PROCEEDINGS OF SCIENCE

Science with the Cherenkov Telescope Array: The Multi-wavelength and multi-messenger scene

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The scientific potential of the Cherenkov Telescope Array (CTA) is extremely broad: from understanding the role of relativistic cosmic particles, to the search for dark matter. CTA will be an explorer of the extreme universe, surveying the high-energy sky hundreds of times faster than previous TeV telescopes. The angular resolution of CTA will approach 1 arc-minute at high-energies – the best resolution of any instrument above the X-ray band. With over an order-of-magnitude collection area improvement, CTA will be, for example, three orders of magnitude more sensitive on hour timescales than the Fermi-LAT at the 30 GeV range. Furthermore, the observatory will operate arrays on sites in both hemispheres to provide full sky coverage and hence maximize its discovery potential of rare phenomena such as nearby supernovae, GRBs or gravitational wave transients. The first CTA telescope has been inaugurated in the Canary Islands in 2018, and as more telescopes are added in the coming years, flexible operation will be possible, with sub-arrays available for performing specific tasks. All this considered, CTA will have important synergies with many of the new generation, major astronomical and astroparticle observatories. Multi-wavelength and multi-messenger approaches combining CTA data with those from other instruments will lead to a deeper understanding of the broad-band non-thermal properties of target sources, elucidating the nature and environment of gamma-ray emitters. In this talk I will introduce the broad scope of CTA science, and present some specific science cases and multi-instrumental synergies, as well as the potential for cooperation of other wavebands and astronomical messengers with CTA.

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1. Introduction

Ground-based gamma-ray astronomy is a novel field with enormous scientific potential. Since the first successful measurement of an astrophysical source at TeV energies, with the detection of a signal from the Crab Nebula by the Whipple Telescope in 1989 (exactly 30 years ago), both the imaging atmospheric Cherenkov technique (IACT) and its associated telescopes and instrumentation have greatly evolved. Today, the field is an established discipline of observational astrophysics, enjoying almost 200 detected sources in its catalogue, and discoveries which have generated great impact in wider domains of physics and astrophysics over the past decade or so.

The Cherenkov Telescope Array (CTA) will be the major global observatory for very-high energy (VHE) gamma-ray astronomy over the next decade and beyond. Covering photon energies from 20 GeV to 300 TeV, CTA will improve on all aspects with respect to current IACT instruments, allowing detailed imaging of a large number of gamma-ray sources, and being a powerful instrument for time-domain astrophysics. As we will demonstrate below, despite this much recent success, the discovery space of the VHE sky is just opening up, with several areas still unexplored, specially in the most extreme energies and the fastest transient astrophysical domains. The scientific planing of an observatory like the Cherenkov Telescope Array, at the forefront of a new field of observational astrophysics, needs to anticipate for this vastly unexplored range of sources and source activities, a glimpse of which the new windows of multi-messenger astrophysics have just (and timely!) provided us over the past 2 or 3 years.

2. The New Era of Multi-messenger Astrophysics

The field of multi-wavelength astrophysics has greatly changed with recent results from astroparticle multi-messengers. Most of these new results involve transient astrophysical sources. This emphasises that there is still a vast discovery space in our sky when new modes of observation and new energy ranges are open to observation. More than ever before, efficient multi-instrument coordination and cooperation is essential for contemporaneous astrophysical research.

Two results clearly stand out in this respect, and open up new fields and new modes for observational astrophysics. The first one, which represents the de facto birth of multi-messenger astrophysics was the binary neutron star merger, GW170817 [1], observed both in gravitational waves (GW) and throughout the electromagnetic spectrum. The merger coincided with a burst of GeV emission see by the Fermi Large Area Telescope, which preceded several other detections in the electromagnetic broadband. This event, which turned out to be a faint short-duration GRB, was later associated to the powering of an optical Kilonova, fuelled by nuclear reactions in the ejecta.

The other new association between a multi-messenger event and gamma-ray emission that recently emerged is the coincidence between gamma-ray flares in the blazar TXS0506+056 [14] with an IceCube neutrino event [10], which stressed the need for monitoring of transient sources with as wide a coverage as possible throughout the multi-messenger and multi-wavelength domains.

In addition to these results, the growing number of detections of multi-TeV emission from a range of sources in the Galaxy [3], signalling to processes which may lead to particle acceleration up to 100 TeV and beyond, open the way for uncovering the most energetic sites of cosmic-ray production in the Galaxy (the PeVatron accelerators) and a future astronomy of cosmic-rays.

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3. The CTA Extragalactic Sky

CTA will conduct a census of particle acceleration in our universe, by performing surveys of the sky with unprecedented sensitivity at very-high energies. The Extragalactic Survey will be the first of its kind to be performed with IACTs, and will cover 1/4 of the sky to a depth of $\sim$ 6 mCrab. This represents a large development in comparison to the modest sensitivity, limited angular and energy resolution of existing VHE surveys, using ground-level particle detectors [2, 4].

Likewise, CTA will be a unique instrument for the exploration of the violent and variable universe, with unprecedented potential both in terms of energy reach and sensitivity to short timescale phenomena, expressed, for example, in a four-orders of magnitude better sensitivity than Fermi-LAT to minute timescale phenomena at energies around 25-30 GeV. Event at variability timescales of 1 month, CTA will be a factor of 100 more sensitive than the Fermi-LAT [9].

3.1 Active Galactic Nuclei

As a result of the extragalactic survey, CTA will provide the first snapshot of activity in an unbiased sample of active galactic nuclei (AGN). Beyond that, the study of AGNs by CTA will be dominated by flaring events, with multi-instrumental coordination being a critical ingredient for its success, as blazars, the most abundant AGN type in the VHE sky, exhibit very fast variability at TeV energies, down to 1 minute timescales [6].

From the multi-messenger point of view, AGNs have always been considered prime candidate sources for ultra high-energy cosmic-rays (UHECRs), and this suspicion has only been enhanced by the claimed association between IceCube neutrino event 170922A and blazar TXS0506+056. VHE gamma-ray observations of AGNs can provide the most direct view of particle acceleration in jets, and are thus a central piece to further study these multi-messenger associations, but constraining the detailed physical processes in play depend on ample multi-wavelength (MWL) coverage. Resolving the longstanding debate about the leptonic or hadronic dominance of jets, and the acceleration mechanisms working in these environments, are examples of fundamental questions that require coordinated observations across the electromagnetic spectrum to be addressed.

3.2 Extreme Extragalactic Transients

The CTA Extragalactic Science is not limited to AGNs, but comprises a broader range of multi-wavelength and multi-messenger alerts, including GRBs, gravitational waves, as well as the already-mentioned neutrino events, and futurely, possibly, the elusive fast-radio bursts. With respect to the gravitational wave events, despite GW170817 being only the single event to date with an electromagnetic counterpart and at VHEs – but not seen by an IACT –, the prospects for further detections of GRBs associated with GW events by CTA has lately seen a significant boost, thanks to the announcement by MAGIC [12] of the detection of the first GRB detection by a ground-based gamma-ray instrument, which open the window for the study of these sources by IACTs.

Such sources may actually be significantly more common than the brighter GRBs currently picked up by Fermi, which argues for a potential new population of extragalactic objects that only CTA could discover. As a matter of fact, it is expected that future observational runs by the current gravitational wave detectors will produce a rate of GW events of as much as 1 per day, already in the coming years, greatly changing the perspectives and dynamics of the field.

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4. The Multi-wavelength Galaxy with CTA

The fundamental questions related to the CTA science of the Galaxy are centred around similar topics to those investigated in the extragalactic sky, involving the conversion of gravitational energy from accretion into compact objects, which power bulk plasma motions that in turn cascade to microscopic particle acceleration in magnetised environments [13]. Understanding these processes and environments holds the key to identifying the sources of cosmic rays, not only in the ultra-high energy extragalactic environments, but also in the Galaxy. In here, high-energy transients represent the most interesting science cases, as they are primarily non-thermal sources and directly reveal the explosive transfer of energy from magnetic to kinetic form, as well as from particles to radiation. These provide excellent probes of the mechanisms that generate, enact and channel the efficient macro- to micro-physics energy transfers that generate cosmic-rays and their electromagnetic counterparts.

VHE gamma-rays are the most direct probes of particle acceleration, as there is no other physical processes that are able to generate non-thermal photons of such energies. The good angular resolution of VHE gamma-ray observations provided by current instruments, and even more by CTA in the near-future, allied to the absence of deflection on the path of these carriers, make VHE gamma-rays the best direct tracers of the radiative dissipation zones associated to cosmic-ray production in turbulence, shock acceleration and/or magnetic reconnection sites. And if gamma-rays alone cannot break the ambiguity between leptonic and hadronic origins of the radiative emission – except perhaps for measurements beyond the 100s TeV, where a leptonic origin is strongly disfavoured – multi-wavelength and neutrino information come across here as fundamental observational counterparts, reinforcing the multi-instrumental links of future CTA science.

Among the Galactic sources, the study of compact binary system transients is a prime science case for multi-wavelength observations. These accretion-powered sources are powerful X-ray emitters, where it has also been shown that optical/IR activity precedes or is somehow associated to the observed VHE emission [8]. This is thought to happen because the thermal disc activation, first seen in optical/IR wavelengths, prompts the microquasar jets and shocks that in turn give origin to the VHE emission. Following this, some recent observational programmes have successfully used optical/IR emission as triggers to their multi-wavelength campaigns on Galactic transients [7, 11].

In addition to X-ray binaries, pulsar wind nebulae flares, magnetars giant flares and novae transients are other potentially MWL-intensive Galactic science cases for CTA, and CTA is expected to observe / follow-up several variability episodes from such sources every year. Serendipitous discoveries resulting from observations within the CTA Galactic Plane Survey programme are also expected, and will be of extreme scientific interest, requiring that a strategy be in place for rapid-response, MWL campaigns to be activated for the coordinated follow-up and detailed study of such discoveries, throughout the entire electromagnetic spectrum.

As a final note to this section, the Galactic Plane Survey (GPS) will consist of a deep survey (down to ~ 2 mCrab) of the inner Galaxy and the Cygnus Region, coupled with a somewhat shallower survey (~ 4 mCrab) of the entire Galactic Plane. For the typical luminosity of known Milky Way sources, the CTA GPS will thus provide a distance reach of about 20 kpc, covering essentially the entire Galaxy, and detecting a large sample of objects one order of magnitude fainter than the current VHE population. Good-resolution MWL surveys will be an important complement to GPS.

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5. Facilities: The Multi-wavelength and multi-messenger scene

Wide field-of-view and survey instruments from the entire range of the electromagnetic spectrum will form the basis of the MWL data necessary to complement CTA science, specially in regard to the extragalactic and Galactic surveys, as well as CTA's survey of the Large Magelanic Cloud. The latter, which we have no yet mentioned, will provide a face-on view of this entire nearby, star-forming galaxy, resolving regions down to 20 pc in size, with sensitivity down to luminosities of 10^{34} erg/s, comparable to the brightest known VHE sources of the Milky Way.

In all these scientific fronts, and also in the transients and multi-messenger domains, CTA will have important synergies with many of the new generation of astronomical and astroparticle observatories. As a matter of fact, being the flagship VHE gamma-ray observatory for the coming decades, CTA plays a similar role in the VHE waveband as the SKA plays in radio, ALMA at millimetre waves, or the giant E-ELT, TMT and GMT will play in optical, providing the best ever sensitivity and resolution compared to prior or other currently active facilities. It is thus expected that these very instruments will be the prime partners of CTA science (and vice-versa).

The situation is not different with the state-of-the-art multi-messenger instruments, either neutrino or gravitational wave detectors, which will provide a number of event triggers for CTA via VOEvents, GCN circulars and Telegrams – or other alert and coordination tools still to be put in place to facilitate and make the timely follow-up of such extreme transient events the most efficient. For the follow-up of gravitational wave alerts, in particular, it is worthy to point out that CTA has huge advantages with respect to most other instruments and wavebands, thanks to the large field of view of its instruments and the flexibility to map very large error boxes, which results from the large number of telescopes of the array and the potential for divergent pointing observation modes [5].

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