Fermi Sky I: (Mostly) non-variable sources

Seth Digel
KIPAC/SLAC

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Outline

• Gamma-ray astronomy and Fermi
• Galactic Diffuse Emission
• Isotropic Diffuse Emission
• External ‘Normal’ galaxies
• Sources in the Milky Way
  – Pulsars
  – Pulsar Wind Nebulas
  – Globular Clusters
  – Supernova Remnants
  – Eta Carinae (not classified)
  – Sun & Moon
• Unassociated sources
Why is there gamma-ray astronomy?

• Nature has a remarkable number of ways to make cosmic rays (CRs, particles with extremely nonthermal energies)
  – Acceleration in shocks – on scales from solar flares to supernova remnants to colliding clusters
  – Intense, moving magnetic fields – rotating (pulsars)
  – Annihilation or decay of hypothetical dark matter particles
• Cosmic rays are not well suited for astronomy but gamma rays from CR interactions have
  – No optical depth (once they escape their emitting regions)
  – No trajectory scrambling by magnetic fields
• They are difficult to detect – but the fluxes are great enough and the technologies have advanced enough for astronomy to be possible
• There’s a lot to learn from gamma rays – both uniquely and from multiwavelength studies
Why is there gamma-ray astronomy? (2)

• 1948-1952, relevant cosmic production mechanisms of gamma rays were understood (Feenberg & Primakoff, Hutchinson, Hayakawa)
• 1951, 21-cm line of H I (Ewen & Purcell, Muller & Oort)
• 1949-1960s, upper limits on cosmic fluxes from balloon and suborbital experiments
• 1960s-1970s, theoretical development from advances in particle physics (Stecker, Ginsburg,...)
Brief History of Detectors* for GeV Gamma-ray Astronomy

- 1967-1968, OSO-3 detected Milky Way as an extended γ-ray source, 621 γ-rays
- 1972-1973, SAS-2, ~8,000 celestial γ-rays
- 1975-1982, COS-B, orbit resulted in a large and variable background of charged particles, ~200,000 γ-rays
- 1991-2000, EGRET, large effective area, good PSF, long mission life, excellent background rejection, and >1.4 × 10^6 γ-rays
- 2007-, AGILE, like 1/16-th LAT, with small calorimeter, sensitivity ~EGRET

* in space
Reminder: The LAT Sky

>1 GeV for three years
The LAT Sky (asides)

- Few thousand gamma-ray sources
- For these we have measured source locations, spectra, light curves, and (for some) angular extent

- Absolutely identifying sources with counterparts at other wavelengths is often not possible
  - But of course it is what we would like to do
  - Identification requires correlated variability or angular extent

- That said, a positional association can be quite confident
  - Within a source class that confidence can often be quantified

- It is worth being careful about the distinction between identification and association
Galactic Diffuse Emission

- Galactic = from the Milky Way
- Diffuse = not from point sources

- Cosmic rays – high-energy particles propagating in the Milky Way
  - More on this from Pasquale Blasi later this morning and over the coming days
- Cosmic rays occasionally interact with interstellar nucleons and interstellar photons
- Interstellar nucleons are in the gas and dust between the stars
  - The mass of the interstellar medium is ~10% of the mass of the stars in the Milky Way, but for Galactic diffuse emission the stars essentially do not matter
  - Point later about the gamma-ray emission from the Sun
- Interstellar photons are starlight, and starlight reprocessed by interstellar dust, and the cosmic microwave background
• In the GeV energy range the Galactic diffuse emission is relatively bright
• ~65% of the celestial gamma rays detected by the LAT are Galactic diffuse
• The Galactic diffuse emission traces the distribution of interstellar gas and also relates to the (generally more smooth) distribution of cosmic rays

Spectrum of the Inner Milky Way with Model Components

Ackermann et al. (2012)
Galactic Diffuse Emission (2)

- An approximation that worked well until Fermi was to consider the Galactic diffuse emission to be a simple combination of model for the interstellar gas with a smooth distribution of cosmic rays (plus a model for inverse Compton emission which is even smoother)
- This is no longer the case, and the reasons for the residuals are various and still being debated
Galactic Diffuse Emission (3)

- For example, here are the additional components required in the model used for the analysis for the 2FGL catalog
- More on Friday

Casandjian on behalf of the LAT Collaboration (Fermi Symposium 2011)
Isotropic Diffuse Emission

• Do we need it? Apparently yes
  – Isotropic diffuse emission was first detected by SAS-2 (Fichtel et al. 1977) and confirmed by EGRET (Sreekumar et al. 1997, Strong, Moskalenko, & Reimer 2004) and by Fermi
  – You should be reasonably concerned that it might be residual cosmic rays
  – But it is not

• That said, it obviously depends on what is attributed to Galactic diffuse emission
  – At high Galactic latitudes, the level of the Galactic diffuse emission depends on the (large) scale heights of cosmic-ray electrons and of the interstellar radiation, both of which are not tightly constrained

• And it depends on the sensitivity and resolving power of your gamma-ray telescope
  – At least some component of it is unresolved point sources
Isotropic Diffuse Emission (2)

- Decomposition into components is irresistible
- Evaluating contributions from blazars (BL Lac and FSRQ) and normal galaxies depends on measuring their luminosity functions
- Potential Dark Matter annihilation signal...

- At the highest energies, absorption from pair production on the extragalactic background light should become important

* Just an example; you can find many other decompositions in the literature
External Normal Galaxies

- Normal means gamma-ray emission from cosmic-ray interactions with the interstellar medium and photons.
- This emission is not beamed and the luminosities are low enough that the Local Group is the best hunting ground.
  - Detections so far: Large Magellanic Cloud, Small Magellanic Cloud, Andromeda (M31).
- Some starburst galaxies are not too far to be detected as well (within ~few Mpc).
Large Magellanic Cloud

- This is the largest in angular size and has the greatest flux (~65 kpc distant)
- The analysis is complicated by the large angular size – several background blazars are present
- It has a fairly large inclination to the line of sight and is classified as an irregular galaxy but studying it from an external perspective has advantages relative to the Milky Way
  - Murphy et al. (2012) quantitative investigation of CR propagation

**LAT image after background model subtraction**

Boxes indicate positions of blazars included in the background model

$N(HI) = 10^{21} \text{ cm}^{-2}$

$>100 \text{ MeV}$

Abdo et al. (2010)
Starburst Galaxies

- The exceptionally large densities of gas and of massive star formation (= lots of SNRs) is responsible for the relatively large gamma-ray luminosities of these galaxies.

- The gamma-ray and infrared luminosities of ‘normal’ galaxies seem to be well correlated…
Sources in the Milky Way: Pulsars

- Rotating magnetized neutron star:
  - Intense magnetic field
  - Rotating fast
  - And the magnetic dipole moment is not aligned with the spin axis

- The gamma-ray beam tends to be broader than in the radio and is associated with particle acceleration in the outer gap

- The spectral energy distribution can peak in gamma rays (in the gamma-ray beam)
  - A number of pulsars are now known to be gamma-ray only

http://www.cv.nrao.edu/course/ast534/Pulsars.html
The brightest persistent LAT sources are gamma-ray pulsars.
With the LAT the number of known gamma-ray pulsars has increased from 7 pre-Fermi to 101 publicly announced.

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Gamma-ray luminosities range from $\sim 10^{32}-10^{37}$ erg s$^{-1}$
• Part of the increase is due to powerful new ways to find periodicity in the gamma-ray data
  – Not a simple problem: Pulsars are slowing down, their positions on the sky are not perfectly known, they sometimes glitch, and for even a bright pulsar the LAT might detect only one gamma ray per 100,000 revolutions
  – Some gamma selected pulsars have since been detected in very deep radio observations
• In some cases LAT pulsar detections have followed from radio pulsations detected in unassociated LAT sources
  – Contemporary ephemerides are essential for phase assignment
  – Many of these are millisecond pulsars, the fastest-spinning and oldest
  – Their magnetic fields are relatively weak but they are spinning rapidly enough to be gamma-ray sources
Pulsars (4)

- Some LAT measurements for Vela (N.B. Not a typical example)

  ![Light Curve (>20 MeV)](image1.png)

  ![Spectral Energy Distribution](image2.png)

- More on pulsar observations and physics from Paul Ray and Pasquale Blasi next Monday

Abdo et al. (2010)
Pulsar Wind Nebulas

- The particles accelerated by pulsars can power nebulas surrounding pulsars
  - The termination shock (where the wind is decelerated by sweeping up ejecta from the SN explosion) can accelerate particles
- PWNs are not angularly resolved by the LAT but can be spectrally resolved (and phase selected to cancel the pulsar) in LAT data – see Vela-X component in the spectrum of Vela
  - The electrons lose energy quickly and the angular size of a PWN decreases with increasing energy
- ~4 PWNs are known in the LAT data and some more at TeV energies
  - They tend to be associated with very energetic pulsars
- More from Pasquale Blasi next Monday
- Also Martin Weisskopf tomorrow and Trevor Weekes next Tuesday about the Crab nebula
Globular Clusters

• Likely not an independent class
• Globular clusters are large clusters of very old stars in the halo of the Milky Way
  – Because of the stellar densities and ages they are good hunting places for millisecond pulsars
• A number of globular clusters are positionally associated with LAT sources (11 in the 2FGL catalog)
• The suspicion long was that they are shining in the light of millisecond pulsars
• Strong evidence for this hypothesis: a detection of a millisecond pulsar

NGC 6624

A millisecond gamma-ray pulsar J1823-3021A was detected in globular cluster NGC 6624 (Freire et al. 2011)
Supernova Remnants

- These accelerate CRs and can be sources of gamma rays, e.g., from interactions of ‘fresh’ CRs with a nearby interstellar cloud
- Some are extended sources for the LAT
- The character of the emission depends on the age (state of evolution) of the SNR
- Particle acceleration models – search for evidence of proton acceleration
  - No ‘smoking gun’ yet
- More on SNRs from Jack Hewitt on Thursday
• Maybe a LAT source anyway
• Eta Carina is a binary star system with a >100 solar mass star
• A bright gamma-ray source is positionally coincident, but does not appear to vary in coincidence with the X-ray variability
• In the 2FGL catalog it is listed as an association but without a classification
• The gamma-ray source is quite interesting, e.g., with a hard high-energy spectrum

Abdo et al. (2010)
‘Quiescent Sun’

- It is a gamma-ray source from CR interactions in the outer atmosphere and inverse Compton scattering of CR electrons in the radiation field
  - The former is essentially only from the rim of the Sun*
  - The latter makes the Sun a sort of all-sky source

- The flux of the Sun depends on the phase of the solar cycle
  - CRs that cannot overcome ‘solar modulation’ cannot interact with the solar atmosphere

- N.B. The Sun also moves
  - The 2FGL catalog flags several sources at low ecliptic latitude that brightened only when the Sun was nearby

* If the Sun were transparent to gamma rays its flux would be $\sim 10^{14}$x greater
Moon

- It shines in gamma rays only from cosmic rays interacting with the rocks
- The favorable direction is forward scattering from cosmic rays just skimming the edge of the Moon (Moskalenko & Porter 2007)
  - The interaction depth is ~20 cm
  - At high energies the center of the disk of the Moon should be very dark (most gamma rays produced are absorbed)
- The gamma-ray brightness of the Moon should vary with the solar cycle

- N.B. The Moon also moves, but it moves much faster than the Sun (~13°/day) and has appreciable orbital parallax for the LAT (~±1°) and so is much less of a contaminator of sources it passes near
Unassociated LAT Sources

• [Not all belong in the ‘non-variable’ category as a class]
• Already mentioned as profitable targets for searches for millisecond pulsars
• In general the unassociated sources are what one would study for evidence of a new population (new class) of gamma-ray sources
• Broadly speaking, classification schemes based on measured properties of sources can made educated guesses regarding whether each unassociated source is a pulsar or a blazar*
• The bottom line is that there’s not much left over

* e.g., Ackermann et al. (2012, in press)
Apparently-missing Source Classes

- What has the LAT not detected that we had expected to?
  - Clusters of galaxies
  - Supernova/OB associations (SNOBs)
  - Colliding Wind Binaries?
  - N.B. Unassociated LAT sources have been studied as potential DM signals – but no detections
Summary

• The steady LAT sources are responsible for >90% of the celestial gamma rays
• The sensitivity, resolution, and energy range of LAT observations, are providing discoveries and forcing new understanding of Galactic diffuse emission
• More than 100 gamma-ray pulsars are now known, enough for population studies of sub-classes such as millisecond pulsars
• PWNs and Globular clusters are in a sense pulsar-derived
• Supernova remnants of a variety of ages have been detected, allowing study of the gamma-ray evolution of SNRs
• Unassociated sources and Eta Carinae – searches for additional new source populations and dark matter signals are ongoing

Next: The Dynamic Fermi Sky
Backup slides
Fermi and the LAT

- Large Area Telescope was launched in June 2008 on the NASA mission now called Fermi
- Major contributions from France, Italy, Japan, Sweden, & U.S.
- LAT collaboration has ~400 members
Fermi and the LAT

- LAT energy range is 20 MeV - >300 GeV (>4 orders of magnitude)
- Peak collecting area is about 8000 cm$^2$ (moderate)
- Field of view is 2.4 sr (huge)

- High-energy gamma-ray astronomy is a relatively young field, partly because at GeV energies it must be done from space

- LAT is by far the most sensitive instrument ever in this energy range
  - Celestial gamma-ray rate is ~2 Hz for the LAT
  - Within the first few weeks of the mission, LAT had collected as many gamma rays than had been detected by all previous missions combined, and measured them with better precision
  - Huge ‘discovery potential’