Space-based Gamma-ray Astronomy

Astr288C Lecture 4
Gamma-ray Astrophysics

- The gamma rays cover a huge swath of the electromagnetic spectrum
- High-Energy gamma-rays probe the non-thermal universe
  - Explore extreme environments hosting powerful particle accelerators
$\gamma$-rays Probe the Extreme, Non-Thermal, Universe

- Dark Nebula
- Dim, young star
- Our Sun
- Globular Cluster
- CMB
- Accretion Disk

Thermal Processes

- Radio
- Microwave
- Infrared
- Visible
- Ultraviolet
- X-ray
- Gamma ray

Extreme Universe
Non-thermal $\gamma$ ray emission

Energy source + Acceleration mechanism $\rightarrow \gamma$-ray production mechanism + Foreground absorption $\rightarrow \gamma$ rays
Energy sources

Explosions

Accretion

Rotating Fields

Exotic particle rest mass
Charged particle acceleration mechanisms

- Charge layer separation
- Rotating B-fields
- Poynting fluxes
- Magnetic reconnection
- Shock acceleration
  - Diffuse (Fermi acceleration)
  - 2\textsuperscript{nd} order (magnetic reflection)

None of these mechanisms are particularly well understood!!!
γ-ray emission mechanisms

- synchotron radiation
- inverse Compton scattering
- bremsstrahlung radiation
- pion production & decay

All of these mechanisms also create non γ-ray radiation
Why look for cosmic gamma rays?

- Supernova explosions release radioactive isotopes
- Cosmic rays are mostly protons
- Radio and later X-ray observations
  - Synchrotron emission from populations of accelerated electrons
- Infrared, optical, and UV observations
  - Target material and low energy photon populations
How to “see” gamma rays

Gamma rays are scattered and absorbed in matter (troublesome for standard focusing techniques)

Cross section depends on material and energy
- Coherent Scattering (electron remains bound to atom)
- Photoelectric Effect
- Compton Scattering
- $e^- e^+$ Pair Production

Gamma rays in Germanium
Credit: Richard Kroeger
Pair production

- Gamma-ray energy is converted to an electron and positron in the presence of a nucleus
- Larger cross-section for heavier nuclei
A problem for astronomy

It’s actually pretty hard to observe from the ground. Black arrows indicate average depth for wavelengths across the electromagnetic spectrum.
Several solutions

- Solution I: put detectors in the upper atmosphere or above it
  - Balloons and rockets
  - Space probes
- Solution II: this is not a problem; the atmosphere is also a detector!
  - Build instruments on the ground that collect the absorption by-products
  - VHE (very high energy) gamma-ray observatories
    - Whipple, Milagro, H.E.S.S., VERITAS, MAGIC, HAWK, CTA
Gamma-ray Spectrum

- **Low** Energy Gammas
  - Space-based
  - Collimator / Coded Aperture + Simple Calorimeter
  - Compton Telescope

- Medium

- **High Energy**
  - Space-based
  - Silicon strip tracker + hodoscopic calorimeter

- **Very High Energy**
  - Ground-based
  - Optical detectors
  - Water tank scintillators

Nuclear Decay Lines

Exotic Particle Decay?

Relativistic Boosting & Shock Acceleration

Rotational Acceleration
Space-Based Detectors

Gamma rays with energy below ~50 GeV must be detected in space

- Using the Compton Effect: keV – MeV
  - Below a few hundred keV, can use X-ray techniques, such as coded masks

- Using pair production: MeV – GeV
  - Above ~50 GeV there are so few gamma rays that satellite detectors, with areas ~ m², are too small
Historical note: Discovery of GRBs by the Vela satellites

- Nuclear weapons test monitoring satellites
- >70 bursts in the 1960’s

First indication of powerful, very short timescale cosmic explosions

Neutron stars in our Galaxy? Not clear until later that these were extragalactic

Vela 5B Credit: NASA HEASARC
SAS 2 mission

Small Astronomy Satellite
November 1972 - June 1973

- Mapped the high energy gamma-ray sky in detail
- Measured high energy gamma-ray background
- Confirmed that gamma rays come from dense regions of the Galaxy
The Compton Gamma Ray Observatory

1991-2000 4 instruments span 30 keV - 30 GeV
Deployed by the space shuttle

- High energy detector, EGRET
  - Pair conversion
  - >270 sources (many unidentified)

- Medium energy, COMPTEL
  - Compton technique

- Gamma-ray burst detectors, BATSE
  - 2704 \( \gamma \)-ray bursts

Credit: NASA
CGRO Gamma-ray Bursts

2704 BATSE Gamma-Ray Bursts

Credit: NASA/BATSE
A close-up of EGRET

Detecting a gamma ray

- Direction
- Energy
- Time

Tracking Layers

Tantalum Foil

Gas (e.g. Neon-ethane mix)

γ e− e+

Calorimeter: 8 radiation lengths of NaI(Tl)

From CGRO Science Support Center
The High Energy Sky circa 2000

EGRET All-Sky Map Above 100 MeV
The Fermi Observatory

Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV

Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV
LAT Detector

- Anti-Coincidence Detector
  - Charged particle veto

- 18-layer Si Tracker
  - Silicon wafers interleaved with tungsten foil
  - Pair-production and particle tracking

- 8-layer hodoscopic Cesium-Iodide crystal calorimeter

- Data rate ~ 400 Hz
  - Gamma rate ~ 2 Hz
LAT Detects Individual $\gamma$ rays (and Cosmic Rays)

Nearly ideal $\gamma$-ray candidate:
1. Starts in middle of TKR
2. Extra hits near track
3. CAL axis aligned with track
4. CAL energy confined near axis

Nearly ideal proton candidate:
1. Starts at top of TKR
2. Few extra hits near track
3. CAL axis not-aligned with track
4. CAL energy “lumpier”
5. Signal in the ACD (not shown)
Survey mode

- Rock north for one orbit and south for the next
- Cover entire sky and always keep LAT FoV away from the Earth limb
- Slew to point at a position when source is not occulted
All-Sky Coverage

- In survey mode, LAT observes the entire sky every two orbits (~3 hrs)

LAT View of the gamma-ray sky with time
LAT Records Individual Events

- Pertinent details recorded for each event detected
  - Energy, direction, time, instrument angles, conversion layer, etc.
- Very sparse data (sometimes only a few hundred photons) requires special analysis techniques
  - Maximum Likelihood analysis (future lecture)
Characterizing the LAT

- Instrument responses determined by Monte Carlo simulation of the entire instrument (and spacecraft)
Instrument Responses

Effective area at normal incidence ($\cos(\theta) > 0.975$)

- P7TRANSIENT_V6
- P7SOURCE_V6
- P7CLEAN_V6

Effective area at $10$ GeV, averaged over $\phi$

- Total
- Front
- Back

PSF at normal incidence

- Total 68% containment
- Front 68% containment
- Back 68% containment
- Total 95% containment
- Front 95% containment
- Back 95% containment

Effective area at $10$ GeV, $\theta = 30^\circ$

- Total
- Front
- Back
The Fermi-LAT Sky

Two years, all photons > 100 MeV.
Aitoff projection in Galactic Coordinates
The Fermi-LAT Sky

Two years, all photons > 1 GeV
LAT Data Available to Public

LAT Photon, Event, and Spacecraft Data Query

April 13 2012: The data server is now loaded with Pass7 photon data. This data has the updated diffuse response columns. We do not recommend mixing the data downloaded before April 18 with the current data if you are doing unbinned analysis. Analysis using Binned Likelihood is unaffected.

NOTE: For queries encompassing the whole sky (or close to it), please use the pre-generated Weekly All-Sky Files available through HEASARC Browse.

NOTE: Additional selections must be applied to data downloaded from the data server prior to use in a data analysis. See recommended data selections and LAT caveats for more details.

The photon database currently holds 250858653 photons, collected between 2008-08-04T15:43:37 UTC and 2013-09-25T00:27:35 UTC (Mission Elapsed Time (MET) 239557417 to 401761655 seconds).

The event database currently holds 1912140316 events, collected between 2008-08-04T15:43:37 UTC and 2013-09-25T00:27:35 UTC (Mission Elapsed Time (MET) 239557417 to 401761655 seconds).

Use xtime to convert between MET and other time systems.

Object name or coordinates: 
Coordinate system: J2000
Search radius (degrees):
Observation dates:
Time system: Gregorian
Energy range (MeV):
LAT data type: Photon
Spacecraft data:

http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi