination. We studied the theoretical consequences of the Kerr–Newman black hole, a solution originating from the coupling of the Einstein and Maxwell equations, by far the most successfully tested theories in all of physics. We shall show in the following how we have been successful in applying these concepts to GRBs. Pressure has been mounting on us to provide a detailed model for the black hole formation. We have taken such a request positively, as a stimulus to reach a deeper understanding of the process of gravitational collapse leading both to the formation of black holes and to the quite different phenomenon of supernovae explosions, which we recall are also still far from being understood (Mezzacappa & Fuller, 2006). Just as for Dirac electrons, it is harder to explain the birth of black holes than it is to explain their observed activities by the theory. Only through an understanding of the GRB phenomenon will we gain information on possible precursors to black holes and how they form. Specifically, in the case of GRBs we believe that there is theoretical evidence not for just one but for a variety of GRB precursors. From the recent progress in understanding GRBs, we are confident that we are close to understanding the formation of Kerr–Newman black holes (see e.g. Ruffini, 2006). This progress will also help to clarify some crucial unexplained features of the gravitational collapse of stars in the range between $3.2M_{\odot}$ and $100M_{\odot}$.

It is interesting that if one turns for a moment to larger black holes, originating in active galactic nuclei and expected to be at least a million solar masses, the situation is equally disappointing from the point of the above mentioned epistemological approach. As of today, there is no explanation for the birth of these maxi black holes. A likely possibility is that the "inos" explaining the dark matter of the host galaxy may form a relativistic cluster in the galactic core, leading to the formation of the black hole (Arbolino & Ruffini, 1988; Merafina & Ruffini, 1989, 1990, 1997; Bisnovatyi-Kogan et al., 1998). The absence of a generally accepted mechanism for their formation should certainly not preclude the study of black holes, possibly charged, to help us understand active galactic nuclei. It would be scientifically unreasonable to stop this work until these somewhat epistemological demands can be answered[1].

Having said this let us go to a quick outline of the work we did on Kerr–Newman geometries and their dyadospheres.

[1] There has been a recent attempt to deny the astrophysical relevance of vacuum polarization processes around a Kerr–Newman black hole by "proving" a no-go theorem for them. This proof consists of setting up a particular "straw man" and then demolishing it, hardly a proof of anything! No-go theorems are often used in physics but to be useful they must be proven results following from a clearly stated set of assumptions which then limit their domain of application. In this specific case the no-go theorem does not appear to have any validity since the counterexample created contradicts known physical facts and violates both energy conservation and causality (see Page, 2006 and the reply in Ruffini, Bianco & Xue, 2007).

11 The concept of the dyadosphere

The evidence for the existence of GRBs with energies predicted by Eq. (9.0.1) convinced us to carefully analyze the vacuum polarization process leading to the creation of an electron–positron pair plasma in the field of a black hole. This pair creation process occurs in an electric field close to the critical value,

$$E_c = \frac{m^2 c^3}{e\hbar} = 1.32 \times 10^{16} \mathrm{V/cm}\,, \tag{11.0.1}$$

where m and e are the electron mass and charge. In Minkowski space, tunneling occurs between the matter–antimatter solutions of the Dirac equation (see Heisenberg & Euler (1935); Schwinger (1951)) leading to pair creation rate that can be expressed in analytic form. Such a treatment has been generalized to the curved spacetime of a Kerr–Newman solution by Damour & Ruffini (1975). The concept of "dyadosphere", which comes from the Greek "*δυάς, δυάδος*" for "pairs", was initially introduced in Ruffini (1998) (see also Preparata, Ruffini & Xue, 1998). For simplicity, and yet to illustrate the basic gravitational and electrodynamical processes, a Reissner-Nordström black hole was assumed. The region outside the horizon where the electric field strength is larger than the critical value was given by Eq. (11.0.1). Clearly, this work excludes neither a more general metric nor the pair creation process in under-critical fields, *a priori*.

In the meantime, the dyadosphere concept has evolved in three major ways. They can occur in a variety of conditions, such as neutron star collapses, highly rotating and magnetized neutron stars and in Kerr–Newman spacetimes. The concept of "dyado-torus" was also introduced to take into account the presence of angular momentum (see Figure 11.1 and, e.g., Ruffini, Vitagliano & Xue, 2007, and references therein).

Since the work of Khriplovich (2000), dyadospheres have been considered with an electric field $E < E_c$. These turned out to be optically thin and characterized by emission of $\sim 10^{21}$ eV particles. They are possibly relevant to Ultra High Energy Cosmic Rays (UHECRs, see e.g. Damour & Ruffini, 1975; Chardonnet et al., 2003). These "under-critical" dyadospheres became an interesting complement to the "over-critical" ones, where $E > E_c$. These are initially optically thick and lead to an ultra-relativistic GRB afterglow, emitting radiation in both X- and γ-rays (Ruffini & Vitagliano, 2002; Ruffini, 2006).

Since 2002, we have considered the dynamical formation of a dyadosphere during gravitational collapse to a black hole. To generate the accelerations

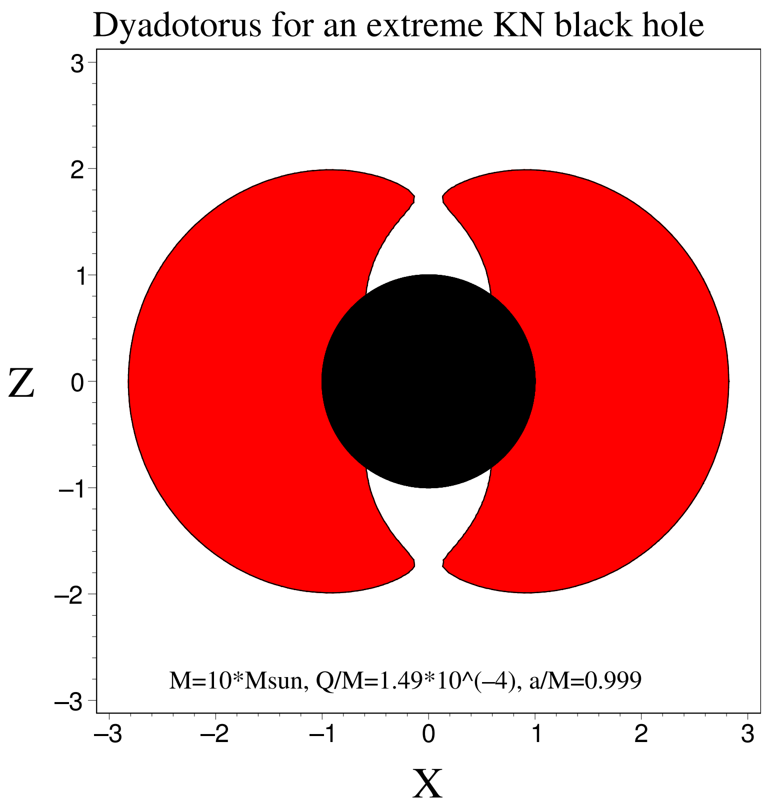


Figure 11.1: The “dyado-torus” is the region outside the horizon of a Kerr–Newman black hole, where the electrodynamical processes generates electron–positron pairs by vacuum polarization processes. Details in Cherubini et al. (2007).

required by GRBs we restricted ourselves to optically thick dyadospheres. We found an explicit analytic treatment for an over-critical field self-sustained over the macroscopical astrophysical time scale of the gravitational collapse and creating an over-critical dyadosphere. To obtain such, we used a charged collapsing shell as our model. We only considered the regime in which the electric field is larger than the critical value given by Eq. (11.0.1). Starting from this assumed initial condition, we took into proper account:

1. the dynamics of the shell (Cherubini, Ruffini & Vitagliano, 2002);
2. the electromagnetic blackholic energy extraction processes (Ruffini & Vitagliano, 2002, 2003);
3. some of the collective effects of the plasma formed by the electron–positron pairs created by the vacuum polarization process, including their feedback on the electromagnetic field and corresponding polarization effects (Ruffini, Vitagliano & Xue, 2003a,b); and
4. especially the electron–positron plasma oscillations, described by the Vlasov–Boltzmann equation (Gatoff, Kerman & Matsui, 1987).

Consistent initial conditions were obviously necessary when solving the field equations. It was also necessary to identify the physical processes that occur in the progenitor star and lead to its gravitational collapse to a black hole. We have identified an appropriate set of initial conditions for the electrodynamical structure of neutron stars offering a natural explanation for the initial existence of an over-critical field. We have therefore given both the field equations and the initial conditions that describe the formation of an over-critical and optically thick astrophysical dyadosphere (see e.g. Ruffini, 2006; Ruffini, Rotondo & Xue, 2006a,b).

12 The dynamics of the electron–positron plasma

Our GRB model, like all prevailing models in the existing literature (see e.g. Piran, 1999; Mészáros, 2002, 2006, and references therein), is based on the acceleration of an optically thick electron–positron plasma (EPP). The specific issue of the origin and energetics of such an EPP, either in relation to black hole physics or to other physical processes, has often been discussed qualitatively in the GRB scientific literature but never quantitatively with explicit equations. The concept of the dyadosphere is the only attempt, as far as we know, to do this. This relates such an electron–positron plasma to black hole physics and to the characteristics of the GRB progenitor star, using explicit equations that satisfy the existing physical laws. Far from being just a formal theoretical work, this is essential to show that the physical origin and energetics of GRBs are the blackholic energy of the Kerr–Newman metric.

If we turn now to the accelerating phase of the electron–positron plasma, our analysis differs from the other ones in the current literature, in both the dynamics and evolution of such a plasma and the details of the transparency condition.

The dynamics of the EPP was considered by Piran, Shemi & Narayan (1993) using a numerical approach, by Bisnovatyi-Kogan & Murzina (1995) using an analytic one and by Mészáros, Laguna & Rees (1993) using one that was both numerical and semi-analytic. We studied it in collaboration with Jim Wilson and Jay Salmonson at Livermore. Numerical simulations were developed at Livermore and a semi-analytic approach was developed in Rome (Ruffini et al., 1999).

A conclusion common to all the treatments is that the EPP is initially optically thick and expands to very high values of the Lorentz gamma factor. A second common result is that the plasma shell expands in its co-moving frame and the Lorentz contraction is such that its width in the laboratory frame appears to be constant: the "Pair-Electro-Magnetic (PEM) Pulse".

In all treatments the EPP is assumed to have a baryon loading. This is acquired in our model when the pure EPP created in the dyadosphere expands to engulf the progenitor remnants. A new pulse is then formed with electron–positron–photons and baryons (PEMB Pulse, see Ruffini et al. (2000)), expanding until transparency is reached. At this point the emitted photons form what we define as the "Proper-GRB" (see Ruffini et al. (2001b)). The baryon loading is defined by a dimensionless quantity

$$B = \frac{M_B c^2}{E_{dya}}, \tag{12.0.1}$$

where E_{dya} is the energy of the pairs created in the dyadosphere, and M_B is the mass of the remnant. B and E_{dya} are the only two free parameters characterizing the source in our theory.

Differences exist between our description of the rate equation for the electron–positron pairs and the ones by the other authors. The analogies and differences have been given in Ruffini et al. (2006b); Bianco et al. (2006). From our analysis (Ruffini et al., 2000) it became clear that such expanding dynamical evolution can only occur (see Figure 12.1) for values of

$$B < 10^{-2}. \tag{12.0.2}$$

It follows that the collapse to a neutron star is drastically different from the collapse to a black hole leading to a GRB. Whilst in the former a very large amount of matter is expelled, in the latter the collapse process is smoother than any other one considered until today: almost 99.9% of the star has to be collapsing simultaneously

We summarize in Figure 12.2 some qualitative aspects of our model as well as the corresponding values of the Lorentz gamma factor as a function of the radial coordinate in the typical case of GRB991216 (Ruffini et al., 2003, 2005a). The self-acceleration phase ends at point 4 where the Proper-GRB (P-GRB) is emitted.

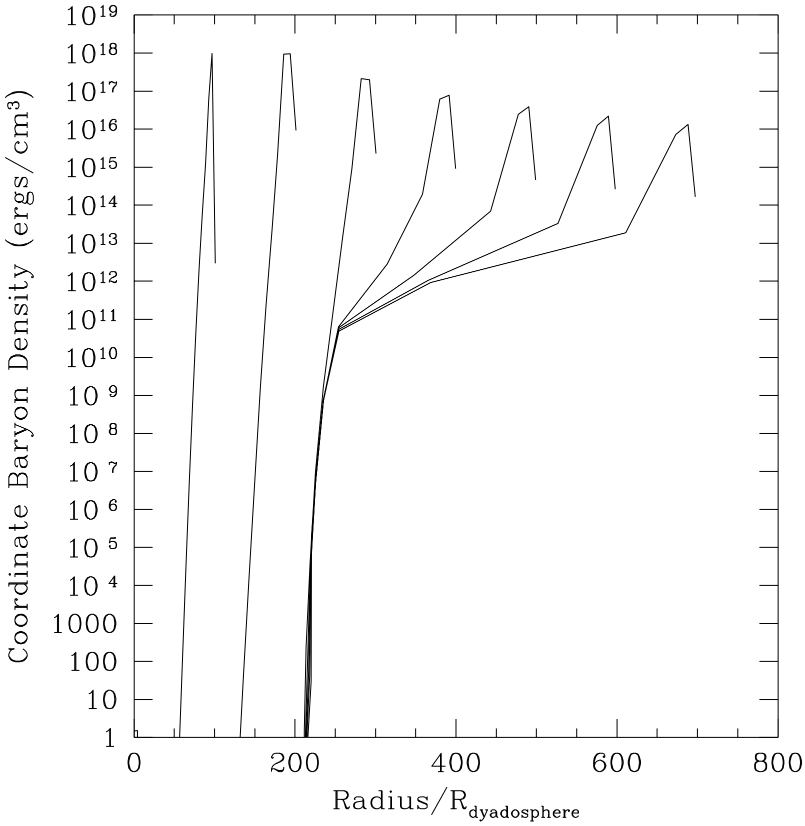


Figure 12.1: The expansion of the PEMB pulse corresponding to a baryon loading $B = 10^{-2}$ is represented as a function of the radial coordinate. The instability following the encounter of the baryonic component is manifest. Details in Ruffini et al. (2000).

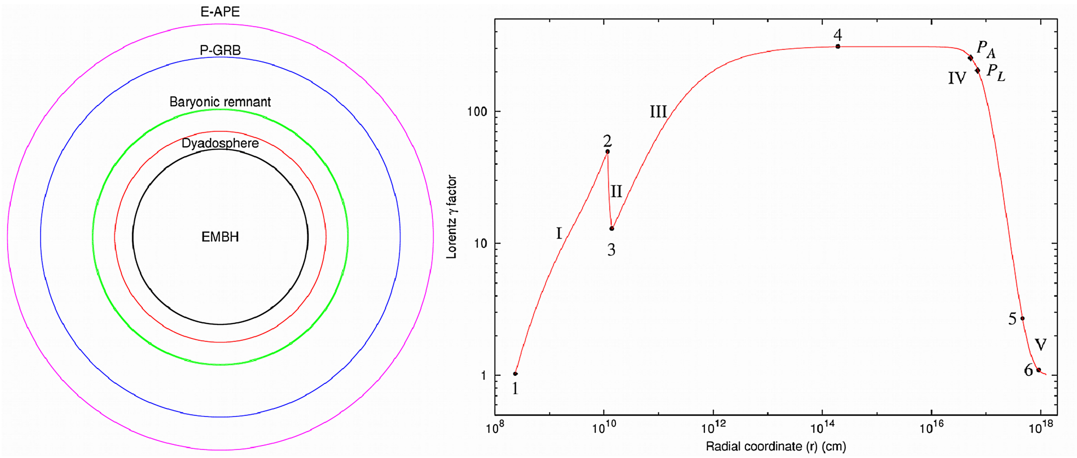


Figure 12.2: The GRB afterglow phase is represented here together with the optically thick phase for GRB991216. The value of the Lorentz gamma factor is given from the transparency point all the way to the ultrarelativisitc, relativistic and nonrelativistic regimes. Details in Ruffini et al. (2003).

13 The interaction of the accelerated baryonic matter (ABM Pulse) with the interstellar medium (ISM): the afterglow

After the plasma becomes transparent and the P-GRB is emitted, the accelerated baryonic matter (the ABM pulse) interacts with the interstellar medium (ISM). This creates the afterglow (see Figure 12.2). I shall first summarize the commonalities between our approach and the ones in the current literature. A thin shell approximation is used in both (see Piran, 1999; Chiang & Dermer, 1999; Ruffini et al., 2003, 2005a; Bianco & Ruffini, 2005b) to describe the collision between the ABM pulse and the ISM:

$$\begin{aligned} dE_{\rm int} &= (\gamma - 1)\, dM_{\rm ism} c^2 \,, && (13.0.1a)\\ d\gamma &= -\tfrac{\gamma^2-1}{M} dM_{\rm ism} \,, && (13.0.1b)\\ dM &= \tfrac{1-\varepsilon}{c^2} dE_{\rm int} + dM_{\rm ism} \,, && (13.0.1c)\\ dM_{\rm ism} &= 4\pi m_p n_{\rm ism} r^2 dr \,, && (13.0.1d) \end{aligned}$$

where $E_{\rm int}$, γ and M are respectively the internal energy, the Lorentz factor and the mass-energy of the expanding baryonic shell, $n_{\rm ism}$ is the ISM number density which is assumed to be constant, m_p is the proton mass, ε is the emitted fraction of the energy developed in the collision with the ISM and $M_{\rm ism}$ is the amount of ISM mass swept up within the radius r:

$$M_{\rm ism} = (4/3)\pi(r^3 - {r_\circ}^3) m_p n_{\rm ism}.$$

Here $r_\circ$ is the starting radius of the baryonic shell, i.e. the plasma transparency radius. $\varepsilon = 0$ ($\varepsilon = 1$) corresponds to the "adiabatic" ("fully radiative") condition (see, e.g., Bianco & Ruffini, 2005b).

In the current literature, following Blandford & McKee (1976), a so-called "ultra-relativistic" approximation $\gamma_\circ \gg \gamma \gg 1$ has been widely adopted to solve Eq. (13.0.1) (see e.g. Sari, 1997, 1998; Waxman, 1997; Rees & Mészáros, 1998; Granot, Piran & Sari, 1999; Panaitescu & Mészáros, 1998; Piran, 1999; Gruzinov & Waxman, 1999; van Paradijs, Kouveliotou & Wijers, 2000; Mészáros, 2002, and references therein). This leads to a simple constant-index power-law relation,

$$\gamma \propto r^{-a}\,, \tag{13.0.2}$$

with $a = 3$ for the fully radiative case and $a = 3/2$ for the fully adiabatic one. We have, instead, obtained the explicit analytic solution of the equations of motion for a shell with constant ISM density, in the entire range from ultra-relativistic to non-relativistic velocities. The resulting expressions, very different from the above power law, can be found in Bianco & Ruffini (2005b).

Knowledge of the equations of motion is essential for calculating the loci of source points of the signals arriving at the observer at the same time (Chandrasekhar, 1939), the "equitemporal surfaces" (EQTSs) . When these are compared to the approximate ones obtained in the current literature, a remarkable difference is found (see Figure 13.1 and Bianco & Ruffini, 2004, 2005a).

The most striking aspect of GRB theory is that these systems are among the very few in physics and astrophysics for which a completely detailed model can be computed in all its essential steps. The final result, however, depends crucially on the correctness of each theoretical step. All the GRB's observational properties are a function of the EQTSs, and all the observables must be calculated correctly.

I shall now turn to the last distinguishing feature between our theoretical model and the other ones in the current literature. We have proposed that the X- and γ-ray radiation has a thermal spectrum in the co-moving frame during the entire afterglow phase (Ruffini et al., 2004). This follows an idea of Fermi, used to calculate a possible thermodynamic limit for high energy collisions between elementary particles. This thermalization procedure is justified for GRBs by recognizing that the ISM density is inhomogeneous. It has a filamentary structure with a density contrast $\Delta\rho/\rho$ as large as 10^9 (Ruffini et al., 2005b). The temperature is given by:

$$T_s = \left[\Delta E_{\rm int} / \left(4\pi r^2 \Delta\tau\sigma\mathcal{R}\right)\right]^{1/4}\,, \tag{13.0.3}$$

where $\Delta E_{\rm int}$ is the internal energy developed in the collision with the ISM in time interval $\Delta\tau$ in the co-moving frame, σ is the Stefan–Boltzmann constant and

$$\mathcal{R} = A_{eff}/A\,, \tag{13.0.4}$$

is the ratio between the "effective emitting area" of the afterglow and the surface area of radius r. This factor $\mathcal{R}$ has to take into due account both the ISM filamentary structure and any possible effect of fragmentation of the baryonic shell. These crucial steps lead to an evaluation of the source luminosity in a given energy band, essential for any comparison with the observational data. The source luminosity at detector arrival time t_a^d, per unit solid angle $d\Omega$ and

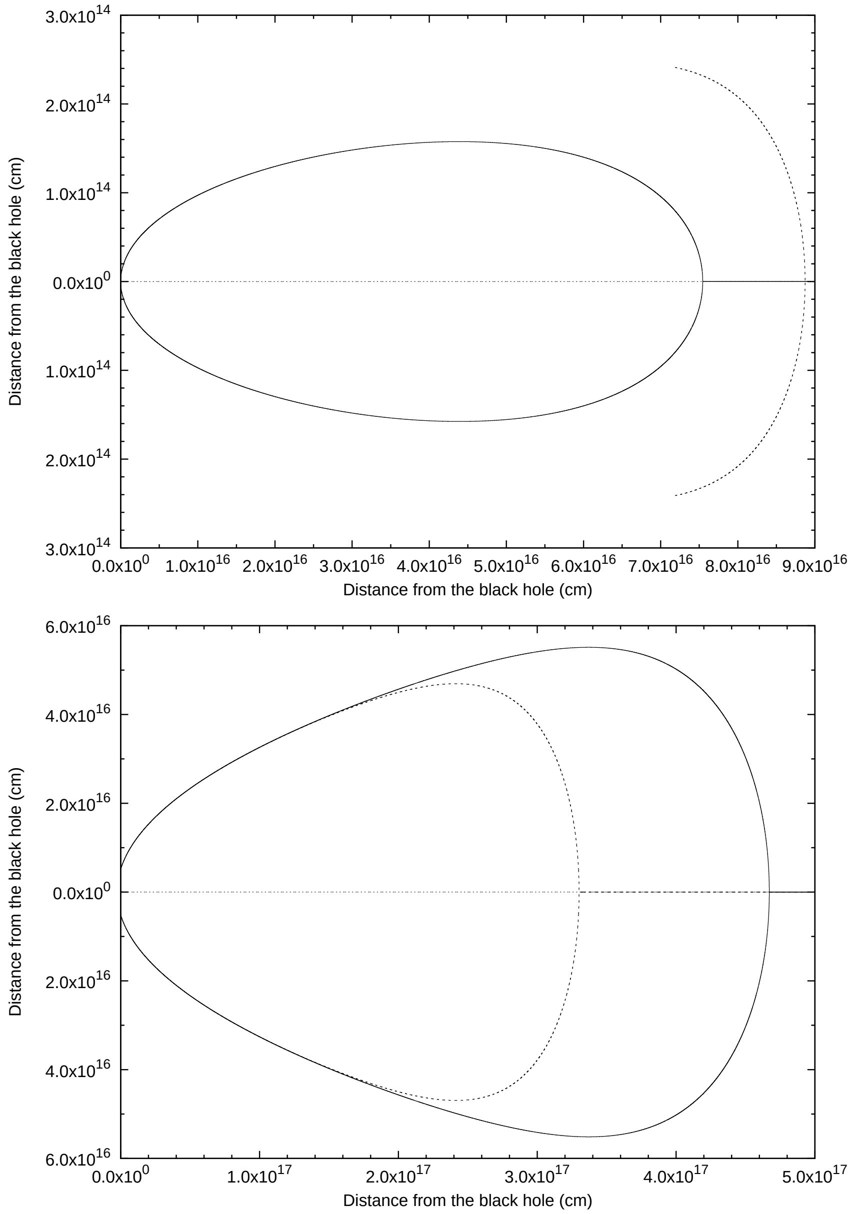


Figure 13.1: Comparison between the EQTSs computed using the approximate formulas given by Panaitescu & Mészáros (1998) (dotted line) in the fully radiative case and the corresponding ones computed using our exact solution (solid line). The upper (lower) panel corresponds to $t_a^d = 35$ s ($t_a^d = 4$ day). Details in Bianco & Ruffini (2004).

in the energy band $[\nu_1, \nu_2]$, is given by (see Ruffini et al., 2003, 2004):

$$\frac{dE_\gamma^{[\nu_1,\nu_2]}}{dt_a^d d\Omega} = \int_{EQTS} \frac{\Delta\varepsilon}{4\pi} \, v \, \cos\vartheta \, \Lambda^{-4} \, \frac{dt}{dt_a^d} W\left(\nu_1, \nu_2, T_{arr}\right) d\Sigma\,. \tag{13.0.5}$$

Here $\Delta\varepsilon = \Delta E_{int}/V$ is the energy density released in the interaction of the ABM pulse with the ISM inhomogeneities measured in the comoving frame, $\Lambda = \gamma(1-(v/c)\cos\vartheta)$ is the Doppler factor, $W\left(\nu_1, \nu_2, T_{arr}\right)$ is an "effective weight" required to evaluate only the contributions in the energy band $[\nu_1, \nu_2]$, $d\Sigma$ is the surface element of the EQTS at detector arrival time t_a^d on which the integration is performed (see also Ruffini et al., 2002) and T_{arr} is the observed temperature of the radiation emitted from $d\Sigma$:

$$T_{arr} = T_s / \left[\gamma\left(1-(v/c)\cos\vartheta\right)(1+z)\right] \,. \tag{13.0.6}$$

The "effective weight" $W\left(\nu_1, \nu_2, T_{arr}\right)$ is given by the ratio of the integral over the given energy band of a Planckian distribution at a temperature T_{arr} to the total integral aT_{arr}^4:

$$W\left(\nu_1, \nu_2, T_{arr}\right) = \frac{1}{aT_{arr}^4} \int_{\nu_1}^{\nu_2} \rho\left(T_{arr}, \nu\right) d\left(\frac{h\nu}{c}\right)^3 \,, \tag{13.0.7}$$

where $\rho\left(T_{arr}, \nu\right)$ is the Planckian distribution at temperature T_{arr}:

$$\rho\left(T_{arr}, \nu\right) = \frac{2h\nu}{h^3\left(e^{h\nu/(kT_{arr})} - 1\right)} \tag{13.0.8}$$

This apparently simple procedure needs a very complicated integration technique. Every value of the luminosity at any given detector arrival time is actually the outcome of an integration over the given EQTS of literally millions of different points, each one characterized by a different temperature and a different value of the Lorentz boost!

Historically, this procedure was used for GRB991216, where for the first time we recognized the existence of the P-GRB and its entire afterglow. Some much more detailed examples were made recently, using data obtained by the INTEGRAL and Swift satellites (Bernardini et al., 2005; Ruffini et al., 2006a).

14 The three paradigms for the interpretation of GRBs

Having outlined the main theoretical features of our model and some recent observational verifications, I would like to recall the three basic paradigms for understanding GRBs proposed already by us in 2001. These assume as a starting point that all GRBs, whether short or long, are characterized by the same basic process of gravitational collapse to a black hole.

The first paradigm, the relative spacetime transformation (RSTT) paradigm (Ruffini et al., 2001a) emphasizes the importance of a global analysis of the GRB phenomenon encompassing both the optically thick and the afterglow phases. Since all the data are received at the detector arrival time it is essential to know the equations of motion for all relativistic phases with $\gamma > 1$ of the GRB sources in order to reconstruct the time coordinate in the laboratory frame. Contrary to other phenomena in nonrelativistic physics or astrophysics where every phase can be examined separately from the others, for GRBs the phases are inter-related by their signals received in arrival time t_a^d. In order to describe the physics of the source at a given arrival time t_a^d, the laboratory time t must be calculated taking necessarily into account the entire past worldline of the source.

The second paradigm, the interpretation of the burst structure (IBS) paradigm (Ruffini et al., 2001b) covers three fundamental issues:

1. the existence, in the canonical GRB, of two different components, the P-GRB and the afterglow related by precise equations determining their relative amplitude and temporal sequence (see Ruffini et al., 2003);

2. the fact that in the "prompt emission", usually considered as a burst in the literature, is not a burst at all in our model — it is just the emission from the peak of the afterglow (see Figure 14.1);

3. the crucial role of the parameter B in determining the relative amplitude of the P-GRB to the afterglow and discriminating between the short and the long bursts (see Figure 14.2).

Both short and long bursts arise from the same physical phenomena, the dyadosphere. For values of the baryon loading $B < 10^{-4}$ (see Figure 14.2) the P-GRB becomes prominent with respect to the afterglow. These correspond to the short bursts. In the limit of $B \to 0$, all the energy is emitted in the

P-GRB and the afterglow goes to zero. The presence of baryonic matter in the range $10^{-4} < B < 10^{-2}$ leads to the prominence of the afterglow energy with respect to the P-GRB one. When the ISM density is large enough ($n_{\rm ism} \sim 1$ particle/cm^3), the afterglow peak emission is prominent with respect to the P-GRB and generates the so-called long bursts.

The third paradigm, the GRB-Supernova Time Sequence (GSTS) paradigm (Ruffini et al., 2001c), deals with the relation between the GRB and the associated supernova process. Models of GRBs based on a single source (the "collapsar") generating both the supernova (SN) and the GRB abound in the literature (see e.g. Woosley & Bloom, 2006). In our approach we have emphasized the concept of induced gravitational collapse, which occurs strictly in a binary system. The SN originates from a normal star and the GRB from collapse to a black hole. The two phenomenon are qualitatively very different. There is still much to be discovered about SNe due to their complexity, while the GRB is much better known since its collapse to a black hole is now understood. The concept of induced collapse implies at least two alternative scenarios. In the first, the GRB triggers a SN explosion in the very last phase of the thermonuclear evolution of a companion star (Ruffini et al., 2001c). In the second, the early phases of the SN induce gravitational collapse of a companion neutron star to a black hole (Ruffini, 2006). Of course, there is also the possibility that the collapse to a black hole that generates the GRB occurs in a single star system, clearly without any SN and fulfilling the very strong condition given by Eq. (12.0.2).

It is clear that GRBs are possibly the most important astrophysical systems ever discovered, both for physics and for astrophysics. Although enormously complex, they offer the possibility of being completely understood, allowing a detailed theoretical description. Through GRBs we are exploring some of the real frontier of physics and astrophysics. These include the first precision analysis of the formation of a Kerr–Newman geometry and the first clear evidence of the creation of electron–positron pairs by vacuum polarization using the blackholic energy. Also, there is the possibility that the early phases of the onset of SNe can be observed. This would provide essential data about this enormously complex and still not understood system.

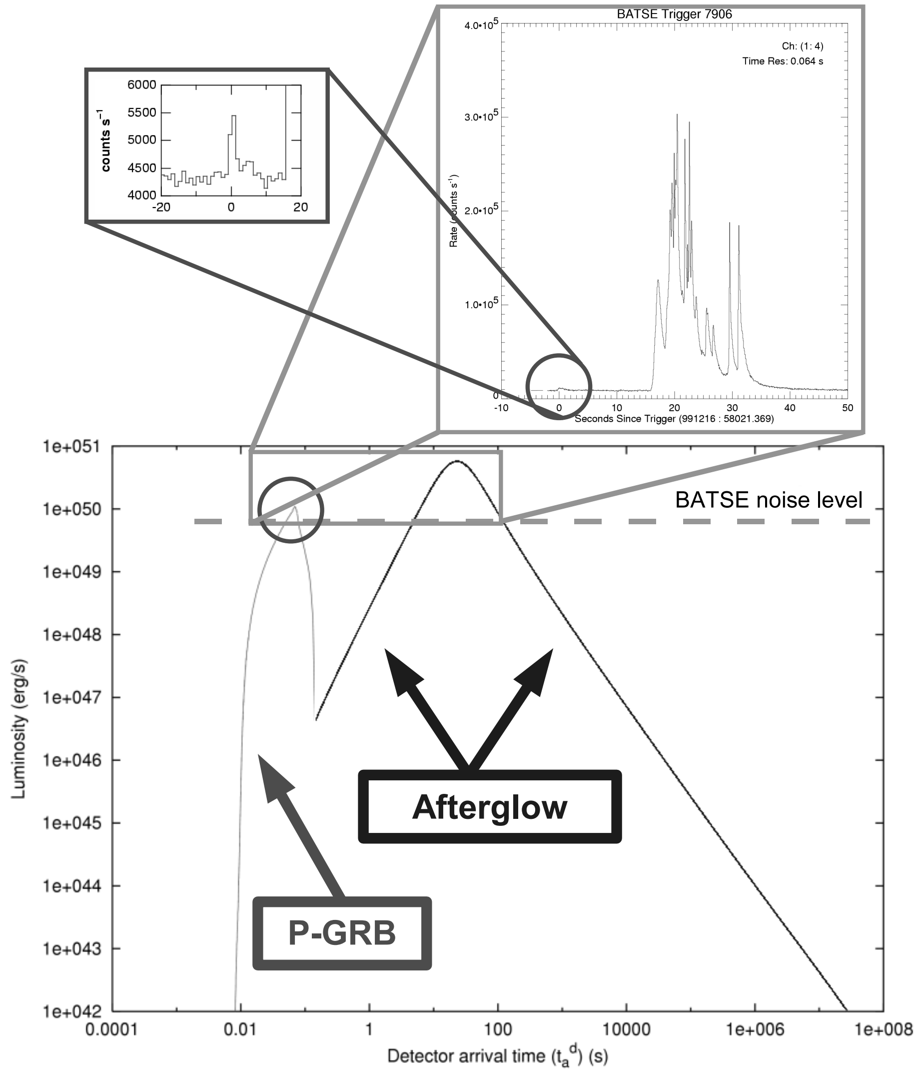


Figure 14.1: GRB 991216 within our theoretical framework. The prompt emission observed by BATSE is identified with the peak of the afterglow, while the small precursor is identified with the P-GRB. Details in Ruffini et al. (2001b, 2002, 2003, 2005a).

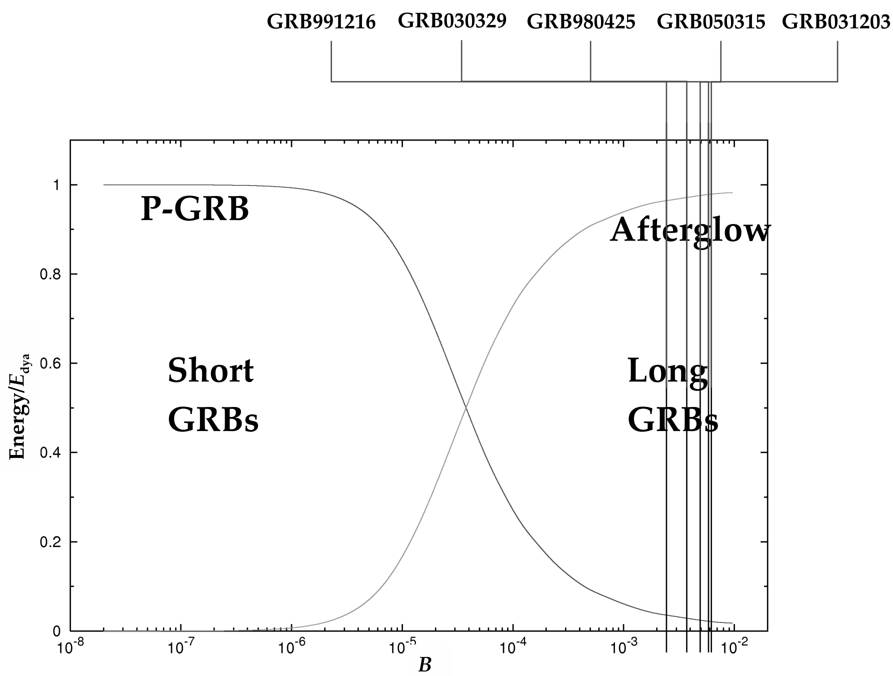


Figure 14.2: The energy radiated in the P-GRB and in the afterglow, in units of the total energy of the dyadosphere (E_{dya}), are plotted as functions of the B parameter. The values of the B parameter computed in our theory for the sources GRB 991216, GRB 030329, GRB 980425, GRB 050315, GRB 031203 are also represented. It is very remarkable that they are all consistently smaller than the absolute upper limit $B < 10^{-2}$ found in Ruffini et al. (2000).

15 The Kerr solution and art and science

The trajectories studied with Mark Johnston (see Johnston & Ruffini, 1974) had become the subject of a sculpture by Attilio Pierelli (see Figure 15.1). This silver sculpture has become the prize of the Marcel Grossmann Awards. We recall that the Marcel Grossmann Awards are traditionally attributed to a scientific institution and to scientists who have distinguished themselves in the field of relativistic astrophysics. In 2006 the Award has been assigned to the Freie Universität Berlin, to Roy Kerr, to George Coyne and to Joachim Trumper. This same figure has become the logo of ICRA, the International Center for Relativistic Astrophysics, and its network ICRANet.

Figure 15.1: The sculpture TEST (Traction of Events in Space and Time) by the Italian artist Attilio Pierelli as photographed by the Japanese artist Shu Takahashi (Imponente, 1985).

16 Acknowledgements

Too many people have contributed through discussions to this manuscript to be mentioned. I would like to acknowledge specifically Roy Kerr, for having read the manuscript and made most important suggestions. I am especially thankful to José Funes, director of the Specola Vaticana, for offering the hospitality to Roy Kerr in the ICRANet office in Castel Gandolfo allowing us to finalize this manuscript. Finally, I like to thank all the members of the GRB group at ICRA and ICRANet, especially Carlo Luciano Bianco, for the preparation of the manuscript.

Figure 16.1: The ICRA and ICRANet logos

Bibliography

Anderson, C.D., *Phys. Rev.*, **43**, 491.

Arbolino, M.V., Ruffini, R. (1988), *Astron. Astroph.*, **192**, 107.

Atkinson, R., Houtermans, F.G. (1929a), *Zeit. für Physik*, **54**, 656.

Atkinson, R., Houtermans, F.G. (1929b), *Zeit. für Physik*, **58**, 478.

Bekenstein, J. (1973), *Phys. Rev. D*, **7**, 2333.

Bekenstein, J. (1974), *Phys. Rev. D*, **9**, 3292.

Bekenstein, J. (2006), "Of gravity, black holes and information", Di Renzo Editore.

Bell, J., Hewish, T. (1967), *Nature*, **213**, 1214.

Bernardini, M.G., Bianco, C.L., Chardonnet, P., Fraschetti, F., Ruffini, R., Xue, S.-S. (2005), *Astroph. J.*, **634**, L29.

Bethe, H. (1939), *Phys. Rev.*, **55**, 103.

Bianco, C.L., Ruffini, R. (2004), *Astroph. J.*, **605**, L1.

Bianco, C.L., Ruffini, R. (2005a), *Astroph. J.*, **620**, L23.

Bianco, C.L., Ruffini, R. (2005b), *Astroph. J.*, **633**, L13.

Bianco, C.L., Ruffini, R., Vereshchagin, G.V., Xue, S.-S. (2006), *J. Kor. Phys. Soc.*, **49**, 722.

Bisnovatyi-Kogan, G.S., Murzina, M.V.A. (1995) *Phys. Rev. D*, **52**, 4380.

Bisnovatyi-Kogan, G.S., Merafina, M., Ruffini, R., Vesperini, E. (1998) *Astroph. J.*, **500**, 217.

Blandford, R.D., McKee, C.F. (1976), *Phys. Fluids*, **19**, 1130.

Blandford, R.D., Znajek, R.L. (1977), *Mon. Not. Roy. Astron. Soc.*, **179**, 433.

Bolton, C.T. (1972a), *Nature*, **235**, 271.

Bolton, C.T. (1972b), *Nature Physical Science*, **240**, 124.

Burbidge, E.M., Burbidge, G., Fowler, W.A., Hoyle, F. (1957), *Rev. Mod. Phys.*, **29**, 547.

Carilli, C.L., Perley, R., Harris, D.E., Barthel, P.D. (1998), *Phys. Plasmas*, **5**, 1981.

Carter, B. (1968), *Phys. Rev*, **174**, 1559.

Chandrasekhar, S. (1930), *Mon. Not. Roy. Astron. Soc.*, **91**, 4.

Chandrasekhar, S. (1935), *Mon. Not. Roy. Astron. Soc.*, **95**, 207.

Chandrasekhar, S. (1939), "An introduction to the study of stellar structure", Univ. Chicago Press.

Chardonnet, P., Mattei, A., Ruffini, R., Xue, S.-S. (2003), *N. Cim. B*, **118**, 1063.

Cherubini, C., Geralico, A., Rueda Hernandez, J.A., Ruffini, R. (2007), *Phys. Rev. D*, submitted.

Cherubini, C., Ruffini, R., Vitagliano, L. (2002), *Phys. Lett. B*, **545**, 226.

Chiang, J., Dermer, C.D. (1999), *Astroph. J.*, **512**, 699.

Christodoulou, D. (1970), *Phys. Rev. Lett.*, **25**, 1596.

Christodoulou, D., Ruffini, R. (1971), *Phys. Rev. D*, **4**, 3552.

Costa, E., et al. (1997), *Nature*, **387**, 783.

Damour, T. (1975), *Ann. New York Acad. Sci.*, **262**, 113.

Damour, T. (1977), in "Proceedings of the first Marcel Grossmann Meeting", R. Ruffini (ed.), North Holland Publishing.

Damour, T. (1978), *Phys. Rev. D*, **18**, 3598.

Damour, T. (1982), in "Proceedings of the second Marcel Grossmann Meeting", R. Ruffini (ed.), North Holland Publishing.

Damour, T., Ruffini, R. (1975), *Phys. Rev. Lett.*, **35**, 463.

Damour, T., Ruffini, R., Hanni, R.S., Wilson, J. (1978), *Phys. Rev. D*. **17**, 1518.

Deruelle, N. (1977), in "Proceedings of the first Marcel Grossmann Meeting", R. Ruffini (ed.), North Holland Publishing.

Eddington, A.S. (1935), *Mon. Not. Roy. Astron. Soc.*, **95**, 194.

Eddington, A.S. (1920), *Brit. Assoc. Repts.*, 45.

Einstein, E. (1939), *Ann. Math.*, **40**, 922.

Fairbank, J.D., Deaver, B.S., Everitt, C.W.F., Michelson, P.F. (1988), "Near Zero: New frontiers of physics", W.H. Freeman and Company.

Fermi, E., et al. (1942), December 2^{nd}, as reproduced in *Am. J. Phys.*, 1952, **20**, 536.

Fermi, E. (1949), "Teoria sull'origine degli elementi", lecture held at the Physics Institute of the University of Rome "La Sapienza" on the 7^{th} of October 1949, translated into English in the book "Fermi and Astrophysics", V. Gurzadyan, R. Ruffini (eds.), World Scientific (Singapore, in press).

Finzi, A., Wolf R.A. (1968), *Astroph. J.*, **153**, 865.

Floyd, R.M., Penrose, R. (1971), *Nature Physical Science*, **229**, 177.

Foresta Martin, F. (1999), *Corriere della sera*, March 7^{th}, p. 27.

Gallo, E., Fender, R., Kaiser, C., Russell, D., Morganti, R., Oosterloo, T., Heinz, S. (2005), *Nature*, **436**, 819.

Gamow, G. (1938), "Nuclear Physics", Oxford.

Gamow, G., Houtermans, F.G. (1928), *Zeit. für Physik*, **52**, 496.

Gatoff, G., Kerman, A.K., Matsui, T. (1987), *Phys. Rev. D*, **36**, 114.

Giacconi, R. (2002), *Nobel Lecture*.

Giacconi, R. (2005), *Ann. Rev. Astron. Astroph.*, **43**, 1.

Giacconi, R., Ruffini, R. (1978), "Physics and astrophysics of neutron stars and black holes", North-Holland.

Gold, T. (1968), *Nature*, **218**, 731.

Gold, T. (1969), *Nature*, **221**, 27.

Granot, J., Piran, T., Sari, R. (1999), *Astroph. J.*, **513**, 679.

Gruzinov, A., Waxman, E. (1999), *Astroph. J.*, **511**, 852.

Gursky, H., Ruffini R. (1975), "Neutron Stars, black holes and Binary X-Ray Sources", Springer.

Harrison, B.K., Thorne, K.S., Wakano, M., Wheeler, J.A. (1965), "Gravitation theory and gravitational collapse", Univ. Chicago Press.

Hawking, S. (1971), *Phys. Rev. Lett.*, **26**, 1344.

Hawking, S. (1974), *Nature*, **238**, 30.

Hawking, S. (1975), *Comm. Math. Phys.*, **43**, 199.

Hawking, S. (1976), *Phys. Rev. D*, **13**, 191.

Heisenberg, W., Euler, H. (1935), *Zeits. Phys.*, **98**, 714.

Imponente, A. (1985), Catalog presentation of the show of A. Pierelli, "TEST, Trascinamento di Eventi Spazio Temporali", Rome, Galleria MR, September–October 1985.

Institut International de Physique Solvay (1958), "La structure et l'évolution de l'univers – Rapports et discussions", XI Conseil de Physique, Université de Bruxelles, June 9–13, 1958, R. Stoops Editor, Bruxelles.

Jacobi, C.G.J. (1997), "C.G.J. Jacobi's Collected Works (Gesammelte Werke)", American Mathematical Society.

Johnston, M., Ruffini, R. (1974), *Phys. Rev. D*, **10**, 2324.

Kerr, R.P. (1963), "Gravitational field of a spinning mass as an example of algebraically special metrics", *Phys. Rev. Lett.*, **11**, 237.

Khriplovich, I.B. (2000), *N. Cim. B*, **115**, 761.

Landau, L.D. (1932), *Physikalische Zeitschrift der Sowjetunion*, **1**.

Landau, L.D., Lifshitz, E.M. (1981), "Quantum Mechanics", Third edition, Butterworth-Heinemann Ltd.

Leach, R.W., Ruffini, R. (1973), *Astroph. J.*, **180**, L15.

Maxwell, J.C. (1986), "Maxwell on Molecules and Gases", E. Garber, S.G. Brush, C.W.F. Everitt (eds.), The MIT Press.

Merafina, M., Ruffini, R. (1989), *Astron. Astroph*, **221**, 4.

Merafina, M., Ruffini, R. (1990), *Astron. Astroph*, **227**, 415.

Merafina, M., Ruffini, R. (1997), *Int. J. Mod. Phys. D*, **6**, 785.

Mészáros, P. (2002), *Ann. Rev. Astron. Astroph*, **40**, 137.

Mészáros, P. (2006), *Rep. Prog. Phys.*, **69**, 2259.

Mészáros, P., Laguna, P., Rees, M.J. (1993), *Astroph. J.*, **415**, 181.

Mezzacappa, A., Fuller, G.M. (2006), "Open Issues in Core Collapse Supernova Theory", World Scientific.

Mirabel, F., Rodrigues, I. (2003), *Science*, **300**, 1119.

Misner, C.W., Thorne, K.S., Wheeler, J.A. (1973), "Gravitation", Freeman.

Ohanian, H.C., Ruffini, R. (1974), "Gravitation and Spacetime", W.W. Norton & Company; 2nd edition.

Oppenheimer, J.R., Serber, R. (1938), *Phys. Rev.*, **54**, 540.

Oppenheimer, J.R., Snyder, H. (1939), *Phys. Rev.*, **56**, 455.

Oppenheimer, J.R., Volkoff, R. (1939), *Phys. Rev.*, **55**, 374.

Paciesas, W.S., et al. (1999), *Astroph. J. Suppl. Ser.*, **122**, 465.

Pacini, F. (1968), *Nature*, **219**, 145.

Page, D.N. (2006), *Astroph. J.*, **653**, 1400.

Panaitescu, A., Mészáros, P. (1998), *Astroph. J.*, **493**, L31.

Penrose, R. (1969), *Riv. N. Cim.*, **1**, 252.

Perrin, J.B. (1920), *Rev. du Mois*, **21**, 113.

Piran, T. (1999), *Phys. Rep.*, **314**, 575.

Piran, T., Shemi, A., Narayan, R. (1993), *Mon. Not. Roy. Astron. Soc.*, **263**, 861.

Preparata, G., Ruffini, R., Xue, S.-S. (1998), *Astron. Astroph.*, **338**, L87.

Punsly, B. (2001), "Black holes gravitohydromagnetics", Springer.

Regge, T., Wheeler, J.A. (1957), *Phys. Rev.*, **108**, 1063.

Rees, M.J., Mészáros, P. (1998), *Astroph. J.*, **496**, L1.

Rees, M.J., Ruffini, R., Wheeler, J.A. (1976), "Black holes, Gravitational Waves and Cosmology", Gordon & Breach Publishing.

Rhoades, C.E., Ruffini, R. (1971), *Astroph. J.*, **163**, L83.

Ruffini, P. (1803), *Memorie di matematica e fisica della Società Italiana delle Scienze*, **10**, 410.

Ruffini, R. (1973) in "black holes", DeWitt, C., & B.S. (eds.), Gordon and Breach.

Ruffini, R. (1998), in "black holes and High Energy Astrophysics", H. Sato, N. Sugiyama (eds.), Universal Acad. Press (Tokyo).

Ruffini, R. (2001a), in "Exploring the Universe", H. Gursky, R. Ruffini, L. Stella (eds.), World Scientific.

Ruffini, R. (2001b), in "Fluctuating Paths and Fields", W. Janke, A. Pelster, H.-J. Schmidt, M. Bachmann (eds.), World Scientific.

Ruffini, R. (2006), in the "Proceedings of the eleventh Marcel Grossmann meeting", R. Jantzen, H. Kleinert, R. Ruffini (eds.), World Scientific (Singapore, in press).

Ruffini, R., Bernardini, M.G., Bianco, C.L., Chardonnet, P., Fraschetti, F., Gurzadyan, V., Vitagliano, L., Xue, S.-S. (2005a), in "Cosmology and Gravitation: XIth Brazilian School of Cosmology and Gravitation", M. Novello, S.E. Perez Bergliaffa (eds.), *AIP Conf. Proc.*, **782**, 42.

Ruffini, R., Bernardini, M.G., Bianco, C.L., Chardonnet, P., Fraschetti, F., Xue, S.-S. (2006a), *Astroph. J.*, **645**, L109.

Ruffini, R., Bianco, C.L., Chardonnet, P., Fraschetti, F., Gurzadyan, V., Xue, S.-S. (2004), *Int. J. Mod. Phys. D*, **13**, 843.

Ruffini, R., Bianco, C.L., Chardonnet, P., Fraschetti, F., Gurzadyan, V., Xue, S.-S. (2005b), *Int. J. Mod. Phys. D*, **14**, 97.

Ruffini, R., Bianco, C.L., Chardonnet, P., Fraschetti, F., Vitagliano, L., Xue, S.-S. (2003), in "Cosmology and Gravitation: Xth Brazilian School of Cosmology and Gravitation", M. Novello, S.E. Perez Bergliaffa (eds.), *AIP Conf. Proc.*, **668**, 16.

Ruffini, R., Bianco, C.L., Chardonnet, P., Fraschetti, F., Xue, S.-S. (2001a), *Astroph. J.*, **555**, L107.

Ruffini, R., Bianco, C.L., Chardonnet, P., Fraschetti, F., Xue, S.-S. (2001b), *Astroph. J.*, **555**, L113.

Ruffini, R., Bianco, C.L., Chardonnet, P., Fraschetti, F., Xue, S.-S. (2001c), *Astroph. J.*, **555**, L117.

Ruffini, R., Bianco, C.L., Chardonnet, P., Fraschetti, F., Xue, S.-S. (2002), *Astroph. J.*, **581**, L19.

Ruffini, R., Bianco, C.L., Vereshchagin, G.V., Xue , S.-S. (2006b), in the proceedings of "Relativistic Astrophysics and Cosmology - Einstein's Legacy" meeting, B. Aschenbach, V. Burwitz, G. Hasinger, & B. Leibundgut (eds.), Springer, in press, `astro-ph/0605385`.

Ruffini, R., Bianco, C.L., Xue, S.-S. (2007), *Astroph. J.*, submitted.

Ruffini, R., Rotondo, M., Xue, S.-S. (2006a), in the "Proceedings of the eleventh Marcel Grossmann meeting", R. Jantzen, H. Kleinert, R. Ruffini (eds.), World Scientific (Singapore, in press).

Ruffini, R., Rotondo, M., Xue, S.-S. (2006b), *Int. J. Mod. Phys. D*, **16**, 1.

Ruffini, R., Salmonson, J.D., Wilson, J.R., Xue, S.-S. (1999), *Astron. Astroph.*, **350**, 334.

Ruffini, R., Salmonson, J.D., Wilson, J.R., Xue, S.-S. (2000), *Astron. Astroph.*, **359**, 855.

Ruffini, R., Sigismondi, C. (2003), "Nonlinear Gravitodynamics", World Scientific.

Ruffini, R., Vitagliano, L. (2002), *Phys. Lett. B*, **545**, 233.

Ruffini, R., Vitagliano, L. (2003), *Int. J. Mod. Phys. D*, **12**, 121.

Ruffini, R., Vitagliano, L., Xue, S.-S. (2003a), *Phys. Lett. B*, **559**, 12.

Ruffini, R., Vitagliano, L., Xue, S.-S. (2003b), *Phys. Lett. B*, **573**, 33.

Ruffini, R., Vitagliano, L., Xue, S.-S. (2007), *Phys. Rep.*, to appear.

Ruffini, R., Wheeler, J.A. (1971a), *Phys. Today*, **24**, 30.

Ruffini, R., Wheeler, J.A. (1971b), in "The significance of space research for fundamental physics", A.F. Moore, V. Hardy (eds.), European space research organization (ESRO) Book No. SP-52.

Ruffini, R., Wilson, J. (1975), *Phys. Rev. D*, **12**, 2959.

Sari, R. (1997), *Astroph. J.*, **489**, L37.

Sari, R. (1998), *Astroph. J.*, **494**, L49.

Shakura, N.I. (1972a), *Sov. Astron. AJ*, **49**, 495.

Shakura, N.I. (1972b), *Sov. Astron. AJ*, **49**, 642.

Shild, A., Schucking, E., Robinson, I. (1965), "Quasi-Stellar Sources and Gravitational Collapse including proceedings of the first Texas symposium on Relativistic Astophysics", Univ. Chicago Press.

Schwinger, J. (1951), *Phys. Rev.*, **82**, 664.

Shklovsky, I.S. (1967), *Astroph. J.*, **148**, L1.

Shvartsman, V.F. (1971), *Sov. Astron. AJ*, **15**, 377.

Størmer, C. (1934), *Astroph. Norvegica*, **1**, 1.

Tavani, M. (1998), *Astroph. J.*, **497**, L21.

van Paradijs, J., Kouveliotou, C., Wijers, R.A.M.J. (2000), *Annu. Rev. Astron. Astroph.*, **38**, 379.

von Weizsäckr, C.F. (1937), *Phys. Zs.*, **38**, 176.

von Weizsäcker, C.F. (1938), *Phys. Zs.*, **39**, 633.

Waxman, E. (1997), *Astroph. J.*, **491**, L19.

Webster, B., Murdin, P. (1972), *Nature*, **235**, 37.

Woosley, S.E., Bloom, J.S. (2006), *Ann. Rev. Astron. Astroph.*, **44**, 507.

Zel'dovich, Ya.B. (1985), "Selected works, particles, nuclei, universe", 2 volumes, Nauka (Moscow).

Zel'dovich, Ya.B., Guseynov, O.K. (1965), *Dokl. Akad. Nauk. USSR*, **162**, 791.

Zerilli, F. (1970), *Phys. Rev. D*, **2**, 2141.

Zerilli, F. (1974), *Phys. Rev. D*, **9**, 860.