

Ultra-high energy inverse Compton emission from Galactic electron accelerators

Mischa Breuhaus^{1,*}, Joachim Hahn^{1,2}, Carlo Romoli¹, Brian Reville¹, Gwenael Giacinti¹, James Anthony Hinton¹, and Richard Tuffs¹

¹Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

²CGI Darmstadt, Rheinstraße 95, 64295 Darmstadt, Germany

Abstract. It is generally held that >100 TeV emission from astrophysical objects unambiguously demonstrates the presence of PeV protons or nuclei, due to the unavoidable Klein–Nishina suppression of inverse Compton emission from electrons. However, in the presence of inverse Compton dominated cooling, hard high-energy electron spectra are possible. We show that the environmental requirements for such spectra can naturally be met in spiral arms, and in particular in regions of enhanced star formation activity, the natural locations for the most promising electron accelerators: powerful young pulsars. Leptonic scenarios are applied to gamma-ray sources recently detected by the High-Altitude Water Cherenkov Observatory (HAWC) and the Large High Altitude Air Shower Observatory (LHAASO). We show that these sources can indeed be explained by inverse Compton emission.

1 Introduction

Only recently we are starting to explore the γ -ray sky at ultra-high energies (UHE, >100 TeV). The first UHE γ -ray catalogue was obtained in 2020 by the High-Altitude Water Cherenkov Observatory (HAWC) collaboration [1] and contained only three sources. One year later the Large High Altitude Air Shower Observatory (LHAASO) collaboration detected 12 sources in this energy regime [2], providing spectra for three of them. The origin of these sources is of paramount interest since these energies probe the sources responsible for the Cosmic Ray (CR) ‘knee’ feature, which potentially marks the transition between Galactic and extragalactic CRs.

The observation of hard γ -ray spectra at these energies might be interpreted as being produced more likely by the collision of CRs with the ambient matter than by inverse Compton (IC) scattering by electrons because of the Klein-Nishina suppression. Yet, in radiation-dominated environments the situation is different, and hard IC spectra can still be possible [3–6]. Therefore, we investigated the possible leptonic origin of UHE γ -ray sources in detail and performed a leptonic modelling of three of the HAWC and LHAASO sources. This proceeding is mainly a summary of the results from our previous publications [6–8].

*e-mail: mischa.breuhaus@mpi-hd.mpg.de

2 Leptonic equilibrium spectra in radiation-dominated environments

The primary radiation mechanism for the production of UHE γ -rays by electrons or positrons is IC scattering. Unfortunately, unlike as for γ -ray production in hadronic collisions, the Klein-Nishina effects at high energies can prevent the occurrence of hard spectra. This is illustrated in the left panel of Figure 1, which shows the γ -ray spectrum produced by power-law distributed electrons IC scattering photons from a thermal radiation field with a temperature of $T = 50$ K. For the electrons, the spectrum is $dN/dE \propto E^{-\alpha}$, with $\alpha = 2$. In the Klein-Nishina regime, the spectral index of the γ -rays softens to $-(\alpha + 1)$. The only way to obtain a hard spectrum until higher energies is a hardening in the electron spectrum itself. Such a hardening occurs naturally in equilibrium situations in radiation energy dominated environments [3–5].

The right panel of Figure 1 shows an electron spectrum in equilibrium between injection and losses in a radiation energy dominated environment. The electron injection spectrum was an exponential cutoff power-law, $dN/dE \propto E^{-\alpha} \cdot \exp(-E/E_{\text{cut}})$. The different cooling processes determine the shape. At energies below ~ 100 TeV IC cooling is dominating. In the Klein-Nishina regime, the energy loss rate is lower and the electron spectrum hardens. This hardening can compensate for the softening of the resulting γ -ray emission. Eventually, synchrotron losses will dominate over IC energy losses in the Klein-Nishina regime, and the electron spectrum softens again. The transition energy E_X where IC and synchrotron losses are equal determines until which energy hard IC spectra can be produced. To be able to observe hard γ -ray spectra until 100 TeV values of $E_X \gtrsim 100$ TeV are required. This can only be achieved in environments where the parameter $\Xi_{\text{IC}} \equiv U_{\text{rad}}/U_B$ is sufficiently high. Here, U_{rad} and U_B are the energy densities of the radiation field and the magnetic field.

The temperatures of the photon fields have an important influence on the required values of Ξ_{IC} . For lower temperatures, the Klein-Nishina transition occurs at higher energies. This implies that a smaller Ξ_{IC} value is sufficient to allow hard IC spectra until a certain energy. Hence, far infrared fields are the most important radiation fields which need to be taken into consideration. For typical Galactic dust temperatures between 10 and 50 K [9, 10] one needs values of $\Xi_{\text{IC}} \sim 10$ and $\Xi_{\text{IC}} \sim 100$ to achieve $E_X = 100$ TeV. For the cosmic microwave background (CMB), already $\Xi_{\text{IC}} \sim 3$ is sufficient. Since the CMB exists everywhere, when-

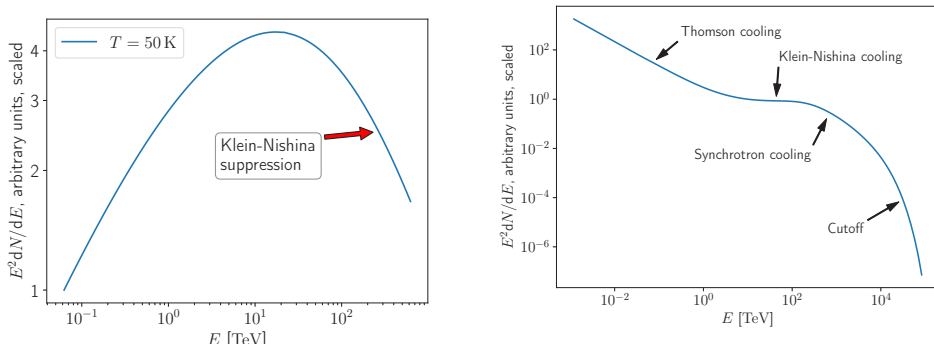


Figure 1. Left: Inverse Compton γ -ray spectrum from power-law distributed electrons with $dN/dE \propto E^{-2}$ with a radiation field of temperature $T = 50$ K. Right: Equilibrium electron spectrum in a radiation-dominated environment, for an injection spectrum $dN/dE \propto E^{-2}$.

ever the magnetic field drops below $1.8 \mu\text{G}$ the conditions to allow the production of hard IC spectra until $\sim 100 \text{ TeV}$ are fulfilled.

3 System constraints and potential Galactic environments

The acceleration of electrons to sufficiently high energies requires the magnetic fields to be sufficiently strong [e.g. 11]. This imposes a lower limit on the size of an accelerator for a given magnetic field strength. On the other hand, the strong radiation fields required to ensure dominance of radiation losses will also absorb the γ -rays, and the potential source could be opaque if it is too large. However, as we showed in [6], for magnetic fields below a few tens of μG a sufficiently large potential parameter space exists. The absorption by the interstellar Galactic radiation fields at 100 TeV is below 0.5 even in the most pessimistic case, but it can be more significant for higher γ -ray energies close to 1 PeV due to the CMB.

Possible PeV electron accelerators are pulsars with spin-down luminosities $\gtrsim 10^{36} \text{ erg s}^{-1}$. However, the strong magnetic fields will prevent values of $\Xi > 1$. Therefore, the pulsar termination shock has to be located far away from the central source where the magnetic fields are sufficiently low. Another possibility is that the electrons are accelerated in a high B -field region but diffuse sufficiently fast outwards without suffering significant energy losses to fill a larger volume where $\Xi > 1$. We demonstrated that this is indeed possible with reasonable diffusion coefficients, and therefore pulsars remain promising candidates for UHE IC sources.

Using the Galactic magnetic field model from [12, 13] and the radiation model from [14], we found that on large scales in the Milky Way the required environmental conditions can only be fulfilled at large Galactic radii or high above or below the disk where sources are scarce. However, the conditions can be very different locally. In star forming regions, far infrared energy densities $\sim 100 \text{ eV cm}^{-3}$ can be maintained over tens of pc [e.g. 15, 16]. Additionally, regions with low magnetic field values $B \lesssim 3 \mu\text{G}$ such as expected in superbubbles [17] are ideal candidates too. Hence, many potential regions exist in the Galactic disk.

4 Leptonic modelling of HAWC and LHAASO sources

To investigate if the sources detected so far can be explained by leptonic scenarios, we first modelled the three sources detected by HAWC with simple equilibrium models. For the radiation field, we used the model from [14], allowing for an additional enhancement factor which we required to be compatible with data from the Infrared Astronomical Satellite (IRAS, [18]). Fixing the magnetic field to $3 \mu\text{G}$ and the power-law indices of the injection spectrum to $\alpha = 2$, reasonable models with enhancement factors below five can explain the data well above energies of 10 TeV where the equilibrium assumption is still valid [for details see 6]. All sources have a potential pulsar counterpart with sufficiently high spin-down power to account for the emission.

Additionally, we modelled the UHE LHAASO sources. Two of the three LHAASO sources for which the spectra are provided in [2] are counterparts to two of the HAWC sources. Hence, both datasets were modelled together. This time we took the finite source age into account and assumed that the electrons are only injected over the lifetime of the potential pulsar counterpart, which exists for all three sources. No enhancement of the large-scale Galactic radiation field was allowed. Free model parameters were fit to the data, **while** some of them such as the magnetic field or the power-law injection index were fixed in different fits. The data can be matched well, and reasonable resulting fit parameters were obtained in different scenarios [for details see 7]. With the γ -ray data from HAWC and LHAASO alone, the fit parameters can not be constrained very well, and additional information about

the source environments is needed for further conclusions. However, each source can be easily explained with leptonic scenarios, and a leptonic origin of at least some of the sources is likely.

5 Summary and conclusion

We showed that environments required to produce hard IC spectra could exist in many local regions in the Milky Way where the far infrared radiation energy density is enhanced and/or the B -fields are low. Hard **spectra** until 100 TeV are possible if IC energy losses dominate until sufficiently high energies. High spin-down power pulsars coincident with star-forming regions and superbubbles are ideal candidates. Superbubbles, star formation, and the creation of new neutron stars are expected to occur together, and it is likely that high spin-down pulsars exist in suitable regions.

The HAWC and LHAASO sources investigated here can be modelled with reasonable leptonic scenarios. However, there is a redundancy in the model parameters, even for the simple models used here. Multiwavelength data **are** crucial to be able to distinguish leptonic from hadronic sources, even at UHE. From the 12 sources detected by LHAASO, only two do not have a potential pulsar counterpart. It might therefore be likely, that several of these sources are indeed powered by pulsars and have a leptonic origin. IC sources are likely an important contributor to the γ -ray sky at energies above 100 TeV.

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