Cosmic explosions dissipate energy into their surroundings on a very wide range of time scales: producing shock waves and associated particle acceleration. The historical culprits for the acceleration of the bulk of Galactic cosmic rays are supernova remnants: explosions on approximately $10^4$ year time scales. Increasingly, however, time-variable emission points to rapid and efficient particle acceleration in a range of different astrophysical systems. Gamma-ray bursts have the shortest time scales, with inferred bulk Lorentz factors of approximately 1000 and photons emitted beyond 100 GeV, but active galaxies, pulsar wind nebulae and colliding stellar winds are all now associated with time-variable emission at approximately teraelectron volt energies. Cosmic photons and neutrinos at these energies offer a powerful probe of the underlying physical mechanisms of cosmic explosions, and a tool for exploring fundamental physics with these systems. Here, we discuss the motivations for high-energy observations of transients, the current experimental situation, and the prospects for the next decade, with particular reference to the major next-generation high-energy observatory, the Cherenkov Telescope Array.

1. Introduction

Transient phenomena are often associated with the most extreme conditions in the Universe, where violent outbursts and explosions create jets and/or shocks in which particle acceleration can occur. Particles accelerated to high energies in these environments produce gamma-rays that have been observed with high-energy instrumentation since the 1960s, but with a breakthrough in sensitivity associated with Energetic Gamma Ray Experiment Telescope (EGRET) [1] observations in the early 1990s and the advent of
sensitive ground-based instruments such as HESS [2] a decade later. The production mechanisms for gamma-ray emission include the decay of neutral pions produced in strong interactions of accelerated protons and nuclei, inverse compton (IC) scattering of high-energy electrons on soft photon fields and Bremsstrahlung emission from electron encounters with ambient material. Two advantages of gamma-ray emission with respect to more conventional probes of high-energy particles, such as synchrotron emission in the radio and X-ray bands, are that $\pi^0$-decay emission probes the (often) energetically dominant accelerated protons and nuclei as well as electrons, and that in the case of electron accelerators IC emission allows unambiguous energy-density measurements, without assumptions such as equipartition with magnetic fields. The use of neutrinos, produced for example in charged pion decay, as a probe of high-energy transient phenomena is being pioneered using large-volume ice and water detectors such as IceCube [3].

Our current view of the GeV ($10^9$ eV) sky as provided primarily by the Fermi satellite is rich in time-variable phenomena with typical time scales ranging from approximately 1 s in gamma-ray bursts (GRBs), to days in galactic novae (e.g. V407 Cyg [4]), to years in the colliding-wind binary $\eta$-Carinae [5]. Active galactic nuclei (AGN) are variable on a wide range of time scales, with the shortest-time-scale variability probed only by the very-large collection area (ground-based) instruments available above approximately 50 GeV. TeV emission ($10^{12}$ eV) is seen from cosmic explosions on time scales up to thousands of years, the ages of the TeV-detected supernova remnants (SNRs), as well as minute to month time scale variability from blazars, radio galaxies and galactic binary systems [6]. Many of these systems are ‘persistent’, but the individual flaring events have much in common with transients such as GRBs.

Study of these time-variable phenomena at high energies, with the possibility to disentangle effects owing to the cooling and transport of particles and the interplay between particles and magnetic fields, is a promising route to improve our understanding of the process of particle acceleration, and the role played by accelerated particles in cosmic explosions and the feedback these events have on their environments. There is a great promise in this area in the future, with the construction of the Cherenkov Telescope Array (CTA) [7] and a window on new types of transients with Advanced LIGO [8]. In the nearer term, the second phase of the HESS project will bring a major boost to approximately 50 GeV studies, and the prospect for neutrino detection of transients with IceCube remains strong.

Here, we discuss first the currently operating detectors, then the results from these instruments and finally the prospects for high-energy transient studies in the decades to come.

2. Current detectors

The Fermi gamma-ray space telescope, launched in 2008, is a two-instrument mission operating between 10 keV and approximately 200 GeV. From a high-energy perspective, Fermi’s Large Area Telescope (LAT) [9], a pair-conversion telescope, is of most interest. LAT operates in the energy range above 25 MeV, has a collection area of approximately 1 m$^2$, and is currently the most sensitive instrument up to approximately 50 GeV, reaching a differential flux sensitivity (i.e. the flux required for detection in four independent spectral bins per decade in energy) of $\approx 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at approximately 300 MeV for a steady extragalactic point-like source in the current $\approx$ 4 year all-sky survey dataset (see figure 4 for the LAT sensitivity in comparison with the planned CTA observatory). The Gamma-ray Burst Monitor (GBM) acts as an all-sky monitor of hard X-ray transients. Together, GBM+LAT are revealing the high-energy spectra of numerous transient sources, with particular important discoveries in the GRB field (§3), and in setting constraints on quantum gravity models by constraining Lorentz invariance violation (e.g. GRB090510) [10].

Two types of ground-based, very-high-energy (VHE) instrument have been used to monitor the gamma-ray sky. Air-shower-particle-detecting arrays such as MILAGRO [11] (and soon
HAWC [12]; and see §4) have wide fields of view (FoV, approx. 1 sr) and very high duty cycle (close to 100%) but modest resolution and collection area. Instruments based on the imaging atmospheric Cherenkov technique (IACT) are more precise and achieve collection areas in excess of $10^5$ m$^2$ but have smaller FoV (approx. 10 square degree) and operate only during darkness. The major current generation IACT arrays are MAGIC [13,14], VERITAS [15] and HESS, all with multiple telescopes with large (greater than or equal to 12 m diameter) segmented mirrors providing stereoscopic imaging of the electromagnetic cascades initiated by high-energy gammarays in the Earth’s atmosphere. IACT sensitivity, angular and energy resolution as well as collection area can all be improved by adding more, or building larger, telescopes. Imaging atmospheric Cherenkov telescopes can and do slew to transient events, alerted by the GRB coordinate network, but are limited by duty cycle and redshift depth is somewhat limited (especially at multi-TeV energies) owing to the gamma-ray opacity of the Universe (owing to pair-production on the extragalactic background light, EBL [16]). The performances of HESS, MAGIC and VERITAS as operating circa 2011 are very similar, with approximately 0.1° resolution (an order of magnitude better than Fermi LAT at 1 GeV) and differential flux sensitivity of a few $10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at approximately 1 TeV for a 50 h observation. Upgrades to these systems are however underway or have been recently completed. Of particular note is the second phase of the HESS project, which involves the addition of a new 28 m diameter telescope (figure 1), bringing the capability to detect photons of much lower, approximately 20 GeV, energies and improving sensitivity by a factor of two or more at 300 GeV. July 2012 saw the first-light of HESS-2, and the first scientific observations are now underway. The new large telescope is designed to slew to any point in the sky in approximately 40 s and transients form a key part of the science programme. The science highlights from the current generation detectors include the census of galactic particle acceleration sites, the detection of distant AGN with implications for the density of far IR photons in the Universe, the discovery of high-energy emission from starburst galaxies and the detailed imaging of TeV emission from SNRs and pulsar wind nebulae (see [6] and references therein). The rapid variability of AGN in the TeV-blazar class is discussed in §3.

Beyond photons, VHE neutrinos and ultra-high-energy (UHE) protons are promising messengers with which to probe the extreme Universe. The prime current facility for high-energy neutrino detection at present is the deep ice Cherenkov detector IceCube. No neutrino sources have so far been identified and the limits derived are constraining models for high-energy phenomena, including GRBs (see §3). The Pierre Auger Observatory (see [17] and references therein) is the most sensitive detector of cosmic rays (and also neutrinos and photons) at energies above approximately $10^{19}$ eV. So far, no strong evidence for individual sources of UHE cosmic rays has been found, and charged messengers such as protons are expected to experience long time delays owing to longer path-lengths with respect to photons, making transient identification at UHE very difficult.
Figure 2. Fermi LAT best-fit spectral models for (a) long GRB 090926A and (b) short GRB 090510, both requiring an additional, high-energy component (adapted from [18,20]). (Online version in colour.)

3. High-energy results

(a) Gamma-ray bursts

GRBs are the most powerful transients in the Universe, releasing of the order of $10^{51}$ erg of energy in shocks produced in a relativistic jet. The jets are formed during stellar collapse at the death of a massive star and the birth of a new black hole and supernova (collapsar); some GRBs may arise from compact object mergers. We are alerted to the onset of a GRB by a huge release of
gamma-rays, with the energy output typically peaking around 1 MeV, lasting anywhere between one and several hundred seconds. Some of these events are now being recorded with *Fermi* to beyond 10 GeV.

*Fermi* LAT is detecting approximately 10 GRBs per year at more than 100 MeV, and the highest-energy photons detected originated with energies of beyond 100 GeV (GRB090902B at $z = 1.822$ [18]).

Both long and short GRBs, thought to be associated with collapsars and compact object mergers, respectively, have been observed at GeV energies. The mechanism by which this prompt emission is produced is not known. The initial GRB spectrum can be described by a band function [19]—a broken power law peaking (in $\nu F_\nu$) in the gamma-ray band, possibly attributable to synchrotron emission. This may be augmented by a thermal or quasi-thermal high-energy ‘bump’, and in some cases also a hard power law peaking beyond 100 GeV and also of unknown origin (figure 2). GRB090926A was observed with LAT, and found to require an extra component at high energies to extend the emission beyond the reach of the band function [20]. This additional component also showed a cut-off at 1.4 GeV which, if as a result of internal pair production, allows the Lorentz factor of the flow to be determined directly. This is a very exciting prospect for GRB physics. Two further LAT GRBs have high-energy components that show no clear cut-off (including short GRB 090510 [21]), whereas an additional high-energy component is not required (but is poorly constrained) in other (fainter) examples. A delayed onset and longer duration of the highest energy emission compared with lower energy photons is also observed. Intriguingly, the delay appears to scale approximately with GRB duration, the long GRBs showing the greatest observed delays, irrespective of GRB luminosity [22]. The long and short GRBs appear to differ only in their fractional radiative output at high energies—reduced in the long GRBs compared with the short GRBs, making VHE observations of short GRBs an exciting, but difficult, proposition.

Observations of GRBs at GeV to TeV energies can provide measurements of the bulk Lorentz factor and total energy budget, and help improve our understanding of the central engine, particle acceleration, jet formation, energy dissipation and GRB progenitors. Additionally, GRBs are unique probes of Lorentz invariance violation, and cosmology via EBL absorption signatures. However, while *Fermi* has driven significant progress in high-energy observations of GRBs, ground-based instruments such as IACTs are yet to make VHE detections. This probably reflects the low rate of GRBs suitable for immediate observation by the ground-based facilities. The flux limits achieved at 1–10 ks after burst triggers demonstrate that, despite absorption by the EBL, under more favourable conditions detections are clearly feasible [23,24]. Indeed, in 2006, HESS was able to observe a *Swift* GRB-like trigger during the entire prompt phase [25], which occurred within the FoV of a pre-planned pointed observation. The trigger turned out to be a galactic neutron star X-ray binary rather than be a GRB [26]. Such comprehensive coverage on a GRB would be extremely valuable in constraining emission mechanisms for the prompt emission.

In the era of gravitational wave detection capability (with advanced-LIGO/-VIRGO), GRBs will be at the forefront of efforts to locate an electromagnetic counterpart to a gravitational wave signal. It is important, therefore, to ensure facilities to detect, localize and follow-up GRBs and other potential counterparts are operational from approximately 2015.

Results from GRB observations with IceCube are negative so far, with zero neutrinos detected from 300 GRBs [27]. This result places the average neutrino flux a factor four below predictions from models where $p-\gamma$ interactions produce neutrons that escape and later decay to produce the observed flux of ultra-high-energy cosmic rays (UHECRs). GRBs are not, however, excluded as the sources of UHECRs, and more sensitive neutrino searches are needed to excluded scenarios with lower neutrino production efficiency.

**(b) Other transient and rapidly variable phenomena**

Several other object classes with (relatively) short-time-scale variability have now been studied at high energies, including novae, binary systems with and without compact objects, AGN and
pulsar wind nebulae. The recent detection of dramatic variability in the high-energy emission from the Crab Nebula [28,29] and in particular the dramatic flare of April 2011 [30] suggests that acceleration of particles up to PeV energies is possible in this object on time scales of approximately 10 h, with transient emission briefly dominating the flux from this object with a diameter of 10 light years. While neither the point of origin within the nebula nor the particle acceleration mechanism is currently understood, a matching new component above 10–100 TeV
is expected [31] and can be probed by instruments such as CTA (§4). The processes at work in the Crab may extend to other ultrarelativistic shocks, such as those found in AGN jets, with important consequences for our understanding of these objects. Indeed, very short-time-scale emission is seen in the TeV band from active galaxies with jets closely aligned with the line-of-sight of the observer: the so-called blazars. The flare from the prominent X-ray and TeV gamma-ray blazar PKS 2155-304 shown in figure 3 is the most dramatic example to date, a factor more than 100 flux increase with respect to the quiescent state and variability on time scales close to 1 min. Such events indicate extremely large bulk Lorentz factors for the emission sites within the AGN jet, approaching the extreme values seen for GRBs [33]. Variability is also seen in objects where jets are not closely aligned with the line-of-sight to the observer, with the day-time-scale TeV variability of M 87 [34] as the best-studied case. Simultaneous very-long-baseline interferometry and TeV observations of M 87 indicate a strong increase in flux from the nucleus during VHE flares [35], suggesting particle acceleration is taking place very close to the central supermassive black hole.

4. Future prospects

In general, the prospects for the VHE and multi-messenger astronomy of transient phenomena seem very bright. So far, IceCube has produced only upper limits for GRBs, but the exposure is steadily increasing and future nearby GRBs would produce very constraining limits if no neutrinos are observed. The larger volume of the planned KM3NeT detector [36] may also help to reach the critical threshold for transient astronomy with high-energy neutrinos.

Gamma-ray observations are perhaps the most exciting area in the near future. Beyond the currently operating detectors described in §2, several important new facilities are under construction or being planned. HAWC [12] will provide continuous coverage of a steradian of sky at TeV energies, providing much greater sensitivity to transient phenomena [37] in comparison with its predecessor MILAGRO owing to its higher altitude site and larger detector area. Completion of HAWC is expected by approximately 2014. The major current ground-based initiative in this area is however the CTA. CTA will bring a huge improvement in all aspects of performance with respect to current IAC systems, including the best energy flux sensitivity and angular resolution (approx. 1’ at 10 TeV) above the X-ray domain. The expected field of view is 8°. It will comprise more than 100 telescopes of three different sizes, some of which will be fast-slewing (to anywhere on the sky in less than a minute), located at two sites. A €185 million European-led project, it builds on expertise gained from HESS, MAGIC and VERITAS among 170 institutes in 27 countries. As figure 4 shows, the sensitivity of CTA is orders of magnitude better than Fermi for minute-time-scale phenomena.

CTA will both find and follow transients with its slewing capabilities and in a survey mode (see [39] and other articles in the Astroparticle Physics CTA Special Issue). The transient follow-up programme will rely on alerts from contemporaneous X-ray/gamma-ray observatories, currently including Fermi and Swift [40], as well as from TeV (e.g. HAWC) and gravitational wave facilities. In addition, rapid photometry and redshifts from optical/near-infrared telescopes will be required to maximize the scientific impact of these observations.

CTA will also generate its own triggers and alert multi-wavelength follow-up facilities to new transients discovered. A wide-field survey mode provides the best chance of serendipitous transient detection (e.g. short GRBs), which could equal the instantaneous HESS sensitivity but over a much larger approximately 30° × 30° patch of sky. CTA surveys [41] will have direct synergies with radio, optical and X-ray surveys, particularly with new facilities such as LOFAR, SKA and Advanced LIGO.

CTA will conduct a census of particle acceleration across the Universe. It can survey approximately 400 times faster than HESS, and the improved resolution avoids source confusion and aids multi-wavelength follow-up. With CTA, we will uniquely probe stellar birth and death, and cosmic ray feedback both in our own Galaxy and up to galaxy-cluster scales.
5. Summary

The transient and variable Universe is taking on increasing importance in astrophysics, with rapidly improving facilities for very wide field monitoring across, and beyond, the electromagnetic spectrum. Observations at VHEs are no exception, with major new facilities planned and enormous potential for transient related science. The acceleration of high-energy particles seems to be a common feature of cosmic explosions and new observations at GeV energies and above, in photons and in neutrinos, offer powerful new probes of this phenomenon and of fundamental physics. CTA stands out as the major instrument in this area in the near future, and a suite of multi-wavelength instruments is required to fully exploit it. In particular, future wide-field X-ray/soft-gamma-ray missions are vitally important for the future of high-energy transient astrophysics.

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References


