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MeV emission from pulsar wind nebulae

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Abstract. Pulsar wind nebulae (PWNe), the structures formed by the interaction between the neutron star's environment and its rotation-powered outflow (or "pulsar wind"), comprise a significant fraction of the identified γ-ray population in the Milky Way. As a result, these sources must produce extremely energetic leptons, but how they do so is poorly understood. As described in this article, measuring the MeV properties of PWN is critical for understanding how PWN are able to accelerate $e^{\pm}$ to PeV energies (and beyond).

Key words. Acceleration of particles, Stars: pulsars: general, ISM: supernova remnants

1. Introduction

A majority of core-collapse supernovae are believed to produce a neutron star, which in many cases is rotating rapidly (period $P \lesssim 1$ s) and has an extremely strong surface dipole magnetic field ($B_{\rm ns} \gtrsim 10^{12}$ G). This combination of a strong magnetic field and rapid rotation generates a powerful electric field at the "polar cap," sufficiently strong to rip charged particles off the surface. The photons emitted by these particles as they travel in the curved magnetic field convert to $e^{\pm}$ pairs in this strong field, triggering a cascade of pair production near the surface. Those particles generated along "open" field lines travel beyond the neutron star's light-cylinder, comprising the "pulsar wind" whose confinement by the surrounding medium creates a pulsar wind nebula (PWN). Some PWNe have been detected up to $\sim$ 50TeV (e.g., Abeysekara et al. 2017), and this class of sources dominate the identified (and likely unidentified) TeV γ-ray source in the Galactic Plane (e.g., H. E. S. S. Collaboration et al. 2018). As a result, these sources must contain leptons with PeV energies. However, how particles are accelerate to such high energies inside a PWN is poorly understood. As described in §2, different models for the maximum particle energy accelerated inside a PWN result in very different evolutions in its MeV luminosity but not in other wavebands. In §3, we present the diverse MeV properties of known PWNe predicted by current models, as well as which physical quantities most significantly impact their emission in this band.

2. Particle acceleration scenarios

The primary sites for a particle acceleration inside a PWN are believed to be the neutron star magnetosphere, and at the "termination shock" where the unshocked pulsar wind first encounters previously injected material. Current models suggest that the maximum particle energy accelerated inside the PWN, $E_{\rm max}$ would be:

– determined the electric potential $\Phi_{\rm psr}$ at the neutron star's polar cap, or (e.g.,

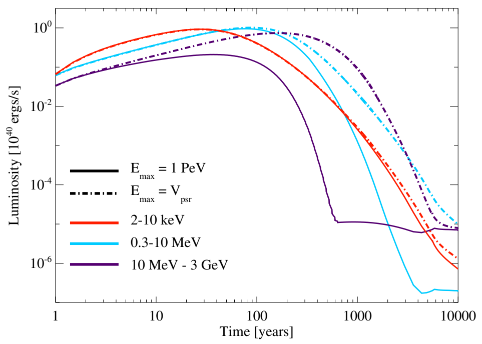

Fig. 1. Evolution of the 2-10 keV (red line), 0.3-10 MeV (cyan), and 10 MeV - 3 GeV (purple) luminosity of a PWN where the only difference is the value of the maximum particle $E_{\rm max}$ – $E_{\rm max}$ = 1 PeV (solid line) and $E_{\rm max} = e\Phi_{\rm psr}$ (dot-dashed line).

Bucciantini et al. 2011):

$$E_{\rm max} \equiv e\Phi_{\rm psr} = e\sqrt{\frac{\dot{E}}{c}} \text{ (cgs units)}, \qquad (1)$$

here e is the charge of the electron, c is the speed of light, and $\dot{E}$ is the spin-down luminosity,

– determined by the maximum particle energy confined within the termination shock (e.g., de Jager, & Djannati-Ataï 2009):

$$E_{\rm max} \propto \sqrt{\frac{\dot{E}}{c}}, \qquad (2)$$

the same temporal evolution as the previous case,

– limited by the saturation of Weibel instabilities which develop in the shock, in which case $E_{\rm max}$ is approximated constant with time (e.g., Sironi et al. 2013)

To investigate the impact of these different prescriptions for the temporal evolution of $E_{\rm max}$, simulate the broadband spectral energy distribution (SED) of a PWN inside a supernova remnant (SNR) using the evolutionary model described by Gelfand et al. (2009) to for identical pulsar, pulsar wind, and supernova properties but different values of $E_{\rm max}$ – $E_{\rm max} = V_{\rm psr} = e\Phi_{\rm psr}$ and $E_{\rm max}$ = 1 PeV (a value comparable to what has been derived from modeling the SED of known PWN; e.g., Gelfand et al. 2015). As shown in Figure 1, the X-ray (2–10 keV) luminosity of the PWN is largely independent of the evolution $E_{\rm max}$ – with only small ($\lesssim 5\%$) differences expected when the system is $>$ 1000 years old. However, the 0.3 – 10 MeV and 10 MeV – 3 GeV luminosities is differs significantly between these two prescription. This is because the synchrotron emission of the highest energy particles peaks at MeV energies. Furthermore, for the chosen set of parameters, with $E_{\rm max} = V_{\rm psr}$ results in a much larger MeV luminosity at late times than $E_{\rm max}$ = 1 PeV – a result of the decreasing nebular magnetic field as the PWN grows in size.

3. Predicted MeV properties of PWNe

While, as described in §2, the MeV properties of a particular PWN is very sensitive to the evolution of $E_{\rm max}$, it is unfeasible to monitor the MeV emission of a PWN over the centuries to millenia timescale needed to observe these differences. Therefore, differentiating between models for particle acceleration in PWNe requires analyzing the SED of different PWNe, each one essentially representing a snapshot in its evolution.

Currently, the best way of determining the spectrum of particles accelerated inside a PWN is to fit its observed properties (e.g., size, SED) using a model for its dynamical and radiative evolution. Several such models exist in the literature, with different models using different prescriptions for $E_{\rm max}$ as described in §2 (see Gelfand 2017, for a recent review). However, as shown in Figure Figure 2, even for a particular prescription of $E_{\rm max}$ (in this case constant $E_{\rm max}$; Gelfand et al. 2009), the predicted MeV properties varies significantly for different PWNe. In the case of G21.5−0.9, very little emission is expected between $\sim$ 0.1 – 1 MeV due to the low value of $E_{\rm max}$ inferred from the softening in the X-ray spectrum observed around $\sim$ 7 keV (e.g., Hitomi Collaboration et al. 2018; Guest et al. 2019). Consequently, the high energy ($\gtrsim$ 1 MeV) emission of this source will be dominated by inverse Compton radiation, whose spectrum is expected to rise steeply between $\sim$ 1 MeV and 3 GeV. Alternatively, for Kes 75 currently modeling predicts this

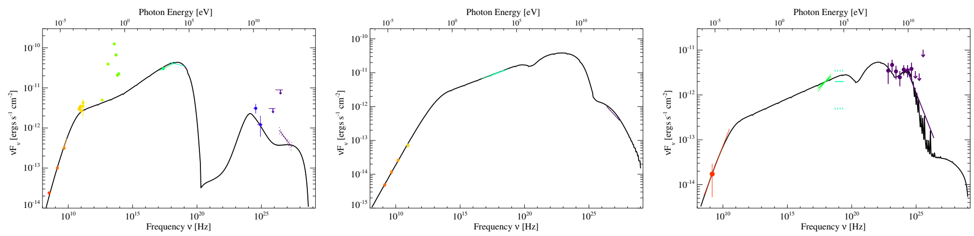

Fig. 2. Observed (color points) and predicted (black line) SED of PWNe G21.5−0.9 (*left*; Gelfand et al. in prep), Kes 75 (*center*; Safi-Harb et al. in prep), and G11.2−0.3 (*right*; Gelfand et al. in prep).

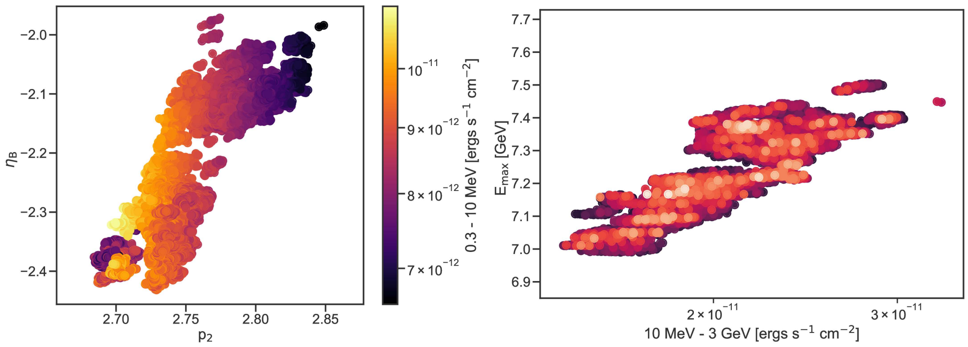

Fig. 3. *Left*: Predicted 0.3 – 10 MeV flux of G11.2−0.3 for different trial values of the wind magnetization $\eta_{\rm B}$ and high-energy particle index p_2. *Right*: Trial value of the maximum energy particle injected at the termination shock $E_{\rm max}$ for different predicted values of the 10 MeV – 3 GeV flux.

source might be very bright at MeV emission, with a broad peak in its SED extending from $\sim 0.1 - 1$ GeV. Last but not least, the SED of G11.2−0.3 is also predicted to have a broad bump from MeV to GeV photon energies, due in part to emission from high-energy particles inverse Compton scattering off an extremely energetic photon field dominated by thermal emission from the SNR shell.

Due to the lack of instruments currently operating at MeV energies, the properties of these sources in this waveband is completely unconstrained in these fits. As a result, their predicted MeV properties can vary significantly within the range of parameter space that reproduces currently measured properties. To illustrate this, we calculated the predicted properties of PWN G11.2−0.3 in two bands, 0.3 – 10 MeV and 10 MeV – 3 GeV chosen since these were the energy ranges of the two instruments on the proposed *e-ASTROGRAM* mission. As shown in Figure 3, the flux of this source in the lower energy band depends on both the magnetization of the pulsar wind $\eta_{\rm B}$ and the high-energy spectral index of particles p_2 injected into the PWN at the termination shock – with higher values of $\eta_{\rm B}$ and lower ("harder") values of p_2 resulting in a higher flux. Emission in this band is dominated by synchrotron radiation from the highest energy particles. Higher values of $\eta_{\rm B}$ result in a stronger nebular magnetic field, increasing the emissivity of these particles, while lower values of p_2 increases their number. These parameters provide important information into the acceleration of particles – since $\eta_{\rm B}$ reflects the conversion of the wind's magnetic to particle energy at the termination shock (thought to be the result of magnetic reconnection which is also responsible for the "hard" particle spectrum inferred from lower photon energies), while p_2 reflects the mechanism responsible for producing the highest energy particles in these sources.

Furthermore, as also shown in Figure 3, the predicted flux of G11.2−0.3 in the higher energy (10 MeV − 3 GeV) band is strongly dependent of the value of $E_{\rm max}$. This is because a larger $E_{\rm max}$ results in more synchrotron emission at higher frequencies, increasing the total flux in this band. It is worth noting that, in these fits, the value of $E_{\rm max}$ derived by this model fitting is significantly higher than that predicted by Equation 1, suggesting that the highest energy particles inside a PWN are produced somewhere other than the pulsar magnetosphere.

4. Conclusions & future prospects

As detailed above, measuring the MeV properties of PWNe is important in understand how, and to what energies, these source accelerate particles. The MeV lightcurve of a PWN is sensitive to how the maximum particle energy $E_{\rm max}$ evolves over its lifetime, and at a given point in time the MeV flux and spectrum provides important information on the magnetization $\eta_{\rm B}$, high-energy particle index p_2 and maximum energy of the shocked pulsar wind. Proposed MeV missions, such as *AMEGO* and *LOX*, will likely numerous PWNe. This information, when coupled with improved measured in other wavebands from new and upcoming facilities like the Jansky Very Large Array, *Athena*, and Cerenov Telescope Array will significantly improve our understanding as to how PWN produce some of the highest energy leptons in the Milky Way.

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