

The Status and future of ground-based TeV gamma-ray astronomy

Reports of Individual Working Groups

1 Galactic compact objects

Group membership:

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1.1 Introduction

Our Galaxy contains astrophysical systems capable of accelerating particles to energies in excess of several tens of TeV, energies beyond the reach of any accelerator built by humans. What drives these accelerators is a major question in astrophysics and understanding these accelerators has broad implications. TeV emission is a key diagnostic of highly energetic particles. Simply put, emission of a TeV photon requires a charged particle at an energy of a TeV or greater. Observations in the TeV band are a sensitive probe of the highest energy physical processes occurring in a variety of Galactic objects. Galactic TeV emitters also represent the sources for which we can obtain the most detailed information on the acceleration and diffusion of high-energy particles and are, thus, our best laboratories for understanding the mechanisms of astrophysical ultra-relativistic accelerators.

Recent results from the new generation of TeV observations, primarily H.E.S.S., have revealed a large population of Galactic sources; see Fig. 1 which shows the known TeV sources in Galac-

tic coordinates. Galactic sources now comprise a majority of the known TeV emitters with object classes ranging from supernova remnants to X-ray binaries to stellar associations to the unknown. Future TeV observations with a more sensitive telescope array will lead to the discovery of many more TeV emitting objects and significantly advance our understanding of the acceleration of the highest energy particles in the Galaxy.

1.2 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, producing 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

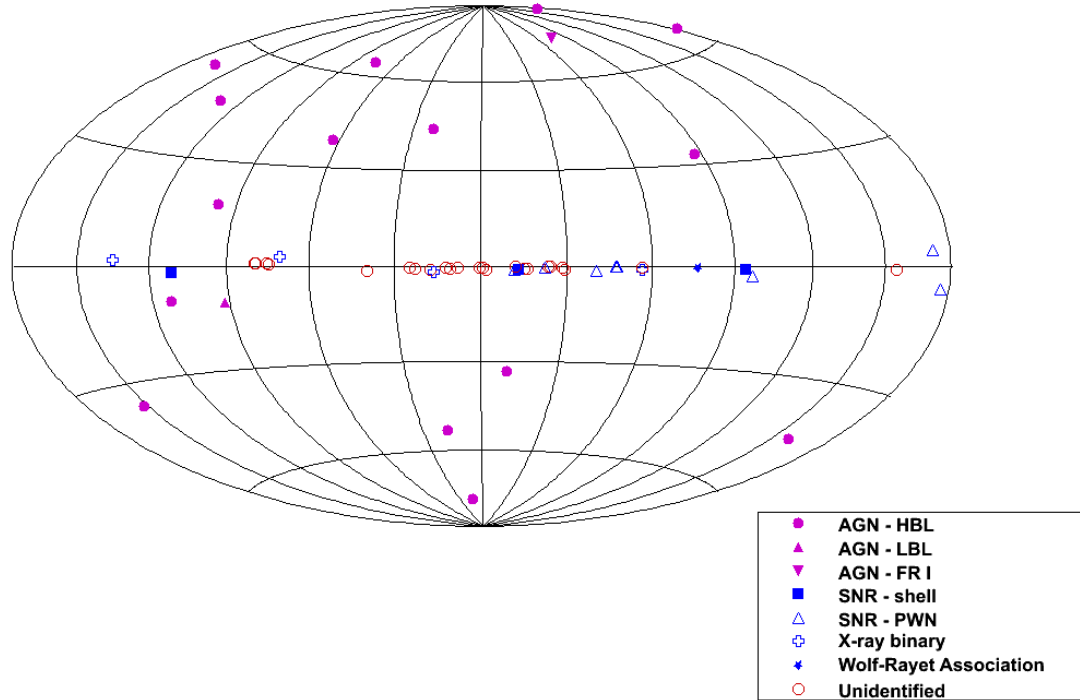


Figure 1: Known TeV emitting objects plotted in Galactic coordinates. The center of the Milky Way is at the center of the ellipse. The Galactic plane is the horizontal midplane. The symbols and colors indicate the source type. Figure courtesy of Dr. E. Hays.

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. Studies of pulsar-powered nebulae also target a number of crucial areas of pulsar astrophysics, including the precise mechanism by which the pulsar spin-down energy is dissipated, the ratio of magnetic to particle energy in the pulsar wind, the electrodynamics of the magnetosphere, and the distribution of young pulsars within the Milky Way.

Observations of TeV emission are essential to resolve these questions. 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. Observation of TeV emission from a significant set of pulsar-powered

nebulae would allow us to study how the pulsar wind varies with pulsar properties such as spin-down power and age. Detection and identification of new nebulae may also lead to the discovery of new young pulsars, particularly those lying in dense or obscured parts of the Galaxy where radio searches are ineffective because of dispersion.

PWNe have proven to be prolific TeV emitters. The Crab nebula was the first TeV source to be discovered. H.E.S.S. has recently detected a number of other Galactic sources, several of which are confirmed to be, and many more thought to be, PWNe [1]. Significantly, H.E.S.S. has discovered new PWNe that were not previously detected at other wavelengths. Furthermore, the high resolution capabilities of H.E.S.S. have allowed imaging of the first TeV jet in the PWN of PSR1509-58 [2], which 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. In addition, TeV imaging has provided a clearer picture of PWNe such as PSR B1823-13 and Vela X [3] that are offset from the position of the pulsar, an effect which may be due to the pressure of the reverse shock [4].

1.2.1 Measurements needed

Broadband modeling of PWNe 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. The spectrum consists of two components: 1) synchrotron emission extending from the radio into the X-ray and, in some cases, the MeV band, and 2) inverse-Compton emission producing GeV and TeV photons. Emission in the TeV band originates primarily from inverse-Compton scattering of ambient soft photons with energetic electrons in the nebula. The ratio of TeV luminosity to pulsar spin-down power varies strongly between different PWN and understanding the cause of this effect will advance our understanding of the physics of PWNe.

All PWNe show spectra that are steeper in the X-ray band than in the radio band, but the nature of the spectral changes between these bands is not well understood. Synchrotron losses result in a spectral break at a frequency that depends on the age and magnetic field strength, while other spectral features can be produced by a significant change in the pulsar input at some epoch, by spectral features inherent in the injection spectrum, and by interactions of the PWN with the reverse shock from its associated supernova remnant. TeV observations provide an independent means to probe the electron energy distribution. Addition of TeV data breaks many of the degeneracies present in analysis of synchrotron emission alone and allows independent

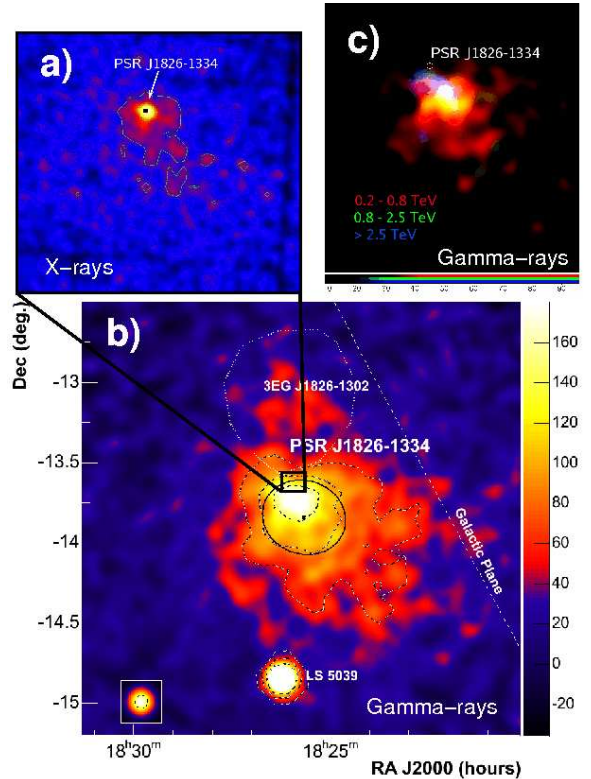


Figure 2: H.E.S.S. map of TeV emission from H.E.S.S. J1825-137 (b), X-ray image of the central part of the field showing the PWN G18.0-0.7 (a), three color image of the TeV emission showing that the nebula is the most compact at the highest energies (c). From [9].

estimates of the electron energy distribution and the nebular magnetic field. TeV observations are essential to understand the PWN electron energy distribution and its evolution.

Highly Extended PWNe Several of the recently-discovered H.E.S.S. sources appear to be PWNe, due to the presence of young radio pulsars nearby, but have unexpected morphologies. Examples include H.E.S.S. J1804-216 [5], H.E.S.S. J1825-137 [6], and H.E.S.S. J1718-385 [7]. There are two issues that require considerable further study for these sources. First, the young pulsars suggested as the engines for these nebulae are distinctly separated from the TeV centroids. The most common explanation is that the supernova remnants in which these PWNe formed (most of which are not observed, to date) are sufficiently evolved that the reverse

shocks have disturbed the PWNe, as appears to be the case in Vela X, which is also observed as an extended TeV source offset from its pulsar [8]. This requires an asymmetric interaction with the reverse shock, which can occur if the SNR expands into a highly non-uniform medium, and there are suggestions that these systems may indeed be evolving in the vicinity of molecular clouds. In this scenario, the reverse shock encounters one side of the PWNe first, and the disruption leaves a relic nebula of particles that is concentrated primarily on one side of the pulsar. More sensitive TeV observations are required to produce higher fidelity maps of these nebulae, and to search for evidence of a steepening of the spectrum with distance from the pulsar.

A second and more vexing question centers on the very large sizes of these PWNe. These sources are observed to be extended on scales as large as 1° [8], significantly larger than their extent in X-rays. One possible explanation for this is that the extent of the synchrotron radiation observed in the X-ray band is confined to the region inside the magnetic bubble of particles that is sweeping up the ambient ejecta, while the IC emission is produced wherever energetic particles encounter ambient photons. If the diffusion length of these energetic particles is extremely large, they can escape the synchrotron-emitting volume, but still produce TeV gamma rays. Because these sources are relatively faint, high-quality maps of this extended emission do not yet exist. Higher sensitivity, along with somewhat improved angular resolution, are crucial for probing more deeply into the structure of these nebulae.

Jets/Magnetization X-ray observations with Chandra and XMM-Newton have revealed jet structures in a large number of PWNe. 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.

H.E.S.S. observations of PSR B1509-58 reveal an extended TeV jet aligned with the known X-ray jet. New TeV observations of similar jets should provide insight into the Poynting fraction and the physics of jet formation.

Discovery Space The recently-discovered H.E.S.S. sources that appear to be previously unknown PWNe highlight the potential for uncovering a large number of PWNe in TeV surveys. For cases where the nebula magnetic field is low, thus reducing the synchrotron emissivity, the IC emission could be the primary observable signature. An increase in sensitivity will be important to enhance the discovery space, and cameras with a large field of view would enable large surveys to be conducted. Given that some of the H.E.S.S. sources in this class are extended, improved angular resolution also holds promise both for identifying the sources as PWNe and for investigating the structure of these systems.

1.3 Pulsed emission from neutron stars

The electrodynamics of pulsars can be probed more directly via observation of their pulsed emission. The high timing accuracy achievable with pulsars has led to Nobel prize winning discoveries, but the mechanism which produces the pulsed emission, from the radio to gamma rays, is not well understood. TeV observations may provide key insights.

A key question that has pervaded pulsar paradigms over the last two decades is where is the locale of the high-energy non-thermal magnetospheric emission? Two competing models have been put forward for gamma-ray pulsars: (1) polar cap scenarios, where the particle acceleration occurs near the neutron star surface, and (2) the outer gap picture, where this acceleration arises out near the light cylinder. Data have not yet discriminated between these scenarios, and our understanding of pulsar magnetospheres has stalled because of this. For energetic young pulsars like the Crab and Vela, TeV telescopes/arrays would offer the greatest impact if

the outer gap model is operable. For millisecond pulsars, TeV telescopes should provide valuable insight regardless of the emission locale. Indeed, the answer to the question may differ according to which subset of pulsars is examined.

Knowing the location of their radiative dissipation will permit the identification of the pertinent physical processes involved and open up the possibility for probing the acceleration mechanism. This could then enable refinement of pulsar electrodynamics studies, a difficult field that is currently predominantly tackled via MHD and plasma simulations. Should polar cap environs prevail as the site for acceleration, then there is a distinct possibility that pulsar observations could provide the first tests of quantum electrodynamics in strong magnetic fields. An additional issue is to determine whether there are profound differences in emission locales between normal pulsars and their millisecond counterparts. High-energy gamma-ray observations are central to distinguishing between these competing models and accordingly propelling various aspects of our knowledge of pulsar electrodynamics.

Detection of pulsed emission at TeV energies has so far been elusive. The observation of high-energy cutoffs below 10 GeV in the pulsed emission spectra of several normal pulsars with high magnetic fields by EGRET [10] has made the prospects of detecting emission at energies above 100 GeV very unlikely. Indeed, such cutoffs are predicted from magnetic pair production in polar cap models [11] and from radiation reaction limits in outer gap models [12]. However, outer gap models predict that a separate component produced by inverse Compton scattering should be detectable at TeV energies, while polar cap models do not expect such a contribution. This provides a key opportunity for distinguishing between these competing pictures. Yet, the outer gap scenario has suffered through a sequence of non-detections (e.g. see [13] for Whipple limits on the Crab’s pulsed signal) in focused observations by TeV telescopes, progressively pushing the pulsed flux predictions down. In a recent addition to this litany, MAGIC has obtained

constraining flux limits at 70 GeV and above to PSR B1951+32 [14], implying turnovers below around 35 GeV in the curvature/synchrotron component, thereby mandating a revision of the latest outer gap predictions of inverse Compton TeV fluxes [15].

This result highlights the importance of lowering the threshold of ground-based ACT arrays. Such saliency is even more palpable for the study of millisecond pulsars (MSPs). Polar cap model predictions can give turnovers in the 30-70 GeV range for MSPs [16], though outer gap turnovers for MSPs are actually at lower energies due to significant primary electron cooling by curvature radiation reaction. While possessing much lower magnetic fields than normal energetic young pulsars, millisecond pulsars can be expected to be as luminous in some portion of the gamma-ray band because their rapid periods imply large spin-down power. Hence, future sub-TeV observations of MSPs should significantly advance our understanding of these objects.

1.3.1 Measurements needed

What is clearly needed to advance the pulsar field is a lower detection threshold and better flux sensitivity in the sub-TeV band. The goal of lower thresholds is obviously to tap the potential of large fluxes from the curvature/synchrotron component. At the same time, greater sensitivity can provide count rates that enable pulse-profile determination at the EGRET level or better, which can then probe emission region geometry. Pulse-phase spectroscopy is a necessary and realizable goal that will enable both model discrimination and subsequent refinement. Since the current generation ACTs cannot quite reach thresholds below 70 GeV, and since the model predictions are very dependent on emission and viewing geometry, it seems that detection of very high-energy emission from millisecond and young pulsars will be unlikely for the current instruments and will require new telescopes. Hence, goals in the field are to both lower the threshold to the 30-50 GeV band, and improve the flux sensitivity by a factor of ten.

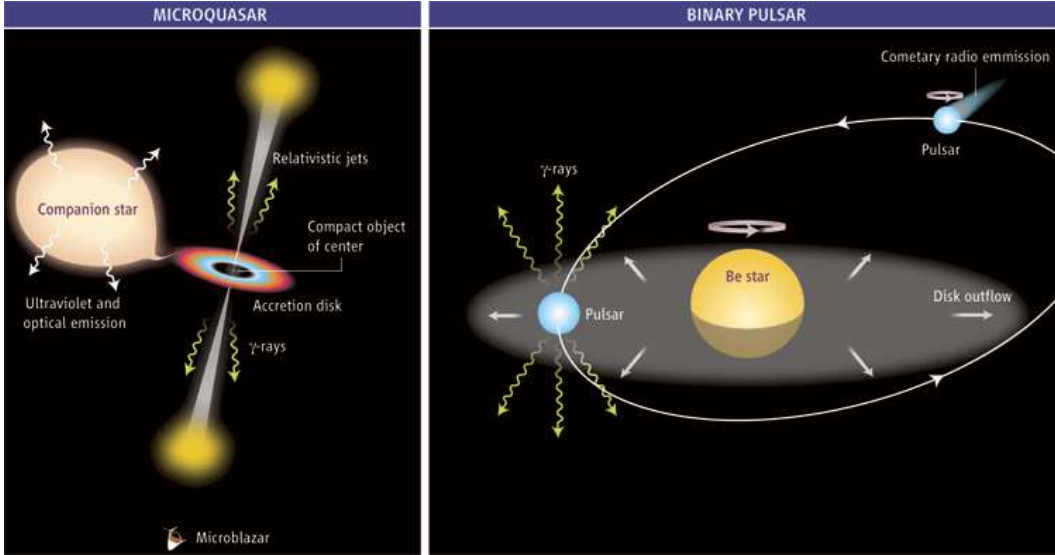


Figure 3: The two types of binaries systems producing TeV emission. The left image shows a microquasar powered by accretion onto a compact object, neutron star or black hole. The right image shows a rotation-powered pulsar (neutron star) in a binary where the relativistic wind from the pulsar leads to the production of TeV photons. From [17].

1.4 Relativistic Jets from Binaries

One of the most exciting recent discoveries in high-energy astrophysics is the detection of TeV emission from binaries systems containing a compact object, either a neutron star or black hole (see Fig. 3). 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 varying. 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.

Key questions that will be addressed by TeV observations include:

- What is the composition of ultra-relativistic jets? Even though ultra-relativistic jets are ubiquitous features of compact objects, occurring in systems ranging from supermassive black holes to neutron stars, the basic question of whether the jets are electron-positron or have a significant hadronic component remains unanswered for almost all objects. The only case with a clear

signature of the composition is SS 433, in which X-ray line emission reveals the presence of iron nuclei. However, even for SS 433, the matter may be entrained from the companion star wind. This question is fundamental in understanding the physics of jet production. Measurement of the time variation of the TeV/GeV/X-ray spectrum from TeV emitting binaries has the potential to resolve this question.

- What is the total energy carried by jets? TeV emission provides a unique probe of the highest energy particles in a jet. These particles often dominate the total energy of the jet and their accurate measurement is essential in understanding the energetics of jets.
- What accelerates particles in jets? Measuring the acceleration time and the spectrum of the highest energy particles in a jet is critical for addressing this question.

1.4.1 Current Status

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 [18, 19]. 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. One, PSR B1259-63 contains a young, rotation-powered pulsar [20]. The nature of the other two systems, LS 5039 and LS I 61 303 [21] is less clear. A lower significance signal (3.2σ after trials) has been reported from the black hole X-ray binary Cyg X-1 [22].

PSR B1259-63 consists of a young, highly energetic pulsar in a highly eccentric, 4.3 year orbit around a luminous Be star. At periastron the pulsar passes within about 1 A.U. of its companion star. Radio and hard X-ray emission, interpreted as synchrotron radiation, from the source suggest that electrons are accelerated to relativistic energies, mostly likely by shocks produced by interaction of the pulsar wind with the outflow from the Be star [23]. However, the electron energy and magnetic field strength cannot be determined independently from the X-ray and radio data and alternative interpretations of the X-ray emission are possible. H.E.S.S. detected TeV emission from PSR B1259-63 [20]. TeV emission was detected over observations within about 80 days of periastron passage and provides unambiguous evidence for the acceleration of particles to TeV energies.

LS I +61 303, a high mass X-ray binary system located at ~ 2 kpc distance which has been a source of interest for many years due to its periodic outbursts in radio and X-ray correlated with the ~ 26.5 day orbital cycle and its coincidence with a COS-B and EGRET GeV gamma-ray source [24, 25, 26]. MAGIC found variable TeV emission from this source [21]. The nature of the compact object in LS I +61 303 is not well established. The identification of LS I +61 303 as a microquasar occurred in 2001 [27] when what appeared to be relativistic, precessing radio jets were discovered extending roughly 200 AU from the center of the source. However, re-

cent repeated VLBI imaging of the binary shows what appears to be the cometary tail of a pulsar wind interacting with the wind from the companion star. This suggests that the binary is really a pairing of a neutron star and a Be main sequence star [28]. The (much) shorter orbital period of LS I +61 303, as compared to PSR B1259-63, makes the system much more accessible for observations. Also, the detection of LS I +61 303 at GeV energies will enable constraints on the modeling which are not possible for PSR B1259-63.

H.E.S.S. has detected TeV emission from the high-mass X-ray binary LS 5039 [29]. The TeV spectral shape varies with orbital phase. LS 5039/RX J1826.2-1450 is a high-mass X-ray binary. Radio jets from LS 5039 have been resolved using the Very Long Baseline Array [30, 31]. This suggests that the compact object is accreting. Optical measurement of the binary orbit also suggests a black hole, although the measurements do not strongly exclude a neutron star [24].

1.4.2 Measurements needed

It should be possible to determine the correct emission mechanism for the TeV emission in both neutron-star and black hole binaries via simultaneous multiwavelength (radio, 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 compo-

ment, 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 [32]. 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. The knowledge gained will be important for essentially all aspects of high-energy astrophysics. If the broad-band spectrum of PSR B1259-63 is modeled assuming that the TeV photons are produced by inverse-Compton interactions of photons from the companion star with the same population of accelerated electrons producing the synchrotron emission, then the TeV data break the degeneracy between electron energy and magnetic field and allow the magnetic field to be estimated to be ~ 1 G. This estimate is similar to the values predicted by magnetohydrodynamical simulations of the pulsar wind. Future more sensitive observation would enable measurement of the time evolution of the magnetic field.

The detection of TeV emission from a black hole binary, perhaps already accomplished, would have important implications. Acceleration of particles to TeV energies is required to produce the TeV emission. It is unlikely that such acceleration occurs in the accretion disk or corona; the particle acceleration likely occurs in the jet. The same is not true about X-ray or hard X-ray emission. This is significant ambiguity about whether any X-ray/hard X-ray spectral component can be attributed to the jet, and the strong X-ray flux from the accretion disk complicates isolation of any jet emission. This makes TeV emission a unique probe of the properties of jet

and observation of TeV gamma rays from the jets of accreting stellar-mass black holes should lead to important information about the jet production mechanism.

There are two possible mechanisms for the generation of the TeV emission. Electrons accelerated to very high energies may inverse-Compton scatter photons emitted from the O6.5V companion star. However, the radiation density from the O star companion at the position of the compact object is very high and the radiative time scale is ~ 300 s. Very rapid acceleration would be required for the electrons to reach the high energies required in the face of such rapid energy loss. Instead, the TeV emission may arise from the interactions of protons accelerated in a jet with the stellar wind.

Even with the ambiguity between an electron versus proton mechanism for the TeV emission, the luminosity in the TeV band indicates an extremely powerful outflow. For very efficient, $\sim 10\%$, conversion of bulk motion into VHE radiation, the jet power must be comparable to X-ray luminosity. For more typical acceleration efficiencies at the level of a few percent, the energy in the outflow would be several times the X-ray luminosity. The result has major implications for our understanding of accretion flows near black holes. The balance between accretion luminosity and jet power is currently a major question in the study of microquasars, but estimation of the total jet kinetic energy from the observed radio luminosity is uncertain [33]. Recently, a radio/optical ring was discovered around the long-known black hole candidate Cyg X-1 [34]. The ring is powered by a compact jet and acts as a calorimeter allowing the total jet kinetic energy to be determined (the energy radiated by the jet is negligible). The jet power is between 7% and 100% of the X-ray luminosity of the system. This implies that the jet is a significant component of the overall energy budget of the accretion flow. It is remarkable that a similar inference can be made directly from the observed TeV luminosity of LS 5039. This suggests that additional TeV sources of black hole jet sources will be important in understanding the balance

between accretion luminosity and jet power and the fundamental role of jet production in accretion dynamics.

A future TeV instrument with improved sensitivity would enable observation of sources at lower luminosities than those currently known. An important current question in the study of Galactic black hole is how the ratio of jet power to X-ray luminosity varies as a function of accretion rate. The observed relation between X-ray and radio flux for black holes producing compact jets [35] has been interpreted as evidence that the jet dominates the accretion flow at low accretion rates [33]. Sensitive TeV observations should enable us to directly probe this relation; the strategy would be to observe a black hole transient in the X-ray and TeV bands as it decays back to quiescent after an outburst. This would provide important information on the nature of the accretion flow at low luminosities which would impact the question of whether the low quiescent luminosities of black holes are valid evidence for the existence of event horizons and also the effect of (nearly) quiescent supermassive black holes (such as Sgr A*) on the nuclei of galaxies.

1.5 Required instrument performance

For the study of PWNe, the performance drivers are improved sensitivity, angular resolution, and extension of the spectral coverage up to 100 TeV. In order to detect large populations of fainter sources, improved sensitivity in the band around 1 TeV is essential. The properties of PWNe and the resident pulsars vary significantly and a large sample of sources is needed to fully understand these objects and it is essential to use them as probes of pulsar astrophysics. Improved angular resolution, with sufficient counting statistics to make effective use of the resolution, is needed to accurately map the TeV emission. Radio and X-ray maps are available with arcseconds precision which cannot be matched in the TeV band. However, angular resolution sufficient to produce multiple pixel maps of the TeV emission is adequate to map the distribution of high-energy particles as needed to understand their diffusion

within PWNe. Extension of the spectral coverage up to 100 TeV would enable us to measure the spectral break and determine the highest energies to which particles are accelerated. This would provide fundamental information on the physics of the acceleration process.

Since many pulsar spectra cut off below 10 GeV, extension of the energy range down to the lowest energies possible is important for the study of pulsed emission. Detection of the pulsed emission from a significant number of pulsars will likely require sensitivity below 50 GeV. However, a search for the inverse Compton component predicted in outer gap models to lie at TeV energies will provide important constraints on models.

For the study of binaries, both neutron star and black hole, sensitivity is the main driver in order to detect additional sources and to study known objects with high time resolution. A factor of ten increase in sensitivity in the ‘canonical’ TeV band (0.2-5 TeV) should significantly increase the number of binaries which are detected in the TeV band, permitting studies of how TeV emission correlates with binary properties; i.e., spin-down power, orbital separation, and companion star type. This will provide insights into the mechanism which produces the TeV photons.

Increased sensitivity is essential to study binaries at faster cadence. All of the binary sources are variable and the differing time evolution at different wavebands will likely be the key to understanding the dynamics of particle acceleration and TeV photon production in these systems. In addition, the ability to monitor a given source on a daily basis for long periods is essential to allow studies of the dependence of the TeV flux on orbital phase. To search for jet emission from quiescent black holes, a flux sensitivity 10^{-14} erg s $^{-1}$ in the 0.25-4 TeV band is required.

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