Association Of Unidentified, Low Latitude EGRET Sources With Supernova Remnants

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Abstract. We propose that some of the unidentified Galactic plane ($-10^\circ < b < 10^\circ$) sources listed in the first EGRET catalog (Fichtel et al. 1994) are associated with nearby supernova remnants. The probability that the association of strong EGRET sources with supernova remnants is due to chance alignment is found to be $\lesssim 1/2200$. Three of the most convincing associations are radio-bright, nearby shell remnants and a fourth is associated with a plerion. We examine possible gamma-ray production mechanisms and conclude that pion production and decay from high-energy protons interacting with the remnant gas could produce the gamma rays. The energetics of this process are in accord with theories of cosmic ray production through supernova shock acceleration. The identification of $\pi^0$-decay features in the gamma-ray spectra of supernova remnants would support this interpretation.

Key words: ISM: supernova remnants, individual: IC443, S147, $\gamma$ Cygni, MSH 11-62 - gamma-rays: observations, theory

1. Introduction

The identified high-energy gamma-ray ($\gtrsim 100$ MeV) sources observed with the EGRET experiment on the Compton Gamma-Ray Observatory have fallen into five general categories: solar flares, pulsars, gamma-ray bursts, normal galaxies, and active galactic nuclei. In addition, the first EGRET source catalog (Fichtel et al. 1994) lists 37 unidentified Galactic plane sources, of which 10 are high-confidence detections ($> 6\sigma$) and 27 are marginal detections (between 5 and $6\sigma$). We have compared the locations of these 37 sources with the locations of the 182 supernova remnants (SNRs) listed in the catalog of Green (1994). For simplicity, the radii of elliptical SNRs were taken to be the average of the semi-major and semi-minor axes of the remnant. We found that of the 37 unidentified high-energy gamma-ray sources, 4 of the high confidence sources and 9 of the marginal detections have SNRs whose radii overlap the 95% confidence EGRET gamma-ray error circle (one of the marginal detections has two possible associations; see Table 1). Two of the gamma-ray sources have SNRs within 8$^\circ$ of the centroid of the EGRET error circle. One of these two sources is at a Galactic longitude of 180$^\circ$ where there are few SNRs and the possibility of chance coincidence is low.

2. Statistical Test

We developed a test to determine if the associations between the 37 EGRET sources and the 182 SNRs are chance alignments. We calculate the angular distance, as measured from the center of the EGRET error circle to the center of the remnant, from each gamma-ray source to the closest three SNRs, $\theta_1$, $\theta_2$, and $\theta_3$. Assuming that the nearest neighbors are randomly distributed about the EGRET source, we then use these distances to define two parameters, $a_1 \equiv (\theta_1^2/\theta_2^2)$ and $a_2 \equiv (\theta_2^2 - \theta_1^2)/(\theta_2^2 - \theta_3^2)$. The quantity $a_1$ is the ratio of the areas of circles with radii $\theta_1$ and $\theta_2$ centered at the location of the EGRET source. The quantity $a_2$ is the ratio of the areas of annuli with inner radius $\theta_1$ and outer radii $\theta_2$ and $\theta_3$, respectively, centered on the EGRET source. If the SNRs are not correlated with the EGRET sources, then $\langle a_1 \rangle$, the average value of $a_1$, should equal 0.5 within statistical errors. If the unidentified EGRET sources are, however, associated with SNRs, then $\langle a_1 \rangle$ should be $< 0.5$. The average value of $a_2$, $\langle a_2 \rangle$, should be 0.5 if our assumption regarding the distribution of nearest neighbors is correct.

Another way of testing the assumption that the distribution of the nearest-neighbor SNRs about an unidentified EGRET source is two-dimensional is to compute the average of the sines of the angles between the directions from the EGRET source to the nearest and second nearest (second and third nearest) SNRs, $\langle \sin \psi \rangle_1$. If the SNR distribution is two-dimensional, $\langle \sin \psi \rangle = 2/\pi = 0.637$. If
the distribution is linear, the average should be much less than 0.637. We find that for the 10 high confidence sources \(\langle \sin \psi_{i(2)} \rangle = 0.69(0.47) \pm 0.10\) where the 1σ error is given by \((0.5 - 4/\pi^2)^{1/2}/\sqrt{N}\), where N is the number of sources. For the 27 marginal sources, \(\langle \sin \psi_{i(2)} \rangle = 0.53(0.64)\pm 0.06\) and for the entire sample \(\langle \sin \psi_{i(2)} \rangle = 0.58(0.60)\pm 0.05\). Thus our assumption appears valid.

We find that given the entire sample of 37 unidentified high-energy gamma-ray sources, \(\langle a_1 \rangle = 0.41\pm 0.05\) and \(\langle a_2 \rangle = 0.45\pm 0.05\), where the errors are statistical, i.e. \(\sigma = 1/\sqrt{12N}\) where \(N\) is the number of sources. Thus there is \(\sim 1.8\sigma\) deviation of \(\langle a_1 \rangle\) from 0.5 while \(\langle a_2 \rangle\) deviates by only 1σ from 0.5. This weakly suggests that the distribution of SNRs closest to the gamma-ray sources is not completely random while supporting the assumption that the distribution of second closest remnants is random. When only the 10 high confidence sources are studied, however, the values of \(\langle a_1 \rangle\) and \(\langle a_2 \rangle\) are 0.21\pm 0.06 and 0.53\pm 0.09, respectively. In this case, there is \(\sim 3.2\sigma\) deviation from 0.5 for \(\langle a_1 \rangle\) while \(\langle a_2 \rangle\) is within 1σ of 0.5, suggesting only a small chance of coincidental alignment with the closest remnants. Computer simulations show that the probability of having \(\langle a_1 \rangle \lesssim 0.21\) is \(\lesssim 1/2200\).

When considering only the marginal gamma-ray source detections, \(\langle a_1 \rangle = 0.48\pm 0.06\) and \(\langle a_2 \rangle = 0.43\pm 0.06\), both roughly consistent with 0.5. The lack of statistically significant association between the weak EGRET-source and supernova-remnant populations is in part because most marginal EGRET detections are located toward the galactic centre region where there is a larger density of SNRs, and the relatively large size of the EGRET error circle reduces the probability of association. We show histograms of the values of \(a_1\) for the high-confidence, marginal, and total set of EGRET sources in Figure 1. Note that all but one of the high-confidence sources has a value for \(a_1 < 0.5\).

We would like to note that Espósito et al. (1994) have independently found a statistically significant correlation between the unidentified EGRET sources and SNRs using a different statistical test.

### 3. Properties of the Associated Supernova Remnants

We now consider the energetics of the SNRs associated with the high confidence gamma-ray detections. Of these, three are radio-bright, nearby shell-type remnants (Green 1994), namely γ Cygni (G 78.2+2.1), IC 443 (G 189.1+3.0), and S147 (G 180.0-1.7), and the fourth, MSH 11-82 (G 291.0-0.1), is a plerion (Weiler & Sramek 1988). The distance to IC 443 is between 0.7 and 2.0 kpc (Green 1994), and Pillet et al. (1988) have estimated its age at 2800-3400 years. γ Cygni has an estimated distance of 1.5 kpc (Green 1989; Landecker, Roger, & Higgs 1980). An age for γ Cygni can be estimated assuming that this remnant is in the Sedov phase using the equation (Kassim, Heritz, & Weiler 1993)

\[
\tau \approx 0.1 (d \theta)^{2.5} \left( \frac{n_{o}}{\epsilon_{51}} \right)^{0.5} \text{years,} \tag{1}
\]

where \(d\) is the distance to the remnant in kpc, \(\theta\) is the angular diameter of the remnant in arcminutes, \(n_{o}\) is the density of the interstellar medium surrounding the remnant in \(\text{cm}^{-3}\), and \(\epsilon_{51}\) is the supernova explosion energy in units of \(10^{51}\) ergs. The ISM density \(n_{o}\) typically has values between 0.1 and 1.0 \(\text{cm}^{-3}\). For simplicity we choose

| EGRET Source | SNR          | \(\theta_i (')^a\) | \(D_{max} (')^b\) | \(\theta_i/D_{max}\) | Type^c | Radio Flux (Jy) |
|--------------|--------------|-------------------|-------------------|-----------------------|--------|-----------------|
| GRO J0542+26 | G 180.0-1.7 (S147) | 116.6             | 248.0             | 0.47                  | S      | 65              |
| GRO J0617+22 | G 189.1+3.0 (IC 443) | 6.7               | 43.5              | 0.15                  | C      | 160             |
| GRO J1110-60 | G 291.0-0.1 (MSH 11-62) | 7.8               | 56.0              | 0.14                  | F      | 16              |
| GRO J2018+40 | G 78.2+2.1 (γ Cygni) | 27.7             | 48.0              | 0.58                  | F      | 340             |
| GRO J0635+05 | G 205.5+0.5 (Monoceros) | 81.6             | 148.0             | 0.55                  | C      | 160             |
| GRO J023-46 | G 263.9-3.3 (Vela) | 87.7             | 127.5             | 0.69                  | S      | 1750            |
| GRO J1416-61 | G 312.4-0.4 | 11.9             | 49.8              | 0.24                  | S      | 44              |
| GRO J1443-60 | G 316.3+0.0 (MSH 14-57) | 35.4             | 39.0              | 0.91                  | C      | 24              |
| GRO J1758-23 | G 6.4-0.1 (W28) | 26.8             | 57.0              | 0.47                  | C      | 310             |
| GRO J1832-12 | G 18.8+0.3 (Kes 67) | 13.0             | 36.8              | 0.35                  | C      | 27              |
| GRO J1842-02 | G 30.7+1.0 | 42.3             | 50.5              | 0.84                  | C      | 6               |
| GRO J1853+01 | G 34.7-0.4 (W44) | 30.7             | 42.5              | 0.72                  | C      | 230             |
| GRO J1904+06 | G 40.5-0.5 | 36.7             | 63.0              | 0.58                  | C      | 11              |
|             | G 41.1-0.3 (3C397) | 46.1             | 53.8              | 0.86                  | C      | 22              |

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^a Angular distance from center of EGRET error circle to center of associated remnant.
^b Sum of the EGRET error circle radius plus the radius of the associated remnant.
^c S=Shell, C=Composite, F=Filled.
yields an age of \( \frac{1}{1} \text{Sauvageot, Ballet, \& Rothenburg} \), \( \text{gives its distance} \) on the other hand, \( \frac{1}{1} \text{S147 is a nearby, old shell-type remnant}. \) with the \( \frac{1}{1} \text{year spin-down age for the Vela pulsar}. \) On the Vela supernova remnant which is in good agreement with the 11,000 year spin-down age for the Vela pulsar. On the other hand, S147 is a nearby, old shell-type remnant. Sauvageot, Ballet, \& Rothenburg (1990) give its distance as \( 1.1 - 1.7 \text{kpc}. \) Given its \( 1.0 \text{diameter}, \) Equation (1) yields an age of \( \approx 70,000 \text{years}, \) much older than the other 2 shell remnants. The age of this remnant along with the large 95\% confidence error circle (158\%) and the large size of the remnant make chance alignment a distinct possibility, although it is located in a region with few other remnants. MSH 11-62 is a plerion with an age of 3000 years and a distance of \( \approx 3.5 \text{kpc} \) (Roger et al. 1986). Therefore its gamma rays could originate from high-energy particles emitted by the pulsar which is presumably responsible for powering this remnant.

We have ordered Green's (1994) catalog of SNRs according to radio flux. \( \gamma \text{Cygni and IC 443 are the fifth (340 Jy) and eleventh (160 Jy) brightest SNRs at 1 GHz, respectively. S147 and MSH 11-62 are significantly dimmer in the radio, and are numbers 25 (65 Jy) and 74 (16 Jy) on the list. When compared with only the flatter spectrum (spectral index \( \leq 0.5 \)) shell remnants, \( \gamma \text{Cygni and IC 443 are the second and seventh brightest. The radio bright SNRs that are not associated with EGRET sources tend to be either farther away than} \) \( \gamma \text{Cygni and IC 443, such as Cas A and W28 at 2.8 and 3.5-4.0 kpc (Green 1994), respectively, or are much older, such as the Lupus Loop at} \approx 50,000 \text{years (Leahy, Nousek, \& Hamilton 1991).} \)

4. Possible Gamma-Ray Production Mechanisms

Gamma-ray emission from MSH 11-62 can be readily understood as either pulsed emission from an associated radio-quiet pulsar with unknown period or as unpulsed emission from a pulsar-energized nebula (plerion) such as the Crab Nebula. Detection of a point source in X-rays by \( \text{ROSAT or ASCA would give evidence for a pulsar source for the emission and could permit a search for the pulsar's period. Gamma rays from shell-type remnants such as} \gamma \text{Cygni and IC 443 (and possibly S147) may involve other production mechanisms, although searches for radio-quiet pulsars associated with these sources should also be pursued. Let us therefore consider the possible origin of the gamma rays from the shell-type SNRs. It is not likely that the high-energy radiation originates from Compton upscattering of a photon field by the synchrotron-emitting electrons. For example, IC 443 at an assumed distance of 1.5 kpc, emits \( \approx 10^{33} \text{ergs s}^{-1} \) in the radio (Green 1994; Mufson et al. 1986), \( \approx 10^{37} \text{ergs s}^{-1} \) in the IR (Mufson et al. 1986), and \( \approx 10^{35} \text{ergs s}^{-1} \) in X-rays (Petré et al. 1988; Mufson et al. 1986). If our proposed association is correct, IC 443 emits \( \approx 5 \times 10^{34} \text{ergs s}^{-1} \) in \( \approx 100 \text{MeV} \) gamma rays (Fichtel et al. 1994). The relationship between the gamma-ray luminosity \( L_{\gamma} \) and the radio luminosity \( L_{r} \) from Compton upscattering and synchrotron radiation, respectively, can be shown to be

\[
\frac{L_{\gamma}}{L_{r}} \approx 50 \approx \frac{L_{ph}}{4\pi\nu^{2}(B^2/8\pi)c},
\]

where \( L_{ph} \) is the luminosity of one of the lower-energy photon fields, \( B \) is the mean magnetic field strength in
the remnant shell [typically of order $10^{-5}$ Gauss (Lozin- 
skaya 1992)], and $r$ is the remnant radius (the rem-
nant thickness does not enter). Equation (2) implies that
$B(10^{-5}$ Gauss) $= 0.01(L_{th}/10^{37} \text{ergs s}^{-1/2})(r/10^{16} \text{pc})$.
Thus, unless the remnant magnetic field is extremely
weak, there are not enough synchrotron-emitting elec-
trons to produce the observed gamma rays by upscat-
tering the known radiation fields or, for that matter, the microwave
background or starlight radiation fields.

The relativistic electrons which produce the observed
radio synchrotron radiation will also produce gamma-
rays through nonthermal bremsstrahlung. The nonther-
nal electron spectrum in IC 443 can be estimated by
comparing the derived synchrotron photon luminosity
with its observed radio luminosity. The synchrotron or
bremsstrahlung luminosity can be written as

$$L = m_{e}c^{2} \int_{1}^{N_{e}(\gamma_{e})} \gamma d\gamma,$$

(3)

where, for synchrotron radiation, $\gamma = \gamma_{\text{syn}} \approx (4/3)\sigma_{t}c/\gamma_{e}^{2}$ and $N_{e}(\gamma_{e}) = N_{e}^{0}\gamma_{e}^{-3}$ is the
electron density per unit $\gamma_{e}$. In order to produce radio photons
with frequencies near $10$ GHz, $\gamma_{e} \approx 1.9 \times 10^{4}B_{-5}^{-0.5}$, where
$B_{-5}$ is the magnetic field in units of $10^{-5}$ Gauss. The
spectral index of the electron population, $q$, must $\approx 1.72$
in order to produce the $0.36$ radio spectral index observed
for IC 443 (Green 1994). Setting Equation (3) equal to
$10^{33}L_{33}$ ergs s$^{-1}$, we find $N_{e}^{0} \approx 4 \times 10^{53}B_{-5}^{1.86}L_{33}^{33}$. For bremsstrahlung radiation, $\gamma = \gamma_{\text{brems}} \approx (1/3)\sigma_{t}c/\gamma_{e}^{2}$ and $n_{H} = 10n_{i}$ cm$^{-3}$ is the mean number density of hy-
drogen atoms in the remnant. The derived bremsstrahlung
luminosity $\approx 9 \times 10^{36}n_{i}B_{-5}^{1.5}L_{33}^{33}$ ergs s$^{-1}$, which
implies $B(10^{-5}$ Gauss) $\approx 0.07(n_{i}L_{33})^{0.67}$ given the observed
gamma-ray luminosity of IC 443.

It was suggested long ago that if SNRs are sites of
{	extit{cosmic-ray}} acceleration, then $\pi^{\pm}$-decay gamma-rays will be
produced as a result of collisions of the cosmic rays with the
interstellar medium (Pineau 1970). The luminosity in secondary
$\pi^{\pm}$s is

$$L_{\pi^{\pm}} \approx c n_{H} \int_{\gamma_{p} = \text{ave}}^{\infty} N_{p}(\gamma_{p})\sigma_{pp}(\gamma_{p})(E(\gamma_{p}))d\gamma_{p},$$

(4)

where $N_{p}(\gamma_{p}) = N_{o}^{0}\gamma_{p}^{-2.2}$ is the number of protons per unit
$\gamma_{p}$ suggested by shock acceleration models (Gaisser 1990),
$\sigma_{pp} \approx 3 \times 10^{-26}$ cm$^{-2}$ (Dermer 1986) is the proton-proton
interaction cross section, and $(E(\gamma_{p})) \approx 1/3(\gamma_{p}m_{p}c^{2}/2)$ is the
average amount of energy per proton-proton interaction
converted to $\pi^{\pm}$-decay gamma rays. By setting Equation
(4) equal to the gamma-ray luminosity of the EGRET
source possibly associated with IC 443, $\approx 5 \times 10^{34}$ ergs s$^{-1}$, we find
$N_{o}^{0} \approx 5 \times 10^{51}n_{i}$ protons. Thus the amount of energy in nonthermal protons required to produce the ob-
served gamma-ray emission is $\approx 4 \times 10^{49}n_{i}^{-1}$ ergs. This
is larger than the amount of energy observed per supernova
that is converted to nonthermal protons in order to
produce the observed cosmic ray energy density $\Psi_{e}$, which we write as $E_{cr} = \Psi_{e}V_{gal}\tau_{gal}/\tau_{gal}$. Here $\Psi_{e} = 10^{-12}\Psi_{-12}$ ergs cm$^{-3}$ (Gaisser 1990), $V_{gal} = 10^{67}V_{07}$ cm$^{-3}$ is
the volume of the galaxy, $\tau_{gal} = 10^{9}$ $t_{50,0}$ seconds is the
time between supernovae in the galaxy, $\tau_{gal} = 3 \times 10^{14}t_{7}$
seconds is the proton confinement time in our galaxy,
and $t_{7}$ is the confinement time in units of $10^{7}$ years.
Thus $E_{cr} \approx 3 \times 10^{49}\Psi_{-12}V_{07}t_{50,0}/t_{7}$ ergs, similar to that
needed to produce the observed gamma-ray flux. Aharo-
nian, Drury, and Völk (1994) have also found that gamma
rays produced by the decay of neutrons could be detectable with
current instruments, particularly if the remnant is adja-
cent to a molecular cloud as is evident in the case for $\gamma$
Cygni and IC 443 (Pollock 1985; Asaoka & Aschenbach 1994)
Observations of pion-decay features at gamma-ray
energies from SNRs with the telescopes on the Compton
Observatory would support the $\pi^{\mp}$ origin of the gamma-ray
emission and be in accord with the scenario that cosmic
rays are accelerated by supernova shocks.

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