Astro2020 Science White Paper

Probing Extreme Environments with Very-High-Energy Gamma Rays

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☒ Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☒ Galaxy Evolution ☒ Multi-Messenger Astronomy and Astrophysics

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Abstract:

Very-high-energy gamma rays (traditionally above ~100 GeV) are the most energetic cosmic electromagnetic radiation observed and trace the presence of charged particles of even higher energy. These gamma rays can provide unique views of the strong magnetic fields around neutron stars and the strong gravitational fields around neutron stars and black holes. At the other extreme of density, they can probe the environment of cosmic voids. This white paper briefly summarizes what can be learned over the coming decade about extreme astrophysical environments through ground-based gamma-ray observations over the 20 GeV to 300 TeV range. The majority of the material is drawn directly from *Science with the Cherenkov Telescope Array* [1], which describes the overall science case for CTA. We request that authors wishing to cite results contained in this white paper cite the original work.

Introduction

Ground-based gamma-ray astronomy is a young field with enormous scientific potential. The possibility of astrophysical measurements at teraelectronvolt (TeV) energies was demonstrated in 1989 with the detection of a clear signal from the Crab nebula above 1 TeV with the Whipple 10m imaging atmospheric Cherenkov telescope (IACT). Since then, the instrumentation for, and techniques of, astronomy with IACTs have evolved to the extent that a flourishing new scientific discipline has been established, with the detection of 200 sources and a major impact in astrophysics and fundamental physics. The current major arrays of IACTs: H.E.S.S., MAGIC, and VERITAS, have demonstrated the huge science potential at these energies as well as the maturity of the detection technique. Many astrophysical source classes have been established, some with many well-studied individual objects, but there are indications that the known sources represent the tip of the iceberg in terms of both individual objects and source classes.

Early in the coming decade, a larger telescope array with improved technology can be implemented and achieve an order of magnitude improvement in sensitivity, combined with better angular resolution and sensitivity over a wider range of energies (20 GeV–300 TeV), which we refer to here broadly as “very high energy,” VHE. The science capabilities of such an instrument (and the optimization of its design) have been studied extensively by the Cherenkov Telescope Array (CTA) Consortium [1]. It would transform our understanding of the high-energy universe and explore questions in physics of fundamental importance. Indeed, such an instrument was a recommended large ground-based project in the Astro2010 decadal survey [2], and the CTA Consortium embodies a unified, worldwide effort working toward that goal. One of the major science themes that can be addressed with an instrument of this type is studies of extreme environments.

This white paper highlights the important progress that can be made in our understanding of extreme environments using VHE gamma rays, taking the well-studied, specific design of CTA as a proxy for a generic instrument of this type, and summarizing the published work of the CTA Consortium [1]. Separate white papers cover the science themes of how VHE gamma rays can be used to study the origin and role of relativistic cosmic particles, how they can be used to explore frontiers of physics, and how they are a critical component of multi-messenger astrophysics. An additional white paper discusses how IACT arrays are outstanding platforms for stellar intensity interferometry, enabling optical studies with exquisite resolution.

Extreme Astrophysical Environments

Particle acceleration to very high energies is typically associated with extreme environments, such as those close to neutron stars and black holes, or in relativistic outflows or explosions. VHE emission from accelerated particles can therefore act as a probe of these environments, providing access to time and distance scales which are inaccessible in other wavebands. VHE emission often escapes from systems where UV and X-ray emission is absorbed, and it provides information independent of assumptions on magnetic field strengths. In addition, VHE photons from distant objects can be used as a probe of the intervening space. Gamma-gamma pair production signatures will allow us to measure the redshift evolution of the UV-IR background, and hence the star-formation history of the universe, to probe magnetic fields in cosmic voids down to values many orders of magnitude below the reach of any other technique. Gamma-ray

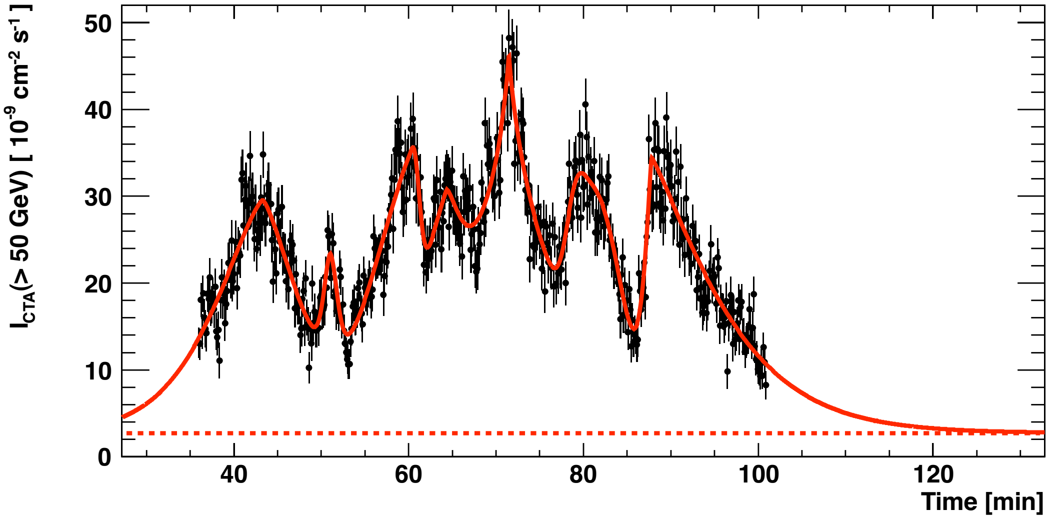

Figure 1: Probing ultra-fast variability in the inner jet of an active galaxy: simulated CTA light curve for the 2006 flare of PKS 2155−304 (reproduced from [3]). Such observations provide access to timescales much shorter than the light-crossing time of the supermassive black hole.

observations can also establish if VHE photons heat the gas in these under-dense regions, suppressing the formation of dwarf satellite galaxies. Below we consider three key areas within this theme where VHE gamma-ray data will have a transformational impact.

Black holes and jets

Active galactic nuclei (AGN) harbor supermassive black holes (SMBHs), accreting material and producing collimated relativistic outflows by a still poorly-understood process. Similarly, accreting stellar mass black holes are known to produce jets, and particle acceleration seems to be universally associated with BH-powered jets. Acceleration may occur extremely close to the SMBH or up to Mpc scales, where the largest AGN jets finally terminate. To explain the remarkably short variability timescales in some systems, see Figure 1, compact emission regions are required. Active galaxies are seen as one of the most likely sites of the acceleration of the ultra-high-energy cosmic rays, with energies up to around 10^{20} eV, but so far there is no strong evidence for hadronic acceleration in AGN jets.

Simultaneous broad-band data is needed to study variable jet emission in both Galactic and extragalactic systems, with VHE gamma-ray data playing a key role: establishing the presence of very high energy particles, identifying the presence of hadrons and studying extremely short-timescale variability that provides information on the smallest spatial scales and probes the bulk ultra-relativistic motions of the inner jet. Time-resolved VHE spectral measurements are key to disentangling leptonic and hadronic emission scenarios (see Figure 2), to study jet power and dynamics, and to probe magnetic fields in this extreme environment.

The low-luminosity AGN at the heart of our own galaxy, Sgr A*, is coincident with a TeV source and has associated non-thermal emission in the radio and X-ray bands. However, the sensitivity, resolution and pointing precision of current gamma-ray telescopes are insufficient

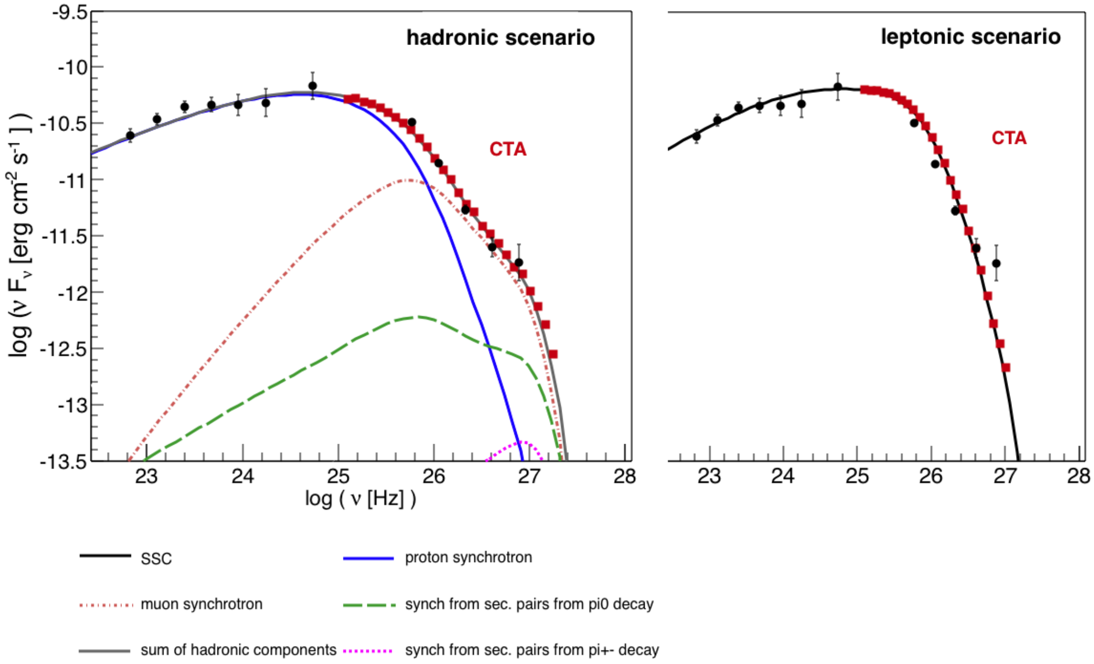

Figure 2: A comparison of the expected CTA spectra for two specific (simple) emission models for the blazar PKS 2155-304. A hadronic scenario, where high-energy emission is caused by proton- and muon-synchrotron photons and secondary emission from proton-photon interactions, is shown on the left, and a standard leptonic synchrotron self-Compton model on the right. The exposure time assumed for the simulations (33 h) is the same as the live time for the H.E.S.S. observations (black data points above 3×10^{25} Hz). The statistical uncertainties in the CTA data points are smaller than the red squares. For more details see [4, 5, 6].

to separate the emission from very nearby sources from the diffuse emission around the Galactic Center. CTA will map this region in unprecedented detail (see Figure 3), probing the relationship between the central source and the diffuse emission and, on much larger scales, up to the Fermi bubbles.

There is evidence from current IACTs for TeV emission from a single system hosting a stellar mass black hole: Cygnus X-1 [7]. The sensitivity of CTA should allow this object to be studied in detail, opening the door to studies of high-energy non-thermal processes associated with stellar mass black holes and allowing the first comparisons to be made with SMBH systems.

The recent discovery of gravitational wave (GW) emission associated with the mergers of massive black holes [8, 9, 10] raises many exciting new possibilities in observational astrophysics and many questions about the evolution of high mass binary systems [9, 11]. Clearly the possibility for jet formation and acceleration of particles to TeV energies in such systems exists, and as GW detections will, for the foreseeable future, all originate within the TeV gamma-ray horizon, such alerts will form a key target for CTA.

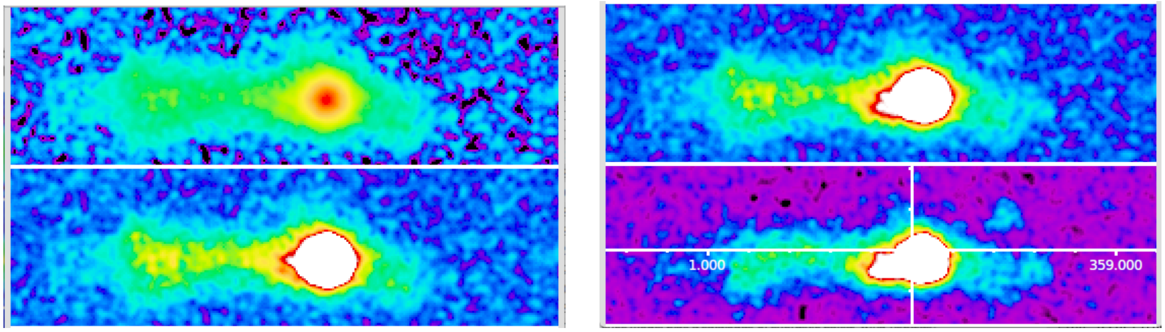

Figure 3: A simulated view of the Galactic Center region as seen by CTA (excess events above 800 GeV after cosmic-ray background subtraction, with Gaussian smoothing). *Left:* the reference model that includes a point-like source at the position of Sgr A* with an exponential-cutoff power-law spectrum matching H.E.S.S. measurements [12], a similarly modeled point-like supernova remnant G0.9+0.1 [13], diffuse emission from a template based on the dense matter distribution deduced from HCN molecule observations [14], and an extended circum-nuclear ring template. The top image is in log scale and the bottom is clipped to show the details of the diffuse emission (thus the point-like central source which is an order of magnitude brighter is washed out). *Upper right:* the reference model plus a catalogue of energetic pulsar-wind-nebulae [15]; here the central source clearly appears extending towards the left. *Lower right:* an alternative model consisting of an extended circum-nuclear ring model assuming the source is produced by the interaction of isotropic cosmic rays with the circum-nuclear ring gas (which has a $1.5'$ diameter), diffuse emission from HCN maps as above, and closeby pulsar wind nebulae [15] (modeled as point-sources). The central source and G 0.9+0.1 are excluded. Cosmic-ray background is subtracted using a model generated from cosmic-ray events; the same background model is used in all cases.

Neutron stars and relativistic outflows

VHE observations will probe the environment around neutron stars via pulsed gamma-ray emission from the magnetosphere of pulsars and study the ultra-relativistic outflows of these systems via mapping and spectral measurements of the associated synchrotron/inverse-Compton nebula and (possibly and uniquely) the unshocked pulsar wind. Two very promising targets are HESS J1825−137 and the Vela pulsar (and associated Vela X nebula).

Binary systems including a pulsar provide a unique opportunity to study a relativistic outflow under changing physical conditions as the orbit progresses, via energy-dependent light-curve measurements.

Merging neutron stars and other compact object mergers are the likely counterparts of short gamma-ray bursts (GRBs), and are of course the targets of the young field of gravitational wave astronomy. Long GRBs probably lead to the formation of black holes or neutron stars. CTA will be able to respond rapidly to triggers from GRB or GW instruments, and hence probe the highest energy processes associated with such events.

Cosmic voids

Much of the universe consists of extremely under-dense regions known as cosmic voids. VHE photons traverse these voids and interactions therein allow us to probe the radiation fields and magnetic fields that they contain. The extragalactic background light (EBL) is the integrated emission from stars and galaxies of all types throughout the evolution of the universe. As such, it is an important tool for cosmology but it is extremely difficult to measure directly, due to very strong foregrounds from the Solar System and the Milky Way. However, the EBL leaves an imprint on the measured spectra of gamma-ray sources, via the process of gamma-gamma pair production. Wide-band, high-quality spectra for a large number of objects will allow the EBL spectrum from the optical to the far infrared to be precisely measured at redshift zero. Furthermore, with the expected large sample of blazars up to redshift ~1 detected with CTA, the evolution of the EBL with cosmic time can be probed [16].

Pair production by TeV photons interacting in voids also offers the prospect of measuring the extremely weak magnetic fields thought to exist in these regions. Secondary gamma rays are produced by the primary $e^{\pm}$ pairs via inverse-Compton scattering on the EBL. A cascade can then develop from further pair and inverse-Compton interactions. Depending on the typical value of the intergalactic magnetic field (IGMF), deflections of the secondary particles may either be small enough that secondary components may be observable as *pair echoes*, which arrive with a time delay relative to the primary emission, or as a *pair halo*, potentially resolvable extended emission around the primary source. The properties of the extended emission depend on the IGMF strength and coherence length. A strong enough IGMF ($> 10^{-12}$ G) leads to full isotropisation of the cascade emission and formation of a physical pair halo, while a weaker magnetic field leads to the appearance of an extended emission with an IGMF-dependent size. If the IGMF strength is in the range, $B \sim 10^{-16} - 10^{-12}$ G, the spatially-extended emission may be detectable and resolvable by CTA by virtue of its high sensitivity and angular resolution; e.g., for a source at a distance of 100 Mpc, the extended emission would be on the $\sim 1^{\circ}$ scale and would be comfortably contained within the CTA field of view. Details can be found in [3, 17, 18].

If, as has been recently suggested, TeV electrons produced in gamma-gamma interactions in the voids do not initiate cascades but rather *heat* the ultra-low density plasma [19], CTA will allow this hypothesis to be proven and the heating rate to be very well constrained. This mechanism could be the dominant means of heating in low density regions after redshift ~2, and could solve the problem of the missing dwarf satellite galaxies. Hence, this measurement would be a very valuable addition to cosmology.

Conclusions

Observations with VHE gamma rays have begun to deliver insights on the most extreme astrophysical environments, such as cosmic voids, the magnetospheres of neutron stars, and black holes from stellar to giga-stellar masses. IACT arrays with better angular resolution, wider coverage in energy, and an order of magnitude improvement in sensitivity are achievable early in the coming decade. Among the wide range of science that could be done, our understanding of extreme environments could be transformed.

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