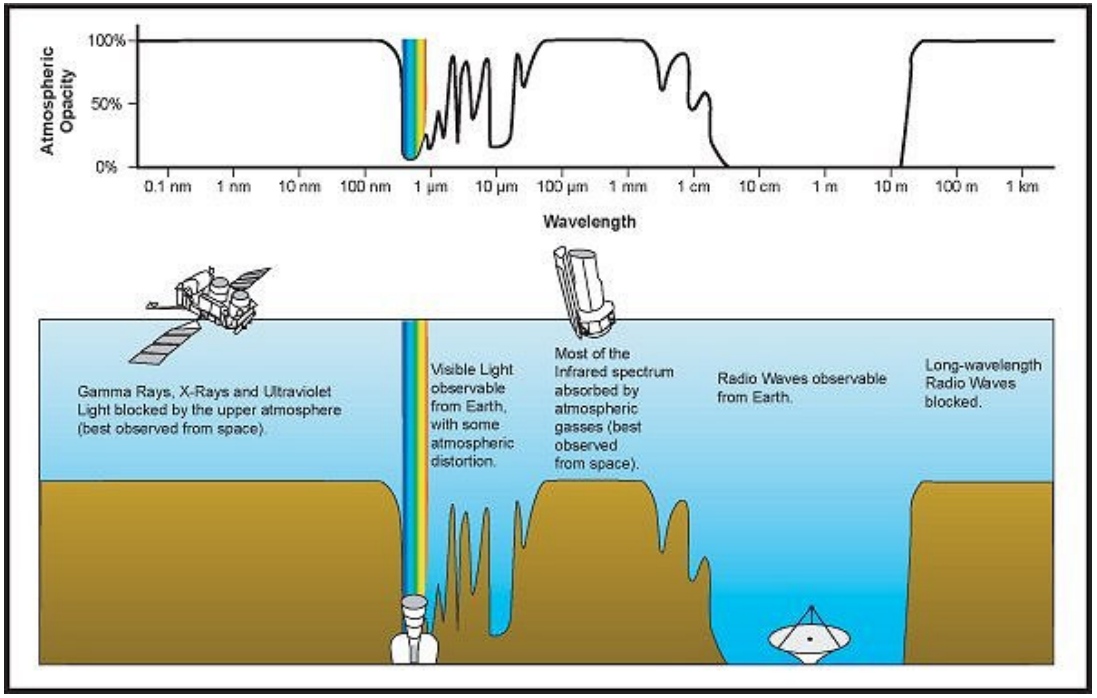
1. X-ray and gamma-ray Astronomy

Early history of X-ray Astronomy in short

- All radiation from the extreme UV (~ 1000 A) up to high energy γ-rays ($\sim 10^{-4}$ A) fails to penetrate below 30 km because of the atmopsheric opacity (only radio, optical and some narrow infrared bands can reach the Earth)
  - *Hard X-rays* detectable above 99% of the atmosphere ($\sim$ 30 km) with ballons
  - *Soft X-rays* detectable only with 1 millionth of the atmosphere above the detector (> 100 km) by rocket or satellite



- Early years (1946–**1962**)

- First technology with captured V2 rockets after the II World War $\longrightarrow$ discovery of the Sun as a powerful source of UV and X-rays (Friedman). During the 1950s observations mainly devoted to the Sun. The Naval Research Laboratory tried (without success) to search for other sources.
- In 1962 Riccardo Giacconi's group (inspired by Bruno Rossi) at American Science and Engineering Inc. (AS&E, later renamed NASA) detected the first non-solar cosmic source of X-rays (Sco X–1) in a rocket experiment devoted to search for X-rays from the Moon (produced by interaction with the solar wind particles and by fluorescence due to the solar X-ray flux). Thanks to this and other discoveries in the pioneering field of X-ray Astronomy, in 2002 Giacconi was awarded the Nobel prize.

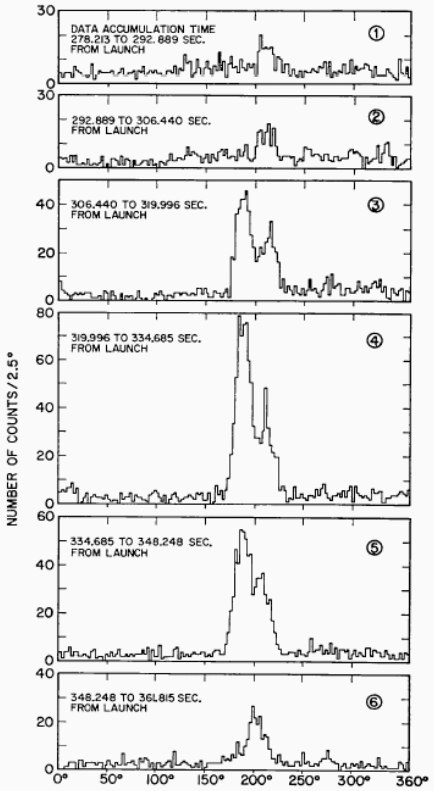


Fig. 10. Azimuthal distribution of counts recorded in a Geiger counter during the August 1964 rocket flight by the ASE-MIT group. The counts are grouped in six time intervals.

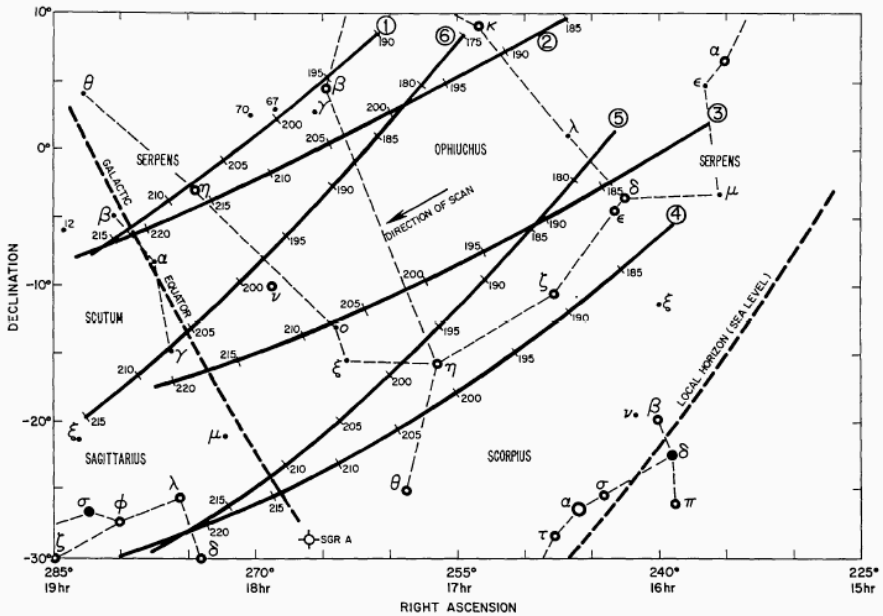
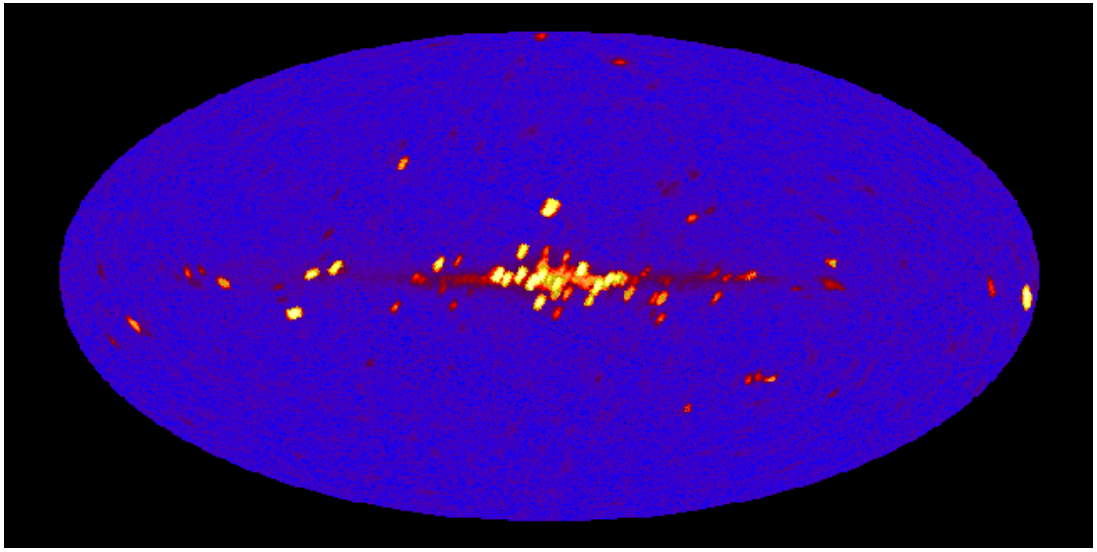


Fig. 11. Traces of the detector axis are shown in the region of the celestial sphere containing the two sources. The circled numbers refer to correspondingly numbered distributions in Figure 10. The angles given along the traces correspond to those in Figure 10.

From Giacconi & Gursky (1965, Space Science Reviews, 4, 151).

- Early history
  - In 1964, lunar occultation of the Crab Nebula. First optical identification of an X-ray source by the group at the Naval Research Laboratories (NRL; Bowyer et al. 1964, Science, 146, 912)
  - In 1966 and 1967, optical identification of Sco X-1 (Sandage et al. 1966, ApJ, 146, 316) and Cyg X-2 (Giacconi et al. 1967, ApJ, 148 ,129) using modulation collimators
  - In 1969, Meekins et al. identified the Coma cluster (which contains no active galaxies) as an X-ray source (emission stronger than expected from sum of normal galaxies)
  - In 1971, Coma cluster discovered to be an extended X-ray source with UHURU (Gursky et al. 1971, ApJ, 167, L81)
  - In 1971 and 1972, discovery of the binary X-ray pulsars Cen X-3 (Giacconi et al. 1971, ApJ, 167, L67) and Her X-1 (Tananbaum et al. 1972, ApJ, 174, L143): neutron star spin, mass and proof of binary behavior
  - In 1975, X-ray bursters in globular clusters were discovered with the Astronomical Netherlands Satellite (Grindlay & Heise 1975, IAUC, 2879) and with the VELA 5 satellites (Belian et al. 1976, ApJ, 206, L135; Los Alamos National Laboratories). A separate charged particle detector needed for discriminating real X-ray events.



X-ray Observatories: major past, present and future missions

UHURU

Uhuru, also known as the Small Astronomical Satellite 1 (SAS-1) was the first earth-orbiting mission dedicated entirely to celestial X-ray astronomy. It was launched on 12 December 1970 from the San Marco platform in Kenya. December 12 was the seventh anniversary of the Kenyan independence and in recognition of the hospitality of the Kenyan people, the operating satellite was named Uhuru, which is the *Swahili word for freedom*.

- Mission Characteristics:
  - Lifetime: 12 Dec 1970 - March 1973
  - Energy Range: 2-20 keV
  - Payload: Two sets of proportional counters (eff. area of 840 cm^2)
- Science Highlights:
  - ➠ First comprehensive and uniform X-ray all sky survey (sensitivity 10^{-3} times the Crab intensity)
  - ➠ 339 detected X-ray sources: binaries, supernova remnants, Seyfert galaxies and clusters of galaxies
  - ➠ Discovery of the diffuse X-ray emission from clusters of galaxies
- Archive: 4th Uhuru Catalog

EINSTEIN

The second of NASA's three High Energy Astrophysical Observatories, HEAO-2, renamed Einstein after launch, was the first fully imaging X-ray telescope put into space. The few arcsecond angular resolution, the field-of-view of tens of arcminutes, and a sensitivity several 100 times greater than any mission before it provided, for the first time, the capability to image extended objects, diffuse emission, and to detect faint sources. It was also the first X-ray NASA mission to have a Guest Observer program. Overall, *it was a key mission in X-ray astronomy and its scientific outcome completely changed the view of the X-ray sky*.

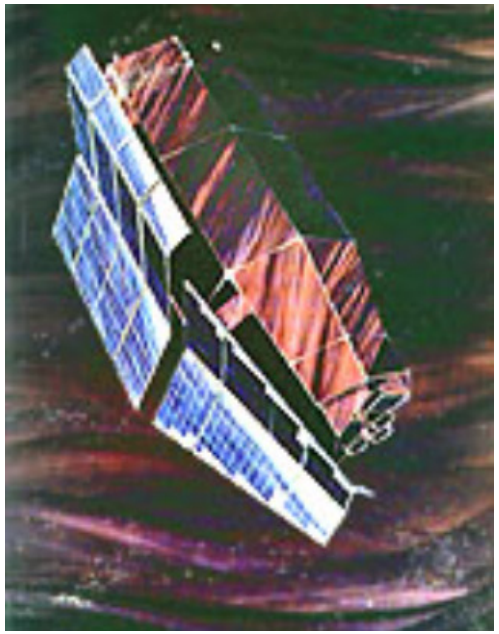


Figure 1: High Energy Astrophysical Observatory HEAO-2, renamed Einstein

- Mission Characteristics:
  - Lifetime: 12 November 1978 - April 1981
  - Energy Range: 0.2-20 keV
  - Special Features: First imaging X-ray telescope in space
  - Payload:
    - (Wolter Type I) grazing incidence telescope (0.1-4 keV)
      Four instruments could be rotated, one at a time, into the focal plane: Imaging Proportional Counter (IPC; 0.4-4.0 keV, eff. area 100 cm^2), High Resolution Imager (HRI; 0.15-3.0 keV, $\sim$2 arcsec spatial resolution) Solid State Spectrometer (SSS; 0.5-4.5 keV, E/ΔE=3-25) Focal Plane Crystal Spectrometer (FPCS; 0.42-2.6 keV, E/ΔE=100-1000 for E $>$ 0.4 keV)
    - Monitor Proportional Counter (MPC; 1.5-20 keV)
    - Objective Grating Spectrometer (OGS)

- Science Highlights:
  - ➠ First high resolution spectroscopy and morphological studies of supernova remnants
  - ➠ First study of the X-ray emitting gas in galaxies and clusters of galaxies revealing cooling inflow and cluster evolution
  - ➠ Detected X-ray jets from Cen A and M87 aligned with radio jets
  - ➠ First medium and Deep X-ray surveys
  - ➠ Discovery of thousands of “serendipitous” sources, including X-ray sources in nearby galaxies

ROSAT

The Roentgen Satellite, ROSAT, a Germany/US/UK collaboration, was launched on June 1, 1990 and operated for almost 9 years. The first 6 months of the mission were dedicated to the all sky-survey (using the Position Sensitive Proportional Counter detector), followed by the pointed phase. The survey obtained by ROSAT was the *first X-ray and XUV all-sky survey using an imaging telescope* with an X-ray sensitivity of about a factor of 1000 better than that of UHURU.

- Mission Characteristics
  - Lifetime: 1 June 1990 - 12 February 1999
  - Energy Range: X-ray 0.1-2.5 keV, EUV 62-206 eV
  - Special Feature: All sky-survey in the soft X-ray band
  - Payload :
    - A Position Sensitive Proportional Counter (PSPC; 0.1-2.5 keV); eff. area 240 cm^2 at 1 keV; $E/\Delta E \simeq 2.3$ at 0.93 keV
    - A High Resolution Imager (HRI; 0.1-2.5 keV); eff. area 80 cm^2 at 1 keV; $\sim$2 arcsec spatial resolution (FWHM)
    - A Wide Field Camera with its own mirror system (62-206 eV)
- Science Highlights:
  - ➠ X-ray all-sky survey catalog, <u>more than 150000 objects</u>; XUV all-sky survey catalog (479 objects)
  - ➠ Source catalogs from the pointed phase (PSPC and HRI) containing $\sim$100000 serendipitous

sources

- Detailed morphology of supernova remnants and clusters of galaxies
- Detection of pulsations from Geminga and discovery of isolated neutron stars
- Observation of X-ray emission from comets and from the collision of Comet Shoemaker-Levy with Jupiter

RXTE

The Rossi X-ray Timing Explorer, RXTE, was launched on December 30, 1995. RXTE is designed to facilitate the *study of time variability* in the emission of X-ray sources with moderate spectral resolution. Time scales from microseconds to months are covered in a broad spectral range from 2 to 250 keV.

- Mission Characteristics Lifetime:
  - Lifetime: 30 December 1995 to 5 January 2012
  - Energy Range: 2 - 250 keV
  - Special Features: Very large collecting area and all-sky monitoring of bright sources
  - Payload:
    - Proportional Counter Array (PCA; 2-60 keV), eff. area 6500 cm^2, time resolution 1 microsec
    - High Energy X-ray Timing Experiment (HEXTE; 15-250 keV)
    - All-Sky Monitor (ASM; 2-10 keV)
- Science Highlights:
  - ➠ Discovery of kilohertz QPOs and of NS spin periods in Low Mass X-ray Binaries
  - ➠ Detection of X-ray afterglows from Gamma Ray Bursts

XMM-NEWTON

The European Space Agency's X-ray Multi-Mirror Mission (XMM-Newton) was launched by Ariane on December 10, 1999. XMM-Newton is ESA's second cornerstone of the Horizon 2000 Science Programme. It carries high throughput X-ray telescopes with an unprecedend effective area, and an optical monitor, the first flown on a X-ray observatory. The large collecting area and ability to make long uninterrupted exposures provide highly sensitive observations.

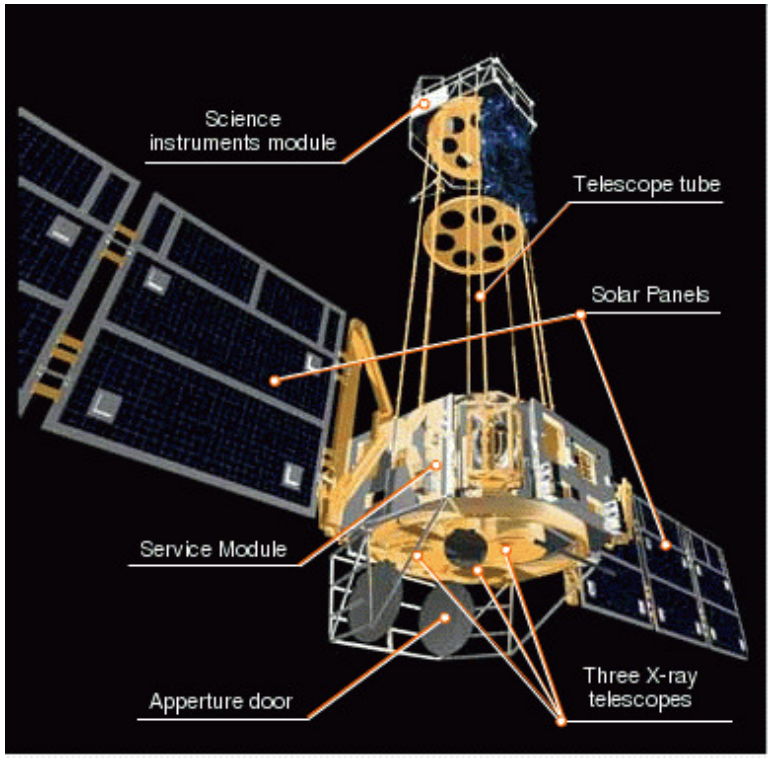


Figure 2: XMM-Newton

- Mission Characteristics
  - Lifetime: December 1999 - (nominal 10 year mission)
  - Energy Range: 0.1-15 keV (0.3-10 keV)
  - Special Features: Very large collecting area. Simulataneous X-ray, UV & Optical observations.
- Payload:
  - Three co-aligned (Wolter Type I) grazing incidence gold-coated imaging X-ray telescopes each; spatial resolution 6 arcsec (FWHM). There are three type of instruments:
    - European Photon Imaging Camera, Metal-Oxide-Silicon (EPIC-MOS; 0.1-15 keV; 2 units): Each units consist of an array of 7 CCDs and each CCD is 600X600 pixels ($E/\Delta E \sim$20-50, eff. area 922 cm^2 at 1keV)
    - European Photon Imaging Camera-pn (EPIC-pn; 0.1-15 keV) This is an array of 12 CCDs (64X200 pixels each, $E/\Delta E \sim$20-50, eff. area 1227 cm^2 at 1 keV)
    - Reflection Grating Spectrometer (RGS; 0.35-2.5 keV, 2 units) + EPIC-MOS
      The gratings, mounted under the two telescopes, deflect about 50% of the X-ray light onto an array of CCD detectors ($E/\Delta E$=200-800, eff. area 185 cm^2 at 1 keV)
  - Optical Monitor (OM; 180-650 nm): co-aligned 30 cm optical/UV telescope

CHANDRA (AXAF)

Full resolution image Chandra NASA's Advanced X-ray Astrophysics Facility, (AXAF), renamed the Chandra X-ray Observatory in honor of Subrahmanyan Chandrasekhar, was launched and deployed by the Space Shuttle Columbia on the 23 of July 1999. The combination of high resolution, large collecting area, and sensitivity to higher energy X-rays make it possible for Chandra to study extremely faint sources, sometimes strongly absorbed, in crowded fields. Chandra was boosted into an elliptical high-earth orbit that allows long-duration uninterrupted exposures of celestial objects.

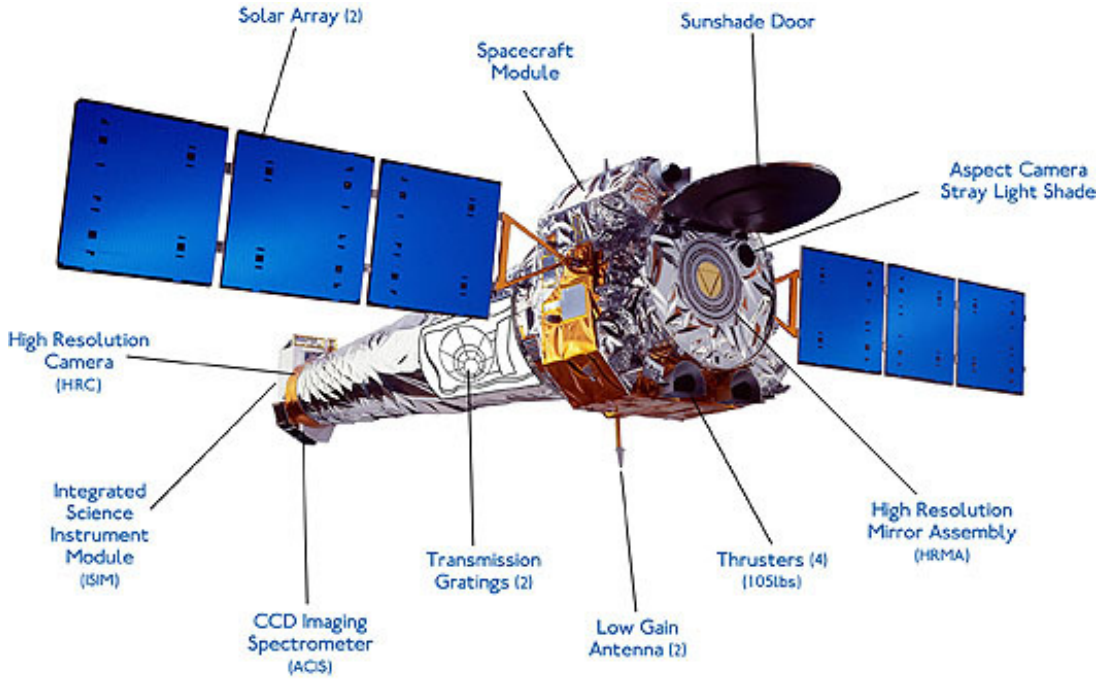


Figure 3: Chandra

- Mission Characteristics:
  - Lifetime: 23 July 1999 - (nominal 5 year mission)
  - Energy Range: 0.1-10 keV
  - Special Features: 64 Hours highly-eccentric Earth orbit
  - Spatial resolution $<$ 1 arcsec
- Payload:
  - A single (Wolter Type 1) grazing incidence iridium-coated imaging telescope. Four detectors can be inserted, one at a time, into the focal plane. Two of these were designed to be used primarily with the gratings.
    - AXAF Charged Coupled Imaging Spectrometer (ACIS; 0.2-10 keV): 2 CCD arrays for a total of 10 chips (8 front illuminated and 2 back illuminated, eff. area 340 cm^2 at 1 keV, E/ΔE=9-50): ACIS-I (one 4-chip imaging array, all front illuminated), ACIS-S (one 6-chip spectroscopic array, to be used primarily with the grating)
    - High Resolution Camera (HRC; 0.1-10 keV): 2 micro-channel plate detectors: HRC-I (eff. area 225 cm^2 at 1 keV, $\sim$0.5 arcsec spatial resolution), HRC-S (optimized for use with the LETG transmission gratings experiment)
    - High Energy Transmission Grating + ACIS-S (HETG; 0.5-10 keV; E/ΔE=60-1000)
    - Low Energy Transmission Grating + HRC-S (LETG; 0.08-6 keV; E/ΔE=30-2000)

OTHER ACTIVE HIGH ENERGY MISSIONS

- MAXI: Monitor of All Sky X-ray Image (Japan Aerospace Exploration Agency). Gas Slit Camera (GSC; 2-30 keV) with a total effective area of 5000 cm^2. Solid-state Slit Camera (SSC; 0.5-10 keV) with a total effective area of 200 cm^2
- NICER: Neutron star Interior Composition Explorer Mission (NASA). It is an International Space Station (ISS) payload devoted to the study of neutron stars through soft X-ray timing. X-ray Timing Instrument (XTI): array of 56 X-ray (0.2-12 keV) "concentrator" optics (XRC; each covering roughly 30 arcmin^2) and silicon drift detector (SDD) pairs. GPS position and absolute time reference to better than 300 ns.
- ASTROSAT: General purpose observatory. Three units of Large Area Xenon Proportional Counters (LAXPC; 3-80) keV with an effective area of 6000 sq.cm. at 10 keV. A Soft X-ray Telescope (SXT; 0.3-8 keV) with an effective area of 200 sq.cm. at 1 keV. A coded-mask imager (CZTI; 10-150 keV).
- Swift: Burst Alert Telescope (15-150 keV), X-Ray Telescope (0.2-10.0 keV), UV/Optical Telescope (UVOT): 170-600 nm. Multi-wavelength observatory dedicated to the study of gamma-ray burst (GRB) science.
- INTEGRAL: Gamma-ray observatory. Spectroscopy and imaging of gamma-ray emissions in the energy range from 15 keV to 10 MeV (SPI and IBIS instruments) and concurrent monitoring in the X-ray band (4-35 keV) using JEM-X.
- AGILE: Gamma-ray observatory. A gamma-ray (AGILE-GRID) and a hard X-ray (SuperAGILE) in-

strument, for the simultaneous detection and imaging of photons in the 30 MeV-50 GeV and in the 18-60 keV energy ranges.

- Fermi (formerly GLAST): Gamma-ray observatory. Fermi space satellite observes the entire sky mainly in survey mode. All the high-energy gamma-ray sky is scanned every 3 hours in a wide energy range (10 keV-300 GeV) with unprecedented sensibility. Fermi employs two instruments: Large Area Telescope (LAT), Fermi (Glast) Burst Monitor (GBM).
- NuSTAR is the first mission to use focusing telescopes to image the sky in the high-energy X-ray (3-79 keV) region.

FUTURE X-RAY OBSERVATORIES

ATHENA (ESA)

- Athena is a mission proposed to address the Science Theme "The Hot and Energetic Universe", which has been selected by ESA in its Cosmic Vision program. It is a large X-ray observatory "offering spatially-resolved X-ray spectroscopy and deep wide-field X-ray spectral imaging with performance greatly exceeding that offered by current X-ray observatories."
- The Athena observatory consists of a single X-ray telescope with a fixed 12 m focal length (Willingale et al. 2013), based on ESA's Silicon Pore Optics (SPO) technology, and two interchangeable instruments in the focal plane.
  - X-ray Integral Field Unit (X-IFU): 0.2 to 12 keV, cryogenic X-ray spectrometer providing spatially-resolved high resolution (2.5 eV) X-ray spectroscopy
  - Wide Field Imager (WFI): 0.2-15 keV, imaging over a wide field, simultaneously with spectrally and time-resolved photon counting

e-ROSITA

- It will perform the first imaging all-sky survey in the medium energy X-ray range up to 10 keV with an unprecedented spectral and angular resolution.

eXTP: enhanced X-ray Timing and Polarimetry mission (Chinese and European consortium)

- Designed to study the state of matter under extreme conditions of density, gravity and magnetism.

Primary goals are the determination of the equation of state of matter at supra-nuclear density, the measurement of QED effects in highly magnetized stars, and the study of accretion in the strong-field regime of gravity.

- Spectroscopic Focusing Array (SFA): 0.5-10 keV (9 X-ray telescopes, each with 12 arcmin field-of-view; spectral resolution < 180 eV)
- Polarimetry Focusing Array (PFA): 2-10 keV (4 X-ray telescope, each with 12 arcmin field-of-view; equipped with imaging gas pixel photoelectric polarimeters)
- The Large Area Detector, LAD: 2-30 keV (640 Silicon Drift Detectors with a total effective area of $\sim$3.4 m^2 at 6-10 keV)
- The Wide Field Monitor, WFM: 2-50 keV, 3.7 sr field-of-view

XRISM: X-ray Imaging and Spectroscopy Mission (JAXA and ESA)

➠ High-throughput imaging and high-resolution X-ray spectroscopy. Designed to resume with most of the the science capability lost with the Hitomi (ASTRO-H) mishap.

- Resolve: 0.3-12 keV (X-ray calorimeter spectrometer with 5-7 eV energy resolution)
- Xtend: 0.4-13 keV (soft X-ray imager with a larger field-of-view of 38')

IXPE: Imaging X-ray Polarimetry Explorer (NASA)

➠ Designed to measure X-ray polarization and understanding of X-ray production in objects such as neutron stars and pulsar wind nebulae, as well as stellar and supermassive black holes.

- Resolve: 0.3-12 keV (X-ray calorimeter spectrometer with 5-7 eV energy resolution)
- Xtend: 0.4-13 keV (soft X-ray imager with a larger field-of-view of 38')

For a list of upcoming and recently launched High-Energy Astrophysics Missions:

https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/upcoming.html

OBSERVATORIES FOR VERY HIGH ENERGY (VHE) GAMMA-RAYs

Cherenkov Telescopes

The photon fluxes of VHE ($>$30 GeV) gamma-rays decrease rapidly with energy, so the event statistics with satellite detectors, e.g. Fermi LAT, becomes too low. Indirect detection is used, via rapid ($\sim$10 ns) flashes of blueish Cherenkov light generated by atmospheric showers, cascades of charged relativistic particles, resulting from the interaction of the primary gamma-rays in the high atmosphere.

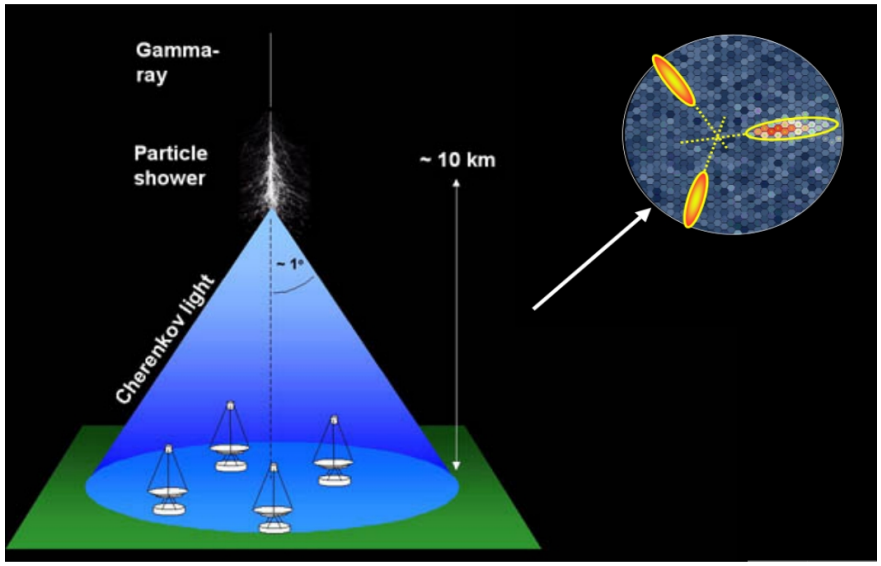


Figure 4: Schematic idea of the detection of Cherenkov light emitted from a primary VHE photon interacting with the atmosphere.

Presently operating Imaging Atmopsheric Cherenkov Telescopes (IACTs):

- MAGIC: 30 Gev - 100 TeV, two 17 m diameter IACTs
- HESS: tens of GeV to tens of TeV, four 12 m + one 28 m IACTs
- VERITAS: 50 GeV - 50 TeV, four 12 m IACTs

More than 150 VHE gamma-ray sources, both Galactic and extra-galactic, have been discovered and studied.

The future IACT: the Cherenkov Telescope Array (CTA; 20 GeV - 300 TeV)

CTA will be the world's largest and most sensitive high-energy gamma-ray observatory, with more than 100 telescopes of different diamters (4 m, 12 m, 23 m) located in the northern hemisphere (at the Roque de los Muchachos astronomical observatory on the island of La Palma, Spain) and the southern hemisphere (near the existing European Southern Observatory site at Paranal, Chile).

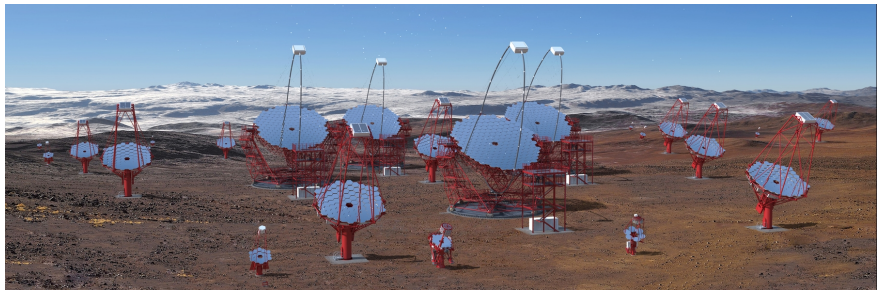


Figure 5: View of the future Cherenkov Telescope Array.