The Crab Nebula in Gamma-Rays

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The Crab nebula is one of the best studied objects in the sky, second only to the Sun. It is the remnant of a supernova explosion occurred in A. D. 1054, and it represents the prototype of an entire class of supernova remnants: Pulsar Wind Nebulae.
It consists of two different bright non-thermal sources — the pulsar and the nebula. Both objects have played a key role in the development of high-energy astrophysics. Thanks to their bright emission at all wavelengths, they have been observed by virtually all new astronomical instruments and have been at the origin of a wealth of important scientific discoveries.

pulsars: general   radiation mechanisms: nonthermal

This entry mostly deals with the gamma-ray phenomenology of the Crab pulsar and nebula and is based on the review paper "The Crab Pulsar and Nebula as seen in gamma-rays"[1].

1. The Crab pulsar in gamma-rays:

The Crab pulsar was one of the first detected pulsars ever, and actually the one that provided smoking gun evidence for the identification of these radio sources as neutron stars. Its existence had been predicted even before discovery[2], based on the need for an energy source to power the Crab nebula. Indeed, most of the pulsar spin-down energy dE/dt ≈ 10^{38} erg/s, ends up in a magnetized wind expanding with relativistic bulk speed. At some distance from the star, the wind is slowed down to match the conditions of non-relativistic expansion of the conducting cage of supernova ejecta that confines it. This transition is thought to occur at a termination shock (TS hereafter), where the bulk energy of the outflow is dissipated and particles are accelerated, giving rise, thereafter, to the bright non-thermal nebula.

The Crab pulsar is the source in this class with the broadest detected emission spectrum, extending from a few ×100 MHz to PeV photon energies[3]. While the advent of Fermi-LAT has revealed that High Energy (100–300 MeV photons; HE hereafter) gamma-ray pulsations are not uncommon among pulsars[4], despite recent efforts[5], no other pulsar has been firmly detected at VHE. Gamma-ray emission has long been thought to hold the key to understanding the hidden workings of pulsars magnetospheres[6], despite it only accounts for ~1% of the spin down power. The observation of the Crab pulsar in gamma-rays of progressively higher energy has had a tremendous impact on our ideas about pulsar magnetospheres and the mechanisms behind their emission in the different wavebands.

One of the open and controversial subjects of pulsar physics is the exact amount of pair production that should be expected from the magnetosphere of a given pulsar (the so called pair multiplicity, see e.g. Timokhin & Harding 2019[7]). The multiplicity can be estimated indirectly comparing PWNe observations and models, but the results obtained from this kind of observations are controversial in the case of the Crab nebula.

Gamma-ray observations allow for alternative constraints on pulsars magnetospheric models and on the number of pairs they produce. Particles extracted from the star quickly accelerate during the extraction process and emit high-energy photons. In the intense magnetic field close to the star, photons with sufficiently large energies are absorbed and initiate a pair production cascade. The threshold energy for photons to escape rather than be absorbed, and give rise to a new generation of pairs, depends on the magnetic field strength; therefore, it will be different at different locations in the magnetosphere. Three main possible locations have been suggested since the early times of pulsar studies — the polar caps, with emission coming from the pulsar vicinity[8][9], the slot gaps [10][11] and the outer gaps[12], with emission coming from larger distances from the pulsar and being the result of curvature or Inverse Compton radiation, rather than synchrotron. In addition to gap models, another scenario that satisfies this constraint is one in which particle acceleration and subsequent gamma-ray emission occurs in the equatorial current sheet of the pulsar wind[13].

The detection by Fermi of a large number of gamma-ray pulsars seemed to disfavor polar caps as the main site of gamma-ray emission[14]: the simplest argument in this sense is the large number of detected pulsars, easier to reconcile with the wider beam of radiation predicted by models locating the emission further from the pulsar. Further evidence for an origin of the emission far from the star surface came from the detection of VHE pulsations from the Crab pulsar by MAGIC[15][16] and VERITAS[17].

2. The Crab nebula in gamma-rays:

The Crab nebula has been known as a source of VHE gamma-rays since the late 1980s[18], and was detected, for the first time, at MeV photon energies in the early 1990s[19]. The observed emission was readily interpreted as the result of IC scattering between the relativistic leptons populating the nebula and ambient photons, mainly contributed by the cosmic microwave background (CMB), thermal dust emission, and nebular synchrotron emission[20][21]. In the last 15 years, the advent of the current generation of HE (Fermi-LAT and AGILE) and VHE (MAGIC, VERITAS, H.E.S.S., HAWC, Tibet As-γ, LHAASO) gamma-ray telescopes has allowed us to gain much deeper insight in the properties of the Crab nebula at these highest energies, and has also brought two big surprises: variability in the MeV range[22][23][24] and detection up to unexpectedly high energies[25].

The Crab nebula is the PWN for which most models were developed and over which most of our understanding of the entire class is based. The largest amount of the rotational energy lost by the pulsar goes into accelerating a relativistic outflow, mostly made of pairs (though the presence of ions is not excluded) and a toroidal magnetic field. The outflow starts out cold (low emissivity, as highlighted by the presence of an underluminous region surrounding the pulsar[2]) and highly relativistic, until it reaches the termination shock (TS). Since the outflow is electromagnetically driven, it must start out as highly magnetized at the pulsar light cylinder (where the coronating magnetosphere opens): the ratio between Poynting flux and particle kinetic energy, σ, is thought to be $\sigma(R_{LC}) \approx 10^4$ [26][27]. In contrast, the magnetization must be much lower at the TS, in order for the flow to be effectively slowed down. Steady-state 1D magnetohydrodynamics (MHD) models predict a very low magnetization at the TS, $\sigma \sim 10^{-3}$. This estimate has later been revised towards larger values of σ in light of 3D MHD numerical modeling, but the general consensus is still that $\sigma(R_{TS})$ cannot be much larger than unity. How the conversion of the flow energy from magnetic to kinetic occurs, between the light cylinder and the TS, is still a matter of debate, and this problem is known as the σ-problem.

The morphology of the synchrotron nebula is known in great detail, at photon energies from radio to X-rays, and hence, represents both a driver and a very challenging test for theoretical and numerical models. The most advanced available modeling of the Crab nebula so far is based on the assumption that beyond the TS, MHD provides a good description of the flow dynamics, with models from 1D to more sophisticated 3D able to account for different aspects and fine details of the Crab structure. 3D MHD simulations[28][29][30][31] in particular show that, with the third spatial dimension available, kink-type plasma instabilities produce considerable mixing of the magnetic field in the entire nebula, with an ensuing high level of magnetic dissipation. This definitely allows for the increase of the initial magnetization in the pulsar wind to values of order unity, but with a final average magnetic field only a factor ~2 larger than what estimated in 2D. The synchrotron emission maps computed on top of these simulations show that, for parameters appropriate to reproduce the jet-torus X-ray morphology, the surface brightness distribution at radio and optical frequencies becomes much more uniform in 3D than in 2D, reflecting the structure of the magnetic field. The main limitation of 3D models is that they require a huge amount of numerical resources and time to be performed with present facilities, and thus only a limited part of the sources evolution can be actually reproduced.

As far as gamma-rays are concerned, no detailed morphological information is available, due to the very limited angular resolution of gamma-ray telescopes. For a long time, the only available information simply constrained the gamma-ray nebula to lie within the radio synchrotron one [32][33][34]. Only recently an estimate of the Crab nebula extension in gamma-rays became available: it turns out to be ∼52″ in the 700 GeV—5 TeV energy range, and hence, smaller than in the UV (where the extension is ∼2.5′) and very similar to the X-ray size (∼50″), which is perfectly consistent with a picture in which TeV gamma-rays are produced by synchrotron X-ray emitting particles, and in good agreement with numerical results[35].

3. Acceleration of particles in the Crab nebula:

The era of multi-D MHD simulations also opened up the possibility of using spatially resolved time-variability as an additional, powerful diagnostic for the physical properties of the plasma in the nebula and, most notably, for the processes responsible for particle acceleration within it. Brightness variations of the nebular structures has been known to occur, at optical frequencies, for a long time: the so-called wisps were first identified by Scargle 1969[36]. These features, strongly resembling outward propagating plasma waves, appear at distances from the pulsar comparable with the TS radius in the equatorial plane, and then progressively fade while moving outward, with time-scales from weeks to months[37]. Similar features were later observed both in the X-rays[38] and in the radio band[39][40]. In spite of these morphology variations, however, the integrated emission was found to vary only by a few percent per year[41]. The wisps appearance and time evolution, however, is not the same at all wavelengths[42], and varies in a way that, within the MHD framework, can only be interpreted as due to differences in the particle spectrum at different locations along the shock front, or, in other words, to particles in different energy ranges being accelerated in different places[43]. On the other hand, the plasma conditions along the TS front are expected to be highly non-uniform, especially in terms of magnetization of the flow, and this is an important parameter to determine the kind of acceleration process that can be locally at work.

The nebular synchrotron spectrum is consistent with a broken power-law, with a particle spectral index $\gamma_R = 1.6$ for radio-emitting particles and $\gamma_X = 2.2$ for X-ray-emitting ones[44]. At the highest energies, particles must be accelerated at the TS; otherwise, the decrease in size of the nebula with increasing frequency could not be explained. On the other hand, radio-emitting particles could be, in principle, accelerated anywhere in the nebula. In the MHD framework, the observed differences in the wisps properties at the different wavelengths can only be accounted for if X-ray-emitting particles are accelerated in the equatorial sector of the TS (where the Fermi-I process could work if efficient reconnection taking place in the magnetically striped part of the wind ensures low enough magnetisation), while lower-energy particles are predominantly accelerated elsewhere, either in the body of the nebula (where Fermi-II, turbulent acceleration could be at work) or at high latitudes along the TS[43] (where either magnetic reconnection or resonant absorption of ion cyclotron waves , with the latter requiring the presence of ions in the wind[45][46] could operate).

The possibility of analyzing spatially resolved time-variations in the gamma-rays would provide essential clues to the acceleration mechanism, but this type of analysis is currently out of reach due to the poor spatial resolution of the observations.

3. Crab flares:

A much unexpected discovery that came from gamma-ray observations of the Crab Nebula was that of episodes of extremely fast gamma-ray variability, the so-called gamma-ray flares. Global variations of the emissivity were predicted in the Fermi band as a consequence of rapid synchrotron burn-off of particles at the high-energy cut-off of the distribution[47]. Assuming radiation reaction limited acceleration, the maximum energy up to which electrons can be accelerated is $E_{max,rad} \sim 6$ PeV $\eta(B_{-4})^{-1/2}$, assuming an acceleration due to an electric field ηB, with B the magnetic field strength (expressed in units of 10^{-4} G). PeV energies can then be reached only if $\eta \sim 1$ and B is not much in excess than 10^{-4} G. In this synchrotron-loss limited regime the maximum energy of synchrotron-emitted photons is ~230 MeV, and global emissivity variations are then expected in the MeV range on timescales of months.

The big surprise came with Agile[22] and Fermi[23] observations showing, on top of continuous small variations, some dramatic events, where not only the flux increases by a factor of several (up to 30 for the most spectacular event, in April 2011) over a period of one to a few weeks, but the emission extends well beyond 230 MeV, reaching GeV photon energies. In addition, the amount of energy released is typically non-negligible, and in the biggest detected flare, was really huge, corresponding to an isotropic luminosity of 0.01 the pulsar spin-down one. At present, 17 flares have been clearly identified[48], with a flare rate of 1.5 per year. In addition to episodes of sudden increase of the gamma-ray flux, dips are observed in the same energy band[49].

The flares are not easy to interpret, and up to now, there is still no accepted model to explain them. First of all, emission beyond 230 MeV implies $\eta > 1$, which cannot be accommodated within ideal MHD. The possible solutions to this puzzle are as follows:

1. the acceleration is due to a non-ideal mechanism with $\eta \gg 1$, as can be the case for magnetic reconnection[50][51][52][53][54][55][56];
2. the acceleration occurs in a region of low magnetic field and then the emission occurs in a more magnetized region[49][57];
3. the emission comes from particles with mildly relativistic bulk motion, so that the frequency and power of the radiation are Lorentz-boosted[58][59].

All these possibilities have been widely explored in the literature.

4. Constraining the pulsar wind composition:

The pulsar wind is generally considered to be mostly composed of electron–positron pairs, while the possible presence of a hadronic component is still a matter of debate[21][60][61][62]. If present, despite being a minority by number, hadrons could even be energetically dominant in the wind, changing drastically our understanding of the pulsar wind properties. The relativistic hadrons possibly present in the Crab nebula could generate electromagnetic emission in the form of VHE gamma-rays deriving from decay of neutral pions produced in nuclear collisions with the gas in the SN ejecta. This spectral contribution is only expected to become detectable above 100∼150 TeV, where IC scattering emission starts to be suppressed by the Klein–Nishina effect. The current IACTs (Imaging Atmospheric Cherenkov Telescopes), such as H. E. S. S. and MAGIC, could find no evidence of hadronic emission up to their sensitivity limit around tens of TeV. Emission beyond 100 TeV is currently only accessible with sufficient sensitivity by water Cherenkov detectors and air shower detectors. Indeed, the Crab nebula was detected above 100 TeV by HAWC employing the former technique[63] and by Tibet AS-γ[64] employing the latter. Very recently, LHAASO, combining both techniques, has obtained the record-breaking detection of >PeV photons from this source[25], opening up a window to finally see the possible emergence of the hadronic contribution. In fact, the increasing uncertainties above 500 TeV make the LHAASO spectrum still consistent with a purely leptonic origin of the emission. Under such an assumption, the PeV range data can be effectively used to constrain the strength of the magnetic field at the shock, which cannot exceed (112 ± 15) μG or otherwise radiation reaction would make it impossible to achieve particle acceleration up to the 2.8 PeV energy needed to explain the highest energy data point as due to IC scattering in the Klein–Nishina regime.

A side remark is that in such a field even a 2.8 PeV electron would emit synchrotron radiation at 50 MeV; even a Lorentz boost by a factor $\Gamma_w \sim 3$–4 would not be enough to account for the Crab gamma-ray flares. In other words, the flares should come from a different region of the nebula, with higher magnetic field, or otherwise imply the presence of 10 PeV electrons, extremely close to the maximum potential drop available from the Crab pulsar, which is also the limiting energy for particles accelerated anywhere in the nebula. On the other hand, taken at face value, the LHAASO data seem to suggest that a new component might be showing up at the highest energies. This new component is consistent with a quasi-monochromatic distribution of protons with energy around 10 PeV. This is exactly what would be expected by models assuming that protons are part of the wind emanating from the Crab pulsar with a Lorentz factor ≈107. Of course, smoking gun evidence would be the detection of neutrinos[60], likely possible with the upcoming sensitivity improvement of dedicated experiments.

Recently, LHAASO[65] has also detected about ten more EHE emitters in the Galaxy (partially overlapping with the sources already detected by HAWC[66] beyond 56 TeV). For the majority of these sources, the distance between the center of the emission and the nearest pulsar is less than, or comparable with, the instrument PSF, so it is not unlikely that almost all these PeVatrons are associated with pulsars (and possibly leptonic in nature[67]). The much better spatial resolution of IACTs might also help to shed light on the real nature of these extreme accelerators, and assess whether acceleration of particles to PeV energies and beyond is a generic property of PWNe powered by energetic pulsars, rather than a unique property of Crab.

5. Conclusions:

The Crab nebula and its pulsar are certainly among the most-studied astrophysical sources in the sky, and as such, they provide an excellent laboratory to investigate many aspects of high-energy astrophysics and relativistic plasma physics. At the same time, this system has proven to be an endless source of surprises. The discovery of the Crab pulsar was the confirmation that radio pulsars are actually rotating neutron stars, while the study of the Crab nebula has taught us that most of the pulsar spin-down energy goes into a highly relativistic and magnetized outflow. In this article, we reviewed what we have learned about the pulsar and the nebula in the last two decades. While both objects have a very broad emission spectrum, high-energy observations, and gamma-ray observations in particular, have played a special role in recent developments.

The Crab Nebula is very different, in many respects, from the evolved PWNe that future IACTs will detect in very large numbers. In this sense, the Crab is not the source to look at if the purpose is that of learning about the average properties of gamma-ray-emitting PWNe. On the other hand, the Crab keeps being the best place to learn about the processes that make these objects such extreme accelerators, both in terms of efficiency and achievable energies. By looking at this ever-surprising source, future IACTs might be able to tell us that PWNe are themselves hadronic PeVatrons.

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