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 the Galactic dark matter; such clouds can be revealed by the gamma-ray emission which 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 $\sim 250$ EGRET sources are predicted by this model, with a median Galactic latitude of $13^\circ$ for the population, and a median angular size of $2.3^\circ$. These predictions are broadly consistent with the observed properties of the major part of the UID EGRET source population, and we therefore propose that the observed sources be interpreted as clusters of cold gas clouds. This interpretation implies that there should be microwave counterparts to the UID sources, and will thus be strongly constrained by data from the present generation of microwave anisotropy experiments.

Subject headings: galaxies: Milky Way — galaxies: halos — dark matter — gamma-rays: general — cosmic-rays: general — 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 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 focussed on the possibility that the UID sources are related to young pulsars and/or supernova remnants (e.g. Bailes and Kniffen 1992; Roberts, Romani and Johnston 2001; Grenier and Perrot 2001). However, the observed latitude distribution of the UID sources is too broad to be readily compatible with young pulsars (Yadigaroglu and Romani 1997), and supernova remnants should presumably have a similar latitude distribution. Gehrels et al (2001) have argued that the sky distribution of UID sources is
consistent with a strong contribution from objects in Gould’s Belt.

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 model (e.g. Peebles 1992), stipulates that the dark matter is composed of weakly interacting particles; it is possible that these particles are massive – i.e. they are WIMPS – and could yield gamma-rays by annihilation or decay. This possibility has been explored by many authors, e.g. Calcáneo-Roldán and Moore (2000), Bergström, Edsjö and 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 and Martinet 1994; Gerhard and Silk 1996; Combes and Pfenniger 1997; Walker and Wardle 1999). There are many astrophysical motivations for considering dark matter in this form, ranging from the properties of late-type galaxies (Pfenniger, Combes and Martinet 1994; Walker 1999), to observations of radio-wave scintillation (Henriksen and Widrow 1995; Walker and Wardle 1998), and the “Blank Field” SCUBA sources (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 and Tyson 1999), but these arguments are not entirely free of loopholes (Hogan 1993; Walker and Wardle 1999) and direct constraints are desirable. There is not yet any direct observational evidence which excludes a substantial fraction of the Galactic dark matter being in the form of cold, dense gas clouds (Pfenniger, Combes and Martinet 1994; Gerhard and Silk 1996; Walker and Wardle 1999; Rafikov and Draine 2000; Ohishi, Mori and Walker 2002; Walker and Lewis 2002). 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 and 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 \( \sim 10^{-4} M_\odot \) of the individual clouds renders them undetectable 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 organised as follows: we begin by describing the model we have employed for the distribution of cold gas clouds (§2), and the emission which 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 to 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 Cold Dark Matter (CDM) model (e.g. Blumenthal et al 1984; Davis et al 1985; Peebles 1992), argues that any acceptable model must possess clustering properties that are similar to those of CDM, in order to match the data on large-scale structure. In CDM simulations it is found that the dark matter within individual galaxy halos is clustered into mini-halos, with roughly equal contributions to the total dark matter density being made by all mini-halo mass scales (Moore et al 1999) — i.e. \( dn/dM \propto M^{-2} \), for mini-halos of mass \( M \) and number density \( n \). Following Walker, Ohishi and Mori (2002: WOM02 hereafter), we adopt this mass spectrum for our calculations, spanning the mini-halo mass range \( 0.1 < M/M_\odot < 10^{10} \). We further assume that all of the Galactic dark matter is in the form of cold gas clouds, clustered into mini-halos. Numerical simulations of structure formation typically show only \( \sim 10\% \) of the dark matter within a halo to be clustered into mini-halos (Ghigna et al 1998; Klypin et al 1999; see also Kauffmann, White and Guideroni 1993). However, these simulations do not have the resolution required to find low mass \((M < 10^8 \ M_\odot)\)
mini-halos, and are relevant to only the top 20% (mass fraction) of our adopted spectrum. Assuming that the true clustering spectrum does indeed extend to $M \ll 10^8 M_\odot$, we thus expect that the total mass fraction in mini-halos 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 mini-halo mass spectrum is assumed to be the same throughout the Galaxy, but the normalisation (i.e. total number density of mini-halos) 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 $\Sigma \simeq 140 \text{ g cm}^{-2}$, and hence a preferred model for the Galactic dark matter density distribution. We adopt this model, namely an isothermal sphere, with circular speed of 220 km s$^{-1}$, and a core radius of 6.25 kpc (Walker 1999).

The density profile of the individual mini-halos 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 mini-halos are not expected to be point-like gamma-ray sources, and we are therefore interested in estimating their sizes. We follow WOM02 in assuming (see Ghigna et al 1998; Moore et al 1999) that the mini-halos are tidally truncated at perigalacticon, with the location of the latter estimated as one half of the Galactocentric radius of the mini-halo. 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 for diffuse gas because the cosmic-ray spectrum is substantially modified by transport through the cloud (Kalberla, Shchekinov and Dettmar 1999; Sciama 2000). Scattering and absorption of the emergent gamma-rays is similarly important. We have therefore used the Monte Carlo event simulator GEANT\(^1\) to estimate the gamma-ray spectrum resulting from cosmic-ray bombardment of dense gas clouds (Ohishi, Mori and Walker 2002). 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 $\Sigma$ (§2). For the most part we shall need only the integrated gamma-ray emissivity of the gas clouds. In the solar neighbourhood we estimate the emissivity due to cosmic-ray protons to be $J = 5.14 \times 10^{-2} \text{ ph g}^{-1}\text{s}^{-1}$ above a gamma-ray energy of 100 MeV (Ohishi, Mori and Walker 2002).

4. Cosmic-rays

Most of our information on the Galactic cosmic-ray spectrum comes from direct observation of energetic particles in the solar neighbourhood, 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 and Protheroe 1997, Strong, Moskalenko and Reimer 2000), such models introduce an additional layer of complexity which 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. A simple approximate form can be deduced from the analysis given by Webber, Lee and Gupta (1992: WLG92). 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.

\(^1\)http://wwwinfo.cern.ch/asd/geant
The various spectra of cosmic-ray isotope ratios considered by WLG92 favour 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 cosmic-ray density 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. $h \simeq 1.5$ kpc.

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

$$\frac{U}{U_\odot} = \left(\frac{R}{R_0}\right)^{0.6} \exp[(R_o - R)/\varrho - |z|/h], \quad (1)$$

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

5. Results

Using the model described above, we simulated $\sim 2 \times 10^6$ halos with masses $10^2 \leq M/M_\odot \leq 10^{10}$ located within 50 kpc of the Galactic Centre. The model mini-halo mass spectrum which we utilised extends to lower masses ($0.1 \ M_\odot$); these very-mini-halos (pico-halos?) were not included in the simulation because a negligible fraction of them are detectable (see later). 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 $7 \times 10^{-9}$ ph 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 ($\gg 50$ kpc), mini-halos with Galactocentric radii greater than 50 kpc are typically undetectable because of the low cosmic-ray energy density at these radii. The total

Fig. 1.— The source counts, as a function of flux (above 100 MeV), for the simulated mini-halo population.

Fig. 2.— Sky distribution of simulated gamma-ray sources lying above the EGRET flux limit ($7 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ above 100 MeV). The size of the circle plotted for each source increases according to the source flux.
The mass distribution of the detectable mini-halos is shown in figure 3. At the high mass end the sources are typically very luminous and can be detected through most of the volume considered. At the low mass end, the luminosity is much smaller, and only the closest mini-halos are detectable. The competition between increasing mini-halo number density and declining luminosity, towards lower mini-halo 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 mini-halo of this mass is expected to have a luminosity of approximately $8 \times 10^{34} \text{erg s}^{-1}$, 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 $\sim 10^{35} \text{erg s}^{-1}$. The median line-of-sight distance for the mini-halos with flux greater than the EGRET detection limit is 3.7 kpc.

Bearing in mind that both Active Galactic Nuclei (AGN) and pulsars are effectively point-like gamma-ray sources, the non-trivial angular size predicted for the gamma-ray emission from dark
mini-halos is an important feature of the model. We characterise the size of the sources by $\theta_t$, the tidal radius of the mini-halo; this is the radius which encloses all of the flux from the model source. We compute $\theta_t$ using the same procedure as WOM02. 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 $\langle \theta_t \rangle = 2.3^\circ$, for sources detectable by EGRET. The full distribution of $\theta_t$ is shown in figure 4.

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 ($\sim 40\%$) of the catalogued sources are considered to be identified. However, it must be acknowledged that our model 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 which leads to an over-prediction of the source counts: we have assumed that all of the dark matter in the Galactic halo is bound into mini-halos (§2; WOM02), but this cannot be the case. Even if all the dark matter were initially in mini-halos, the process of tidal stripping will gradually unbind material, leading to a significant fraction in the form of dark matter “streams”. Considering these uncertainties, the model performs acceptably in its prediction of total UID source count.

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 for the population. However, it does not exhibit the two component (thin-disks plus thick-disks) source population which the data suggest (Gehrels et al 2001).

6.2. Spectra

The spectrum predicted by the present model is given in Ohishi, Mori and Walker (2002): 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 $E^{-2.8}$ at $E \gg 1 \text{ GeV}$.

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 don’t 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 $E \gtrsim 1 \text{ GeV}$ (Hunter et al 1997) is difficult to understand if the Galactic cosmic-ray spectrum is everywhere the same as in the solar neighbourhood, suggesting that the typical cosmic-ray spectrum may be harder than measured locally (Mori 1997).

Secondly, the sources are predicted to be extended, with low-intensity wings on the profile extending out to $\sim 2^\circ$, typically. 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 which is intrinsically steady on observationally accessible time-scales; it is therefore not relevant to any sources which are known to vary significantly. Most of the UID EGRET sources are not bright enough to permit strong constraints on their variability. Only a small fraction, roughly one in six,
of the UID EGRET sources have been shown to be significantly variable (McLaughlin et al 1996; Wallace et al 2000) — but see also Torres et al (2001), who suggest that the fraction may be as large as one third, in the case of low-latitude UID sources.

6.4. Angular Structure

Although the estimated angular sizes of the detectable mini-halos are large (of order degrees), the resolving power of EGRET is quite modest, with a point-spread-function of 5° Full-Width-Half-Maximum (FWHM) at 100 MeV (Thompson et al 1993). The EGRET angular resolution improves with increasing energy; however, if dN/dE is close to E−2, half of the photons contributing to a source detection are within a factor ∼ 2 of the low-energy threshold. We therefore adopt a FWHM of 4° as the relevant instrumental width; sources would therefore need to be at least 8° across in order to be fully resolved. For an isothermal density distribution within each mini-halo (§5), the predicted FWHM of the source is approximately equal to θi; referring to figure 4 we thus find that only a tiny fraction of the synthetic population could be fully resolved by EGRET.

If the instrumental FWHM is comparable to the source size its 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.) If these indications from the data are correct, then we have a vital clue as to the nature of the UID sources.

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 modelled 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, Combes and Martinet (1993); Gerhard and Silk (1996); Combes and Pfenniger (1997); Walker and 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 (Wardle and Walker 1999; Sciama 2000; Lawrence 2001). An important point to note is that gamma-ray and microwave luminosities are proportional to both mini-halo mass and cosmic-ray density; consequently the microwave flux can be estimated simply by scaling the observed EGRET flux.

To determine the bolometric microwave flux we need only take the ratio of the thermal emissivity (Γ0 ∼ 10−4 erg s−1 g−1; WOM02) to the gamma-ray emissivity (cosmic-ray protons alone contribute J ∼ 5.1 × 10−2 ph s−1 g−1 above 100 MeV; §3), yielding a microwave flux of S ∼ 2 × 10−10 Fγ erg cm−2 s−1. Here the gamma-ray flux above 100 MeV is 10−7 Fγ ph cm−2 s−1. The atmospheric temperature is estimated to lie in the range 4.2 – 4.9 K (WOM02), depending on the mass of the cloud. The principal remaining uncertainty then lies with the nature of the emitted spectrum: we have previously assumed a blackbody spectrum (WOM02), whereas Lawrence (2001) concludes that this is inconsistent with the observed spectrum of the Blank Field SCUBA sources (which he interprets as perhaps being examples of cold, planetary-mass gas clouds). More generally we can take Sν ∝ να Bν, with α = 0 for blackbody emission, and α = 2 for emission from small particles whose absorption increases in proportion to ν. Lawrence (2001) concludes that the latter spectrum is consistent with the data on the Blank Field SCUBA sources. Here we restrict attention to two cases which 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 (α = 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 Sν ∼ 4.5 ν2 Fγ mJy (blackbody) and Sν ∼ 1.4 × 10−5 ν4 Fγ mJy (dust), with ν 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 $F_{7} \approx 7$, 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 mini-halo is certainly not point-like. In fact it would fill the primary beam of the radio telescope, and would be resolved-out on all but the shortest interferometric baselines. Thus the very extended sources predicted by the present model are expected to be practically invisible to radio interferometers designed 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 Cosmic Microwave Background (CMB). In particular, the MAP satellite\(^2\), 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 of the 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 $S_{\nu} \approx 21 F_{7}$ Jy, but only $S_{\nu} \approx 0.6 F_{7}$ Jy for the “dust” model (see figure 5). The point-source (i.e. single pixel) detection limit for MAP at this frequency should be approximately 1.7 Jy (5σ, 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 mini-halos have a blackbody spectrum they might not be detected by MAP, because its 0.3° pixels are substantially smaller than the predicted mini-halo sizes. For an isothermal mini-halo density profile, the enclosed flux varies roughly in proportion to radius. With a predicted median source radius of 2.3°, it is evident that the largest single-pixel flux expected from a typical mini-halo 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 ought to be detectable by MAP even if the spectra are blackbody. However, we note that sources which 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 mini-halos. In particular, the High Frequency Instrument on the Planck satellite\(^3\) and its prototype, the balloon-borne Archeops (Benoit et al 2002), will map the sky at 353 and 545 GHz. These frequencies sandwich the point – around 400 GHz (see figure 5) – where our model spectra cross. At these frequencies the predicted flux of a typical UID EGRET source is of order 30 Jy, for either spectral model. Observing at these high frequencies has the additional advantage of less confusion from the degree-scale CMB anisotropies. We note that a substantial fraction of the sky has already been mapped by the Archeops experiment (Hamilton 2000), and UID EGRET source counterparts might be present in the existing data. Counterparts are best searched for, initially, well away from the Galactic plane as this region is likely to be confused at high frequencies.

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

In addition to tidal streams associated with identifiable mini-halos, it is expected that some mini-halos have been completely disrupted by the tidal fields they have experienced. In these cases

\(^2\)http://map.gsfc.nasa.gov

\(^3\)http://sci.esa.int/home/planck
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 and Quinn 1988; Hernquist and Spergel 1992).

The Gamma-ray Large Area Space Telescope\(^4\) (GLAST) 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 instrumentation (Aharonian et al 1997), even if their spectra are as steep as \(E^{-2.8}\) 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 arcminute) 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 which are broadly similar to those of the UID EGRET sources. In particular: the total number, latitude distribution, and size distribution anticipated in the model find support in the EGRET data. The intrinsically “dark” nature of the 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 \(\sim\) degree-sized sources. 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 in each case.

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\(^4\)http://glast.gsfc.nasa.gov
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Fig. 5.— Model mini-halo thermal spectra. The dashed line shows a blackbody spectrum at $T = 4.2$ K, and the solid line shows a dusty ($\alpha = 2$) spectrum at $T = 4.9$ K. The thermal flux ($S_\nu$) scales in direct proportion to the gamma-ray flux, and this plot is made for a gamma-ray flux of $10^{-7}$ ph cm$^{-2}$s$^{-1}$ above 100 MeV.