Activities with Brazil

Contents

1 Topics

In general, the scientific collaboration between ICRANet and Brazil is based on the following activities:

- Production of scientific research;
- IRAP Ph.D. and the Brazilian doctorate programs;
- Postdoctoral programs;
- Professors/researchers visitor programs;
- Organization of conferences, meetings, and workshops.

The research collaboration between ICRANet and Brazil encompasses a series of topics in relativistic astrophysics mainly connected to the physics and astrophysics of compact objects such as white dwarfs, neutron stars, and black holes. Some topics of research include:

- Equation of state (EOS) of compact stars (white dwarfs, neutron stars, hybrid stars, quark stars).
- Temperature effects on compact star EOS and structure.
- Magnetic field effects in compact stars EOS and structure.
- Rotation effects in compact stars structure.
- White dwarfs in astrophysical systems: binaries, mergers, type Ia supernovae.
- Neutron stars in astrophysical systems: binaries, mergers.
- Radiation mechanisms of compact stars, such as electromagnetic emission, neutrino emission, gravitational waves, accretion disks, compact object magnetospheres, etc.

Below, we summarize and highlight the main activities and results achieved in all the above areas in 2024.

2 Participants

Below, we list professors, senior researchers, postdocs, and graduate students from ICRANet and Brazil who are in active scientific collaboration.

2.1 ICRANet

- J. A. Rueda (ICRANet, Italy)
- R. Ruffini (ICRANet, Italy)

2.2 Professors/senior researchers in Brazil

- U. Barres de Almeida (Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil)
- R. Camargo (Universidade do Estado de Santa Catarina, Florianópolis, Brazil)
- G. A. Carvalho (Universidade Tecnológica Federal do Paraná, Brazil; Universidade do Vale do ParaÃba, Brazil)
- J. G. Coelho (Universidade Federal do EspÃrito Santo, Brazil)
- J. C. N. de Araujo (Instituto Nacional de Pesquisas Espaciais, Brazil)
- E. O. da Silva (Universidade Federal do Cariri, Brazil)
- G. de Barros (Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil)
- R. C. dos Anjos (Universidade Federal do ParanÃ¡, Brazil; Universidade Federal da Fronteira Latino-Americana, Brazil; Universidade Federal do ParanÃ¡, Brazil)

- M. M. Guzzo (Universidade Estadual de Campinas, Brazil)
- S. O. Kepler (Universidade Federal do Rio Grande do Sul, Brazil)
- R. V. Lobato (Universidade Cidade de SÃ£o Paulo, Brazil)
- M. Malheiro (Instituto Tecnológico de Aeronáutica, Brazil)
- R. M. Jr. Marinho (Instituto Tecnológico de Aeronáutica, Brazil)
- D. P. Menezes (Universidade Federal de Santa Catarina, Brazil)
- C. V. Rodrigues (Instituto Nacional de Pesquisas Espaciais, Brazil)
- F. Rossi-Torres (Universidade Estadual de Campinas, Brazil)
- C. A. Z. Vasconcellos (Universidade Federal do Rio Grande do Sul, Brazil)

2.3 Postdocs

- J. P. Pereira (Universidade Federal do EspÃrito Santo, Brazil)
- M. F. Sousa (Universidade Federal do ParanÃ¡, Brazil)

2.4 Graduate Students

- S. V. Borges (University of Wisconsin-Milwaukee, USA)
- T. Oliveira (Universidade Federal do EspÃrito Santo, Brazil)
- T. Ottoni (Universidade Federal do EspÃrito Santo, Brazil)
- K. Kianfar (Instituto Tecnológico de Aeronáutica, Brazil)
- A. Rodrigues (Universidade Federal do EspÃrito Santo, Brazil)

3 Summary and Highlights 2024

This year has seen a particularly intensive collaboration with Brazilian professors, researchers, graduate students, and postdoctoral fellows from Universidade Tecnológica Federal do Paraná (UTFP), Universidade Federal do Paraná (UFPR), Instituto Tecnológico de Aeronáutica (ITA), Universidade Federal do Espírito Santo (UFES), Instituto Nacional de Pesquisas Espaciais (INPE), Universidade Federal Fluminense (UFF), Universidade do Estado de Santa Catarina (UDESC), and Universidade Federal de Santa Catarina (UFSC).

From a scientific publication viewpoint, the collaboration with Brazil has resulted in publishing four articles in journals with high-impact factors (more details are given below).

Brazilian colleagues participated in the 17th Marcel Grossmann Meeting organized by ICRANet on July 4-12, 2024, in Pescara. The parallel session *Massive white dwarfs and related phenomena* has been co-chaired by Jaziel Goulart Coelho, coordinator at UFES of the UFES-ICRANet collaboration agreement.

The Ph.D. student from UFES, Tulio Ottoni, performed a six-month academic visit at ICRANet-Ferrara from 15 November 2023 to 15 May 2024. This activity takes part within the context of the participation of ICRANet in the *International Ph.D. Program in Astrophysics, Cosmology, and Gravitation* (PPG-Cosmo) through the co-supervision of Ph.D. research. The research and thesis of T. Ottoni are co-supervised by Prof. Jaziel Coelho from UFES and Prof. Jorge A. Rueda from ICRANet-Ferrara. The thesis is entitled *Pulsar pulse profiles in scalar-tensor theories of gravity and some astrophysical tests*. The aim is to investigate gravitational theories in the strong field regime with the high energy light curve of pulsars. The results of the research, finished during the student visit at ICRANet-Ferrara, have been presented in an article published in the European Physical Journal C. In addition, in collaboration with Prof. Piero Rosati at the University of Ferrara, the student Ottoni is performing additional research on constraints of alternative theories of gravity using gravitational lensing data from galaxy clusters. Additional work on dark matter is still ongoing with the student.

Within the same collaboration between ICRANet, UFES, and the PhD Program PPGCosmo, the two students, Tales Oliveira and Alexandre Magno Rodrigues from UFES, started on November 2024 a six-month academic visit to ICRANet-Ferrara. Oliveira's research is based on high-energy radiative processes (e.g., quantum electrodynamics processes like Cherenkov radiation or charged particle collisions) in pulsars and black holes. Rodrigues' research is based on radiative processes in cataclysmic transients like double white dwarf mergers. The research and theses of the two students are co-supervised by Prof. Jaziel Coelho from UFES and Prof. Jorge A. Rueda from ICRANet-Ferrara.

The organization, development, and success of the collaborations have led to the full fruition of the bilateral agreements established by ICRANet over the years with Brazilian institutions such as universities, research centers, and national agencies to promote research throughout Brazil's territory.

In 2024, ICRANet renewed collaboration agreements with the following Brazilian institutions:

- Universidade Federal do Rio Grande do Sul (UFRGS).

In 2024, ICRANet signed new collaboration agreements with the following Brazilian institutions:

- Universidade Federal do EspÃrito Santo (UFES)
- Universidade Federal do Cariri (UFCA)

Therefore, as of this writing, ICRANet has active collaboration agreements with the following Brazilian institutions:

- Governo dello Stato di CearÃ¡
- Universidade Federal do Rio Grande do Sul (UFRGS)
- Universidade Estadual de Campinas (UNICAMP)
- Universidade do Estado de Santa Catarina (UDESC)
- Instituto Tecnológico de Aeronáutica (ITA)
- Universidade Federal Fluminense (UFF)
- Universidade Federal de ItajubÃ¡ (UNIFEI)

- Universidade Federal da ParaÃba (UFPB)
- Universidade Federal de SÃ£o Carlos (UFSCar)
- Universidade Federal do EspÃrito Santo (UFES)
- Universidade Federal do Cariri (UFCA)

For a summary of the collaboration agreements between Brazilian universities and research centers with ICRANet, please visit the dedicated page on the ICRANet website:

`https://www.icranet.org/index.php?option=com_content&task=view&id=1427`

See also:

`https://www.icranet.org/documents/ICRANet_Brazil_Agreements_total.pdf`

Special mention goes to the young Brazilian scientists to whom ICRANet has contributed to their academic formation via the IRAP Ph.D. Program, postdoctoral, and educational exchange programs like the CAPES-ICRANet Program that have obtained permanent professorship positions in Brazilian universities in 2024. ICRANet keeps track of and encourages young professors' scientific careers. A report with this and additional information on the activities of ICRANet with Brazilian colleagues is continuously updated and publicly available on the ICRANet website.

For a summary of the collaboration activities of ICRANet with and in Brazil, including the scientific activities of Ph.D. students, postdocs, and professors, we refer to the following detailed report:

`https://www.icranet.org/documents/ICRANet_activities_Brazil.pdf`

4 Publications 2024

The year 2024 has seen a strong and fruitful collaboration with Brazil. From the scientific publication viewpoint, four articles in high-impact factor journals have been published with Brazilian colleagues, including professors, PhD students, and postdoctoral fellows. We published one article in Physical Review D, one in the European Physical Journal C, and two in The Astrophysical Journal.

The research topics of these publications have been in the context of the astrophysics of neutron stars from the theoretical point of view, as well as their role in gamma-ray bursts.

1. S. R. Zhang, J. A. Rueda, R. Negreiros, *Can the central compact object in HESS J1731–347 be indeed the lightest neutron star observed?*, The Astrophysical Journal 978, 1 2025.

   The exceptionally low mass of $0.77^{+0.2}_{-0.17} M_\odot$ for the central compact object (CCO) XMMU J173203.3â€"344518 (XMMU J1732) in the supernova remnant (SNR) HESS J1731â€"347 challenges standard neutron star (NS) formation models. The nearby post-AGB star IRAS 17287â€"3443 ($\approx 0.6 M_\odot$), also within the SNR, enriches the scenario. To address this puzzle, we advance the possibility that the gravitational collapse of a rotating pre-SN iron core ($\approx 1.2 M_\odot$) could result in a low-mass NS. We show that angular momentum conservation during the collapse of an iron core rotating at $\approx 45\%$ of the Keplerian limit results in a mass loss of $\approx 0.3 M_\odot$, producing a stable newborn NS of $\approx 0.9 M_\odot$. Considering the possible spin-down, this indicates that the NS is now slowly rotating, thus fulfilling the observed mass-radius relation. Additionally, the NS's surface temperature ($\approx 2 \times 10^6$ K) aligns with canonical thermal evolution for its ≈ 4.5 kyr age. We propose the pre-SN star, likely an ultra-stripped core of $\approx 4.2 M_\odot$, formed a tidally locked binary with IRAS 17287â€"3443, having a 1.43-day orbital period. The supernova led to a $\approx 3 M_\odot$ mass loss, imparting a kick velocity $\lesssim 670$ km s^{-1}, which disrupted the binary. This scenario explains the observed 0.3 pc offset between XMMU J1732 and IRAS 17287â€“3443 and supports the possibility of CCOs forming in binaries, with rotation playing a key role in core-collapse, and the CCO XMMU J1732 being the lightest NS ever observed.

The link to the publication in The Astrophysical Journal website is:

https://iopscience.iop.org/article/10.3847/1538-4357/ad96b5

2. Ottoni, Tulio; Coelho, Jaziel G.; de Lima, Rafael C. R.; Pereira, Jonas P.; Rueda, Jorge A., *X-ray pulsed light curves of highly compact neutron stars as probes of scalar-tensor theories of gravity*, Eur. Phys. J. C, 84, 1337, 2024.

   The strong gravitational potential of neutron stars (NSs) makes them ideal astrophysical objects for testing extreme gravity phenomena. We explore the potential of NS X-ray pulsed lightcurve observations to probe deviations from general relativity (GR) within the scalar-tensor theory (STT) of gravity framework. We compute the flux from a single, circular, finite-size hot spot, accounting for light bending, Shapiro time delay, and Doppler effect. We focus on the high-compactness regime, i.e., close to the critical GR value $GM/(Rc^2) = 0.284$, over which multiple images of the spot appear and impact crucially the lightcurve. Our investigation is motivated by the increased sensitivity of the pulse to the scalar charge of the spacetime in such high compactness regimes, making these systems exceptionally suitable for scrutinizing deviations from GR, notably phenomena such as spontaneous scalarization, as predicted by STT. We find significant differences in NS observables, e.g., the flux of a single spot can differ up to 80% with respect to GR. Additionally, reasonable choices for the STT parameters that satisfy astrophysical constraints lead to changes in the NS radius relative to GR of up to approximately 10%. Consequently, scalar parameters might be better constrained when uncertainties in NS radii decrease, where this could occur with the advent of next-generation gravitational wave detectors, such as the Einstein Telescope and LISA, as well as future electromagnetic missions like eXTP and ATHENA. Thus, our findings suggest that accurate X-ray data of the NS surface emission, jointly with refined theoretical models, could constrain STTs.

   The link to the publication in the European Physical Journal C website is:

   https://doi.org/10.1140/epjc/s10052-024-13721-6

3. Pereira, Jonas P.; Ottoni, Tulio; Coelho, Jaziel G.; Rueda, Jorge A.; de Lima, Rafael C. R., *Impact of stratified rotation on the moment of inertia of neutron stars* , Physical Review D 110, 103014, 2024.

   Rigid (uniform) rotation is usually assumed when investigating the properties of mature neutron stars (NSs). Although it simplifies their description, it is an assumption because we cannot observe the NS's innermost parts. Here, we analyze the structure of NSs in the simple case of almost rigidity, where the innermost and outermost parts rotate with different angular velocities. This is motivated by the possibility of NSs having superfluid interiors, phase transitions, and angular momentum transfer during accretion processes. We show that, in general relativity, the relative difference in angular velocity between different parts of an NS induces a change in the moment of inertia compared to that of rigid rotation. The relative change depends nonlinearly on where the angular velocity jump occurs inside the NS. For the same observed angular velocity in both configurations, if the jump location is close to the star's surfaceâ€"which is possible in central compact objects (CCOs) and accreting starsâ€"the relative change in the moment of inertia is close to that of the angular velocity (which is expected due to total angular momentum aspects). If the jump occurs deep within the NS, for instance, due to phase transitions or superfluidity, smaller relative changes in the moment of inertia are observed; we found that if it is at a radial distance smaller than approximately 40% of the star's radius, the relative changes are negligible. Additionally, we outline the relevance of systematic uncertainties that nonrigidity could have on some NS observables, such as radius, ellipticity, and the rotational energy budget of pulsars, which could explain the x-ray luminosity of some sources. Finally, we also show that nonrigidity weakens the universal I-Love-Q relations.

   The link to the publication in the Physical Review D website is:

   `https://doi.org/10.1103/PhysRevD.110.103014`

4. Becerra, L. M.; Cipolletta, F.; Fryer, C. L.; Menezes, Débora P.; Providência, Constança; Rueda, J. A.; Ruffini, R., *Occurrence of Gravitational Collapse in the Accreting Neutron Stars of Binary-driven Hypernovae*, The Astrophysical Journal 976, 80, 2024.

   The binary-driven hypernova (BdHN) model proposes long gamma-ray bursts (GRBs) originate in binaries composed of a carbon-oxygen (CO) star and a neutron star (NS) companion. The CO core collapse generates a newborn NS and a supernova that triggers the GRB by accreting onto the NSs, rapidly transferring mass and angular momentum to them. This article aims to determine the conditions under which a black hole (BH) forms from NS collapse induced by the accretion and the impact on the GRB's observational properties and taxonomy. We perform three-dimensional, smoothed particle hydrodynamics simulations of BdHNe using up-to-date NS nuclear equations of state, with and without hyperons, and calculate the structure evolution in full general relativity. We assess the binary parameters leading either NS in the binary to the critical mass for gravitational collapse into a BH and its occurrence time, $t_{\rm col}$. We include a nonzero angular momentum of the NSs and find that $t_{\rm col}$ ranges from a few tens of seconds to hours for decreasing NS initial angular momentum values. BdHNe I are the most compact (about 5 minute orbital period), promptly form a BH, and release $\gtrsim 10^{52}$ erg of energy. They form NS-BH binaries with tens of kiloyears merger timescales by gravitational-wave emission. BdHNe II and III do not form BHs, and release $\sim 10^{50}$–10^{52} erg and $\lesssim 10^{50}$ erg of energy, respectively. They form NS-NS binaries with a range of merger timescales larger than for NS-BH binaries. In some compact BdHNe II, either NS can become supramassive, i.e., above the critical mass of a nonrotating NS. Magnetic braking by a 10^{13} G field can delay BH formation, leading to BH-BH or NSâ€“BH with tens of kiloyears merger timescales.

The link to the publication in The Astrophysical Journal website is:

`https://iopscience.iop.org/article/10.3847/1538-4357/ad82ea`