

Abstract  Population synthesis is used to study the contribution from unresolved sources to the Galactic ridge emission measured by EGRET. Synthesized source counts are compared with the 3rd EGRET catalogue at low and high latitudes. For pulsar-like populations, 5-10% of the emission > 100 MeV comes from sources below the EGRET threshold. A steeper luminosity function can increase this to 20% without violating EGRET source statistics. Less luminous populations can produce much higher values without being detected. Since the unresolved source spectrum is different from the interstellar spectrum, it could provide an explanation of the observed MeV and GeV excesses above the predictions, and we give an explicit example of how this could work.

Keywords  gamma rays · diffuse emission · gamma-ray sources

1 Introduction

The Galactic plane is known to be an intense emitter of X-rays and γ-rays from keV to at least 100 GeV. At X-ray energies, it has recently been claimed (Revnivtsev et al. 2006) that the 2-10 keV emission can be explained entirely by a population of weak sources, mainly CVs. Above 50 keV, unresolved sources also appear to be required to explain the hard-power law emission observed by INTEGRAL (Strong et al. 2005; Bouchet et al. 2005); AXPs and/or pulsars are potential candidates. This raises the question of the situation for γ-rays, in particular the range observed by EGRET, 30 MeV - 100 GeV. γ-ray telescopes are relatively insensitive and reveal only the ‘tip of the iceberg’ of the sources, so most of them will go undetected unless it happens that only strong sources exist in the Galaxy. Conventional wisdom is that the source contribution to the unresolved ridge emission is at the few percent level, The problem of the GeV excess in the diffuse emission compared to the expected spectrum from interstellar processes (Strong et al. 2004a), is however a hint that the emission may have other components whose contribution is also energy-dependent. The failure to explain the 1-30 MeV emission measured by COMPTEL from interstellar components is another pointer to a source population.

This topic has wide ranging implications: for example it has been claimed that the GeV excess is a signature of dark matter decay (de Boer et al. 2005), but this is only plausible if all viable alternatives are excluded, and source populations provide one important such candidate.

2 γ-ray source properties

The 3rd EGRET Catalogue contains 271 sources, including 66 well-identified extragalactic sources (AGN), leaving about 200 for the present study. A subset of these may also be extragalactic. Almost the only definite Galactic identifications are 6 pulsars (+ some other pulsar candidates) and the Crab nebula, which have isotropic luminosities $L_\gamma(>100\text{ MeV})$ ranging from $10^{37}\text{ ph s}^{-1}\times(10^{33}\text{ erg s}^{-1})$ (Geminga) to $10^{39}\text{ ph s}^{-1}\times(10^{35}\text{ erg s}^{-1})$ (Crab pulsar). A summary of γ-ray pulsar observations is given by Thompson et al. (1999). The Crab at 2 kpc is perhaps the most luminous and distant Galactic source detected, while Geminga at 160 pc the least luminous and nearest. The Vela pulsar is intermediate in distance (300 pc) and luminosity $10^{38}\text{ ph s}^{-1}\times(10^{34}\text{ erg s}^{-1})$ although it is the brightest source on the sky ($8\times10^{-6}\text{ cm}^{-2}\text{ s}^{-1}$ compared to $2\times10^{-6}\text{ cm}^{-2}\text{ s}^{-1}$ for the Crab). Other detected or candidate pulsars also lie in this luminosity range. Apart from pulsars, plausible identifications exist e.g. for the microquasars LS5039 and LSI +61 303, but these do not significantly help the present investigation. Most sources with $L_\gamma(>100\text{ MeV})<10^{33}\text{ erg s}^{-1}$ are invisible to us with present instrumentation. The data are too sparse to construct a luminosity function directly, so we leave this as a parameterized input.

1 but see critique by Bergström et al. (2008).

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We approach the problem using population synthesis, comparing the models both with source counts and the intensity of diffuse emission.\footnote{We will often refer to unresolved emission generically as ‘diffuse’ regardless of its true nature.} Comparison in various sky regions increases the discrimination power of the comparisons. Thus source counts in high-latitude regions constrain the low-luminosity, nearby source population while counts in low-latitude regions constrain the high-luminosity sources, and diffuse emission in low-latitudes constrains both low and high-luminosity populations.

As usual in such studies a major uncertainty is the spatial distribution of sources, but with plausible assumptions this can be modelled. Once the spatial distribution is assumed, the observed (source-produced) gamma-ray sky depends only on the luminosity function.

For the truly diffuse (interstellar) emission we make use of the \textit{galprop} models (\cite{Strong2004a}).

The present study is designed to be independent of the physical details of the sources, making use of, for example, theoretical gamma-ray luminosity functions of pulsars only for guidance. We do not want to restrict attention to known classes of objects. The essential input is only geometry, the inverse square law, simple luminosity functions, the EGRET source catalogue and EGRET skymap data.

### 3 Previous studies

Most previous population studies have been aimed at deducing the nature of the EGRET unidentified sources, either generally or in particular as pulsars. Although the nature of the sources is not our goal here, these studies are still relevant. A population synthesis study of the 2nd EGRET catalogue (\cite{Kanbach1996}) showed that the unidentified sources had luminosities $>100$ MeV in the range $10^{38} - 3 \times 10^{39}$ erg s$^{-1}$, with 700–3400 objects in the Galaxy. Flux distributions of EGRET unidentified sources were constructed by \cite{Reimer2001} and \cite{Gehrels2000} in attempts to deduce the properties of unidentified sources, including division by variability and angular distribution. \cite{Chen2001} made a population synthesis study of the 3EG catalogue, including disk and isotropic source distributions.

Other studies considered pulsars specifically. Very detailed physical pulsar population synthesis studies by \cite{Gonthier2002} and \cite{Gonthier2004} using their polar-cap model were aimed at establishing the relation between radio and gamma-ray properties and predicting detections for future missions like GLAST. \cite{Harding2001, Gonthier2003, Harding2004} considered the possibility that gamma-ray sources in the Gould’s Belt are nearby pulsars.

\cite{Zhang1998} proposed that pulsars can account for the diffuse GeV excess. \cite{Zhang2000} made a detailed population synthesis based on the outer-gap model, and also studied the properties of 38 low-latitude unidentified sources, proposing an a correlation with SNR and OB associations. \cite{Yadigaroglu1997} proposed that the EGRET unidentified sources are compatible with young pulsars, while in contrast \cite{Bhattacharya2003} claim they are better traced by spiral arms and molecular clouds.

In view of the uncertainty in the nature of the unidentified sources, a flexible approach to modelling is desirable, as described in this paper.

### 4 Population synthesis

A general-purpose population synthesis code has been written. Sources are assigned a density $\rho(R, z, L_\gamma)$ and sampled by standard Monte-Carlo techniques. Oversampling is used to reduce statistical fluctuations. The density is normalized to $\rho$ at $R = 8.5$ kpc, in units of sources kpc$^{-3}$. Power-law luminosity functions within given $L_\gamma$ limits can be generated. The $(R, z)$ source distribution is here based on pulsars \cite{Lorimer2004} as representative of gamma-ray sources, but other distributions are also possible and will be addressed in future work. The resulting source list is analyzed to generate differential source counts $N(S)$ and the total emission spectrum both above and below a given detection threshold. The total spectrum is then combined with interstellar emission models from \textit{galprop} (\cite{Strong2004a}). We use source counts for one energy range ($> 100$ MeV) only; it would be preferable to consider the energy-dependence of $N(S)$ but the spectral information in the available catalogues is limited. In future (e.g. for GLAST) this will be feasible. A note about beamed sources, in particular pulsars. For the present purpose a populations of randomly-oriented beamed sources is fully equivalent to a population of unbeamed sources with a lower spatial density of sources having an isotropic emission. Therefore we do not explicitly include beaming in our population synthesis.

#### 4.1 Pulsar luminosity function

We use pulsars just as an guide to the choice of luminosity function. For this we use the luminosity as a function of spin-down power $\dot{E}$: $L_\gamma \propto \dot{E}^\beta$ for which a wide spread exists in the literature depending on the model. The luminosity function can be then estimated as follows: $N(L_\gamma) = \frac{dN}{dL_\gamma} \propto \frac{dL_\gamma}{\dot{E}} \propto \frac{dL_\gamma}{\dot{E}} \propto \frac{dL_\gamma}{\dot{E}} \propto \frac{dL_\gamma}{\dot{E}}$ for constant birthrate. Since $\dot{E} \propto B^2 / P^4 \propto P_s^4$, $d\dot{E} / dt \propto \dot{E} / P^2$ and hence $N(L_\gamma) \propto B^{-1}L_\gamma^{-1.5}$ according to the polar-cap model of \cite{Gonthier2002} $\beta \approx 1$, so $N(L_\gamma) \propto L_\gamma^{-2}$. The slot-gap model of \cite{Muslimov2003} gives $\beta = 4$ so $N(L_\gamma) \propto L_\gamma^{-3}$. The outer-gap model of \cite{Zhang2004} gives $\beta = 0.4 - 1$ so $N(L_\gamma) \propto L_\gamma^{-2.3} - L_\gamma^{-1.5}$. The dynamic range of gamma-ray luminosity in these models is about 1000.
4.2 Known populations

We start with the EGRET catalogue sources (excluding AGN identifications), attempt to reproduce their source counts by population synthesis and hence estimate the contribution of unseen members of this population to the diffuse emission. The luminosity function is assumed to be a power law, the index and limits being free parameters. In our reference model the range of luminosities considered is \( L_{\gamma}(>100 \text{ MeV}) = 10^{36} - 10^{39} \text{ s}^{-1} \), covering the range of detected pulsars as discussed in the Introduction. The local density \( \rho \) is fixed by the requirement that the low-latitude source counts are reproduced.

For EGRET we use a limiting flux \((>100 \text{ MeV})\) of \(10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \); fainter sources are detected by EGRET at high latitudes but in the plane the limit is higher: 1.6 \(10^{-7} |b| < 10^0, 0.7 \times 10^{-7} |b| > 10^0 \). For a luminosity function index \(-1.5, \rho = 37 \text{ kpc}^{-3} \) (model 1b), the low-latitude source counts in \(300^\circ < l < 60^\circ, |b| < 10^0\) (hereafter region H) are reproduced (37 above threshold), the high-latitude sources are very few (so they must be extragalactic in this case), and about 6% of the Galactic emission \((2 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1})\) in this region comes from the 4000 sources below the threshold. The fluxes above and below the threshold are about equal, \(1.5, 1.2 \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1} > 100 \text{ MeV}\) in the simulation, compared to \(1.4 \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1}\) for the 37 EGRET sources in region H.

For a luminosity function index \(-2.0\), model 1c, again choosing \(\rho\) so that the low-latitude source counts in region H are reproduced, 13% of the Galactic emission in this case is from the 26000 sources below the threshold.

How critical is the luminosity function shape? Flattening the luminosity function index from -1.5 to -1.0, about 4% of the Galactic emission comes from the 728 sources below the threshold. Steepling the luminosity function index to -2.5, about 28% of the Galactic emission comes from the 10^5 sources below the threshold. So even a major difference in assumed luminosity function shape does not change the conclusion that a significant contribution to the diffuse emission must come from sources physically like those in the EGRET catalogue but below the detection threshold. A steeper luminosity function or a lower minimum luminosity leads to a larger contribution from unresolved sources.

The high-latitude source counts are not very constraining, due to the low space density for these high luminosity sources, but the predicted counts are consistent with (i.e. do not exceed) the observed counts. For a steep luminosity function (index \(-2.0\)) or a low minimum luminosity \((10^{35} \text{ ph s}^{-1})\), a significant fraction of the high-latitude sources can be Galactic. With the small statistics a quantitative comparison of observed and predicted shape of N(S) is difficult, any index considered here reproduces the observed counts reasonably, and no distinction between the various indices can be made.

4.3 Unseen / dim populations

We turn now to source populations mainly below the detection threshold, with the aim of placing constraints on their properties. The relevant models are 2, 3 and 4 in Table 1.

The luminosity function is assumed to be a power law with index \(-1.5\) and various luminosity ranges. The normalization is chosen to give about a tenth of the EGRET diffuse emission, as an illustration of a plausible level. Consider first \(L_{\gamma}(>100 \text{ MeV}) = 10^{36} - 10^{37} \text{ ph s}^{-1}\), model 2. For \(\rho = 500, 15\%\) of the diffuse emission in region H is from the 5 \(10^4\) sources below the threshold and 44 of the EGRET unidentified high-latitude sources are Galactic and 17 (cf 3rd EGRET Catalogue: 37) sources are above the limit in region H. Longitude profiles (not shown here) indicate that the sources below the threshold cause fluctuations in the emission which however are not distinguishable from the interstellar emission. For \(L_{\gamma}(>100 \text{ MeV}) = 10^{35} - 10^{36} \text{ ph s}^{-1}\), \(\rho = 2 \times 10^3\), (model 3), 7% of the diffuse emission in region H is from the 2 \(10^2\) sources below the threshold, 2 sources are above threshold in region H, and 19 at high latitudes. For \(L_{\gamma}(>100 \text{ MeV}) = 10^{34} - 10^{35} \text{ ph s}^{-1}\), \(\rho = 2 \times 10^4\) (model 4), 7% of the diffuse emission in region H is from the 2 \(10^3\) sources below the threshold, no sources are above the threshold in region H, and only 5 at high latitudes. It follows that for \(L_{\gamma}(>100 \text{ MeV}) < 10^{35} \text{ ph s}^{-1}\) all of the ‘diffuse' emission could come from sources without violating source counts anywhere on the sky (e.g. by scaling up \(\rho\) in model 4). This is of course highly unlikely given our knowledge of interstellar emission processes but cannot be excluded from \(\gamma\)-ray data alone.

If we consider that all the high-latitude unidentified sources are Galactic then a dim dense population like in models 2, 3, 4 is necessary in addition to the bright population. Strict limits are then set by the requirement of not violating the observed diffuse emission considering plausible interstellar emission. If instead they are extragalactic, the dim Galactic population is not required.

5 Comparison with physical pulsar population synthesis

It is interesting to see how our simple generic approach matches detailed specific models. In their pulsar population synthesis based on their polar cap model, Gonthier et al. (2004) find 26 pulsars detectable by EGRET, which presumably would mean a substantial fraction of the unidentified sources are pulsars. They predict that 600 pulsars will be detectable by GLAST for a threshold \(2 - 5 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}\). This matches best our model 1b (index -1.5).

The outer gap model of Zhang et al. (2000) predicts 32 pulsars detectable by EGRET, which again would mean a substantial fraction of the unidentified sources are pulsars. This model predicts 1180 GLAST pulsars, for assumed threshold of \(4 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}\) matching best our model 1c with luminosity function index -2.0.
6 Sources can produce the MeV, GeV excesses

The unresolved source fraction is energy-dependent, so that one can ask whether it can produce the well-known GeV excess over the standard cosmic-ray interaction models. Consider first model 1c (Fig 3c) with spectral index -2.0 and luminosity function index -1.0, -1.5, -2, -2.5, combined with the conventional interstellar emission model from Strong et al. (2004a), but with the cosmic-ray source distribution from Strong et al. (2004b). The GeV excess is not reproduced. However for this source spectrum the source contribution to the COMPTEL (1–30 MeV) and INTEGRAL (.02 – 1 MeV) ranges might provide an explanation of the excess above the interstellar emission at those energies. Sources with a Crab-pulsar-like index of -2.1 with a break above 4 GeV (Fierro et al., 1998; Kuiper et al., 2001) would be too steep to reproduce the GeV excess, but the COMPTEL diffuse emission could be fitted.
Fig. 2 Spectra in region H ($300^\circ < l < 60^\circ$, $|b| < 10^\circ$) for models 1a-d. Luminosity index $-1.0,-1.5,-2,-2.5$ (left to right, top to bottom). Sources below (dotted, cyan) and above (dashed, cyan) the EGRET detection limit are also shown together with sources below the limit added to the conventional interstellar model from Strong et al. (2004a) (continuous, cyan). Data: EGRET, COMPTEL.

Fig. 3 Sources like Geminga, Vela pulsars can produce the GeV excess: spectra in $330^\circ < l < 30^\circ$, $|b| < 5^\circ$(region A of Strong et al. (2004a)) for $L(>100 \text{ MeV}) = 10^{36} - 10^{39}$ s$^{-1}$. Luminosity index 2.0, spectral index -1.5, break at 2 GeV to -2.0 to match Geminga, Vela. $\rho = 150$. Sources below (dotted, cyan) and above (dashed, cyan) the EGRET detection limit are also shown together with sources below the limit added to the conventional interstellar model from Strong et al. (2004a) (continuous, cyan). Data: EGRET, COMPTEL.
Consider now sources with hard spectra like the Geminga (index -1.42, 30–2000 MeV) and Vela (index -1.62, 30–1000 GeV) pulsars [Fierro et al. (1998)] (also B1706, B1055 have hard spectra with a GeV break); we adopt a spectral index -1.5, with a break at 2 GeV to -2.0, luminosity index 2.0, $\rho = 30$ (cf. model 1c); the GeV excess is easily produced (Fig 3). Indeed these pulsars show maxima in $E^3 F(E)$ around 2 GeV very reminiscent of the Galactic GeV excess. This explanation of the GeV excess was also proposed by Zhang & Cheng (1998) on the basis of their outer-gap pulsar model, but our result is not dependent on a particular physical model.

However the diffuse emission below 30 MeV is not explained by such sources. It is then tempting to propose a mixture of Crab-like and Geminga/Vela-like pulsars to produce both the MeV and GeV excesses and reproduce the entire ridge spectrum.

The spectra of the unidentified low-latitude sources scatter broadly around -2 (-1.7 to -2.7) [Zhang et al. (2000)] but the details of the spectra are not sufficient to determine whether this supports our hypothesis about the GeV excess. GLAST will contribute significantly on this point.

### 7 Will GLAST resolve the issue?

Although GLAST will not detect all the $\gamma$-ray sources in the Galaxy, it will resolve essentially all the source flux of the bright populations. Thus for model 1c (luminosity index -2.0), 75% of the source flux is above a threshold $4 \times 10^{-9}$ cm$^{-2}$ s$^{-1}$, compared to 35% for the EGRET threshold. For model 1b (luminosity index -1.5), 96% of the source flux is above the GLAST threshold, compared to 55% for the EGRET threshold. For the dimmer populations ($L_{\gamma}(>100$ MeV) $< 10^{37}$ ph s$^{-1}$) progressively less of the flux will be resolved. Even for $L_{\gamma}(>100$ MeV) $= 10^{36} - 10^{37}$ ph s$^{-1}$ (model 2) only 44% of the flux is above the GLAST threshold, so the analysis will remain a challenge.

### 8 Conclusions

1. Modelling the contribution from unresolved sources is essential to understanding the diffuse Galactic emission.
2. The contribution from unresolved sources to the EGRET low-latitude emission is at least 5-10%, and can be 20% for steep luminosity functions.
3. An arbitrarily large fraction of the diffuse emission could come from sources $L_{\gamma}(>100$ MeV) $< 10^{35}$ ph s$^{-1}$ from sources without violating EGRET source counts anywhere on the sky.
4. The GeV excess can be produced naturally by a sufficient population of sources like Geminga and Vela, but this has to be studied with more detailed models.
5. Crab-like sources can produce the COMPTEL excess but not the GeV excess.

6. A combination of source populations combined with the conventional model of interstellar emission could explain the full COMPTEL/EGRET Galactic ridge spectrum.
7. Whether GLAST can settle these issues depends critically on the source luminosity function.

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