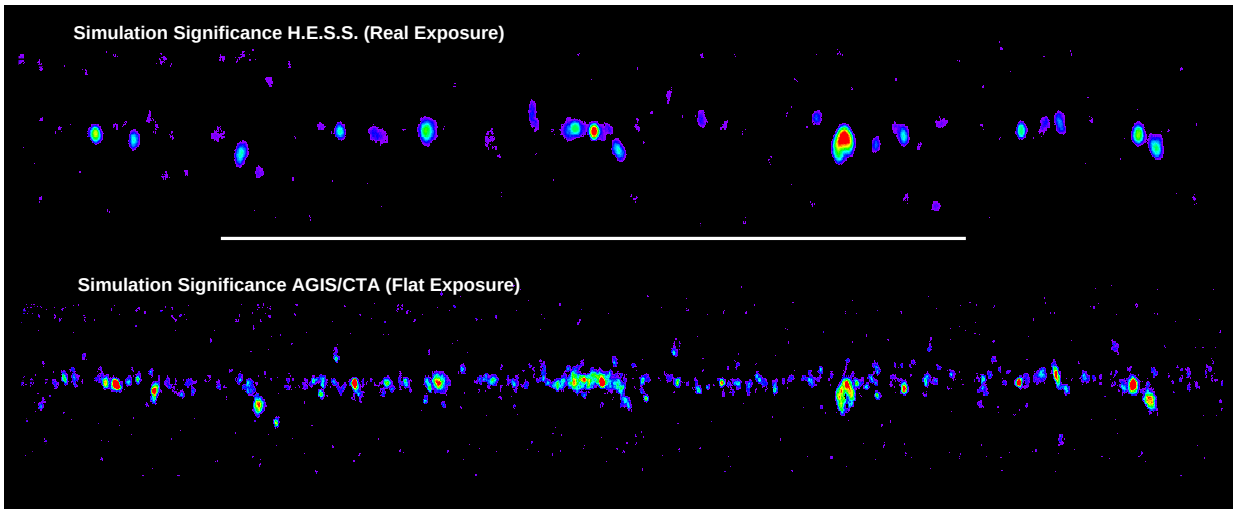


# Particle Acceleration in Stellar Remnants

A White Paper submitted to Astro2010: The Astronomy and Astrophysics Decadal Survey based in part on "The Status and Future of Ground-based TeV Gamma-ray Astronomy", a White Paper prepared at the request of the Division of Astrophysics of the American Physical Society to summarize the status and future of ground-based $\gamma$-ray astronomy.

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The images above illustrate the richness available to future very high energy gamma-ray instruments. The top panel shows a TeV map of the inner Galaxy at the resolution and sensitivity of current TeV telescopes. The bottom panel shows a simulated sky map as would be observed with a future atmospheric Cherenkov telescope with improved sensitivity and angular resolution that could be constructed during the coming decade. The images are from Funk, Hinton, Hermann, and Digel, arXiv:0901.1885.

## Introduction

Our Milky Way galaxy is filled with energetic particles, electrons, protons and fully-ionized atoms, traveling through space with tremendous energies. The mechanisms that accelerate these particles, the specific astrophysical objects responsible, and the influence of these particles on the interstellar medium are fundamental unsolved problems in modern astrophysics. Candidates for particle accelerators are shocks formed in cosmic plasmas when a star explodes, when a rapidly spinning neutron star expels electromagnetic energy, or when an accreting black hole spews out matter at nearly the speed of light. Understanding these accelerators and the population of high energy particles in the Galaxy has broad implications.

Charged energetic particles constitute a very tenuous medium; each particle carries extreme energy, but the particles are few. However, in the Milky Way, the energy density in high-energy particles is approximately the same as in gas, the magnetic field between stars, or star light. The processes that determine their energy and spatial distribution are different from those that shape ordinary gases on Earth, because they rely almost entirely on electric and magnetic fields. Most gases on Earth are "thermal": the energy of the gas is distributed approximately equally among the atoms or molecules of the gas. In contrast, matter in the Universe is often far from equilibrium. In the dilute plasmas that fill most interstellar space, nature endows a small number of particles with an extreme amount of energy. We witness a fundamental self-organization that, through interactions between particles and electromagnetic fields, arranges the atoms and available energy in three components: a cool or warm gas that carries the bulk of the mass, energetic particles with a wide range of energies, and turbulent electromagnetic fields that link the two.

While the broad picture is clear, much is uncertain and fundamental questions remain unanswered: How does nature produce very energetic particles? Do interactions of high-energy particles influence or even generate the magnetic field that permeates interstellar space? What is the distribution of particle accelerators within the Galaxy?

To address these questions, we need to measure much more than simply the detailed properties of the energetic particles. We must probe the physical processes governing the sites of their creation and interaction with the interstellar medium. Very high-energy gamma-rays, which must be produced by particles with even more energy, provide the unique means to understand the most violent processes in the Galaxy.

The unifying question of this document is **"How do stellar remnants accelerate highly energetic particles and how do those particles influence the interstellar medium?"**. Several different classes of stellar remnants are known to be prolific particle accelerators: supernova remnants, rapidly rotating neutron stars, accreting black holes, gamma-ray bursts. It is highly likely that many of the unidentified TeV sources (or 'dark accelerators') near the Galactic plane are also stellar remnants. While we focus on stellar remnants, answering this question will have implications for other cosmic accelerators such as active galactic nuclei. A broader version of our unifying question would be "How Do Cosmic Accelerators Work and What Are They Accelerating?", as was posed by the Board on Physics and Astronomy (BPA) in the report on "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century". As we discuss below, because of their relative proximity and brightness, stellar remnants within the Milky Way offer the best laboratories to understand particle acceleration.

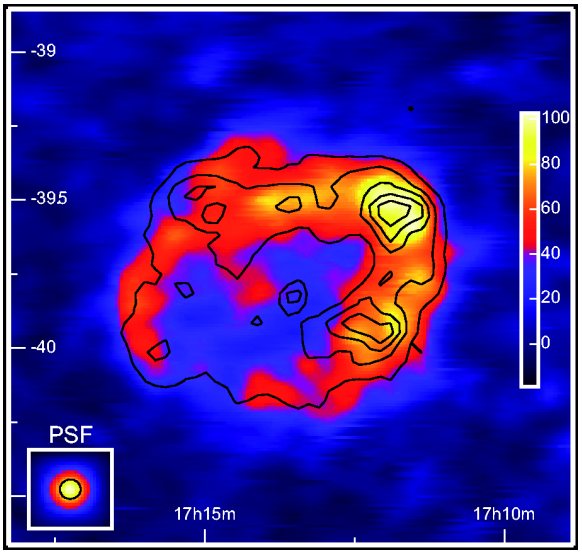


Figure 1: An image of the acceptance-corrected gamma-ray excess rate in the TeV band from the SNR RX J1713-3946 [19]. The inset labeled PSF indicates how a point source would appear in this image. Overlaid are black contour lines that indicate the X-ray intensity at 1-3 keV. Note the similarity between the X-ray and TeV-band images. A future TeV observatory would improve the angular resolution by a factor of 3 enabling a more detailed examination of SNR RX J1713-3946 and a similar level of detail for a large set of SNRs.

## Particle Acceleration in Supernova Remnants

The acceleration of relativistic charged particles is a fundamental unsolved problem in astrophysics. Only in the case of supernova remnants (SNRs) do we have an opportunity to perform spatially resolved studies in systems with known geometry. The plasma physics deduced from these observations will help us to understand other systems where rapid particle acceleration is believed to occur but where observations as detailed as those of SNRs are not possible.

In situ observations in the heliosphere show that collisionless shocks can accelerate particles. The process of particle acceleration in non-relativistic shocks that occur in SNRs is intrinsically efficient [1]. Thus, the population of energetic particles produces a back-reaction, strongly modifying the shock. Also, the particles with the greatest energies escape, making energy losses significant and increasing the shock compression ratio [2]. A fundamental consequence of particle acceleration at cosmic-ray modified shocks is that the particle spectrum is no longer a power law, but a concave spectrum, as hard as $N(p) \propto p^{-1.5}$ at high momenta [3, 4]. Gamma-ray observations in the GeV-TeV band appear to be the best means to measure the particle spectra and thus probe the acceleration processes in detail.

Particle confinement near shocks is supported by self-generated magnetic turbulence ahead of and behind the shocks that quasi-elastically scatters the energetic charged particles and thus makes their propagation diffusive. The amplitude of the turbulence determines the scattering frequency, and thus the acceleration rate [5]. The instabilities by which cosmic rays drive turbulence in the upstream region were long thought to be weak enough so that quasilinear approximations were realistic, but recent research suggests that the amplitude of the turbulent magnetic field excited by the streaming cosmic rays may actually exceed that of the homogeneous, large-scale field [6, 7]. More recent studies [8] suggest that ahead of the shock non-resonant, nearly purely growing modes of short wavelength may be more efficiently excited than resonant plasma waves.

A new gamma-ray instrument is needed to understand the acceleration and interactions of energetic nucleons and electrons in SNRs. An advanced gamma-ray facility can, in conjunction with current X-ray telescopes, provide detailed information on the division of the energy budgets in shocked SNR environs; namely, how the energy is distributed between cosmic ray electrons, ions and magnetic field turbulence. It would also investigate in detail the new and exciting topic of

magnetic field amplification. The key parameters for a new gamma-ray instrument are collecting area and angular resolution. Significant advance in our understanding of SNR particle acceleration will require spatially resolved spectra; current telescopes are limited by photon statistics and a collecting area of approximately 1 km$^2$ is needed to collect sufficient photons, particularly at the highest energies. Increased sensitivity is needed to perform studies on a whole population of SNRs of different ages and environments. The angular resolution of current TeV instruments, $\sim 6'$ varying with energy, is adequate to resolve some SNRs, but a modest improvement in angular resolution would enable mapping of a much larger set of SNRs. New TeV observations of SNRs will elucidate plasma shocks, generation of magnetic turbulence, and cosmic ray acceleration in the cosmos.

## Particle Acceleration in Pulsar Wind Nebulae

Pulsar wind nebulae (PWNe) are powered by relativistic particles accelerated in the termination shock of the relativistic wind from a rotation-powered pulsar. The basic physical picture is that the rotating magnetic field of the pulsar drives a relativistic wind. A termination shock forms where the internal pressure of the nebula balances the wind ram pressure. At the shock, particles are thermalized and re-accelerated to Lorentz factors exceeding $10^6$. The energy in the Poynting flux is transferred, in part, to particles. The high energy particles then diffuse through the nebula, partially confined by nebular magnetic fields, and cool as they age due to synchrotron losses, producing radio to X-ray emission, and inverse-Compton losses, yielding gamma-ray emission.

Studies of PWNe address several central questions in high-energy astrophysics, the most important of which is the mechanism of particle acceleration in relativistic shocks. PWNe provide a unique laboratory for the study of relativistic shocks because the properties of the pulsar wind are constrained by our knowledge of the pulsar and because the details of the interaction of the relativistic wind can be imaged in the X-ray, optical, and radio bands. Relativistic shock acceleration is key to many astrophysical TeV sources, and PWNe are, perhaps, the best laboratory to understand the detailed dynamics of such shocks.

PWNe have proven to be prolific TeV emitters. The Crab nebula was the first TeV source to be discovered, by the Whipple observatory in 1989 [9]. Current TeV telescopes have recently detected a number of other Galactic sources, many of which are confirmed to be, and many more thought to be, PWNe [10]. Significantly, TeV observations have lead to the discovery of new PWNe that were not previously detected at other wavelengths. TeV imaging has provided a clearer picture of PWNe such as PSR B1823-13 and Vela X [12] that are offset from the positions of the pulsars, an effect which may be due to the pressure of the reverse shock [13]. The TeV spectral morphology of the PWN of PSR J1826-1334 has been mapped: the TeV spectrum softens with increasing distance from the pulsar [14]. This allows study of particle energy loss within the nebula and shows that the high gamma-ray luminosity of the source cannot be explained on the basis of constant spin-down power of the pulsar – higher injection power is required in the past.

Measurement of the spectrum from the keV into the TeV range allows one to constrain the maximum particle energy, the particle injection rate, and the strength of the nebular magnetic field. The broadband spectrum of a PWN provides constraints on the integrated energy injected by the pulsar as well as the effects of adiabatic expansion and the evolution of the magnetic field. Spatially-resolved spectra allow constraints on the diffusion and energy loss of energetic particles and their time history. The key for future observations is an improvement in sensitivity so that high quality spectra can be obtained from PWNe already detected in the TeV band and so that the

sample of TeV PWNe can be extended. Improved spatial resolution would also be useful to allow mapping of more PWNe.

X-ray observations with Chandra and XMM-Newton have revealed jet structures in a large number of PWNe. Recently, the first TeV image of a PWN jet, in the PWN of PSR1509-58, has been obtained [11]; this is also the first astrophysical jet resolved at gamma-ray energies. Comparison of the gamma-ray jet with the one detected by Chandra in X-rays, which is less extended and has a flatter spectral index, shows that the evolution of emitting particles in the jet is consistent with synchrotron cooling. Models for the formation of these jets indicate that some fraction of the equatorial wind from the pulsar can be redirected from its radial outflow and collimated by hoop stresses from the inner magnetic field. The formation of these jets is highly dependent upon the ratio of the Poynting flux to the particle energy density in the wind. TeV observations of PSR B1509-58 reveal an extended TeV jet aligned with the known X-ray jet. New TeV observations with improved sensitivity and angular resolution should provide insight into the Poynting fraction and the physics of jet formation.

## Cosmic Rays in the Milky Way

Because cosmic rays are an energetically important part of the interstellar medium, understanding the cosmic ray population will be essential in understanding of the energy balance and evolution of the interstellar medium in the Milky Way and other galaxies. Theoretical models suggest that CR feedback on the dynamics of the interstellar medium may play an important role in determining star formation rates and enrichment histories within galaxies.

Cosmic rays consist of both electrons and hadrons. The hadrons dominate the energy budget, and the acceleration of hadrons is the key issue in understanding the origin of cosmic rays. The energy density in local cosmic rays, when extrapolated to the whole Galaxy, implies the existence of powerful accelerators in the Galaxy. Supernova remnants (SNRs) have long been thought to be those accelerators[15], but there is no definitive proof that hadrons are accelerated in SNRs[16]. The classical argument that shocks in shell-type SNRs accelerate cosmic rays is that supernova explosions are one of the few Galactic phenomena capable of satisfying the energy budget of cosmic-ray nuclei, although even supernovae must have a high efficiency ($\sim$10%-20%) for converting the kinetic energy of the SNR explosions to particles [17]. However, these arguments are indirect. Other source classes may exist that have not been considered to date, and one may ask what role is played by the many sources seen in the TeV-band that do not have an obvious counterparts in other wavebands [18] – the so-called 'dark accelerators'. Observations of TeV photons from SNRs offer the most promising direct way to confirm whether SNRs are, in fact, the main sources of cosmic ray ions below $10^{15}$ eV and also offer the best means to discover other cosmic ray accelerators.

The in-situ population of cosmic rays within the Galaxy can be probed by interactions of cosmic rays with the interstellar medium that lead to the production of photons. NASA's $Fermi$ Large Area Telescope has completed 6 months of science operations and is making the deepest, most uniform survey yet of the gamma-ray sky, including of course the diffuse gamma-ray emission of the Milky Way. The LAT will detect tens of millions of gamma rays per year from the Milky Way, from 20 MeV to greater than 300 GeV. The per-photon angular resolution of the LAT improves with energy, reaching $\sim 0.1^\circ$ above 30 GeV but owing to the steepness of the spectrum of the diffuse emission ($\sim E^{-2.7}$ in photon number), at high energies the useful angular resolution is determined more by the photon statistics than the intrinsic angular resolution. Fermi will pro-

vide invaluable spectral information on the diffuse Galactic gamma-ray emission in the GeV band with degree-scale angular resolution. TeV-band measurements, with the much greater effective area of ground-based observatories for energies above $\sim$100 GeV, will produce complementary images and spectra with much better angular resolution for selected regions of the sky that will be particularly useful where imaging with Fermi suffers from limited statistics.

Photons at the highest energies, above about 100 TeV, trace hadronic cosmic rays since electrons at these energies cool very rapidly. Thus, an all-sky map in the upper end of the TeV band could provide the key to understand the origin of cosmic-ray hadrons and their distribution within the Galaxy. The need for both all-sky coverage extending to very high energies and detailed mapping in the 0.1-10 TeV band call for complementary observational techniques. Air Cherenkov telescope arrays are the best choice for sensitivity and good angular resolution in the 0.1-10 TeV band. Water Cherenkov detectors, pioneered by the Milagro instrument and proposed for the future in the HAWC instrument, offer instantaneous coverage of a large fraction of sky that is essential for obtaining photon statistics at the highest energies where the fluxes are very low. The GeV survey data from Fermi, air Cherenkov observations of particular sources and regions of the sky, and all sky coverage above 10 TeV from water Cherenkov detectors can be combined to understand the origin and propagation of energetic particles in the Galaxy.

## Relativistic Jets from Binaries

One of the most exciting recent discoveries in high-energy astrophysics is the detection of TeV emission from binary systems containing a compact object, either a neutron star or black hole. TeV emission requires particles at TeV or higher energies and promises to give unique insights into the acceleration of ultrarelativistic particles in X-ray binaries. The TeV emission is found to be strongly time variable. Hence, multiwavelength (TeV, GeV, X-ray, optical, and radio) light curves will strongly constrain models of high-energy particle acceleration and interaction within these systems.

The first evidence that binary systems containing stellar-mass compact objects could accelerate particles to TeV energies came from observations of X-ray synchrotron radiation from the large-scale jets of XTE J1550-564 [20, 21]. The detection of deceleration in these jets suggests that the high-energy particles are accelerated by shocks formed by the collision of the jet with the interstellar medium. The acceleration is likely powered by the bulk motion of the jets. More recently, three TeV-emitting compact-object binaries have been found at high confidence [22, 23, 24, 25]. One of these sources, PSR B1259-63, contains a young, rotation-powered pulsar and the acceleration of particles to TeV energies mostly likely occurs in shocks produced by interaction of the pulsar wind with the outflow from the companion Be star. The nature of the compact object in the other two sources is less clear, they may be either rotation-powered pulsars or accreting neutron stars or black holes.

It should be possible to determine whether the TeV emission is produced by hadrons or leptons via simultaneous multiwavelength (radio, optical, X-ray, GeV, TeV) observations of the time variable emission. Important in this regard will be measuring how the various emission components vary with orbital phase. The key here is adequate cadence, which requires good sensitivity even for short observations. Understanding the correct emission mechanism will place the interpretation of the TeV observations on a firm footing and allow one to use them to make strong inferences about the jet energetics and the populations of relativistic particles in the jets. If the TeV emission from a given system can be shown to arise from interactions of relativistic protons with a stellar wind,

then this would show that the jet contains hadrons. This would provide a major advance in our understanding of the physics of jets.

If the jets do have a significant hadronic component, then they are potential neutrino sources. The calculated neutrino flux levels, assuming a hadronic origin for the observed TeV emission, are detectable with neutrino observatories now coming on line, such as ICECUBE [26]. The detection of neutrinos from a compact object binary would be very exciting in opening up the field of neutrino astronomy and would be definitive proof of a hadronic jet.

Detailed light curves will also allow us to extract information about the interaction of the pulsar wind or black hole jet with the outflow from the stellar companion. This is a very exciting possibility which will provide a direct confrontation of magnetohydrodynamical simulations with observation and significantly advance our understanding of time-dependent relativistic shocks. Modeling using currently available data on PSR B1259-63 shows that the TeV data break the degeneracy between electron energy and magnetic field present in the interpretation of X-ray and radio observation and allow the magnetic field to be estimated to be $\sim 1$ G, similar to the values predicted by magnetohydrodynamical simulations of the pulsar wind. The key for future TeV observations will be to measure the spectral evolution of binary systems with rapid cadence. The time variability of binaries due to the changing orientation, illumination, and wind geometry make these systems the natural laboratory of choice for studying relativistic shocks. The knowledge gained will be important for many areas of high-energy astrophysics.

## Conclusions

Acceleration of particles to very high energies is a topic of key importance over a broad range of astrophysics. New observations of very high energy gamma-rays from compact stellar remnants offer a powerful means to understand the mechanisms of particle acceleration, the population of particle accelerators in the Galaxy, and the distribution of the energetic particles within the Galaxy. The key observational requirements are 1) increased collection area, to the level of $\sim$1 km$^2$; 2) increased sensitivity via an increase in collection area and a decrease in background counting rate to achieve a different flux sensitivity $\sim 10^{-13}\mathrm{erg\,cm^{-2}\,s^{-1}}$ near 1 TeV in routine observations; and 3) improved angular resolution and increased collecting area to allow energy-resolving mapping of SNRs and PWNe. A new generation of gamma-ray observatories such as the Advanced Gamma-Ray Imaging System (AGIS), the Cherenkov Telescope Array (CTA), and the High Altitude Water Cherenkov Experiment (HAWC) could be built within the coming decade and provide the improvements in observational capabilities needed to fundamentally advance our understanding of the acceleration of very high energy particles in the Universe.

## Further Reading

This document draws heavily on "The Status and future of ground-based TeV gamma-ray astronomy", a White Paper prepared at the request of the Division of Astrophysics of the American Physical Society to summarize the status and future of ground-based $\gamma$-ray astronomy. The APS/DAP White Paper is available at http://cherenkov.physics.iastate.edu/wp/. The sections of the APS White Paper most relevant to the topics discussed here are the Sections on Supernova Remnants and Cosmic Rays, available at http://arxiv.org/abs/0810.0673 and Galactic Compact Objects, arxiv.org/abs/0810.0683. The individual sections are also available via links on the main APS/DAP White Paper web page.

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