The Gamma Ray Milky Way

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1 Introduction

Gamma rays (γ-rays) are photons of the most energetic electromagnetic radiation, with frequencies below 10pm and energies exceeding 120 keV. The large amount of energy associated with γ-rays is highly ionizing, and is easily able to break down many atoms and organic material. The presence of γ-rays on a planet would be disastrous to life like ours, so it is fortunate for organisms on Earth that most radiation with energy higher than visible light (including γ radiation) is unable to easily penetrate Earth’s atmosphere - the danger of sterilizing γ-rays reaching the surface is avoided. The opacity of Earth’s atmosphere to gamma radiation, however, makes it challenging to make observations of γ-ray emitting objects. Reaching the large amounts of energy required to produce a photon of gamma radiation is challenging too. Instead of the blackbody emission that most lower energy radiation comes from, γ-rays often involve the conversion of mass to energy or other high density, high energy nuclear reactions.

2 Gamma-ray Telescopes and Instruments

There are two techniques used to observe gamma radiation. On the surface of Earth, we can do indirect observations of γ-rays by observing the effects of gamma radiation hitting the atmosphere. This however, requires a reconstruction of the γ spectrum, and is subject to more uncertainty due to low intensities over very short times (∼ 10 ns) - photomultipliers with wide angles are used to observe these events. Gamma rays cause particle/antiparticle pair production (§3.3) upon atmospheric entry, with non-thermal Bremsstrahlung radiation reducing the energy of the pair by creating lower energy gamma rays, which result in showers of particles. Detecting γ-rays from the surface is done by using instruments called imaging Air Cherenkov Telescopes (IACTs), which observe the cascades of secondary particles and attempt to reconstruct the γ image [Bringmann and Weniger, 2012]. Some impor-
tant systems that use this method for astronomical observations are the High Energy Stereoscopic System (H.E.S.S), the Very Energetic Radiation Imaging Telescope Array System (VERITAS), and the Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes (MAGIC) (Fig.2). VERITAS, H.E.S.S., and MAGIC all consist of arrays of telescopes, using five, four, and two reflectors respectively to reconstruct images after detecting Cherenkov light in the atmosphere [Baixeras, 2003, Konopelko, 1999].

We can also make direct observations of γ-rays using space telescopes. Currently there are a few space telescopes dedicated to observing γ-rays: NASA’s Fermi Gamma-ray telescope launched, the Italian Space Agency’s **Astro-Rivelatore Gamma a Immagini Leggero** (AGILE), ESA’s **INTErnational Gamma-Ray Astrophysics Laboratory** (INTEGRAL) and the High Energy Transient Explorer 2 (HETE-2) are some of the more important ones [Tavani et al., 2009, Rando et al., 2013, Teegarden and Sturman, 1999]. Some past telescopes that have also been important to Gamma-ray astronomy have been NASA’s Swift, and the Italian-Dutch BeppoSAX, although they involved more in looking at cosmological γ-rays than Galactic γ-rays.

3 Gamma-ray Sources

3.1 Dark Matter Annihilation

The dark, non-baryonic matter that causes galaxies to have flat rotation curves out to radii far past the stellar distribution has a few theories surrounding its true nature. The existence of Weakly Interacting Massive Particles (WIMPS) is one of the more promising theories, with a leading candidate for dark matter particles being one of the one predicted by supersymmetry, the neutralino χ [Bergström, 1999]. This particle may be able to be observed through scattering reactions with detectors on Earth, or in a particle collider, or indirectly via looking for results of annihilation. There are two processes involving χ that result in the production of gamma radiation:

\[ \chi\chi \rightarrow Z\gamma \]  \hspace{1cm} (a)

and

\[ \chi\chi \rightarrow \gamma\gamma. \]  \hspace{1cm} (b)

The γ-rays that result from the reactions in [Eq. a,b] have a certain energy, causing emission lines of monochromatic γ-rays. The theorized energy for these states are \( E_\gamma \simeq M_\chi \) and \( E_\gamma \simeq M_\chi \left( 1 - M_Z^2/4M_\chi^2 \right) \), with 5 GeV ≤ \( M_\chi \) ≤ 1 TeV, \( M_Z \simeq 91 GeV \). [Ackermann et al., 2011][Hooper and Goodenough, 2011].
In order to indirectly detect WIMPs, we look for signs of these $\gamma$-rays due to $\chi$ annihilation - gamma-ray signatures are important because of the geometry of their travel, they are not perturbed easily and as such give good spatial signatures [Bringmann et al., 2012]. The gamma ray flux in the Galactic halo due to $\chi$ neutralino annihilations into $\gamma\gamma$ is believed to be describable by:

$$\frac{dJ_{\gamma}}{dE d\Omega} (\xi) = \frac{\langle \sigma v \rangle_{\chi\chi \to \gamma\gamma}}{8\pi M_{\chi}^2} 2\delta(E - E_{\gamma}) \int_{l.o.s} ds \rho_{dm}^2(r),$$

where $\xi$ is the angle to the galactic centre, $\langle \sigma v \rangle_{\chi\chi \to \gamma\gamma}$ is the partial annihilation cross section of the $\chi\chi \to \gamma\gamma$ interaction, and $\rho_{dm}^2$ is the dark matter density as a function of the Galactocentric distance $r$ [Weniger, 2012]. $\rho_{dm}$ may be one of several profiles, including the generalized Navarro-Frenk-White (NFW) profile [Navarro et al., 1996]. In addition to the line emission in $\gamma\gamma$ and $Z\gamma$, gamma rays may also be given off in other reactions that involve the $\chi$ neutralino. Internal (non-thermal) Bremsstrahlung (IB) radiation may also give off gamma radiation when $\chi$ neutralinos annihilate into charged particles [Bringmann et al., 2008]. IB causing events and intermediate events (like $\chi\chi \to \phi\phi$, $\phi \to \gamma\gamma$) are less likely than the $ZZ$ and $\gamma Z$ products, and therefore are only believed to make up a small amount by total percentage of the products resulting from $\chi\chi$ annihilation - the bulk of $\gamma$-ray radiation from $\chi$ neutralinos should be the monochromatic $\gamma$-ray emission lines from the $\chi\chi \to Z\gamma$ and $\chi\chi \to \gamma\gamma$ [Birkedal et al., 2005].

3.2 Gamma Ray Pulsars

The high gravity and magnetic fields around a pulsar provide the extreme conditions needed for the production and emission of gamma radiation. The high rotation rate, combined with these conditions, make the environment of a neutron star very much like that of a particle accelerator [Caraveo, 2014]. There are two main classes of pulsars that give off $\gamma$ radiation, ordinary pulsars and millisecond pulsars (MSPs). One of the supporting theories as to how ordinary pulsars emit gamma radiation is called the Polar Cap (PC) model [Harding and Muslimov, 1998]. In the PC model, electron-positron pairs are formed in a plasma in the polar field lines at the poles of a pulsar, where the particles move at ultrarelativistic speeds [Arons, 1983]. The site of this behaviour is called a pair formation front (PFF). As the particles move at ultrarelativistic velocities, they may lose energy via curvature radiation (CR) mostly, but also to inverse Compton scattering (ICS), causing the release of $\gamma$ rays [Harding and Muslimov, 1998]. The released $\gamma$ radiation may then cause the production of a secondary
electron/positron pair (§3.3), as photons more energetic than 1 GeV are absorbed into the magnetic field. These particles will give off more radiation in the form of more γ-rays as they revolve in the magnetic field. The new γ-rays go on to create more pairs, which release more synchrotron radiation again and cascade more generations of pairs until the synchrotron γ radiation is not energetic enough to create an $e^-/e^+$ pair, and the escaping radiation allows us to observe the pulsar as a γ-ray pulsar [Caraveo, 2014].

Other additional models describing the γ emission of these pulsars are the slot gap (SG) and outer gap (OG) pulsar models. The SG model has a slot gap in the magnetic field lines of the pulsar, which allows the electrons released from the surface to accelerate to reach high altitudes, while the OG model has an outer gap, allowing them to reach even further out. All models have the same basic processes involved, but the energy measured in the emitted gamma-rays is different for different altitudes - higher energy gamma rays come from higher up in the pulsar’s magnetosphere [Aliu et al., 2008]. MSPs are rotating neutron stars that have periods on the order of 1-10 milliseconds. The magnetic fields of millisecond pulsars have been measured to be quite lower than that of the magnetic fields in ordinary pulsars, being around 3 orders of magnitude less than that of the average radio pulsar [Wijnands and van der Klis, 1998]. MSPs are believed to originally have been normal neutron stars in binary systems - many MSPs have been found in binary systems. As the neutron star became older and lost some magnetic field strength, it also spun up by taking angular momentum from binary companions via accretion of matter [Kiziltan and Thorsett, 2009]. The different magnetic fields and rotation of MSPs suggests a different mechanism might
Figure 3: Top: An all sky map of gamma radiation, showing the locations of γ-ray pulsars from Fermi-LAT. Bottom: Positions of radio-loud and radio-quiet pulsars are indicated in green and blue, with MSPs indicated in red and orange triangles. Here, black dots are other pulsars (no γ emission) and grey dots are globular clusters. [NASA/DOE/Fermi LAT Collaboration][Caraveo, 2014].
be needed to explain the $\gamma$ radiation. In MSPs the process is similar, with primary and secondary particles being accelerated through the magnetic fields of the pulsar. CR and ICS radiation also play an important part in MSPs, but there is also cyclotron resonant radio emission absorption by the ultrarelativistic pairs that are created. Synchrotron radiation emission then follows, and the process continues like in ordinary pulsars [Harding et al., 2005]. Figure 3 shows an all-sky $\gamma - ray$ map that shows the location of several $\gamma$-ray pulsars found by Fermi.

### 3.3 Particle-Antiparticle Annihilation

When a particle and its antiparticle collide, they are completely annihilated and give off high energy photons based on the energy of the particles. The interaction of a positron and electron is called the Dirac process, a reaction of the form:

$$e^+ + e^- \rightarrow 2\gamma$$

creating 2 $\gamma$ rays for conservation of linear momentum [Ruffini et al., 2010]. In the case of slowly moving particles, the energy is close to the rest mass energy $E = m_e c^2$, and the two $\gamma$ rays released are 511 keV photons [Hubbell, 2006], but for relativistic particles more emission may be present. Particle-antiparticle pairs may also be created by gamma rays through interaction with nuclei, electrons, or other gamma rays, and create gamma rays upon their annihilation. If a gamma ray has enough energy, it may spontaneously create an elementary particle and its anti-particle [Hubbell, 2006].

### 3.4 Stellar Atmospheres & Flares

Gamma rays are also created in small amounts in stellar atmospheres - the high temperatures and high energies associated with magnetic field events like solar flares also provides an environment in which low energy $\gamma$ rays can be formed from the interaction of relativistic particles with ambient plasma [Ramaty and Mandzhavidze, 1998]. Bremsstrahlung radiation from highly relativistic electrons and positrons also emits a continuum of $\gamma$ rays, as electrons and positrons collide with heavier particles in stellar chromospheres. Gamma radiation from protons, neutrons, and $\alpha$ particles colliding with heavier nuclei is also observed in the form of de-excitation lines, as well as any particle-antiparticle annihilation. We also observe $\gamma$ radiation from positrons released from radioactive nuclei in decay reactions, adding to the lines from de-excitation and the continuum from the Bremsstrahlung radiation. Looking at the $\gamma$-ray emission from stellar flares, it gives information on the abundances and some physical quantities in stellar atmospheres. [Aschwanden, 2004]
3.5 Gamma rays from Supernovae

The high energies of $\gamma$ rays are particularly hard to reach via traditional nuclear transitions, so the most common sources of $\gamma$ radiation involve extreme conditions. When a massive star ceases core fusion and progresses into a supernova, high amounts of energy in a high density medium allow for many collisions of nuclei with other particles, particularly free neutrons - charged particles are often unable to overcome the Coulomb potential barrier needed to get close to the nucleus. When a neutron collides with a nucleus, we see a reaction resulting in a more massive nucleus [Carroll and Ostlie, 2007]:

$$\frac{A}{Z}X + n \rightarrow \frac{A+1}{Z}X + \gamma$$

which, if unstable, will then undergo a $\beta$-decay:

$$\frac{A+1}{Z+1}X \rightarrow \frac{A+1}{Z+1}X + e^- + \bar{\nu}_e + \gamma$$

If the $\beta$-decay is on a shorter time scale than the neutron capture, then the process is called an s-process, and if the decay is on a longer time scale than the neutron capture then the process is called an r-process. Both of these processes involve the production of high energy $\gamma$-ray emission lines, but are particular to supernovae [Carroll and Ostlie, 2007]. As such, we don’t see much Galactic $\gamma$ ray production from supernovae nucleosynthesis due to the low frequency of supernovae in the Milky Way. There are, however, small amounts of $\gamma$ rays from supernova remnants that we observe in the Milky Way (Fig 3.5). The expanding material after a supernova is believed to be a site for the formation of, highly relativistic and energetic particles, or cosmic rays.

Figure 4: A theoretical spectrum of the $\gamma$-ray flux received from the sun, set to observations, showing the range of fluxes for $\gamma$ radiation. This can give a perspective of how stellar flares in magnetic stars throughout the Galaxy emit $\gamma$-rays. A Bremsstrahlung continuum with pion decay radiation dominates in the more energetic end with lower photon flux, while the less energetic but brighter end is dominated by emission lines. [Ramaty and Mandzhavidze, 1998].
Long after a supernova takes place, shockwaves will continue to propagate outward, propelling particles to relativistic energies as they encounter the shock front. [Blandford and Ostriker, 1978, Bell, 1978]. These relativistic particles may then collide with ambient gas surrounding the supernova, which may produce similar results to that in §3.4, as they may experience ICS and non-thermal Bremsstrahlung radiation, releasing $\gamma$-rays. Alternatively, the collisions with the ambient gas may prompt the emission of $\pi^0$ pions which then decay and release $\gamma$-rays. Note that $\pi^0$ pion decay is most likely to be of one of the two forms

$$\pi^0 \rightarrow 2\gamma, \text{ or } \pi^0 \rightarrow \gamma + e^- + e^+.$$  

Cosmic rays that escape supernovae and their remnants (or AGN and quasars) may travel through the intergalactic and interstellar media and produce similar results. The small amount of cosmic rays that make it to gas clouds may interact with nuclei in the gas, leading to the emission of gamma rays as $\pi$ decay, ICS, and non-thermal Bremsstrahlung radiation. This gives of a small amount of $\gamma$ radiation as a faint glow [Knödlseder, 2010]. In addition to supernova remnants, $\gamma$-rays may also be found coming from black holes, like the stellar mass black hole Cygnus X-1. While not a steady source of $\gamma$-ray

Figure 5: Locations of some supernovae remnants as observed by the Fermi telescope. Note their position along the plane of the Galaxy, compared to the $\gamma$-ray pulsars that exist off the plane of the Milky Way, as well as along the plane. [NASA/DOE/Fermi LAT Collaboration]
emission, some amounts of $\gamma$-ray signals may be detected coming from binary black holes due to inverse Compton scattering, and possibly synchrotron interactions in accretion disks as the black hole accretes matter from its binary companion [Laurent et al., 2011].

4 Gamma-ray Observations

4.1 The Crab Nebula, and its pulsar B0531+21

Several observations have been done on the Crab Nebula and the pulsar that remains of the supernova that caused the crab nebula in 1054 AD. The Crab system emits radiation at many wavelengths, including extremely high energy $\gamma$-rays of up to 100 TeV from the nebula. Many observations of the Crab system have been done using many telescopes, with the MAGIC, H.E.S.S and Fermi telescopes doing the majority of $\gamma$-ray measurements over time. Observations of the Crab pulsar have improved our knowledge of the PC, OG, and SG models [MAGIC Collaboration et al., 2014], and we see many signs of inverse Compton scattering from the nebula as expected from (§3.5). The pulsed emission coming from the Crab pulsar itself ranges up to and exceeds ...
25MeV, suggesting that an OG model may be the source of the observed γ-ray emission [Aliu et al., 2008].

4.2 Milky Way Halo & Dark Matter Annihilation

The central cusp of the Milky Way, as well as some sub-haloes have been shown to exhibit signs of dark matter annihilation via γ-ray observations in some studies. The observed γ radiation is not correlated to the Fermi bubbles (§4.4), and observation of an emission-line type spectra with a 130 GeV peak (to 4.5 σ, Fig. 4.2) as detected by Fermi observations leans toward the idea that both the χχ → γγ and χχ → γZ are sources of γ-ray emission as dark matter neutralinos annihilate [Tempel et al., 2012].

![Figure 7: Evidence of line-like γ-ray emission at (l, b) = (−1°, −0.7°) on the left and (l, b) = (−10°, 0°) on the right, with the 130 GeV peak clearly visible as shown by the red line over the black background radiation line, as observations suggest possible χχ annihilation into γ radiation [Tempel et al., 2012].](image)

4.3 Galactic Globular Clusters

A relatively high amount of gamma rays are observed in globular clusters (see Fig. 3). The presence of millisecond pulsars in globular clusters seems to be the reason for this - globular clusters have large populations of millisecond pulsars, and have been shown to have more binary systems than the Galactic disk by mass. Often, it is difficult to resolve the individual pulsars in globular clusters due to intrinsic dimness and interstellar scattering, but by looking at the γ-ray signatures the presence of (sometimes several) MSPs can be inferred [Abdo and Ackermann, 2010].
4.4 The Galactic Centre and the Fermi Bubble

Gamma observations along the disk and toward the centre of the Milky Way show diffuse $\gamma$-ray emission released from protons interacting with ionized gas and dust in the ISM, causing $\pi^0$ decay, along with ICS emission and CR emission like mentioned in §3.5 and §3.4 [Hooper and Slatyer, 2013]. This can be seen along the plane of the galaxy in (Fig 4.4). Fermi-LAT observations made of the galactic centre (GC) have shown giant plasma bubbles in the $\gamma$ spectrum, extending several kiloparsecs above and below the plane of the Milky Way, after masking of bright sources and removing of the diffuse emission from the plane of the galaxy. The environment from which these bubbles arise seems to be around the supermassive black hole at the centre, Sagittarius A ($\text{Sgr } A^*$), surrounded by molecular clouds and star clusters. These Fermi bubbles show signs of strong shocks, and are coincident with huge magnetic outflows, which suggests that these events may be related. There are a few theories surrounding their formation: the bubbles can be due to WIMP annihilation events, recent AGN activity, or due to recent star formation close to the GC. A few simulations show that recent star forming activity around the GC, with feedback leading to accretion of matter around Sgr A* can account for this $\gamma$ emission, while the structure of the bubble formation leads many to believe that dark matter annihilation can not be the source of this [Zubovas et al., 2011, Su et al., 2010, Carretti et al., 2013].

Figure 8: The same gamma-ray observations of the Milky Way as shown in Fig 3 and 5, with the contrast stretched and the bright sources masked out, showing diffuse emission on the left due to $\pi^0$ decay and emission from cosmic rays interacting with ISM, and on the right are the Fermi bubbles after the diffuse emission on the left is removed [NASA/DOE/Fermi LAT Collaboration].
5 Conclusion

The radiation of low intensity $\gamma$-rays is fairly common in the Milky Way - but very high energy occurrences are needed to produce any $\gamma$ radiation. Stars, pulsars, black holes, dark matter, and cosmic rays all have conditions that create energetic interactions needed to be a $\gamma$-ray emitter in our galaxy. Observations of the Galactic centre are ideal for looking at $\gamma$ rays, and can give insight as to previous activity in the Milky Way.

6 References


