High-Energy Astrophysics Overview

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Abstract

High-energy astrophysics is the study of objects and phenomena in space with energy densities much greater than that found in normal stars and galaxies. These include black holes, neutron stars, cosmic rays, hypernovae and gamma-ray bursts. A history and an overview of high-energy astrophysics will be presented, including a description of the objects that are observed. Observing techniques, space-borne missions in high-energy astrophysics and some recent discoveries will also be described. Several entirely new types of astronomy are being employed in high-energy astrophysics. These will be briefly described, along with some NASA missions currently under development.
High-Energy Astrophysics
- An Overview

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Sweden Presentation - May 2007
Electromagnetic Spectrum / Temperature Scale

Degrees K

1 100 10,000 10 Million 10 Billion

Radio  Microwave  Infrared  Optical  UV  X-ray  Gamma Ray
Discovery of Cosmic Rays - 1912

• In a balloon, at an altitude of 5,000 meters Victor Hess, the father of cosmic ray research, discovered "penetrating radiation" coming from space.

V.F. Hess (1883-1964) – Nobel Prize 1936
Dr. von Braun, Dr. Van Allen & Dr. Pickering

Holding a Model of Explorer 1 after its Successful Launch
Explorer-11

- First Gamma-Ray Astronomy Experiment in Space – 1961
  - Detected 22 gamma-rays!
  - Discovered Galactic Distribution
  - S:N ~ 1:1000
Discovery of a Cosmic X-ray Source (Sco X-1) by AS&E/MIT Group

1962

R. Giacconi
2002 Nobel Laureate
UHURU – Explorer Spacecraft
First X-ray Astronomy Satellite
1970-1974
UHURU Sky Map

- Coma
- Virgo
- 3C273
- Sco X-1
- Cyg A
- Cyg X-3
- Perseus
- M31
- Cyg X-1
- SMC
- LMC
- Crab
- £en X-3
HEAO Program: 1978 - 1982

High Energy Astronomy Observatory
**NASA’s Great Observatories:**

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Launch</th>
<th>End</th>
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<tbody>
<tr>
<td>Hubble Space Telescope</td>
<td>1990</td>
<td>~2009?</td>
</tr>
<tr>
<td>Compton Gamma-Ray Observatory</td>
<td>1991</td>
<td>2000</td>
</tr>
<tr>
<td>Chandra X-Ray Observatory</td>
<td>1999</td>
<td>~2020?</td>
</tr>
<tr>
<td>Spitzer Space Infrared Telescope</td>
<td>2003</td>
<td>~2007</td>
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</table>
Hubble Space Telescope (HST)
Chandra Optics

Field of View ±5 Deg
Focal Surface

10 meters

4 Nested Hyperboloids
Doubly Reflected X-rays

4 Nested Paraboloids
X-rays

Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter
X-ray Calibration Facility, NASA-MSFC
Huntsville, AL
The Crew
Compton GRO
(Gamma-Ray Observatory)
Compton GRO - In Orbit
Stellar Evolution

* More massive stars evolve faster
* The fate of a star depends on its mass

The fate of a star depends on its mass (size not to scale)
The Crab Nebula
A Star that Exploded in 1054 AD
> Supernova <

X-ray
(Chandra)

Optical
(Hubble)
Neutron Star – cross section

Atmosphere
Superhot plasma

Outer crust
Starquakes
Crystal lattice: 200 m deep
nuclei + electrons

Inner crust
Starquakes
Crystal lattice: 1 km deep
nuclei + electrons + neutron drip

Outer core
Atomic particle fluid

Inner core
Solid block of subatomic particles?
Cosmic Jet – Artist’s Concept
A UNIVERSAL MECHANISM

Mirabel & Rodriguez; Sky & Telescope, May 2002

(Microblazar)
Multi-wavelength Jets: M87

Chandra X-Ray

VLA Radio

HST Optical
Gamma-Ray Bursts

- The Most Powerful Explosions in the Universe

- BATSE's Primary Objective
2704 BATSE Gamma-Ray Bursts

(Galactic Coordinates)

Apr. 1991 – May 2000
**Gamma Ray Bursts - Theories**

**BURSTING OUT**

FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

**Merger Scenario**

- **Neutron Stars**
- **Black Hole**
- **Disk**
- **Central Engine**
- **Massive Star**
- **Hypernova Scenario**

**JET COLLIDES WITH AMBIENT MEDIUM** (external shock wave)

**Blobs Collide** (internal shock wave)

**Gamma Rays**

**Gamma-Ray Emission**

**Preburst**

**Afterglow**

**X-Rays, Visible Light, Radio Waves**

Juan Velasco
Merging Neutron Stars
Diversity of GRB Profiles

Trigger Number 444
24.080: 100000. keV
Rate (count/s)

Trigger Number 451
23.064: 100000. keV
Rate (count/s)

Trigger Number 7170
23.080: 100000. keV
Rate (count/s)

Trigger Number 1663
22.600: 100000. keV
Rate (count/s)

Trigger Number 1676
25.881: 100000. keV
Rate (count/s)
Examples of Double-Peaked GRBs
Multiple-Episode Bursts

DISCSC, Trigger No. 7012
18.385: 100000 kev

DISCSC, Trigger No. 3488
24.756: 100000 kev

DISCSC, Trigger No. 3488
24.691: 100000 kev
Distinct subclasses of γ-ray bursts:
short/hard & long/soft

![Graph showing two distinct classes of γ-ray bursts, short/hard and long/soft, with T_{90} (seconds) on the x-axis and number of bursts on the y-axis.](image)
Figure 4.—Hardness-ratio and duration characteristics of GRB’s. When GRB’s are plotted against hardness ratio and duration, two classes become evident: short/hard and long/soft.
Typical GRB Spectrum

– the Band function
Grbic GRB spectrum

GRB 990123

Flux (photons cm\(^{-2}\) s\(^{-1}\) MeV\(^{-1}\))

\[ \log_{10}(F) = -3 \]

\[ \log_{10}(\Phi) = -1 \]

\[ \log_{10}(E) = 1 \]

E\(^{2}N_{E}\) (erg cm\(^{-2}\) s\(^{-1}\))

\[ \log_{10}(E^{2}N_{E}) = 8 \]

\[ \log_{10}(E^{2}N_{E}) = 7 \]

\[ \log_{10}(E^{2}N_{E}) = 6 \]

\[ \log_{10}(E^{2}N_{E}) = 5 \]

\[ \log_{10}(E^{2}N_{E}) = 4 \]

\[ \log_{10}(E^{2}N_{E}) = 3 \]

\[ \log_{10}(E^{2}N_{E}) = 2 \]

\[ \log_{10}(E^{2}N_{E}) = 1 \]

\[ \log_{10}(E^{2}N_{E}) = 0 \]

\[ \log_{10}(E^{2}N_{E}) = -1 \]

\[ \log_{10}(E^{2}N_{E}) = -2 \]

\[ \log_{10}(E^{2}N_{E}) = -3 \]

\[ \log_{10}(E^{2}N_{E}) = -4 \]

\[ \log_{10}(E^{2}N_{E}) = -5 \]

\[ \log_{10}(E^{2}N_{E}) = -6 \]

\[ \log_{10}(E^{2}N_{E}) = -7 \]

\[ \log_{10}(E^{2}N_{E}) = -8 \]

Photon Energy (MeV)

Briggs, et al. 1999
Spectral Evolution of GRBs

What is the trigger?

The duration of the burst is given by the fall-back time of the gas.

The duration of the burst is determined by the viscous timescale of the accreting gas.

- **NS - NS merger**: very, very fast jet
  - 0.01 - 0.1 M\(_{\odot}\) torus
- **BH - NS merger**: 0.05 - 0.5 M\(_{\odot}\) torus
- **BH - WD merger**: 1 M\(_{\odot}\) torus
- **NS/BH - He core merger after common envelope**: few M\(_{\odot}\) torus
- **collapsar = rotating, collapsing "failed" supernova**: 0.05 - 0.5 M\(_{\odot}\) torus

Special Evolution of GRBs
Collapsar Model

- Supermassive star burns off H, becomes Wolf-Rayet star with He, Fe core
- Core burned, star collapses and forms black hole with matter accretion jets
- Jets shatter outer shell of star, creates hypernova
- Jets speed on and collide with other nearby material to create the subsequent gamma-ray burst
Jet Simulation - Launched from a Collapsing Core
GRB Afterglow Decay

- The jet spreads sideways quickly
- The jet remains within initial cone
- Radiation is beamed into a narrow cone
- Jet break

Inset:
- Radiation is beamed into a large cone
- Jet break

[Diagram showing the decay process of a GRB afterglow with labeled components]
Gamma-ray Bursts

• Or the death of life on Earth?
SWIFT - GRB Satellite
Launched Nov. 2004
The Sun in X-rays - Yokoh
GLAST
Gamma-ray Large Area Space Telescope
- Scheduled for Launch in 2007

Credit: Hytec
10^{12} \text{ eV} \ (1 \text{ TeV})

PRIMARY Y - RAY
or CHARGED PARTICLE COSMIC-RAY

UPPER ATMOSPHERE

SHOWER DEVELOPING

TYPICALLY 16 \text{ km}

SHOWER AT MAXIMUM

1 \text{ Meter}

LIGHT FLASHES

GROUND

10 - 100 \text{ m}

CHERENKOV LIGHT

PULSE COUNTING ELECTRONICS

PHOTOTUBE

MIRROR
Second Generation Systems Atmospheric Cherenkov Imaging

Cherenkov Imaging gives the ability to distinguish compact images of gamma-ray showers from more irregular images from hadronic showers.
Types of images seen by atmospheric Cherenkov camera

- Hadron
- Gamma ray
- Muon Ring
- Sky Noise
EUSO & OWL

Observe Extremely H.E. Cosmic Rays from optical emissions from above:

- Cosmic ray
- Fluorescence
- Čerenkov
Neutrino Astronomy
ICECUBE

80 Strings
5000 Sensors
Volume: 1 km³
Gravitational Wave Astronomy
LIGO
Gravitational Wave Astronomy

**Space**

- **LISA**
  - Space-based Interferometer
- Coalescence of Massive Black Holes
- Resolved Galactic Binaries
- Unresolved Galactic Binaries

**Ground**

- **LIGO**
  - NS-NS and BH-BH Coalescence
  - SN Core Collapse

Graph showing the gravitational wave amplitude as a function of frequency (Hz): 10^{-18} to 10^{-24}.
Some Future

NASA Astronomy Missions
Constellation – X

Two Spacecraft in Atlas V Shroud

Atlas V DM Launch Configuration - Side View

October 6, 1999
OES
The Constellation-X Mission (Four Spacecraft)
Energetic X-ray Imaging Survey Telescope (EXIST)
Detector-collimator & Telescope

Side View