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Editorial

Multi-Wavelength Properties of Gamma-Ray Binaries

Maria Chernyakova [1,2,*] and Denys Malyshev [3]

[1] School of Physical Sciences and Centre for Astrophysics & Relativity, Dublin City University, D09 W6Y4 Glasnevin, Dublin 9, Ireland
[2] Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, D02 XF86 Dublin 2, Ireland
[3] Institut für Astronomie und Astrophysik Tübingen, Universität Tübingen, Sand 1, D-72076 Tübingen, Germany
* Correspondence: masha.chernyakova@dcu.ie

Gamma-ray binaries are a subclass of high-mass binary systems whose energy spectrum peaks at high energies (MeV–GeV energy range) and extends to very high energy (GeV–TeV) γ-rays. In these systems, a compact object is orbiting around a young, massive, either O- or B-type star. While high-mass binaries represent a substantial fraction of galactic X-ray sources detected above 2 keV, less than ten binaries were detected in the γ-ray band by the current generation of Cherenkov telescopes. As such, γ-ray binaries represent a relatively new and unexplored class of astrophysical objects able to accelerate particles with very high efficiency.

Intensive studies during the last decade demonstrate that one should take into account all available timing and broad band information to understand physical processes governing the broad band emission of these peculiar sources. In order to provide the reader with an updated overview of the recent advances in the field from the theoretical and observational points of view, we have organized a Special Issue dedicated to the multi-wavelength properties of gamma-ray binaries. This Special Issue includes seven manuscripts, which we summarize briefly in the following editorial.

The first two papers of this Special Issue are devoted to the numerical modeling of the wind/disk outflow from Be stars and its collision with the pulsar wind.

- "Modeling of the Wind/Disk Outflow from Be Stars", by S. Bogovalov and M. Petrov [1]. The objective of this work is to reproduce the formation of the fast polar wind and viscous disk outflow from Be stars in a unified physical picture. Numerical modeling of the plasma outflow from fast-rotating stars was performed taking into account the acceleration of the plasma due to the scattering of the radiation of the star in lines of plasma ions and the excitation of the hydrodynamic turbulence in the outflow. The fast polar wind naturally arises in this picture with an expected flow rate. For the first time, it is shown that a disk-like outflow with a relatively high level of turbulence is formed at the equator of fast rotating stars emitting radiation-driven wind. However, the level of turbulent viscosity is well below the level necessary for the formation of a Keplerian disk
- "The Major Role of Eccentricity in the Evolution of Colliding Pulsar-Stellar Winds", by M. Barkov and V. Bosch-Ramon [2].
  Binary systems that host a massive star and a non-accreting pulsar can be powerful non-thermal emitters. The relativistic pulsar wind and the non-relativistic stellar outflows interact along the orbit, producing ultrarelativistic particles that radiate from radio to gamma rays. To properly characterize the physics of these sources, and better understand their emission and impact on the environment, careful modeling of the outflow interactions, spanning a broad range of spatial and temporal scales, is needed. Full three-dimensional approaches are very computationally expensive, but simpler approximate approaches, while still realistic at the semi-quantitative level, are available. The authors present here the results of calculations performed with a

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quasi three-dimensional scheme to compute the evolution of the interacting flows in a region spanning in size up to a thousand times the size of the binary. In particular, they analyze for the first time the role of different eccentricities in the large-scale evolution of the shocked flows. The authors find that the higher the eccentricity, the closer the flows behave like a one-side outflow, which becomes rather collimated for eccentricity values $\geq$0.75. The simulations also unveil that the pulsar and the stellar winds become fully mixed within the grid for low-eccentricity systems, presenting a more stochastic behavior at large scales than in the highly eccentric systems.

The next paper is devoted to the methods of revealing the binary nature of the gamma-ray sources.

- "Searching for Gamma-Ray Binaries in Multiwavelength Catalogs", by J. Martí and P.L. Luque-Escamilla [3].
  The number of gamma-ray binaries currently known is still so small that each new finding would represent a significant expansion of its population. This paper presents a possible hunting strategy based on screening different catalogs to filter potential peculiar stars consistent with gamma-ray sources whose association at lower energies is not yet certain. The applications of this strategy allowed the authors to propose two candidate binary systems, HD 3191 and LS 4686, as a plausible counterparts of the unidentified Fermi sources 4FGL J0035.8+6131 and 4FGL J1808.8-1949c.

Four more papers are devoted to the recent multi-wavelength observations of the classical gamma-ray binaries PSR B1259-63, LSI +61°303 and HESS J0632+057.

- "Multi-Wavelength Properties of the 2021 Periastron Passage of PSR B1259-63", by M. Chernyakova et al. [4].
  PSR B1259-63 is a gamma-ray binary system hosting a radio pulsar orbiting around a O9.5Ve star, LS 2883, with a period of 3.4 years. The interaction of the pulsar wind with the LS 2883 outflow leads to unpulsed broadband emission in the radio, X-ray, GeV and TeV domains. One of the most unusual features of the system is an outburst of GeV energies around the periastron, during which the energy release substantially exceeds the spin down luminosity under the assumption of the isotropic emission. In this paper, the authors present the first results of a recent multi-wavelength campaign (radio, optical and X-ray bands) accompanied by the analysis of publicly available GeV Fermi/LAT data. The campaign covered a period of more than 100 days around the 2021 periastron and revealed substantial differences from previously observed passages. The authors report a major delay in the GeV flare; weaker X-ray flux during the peaks, which are typically attributed to the times when the pulsar crosses the disk; and the appearance of a third X-ray peak never observed before. The authors argue that these features are consistent with the emission cone model in the case of a sparser and clumpier disk of the Be star.
- "Fermi-LAT Observation of PSR B1259-63 during Its 2021 Periastron Passage", by Zhi Chang et al. [5]
  In this paper, authors compare all available Fermi-LAT data covering several periastron passages of PSR B1259-63 and confirm that the delay of the GeV flare in 2021 is larger than it was during the 2017 periastron and much larger than during earlier periastrons. To explain such a behaviour, the authors explore the possibility that the observed delay is due to a slow precession of the warped Be star equatorial disk.
- "A Precessing Jet Scenario for the Multi-Wavelength Long-Term Modulation of LSI +61°303", by F. Jaron [6].
  The high-mass X-ray binary LSI +61°303 is detected across the electromagnetic spectrum from radio until the very high energy γ-ray regime. The emission is not only highly variable on many time scales but is also periodic at all observed wavelengths. Periodic modulation was observed on different time-scales, ranging from hours, over months to several years. The subject of this article is study of a super-orbital, long-term modulation of $\sim$4.6 years. The authors review the observation of this periodic

modulation at multiple wavelengths and investigate systematic relationships between them. In particular, radio observations reveal that the long-term modulation is a very stable feature of the source. Observations at other wavelengths result in a phase-shift of the modulation pattern that is a systematic function of energy. The stability of this period favors a scenario in which the long-term modulation is the result of a precessing jet giving rise to periodic changes in the Doppler factor, beating with the orbital modulation of the accretion rate. The authors explain the phase-shifts across energy bands in a scenario with shorter wavelengths originating closer to the base of the presessing jet. A significant deviation in the TeV emission from this trend possibly requires a different explanation related to magnetic reconnection events.

- "Optical and near-infrared monitoring of gamma-ray binaries hosting Be Stars", by Yu. Moritani and A. Kawachi [7].
  In this paper, authors compile optical and near-infrared observations for the three gamma-ray binaries hosting Be stars: PSR B1259-63, LSI +61°303 and HESS J0632+057. The emissions from the Be disk are considered to vary according to the changes in its structure, some of which are caused by interactions with the compact object. Due to the high eccentricity and large orbit of these systems, the interactions and the resultant observables depend on the orbital phase. To explore such variations, multi-band photometry and linear polarization were monitored for the three considered systems, using two 1.5 m class telescopes: IRSF at the South African Astronomical Observatory and Kanata at the Higashi–Hiroshima Observatory. The long-term light curves indicate the orbital modulations in all the systems, although the variations differs from system to system. The diversity of the variation is possibly related to the difference in the size and base density of the Be disk, the disk size compared to the orbit, and the alignment of the Be disk plane with respect to the orbital plane.

All papers included in this Special Issue report recent progress in the field and demonstrate that despite intensive theoretical and observational efforts further studies are necessary to clarify the existing problems and to advance this exiting area.

Conflicts of Interest: The authors declare no conflict of interest.

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