Astrophysics with GLAST: dark matter, black holes and other astronomical exotica

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Outline:

• Multi-band perspective on astronomy - and gamma-rays

• Stanford’s involvement in the future observatories: Gamma-ray Large Space Telescope (GLAST )

• What will GLAST study?
  - supernova remnants, clusters of galaxies, active galaxies
X-rays and gamma-rays in perspective

- Optical band is only a small part of the electromagnetic spectrum
- Radio band, opened in the 1930s, revealed the world of exotic processes
- Studying astronomical sources in other spectral ranges besides the optical band can reveal very rich physical phenomena
X-ray and $\gamma$-ray observations require detectors above the atmosphere.

Opacity of the atmosphere as a function of photon energy.

First observations were conducted using rocket-based instruments.
Chandra Observatory: sensitive to X-rays in the 0.3 ñ 10 keV band
Compton Gamma-ray Observatory

Featured instruments sensitive from ~ 40 keV (OSSE) up to nearly 100 GeV (EGRET)
Future of γ-ray observations is here: GLAST

EGRET all-sky survey (galactic coordinates) E>100 MeV

Features of the MeV/GeV γ-ray sky:

* Diffuse extra-galactic background (flux \(\sim 1.5 \times 10^{-5} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\))

* Galactic diffuse and galactic sources (pulsars etc.)

* High latitude (extragalactic) point sources – blazars and new sources? - typical flux from EGRET sources \(10^{-7} - 10^{-6} \text{ cm}^{-2}\text{s}^{-1}\)

* Need an instrument with a good sensitivity and a wide field of view

* Gamma-ray Large Area Space Telescope (GLAST) – with a detector built at Stanford / SLAC - has just been launched!
Schematic principle of operation of the GLAST Large Area Telescope

- γ-rays interact with the hi-z material in the foils, pair-produce, and are tracked with silicon strip detectors
- The instrument "looks" simultaneously into ~ 2 steradians of the sky
- Energy range is ~ 30 MeV – 300 GeV, with the peak effective area of ~ 12,000 cm²
- This allows an overlap with TeV observatories
GLAST LAT instrument overview

Si Tracker
- Pitch = 228 µm
- 8.8 × 10^5 channels
- 12 layers × 3% X₀
- + 4 layers × 18% X₀
- + 2 layers

CsI Calorimeter
- Hodoscopic array
- 8.4 X₀, 8 × 12 bars
- 2.0 × 2.7 × 33.6 cm
- ⇒ cosmic-ray rejection
- ⇒ shower leakage correction

Data acquisition

ACD
- Segmented scintillator tiles
- 0.9997 efficiency
- ⇒ minimize self-veto

Grid (& Thermal Radiators)

3000 kg, 650 W (allocation)
1.8 m × 1.8 m × 1.0 m
20 MeV – >300 GeV

LAT managed at SLAC

Flight Hardware & Spares
- 16 Tracker Flight Modules + 2 spares
- 16 Calorimeter Modules + 2 spares
- 1 Flight Anticoincidence Detector
- Data Acquisition Electronics + Flight Software
GLAST LAT has much higher sensitivity to weak sources, with much better angular resolution.
LAT Integration at SLAC

Calorimeter module
Tracker module

LAT Integration & Test Team

Anti Coincidence Detector being integrated with 16 towers
Supernovae and their remnants

- Early Universe contained only the lightest elements: hydrogen, helium

- “Heavy” elements were all “cooked” in stars and ejected into the interstellar space via supernova explosions

⇒ We are made of those elements!

- The process of “pollution” of the interstellar space with the heavy elements is best studied with X-rays:
  
- This is because the expected velocity of the ejecta, \( \sim 10,000 \text{ km/s} \), corresponds to temperatures in the keV (10\(^7\) K) range

  iThis temperature range is rich in atomic transitions studied via X-ray spectroscopy

Kepler’s supernova remnant
Pulsars: rotating neutron stars

• Neutron stars left behind the explosion are fascinating objects – when they rotate and are not perfectly symmetric, they will send out radiation in precisely timed "pulses," seen also in γ-rays.
Supernova remnants as sources of cosmic rays

* Cosmic rays are very energetic particles that come from interplanetary or interstellar space – but what is their origin?

* Since they are protons and electrons => “charged particles” - we cannot trace them back to their origin as the trajectories are affected by Galactic magnetic field

* Have to use photons to infer their origin

Tycho’s supernova remnant (Chandra Observatory X-ray image)
Spectrum and origin of cosmic rays

Is strong TeV γ-ray emission from supernova remnants also implicating them as sources of cosmic rays?

(Spectrum of cosmic rays (from Gaisser 2001))

(HESS data, Aharonian et al. 2004)
Clusters of galaxies

“Normal” galaxy Messier 100  
Cluster of galaxies in constellation Coma

- Galaxies don’t live “alone” but often are associated with each other in “clusters” bound by gravity
Clusters of galaxies and their X-ray emission

• Clusters of galaxies are largest gravitationally bound and relaxed structures in the Universe – they “condensed” from original “perturbations” in the Universe.

• Their mass and number density as a function of time are probes of cosmological parameters.

• Clusters of galaxies are bright, extended X-ray emitters – since we understand physics, we can “weigh” them: - and we can’t account for all the gravitational pull - member galaxies + hot gas are not enough!

Conclusion of those studies is that dark matter is required.
Clusters are gravitational lenses

• Gravitational lensing of background galaxies provides an independent estimate of the mass of the cluster.

• Masses inferred from lensing data generally (but not always!) agree with the X-ray data.

Hubble space telescope image of cluster Abell 2218
Can’t explain all this just via “tweaks” to gravitational laws…

Offset between gas and mass peaks → Dark Matter exists!
(Clowe et al. 2004)
Cosmology with clusters

The earliest Universe we can observe was very smooth, but today it is very "clumpy" -> gravity at work

What was the history of the formation of structure in the Universe? How did gravity form the current Universe?

Map of the Universe collected with the WMAP satellite:

“Ripples” have amplitude of less than 0.1%

* very smooth…
Comparison of independent cosmological constraints (CDM)

Cluster $f_{\text{gas}}$ analysis including standard $\Omega_b h^2$, $h$ and $b$ priors (Allen et al. 2004)

CMB data (WMAP + CBI + ACBAR) weak prior $0.3 < h < 1.0$

Supernovae data from Tonry et al. (2003).

Figure and analysis from Allen et al. 2004
Cosmology with gamma-rays:
Observable signatures of dark matter

Extensions to Standard Model of particle physics provide postulated dark matter candidates

If true, there may be observable dark matter particle annihilations producing gamma-ray emission

This is just an example of what may await us!
Active galaxies and strong gravity

- Many galaxies contain exceptionally bright nuclei that are also point-like sources of radio and X-ray emission.
- In some cases, the nuclei are so bright that the galaxy can be barely detected.
- We now believe that the origin of this emission is the release of gravitational energy by matter flowing onto a supermassive black hole, with a mass of $10^6$ or more times the Sun.

“Normal” galaxy M74
Radio galaxy M87 (Virgo-A) studied with the Hubble Space Telescope

- Black holes are a common ingredient of nearly all (!) galaxies
- When “fed” by galaxian matter, they shine – or produce jets – or both
- The BH mass is very important to understand physical processes involved

Seyfert galaxy NGC 4258 studied using H$_2$O megamaser data

Weighing the central black hole
Unified picture of active galaxies

- Best scenario has all AGN powered by the same basic “engine”: a black hole accreting via disk-like structure
- Some active galaxies possess strong jets
- Such a jet is most likely relativistically boosted and thus much brighter than the rest

Diagram from Padovani and Urry
Radio, optical and X-ray images of the jet in M87 galaxy

* Jets are common in AGN – and are clearly seen in radio, optical and X-ray images

* When the jet points close to the our line of sight, its emission can dominates the observed spectrum, often extending to the highest observable energy (TeV!) gamma-rays – and this requires very energetic particles to produce the radiation…

* Another remarkable example of “cosmic accelerators”
Most prevalent point-like $\gamma$-ray sources on the sky: active galaxies dominated by emission from relativistic outflows (=jets)

Two examples of broad-band spectra:
$\gamma$-ray emission dominates the $E \times F(E)$ spectrum – energetically important

Bright EGRET-detected GeV emitting blazar: 3C279
(data from Wehrle et al. 1998)

First TeV-emitting blazar: Mkn 421
(data from Macomb et al. 1995)
Summary:

* Energetic $\gamma$-ray astrophysics is uncovering a plethora of new phenomena in the Universe
* Following the spectacular discoveries of EGRET, the recently-launched GLAST soon will bring much improved sensitivity and angular resolution, expanded bandpass, and all-sky monitoring capability
* GLAST will allow us to better understand the structure and physical processes responsible for radiation in the known $\gamma$-ray sources such as pulsars, jets in active galaxies, $\gamma$-ray bursts, and supernova remnants contributing to the Galactic diffuse $\gamma$-ray emission
* Much of the improved understanding of those sources will be via multi-band studies, involving radio, optical, and X-ray bands

* The most exciting discoveries will be via the new classes of astrophysical $\gamma$-ray emitters – one example may be $\gamma$-rays resulting from annihilation of postulated dark matter particles