DENSE GAS CLOUDS AND THE UNIDENTIFIED EGRET SOURCES

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ABSTRACT

Cold, dense gas clouds have been proposed as a major component of Galactic dark matter; such clouds can be revealed by the gamma-ray emission that arises from cosmic rays interacting with the gas. If this dark matter component is clustered, then highly luminous GeV sources result, preferentially at low-to-mid Galactic latitudes, where they lie within the cosmic-ray disk. The predicted emission for such clusters is steady, continuum emission with peak power emerging at several hundred MeV. These sources would not have obvious counterparts at other wavelengths and are thus of interest in connection with the Unidentified (UID) EGRET sources. Here we present a Monte Carlo simulation of the gamma-ray source population due to cold gas clouds, assuming a cold dark matter–like mass spectrum for the clustering. We find that ~280 EGRET sources are predicted by this model, with a median Galactic latitude of 12° for the population and a median angular size of 2°/2. The latitude and size distributions are consistent with the UID EGRET source data, but the source counts are clearly overpredicted. On the basis of these results we propose that clusters of cold gas clouds comprise the majority population of the observed UID EGRET sources. Our interpretation implies that there should be microwave counterparts to most of the UID sources and will thus be strongly constrained by data from the present generation of microwave anisotropy experiments.

Subject headings: cosmic rays — dark matter — galaxies: halos — gamma rays: observations — ISM: clouds

1. INTRODUCTION

The nature of the Unidentified (UID) EGRET sources (Hartman et al. 1999) is one of the most interesting puzzles in contemporary high-energy astrophysics. This puzzle persists primarily because of the dimensions—typically of order a degree—of the gamma-ray error boxes; large uncertainties in the source position prohibit deep searches for counterparts at other wavelengths. We know, however, that this is only part of the problem; in some cases the EGRET source is bright enough that it can be located quite accurately, yet still no clear counterpart can be found (e.g., Mirabel et al. 2000; Reimer et al. 2001).

The majority of the discrete sources detected by the EGRET instrument are UID sources (Hartman et al. 1999); it is not clear at present whether they are fundamentally similar to the known GeV emitters or whether they represent an entirely new population. Because the UID sources are predominantly located at low-to-mid Galactic latitudes, they must be a Galactic population. This rules out one of the major classes of known discrete celestial GeV gamma-ray sources, namely, the flat-spectrum radio quasars, as these are extragalactic and hence isotropically distributed on the sky. Much attention has therefore focused on the possibility that the UID sources are related to massive stars and their evolutionary endpoints. In particular, there has been intense interest in young pulsars as a contributor to the UID population (e.g., Bailes & Kniffen 1992; Kaaret & Cottam 1996; Roberts, Romani, & Johnston 2001; Grenier & Perrot 2001); several of the identified GeV sources are young pulsars (Hartmann et al. 1999). However, the observed latitude distribution of the UID sources is too broad to be readily compatible with young pulsars (Yadigaroglú & Romani 1997). Supernova remnants (Sturner, Dermer, & Mattox 1996; Torres et al. 2003), molecular clouds, and massive star clusters (Montmerle 1979; Benaglia et al. 2001) share this difficulty; but Gehrels et al. (2000) have noted that the sky distribution of UID sources is consistent with a strong contribution from objects in Gould’s belt, thus supporting a connection with massive stars.

Given the difficulty of detecting counterparts to the UID EGRET population, it is natural to consider the possibility that these sources may be connected with the dark matter problem. The currently popular cosmological model, the cold dark matter (CDM) model (e.g., Peebles 1993), stipulates that the dark matter is composed of weakly interacting particles; it is possible that these particles are massive—i.e., they are weakly interacting, massive particles (WIMPS)—and could yield gamma rays by annihilation or decay. This possibility has been explored by many authors, e.g., Calcáneo-Roldán & Moore (2000) and Bergström, Edsjö, & Gunnarsson (2001).

There are of course other types of dark matter. Of particular interest in the present context is baryonic dark matter in the form of cold, dense gas clouds; unlike diffuse gas, cold, dense clouds are difficult to detect directly (Pfenniger, Combes, & Martinet 1994; Gerhard & Silk 1996; Combes & Pfenniger 1997; Walker & Wardle 1999). There are many astrophysical motivations for considering dark matter in this form, ranging from the properties of late-type galaxies (Pfenniger et al. 1994; Walker 1999) to observations of radio wave scintillation (Henriksen & Widrow 1995; Walker & Wardle 1998) and the “blank-field” SCUBA sources.

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(Lawrence 2001). Indirect constraints—from the small amplitude of fluctuations in the cosmic microwave background (CMB) and from big bang nucleosynthesis—are generally supposed to exclude any significant amount of baryonic dark matter (e.g., Turner & Tyson 1999), but these arguments are not entirely free of loopholes (Hogan 1993; Walker & Wardle 1999), and direct constraints are desirable. There is not yet any direct observational evidence that excludes a substantial fraction of the Galactic dark matter being in the form of cold, dense gas clouds (Pfenniger et al. 1994; Gerhard & Silk 1996; Walker & Wardle 1999; Rafikov & Draine 2001; M. Ohishi, M. Mori, & M. A. Walker 2003, in preparation; Walker & Lewis 2003). But the key motivation here for considering this form of dark matter is that gas clouds are expected to emit gamma rays if they reside in the cosmic-ray disk (e.g., Bloemen 1989), and any unexplained gamma-ray flux might therefore be a signature of dark matter in this form (De Paolis et al. 1995; Kalberla, Shchekinov, & Dettmar 1999; Sciama 2000). The Galactic gamma-ray halo reported by Dixon et al. (1998) has, for example, been interpreted in these terms (De Paolis et al. 1999). The low mass (∼10⁻⁴ Mₘₜₜ) of the individual clouds renders them undetectable by EGRET when they exist in isolation (see § 5). However, clustering is ubiquitous in gravitating systems, and we therefore consider the possibility that the UID EGRET sources are simply clusters of cold, dense gas clouds.

The present paper is organized as follows: we begin by describing the model we have employed for the distribution of cold gas clouds (§ 2) and the emission that is expected from the gas as a result of cosmic-ray interactions (§ 3); our model cosmic-ray distribution is given in § 4; we present the results of our Monte Carlo simulation in § 5 and then compare these results with the EGRET data in § 6.

2. DARK MATTER MODEL

To proceed with a calculation we need to specify a model for the clustering and distribution of the dark matter. The success of the modern structure formation paradigm, exemplified by the CDM model (e.g., Blumenthal et al. 1984; Davis et al. 1985; Peebles 1993), argues that any acceptable model must possess clustering properties that are similar to those of CDM in order to match the data on a large-scale structure. In CDM simulations it is found that the dark matter within individual galaxy halos is clustered into minihalos, with roughly equal contributions to the total dark matter density being made by all minihalo mass scales (Kauffmann, White, & Guideroni 1993; Moore et al. 1999; Klypin et al. 1999)—i.e., dn/dM ∝ M⁻²—for minihalos of mass M and number density n. Following Walker, Ohishi, & Mori (2003, hereafter WOM03), we adopt this mass spectrum for our calculations, spanning the minihalo mass range 0.1 ≤ M/Mₘₜₜ ≤ 10¹⁰. We further assume that all of the Galactic dark matter is in the form of cold gas clouds, clustered into minihalos. Numerical simulations of structure formation typically show only ∼10% of the dark matter within a halo to be clustered into minihalos (Ghigna et al. 1998; Klypin et al. 1999). However, these simulations do not have the resolution required to find low-mass (M < 10⁸ Mₜₜ) minihalos and are relevant to only the top 20% (mass fraction) of our adopted spectrum. Assuming that the true clustering spectrum does indeed extend to M < 10⁸ Mₜₜ, we thus expect that the total mass fraction in minihalos is actually several times larger than is revealed by simulations. We have therefore adopted the extreme model in which all of the dark matter is clustered; this has the virtue of being a limiting case.

The adopted minihalo mass spectrum is assumed to be the same throughout the Galaxy, but the normalization (i.e., total number density of minihalos) varies in direct proportion to the mean dark matter density of the Galaxy. Gas clouds are a collisional form of dark matter, so that an initially singular isothermal halo develops a core whose radius increases with time (Walker 1999). Simple calculations of this evolution lead to a preferred value for the column density of the individual gas clouds of Σ ≈ 140 g cm⁻² and hence a preferred model for the Galactic dark matter density distribution. We adopt this model, namely, an isothermal sphere, with a circular speed of 220 km s⁻¹ and a core radius of 6.25 kpc (Walker 1999).

The density profile of the individual minihalos themselves is also of some interest to us, in that it determines the apparent structure of the gamma-ray sources. At present there is little motivation for a detailed appraisal of these properties. The key point, however, is that the minihalos are not expected to be pointlike gamma-ray sources, and we are therefore interested in estimating their sizes. We follow WOM03 in assuming (see Ghigna et al. 1998; Moore et al. 1999) that the minihalos are tidally truncated at perigalacticon, with the location of the latter estimated as one-half of the Galactocentric radius of the minihalo. This leads to gamma-ray sources with estimated angular sizes of order degrees.

3. GAMMA-RAY EMISSIVITY

For high column density gas clouds, predicting the effects of cosmic-ray bombardment is more complicated than that for diffuse gas because the cosmic-ray spectrum is substantially modified by transport through the cloud (Kalberla et al. 1999; Sciama 2000). Scattering and absorption of the emergent gamma rays is similarly important. We have therefore used the Monte Carlo event simulator GEANT⁴ to estimate the gamma-ray spectrum resulting from cosmic-ray bombardment of dense gas clouds (M. Ohishi et al. 2003, in preparation). By using GEANT we are able to study the transport of cosmic rays into dense gas clouds, and their resulting gamma-ray emission, with all relevant interactions included. We employ the results of GEANT simulations for clouds of mean column density 100 g cm⁻², this being the closest simulated case to our preferred value of Σ (§ 2). For the most part we shall only need the integrated gamma-ray emissivity of the gas clouds. In the solar neighborhood we estimate the greater than 100 MeV emissivity due to cosmic-ray hadrons (mainly protons) to be Jₛ = 5.1 × 10⁻² photons g⁻¹ s⁻¹, while that due to cosmic-ray electrons is Jₑ = 5.2 × 10⁻³ photons g⁻¹ s⁻¹ (M. Ohishi et al. 2003, in preparation). Here we have adopted the median cosmic-ray proton spectrum of Mori (1997) and the cosmic-ray electron spectrum of Skibo & Ramaty (1993). The total emissivity is thus estimated to be J = J₊ + Jₑ = 5.6 × 10⁻² photons g⁻¹ s⁻¹.

⁴ Information on the Monte Carlo event simulator GEANT can be found at http://wwwinfo.cern.ch/asd/geant.
4. COSMIC RAYS

Most of our information on the Galactic cosmic-ray spectrum comes from direct observation of energetic particles in the solar neighborhood, and we know very little about the spectrum at other locations in the Galaxy. Although it is possible to construct theoretical models of the cosmic-ray spectrum and distribution throughout the Galaxy, based on assumed sources, sinks, and diffusive particle propagation (e.g., Porter & Protheroe 1997; Strong, Moskalenko, & Reimer 2000), such models introduce an additional layer of complexity that is unwarranted in the present context. Here we adopt the simple assumption that the shape of the cosmic-ray spectrum is the same throughout the Galaxy.

It then remains to specify the cosmic-ray energy density as a function of position in the Galaxy. Webber, Lee, & Gupta (1992, hereafter WLG92) constructed numerical models of cosmic-ray propagation in the Galaxy; they did not give any analytic forms for their model cosmic-ray distributions, but an appropriate analytic approximation can be deduced from the results that they obtained. They found that the cosmic-ray radial distribution reflects, in large part, the radial dependence of cosmic-ray sources, with a modest smoothing effect introduced by diffusion. We have therefore adopted WLG92’s preferred model (their model 3) for the radial distribution of sources as our model for the radial distribution of cosmic rays.

The various spectra of cosmic-ray isotope ratios considered by WLG92 favor models in which the diffusion boundaries are in the range 2–4 kpc above and below the plane of the Galaxy. We adopt the midpoint of this range. WLG92 do not give a simple functional form for the vertical variation of the Galaxy. We adopt the midpoint of this range. WLG92 do not give a simple functional form for the vertical variation of cosmic rays within this zone, so we have simply assumed an exponential model: \( \exp(-|z|/h) \). We know that in WLG92’s models the cosmic-ray density is fixed at zero at the diffusion boundaries, and consequently, the scale height of the exponential should be approximately half of the distance to the diffusion boundary, i.e., \( h \approx 1.5 \) kpc.

These considerations lead us to the model cosmic-ray density distribution \( U(R, z) \),

\[
U = \left( \frac{R}{R_0} \right)^{0.6} \exp \left( \frac{R_0 - R}{\varrho} - \frac{|z|}{h} \right),
\]

in terms of cylindrical coordinates \( (R, z) \). Here \( R_0 \approx 8.5 \) kpc is the radius of the solar circle, while \( \varrho = 7 \) kpc and \( h = 1.5 \) kpc; \( U_\odot = U(R_0, 0) \) is the cosmic-ray density in the solar neighborhood. This distribution has the character of a disk with a central hole.

5. RESULTS

Using the model described above, we simulated \( \sim 2 \times 10^8 \) halos with masses \( 10^2 \leq M/M_\odot \leq 10^{10} \) located within 50 kpc of the Galactic center. The model minihalo mass spectrum that we utilized extends to lower masses (0.1 \( M_\odot \)); these very mini halos (picohalos?) were not included in the simulation because a negligible fraction of them can be detected (see later in this section). By the same token, the individual gas clouds themselves \( (M \sim 10^{-4} M_\odot) \) are not expected to be detectable by EGRET. In particular, if all of the dark matter is assumed to be in a spherical halo of unclustered clouds, then the closest example to the Sun should lie at a distance of order 0.1 pc and have a flux of order \( 7 \times 10^{-9} \) photons cm\(^{-2}\) s\(^{-1}\) above 100 MeV; this is roughly an order of magnitude below the detection limit of EGRET.

Although the dark halo of the Galaxy extends to very large radii (\( \geq 50 \) kpc), minihalos with Galactocentric radii greater than 50 kpc are typically undetectable because of the low cosmic-ray energy density at these radii. The total mass of dark matter simulated is approximately \( 3.3 \times 10^{11} M_\odot \); this is only 8/11 of the total amount of dark matter within the simulated volume, with the remaining 3/11 being made up of clusters in the mass range \( 10^{-1} \leq M/M_\odot < 10^2 \).

We find that a fraction \( \sim 1.5 \times 10^{-6} \) of the simulated minihalos have a predicted photon flux above 100 MeV of more than \( F = 7 \times 10^{-8} \) photons cm\(^{-2}\) s\(^{-1}\), thus placing them above the approximate EGRET threshold (cf. Gehrels et al. 2000). In other words, the simulations yield \( \sim 280 \) sources bright enough that they should appear in the EGRET catalog. The source counts as a function of flux are shown in Figure 1; the relation is clearly flatter than the usual Euclidean result \( (N \propto S^{-3/2}) \) and at low flux levels is well approximated by \( N \propto S^{-1} \).

The locations of the synthetic sources on the sky are shown in Figure 2, where it can be seen that although they...
sources that lie above the EGRET flux limit. The median value is $5 \times 10^6 M_\odot$.

The competition between increasing minihalo number density and declining luminosity toward lower minihalo masses results in a characteristic (median) mass of $5 \times 10^6 M_\odot$ for the detectable sources. In the vicinity of the Sun, a minihalo of this mass is expected to have a luminosity of approximately $8 \times 10^{34}$ ergs s$^{-1}$ in photons of energy above 100 MeV. This result is in accord with the analysis of the UID EGRET source population by Kanbach et al. (1996), who concluded that their typical luminosity is $\sim 10^{35}$ ergs s$^{-1}$. The median line-of-sight distance for the minihalos with flux greater than the EGRET detection limit is 3.9 kpc.

Bearing in mind that both active galactic nuclei and pulsars are effectively pointlike gamma-ray sources, the nontrivial angular size predicted for the gamma-ray emission from dark minihalos is an important feature of the model. We characterize the size of the sources by $\theta_t$, the tidal radius of the minihalo; this is the radius that encloses all of the flux from the model source. We compute $\theta_t$ using the same procedure as WOM03. For a singular isothermal sphere, the surface brightness is $I \propto 1/\theta$ at all radii, and we expect roughly half of the flux to be contained within $\theta_t/2$. The median value of the tidal radius is $\langle \theta_t \rangle = 2^{/2}$ for sources detectable by EGRET. The full distribution of $\theta_t$ is shown in Figure 4.

Intrinsic source confusion, i.e., the regime where sources are so numerous that they overlap on the sky, becomes a major problem in the region around the Galactic center. Within 10° latitude/longitude of the Galactic center (an area of roughly 400 deg$^2$) we find 32 sources, covering about 100 deg$^2$ (the sources are smaller than average). This figure is an overestimate in the sense that our model predicts too many sources—see § 6. With more sensitive instrumentation, having a lower flux limit, intrinsic source confusion becomes a major issue, as the minihalo population covers the entire sky (WOM03).

6. COMPARISON WITH OBSERVATIONS

It is clear that the model we have presented predicts too many EGRET sources. The entire EGRET source list contains only about as many sources as our simulation predicts, and many (~40%) of the cataloged sources are considered to be identified. Furthermore, we must expect that there will be many examples of known types of gamma-ray sources, such as pulsars, among the UID EGRET sources, implying that our model overpredicts the source count by a factor $\gtrsim 2$. However, it must be acknowledged that the model we have presented involves substantial extrapolation into poorly charted territory and is therefore illustrative, not definitive. There are, for example, considerable uncertainties in the cosmic-ray distribution model in the shape of the Galaxy’s dark halo and in the mass spectrum of the clustering. In addition, we can immediately point to one aspect of the dark matter model that leads to an overprediction of the source counts; we have assumed that all of the dark matter in the Galactic halo is bound into minihalos (§ 2; WOM03), but this cannot be the case. Even if all the dark matter were initially in minihalos, the process of tidal stripping will gradually unbind material, leading to a significant fraction in the form of dark matter “streams.” Considering these uncertainties, we recognize that the overprediction of source counts is not a fundamental deficiency of the model.

Other basic features of the UID source population can be used to gauge the success of the model: the distribution on the sky, spectra, variability, angular structure, and observations made in other wave bands. We now address each of these aspects in turn.

6.1. Sky Distribution

The model correctly predicts a preponderance of sources at low-to-mid Galactic latitudes, with about the right median latitude (12°) for the population. However, it does
not exhibit the two-component (thin-disk plus thick-disk) source population that the data suggest (Gehrels et al. 2000).

Figure 2 shows a relatively strong concentration toward the Galactic center region, compared with the data. However, in this region the predicted source density is sufficiently high that source confusion is expected to be a major problem with EGRET observations of such a population. The predicted confusion is predominantly instrumental, because the sources are typically unresolved (see § 6.4). We find approximately 100 sources within \( \pm 30^\circ \) of latitude and longitude of the Galactic center—an area of roughly 3400 deg\(^2\). By comparison, the point-spread function of EGRET has a FWHM of approximately 4\(^\circ\) (see § 6.4), implying that this entire region appears, to EGRET, to be “covered” with overlapping sources.

6.2. Spectra

The spectrum predicted by the present model is given in M. Ohishi et al. (2003, in preparation); it exhibits a peak power—i.e., a peak in \( E^2 dN/dE \)—at several hundred MeV. At this point the spectrum rolls over from \( dN/dE \propto E^{-1} \) at low energies, approaching \( E^{-2.75} \) at \( E \geq 1 \) GeV.

In comparing this prediction with the data (e.g., Merck et al. 1996), there are two important points to bear in mind. First, the model gamma-ray emission spectrum is unique only by default: we do not know the cosmic-ray spectrum elsewhere in the Galaxy. The simple fact that various gamma-ray spectra are observed should therefore not be used as an argument against the present model. We note that the diffuse Galactic plane emission at \( E \geq 1 \) GeV (Hunter et al. 1997) is difficult to understand if the Galactic cosmic-ray spectrum is the same everywhere as in the solar neighborhood, suggesting that the typical cosmic-ray spectrum may be harder than measured locally (Mori 1997).

Second, the sources are predicted to be extended, with low-intensity wings on the profile typically extending out to \( \approx 2^\circ \). Although the spectrum should be uniform across the source, the fact that the point-spread function of the detector changes with energy, coupled with the low-level “wings” on the source profile, could lead to spurious estimates of spectral shapes. In particular, some fraction of the source flux will be absorbed into the estimate of the background intensity, and this fraction will vary with photon energy. These problems, coupled with the low signal-to-noise ratio of many of the UID sources, make it difficult to assess the success of the model spectral predictions.

6.3. Variability

The model we have presented involves emission that is intrinsically steady on observationally accessible timescales; it is therefore not relevant to any sources that are known to vary significantly. Most of the UID EGRET sources are not bright enough to permit strong constraints on their variability. There is no consensus in the literature regarding the variability of the UID sources; McLaughlin et al. (1996) find that only a small fraction, roughly one in six, of the UID EGRET sources are significantly variable (see also Wallace et al. 2000); in contrast, Torres et al. (2001b) suggest that the fraction may be as large as one-third in the case of low-latitude UID sources (see also Torres, Pessah, & Romero 2001a; Tompkins 1999). We note that large-amplitude variations do not sit easily with the multiple/extended source designation carried by \( \approx 50\% \) of the UID EGRET sources (Hartman et al. 1999).

6.4. Angular Structure

Although the estimated angular sizes of the detectable minihalos are large (of order degrees), the resolving power of EGRET is quite modest, with a point-spread function of 5\(^\circ\) FWHM at 100 MeV (Thompson et al. 1993). (The in-flight calibration data are consistent with the prelaunch calibration in respect to the point-spread function; Esposito et al. 1999.) The EGRET angular resolution improves with increasing energy, scaling roughly as \( E^{-0.534} \). However, if \( dN/dE \) is close to \( E^{-2} \), half of the photons contributing to a source detection are within a factor of \( \approx 2 \) of the low-energy threshold. We therefore adopt a FWHM of 4\(^\circ\) as the relevant instrumental width; sources would thus need to be at least 8\(^\circ\) across in order to be fully resolved. For an isothermal density distribution within each minihalo (§ 5), half of the total flux is contained within a diameter approximately equal to \( \theta_i \). Referring to Figure 4 we then find that only a tiny fraction of the synthetic population could be fully resolved by EGRET.

If the instrumental FWHM is comparable with the source size, then the source structure will not be resolved, but the data can nevertheless indicate that the source is extended, by virtue of the observed intensity profile being broader than the point-spread function. Most of the synthetic sources fall into this category. It is notable that half of the UID EGRET sources are recorded as extended/multiple by Hartman et al. (1999). (The two possibilities cannot be differentiated if the source structure is not fully resolved.)

6.5. Counterparts at Other Wavelengths

The basic criterion for an EGRET source to be classified as UID is that it should not have an obvious counterpart at other wavelengths. The population we have modeled clearly meets this requirement because the emission comes from dark matter. The detectability of cold, dense gas has been discussed by a number of authors: Pfenniger et al. (1993), Gerhard & Silk (1996), Combes & Pfenniger (1997), Walker & Wardle (1999), and Sciama (2000). Perhaps the simplest and most robust of expectations is that there will be thermal emission from the clouds, implying bright microwave sources coincident with the gamma-ray sources. An important point to note is that gamma-ray and microwave luminosities are both proportional to minihalo mass and cosmic-ray density; consequently, the microwave flux can be estimated simply by scaling the observed EGRET flux (Wardle & Walker 1999; Sciama 2000).

To determine the bolometric microwave flux we need only take the ratio of the thermal emissivity due to cosmic rays (\( \Gamma_0 \approx 10^{-4} \) ergs s\(^{-1}\) g\(^{-1}\); WOM03) to the gamma-ray emissivity, \( (J = J_x + J_\gamma \approx 5.6 \times 10^{-2} \) photons s\(^{-1}\) g\(^{-1}\) above 100 MeV; § 3), yielding a microwave flux of \( S \approx 1.8 \times 10^{-10} F_\gamma \) ergs cm\(^{-2}\) s\(^{-1}\). Here the gamma-ray flux above 100 MeV is \( 10^{-7} F_\gamma \) photons cm\(^{-2}\) s\(^{-1}\). The atmospheric temperature is estimated to be in the range 4.2–4.9 K, if the individual clouds have mass \( M \approx 10^{-4} \) to \( 10^{-5} M_\odot \) (WOM03). The principal remaining uncertainty then lies with the nature of the emitted spectrum; we have previously suggested a blackbody spectrum (WOM03), whereas Lawrence (2001) concludes that this is inconsistent with the observed spectrum of the blank-field
SCUBA sources (which objects he interprets in terms of cold, planetary-mass gas clouds). More generally we can take $S_\nu \propto \nu^\alpha B_\nu$, with $\alpha = 0$ for blackbody emission and $\alpha = 2$ for emission from small particles whose absorption increases in proportion to $\nu$. Lawrence (2001) concludes that the latter spectrum is consistent with the data on the blank-field SCUBA sources, provided $4.7 < T(K) < 6.4$. Here we restrict attention to two cases that adequately represent the plausible range of thermal emission spectra for the dense gas: a $T = 4.2$ K blackbody, and a $T = 4.9$ K “dusty” ($\alpha = 2$) spectrum.

Our adopted spectra differ greatly in the expected flux at radio frequencies, where we are far below the peak thermal emission—see Figure 5. At low frequencies the two spectral models can be approximated by $S_\nu \approx 4.2 \nu^2 F_\nu$ mJy (blackbody) and $S_\nu \approx 1.4 \times 10^{-2} \nu^2 F_\nu$ mJy (dust), with $\nu$ in GHz. However, even in the blackbody case, where the radio emission is relatively strong, the predicted flux would be difficult to detect because it is so extended. Taking the bright UID EGRET source 3EG J1835+5918 as an example (Hartman et al. 1999; Mirabel et al. 2000; Reimer et al. 2001) with $F_\nu \approx 7$, we find a predicted flux at 1.4 GHz of roughly 60 mJy in the blackbody case. This estimate is well above the point-source detection limit of the observations, reported by Mirabel et al. (2000), of 2.5 mJy. However, a minihalo is certainly not pointlike. In fact, it would fill the primary beam of the radio telescope and be resolved out on all but the shortest interferometeric baselines. The very extended sources predicted by the present model are expected to be difficult to detect using radio interferometers configured for high-resolution imaging.

7. DISCUSSION

Although the predicted microwave counterparts to UID EGRET sources are not expected to have been detected in the counterpart searches to date, they could be revealed in the near future by some of the various experiments designed to study anisotropies in the CMB. In particular, the Micro-wave Anisotropy Probe (MAP) satellite\(^5\) has now completed a sensitive all-sky survey at several frequencies, and the data are about to be released. Should MAP have detected the predicted microwave counterparts? The answer to this question depends on the spectrum of the emission, because all MAP frequencies are well below the thermal peak. Even considering the highest frequency channel (90 GHz), the two spectral models differ by a large factor in their predicted flux. If the emission is blackbody, then $S_\nu \approx 20 F_\nu$ Jy, but only $S_\nu \approx 0.6 F_\nu$ Jy for the “dusty” model (see Fig. 5). The point-source (i.e., single-pixel) detection limit for MAP at this frequency should be approximately 1.7 Jy (5 $\sigma$, and we have taken the CMB contribution to be roughly equal to the thermal noise of the instrument). On this basis we do not expect the typical UID sources to be detected by MAP if they have a dusty spectrum.

Even if the minihalos have a blackbody spectrum, they might not be detected by MAP, because its 0.3 pixels are substantially smaller than the predicted minihalo sizes. For an isothermal minihalo density profile, the enclosed flux varies roughly in proportion to radius. With a predicted median source radius of 2.2 $\rho_\circ$, it is evident that the largest single-pixel flux expected from a typical minihalo is not much above the MAP detection limit. Computing the peak single-pixel flux for each source in our simulation, we expect that only 40% of the predicted population would be detectable by MAP, even if the spectra are blackbodies. However, we note that sources that are individually undetected may still be useful for constraining the typical microwave/gamma-ray flux ratio of the UID EGRET population.

Other satellite and balloon-borne CMB experiments will provide robust constraints on the model we have presented, by virtue of observing close to the predicted thermal peak of the minihalos. In particular, the high-frequency instrument on board the Planck satellite\(^6\) and its prototype, the balloon-borne Archeops telescope (Benoit et al. 2002), will map the sky at 353 and 545 GHz, sandwiching the point—around 400 GHz (see Fig. 5)—where our model spectra cross. At these frequencies the predicted flux of a typical UID EGRET source ($F_\nu = 1$) is of order 30 Jy for either spectral model. By contrast, the limiting flux (5 $\sigma$) for Planck, at 353 GHz, will be 100 mJy in a single pixel and roughly 5 Jy for a source of 2.2 $\rho_\circ$ radius. (Observing at these high frequencies has the additional advantage of less confusion from the degree-scale CMB anisotropies.) Planck should therefore detect microwave counterparts to any of the UID EGRET sources in which the gamma rays arise from cosmic-ray interactions with dense gas. We note that a substantial fraction of the sky has already been mapped by the Archeops experiment (Benoit et al. 2002), and UID EGRET source counterparts might be present in the existing data. Counters are best searched for, initially, well away from the Galactic plane, as the latter region is likely to be confused at high frequencies. The Archeops team advises (F. X. Désert 2003, personal communication) that the sensitivity of their sky maps is roughly 12 Jy (1 $\sigma$) for a single pixel (20$'$) at 353 GHz. For the extended sources predicted by the present model, this experiment could therefore only detect (at 5 $\sigma$) counterparts to the brightest of the EGRET

\(^5\) Information on the MAP satellite can be found at http://map.gsfc.nasa.gov.

\(^6\) Information on the high-frequency instrument on board the Planck satellite can be found at http://sci.esa.int/home/planck.
sources, with (>100 MeV) fluxes exceeding 3 × 10^{-6} photons cm^{-2} s^{-1}.

We note that the balloon-borne MAXIMA and BOOMERANG experiments also covered frequencies close to the thermal peak of cold gas emission, but these experiments covered only ~1% of the sky (Hanany et al. 2000; Coble et al. 2003), and these data are therefore of limited utility in the present context. Ground-based studies are similarly limited to small patches of the sky, when observing at 400 GHz, but would nevertheless be helpful if the UID EGRET source population is specifically targeted for observations.

If microwave counterparts are discovered, then we will be able to study the density profiles of dark matter minihalos directly. Further to the properties noted in § 2 for the individual source profiles, we can make some generic predictions for their structure: (1) the intensity should rise to a high central peak, but there should be a core (Walker 1999) in the surface brightness profile; (2) the limb of the source should exhibit a sharp cutoff due to tidal truncation; and (3) there may be tidal streams extending along the minihalo’s orbit.

In addition to tidal streams associated with identifiable minihalos, it is expected that some minihalos have been completely disrupted by the tidal fields they have experienced. In these cases the tidal streams are not associated with a bound cluster and thus represent a distinct category of microwave/gamma-ray source predicted by the model. Shells with sharply defined edges could also appear in the microwave/gamma-ray maps, as these are a common feature of tidal debris (Hernquist & Quinn 1988; Hernquist & Spergel 1992).

The Gamma-Ray Large Area Space Telescope (GLAST)\(^7\) will provide a significant advance in our understanding of the UID sources, because GLAST will be much more sensitive than EGRET and will have better angular resolution. These improved capabilities will permit powerful tests of the model we have presented. However, the data from MAP and the balloon-borne CMB experiments will be available on a much shorter timescale than those from GLAST, and it should be possible to make considerable progress with the microwave data alone. In particular, our prediction of bright, extended thermal microwave counterparts is unique amongst existing models of the UID EGRET population.

Finally, we note that some of the UID EGRET sources are sufficiently bright that they may be detectable by ground-based TeV telescopes (Aharonian et al. 1997), even if their spectra are as steep as E^{-2.75} between the GeV and TeV bands. Studying UID sources at TeV energies may permit their nature to be discerned. For example, the extended nature of the sources predicted by the present model is unusual for gamma-ray sources, and the slightly extended (6’) TeV source in the vicinity of 3EG J2033+4118, reported by Aharonian et al. (2002), is of interest in this context.

8. CONCLUSIONS

If our Galaxy contains a significant component of dark matter in the form of cold, dense gas clouds clustered into large aggregates, some of those clusters should have been detected by EGRET. Using a CDM-like mass spectrum for the clustering, we have shown that the predicted gamma-ray source population has properties that are broadly similar to those of a large fraction of the UID EGRET sources. In particular, the Galactic latitude distribution and the source size distribution anticipated in the model find support in the EGRET data. Furthermore, the intrinsically “dark” nature of the predicted sources naturally explains most of the difficulty in finding counterparts; however, the large angular size of the clusters also plays a role, because counterpart searches to date have had poor sensitivity to approximately degree-sized sources. The total number of UID sources predicted by the model is too large, particularly bearing in mind that many of the observed UID sources are likely to be examples of known types of gamma-ray emitters. Data returned by the various CMB experiments will provide a powerful test of the interpretation we have presented; counterpart thermal microwaves should be detected from the cold gas, and the source structure should be resolved.

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\(^7\)Information on GLAST can be found at http://glast.gsfc.nasa.gov.

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