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New stellar γ-ray source classes and their theoretical implications

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Gamma-ray emission from stellar sources has been detected at very high energies by the Cherenkov telescopes and/or at high-energy gamma-rays by space-borne instruments. In addition to the well-known X-ray binaries systems detected by H.E.S.S. and MAGIC, new types of stellar γ-ray sources have emerged recently. Here I summarize the main observational results and theoretical aspects of these sources as well as of the new potential candidates.

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1. Introduction

In the last years, a major progress has taken place in the detection of γ-ray emission from stellar systems. The Cherenkov telescopes H.E.S.S., MAGIC and VERITAS have contributed to the discovery of stellar sources as a class in the very high-energy (VHE) γ-ray sky. In the high-energy (HE) γ-ray range, *AGILE* and *Fermi* are detecting sources already observed at very high energies and discovering also new ones. Among the sources found in the HE and VHE band, there are several binary systems that contain a compact object, a black hole (BH) or a neutron star, and a high-mass bright star. More recently, colliding wind binaries like η Car, or star forming regions like Westerlund 2 have also turned out to be γ-ray sources. In the following sections we describe the different types of stellar sources that either have been detected at γ-rays or are potential γ-ray emitters.

2. Accreting X-ray binaries

Cygnus X-1 is the first binary system for which dynamic evidence for a BH was found [1]. It is also the brightest persistent high-mass X-ray binary (HMXB) in the Galaxy, radiating a maximum X-ray luminosity of a few times 10^{37} erg s^{-1} in the 1–10 keV range. At radio wavelengths the source displays a $\sim$15 mJy flux density and a flat spectrum, as expected for a relativistic compact jet (one-sided, with velocity $v > 0.6c$) during the low/hard state [2]. Arc-minute extended radio emission around Cygnus X-1 was also found using the VLA [3]. Its appearance was that of an elliptical ring-like shell with Cygnus X-1 offset from the center. Later, in [4] such structure was recognised as a jet-blown ring around Cygnus X-1. This ring could be the result of a strong shock that develops at the location where the pressure exerted by the collimated jet, detected at milliarcsec scales, is balanced by the ISM. The observed radiation would be produced through thermal Bremsstrahlung by ionized gas behind the bow shock.

MAGIC observed Cygnus X-1, and strong evidence (4.1σ post-trial significance) of TeV emission was found during a short-lived flaring episode [5]. These TeV measurements were coincident with an intense state of hard X-ray emission observed by *INTEGRAL*, although no obvious correlation between the X-ray and the TeV emission was found [6]. The detection occurred slightly before the superior conjunction of the compact object, phase at which the highest VHE γ-ray opacities are expected. After computing the absorbed luminosity that is caused by pair creation for different emitter positions, it has been suggested that the TeV emitter is located at the border of the binary system not to violate the X-ray observational constraints [7]. A recent study of the opacity and acceleration models for the TeV flare shows, under the assumption of negligible magnetic field, that an electromagnetic cascading model can explain qualitatively the observed TeV spectrum, but not its exact shape [8].

Cygnus X-3 is among the most intensively studied microquasars in the Galaxy. The system is a high-mass X-ray binary with an orbital period of 4.8 hours, with a WN Wolf-Rayet companion star seen through a high interstellar absorption ($A_V \geq$10 mag) that renders the optical counterpart undetectable in the visual domain. The nature of the compact object, black hole or neutron star, is not yet firmly established. The system undergoes strong radio flares one or two times per year, with flux density increments of almost three orders or magnitude above the normal quiescent level of

$\sim$0.1 Jy at cm wavelengths. Collimated relativistic jets from this microquasar were reported soon after some of these flaring episodes, flowing away in the North-South direction (see e.g. [9, 10].

The *AGILE* and *Fermi* satellites detected transient γ-ray emission above 100 MeV associated with Cygnus X-3 [11, 12]. These results show that Cygnus X-3 is a new HE γ-ray source. At TeV energies, Cygnus X-3 has not been detected yet by the new generation of Cherenkov telescopes [13].

3. Pulsar wind binaries

PSR B1259$-$63 is a binary system containing a Be main sequence donor, known as LS 2883, and a 47.7 ms radio pulsar orbiting its companion every 3.4 years in a very eccentric orbit, with $e = 0.87$ [14]. The radiation mechanisms and interaction geometry in this pulsar/Be star system were studied in [15]. These authors concluded that the star-pulsar wind interaction was the most feasible radiation powering mechanism. This was the first variable galactic source of VHE gamma-rays discovered [16]. The TeV lightcurve shows significant variability and the observed time-averaged energy spectrum can be fitted with a power law with a photon index $\Gamma_{\rm VHE} = 2.7 \pm 0.2_{\rm stat} \pm 0.2_{\rm sys}$. Different models have been recently proposed to try to explain these observations. In a hadronic scenario, the emission and lightcurve at TeV, as well as in the radio/X-ray band, could be produced by collisions of high energy protons accelerated by the pulsar wind and protons of the the circumstellar disk (pp), plus the emission from the pp secondary particles [17]. A leptonic scenario is presented in [18], in which it is shown that the X-ray and the TeV lightcurves can be explained by an X-ray/IC scenario of non-thermal emission.

4. Dubious cases and new candidates

There are two X-ray binaries that produce variable GeV and TeV emission LS I +61 303 [19] and LS 5039 [20]. Presently, there is not strong evidence supporting the black hole or neutron star nature of the compact object.

LS I +61 303 shows periodic non-thermal radio outbursts on average every $P_{\rm orb}$=26.496 days [21]. In [22] it was reported the discovery of an extended jet-like and apparently precessing radio emitting structure with angular extensions of 10–50 milliarcseconds. VLBA images obtained during a full orbital cycle show a rotating elongated morphology [23], which may be consistent with a model based on the interaction between the relativistic wind of a young non-accreting pulsar and the wind of the stellar companion ([24]; see nevertheless [25] for a critic review of this scenario).

The radio emission of LS 5039 is persistent, non-thermal and variable but no strong radio outbursts or periodic variability have been detected so far [26, 27]. VLBA observations allowed the detection of an elongated radio structure, interpreted as relativistic jets [28]. The discovery of this bipolar radio structure, and the fact that LS 5039 was the only source in the field of the error box of the EGRET source 3EG J1824$-$1514 showing X-ray and radio emission, led Paredes and collaborators [28] to propose their physical association. High-resolution (VLBI) radio observations of LS 5039 along the orbit are necessary for the detection of morphological and astrometric changes, which can be useful to disentangle the nature of the compact source (see [29]). A theoretical discussion of the radio properties of LS 5039 can be found in [30].

Some properties of LS 5039 and LS I +61 303 and an individual description of them can be found in [31]. Also, a thorough discussion of the different theoretical models for these systems is presented in [32].

A new TeV binary candidate, HESS J0632+057, was discovered by the H.E.S.S. telescope array as a point-like source [33]. Its energy spectrum is consistent with a power law with photon index $\Gamma_{\rm VHE} \approx 2.53$. No evidence of flux variability was found. Observations with *XMM-Newton* revealed a variable X-ray source, XMMU J063259.3+054801, which is positionally coincident with the massive B0pe spectral type star MWC 148 (HD 259440) and compatible in position with HESS J0632+05 [34]. The X-ray spectrum is hard, and can be fitted with an absorbed power-law model. The spectral energy distribution of HESS J0632+057, assuming that the sources associated at different spectral bands are the real counterparts, looks similar to that of the TeV binaries LS I +61 303 and LS 5039. VERITAS observed HESS J0632+057 during three different epochs obtaining no significant evidence for γ-ray emission [35]. The H.E.S.S. detection and the VERITAS non detection seem to point to a long-term γ-ray variability. This seems to happen also in the X-ray band, when comparing the *XMM-Newton* data [34] and *Swift* data taken contemporaneously with VERITAS [35]. VLA and GMRT radio observations have found a faint and unresolved source at the position of MWC 148, with a significant flux variability on month timescales [36]. The TeV variability, as well as the X-ray and the radio variability clearly associated with MWC 148, gives support to the idea proposed by [34] that HESS J0632+057 is likely a new γ-ray binary. However, further observations are necessary to determine the binarity of MWC 148 (see, e.g., [37]).

5. Colliding winds in massive binary systems

Massive hot stars can generate strong winds with high mass-loss rates at the level of 10^{-6} – 10^{-5} $M_\odot$ yr^{-1}. These winds strongly affect the environment and shocks are expected to form, especially in massive star binaries, in which the winds from both stars collide. In some cases, the colliding wind region can be resolved at radio wavelengths [38, 39, 40]. Such region presents non-thermal radiation of synchrotron origin, indicating the presence of relativistic electrons. The existence of relativistic particles in an environment with a dense photon field makes inverse Compton losses unavoidable, and hence several authors have suggested that colliding wind binaries should be high-energy sources [41, 42, 43]. Based on specific radio information from some Wolf-Rayet (WR) binaries, some detailed models have been recently developed [44, 45, 46]. Two of these systems, WR 146 and WR 147, have been observed with the MAGIC telescope. Although the obtained results are compatible with background fluctuations, these are the first experimental limits on these objects [47]. The long orbital period (1350 yr, [48]) of this system makes it unlikely that γ-ray attenuation produces any distinctive feature in the spectrum. However, anisotropic IC scattering can produce flux variations that can allow one to estimate system parameters such as the inclination [46]. In this context, MAGIC data point to a high inclination for the WR 147 system.

Eta Car is one of the most remarkable objects of our Galaxy. It is a very massive star (~ 100 $M_\odot$) showing strong mass-outflow eruptions (e.g., [49]). Extensive spectral observations of η Car yield a period of 2020±4 days, giving strong support to a binary scenario [50]. The system would be highly eccentric ($e \sim 0.9$), with an O star companion of ~ 30 $M_\odot$. *INTEGRAL* detected very hard

X-ray emission from η Car in the 22–100 keV energy range, with a luminosity of 7×10^{33} erg s^{-1} [51].

The Carina region was observed with EGRET in the past, with no positive detection above 100 MeV. The γ-ray satellite *AGILE* has observed extensively this region, reporting the detection of a γ-ray source, 1AGL J1043$-$5931, consistent with the position of η Car, which is well within the 95% confidence radius error box of the *AGILE* source. The average γ-ray flux (>100 MeV) is $(37\pm5)\times10^{-8}$ ph cm^{-2} s^{-1}, which corresponds to an average γ-ray luminosity of 3.4×10^{34} erg s^{-1} for a distance of 2.3 kpc [52]. The *AGILE* γ-ray lightcurve was roughly constant during all the observations, although a few day timescale gamma-ray flare was detected a few months before periastron.

The association of 1AGL J1043$-$5931 with η Car, if confirmed, would imply the first evidence of >100 MeV γ-ray emission from a colliding wind system. The results obtained by *AGILE* seems to agree with what is expected from IC and neutral pion processes in colliding wind binaries [43, 45].

6. Massive stellar associations

Collective effects of the stellar winds of hot stars might play an important role in a rather young OB association (e.g. [53, 54, 55]), and the produced emission should be added to that generated by individual colliding wind binaries [41, 43, 45, 44].

The H.E.S.S. telescope detected the source HESS J1023-575, which is coincident with the young stellar cluster Westerlund 2 in the well-known HII complex RCW49. The source is extended and was detected with a high statistical significance [56]. Several sources that could be responsible for the TeV emission have been proposed [56]. One of these sources is the massive binary system WR20a, which is hosted by the open cluster Westerlund 2. However, the extension of the TeV emission does not support this binary as a possible counterpart. On the other hand, an scenario based on collective stellar winds from the massive and hot stars in the Westerlund 2 could be feasible. The association of HESS J1023-575 with Westerlund 2, if confirmed, would make of open clusters a new class of VHE γ-ray sources.

7. Gamma-rays from massive protostars

Massive protostars have associated bipolar outflows with velocities of hundreds of km/s. These outflows can produce strong shocks when interact with the ambient medium leading to regions of non-thermal radio emission. A non-thermal component has been found in some outflows, all of them associated with massive YSOs: Serpens [57], HH 80-81 [58], Cep A [59], W3(OH) [60] and IRAS 16547$-$4247 [61, 62]. Several works have explored the possible production of gamma-rays at the terminal points of jets that emanate from massive protostars embedded in dense molecular clouds [63, 64, 65]. These models predict that under certain conditions, the population of relativistic particles accelerated at the terminal shocks of the protostellar jets can produce significant γ-ray emission, that could be detectable by *Fermi* after few years of observations. At energies above 100 GeV, the emission level expected is of about 0.01 Crab, which could be detectable by Cherenkov telescopes for ~50 hours of observation time.

8. Summary

Several binary systems have been detected at HE and/or VHE gamma-rays. Two of them, Cygnus X-1 and Cygnus X-3, are accreting X-ray binaries showing relativistic radio jets. A very different system detected at TeV is PSR B1259−63, in which the power comes from the pulsar wind and not from accretion. There are two other systems, LS I +61 303 and LS 5039, which have been detected both at HE and VHE gamma-rays and the nature of the compact object is not known. Although the power mechanism of these systems is different (accretion, pulsar), all of them are radio and X-ray emitters and have a high-mass bright companion (O or B) star, which is a source of seed photons for IC scattering and target nuclei for hadronic interactions.

New types of stellar γ-ray sources have emerged recently. In particular, colliding wind binaries (Eta Carinae) and star forming regions (Westerlund 2) have been detected at HE and VHE respectively, whereas new potential candidates such as super fast X-ray transients [66, 67], massive young stellar objects [63], and low-mass X-ray binaries [64], have chances to be detected by the current generation of γ-ray telescopes .

INTEGRAL can be particularly useful to find/study γ-ray emitting sources that are deeply embedded in a dense environment, mainly sources related to massive star (e.g. SFXT, massive YSO, high-mass microquasars), since these sources may not be easily detectable in radio or soft X-rays because of strong free-free and photo-electric absorption.

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