Highlights of Galactic Science with the MAGIC telescopes

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PROCEEDINGS OF SCIENCE

Highlights of Galactic Science with the MAGIC telescopes

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There are several types of Galactic sources that can potentially accelerate charged particles up to GeV and TeV energies. These accelerated particles can produce Very High Energy (E>100 GeV) gamma-ray emission through different non-thermal processes such as inverse Compton scattering of ambient photon fields by accelerated electrons or pion decay after proton-proton collisions. Here we present highlight results of observations with the MAGIC telescopes on Galactic sources: millisecond pulsars, supernova remnants (SNRs), pulsar wind nebulae (PWNe), novae and binary systems. In particular, we present the promising PeVatron candidate SNR G106.3+2.7 containing an energetic PWN named Boomerang. Also, in the ongoing search for new source classes we looked for very-high-energy emission from the millisecond pulsar PSR J0218+4232 that has long been considered as one of the best candidates. Furthermore, we present the observations during an exceptionally bright X-ray outburst from the low mass X-ray binary MAXI J1820+070. Finally, we highlight the MAGIC results of the first nova detected at VHEs: RS Ophiuchi, a recurrent symbiotic nova located in the Milky Way. The detection with the MAGIC telescopes proves a hadronic origin of the the gamma-ray emission, and helps in understanding the contribution of novae to the cosmic-ray budget.

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Our home galaxy, the Milky Way, hosts sources accelerating the bulk of cosmic rays (CRs) up to at least the so-called CR knee, a break in the CR energy spectrum at ~ 3 PeV. Via radiation processes such as pion decay after proton-proton collisions or inverse Compton (IC) scattering of ambient photon fields by accelerated electrons, this population of non-thermal particles makes the Milky Way to shine bright in gamma rays. Thus in return, gamma rays are the perfect messengers to identify how CR are accelerated in the emitting sources, how they escape from the acceleration side, and finally how they diffuse into the interstellar medium (ISM). Among the known gamma-ray sources are objects such as Supernova Remnants (SNRs), Pulsar and Pulsar Wind Nebulae, Binary systems, massive stellar clusters, and symbiotic novae among others.

In this contribution, we will present recent results on Galactic sources from the MAGIC (Major Atmospheric Gamma Imaging Cherenkov) telescopes, a system of two imaging Cherenkov telescopes (IACTs) located at 2200 m altitude above sea level at the Observatorio del Roque de los Muchachos on the Canary island La Palma, Spain ($28^\circ\,46'$ N, $17^\circ\,53'$ W). The telescopes cover the energy range from ~ 30 GeV to $E > 100$ TeV. Within 50 h of observations at low zenith angles $Zd < 30^\circ$ MAGIC can detect point sources above 200 GeV as weak as $(0.66 \pm 0.03)\%$ of the Crab Nebula flux [1]. The results include the SNRs G106.3+2.7 and G78.2+2.1, the binary systems HESS J0632+057 and MAXI J1820+070, the millisecond pulsar PSR J0218+4232, and the recurrent, symbiotic nova RS Ophiuchi.

1. Binaries

Binary systems are systems of two gravitationally bound objects orbiting each other. Depending on the type of the companions (massive stars, black holes, or neutron stars) these kind of systems are capable of accelerating CR to high energies. A subclass of binary systems are gamma-ray binaries, whose energy spectrum peak at high energies above 100 MeV and extends up to very-high-energy (VHE) gamma rays above 100 GeV. One example of a gamma-ray binary is HESS J0632+057 consisting of a Be star (MWC 148) and most likely neutron star as the compact object, which interacts with the circumstellar disk of the former. In a 15 yr long study between 2004 and 2019, the current generation of IACTs, H.E.S.S., MAGIC, and VERITAS, collected ~ 450 hr of data on this system [2]. The extend of the large data set for the first time allowed to determine the orbital period from the gamma-ray data alone. The search found an orbital period of 316.7±4.4 days, which is consistent with the duration found at X-ray energies (317.3±0.7 days). Fig. 1 shows the light curves of the X-ray instruments and IACTs folded with the orbital period determined from the X-ray data. A correlation between the X-ray and gamma-ray emission confirmed the significant correlation found in previous studies with no indication of a time lag between these emission bands. No correlation was found between optical Hα measurements and X rays or gamma rays. The spectrum of HESS J0632+057 does not show any variations with the orbital period, but shows variability on flux decay time scales of < 20 days. This orbit-to-orbit variability together with uncertainties in the orbital solution poses a difficulty for modelling the spectrum of this source, though the correlation between X rays and gamma rays suggests a single population of (leptonic) particles. Future optical and gamma-ray campaigns reducing the limitations resulting from the candence of the current data.

MAXI J1820+070 on the other hand is a low-mass X-ray binary with a black hole (BH) as a compact object. Between March and October 2018, it underwent a bright X-ray outburst reaching

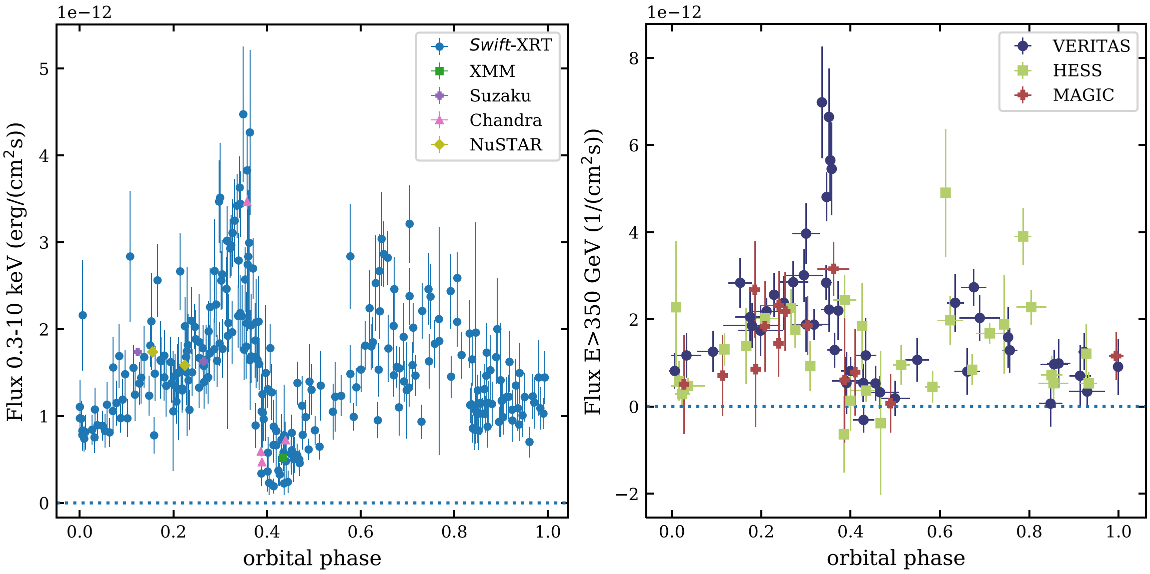


Figure 1: X-ray (0.3–10 keV; left) and gamma-ray (> 350 GeV; right) light curves as a function of the orbital phase, assuming an orbital period of 317.3 days (MJD_0 = 54,857.0). Vertical error bars indicate statistical uncertainties; note that these are smaller than the marker size for all X-ray instruments except for Swift-XRT. Fluxes are averaged over time intervals indicated by the horizontal lines (for most flux points these are smaller than the marker size). Figure from [2].

~ 4 times the X-ray flux of the Crab Nebula. Together with H.E.S.S. and VERITAS, MAGIC observed the MAXI J1820+070 outburst above 200 GeV for a combined total of 59.5 h [3]. The data were complemented by *Fermi* Large Area Telescope (LAT) data between 0.1 and 500 GeV, and multi-wavelength observations from radio to X-rays. Despite evidence of a non-thermal particle population seen in radio emission during the whole outburst, no gamma-ray emission from the source was observed. Still the obtained upper limits (ULs) and the multi-wavelength data allow setting meaningful constraints on the source properties with reasonable assumptions regarding the non-thermal leptonic particle population and the jet synchrotron spectrum. In particular, it is possible to show that, if a high-energy gamma-ray emitting region is present during the hard state of the source, its predicted flux should be about a factor of 20 below the *Fermi*-LAT ULs, and 4 lower than the UL for magnetic fields significantly below equipartition. During the state transitions from hard to soft state, assuming that electrons are accelerated up to ~ 500 GeV, the multi-wavelength data and the gamma-ray ULs allow constraining the distance between a potential high-energy and very-high-energy emitting region and the BH. The estimates consistently suggest a distance between 10^{11} and 10^{13} cm from the BH. Due to the relatively narrow range of allowed distances, similar outbursts from MAXI J1820+070 or other low-mass X-ray binaries might be detectable in the near future with upcoming instruments such as the Cherenkov Telescope Array (CTA).

2. Millisecond pulsars

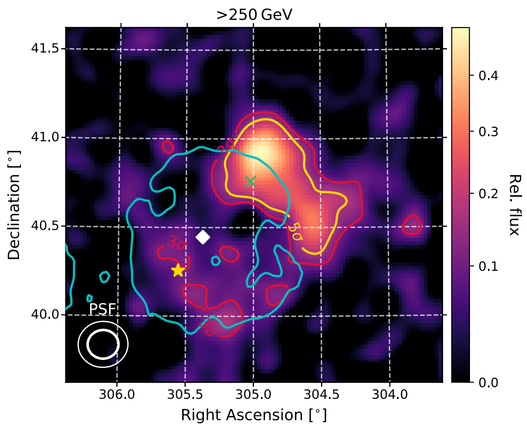
Pulsars are highly magnetised fast spinning neutron stars emitting beams of photons. Millisecond pulsar with periods of < 10 ms are a special case of this already extreme class of objects. The

PSR J0218+4232 is one of the most energetic pulsars (spin-down power of 2.4×10^{35} ergs^{-1}) of this kind and has long been considered as one of the best candidates for VHE gamma-ray emission. MAGIC observed this source between November 2018 and November 2019 and collected 87 h of good quality data [4]. These data were combined with 11.5 yr of *Fermi*-LAT data between 100 MeV and 870 GeV. The search for pulsed high-energy gamma-ray emission based on the *Fermi*-LAT data showed evidence for emission > 10 GeV and marginally for > 25 GeV. The emission is consistent with the clearly detection between 1 and 10 GeV. At higher energies no emission was found. Also the MAGIC data covering the range from 20 to 200 GeV showed no hint for emission, neither pulsed nor unpulsed, at higher energies. Modelling the broadband spectrum of PSR J0218+4232 from UV to VHE gamma rays results in predictions well below the MAGIC ULs. The curvature radiation component from particles accelerated mostly in the current sheet is expected to fall to flux levels too low to be detected by IACTs and the IC components are predicted to be at even lower flux levels. Hence, it will remain extremely challenging to detect VHE emission from PSR J0218+4232 maybe even with future ones, such as the Cherenkov Telescope Array.

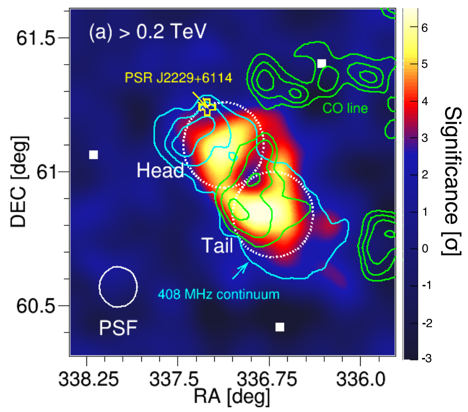
3. Supernova Remnants

Among the candidates for the main emitter of the Galactic component of CRs, SNRs are considered the most plausible one. The arguments in favour of SNRs are often collectively referred to as the "supernova paradigm," which includes the agreement between observed Galactic CRs and the predicted CRs from SNRs in terms of total energy density and spectral particle distribution (see [5] for a review). However, a comprehensive understanding of CR acceleration by SNRs and determining whether they are indeed the primary emitters of CRs in our Milky Way galaxy requires further evidence, particularly in three key aspects: 1.) Observational confirmation of SNR's ability to accelerate CRs to PeV energies, 2.) Comprehension of the particle escape mechanism from the accelerator into the ISM, and 3.) Understanding the propagation of CRs from their origin to Earth.

Between May and November 2015, as well as between April and September 2017, MAGIC conducted observations on the γ Cygni SNR, G78.2+2.1, accumulating an effective observation time of 85 hours [6]. This SNR is believed to be the remnant of a core-collapse supernova with an age estimated of $\sim$ 7000 years, placing it in the Sedov-Taylor phase. During this adiabatic phase, the speed of the SNR shock wave decreases, potentially enabling CRs to escape into the ISM. By combining the MAGIC data with 9 years of *Fermi*-LAT observations, three distinct emission regions in the vicinity of the SNR's radio shell were identified (Fig. 2a): emission from within the shell, emission from the surrounding ISM, and a region where the shock may be interacting with a molecular cloud. The most plausible and consistent interpretation for all three regions is a scenario in which the emission is dominated by hadrons and CRs currently escape the system. It is the first observation of CR escape from a system that concurrently confines less energetic particles. Modeling the gamma-ray emission within this scenario, we inferred the level of turbulence to be approximately $\delta B/B \approx 25\,\%$ and the time dependence of the maximum energy of the confined particles to follow $p_{\max} \propto t^{-2.55}$, which is steeper than the reduction resulting from the decrease in shock speed ($p_{\max} \propto t^{-1/5}$). The latter suggests that the level of turbulence also decreases over time.



(a)



(b)

Figure 2: (a) Sky map in units of relative flux (excess over background) of the γ Cygni region as observed by MAGIC at Energies > 250 GeV. Regions exceeding the 3σ (5σ) local, pre-trial test statistics significance for a point source are indicated by red (yellow) contours. The cyan line is the 400 K contour of the 408 MHz observation by the Canadian Galactic Plane Survey. The white diamond gives the position of the pulsar PSR 2021+4026, the green X the position of VER J2019+407, and the yellow star the position of Sadr (γ Cyg star; mag = 2.2). The inlay in the lower left corner shows the 39 % and 68 % containment contours of the MAGIC PSF. Figure from [6]. **(b)** Skymap of SNR G106.3+2.7 above 200 GeV. The position of PSR J2229.0+6114 is marked with the open yellow cross. The cyan contours show the radio emission of SNR G106.3+2.7 at 408 MHz by DRAO. The green contours represent 12CO (J = 1– 0) line intensity integrated over the velocity range from −6.41 to −3.94 km s^{-1}. Figure from [7].

MAGIC also studied the SNR G106.3+2.7, one of the most promising PeVatron candidates [7]. Various gamma-ray facilities have reported emission of 1-100 TeV from this object. In the radio band, this SNR exhibits a cometary shape, comprising a head and a tail region with distinct physical conditions. However, the specific region responsible for the 100 TeV emission as well as whether the nature of the emission is leptonic or hadronic remained uncertain. With 121.7 h of effective observation time between May 2017 and August 2019, we observed gamma-ray emission that spatially coincides with the radio continuum emission at both the head and tail of the SNR G106.3+2.7 (see Fig. 2b). Our results suggest that the emissions above 10 TeV detected by air shower experiments (Milagro, HAWC, Tibet ASγ, and LHAASO) originate solely from the SNR tail. Under this assumption, the multi-wavelength spectrum of the head region can be explained by either hadronic or leptonic models. In contrast, the observed spectrum in the tail can be reproduced by a hadronic model, assuming a proton spectrum with a cutoff energy of approximately 1 PeV for that region. This high-energy emission in a middle-aged SNR (4-10 kyr) can be attributed to a scenario in which protons that escaped from the SNR in the past interact with dense surrounding gases in the present. This makes this SNR the only observed possible PeV accelerator.

4. The first recurrent nova at VHE: RS Ophiuchi

Novae are luminous eruptions in close star binary systems with a white dwarf (WD) as compact companion, and in case of a symbiotic Nova a red giant. When the WD accreted a critical amount

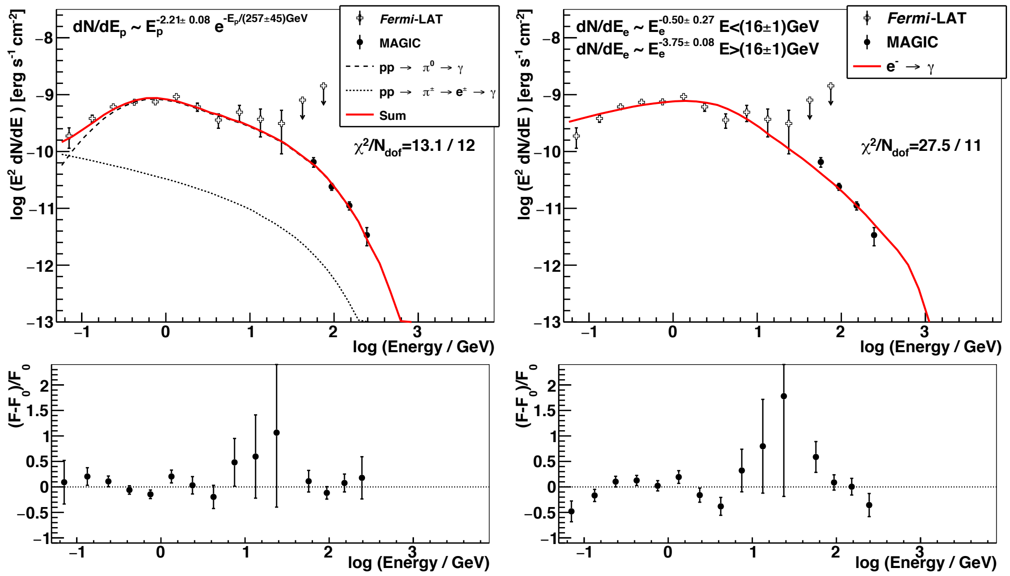


Figure 3: Spectral energy distribution of gamma-ray emission from the 2021 outburst of RS Oph measured by *Fermi*-LAT and MAGIC. The hadronic (*left*) and leptonic (*right*) models are tested. Figure from [10].

of matter from its companion a thermonuclear explosion is triggered on the surface of the WD. Though novae have been revealed to be high-energy gamma-ray emitters through observations by *Fermi*-LAT [8, 9], their mechanism of the gamma-ray emission remained unclear. A subclass of objects called recurrent novae, which allow us to observe repeated outbursts over a human lifespan. One well known recurrent nova is RS Ophiuchi (Oph) with a recurrence time scale of ∼15 years. In August 2021, it underwent a new outburst detected in the optical and GeV gamma-ray band. Responding alerts, MAGIC promptly started observing RS Oph, about one day after the burst's onset [10]. During the first four days following the eruption, MAGIC detected VHE gamma rays from RS Oph between 60 and 250 GeV with a statistical significance of 13.2σ. Thus, together with the H.E.S.S. telescopes [11] and the first Large-sized telescope of the CTA [12], MAGIC achieved the first detection of VHE gamma rays from a nova ever. The contemporaneous gamma-ray spectrum measured by *Fermi*-LAT and MAGIC suggests a common single component between 50 MeV and 250 GeV, as shown in Fig. 3.

Though both, protons and electrons, might be accelerated in the nova shock and emit gamma rays, the data strongly suggest a hadronic origin of the gamma-ray emission. The data suggest an increase of the particle maximum energy over time, which is in line with only mild cooling for protons, whereas electrons are expected to be subject to strong energy losses due to IC scattering. On top of the cooling, the leptonic model requires an break in the intrinsic electron spectrum, while the hadronic model can well describe the data with a power-law proton distribution with index of -2 and an exponential cut-off. Despite these additional free parameters the leptonic model yields a significantly worse fit than the hadronic one.

The VHE gamma-ray detection of RS Oph revealed the hadronic origin of the gamma-ray emission in the nova. It thereby introduced a new source class, which however probably only contributes a minor fraction to the CR sea ($\sim 0.1\,\%$). Still, novae eruptions can create bubbles of enhance CR density in their close environment. It remains to be seen if the acceleration and radiation mechanism observed in RS Oph is common among all novae, including classical novae, or if the mechanisms are unique to recurrent symbiotic novae.

5. Conclusion

These highlights already show the wide range of Galactic gamma-ray science, which can be performed with the current generation of IACTs like MAGIC. All of the studies presented above are multi-wavelength studies highlighting the importance of combining multiple instruments. Together air shower instruments in the northern hemisphere such as HAWC, LHAASO pushing gamma-ray energy range to PeV energies and even neutrino detectors like IceCube entering the field of Galactic science [13], MAGIC will continue to yield valuable insights into the CR acceleration processes in different Galactic environments in the coming years.

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