CAN ASTROPHYSICAL GAMMA-RAY SOURCES MIMIC DARK MATTER ANNIHILATION IN GALACTIC SATELLITES?

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ABSTRACT

The nature of the cosmic dark matter is unknown. The most compelling hypothesis is that dark matter consists of weakly interacting massive particles (WIMPs) in the 100 GeV mass range. Such particles would annihilate in the Galactic halo, producing high-energy gamma rays that might be detectable in gamma-ray telescopes such as the Gamma-Ray Large Area Space Telescope (GLAST). We investigate the ability of GLAST to distinguish between WIMP annihilation sources and astrophysical sources. Focusing on the Galactic satellite halos predicted by the cold dark matter model, we find that the WIMP gamma-ray spectrum is nearly unique; separation of the brightest WIMP sources from known source classes can be done in a convincing way by including spectral and spatial information. Candidate WIMP sources can be further studied with imaging atmospheric Cerenkov telescopes. Finally, Large Hadron Collider data might have a crucial impact on the study of Galactic dark matter.

Subject headings: dark matter — elementary particles — Galaxy: halo — gamma rays: theory

1. INTRODUCTION

It is now firmly established that the majority of matter in the universe is nonbaryonic. Evidence for this standard cosmology includes the microwave background anisotropies (Spergel et al. 2006) and the power spectrum of density fluctuations on galactic scales (Tegmark et al. 2006). The “dark matter” is of unknown composition, but indirect evidence from particle physics and cosmology indicates that it is likely to consist of weakly interacting massive particles (WIMPs) in the mass range 30 GeV to 3 TeV. Such particles would be expected to annihilate slowly in galactic halos. In most WIMP models, a large fraction of the annihilation radiation is expected to be gamma rays from the decays of the $\pi^0$ meson, produced copiously in any energetic interaction involving hadrons.

In the cold dark matter paradigm (Blumenthal et al. 1984; Peebles 1984), it is well known that structure forms hierarchically: the dark halos of galaxies such as the Milky Way are expected to contain large numbers of subhalos. For WIMPs, the subhalo mass spectrum is expected to extend down to $10^{-6} M_\odot$ (Green et al. 2005; Diemand et al. 2005). The substructure is expected to be nearly isotropic; thus, annihilation in the subhalos can be away from the Galactic plane, where astrophysical sources are concentrated.

The brightest source of WIMP annihilation radiation is expected to be the Galactic center (GC), where the WIMPs are most concentrated. The H.E.S.S. collaboration has concluded that dark matter annihilation radiation is at most a small fraction of the emission coming from the GC above 100 GeV (Aharonian et al. 2006). The MAGIC collaboration has confirmed these results (Albert et al. 2006). To explain these data in terms of dark matter annihilation, WIMPs of order 10 TeV mass would be required. We will proceed with the plausible assumption that the GC emission is predominantly astrophysical. In fact, it has been shown that there is only a narrow window in which dark matter annihilation could be discovered at the GC, given the H.E.S.S. source and its extrapolation below 100 GeV (Zaharijas & Hooper 2006). This emphasizes the point that Galactic satellites may be the most promising sources of WIMP annihilation radiation.

Many authors have discussed the possibility of annihilations in Galactic substructure (Bergström et al. 1999; Baltz et al. 2000; Calcáneo-Roldán & Moore 2000; Tasitsiomi & Olinto 2002; Stoehr et al. 2003; Taylor & Silk 2003; Evans et al. 2004; Aloisio et al. 2004; Koushiappas et al. 2004; Bi 2006; Diemand et al. 2007). In this Letter, we will illustrate that WIMP annihilation sources are distinguishable from all known (observed) astrophysical source classes. The detection of a steady, extended high-latitude source with a WIMP annihilation spectrum (e.g., by the GLAST satellite) would provide strong evidence that the dark matter in the Galaxy actually consists of particles in the 100 GeV mass range, a crucial piece of the dark matter puzzle.

2. GAMMA RAYS FROM HADRONIC INTERACTIONS

Collisions of relativistic hadrons, such as when cosmic-ray protons impinge on the interstellar medium (ISM), are typically inelastic. Energy is lost mostly to $\pi^+, \pi^0, \pi^-$ mesons, in roughly equal numbers. The decays of the $\pi^0$ mesons dominate the gamma rays from hadronic interactions. The $\pi^0$ has a mass $m_\pi = 135.0$ MeV, and it has two common decay modes: $\pi^0 \to 2\gamma$ (98.8%) and $\pi^0 \to e^+e^-$ (1.2%) with rare modes contributing less than 0.01%. As a pseudoscalar particle, it decays isotropically. The photons emitted in $\pi^0 \to 2\gamma$ have energies of $E_\gamma = m_\pi/2 = 67.5$ MeV in the $\pi^0$ rest frame. In the lab frame, the energies are $E_\gamma = E_\gamma (1 \pm \beta \cos \Theta_{CM})$. The isotropy of the decay implies that $\cos \Theta_{CM}$ is uniformly distributed, and thus the spectrum $dN/dE$ is constant between the minimum and maximum energies $E_{min,max} = E_\gamma (1 \pm \beta)$. The spectrum $dN/dE(\ln E)$ is symmetric about $\ln E_\gamma$ because $E_{min}/E_0 = E_\gamma/E_n$. The observed spectrum from a source will have this property if the pion distribution is isotropic, true for both WIMP annihilation and cosmic-ray interactions.

The photon spectrum from a single pion energy must be convolved with the pion spectrum. We consider the process

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3 There is a range of predictions for the annihilation rate at the GC. Baryons are crucial: a massive bar can disrupt the central cusp, while adiabatic contraction can strengthen it. Satellites are simpler as their baryons cannot cool. The GC brightness is thus decoupled from the brightness of satellites.
$\chi \chi \rightarrow b\bar{b}$, the annihilations of pairs of self-conjugate dark matter particles to pairs of $b$ quarks. The process is nonrelativistic, giving monochromatic quarks with energy $E_q = m_\chi$. The quarks each form “jets” dominated by $\pi$ mesons. In Figure 1 we plot the photon spectra from annihilations as calculated by DarkSUSY (Gondolo et al. 2004), which uses results from Pythia (Sjostrand et al. 2006). The spectrum is universal: even $\chi \chi \rightarrow W^+W^-$ or $Z^0Z^0$ gives similar results. Only the $\chi \chi \rightarrow \tau^+\tau^-$ channel differs appreciably (Cesarini et al. 2004; Fornengo et al. 2004; Hooper & Taylor 2006), but this is difficult to arrange for WIMPs from supersymmetry.

3. DETECTABILITY OF GALACTIC DARK MATTER SATELLITES

The GLAST satellite (Atwood 1994; Bloom 1996; Gehrels & Michelson 1999) is well suited to measuring gamma rays from dark matter annihilations. It has an effective area of $\approx 1$ m$^2$, a solid angle acceptance of $\approx 3$ sr, and a point-spread function (PSF) of 0.4$''$ at 1 GeV energy. It will measure gamma-ray energies between 20 MeV and 300 GeV. Most data will be taken in survey mode, mapping the sky with equal coverage with a large duty cycle. The exposure to any source will reach roughly $3 \times 10^{11}$ cm$^2$ s in a 5 year mission.

We have estimated the number of Milky Way dark matter satellites observable by GLAST. The calculation was performed with the semianalytic method of Taylor & Babul (2004, 2005a, 2005b). The satellite mass distribution has the expected $dN/dM \propto M^{-2}$ (Ghigna et al. 1998), cutting off below $10^6 M_\odot$ due to computational limitations. The spatial distribution of satellites is roughly spherically symmetric about the Galactic center and extends well beyond the solar orbit; thus, the dark matter satellites are located mostly out of the Galactic plane. Individual sources have NFW density profiles (Navarro et al. 1997), with central cusps. Satellites with steeper profiles (e.g., Moore et al. 1999), would be easier to detect. We find that the brightest sources have masses in the $10^6$–$10^8 M_\odot$ range. These brightest sources have tidal radii of order 100 pc, typically corresponding to $1^{\circ}$ on the sky. We note that most of these objects are severely stripped. They have scale radii $r$ much larger than their tidal truncation radii; thus, they have nearly pure $r^{-1}$ density profiles out to $r = r_t$.

The surface brightness in gamma rays is proportional to the parameter $J \propto \rho^2 dr$ (Bergström et al. 1998). For a stripped NFW clump, at a fixed angular distance from its center, $J \propto M^2 r_t^4 D^2$, where $D$ is the distance. If the mass spectrum of clumps is $dN/dM \propto M^{-1}$ and the tidal radius $r_t \propto M^{1/3}$. Our simulations indicate that $\alpha \approx 1$ and $\beta \approx 1/2$; thus $J \propto M^{1/3}$. Lower mass clumps are brighter, but they appear smaller ($\theta \approx r_t/D \propto M^{2/3} \propto M^{1/3}$). Less massive clumps would be seen as point sources. These results are sensitive to $\alpha$ and $\beta$; thus extrapolations are difficult.

As a fiducial case, we assume a WIMP mass of 100 GeV and an annihilation cross section to $b\bar{b}$ of $\langle \sigma v \rangle = 1.6 \times 10^{-26}$ cm$^3$ s$^{-1}$, giving 14.2 photons per annihilation above 1 GeV. Assuming a 5 year GLAST mission, and integrating a $1^{\circ}$ radius around the source, the number of background counts is 375 (based on the EGRET extragalactic background; Sreekumar et al. 1998). The typical brightest clump has $\langle J \rangle (1^{\circ}$ radius) $= 1400$. For an example of such an object, take $2 \times 10^9 M_\odot$, 3 kpc distant, tidal radius 50 pc, thus subtending $1^{\circ}$ on the sky. The number of signal counts above 1 GeV within $1^{\circ}$ for 30, 60, 100, 150, 200, and 300 GeV WIMPs is 3450, 1680, 900, 520, 345, and 190, respectively. The number of detectable dark matter satellites is shown in Figure 2.
4. ASTROPHYSICAL SOURCES

A pure dark matter Galactic satellite has four distinguishing characteristics: hadronic spectrum from monochromatic quarks, spatial extent, lack of variability, and no emission at other wavelengths except for very diffuse inverse Compton and synchrotron (Baltz & Wai 2004). We will focus on the energy spectrum, but we note that a satellite with an NFW profile has a brightness proportional to \( \frac{1}{r} \), meaning equal flux in equal width annuli. With the 0.4\(^{\circ}\) PSF of GLAST above 1 GeV, and the typical 1\(^{\circ}\) size, we expect that the spatial extent should be detectable. Naively, emission between \( r = 0.5^{\circ} \) and 1\(^{\circ}\) has 58% of the total significance.

To mimic a Galactic satellite, a source would need to have a broken power-law spectrum, no counterparts in other wavelengths, and degree scale extended emission constant in time. Each of these is exhibited by known sources, but none exhibits them all. A class of such sources would need to have identical spectra (as measured), as dark matter satellites would.

In Figures 3–5 we plot the spectrum of the typical brightest clump (\( J = 1400 \)) with 30, 100, and 200 GeV WIMPs together with fits for several astrophysical source classes. The 1 \( \sigma \) errors for GLAST are shown as shaded boxes. In Figure 2 we illustrate the detection significance required to distinguish dark matter from molecular clouds and pulsars.

The gamma-ray spectrum from molecular clouds is generated by cosmic-ray protons, which have a featureless power-law spectrum over many decades in energy. This is exactly what is plotted with dotted lines in Figure 1. The long dashed lines in Figures 3–5 show the best-fit molecular cloud spectra, ruled out at high confidence in each case. Gamma rays from molecular clouds are expected to be extended and nonvariable; it would be comforting to rule out counterparts, e.g., CO emission. In fact, GLAST is likely to detect extended, high-latitude molecular clouds (Torres et al. 2005).

Gamma-ray pulsars are potentially the most problematic of the astrophysical sources. Their spectra can be parameterized as \( dN/dE \propto E^{-\Gamma} \exp\left[-(E/E_0)^c\right] \) (Nel & de Jager 1995). The few known examples have \( \Gamma > 4/3 \). In fact, most models for gamma-ray pulsars require this (e.g., the outer gap model; Romani 1996), but \( \Gamma \to 2/3 \) is in principle possible.

The short dashed lines in Figures 3–5 show the best-fit gamma-ray pulsar spectra. The \( \Gamma = 4/3 \) spectrum is ruled out except in the 200 GeV case, where it is consistent at the 8% level. Gamma-ray pulsars are potentially the most problematic of the astrophysical sources. Their spectra can be parameterized as \( dN/dE \propto E^{-\Gamma} \exp\left[-(E/E_0)^c\right] \) (Nel & de Jager 1995). The few known examples have \( \Gamma > 4/3 \). In fact, most models for gamma-ray pulsars require this (e.g., the outer gap model; Romani 1996), but \( \Gamma \to 2/3 \) is in principle possible.

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level. If the low-energy slope $\Gamma \rightarrow 1$, the spectra become nearly impossible to disentangle for any WIMP mass.

Gamma-ray pulsars tend to have multiwavelength counterparts and also tend to be near the Galactic plane. A notable exception is 3EG J1835+5918, which is located at high latitude, but does have a faint X-ray counterpart (Halpern et al. 2002). The well-known radio-quiet gamma-ray pulsar Geminga is located within $5^\circ$ of the Galactic plane.

The variability of the pulsar is difficult to determine in a blind search of the period-period derivative plane. To mimic an extended Galactic satellite, a cluster of pulsars would be required, with no counterparts in other wavelengths.

Blazars are variable point sources with a power-law gamma-ray spectrum, and have counterparts. They contradict all four necessary qualities of dark matter satellite emission.

5. DISCUSSION

We have shown that the brightest dark matter satellites seen by GLAST should be distinguishable from other known types of astrophysical sources, for WIMPs less massive than about 150 GeV and cross sections $\sigma v = 1.6 \times 10^{-26} \text{ cm}^2 \text{ s}^{-1}$. Sub-substructure could enhance these signals by a factor of a few (Diemand et al. 2007), extending the accessible masses and cross sections. Dimmer sources (extended only, to minimize pulsar contamination) could be stacked, improving the discrimination. Any sources mimicking dark matter annihilation would be very interesting and would be compelling targets for study in a multiwavelength campaign.

Dark matter sources are excellent targets for imaging atmospheric Cerenkov telescopes (IACTs). The mass of the WIMP must be above the IACT analysis threshold, at the present time around 100 GeV. The sensitivity of IACTs is currently limited by the charged particle background.

A follow-up campaign of 500 hr with an IACT of 0.2 km$^2$ on our brightest clump, taking the 100 GeV model, can provide a $5 \sigma$ detection of line emission from the process $\chi \chi \rightarrow \gamma \gamma$, for a branching ratio $B = 1.2\%$. This assumes 99% rejection of hadrons and 15% energy resolution. If the hadron rejection were improved by a factor of 10, the electron background dominates and line sensitivity improves to $B = 0.005$. If the electron background were also eliminated, the extragalactic gamma-ray background would limit the sensitivity to $B = 0.0003$. The predicted branching ratio is $B \sim 0.001$. Obviously, the detection of a line at these energies would demonstrate the existence of particle dark matter.

The Large Hadron Collider (LHC) may discover a candidate WIMP and measure its mass at the 10% level on a timescale that matches the GLAST program. A simple estimate shows that GLAST can constrain the mass at the 25% level, for a 100 GeV WIMP. If the GLAST and LHC mass estimates match, the WIMP hypothesis would be greatly strengthened. With strong evidence for particle dark matter in hand, including accelerator measurements of cross sections (Baltz et al. 2006), it would become possible to map the Galactic dark matter in the gamma-ray sky.

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