ABSTRACT

In a recent paper, Romero et al. (1999) have presented the results of a positional correlation analysis of the low-latitude unidentified gamma-ray sources in the Third EGRET catalog with complete lists of galactic objects like supernova remnants, early type stars with strong stellar winds, and OB associations (considered as pulsar tracers). We have now carried out a study of those 42 sources at $|b| < 10^\circ$ for which no counterpart was found at all. A variability analysis shows that this sample contains a population of sources with high levels of variability at gamma-rays. The surface density of these variable sources is 5 times higher than what is expected for unidentified AGNs seen through the Galactic plane. We discuss the origin of this presumed Galactic population of gamma-ray objects and the role that INTEGRAL could play in their physical identification.

Key words: Gamma ray sources: unidentified; black holes.

1. INTRODUCTION

The Third EGRET (3EG) catalog of high-energy gamma-ray sources lists 271 point-like sources detected at $E > 100$ MeV (Hartman et al. 1999). Among these sources there are 66 high-confidence identifications with blazars, 7 confirmed gamma-ray pulsars, and about 170 unidentified sources. The distribution of the unidentified sources with Galactic latitude shows a strong density gradient towards the Galactic plane, which indicates a strong contribution from sources belonging to our Galaxy (see Figure 1). Additionally, a group of mid-latitude sources has been recently found to be correlated with the Gould belt, a nearby region of active star formation (Grenier & Perrot 1999, Gehrels et al. 2000).

The positional correlation between the 3EG sources in the Galactic plane and different types of Galactic objects was studied by Romero et al. (1999). They found that 10 sources are coincident, within the positional uncertainties, with Wolf-Rayet and Of stars (which are hot and massive stars endowed with strong supersonic stellar winds), 26 with OB associations (usually considered as pulsar tracers) and 22 with supernova remnants (SNRs). The probability of pure chance superposition with OB associations and SNRs is quite negligible ($< 10^{-5}$). For the stars, the case is suggestive although not so conclusive (probabilities $< 10^{-2}$). Romero et al. (1999) also found a set of 42 gamma-ray sources for which there is not positional superposition with any known Galactic object capable to produce high-energy gamma-rays. The nature of this sub-group of sources remains a mystery.

In this paper we present a variability analysis of the sample of unidentified 3EG sources near the Galactic plane that do not present positional correlation with potential Galactic counterparts. Such an analysis can shed some light on the nature of the parent population, because radio-quiet pulsars and yet undiscovered SNRs are not expected to present high levels of variability on timescales of months. Based upon the results, we shall advance a working hypothesis on the parent objects.

2. VARIABILITY ANALYSIS

There are 81 unidentified sources at $|b| < 10^\circ$ listed in the 3EG catalog. We shall focus our analysis on the sample of 40 sources with no known counterpart.\(^1\)

Zhang et al. (2000) have already presented a variability analysis of the sources that are correlated with OB associations and SNRs, finding that most of these sources could be non-variable. These authors have shown that this group of sources could be mostly originated in a population of young and/or

\(^1\)We have excluded 2 sources that are almost certainly artifacts associated with the proximity of the very bright Vela pulsar (these sources do not show up in a map which excludes the Vela pulsation intervals) and hence the difference with the number of 42 sources mentioned by Romero et al. (1999). There are other 4 possible artifacts that are positionally correlated with SNRs.
radio-quiet gamma-ray pulsars. We aim here at establishing the variability properties of those sources not included in Zhang et al. (2000) analysis.

In order to carry out the variability analysis we define a mean weighted value for the EGRET flux as:

$$\langle F \rangle = \left( \frac{\sum_{i=1}^{N_{vp}} F(i)}{\sum_{i=1}^{N_{vp}} \epsilon(i)^2} \right) \times \left( \frac{\sum_{i=1}^{N_{vp}} 1}{\sum_{i=1}^{N_{vp}} \epsilon(i)^2} \right)^{-1}.$$  

Here, $N_{vp}$ is the number of viewing periods for each gamma-ray source. We take into account only single viewing periods. $F(i)$ is the observed flux in the $i$-period, whereas $\epsilon(i)$ is the corresponding error. For those observations in which the significance ($\sqrt{TS}$ in the EGRET catalog) is greater than $3\sigma$, we took the error as $\epsilon(i) = F(i)/\sqrt{TS}$. However, many of the observations are in fact upper bounds on the flux, with significance below $2\sigma$. For these ones, we assume both $F(i)$ and $\epsilon(i)$ as half the value of the upper bound. This is a rather conservative assumption that is not expected to result in an overestimate of the variability levels, as it could be the case if zero flux is directly adopted. We then define the fluctuation index $\mu$ as:

$$\mu = 100 \times \sigma_{\text{sd}} \times \langle F \rangle^{-1}.$$  

In this expression, $\sigma_{\text{sd}}$ is the standard deviation of the flux measurements, taking into account the previous considerations.

In order to remove as far as possible spurious variability introduced by the observing system, we computed the fluctuation index $\mu$ for the 7 confirmed gamma-ray pulsars (i.e. those listed in the 3EG catalog plus the sources 3EG 0634+0521 and 3EG 1048-5840, which were recently identified by Cusumano et al. 2000 and Kaspi et al. 2000). We adopt the physical criterion that pulsars are –i.e. by definition– non-variable gamma-ray sources. Then, any non-null $\mu$-value for pulsars is attributed to experimental uncertainty. We then define a statistical index of variability, $I$, as

$$I = \frac{\mu_{\text{source}}}{<\mu>_{\text{pulsars}}}.$$  

Then, non-variable sources are defined as those for which $I < 1 + 1\sigma$. Sources with $I > 1$ at a $3\sigma$ level are classified as variable ($1 \sigma = 0.5$). Sources with $I > 1$ at less than $3\sigma$ are dubious cases and we cannot conclude about their variability within the present observational accuracy.

We adopt this criterion, previously used in blazar variability analysis (e.g. Romero et al. 1994), instead of the similar one used by McLaughlin et al. (1996) in order to have a direct comparison with the spurious statistical variability shown by pulsars. Since the $I$-index establishes how variable is a source with respect to the pulsat population, it can be considered as indicative of how confident we can be about the possible physical variation in the gamma emission of the sources.

3. RESULTS

The result of our analysis is presented in Figure 2 in the form of an histogram. We have fitted the distribution with a Gaussian curve in order to estimate the position of the maximum. The peak of the histogram occurs at $I = 2.0$, which means that there is an important contribution from sources that display significant variability over timescales of months. About 30% of the sample (12 sources) presents indices above 2.5, which are clearly variable at more than a $3\sigma$ confidence level. There are sources with indices as high as $I = 8.9$, like 3EG J1735-1500. There are also 18 dubious sources (45 %) with $1.5 < I < 2.5$. Only 10 out of 40 sources (25 %) are clearly non-variable. The variability histogram for the sources in the sample is very similar to that obtained for AGNs in the 3EG catalog (see Figure 3), which is a well known variable population.

Our results are, in general terms, similar to those recently presented by Tompkins (1999), who reanalyzed the EGRET data to take into account not only all sources included in the 3EG catalog, but also the 145 marginal detections not included in the final official list. Two of the sources pointed out by Tompkins as the most variable ones at low latitudes are included in our sample with indices of 3 and 5.3. Although the dubious cases trend to be non variable in the most comprehensive Tompkins analysis, our method is, we think, still the best approach when data from the published catalog are used.

In Figure 4 we present a plot of the variability versus the photon spectral index $\Gamma$ (defined such that $F(E) \propto E^{-\Gamma}$) for sources in our sample. In order...
to provide a comparison we have also included in this plot the population of known gamma-ray pulsars and the population of identified AGNs. All known gamma-ray pulsars are located between the solid horizontal lines. It is interesting to note that those unidentified sources with the steepest spectra seem to have the highest variability indices. The probability of this effect being the effect of chance is $\sim 8\%$, not too low, but sufficient as to encourage further studies.

Figure 5 shows the histogram with distribution of the high-energy photon index $\Gamma$ for the sources of our sample. Notice that known gamma-ray pulsars have hard spectra at $E > 100$ MeV, with indices typically $\Gamma < 2.15$ (e.g. Thompson et al. 1994), contrary to most of the sources here under discussion, which present an average index $\langle \Gamma \rangle = 2.4 \pm 0.2$.

The nature of the variable population of unidentified sources is a very intriguing problem that might be addressed by the INTEGRAL mission.

### 4. MAGNETIZED BLACK HOLES

The variability analysis presented in the previous section clearly shows the existence of a galactic populations of variable gamma-ray sources that do not show up significant emission at other wavelengths. The surface density of variable sources in the sample here under study is five times higher than what is expected for unidentified AGNs seen through the Galactic plane.

Recently, Punsly et al. (2000) proposed that variable galactic sources, which from its gamma-ray properties resemble very much AGNs, could be isolated Kerr-Newman black holes. Punsly (1998) has shown that a magnetospheric charge may be supported in a disk or ring around a charged, rotating black hole of a few solar masses. The total configuration is stable and has zero net charge, hence the hole should not discharge quickly through accretion from the diffuse ISM. Unlike the case of pulsars, magnetized black holes do not present solid surfaces so they do not produce thermal X-ray emission. Strong magnetized bipolar winds are expected in the form of collimated electron-positron jets (Punsly 1998), where gamma-ray emission is generated through inverse Compton scattering of synchrotron photons and pair annihilations.

Detailed calculations of the spectral energy distribution of these objects (Punsly et al. 2000, Combi et al. in these proceedings) show that at MeV energies the annihilation luminosity exceeds the self-
Compton luminosity, producing a break in the spectrum and a steepening at high-energies. The sources with the steepest gamma-ray spectra are those whose jets have the highest pair number densities. Dense jets, in turn, are prone to undergo plasma instabilities. Synchrotron cooling will most likely cause radiative losses of the random transverse (thermal) energy in a magnetized jet. One of the instabilities resulting from the expected pressure anisotropy in a jet is associated with the shear Alfvén wave: the firehose instability. The fastest growing modes of this instability can be applied to the calculation of the pair density in the relativistic flow. The annihilation luminosity is given by (Punsly et al. 2000):

\[ L_0^{\text{ann}} = \frac{3}{32} \sigma_T c (\Gamma - 1)^2 n^2 m_e c^2 V \times \left( \frac{2}{(\Gamma - 1/2)(\Gamma + 1/2)} + \frac{2(2\Gamma - 1)}{\Gamma^2(\Gamma - 1)^2} \right) \]

where \( \sigma_T \) is the Thomson cross section, \( V \) is the volume where the annihilations occur, \( n \) is as before the number density of electron-positron pairs, \( \Gamma \) is the high-energy photon index, and \( m_e \) is the electron rest mass.

Frequent observations of these sources with IBIS will be useful to establish the short-term variability, which in turn can shed light on the involved plasma instabilities. High-resolution radio observations towards those sources detected by IBIS could find the synchrotron radio signature of the jets, that should appear as a point-like non-thermal source of a few tens of mJy at 5 GHz (Punsly et al. 2000).

5. ADDITIONAL COMMENTS

The magnetized black hole hypothesis for the parent population of the low-latitude, variable gamma-ray sources can be tested by the IBIS instrument of INTEGRAL mission. The spectra of these objects should exhibit a broad peak at a few MeV, similar to that observed in MeV blazars (e.g. Bloemen et al. 1995). The expected luminosity of this peak is \( \sim 10^{35} \text{ erg s}^{-1} \) (Combi et al., these proceedings), so if it occurs at, say, 4 MeV in a source at \( \sim 1 \text{ kpc} \), it should be clearly detected (see Combi et al., these proceedings). The exact position of the peak in the spectral energy distribution can be used to infer the Doppler factor of the jets, whereas its measured intensity can be applied to the calculation of the pair density in the relativistic flow. The annihilation luminosity is given by (Punsly et al. 2000):

\[ L_0^{\text{ann}} = \frac{3}{32} \sigma_T c (\Gamma - 1)^2 n^2 m_e c^2 V \times \left( \frac{2}{(\Gamma - 1/2)(\Gamma + 1/2)} + \frac{2(2\Gamma - 1)}{\Gamma^2(\Gamma - 1)^2} \right) \]

where \( \sigma_T \) is the Thomson cross section, \( V \) is the volume where the annihilations occur, \( n \) is as before the number density of electron-positron pairs, \( \Gamma \) is the high-energy photon index, and \( m_e \) is the electron rest mass.

6. CONCLUSIONS

In this paper we have estimated the variability of a sample of 40 low-latitude, unidentified gamma-ray sources that are not positionally correlated with known potential Galactic emitters. We have shown that within this set there exists a group of sources which display high levels of variability over timescales of months to years at gamma-rays. These sources are unlikely to be pulsars or undiscovered SNRs. The INTEGRAL satellite will provide a powerful tool through its IBIS imager to probe the nature of this population of energetic objects and test whether the hypothesis here presented, namely that the gamma-ray emission is produced by isolated magnetized black holes, is correct or not.

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