What Can Be Learned About Cosmic Rays with GLAST?

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Abstract

After decades of cosmic-ray research, the sites where cosmic-ray nuclei are accelerated remain unknown. While evidence is mounting that supernova remnants accelerate cosmic-ray electrons to very-high energies, EGRET observations of remnants have not provided clear evidence that nuclei are also accelerated in these objects. However, observations with GLAST may provide the first crucial evidence that a portion of the gamma-ray spectra of supernova remnants is produced by the decay of neutral pions, that this gamma-ray emission is associated with high-density regions around the remnants, and, hence, that supernova remnants accelerate cosmic-ray nuclei. We have simulated the spectral and spatial results that will be obtained for the remnant γ Cygni using data from a one-year all-sky survey with GLAST. The results emphasize that the superior angular resolution and gamma-ray flux sensitivity of GLAST should make it easy to determine that supernova remnants accelerate cosmic-ray nuclei.

1 Introduction:

Despite many decades of cosmic-ray research, relatively little is known about the details of how cosmic-ray electrons and nuclei are accelerated and how they propagate through the Galaxy. Since these high-energy particles can produce gamma rays via the bremsstrahlung radiation of electrons, the inverse Compton scattering of electrons on the cosmic microwave background radiation, or the decay of neutral pions produced in nuclear interactions, high-energy gamma-ray observations can provide a powerful means of exploring the acceleration and propagation of cosmic rays.

In our galaxy, it is generally thought that supernova remnants are predominantly responsible for the acceleration of cosmic rays to energies ~ 100 TeV (Lagage & Cesarsky 1983) or more (Jokipii 1987; Völk & Biermann 1988). However, this hypothesis has been difficult to prove. Radio observations of many remnants reveal that they contain non-thermal populations of electrons that have energies ~ 1 GeV (Green 1998). X-ray results suggest that at least a few, and perhaps all, young shell-type remnants accelerate electrons to energies ~ 10 TeV (OG.2.2.12; Koyama et al. 1995; Allen et al. 1997; Koyama et al. 1997; Keohane et al. 1997). The radio data also imply that the spectral indices of the electron spectra and estimates of the total energies of the cosmic-ray particles are consistent with the idea that Galactic cosmic rays are predominantly accelerated in the shocks of supernova remnants (OG.2.2.12). However, these results concern electrons, not nuclei. The single, most important missing piece to the proof of this hypothesis is the demonstration that supernova remnants accelerate cosmic-ray nuclei.

The only means of measuring the cosmic-ray nucleon spectrum of a remnant is to measure the gamma-ray spectrum produced by the decay of π^0s in the remnant. Some supernova remnants are reported to be EGRET sources (Esposito et al. 1996; Sturner et al. 1996). In general, these remnants exhibit OH-maser emission (Green et al. 1997), have relatively flat radio spectra (Green 1998), have thermal-composite X-ray morphologies (Rho 1995), and have photon spectra with differential spectral indices of about two. Collectively, these results suggest that the remnants are interacting with molecular clouds and that the gamma rays are produced by the interaction of cosmic rays with these clouds (Esposito et al. 1996; Chevalier 1999). However, these results are uncertain because the angular resolution of EGRET is too poor to resolve the spatial distribution of the gamma rays and because the sensitivity of EGRET is too poor to determine if the spectra of these sources exhibit evidence of π^0 "bumps." Since the angular resolution and sensitivity of GLAST will be much better than the resolution and sensitivity of EGRET (GLAST Science Team 1999), observations with GLAST should provide the first direct evidence that cosmic-ray nuclei are accelerated in the shocks of supernova remnants.

In section 2 we show that it will be possible to determine if the gamma-ray flux of the remnants reported by Esposito et al. (1996) and Sturner et al. (1996) are associated with regions where the shocks of the remnants are interacting with molecular clouds and if the spectra of these remnants exhibit π^0-bump features.

2 Simulations and Discussion:

We have simulated the results that would be obtained for the supernova remnant γ Cygni based on a one-year all-sky survey with GLAST. Radio observations of γ Cygni suggest that it is a shell-type remnant with a diameter of about 1° and a radio spectral index of $\alpha = 0.54 \pm 0.02$ (Zhang et al. 1997). The corresponding differential electron spectral index is $\Gamma = 2\alpha + 1 = 2.08 \pm 0.04$ at electron energies ~ 1 GeV. An X-ray observation reveals a point-like source near the center of the image of the remnant that may be a neutron star (Brazier et al. 1996). Although no evidence of pulsations is reported, the gamma-ray to X-ray flux ratio is consistent with the source being a pulsar (Brazier et al. 1996). Observations with EGRET reveal a gamma-ray source whose position is consistent with the positions of the remnant and the X-ray source and whose spectrum has a photon index $\Gamma = 2.08 \pm 0.04$ (Hartman et al. 1999). This source has the largest signal-to-background ratio of any of the sources in the third EGRET catalog (Hartman et al. 1999) that are positionally coincident with shell-type supernova remnants.

For the purposes of the simulated observations with GLAST, we arbitrarily assume that 60% of the gamma-ray flux is produced by a pulsar at the location of the X-ray source. This pulsar is assumed to have a differential photon index of $\Gamma = 2.08$. The remainder of the gamma-ray emission is attributed to the gamma rays produced by the interaction of cosmic-ray electrons and protons with a molecular cloud. The electron and proton spectra of γ Cygni are assumed to have the shape specified by Bell (1978, eq. 5) with a common relativistic spectral index of $\Gamma = 2.08$. The normalization of the electron spectrum is determined from the radio data by assuming that the magnetic field strength is 100 μG. The normalization of the proton spectrum is determined by assuming that the total number of non-thermal electrons is a factor of 1.2 larger than the number of non-thermal protons. This ratio follows from the assumptions that the relative elemental abundances of the cosmic rays are comparable to the relative elemental abundances of the solar system and that all hydrogen and helium nuclei are fully ionized.

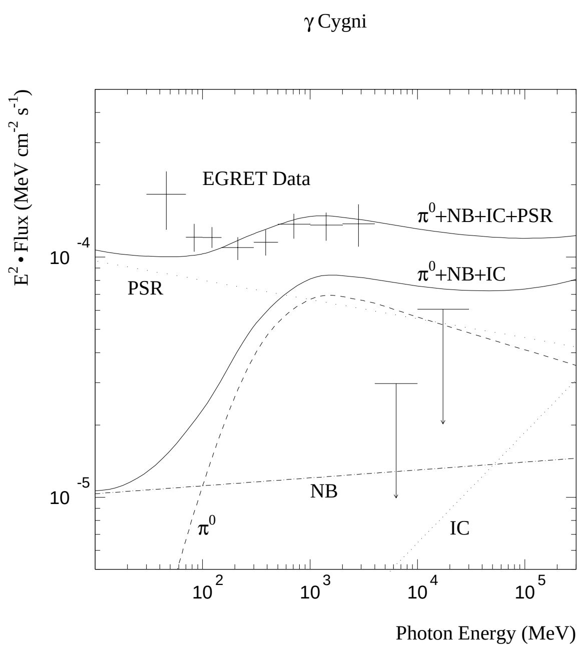

Figure 1: Models of the π^0, non-thermal bremsstrahlung (NB), inverse Compton (IC), and pulsar (PSR) gamma-ray spectra associated with γ Cygni. The sum of the three cosmic-ray components (π^0+NB+IC) of the shell and the sum of all four components (π^0+NB+IC+PSR) are shown. For comparison, the EGRET spectral data (Esposito et al. 1996) is included.

Figure 1 shows the gamma-ray spectra produced by the pulsar, by the decay of neutral pions, by the bremsstrahlung radiation of the electrons, and by the inverse Compton scattering of electrons on the cosmic microwave background radiation. The latter three of these four spectra are obtained using the gamma-ray emissivity results of Gaisser, Protheroe, & Stanev (1998), which have been reproduced by Baring et al. (1999). The non-thermal bremsstrahlung and π^0 spectra are obtained assuming that the average density of the material with which the cosmic rays interact is $n_0 = 190$ atoms cm^{-3}. A density this large is required to make the sum of the four spectral components roughly match the EGRET spectrum of the remnant (fig. 1). Since the cloud is assumed to interact with only a small portion of the surface of the remnant (fig. 2), the average density of the cloud is much larger than $n_0 = 190$ atoms cm^{-3}.

Figure 2 shows the results of the simulation of the spatial distribution of the source and background photons in the vicinity of γ Cygni based on the data that will be obtained in a one-year all-sky survey with GLAST. The dashed circle and plus indicate the locations of the shell of γ Cygni (Higgs et al. 1977) and a putative pulsar (Brazier et al. 1996), respectively. The gamma-ray flux has been partitioned between the pulsar and a bright knot of the radio image (Higgs et al. 1977) that we assume is associated with the interaction of the remnant and a molecular cloud. The diffuse background is assumed to be isotropic with a flux of 4×10^{-4} cm^{-2} s^{-1} sr^{-1} at energies > 100 MeV. This background is consistent with the EGRET background of this region. For the first time, it will be possible to associate the gamma rays with either a pulsar or the shell of the remnant. Therefore, will be possible to separately measure the spectra of the pulsar and the shell.

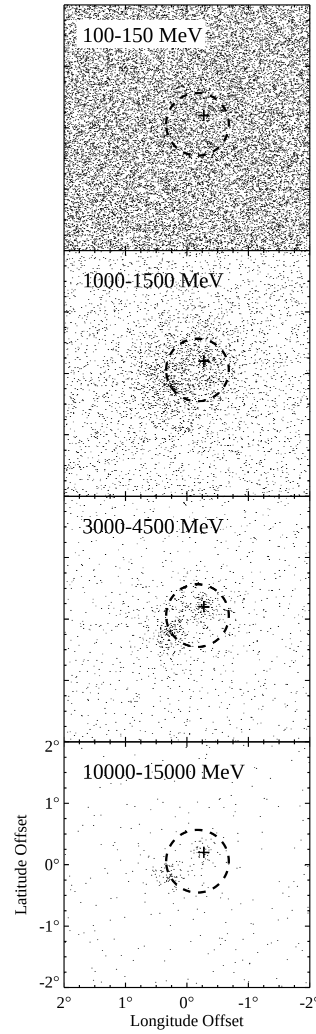

Figure 2: See text.

Figure 3 shows the simulated spectral results for the pulsar and the remnant separately. These spectra are obtained by performing an unbinned maximum likelihood analysis of the spatial and spectral information of the source and background photons. Since the π^0-bump feature is very obvious in the spectrum of the remnant, it will be possible to determine the spectrum of the cosmic-ray nuclei of γ Cygni using GLAST. Although this simulation is optimistic in the sense that γ Cygni has a large signal-to-background ratio and a large fraction of the gamma-ray flux is assumed to be associated with the decay of π^0s, it is clear from figure 3 that it would still be possible to identify a π^0 spectrum for remnants that have much smaller signal-to-background ratios or much smaller π^0-flux fractions. The detection of the π^0 spectrum would also provide a means of determining the ratio of the number density of cosmic-ray electrons to the number density of cosmic-ray nuclei. This ratio is sensitive to the ratio of the π^0 flux to the non-thermal bremsstrahlung flux (Gaisser et al. 1998; Baring et al. 1999). Therefore, if estimates of the relative gamma-ray flux of these two components suggest that cosmic-ray nuclei are more populous than cosmic-ray electrons by a factor of about 100 at 1 GeV, as is observed at Earth, the results will provide additional support for the idea that Galactic cosmic rays are predominantly accelerated in supernova remnants.

3 Conclusions:

We investigated the possibility that it will be possible to measure the π^0 gamma-ray spectrum of the supernova remnant γ Cygni using GLAST. The results of the spatial and spectral simulations are sensitive to the assumptions about the spatial distribution of the gamma rays, the shapes of the cosmic-ray electron and proton spectra, the distribution of the ambient material around the remnant, and the gamma-ray emissivity spectra of the various physical emission processes. Using what we believe are plausible assumptions for γ Cygni, we find that it should be possible to easily measure the π^0 gamma-ray spectrum of γ Cygni and to show that this spectrum is associated with a high-density cloud that is interacting with the remnant. This result would provide the first unambiguous proof that cosmic-ray nuclei are accelerated in the shocks of supernova remnants and, hence, provide a key missing piece to the puzzle about the acceleration of Galactic cosmic rays.

Of course, the importance of GLAST for the study of Galactic cosmic rays is not limited to the study of supernova remnants. For example, observations with GLAST will provide a detailed description of the diffuse gamma-ray emission of our Galaxy and others (e.g. the Large and Small Magellanic Clouds, M31, NGC 253, and M82) and will be useful for studying cosmic-ray interactions in molecular clouds and in clusters of galaxies.

In summary, observations with GLAST should (1) provide the first clear proof that Galactic cosmic-ray nuclei are predominantly accelerated in supernova remnants, (2) determine the shape of the cosmic-ray spectra, and (3) determine if similar cosmic-ray processes are at work in other galaxies.

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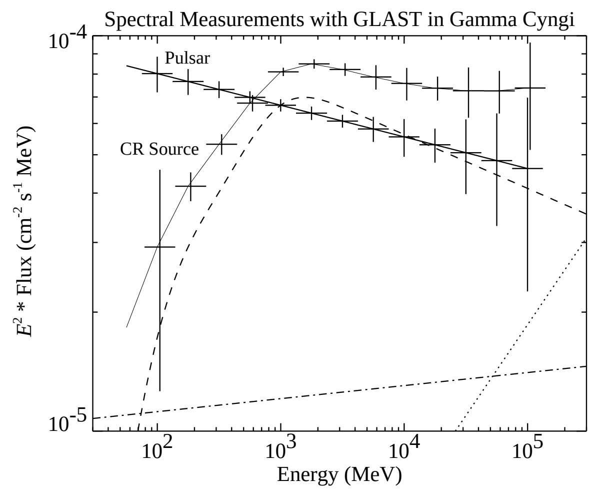

Figure 3: Simulations of the GLAST spectra of the pulsar and the shell of γ Cygni (see fig. 1). Below about 100 MeV, the two sources are not spatially resolved. The error bars indicate the 1 σ uncertainties. These simulations show that it should be possible to easily detect the π^0 component of the cosmic-ray nuclei in the shell.