

The challenge of identifying Galactic TeV sources

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ABSTRACT

Since VHE gamma-ray observations made during the H.E.S.S. Galactic Plane Survey revealed for the first time the existence of dozens of extreme particle accelerators in our Galaxy, source identification became a crucial aspect in ground-based high-energy gamma-ray astronomy. Whereas the general problem resembles that of the unidentified EGRET sources, a low-threshold imaging Cherenkov telescope array's superior angular resolution and resulting imaging capability against a drastically reduced diffuse component enables different identification techniques. Given that IC photons at TeV energies originate from seed photons at keV energies, the wide field X-ray imaging capabilities and high duty cycle of the MAXI mission will provide contemporaneous X-ray observations to essentially all VHE gamma-ray observations to come, and might ultimately help to characterize the underlying particle population of these extreme Galactic gamma-ray emitter. Most particular, the so far sparsely probed domain of time dependent high-energy characteristics offered from all-sky monitoring by MAXI will add new perspectives to the exploration of VHE gamma-ray sources.

KEY WORDS: astrophysics: high-energy — observations: TeV, X-rays — source identification techniques

1. Galactic VHE gamma-ray astronomy

Since several decades space-based exploration of the gamma-ray sky we know that our Galaxy is rich of high-energy sources. The succession of more and more capable instruments operating at high MeV/low GeV energies, starting from SAS-2 (1972-1973) via COS-B (1975-1982) and EGRET (1991-2000) to AGILE and Fermi LAT in orbit now, can be directly seen in relation to our growing knowledge of energetic sources and particle acceleration in our Galaxy. What once started with observing excess emission broadly aligned with the equator of our Milkyway was followed by the discovery of gamma-ray point-sources. The first clue towards their nature was only a spatial location close to the Galactic plane. Meanwhile many dozens of gamma-ray point sources located at energies from 100 MeV to 10 GeV (Hartman et al. 1999) have been cataloged, yet the overwhelming majority of the galactic GeV sources evade their conclusive relation to an unique astrophysical object. These sources are commonly referred to as *Unidentified EGRET sources*. The only exception in the rather disappointing small fraction of cataloged gamma-ray sources compared against a multitude of possible interpretations regarding objects at other wavelengths, is the class of pulsars, which revealed their nature by providing a similar periodic gamma-ray as known from radio- or X-ray observations.

That VHE gamma-ray astronomy would be challenged with a similar severe identification problem was hinted by the HEGRA discovery of the source TEV J2032+4130 (Aharonian et al. 2002), a source located towards a dense stellar association in the Cygnus region (Cyg OB2), but slightly extended compared with the nominal telescope array's response to a celestial point-source. That the inherent quality of stereoscopic observations from observations of nearby AGN found its application also in Galactic TeV objects (Aharonian 1999), was perhaps most impressively documented by the discovery of Cas A (Aharonian et al. 2001) after dedicating 232 hours of observations on this source. Still, the puzzling source TEV J2032+4130 offered several alternatives in its astrophysical interpretation, and it can be seen as a precursor of what to expect from the next generation of ground-based Cherenkov facilities to come.

With the begin of operation of the vastly more sensitive current generation VHE gamma-ray experiments, the problem of Galactic source identification reached finally a scale comparable to what was encountered by satellite-based gamma-ray observations. Most notably, the accomplishments by the High Energy Stereoscopic System (H.E.S.S.) shaped the status of the field of Galactic VHE gamma-ray astronomy. With a dedicated science exploration towards searching for the sources of

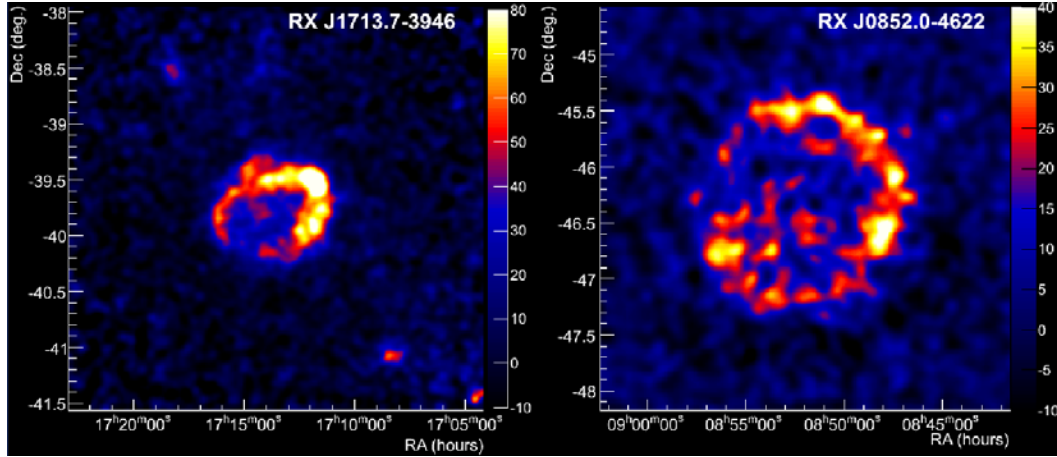


Fig. 1. Morphological resolved shell-type SNRs at VHE energies: RX J1713.7–3946 and RX J0852.0–4622. The observations were made with the H.E.S.S. telescope array. In such cases, the identification with the corresponding astronomical object is conclusive. [from Funk 2007]

Galactic cosmic rays and understanding the underlying acceleration processes, H.E.S.S. systematically scanned the inner part of our Galaxy in a multi-year observation program. With the capability of detecting a point source with flux $F_{\min}(> 100 \text{ GeV}) \sim 4 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ for a 5σ in 25 hrs, and a comparably wide-field imaging camera, the chance for success in scan-type observations were good, and this strategy paid off: The vast majority of the currently known Galactic VHE sources was discovered during this survey (Aharonian et al. 2005a, 2006a, 2008). The perhaps most striking result among the many Galactic discoveries can be seen in the sheer number and diversity among the newly found extreme particle accelerators, a diversity seen in their individual gamma-ray emission morphology (ranging from close resemblance of structures known from other wavebands to morphological features currently unmatched at other wavelengths), as well as in the diversity among their associated astronomical sources, which are presently Supernova remnants (SNRs), Pulsar Wind Nebulae (PWNe), and binary systems, but include also cosmic ray interactions in dense molecular environments, and stellar-wind related acceleration sites.

Whereas prominent young shell-type SNRs (Fig.1) have been identified through their resolved morphology, closely resembling those known from observations at (primarily) X-ray energies (e.g. RX J1713.7-3946, RX J0852./0-4622, RCW 86, SN1006), other VHE sources coincide spatially with known SNRs but cannot readily established as such, particular if their angular size is in the order of the instrumental point spread function or less (H.E.S.S.: approximately Gaussian with a 68% containment radius of 0.1°). For the latter, an inherent ambiguity in associating *unresolved* VHE gamma-ray sources with either the SNR or a

PWN powered from a compact object within the SNR cannot be addressed solely from the perspective of VHE gamma-ray observations. Examples of such SNR-associations, now commonly referred to as *composite SNR*, are SNR G0.9+0.1/HESS J1747-281 (Fig.2 right) G348.5+0.1 (CTB 37A)/HESS J1714-385, or G29.7-0.3 (Kes75)/HESS 1846-029.

In a few cases, however, X-ray data argue favorable for a PWN scenario. G12.8-0.02/HESS 1813-178, or G338.3-0.0/HESS J1640-465, both unresolved at VHE energies, were subsequently targeted by XMM-Newton and Chandra, respectively. The deep X-ray observation revealed, unlike in the case of the morphological resolved SNRs, X-ray emission from a small region inside the shell of these SNRs, indicative rather for a central PWN than shell- or rim-associated SNR emission.

A different scenario is favored in middle-aged SNRs like IC443/MAGIC J0616+225 (Fig.2 left) or W28/HESS J1800-240, where gamma-ray emission is observed inside their, albeit deformed, shell structure, but in good correlation with overdensities in the molecular material traced through MWL observations. They are good candidates for gamma-ray emission interpreted by interactions with giant molecular clouds, and both density and filling factor for their target material constitute promising cases for π^0 -decay related emission.

Leaving the domain where energetic particles are confined inside an astrophysical object (as in young shell-type or composite SNRs), accelerated particles can also diffuse out into the surrounding medium. Here, the size of the emitting region itself defines the spatial extent of the gamma-ray source; consequently, a variety of different source morphologies are seen among the class of VHE PWN (Fig.3). Preceded long since by the Crab Nebular, once more establishing itself as an unique cosmic laboratory through its exceptional broad coverage

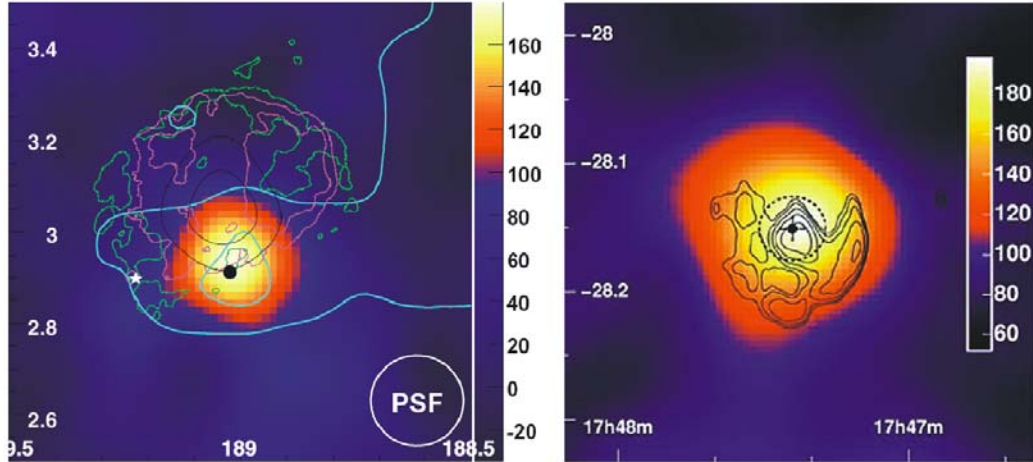


Fig. 2. Left: The case of a composite VHE SNR (G0.9+0.1/HESS J1747-281), where one cannot distinguish between resemblance of a SNR-morphology or conclude on a PWN inside an unresolved VHE source. [from Aharonian et al. 2005b] Right: The case of VHE emission seen well within the shell of a SNR (IC443/MAGIC J0616+225). The proposed scenario here is based on a connection of the VHE excess with overdensities in the molecular material inside the shell, traced by ^{12}CO emission (cyan). [from Albert et al. 2007]

over the entire electromagnetic spectrum, Pulsar wind nebulae meanwhile represent the numerically dominant class of Galactic VHE objects. The observed gamma-ray emission characteristics is manifold: spatially extended, and often asymmetric to the celestial location of the respective pulsar believed to be powering the PWN. Asymmetric PWN have been known from X-ray observations before, but on comparably smaller scales. Given the variety among their VHE gamma-ray emission size, orientation, and center-of-gravity, in some cases the identification with a PWN remains only suggestive, but not settled. Therefore population studies start to fill in the missing pieces, e.g. by systematically probing a connection between the energetics of the powering pulsar and the VHE-detected PWN (Carrigan et al. 2007). In case of observed energy dependent morphology change (e.g. HESS J1825-137), with its gamma-ray spectrum softening with the increasing distance to the PSR, a preference for a Inverse Compton scenario is indicated. But even a peculiar shaped high-energy spectrum as of Vela X (HESS J0835-455, Fig.4 left) does not offer a clear imprint of the underlying radiation processes, and both leptonic and hadronic emission scenarios are able to accommodate the data. The magnetic field strengths becomes the critical parameter in modeling the high-energy emission from a PWN, too.

For those Galactic VHE gamma-ray sources currently lacking a convincing MWL association, the situation for X-ray counterpart searches can become desperate. Many VHE gamma-ray sources are typically characterized by a ratio of VHE gamma-ray energy flux to X-ray energy flux in the order of unity. In case of HESS J1616-508 (Fig.4 right), the upper limit on the X-ray flux (Mat-

sumoto et al. 2006) implies that at least 55 times more energy goes into gamma rays. For an electron accelerator and typical Galactic magnetic fields of about a few μG , one would expect a ratio around unity, ruling effectively out an electronic origin of the gamma-ray emission. However, in that case that synchrotron radiation is observed at energies of some keV their parent particle distribution is electrons at ~ 100 TeV; yet the VHE gamma-rays are produced by lower-energy electrons in the 1 to 10 TeV range. Thus, if the electron energy spectrum has a sharp cutoff between 10 and 100 TeV, the two data sets could be reconciled. Additionally, pronounced levels of gamma-ray production relative to the X-rays are expected when intense target photon fields for Inverse-Compton scattering are required to be considered. Nevertheless, similar sources without a satisfying MWL connection are found in the Galactic VHE source catalog (Aharonian et al. 2008). If no steadily emitting X-ray source can be picked-up by even the most sensitive X-ray instruments, a different element offering some prospects of source identification needs to be pursued: persistent monitoring through an all-sky X-ray instrument like MAXI.

2. Where MAXI enters VHE gamma-ray source identification and characterization

Yet one class of Galactic VHE gamma-ray sources will unquestionably benefit from permanent X-ray monitoring, the gamma-ray binaries. At present, four such systems and one candidate have been established as VHE emitter. These objects show variability in the VHE band directly related to their orbital motion: PSR B1259-

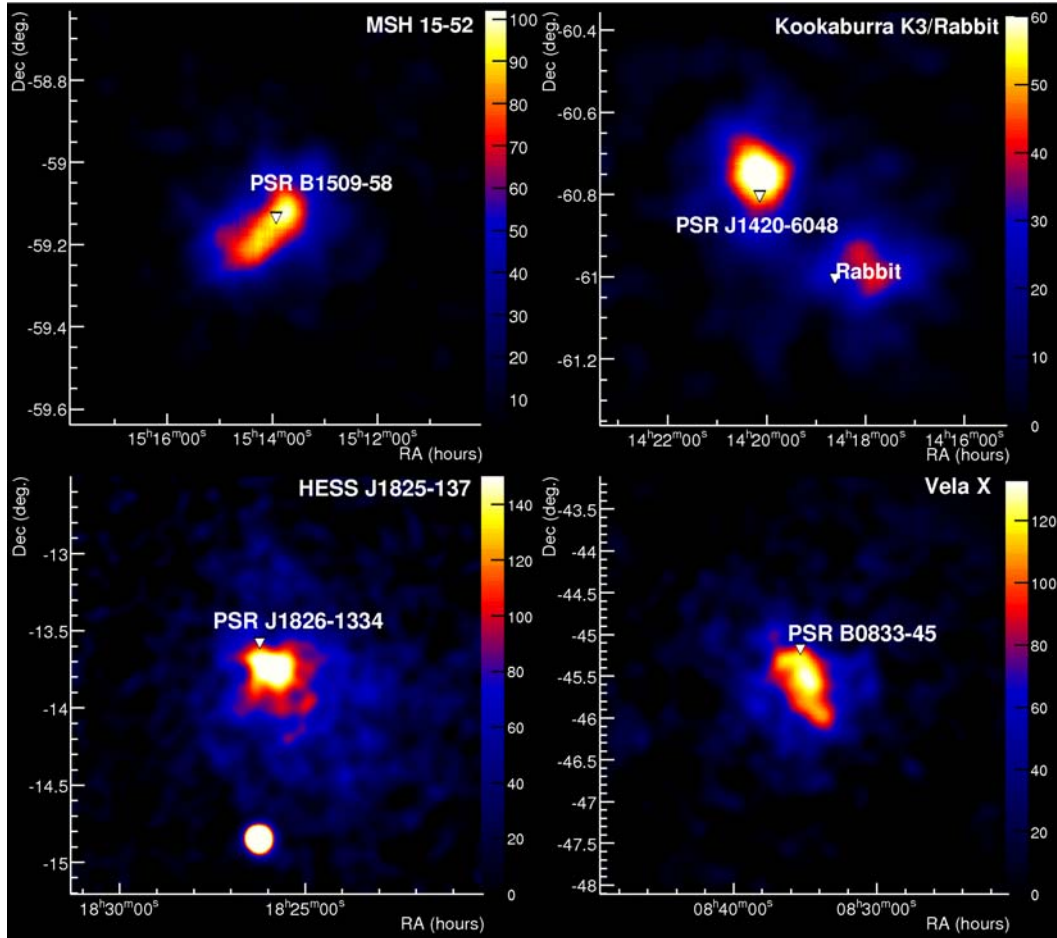


Fig. 3. VHE gamma-ray smoothed excess maps of MSH-15-5 (top left), the Kookaburra region showing the emission coincident with the two non-thermal wings of the Kookaburra (top right), HESS J1825-137 (bottom left) and Vela X (bottom right). Also shown are the energetic pulsars that are thought to power the PWNe. This ensemble documents the variety in the observed morphology in PWN at VHE energies. [from Funk 2007]

63/SS 2883 (Aharonian et al. 2005c), LS 5039 (Aharonian et al. 2005d), and LS I +61 303 (Albert et al. 2006), or transient emission as in the case of Cyg X-1 (Albert et al. 2007). Just recently, a candidate for a further gamma-ray binary was suggested based on its MWL characteristics (HESS J0632+057, Hinton et al. 2008). Since gamma-ray binaries are currently the only variable Galactic sources in the VHE sky, and their variability timescales range from fractions of their orbital cycle (3.9 days for LS 5039 up to 3.8 years for PSR B1259-63/SS 2883), their interpretation in terms of emission scenarios is consequently complex compared to that of non-variable Galactic VHE gamma-ray sources.

The pulsar PSR B1259-63 ($P = 48$ ms) is in a highly eccentric orbit around a Be-type companion star. VHE emission is predominantly produced around its periastron phase where the effects of adiabatic and radiative cooling due to the Inverse Compton process as well as synchrotron losses are strongest. The observed temporal

behavior of the source during its 2004 periastron passage was quite different from what was predicted. Refined models including a more detailed treatment of Inverse Compton scattering in energetic and anisotropic radiation fields as well as adiabatic energy losses can reproduce the observed light curve and provide some crucial predictions to be probed with new observations, if possible over the full orbit. For all VHE observation dedicated to this system, MAXI will effortlessly obtain the needed contemporaneous X-ray data for MWL modeling. Perhaps even more interesting are the two systems LS 5039 and LS I +61 303 which are characterized by significantly shorter orbital periods of 3.9 and 26.5 days, respectively. Being considered as micro-quasars with a steady radio-jet feature, our understanding of these archetypal gamma-ray binaries is perhaps changing towards pulsar winds in interaction with the stellar outflow. Crucial for any considered emission scenario is the absorption of VHE photons due to pair-production in the

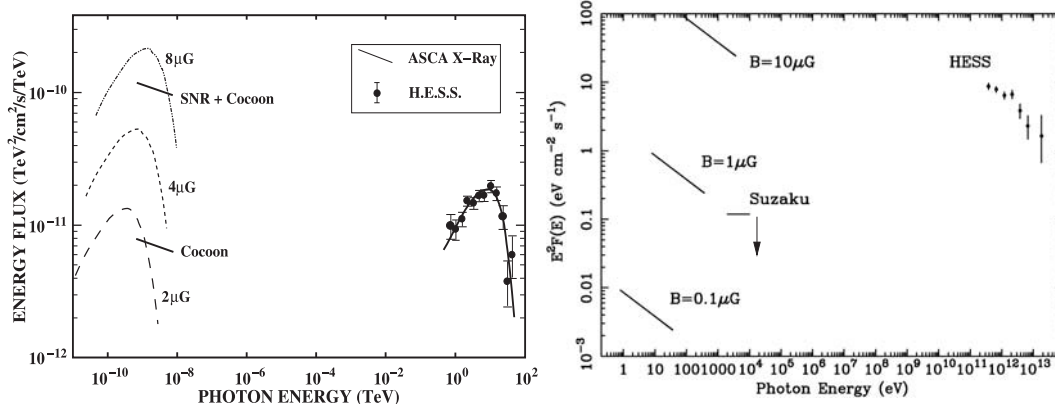


Fig. 4. Left: Spectral energy distribution (SED) of the Vela X (HESS J0835-455) Pulsar Wind Nebula. The broadband fit in an inverse Compton emission scenario is shown. The predicted synchrotron flux is shown for three possible magnetic field strengths, ranging between $2 \mu\text{G}$ and $8 \mu\text{G}$. [from Aharonian et al. 2006b] Right: Spectral energy distribution of HESS J1616-508. The upper limit on the X-ray flux from the Suzaku XIS instrument is well below the measured gamma-ray flux. Assuming that a population of high-energy electrons is responsible for the gamma-ray emission, the expected X-ray level due to synchrotron radiation depends on the magnetic field in the source, as indicated by the lines. Typical interstellar fields are around 5 microGauss, a value for which X-ray energy flux and gamma-ray energy flux should be comparable. Here, we're not picking up the X-ray counterpart to the VHE gamma-ray source, leaving open the possibility of preference of hadronic vs. leptonic emission in a 'Dark Accelerator' [from Matsumoto et al. 2006]

photon field of the stellar companion. If the line-of-sight towards the VHE emission region passes closely of the companion star, absorption will produce notable effects over different orbital phase. To connect the only sporadic monitored flux modulation at VHE energies with regular monitoring through MAXI at keV and Fermi LAT at GeV energies will allow us to study regular or exceptional emission cases (spikes?/transients?) in those systems. Finally, the detection of Cygnus X-1 at VHE energies has exemplified the need of regular X-ray monitoring. Not only different means of evaluation of mildly significant VHE gamma-ray excesses probably corresponding to a rapid emission state change can be accomplished once contemporaneous X-ray data exist, it also enables the chance to investigate e.g. similarities among the lightcurve during activity state changes, X-ray precursor activity to observed VHE outbursts, as well as enable us to pursue the ultimate quest for concluding about time-lags in the photons arriving in different wavebands. Yet another perspective to significantly enhance the scientific return from VHE gamma-ray observations towards binary objects is anticipated: Given that regular monitoring of any microquasar, and black hole candidate binary system is granted, VHE observations can actively respond on alerts issued from MAXI observations in case of serendipitously emission phenomena, or on transitions in their activity states traced by X-ray observations.

3. Unidentified Galactic VHE sources

Most sources so far discussed have been conclusively identified or are at least associated with known astro-

physical objects. However, a sizable number of objects at the Galactic VHE sky still remain to be identified. Among these objects, the Galactic Center source is certainly the most prominent. The central region of our Galaxy contains a super-massive black hole, and mm-, IR-, and X-ray sources associated with Sgr A* have been found to exhibit variability including flares and outbursts with a time-scale of hours. The point-like VHE gamma-ray source in the Galactic Center, seen by all major VHE experiments, needs to be discussed in the context of broadband emission near to the super-massive black hole. If indeed near Sgr A*, emission can be either produced in the high magnetic fields that are believed to be threaded in the accretion disk or from π^0 -decay from energetic protons. Further away from Sgr A*, acceleration in a SNR as well as in stellar winds has been suggested. The accuracy of reconstruction in the position of the VHE-emitting point source has been improved to the level of the pointing accuracy of ~ 6 arc seconds and excludes the Sgr A East SNR (van Eldik et al. 2007). The error box for the VHE source still encompasses at least three possible candidates for VHE emission: Sgr A*, a low-mass X-ray binary system (LMXRb), the stellar system IRS 13, and the PWN G359.95-0.04. Albeit a typical X-ray flare was detected by Chandra during dedicated MWL observations of Sgr A* in summer 2005, the simultaneously taken H.E.S.S.-data lacked the imprint of variability even though the observed rate of VHE photons was sufficiently large to detect a flare of comparable strength as seen in the X-ray data. Given the complex interstellar radiation field and the variety of possible objects that may or may not be related to the observed

VHE gamma-ray emission, detection for correlated variability might offer a distinct way towards understanding the nature of this source.

Finally, the detection of VHE gamma-ray emission from the young stellar cluster Westerlund-2 (Aharonian et al. 2007) was a crucial step towards establishing the role of stellar wind driven cosmic ray acceleration. Whether or not the observed emission can be directly related to the prominent massive Wolf-Rayet binary system WR 20A, or a collective stellar wind emission scenario may be established only in the future through probing variability over timescales possible only by perpetual high-energy monitoring.

4. Beyond known VHE sources?

With extremely capable ground-based VHE gamma-ray observing facilities in regular operation now, one can also speculate about new classes of Galactic sources where MAXI might become critical to trigger subsequent VHE observations, or where VHE gamma-ray astronomy will benefit from supplementary data taken by MAXI. First and foremost we have to consider supernovae, expected to be part of any target-of-opportunity program in ground-based imaging atmospheric Cherenkov experiments. But also Galactic objects prone for sporadic but powerful outbursts like magnetars come to mind. Given the limited field-of-view and both site and night-time constraints for VHE gamma-ray observations, this community will critically depend on timely and reliable trigger mechanism from the instruments of high duty cycle and all-sky survey capability. X-ray observations at keV energies by MAXI will predictably find a place next to the Fermi LAT instrument operating at GeV energies in that regard.

I thank the organizers for inviting me to this workshop as well as for encountering profound interest in the field of VHE gamma-ray astronomy, which will certainly benefit from seeing the *Monitor of All-Sky X-ray Image* instrument in orbit soon.

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