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
<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Radio and Microwave</th>
<th>IR</th>
<th>Vis</th>
<th>UV</th>
<th>X-Rays</th>
<th>Gamma Rays</th>
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<tbody>
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<td>OBSERVATORIES</td>
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<tr>
<td>800</td>
<td>SATELLITES</td>
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</table>
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
HEAO Program: 1978 - 1982

High Energy Astronomy Observatory
# NASA’s Great Observatories:

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

M-87 Core & Jet
Chandra Optics

Field of View ±5 Deg

Focal Surface

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

Low to Average Mass Star → White Dwarf

Large Mass Star → Neutron Star

Very Large Mass Star → ? Black Hole

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?
X-ray Binary Systems
Cosmic Jet – Artist’s Concept
A UNIVERSAL MECHANISM

(Mirabel & Rodriguez; Sky & Telescope, May 2002)
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**

**HYPERNOVA SCENARIO**

- **MASSIVE STAR**

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

- **GAMMA RAYS**

**BLOBs COLLIDE** (internal shock wave)

- **FASTER BLOB**
- **SLOWER BLOB**

**PREBURST**

**GAMMA-RAY EMISSION**

**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)
0 1.0x10^5
5.0x10^4
1.5x10^5
-2 -1 0 1 2 3
Time Since Trigger (s)

Trigger Number 451
23.064: 100000. keV
Rate (count/s)
0 3x10^4
2x10^4
1x10^4
4x10^4
-10 0 10 20
Time Since Trigger (s)

Trigger Number 7170
23.080: 100000. keV
Rate (count/s)
0 6x10^4
4x10^4
2x10^4
-50 0 50 100 150
Time Since Trigger (s)

Trigger Number 1663
22.600: 100000. keV
Rate (count/s)
0 8x10^4
6x10^4
4x10^4
1x10^4
-20 0 20 40 60
Time Since Trigger (s)

Trigger Number 1676
25.881: 100000. keV
Rate (count/s)
0 5x10^4
3x10^4
2x10^4
1x10^4
-20 0 20 40 60 80
Time Since Trigger (s)
Examples of Double-Peaked GRBs
Multiple-Episode Bursts
Distinct subclasses of $\gamma$-ray bursts: short/hard & long/soft
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
GRB 990123

Typical GRB Spectra

Briggs, et al. 1999
Spectral Evolution of GRBs

(from Crider, et al. 1997)
What is the trigger?

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

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

Radiation is beamed into a large cone

Jet break
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
$10^{12}$ eV (1 TeV)

Primary γ-ray or charged-particle cosmic-ray

Shower developing

Shower at maximum

Shower dying

Typically 16 km

Cherenkov light flashes

1 Meter

Light receiver

Ground

10 - 100 m

Upper atmosphere

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
EUSO & OWL

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

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

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

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

Graph showing
- Frequency (Hz) on the x-axis
- Gravitational Wave Amplitude on the y-axis

Graph illustrating
- Unresolved Galactic Binaries
- Resolved Galactic Binaries
Some Future NASA Astronomy Missions
Constellation – X

Two Spacecraft in Atlas V Shroud

Atlas V DM Launch Configuration - Side View
The Constellation-X Mission (Four Spacecraft)
Energetic X-ray Imaging Survey Telescope (EXIST)
The End