VHE Gamma-Ray Astronomy & the Decadal Survey

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GammaSIG, 7 28 Jan 2022
Outline

- Current status of the field
  - Some key results – current instruments

- Future prospects
  - Design drivers
  - The Decadal Survey
  - Instruments under development

- LE or MeV: 0.1 - 100 MeV
- HE or GeV: 0.1 - 100 GeV
- VHE or TeV: 0.1 - 100 TeV

} domain of space-based astronomy

} domain of ground-based astronomy
Gamma-Ray Instrument Synergies

Low-energy threshold - Satellites Fermi-LAT, AGILE: 100 MeV to > 30 GeV
Sky survey, transients

High sensitivity – Current IACTs H.E.S.S., MAGIC, VERITAS: 10s GeV to > 30 TeV
Exceptional sensitivity, but limited field of view, high resolution energy spectra, transients

Large-FoV arrays - HAWC, LHAASO: ~ 0.1 to 100 TeV
High duty cycle, extended sources
VHE Detection Techniques

~100% duty-cycle
Steradian field of view
Modest precision
Modest collection area

~15% duty-cycle
~4 degree field of view
High precision
Large collection area

Slide courtesy Jim Hinton, ICRC 2021
The Three Major IACTs

VERITAS

MAGIC

H.E.S.S.

National Geographic Night Sky Map

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Water Cherenkov Detectors - HAWC

- Sierra Negra mountains, Mexico
- 4100 km asl
- Observes 2/3rd sky every 24 hrs
- 100 GeV – 100 TeV
VHE Gamma-Ray Sky

- More than 200 sources
- 10 different source classes
- Detailed measurements of spectra and light curves
Sensitive Surveys of the Galactic Plane

H.E.S.S. & HAWC Galactic Plane Surveys

- H.E.S.S. survey of the Milky Way < 2% Crab Nebula sensitivity
- 78 sources in H.E.S.S. GPS
- Comparison of the Galactic plane observed with H.E.S.S. and HAWC: results are consistent

**Precision Measurements: Supernova remnants**

**RXJ 1713.7-3946:** Spatially resolved spectra with unprecedented resolution (<0.05°)
- TeV shell morphology, close correlation with X-rays, provides insights into physical processes

**IC 443:** Close match between GeV & TeV shell morphology and distribution of shocked gas

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Multimessenger: Blazar - Neutrino Association

IC170922 and TXS 0506+056: First evidence ($3\sigma$) for a neutrino source
Are blazars the sources of the highest energy cosmic rays?

- Sept 22, 2017: Detection of a high-energy $\nu$ ($E \sim 290$ TeV) by IceCube

IceCube + MWL, Science, 361 (2018)
Multimessenger: EM Counterparts to Gravitational Waves

- GW 170817: The first observation of GWs from a binary NS inspiral
- Detected by LIGO & VIRGO
- EM emission observed in multiple wavelength bands
- Associated with GRB170817A (GBM)
- $z=0.0098$
- Not detected by LAT or IACTs

Gamma-Ray Bursts as VHE Sources

**GRB 190114C** (MAGIC Coll., Nature, 2020)
- long GRB, $z = 0.42$
- for 40’ after T0 +60 s
- 0.2 -1 TeV

**GRB 180720B** (H.E.S.S. Coll., Nature, 2020)
- long GRB, $z = 0.65$
- after T0 + 10h

**GRB 190829A** (H.E.S.S. Coll., Science)
- long GRB, $z = 0.078$
- for 3 nights after T0 + 4,3h
- 0.18-3.3 TeV

**GRB 160821B** (MAGIC Coll. ApjL 2021)
- short GRB, $z =0.162$
- $3\sigma @ E>500$ GeV
- for 4h after T0+24s

**GRB 201015A** (PoS ID 305, Y.Suda)
- long GRB, $z=0.42$
- for 3.4 h after T0+40s
- $3.5\sigma$ above 50 GeV

**GRB 201216C** (PoS ID 395, S.Fukami)
- long GRB, $z=1.1$
- for 20’ after T0+

Credits: NASA, ESA and M. Kornmesser

Slide after R. Zanin ICRC 2021
Nova Shocks – New TeV Source Class

August 2021, ATel #14844:
Detection of VHE gamma-ray emission from the recurrent nova RS Ophiuchi with H.E.S.S.

- RS Ophiuchi: High-mass WD/red giant binary, an orbital period of 455d
- Outburst of recurrent nova RS Ophiuchi, detected with Fermi/LAT
- $>6\sigma$ detection by H.E.S.S.
Gamma-Ray Instruments in the next decade

- LHAASO
- SWGO
- CTA
The Next Decade and Astro2020
Astro 2020 Science:
Three science themes addressing fundamental and profound questions for humanity and for understanding our place in the space and time of the Cosmos.

- A step-by-step path to discovering habitable worlds and life elsewhere.
- Time-domain multi-messenger astrophysics to trace the earliest stages of the observable universe.
- Formation and evolution of stars and galaxies from the Big Bang to today.
LHAASO

High duty cycle: ~100% running time
Large FOV:
- 1/7 of the sky at any time
- 60% of the sky in a diurnal observation

Sichuan, China
4410 m asl
1.3 km²

- WCDA (100 GeV - 30 TeV): VHE (>0.1 TeV) γ-ray astronomy
- KM2A (10 TeV - 10 PeV): UHE (>0.1 PeV) γ-ray astronomy
- WFCTA (10 TeV - 1 EeV)
- All detectors are in DAQ since July 2021

From R. Yang, CDY Extreme Accelerators Talk
https://cdy-institute.ie/

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Detection of more than 530 $\gamma$ at energies above 100 TeV
Up to 1.4 PeV from 12 UHE $\gamma$-ray sources with a statistical significance $> 7\sigma$ (Cao et al. Nature, 594, 33, 2021)

Crab Nebula: An extreme electron accelerator: 2.3 PeV electrons
The Southern Wide-Field Gamma-Ray Observatory

- Complementing LHAASO – a complete view of the TeV-PeV sky
- Formed 2019: ~3-year R&D phase
- Design SWGO & choose Site
- Exploring three concepts → Tanks, artificial pond & natural lake

From Hinton, 2021 ICRC
The Cherenkov Telescope Array (CTA)

Latest updates from Roberta Zanin (CTAO Project Scientist)
ICRC 2021

25 Countries
Over 150 Institutes
About 1500 Members

https://www.cta-observatory.org/
CTA DESIGN drivers

- Sensitivity (x10)
- Full-sky coverage, larger FoV (x2)
- Wide energy range: 20 GeV to 300 TeV
- Arc-min angular resolution
- 10% energy resolution
- Rapid slewing for transient follow-up
Adding U.S.-led Schwarzschild-Couder Telescope (SCT) dual-mirror design
CTA Project Phases

- **Construction phase (5 years):**
  Alpha configuration: Southern Array: 14 MSTs + 37 SSTs;
  Northern Array: 4 LSTs + 9 MSTs

- **Operation & Enhancement phase**
  Depending on the availability of funds aim towards deployment of full scope Omega configuration
  - 4 LSTs + 25 MSTs + 70 SSTs (Southern Array) and 4 LSTs + 15 MSTs (Northern Array), depending on available funds
CTA Large-Sized Telescope

LST-1 already performing science

- Detection of Crab Nebula and pulsar
- AGN Detections: Mrk 501, Mrk 421, 1ES 1959+650, 1ES 0647+250 and PG 1553+113
The SCT: big eyes with a sharper view
The SCT: big eyes with a sharper view

- Superior optical angular resolution over a wide (~8°) field of view
- Light focused on a smaller surface → enables the use of state-of-the-art sensors
- Better sensitivity and reduced observation time
- Better γ-ray PSF across the FoV for morphology, survey, and transients

γ-ray Shower
Energy: 1 TeV

Proton Shower
Energy: 3.2 TeV

DC-MST Images
7.7° field of view, 0.17° pixels
1,855 channels

SCT Images
8° field of view, 0.067° pixels
11,328 channels
The CTA SCT Project

- Jan 23, 2019: First light of the prototype SCT (pSCT)
- Oct 2020: CTA Consortium endorses the development and construction of SCTs to enhance and complement DC-MSTs
- Ongoing: Instrumentation of the focal plane to 11k+ channels with upgraded SiPMs
- 2023: Expected completion of pSCT camera upgrade to full 8° field of view

Astro 2020 Decadal Survey endorses CTA-US contributions of SCT telescopes as an essential element of US multimessenger strategy
VHE/UHE $\gamma$-Ray Astronomy
- US participation in CTA Ground Based Observatory
- CTAO is mature project, ready to move forward
- 10 SCT Telescopes- completed design, move to production
- $40M$ US Construction costs, $3M/year US operations costs

US participation in SWGO
- $20M$ US Construction cost
- Southern hemisphere extension of an air shower detector array for VHE $\gamma$-ray astronomy based upon HAWC technology
Astro2020 Decadal Survey: Continuity of Multi-messenger Capabilities

Multi-Messenger Astronomy Must be Coordinated

Existing/planned projects
Missing capabilities
Endorsed projects

Gravitational Waves
nHz
mHz
kHz
NANOGrav
NANOGrav expanded
SKA bolsters nHz efforts
mHz GW community development
Advanced LIGO/Virgo/Kagra
Improved Advanced LIGO
LISA
Cosmic Explorer

Neutrinos
VHE
IceCube
IceCube-Gen2 (VHE and UHE)

UHE
Discovery uncertain

Gamma Rays
HE
Swift/Fermi ??
Impending gap in monitoring capabilities
New Probes for Multi-Messenger Astro

VHE
IACTs/HAWC/LHAASO
LHAASO
CTA and SWGO

Cosmic Rays
VHE
AMS/DAMPE/CALET
Auger/TAx4

UHE

HE: MeV-GeV, VHE: TeV-PeV, UHE: EeV-ZeV

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Exploring the non-thermal Universe “ASTRO”

- Pulsars/PWN
- Binaries
- SNRs
- Starbursts
- AGN
- GRBs
- SMBH
- SMBH accretion, jets
- VHE γ-rays
- Unknowns (Gal Center)
- Dark Matter
- Cosmological Fields
- PBHs, QGrav

Probing New Physics at GeV/TeV scale “PARTICLE”
Summary and Outlook

- CTA will cover 20 GeV to 300 TeV range, with superior angular resolution and sensitivity

- LHAASO will have unprecedented reach >20 TeV -- Ideal for PeVatron searches

- SWGO will complement LHAASO – a complete view of the TeV-PeV sky

- Synergy between IACTs and Water Cherenkov detectors: Detailed morphology study of PeVatrons, TeV halo, supernova shells now possible

- TeV instruments will be critical partners in multimessenger studies

- Complementary coverage with satellite missions in the MeV – GeV range will be crucial
Thank you