Bull. Astr. Soc. India (2002) **30**, 61–71

Diffuse gamma ray emission: Implications on cosmic ray origin

P. Sreekumar

ISRO Satellite Centre, Bangalore-560 017, India.

Abstract. The Compton Gamma Ray Observatory (CGRO) produced the first full sky survey in gamma rays resulting in significantly improved data on the spectral and spatial distribution of diffuse gamma-rays from our galaxy. The intense diffuse gamma-ray emission arising from the Galaxy is understood as primarily arising from the interaction of energetic cosmic rays with the interstellar matter and radiation and is an excellent tool to study cosmic ray spectral characteristics and its distribution within the Galaxy. Comparison of the new data with simple cosmic ray models have led to important conclusions on the spectrum of cosmic-ray protons and electrons. We discuss the current understanding of these models and its implications for a galactic origin of cosmic rays.

Key words: Cosmic Rays, Diffuse Gamma Rays, Supernova

1. Introduction

The new era of gamma-ray astronomy was long sought after as a new approach towards understanding cosmic ray origin and acceleration in the Galaxy. As early as 1952, Hayakawa (1952) and Hutchinson (1952) had shown that cosmic ray interactions in the interstellar medium can give rise to high-energy gamma rays. The early balloon-borne and satellite-borne experiments starting from the 1960's to 1980's which provided clear evidence for gamma-ray emission from our galaxy, include the OSO-3 observations of Kraushaar *etal.* (1972) and the balloon-borne experiment of Fichtel *etal.* (1972). These showed the first clear evidence for high-energy diffuse gamma ray emission from the galactic plane, the emission being strongly concentrated within 100 degrees about the galactic center. The SAS-2 gamma-ray satellite (Fichtel *etal.* 1975) during its rather short life provided the first survey of the diffuse gamma-ray emission from the Milky Way. It also provided the first evidence for an extragalactic gamma-ray background. The next significant advancement came from the European COS-B satellite which observed the gamma-ray sky for more than 6 years and produced extensive data on diffuse emission from the Galaxy, its spatial distribution in galactic longitude and latitude A radial gradient in the cosmic ray density distribution was also evident from a detailed modeling of the COS-B data (Mayer-Hasselwander *etal.* 1982; Strong *etal.* 1988; Bloemen *etal.* 1986).

The intense emission from the Galactic plane is interpreted as primarily arising from cosmic ray interactions with interstellar matter and radiation. The primary processes that produce diffuse gamma-ray emission are the decay of neutral pions from proton-proton collisions, bremsstrahlung by cosmic ray electrons and inverse Compton upscattering of low-energy photons by cosmic ray electrons. Bignami & Fichtel (1974) developed a cosmic ray-ISM coupling model to explain the observed gamma-ray distribution from the SAS-2 satellite. This was further improved with the introduction of a spiral-arm model for matter distribution (Bignami *etal.* 1975) and the incorporation of revised atomic and molecular hydrogen distribution in the Galaxy (Kniffen, Fichtel & Thompson 1977). These models could explain intensity enhancements at specific longitudes as resulting from cumulative line-of-sight contributions along tangents to spiral arms. Other models which included coupling to the interstellar magnetic field (Schlickeiser & Thielheim (1974); Thielheim (1975)) also showed reasonable agreements with observations. Paul, Casse and Cesarsky (1976) and Kniffen, Fichtel & Thompson (1977) used the proportionality between cosmic ray density, matter density and galactic magnetic field energy density to refine these diffuse emission models. Based on the assumption that cosmic rays are produced by galactic supernovae, Stecker (1975) and Paul, Casse & Cesarsky (1976) showed that cosmic ray models based on known supernova distribution also explained the diffuse gamma ray observations. Contribution from star-light photons upscattered by cosmic ray electrons via the inverse Compton process was emphasised by Cowsik & Voges (1975), Fichtel, Simpson & Thompson (1977) and Stecker (1979). The observational data has clearly shown the need for an inverse Compton component to explain the diffuse spectrum.

Major impediments towards a detailed understanding of the galactic cosmic ray distribution using SAS-2 and COS-B observations included limited photon statistics and poor angular resolution. This led to large uncertainties in the point-source contribution to the derived diffuse emission. In 1991 with the launch of CGRO, point source resolution was significantly enhanced (source positioning to sub-degree scale), more than an order of magnitude increase in effective area yielding large photon statistics over a multi-year mission. CGRO's broad-band spectral coverage from 20 keV to 10 GeV (Gehrels *etal.* 1993) including wide FOV instruments in the 1 MeV to 10 GeV band (COMPTEL and EGRET) has resulted in the most detailed spectral and spatial distribution data to date. This has provided a wealth of data to carefully address spectral characteristics of diffuse gamma-ray emission at various spatial scales throughout the Galaxy. Here, we examine some of the results from CGRO in the context of current diffuse models and discuss impacts on the distribution and origin of cosmic rays in our galaxy.

2. Current diffuse models

The near transparency of the Galaxy to gamma-rays and the availability of fairly detailed radio and mm data on H1 and CO distributions makes the basic calculation of the galactic diffuse emission rather straightforward. With the significantly improved sensitivity and angular resolution of MeV/GeV instruments on CGRO, it was essential to generate a detailed model of the spatial distribution of atomic hydrogen, molecular hydrogen, ionized hydrogen, starlight photons and cosmic rays. Bertsch *etal.* (1993), Hunter *etal.* (1997) and Strong *etal.* (1986) have developed such models both towards understanding the diffuse emission as well as to permit analysis of other point sources embedded in the strong diffuse emission from the galactic disk. Bertsch *etal.* (1993) discussed in detail the relevant gamma-ray production mechanisms and the approach towards the construction of a 3-D model of the interstellar matter (H1, H_2) and radiation necessary to model the diffuse emission. Strong *etal.* (1997) extensively modeled the diffuse emission in the 1-30 MeV range using data from COMPTEL using a self-consistent cosmic ray model while Hunter *etal.* (1997) used data from EGRET to examine the spatial and spectral characteristics of the higher energy (> 30 MeV) diffuse emission.

3. Results from CGRO

Gamma-ray sky survey in the 1-30 MeV range was carried out by COMPTEL and in the 30 MeV to 30 GeV range by EGRET. We do not discuss here < 1 MeV results from the OSSE experiment due to the limited sky coverage of OSSE compared to the other two wide FOV instruments. Hunter *etal.* (1997) extensively summarised the results for the 30 MeV to 30 GeV band while Strong *etal.* (1997) discussed the 1-30 MeV range. Strong, Moskalenko & Reimer (2000) has also carried out a combined 1 MeV to 10 GeV analysis of the diffuse spectrum.

3.1 Spatial distribution

The detailed examination of the emission profiles (observed emission - resolved point sources) in galactic longitude and latitude shows excellent agreement below 1 GeV with the model predictions (see fig 1; Hunter *etal.* 1997 (fig 2,3)). Longitudinal profiles indicate good correlations with tangents to the spiral arms where the product of cosmic-ray density and interstellar matter density integrated over the line-of-sight are enhanced. Deviants from the overall profile in regions such as molecular cloud locations are also well reproduced by the model (fig 2). In the final plot in figure 1, the calculated model intensities fall well below the observations. If the model intensity values are scaled up, it shows good agreements with the longitudinal structural details (see fig 2 of Hunter *etal.* 1997), suggesting proper accounting of relative density enhancements but incorrect normalisation factor for the model above 1 GeV.

3.2 Spectral distribution

The observed diffuse spectrum is fit using the predicted contributions from the three important diffuse gamma-ray production processes. The average spectrum from the inner galaxy shows for the first time clear evidence for a π^0-decay component around 70-100 MeV (fig 4. in Hunter *etal.* 1997). This is the clearest evidence for cosmic ray protons in the ISM with the gamma-ray data providing the unique capability to deduce the spectrum of the source protons. Below 1 GeV, the observed spectrum well fits the models based on cosmic ray interactions with interstellar matter and radiation (Hunter *etal.* 1997; Strong *etal.* 1997). No significant variations in the diffuse spectrum is observed

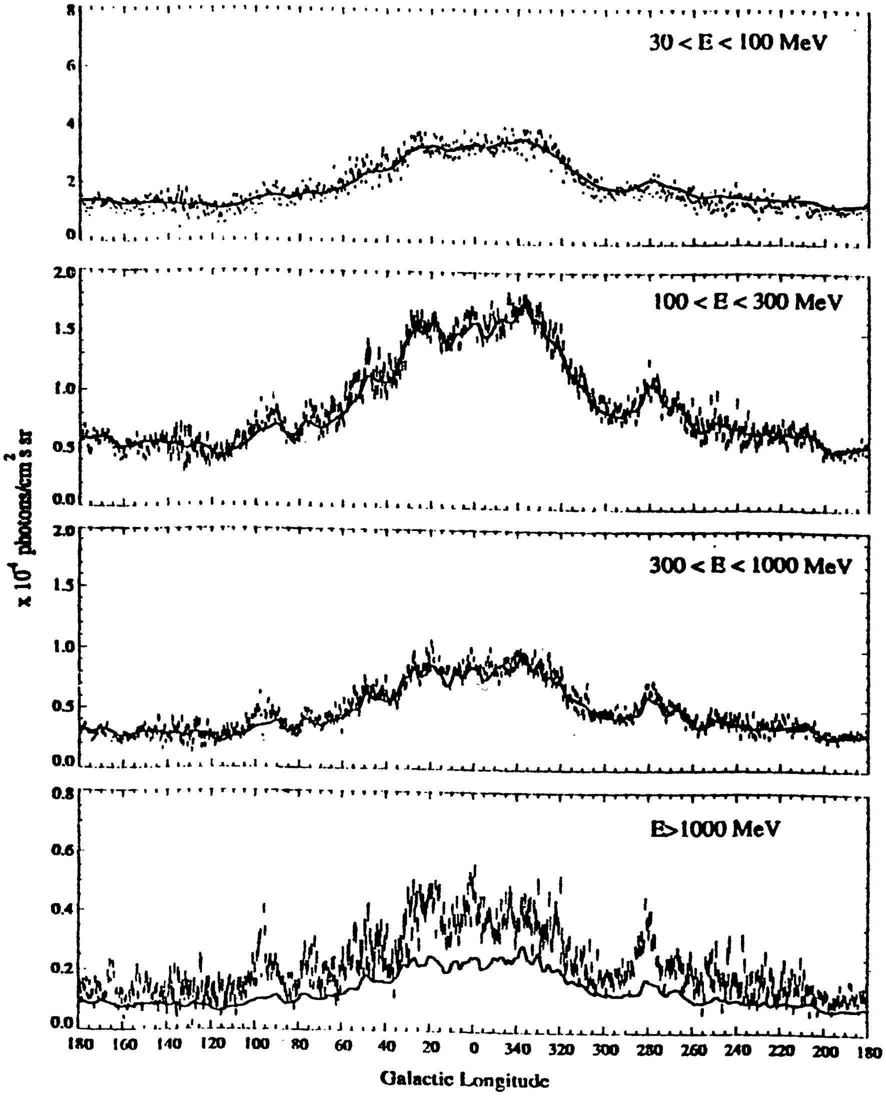

Figure 1. Longitudinal profiles at 4 broad energy bands showing the Hunter *etal.* (1997) model predications against source-subtracted EGRET data. The observational data above 1 GeV is clearly underpredicted by the model.

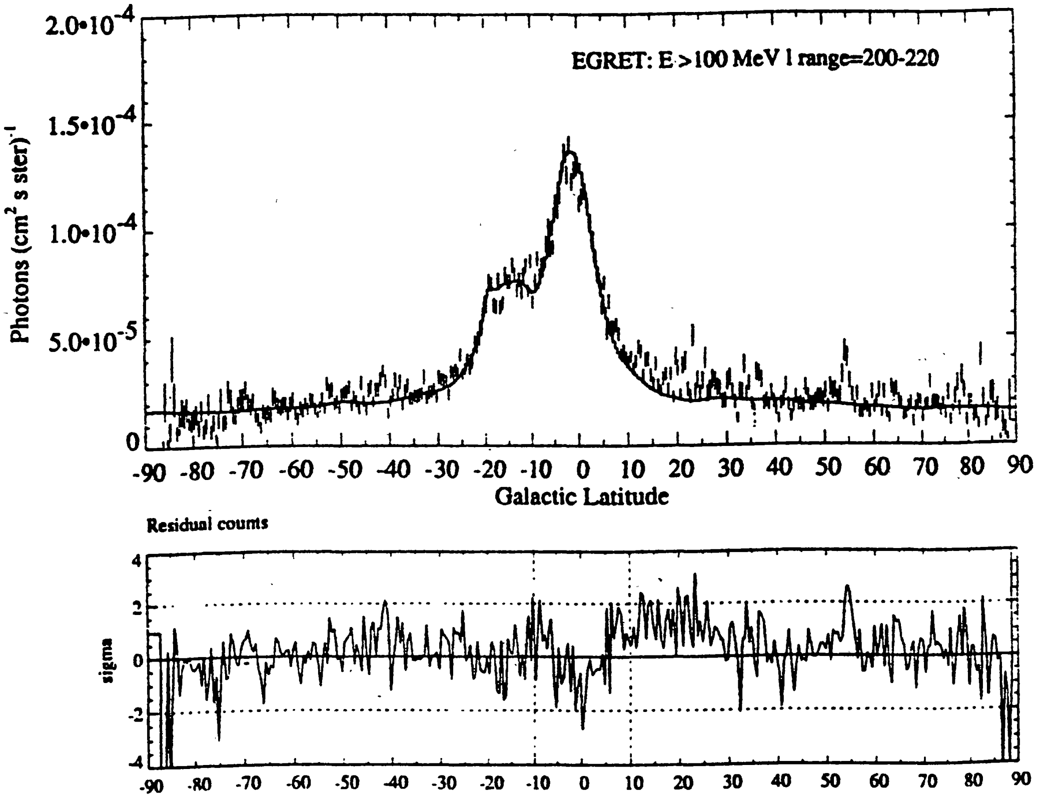

Figure 2. Latitude profile (> 100 MeV) showing the Hunter *etal.* (1997) model predications against source-subtracted EGRET data. Note the good fit even at locations populated by large molecular clouds.

as the data are examined at independent latitude/longitude intervals (Hunter *etal.* 1997). Hence there are no measurable large scale variations in the cosmic ray electron to proton ratio throughout the Galaxy at least within EGRET sensitivity/energy-resolution limits. This points to a fairly robust understanding of the diffuse emission process as well as good indications of the galaxy-wide proton and electron spectra being similar to that measured directly near earth. However, EGRET observations also show that above 1 GeV, the intensity of diffuse gamma rays from the galactic plane exceeds the calculations from most models that successfully explain the emission spectrum below 1 GeV. The nearly 50% underprediction of the overall GeV intensity is further constrained by the need for a harder spectral component to explain the observations. We discuss below possible explanations for this discrepancy.

3.3 Galactocentric radial gradient in cosmic-rays

Hunter, Kinzer & Strong (1997) reviewed the radial emissivity gradient of cosmic rays derived from diffuse gamma-ray studies. There is clear evidence for a radial gradient with the enhancement in cosmic ray density near the Galactic center and decreasing with increasing Galactocentric radius (see fig 9 in Hunter, Kinzer & Strong (1997)). Preliminary evidence for such a gradient was present even from earlier studies. Kniffen, Fichtel & Thompson (1977) had concluded from SAS-2 observations that the dynamic intercoupling of cosmic rays, magnetic fields and the neutral interstellar medium naturally leads to cosmic-ray density enhancements in regions of high matter density. This results in reduced cosmic ray density with increasing galactocentric radius. This is confirmed by the inconsistency of uniform cosmic ray density models with observations. Similarly, radial gradient in the cosmic ray density distribution was also evident from a detailed modeling of the COS-B data (Strong *etal.* 1988; Bloemen *etal.* 1986).

3.4 X-factor determination

The factor used to convert CO line intensity to H_2 column density is often referred to as the 'X-factor'. This is an important factor since it determines the amount of molecular hydrogen in the Galaxy and is relevant for various studies such as estimation of total mass in molecular clouds and star-formation regions. It has been recognised over the years that diffuse gamma rays which can map out neutral target material in the Galaxy for cosmic ray interactions, is an excellent tool to determine the X-factor. Though various authors have discussed variations of the X-factor within the Galaxy through dependence on galactic longitude, latitude and metallicity, current gamma ray data have been used only to address the large scale galaxy-averaged X-factor. Strong *etal.* (1988) derived a value of 1.9±0.3 from a detailed analysis of the COS-B data. Early studies by Bhat *etal.* (1985) had predicted much lower values approaching unity. Hunter *etal.* (1997) derived a value of 1.56±0.05 using EGRET data. From studies of select molecular cloud complexes, Digel *etal.* (1996,1997) and Hunter *etal.* (1994) derived values of (0.92±0.14 (local arm); 1.56±0.29 (Monoceros), 1.1±0.2 (rho Ophiuchus), (1.06±0.14 (Orion), 2.48±0.89 (Perseus arm)) and found only a weak evidence for slightly larger X-factor in the outer Galaxy. There has been a clear decrease in the average X-factor from the days prior to CGRO.

3.5. Uncertainties in the models

The analysis of Hunter *etal.* (1997) used basic principles of equipartition and coupling of cosmic-rays to the ISM to derive a diffuse gamma ray model that adequately explains the large scale spatial distribution and the energy spectrum below 1 GeV. Numerous simplifying assumptions were made in deriving this model. These include, uniform coupling of the cosmic rays to the ISM throughout the Galaxy, location-independent cosmic ray electron and proton spectra identical to that measured locally near the Sun, standard ratio of cosmic ray electrons to protons throughout the Galaxy, and negligible contributions from secondary electrons. Similarly, Strong, Moskalenko & Reimer (2000) have successfully derived important cosmic ray model parameters such as injection spectra, cosmic ray halo size, positron fraction, etc using consistency arguments with the 1 MeV - 10 GeV data. The derived large cosmic ray scale heights of 4-10 kpc (Strong, Moskalenko & Reimer 2000) are significantly larger than those derived from other studies such as synchrotron data (Haslam 1982). In all these models significant uncertainly in the inverse Compton contribution arises from poor models of starlight distribution in the Galaxy and uncertain cosmic ray halo size. A larger halo naturally leads to an increased inverse Compton contribution from cosmic microwave background.

4. Implications on cosmic ray origin

Using the first galactic plane survey in gamma rays by the SAS-2 satellite, Kniffen, Fichtel & Thompson (1977) and Hartman *etal.* (1979) showed that a uniform cosmic ray density distribution in the Galaxy cannot explain the observed diffuse gamma-ray observations. The observations required a cosmic ray gradient in the Galaxy suggesting a galactic origin for the bulk of the cosmic rays. Diffuse emission models have in general concluded that enhancements in cosmic ray densities at regions of high matter density are necessary to explain the observed longitudinal and latitudinal profiles. If we represent this as

$$\mathrm{L}_\gamma I = \rho_{CR}^n$$

where L_γ is the observed gamma-ray intensity and ρ_{CR} is a measure of the local cosmic ray density, then most analysis indicate $1 < n < 2$. Thus gamma-ray observations provide a high contrast image of the galactic cosmic ray distribution, an important advantage in studying the origin and acceleration of cosmic rays in our galaxy and beyond.

The fundamental question of whether the bulk of cosmic rays originate within our galaxy or are extragalactic was a subject of debate until recently. Cosmic ray electrons were already understood to be of galactic origin considering large energy loss process as electrons traverses the ISM and from constraints of overproduction of extragalactic diffuse gamma-rays via the inverse Compton upscattering of the microwave background. CGRO observations were key in addressing the galactic or extragalactic origin of cosmic ray protons. The presence of a clear gradient in cosmic ray density with galactocentric radius derived from diffuse gamma rays in the Galaxy and the gamma-ray observations of the nearby Large and Small Magellanic Clouds (Sreekumar *etal.* 1992; 1993) conclusively prove that the bulk of the cosmic rays are of galactic origin. We examine below possible sites for a galactic origin.

2002BASI...30...61S

4.1 Supernova Remnant origin

Supernova remnants have always been considered prime sources for the production and acceleration of galactic cosmic rays. Typically SNRs put out 10^{51} ergs into the interstellar medium with about 10% of this in the form of energetic particles. With a mean rate of 3 SN per century, and typical active Sedov phase of $\sim 10^5$ years, SNRs are indeed excellent candidates for the production of cosmic rays. As discussed before, the interaction of these cosmic rays in the vicinity of the remnant can give rise to observable gamma-ray emission.

The determination of the SNR distribution in the Galaxy is constrained by the limited distance to which a remnant can be resolved at photon energies below MeV energies. Case and Bhattacharya (1997) carried out an extensive survey to catalog the distances to SNRs in the Galaxy and derived a radial distribution of SNRs. A direct comparison of the gamma-ray derived cosmic ray radial gradient with the SNR radial distribution shows incompatibility; the SNR distribution being sharply peaked in the inner galaxy. Considering the effects of diffusion and other propagation effects on the SNR distribution, the derived cosmic-ray density distribution changes too slowly with radius to be consistent with a primary origin at supernova sites. This appears to suggest that SNRs are not the dominant sites for cosmic ray origin and maybe propagating interstellar shocks are more effective in accelerating cosmic rays.

Let us examine the evidence for gamma-ray detection of supernova remnants. Observationally, only a few remnants have been associated with gamma-ray source error boxes (Sturner & Dermer 1995, Esposito *etal.* 1996). Early EGRET observations showed the presence of four candidate SNRs associated with galactic plane gamma-ray point sources (Esposito *etal.* 1996). Distinct from most extragalactic gamma-ray point sources, these sources show steady gamma-ray luminosity, consistent with that expected from diffuse origin from SNRs. Unlike the galactic diffuse spectrum, the spectral data from these SNR candidate sources shows no tell-tale signature of the "pion-bump" at around 70 MeV that would be indicative of a diffuse origin. Further, from multifrequency radio synchrotron data and using equipartition arguments it can be shown that the estimated enhancement in the mean cosmic ray density is insufficient to explain the gamma-ray luminosity of these remnants unless one includes the presence of significant concentrations of matter (e.g. molecular clouds) in the vicinity of the remnants (Aharonian *etal.* 1994; Esposito *etal.* 1996). In this scenario, the enhanced density of target material can produce the observed gamma ray emission as opposed to enhanced cosmic ray density. Could some of the few hundred unidentified gamma-ray sources (Hartman *etal.* 1998) be gamma-ray bright SNRs? Interactions between cosmic-rays and dense ISM can give rise to OH maser emission at 1720 MHz (Claussen *etal.* 1997). A detailed search of a subset of other unidentified EGRET source error boxes have not yielded any new maser detections (Arzoumanian *etal.* 2001). This lends support to the conclusion that SNRs do not form a major source class associated with the unidentified gamma-ray sources along the galactic plane. Alternately, if gamma-ray luminosity of SNRs are driven by the presence of enhanced matter in the vicinity, this could imply that there is only a low probability of finding adequate target materials near remnants. Clearly, the insufficient detections of SNRs in high-energy gamma-rays remains a concern with respect to models where they produce the bulk of galactic cosmic rays. Finally, the possibility that the observed gamma-ray emission from SNR candidates arises from young, rotation-driven pulsars associated with these remnants is possible even though the gamma-ray data show no evidence for associated pulsations.

4.2 Implications of the GeV excess

The observed diffuse spectrum above 1 GeV shows an excess over that predicted by the model of Hunter *etal.* (1997). At these energies the dominant contribution is expected from the decay of neutral pions. The spectral slope above 1 GeV is found to be flatter than that predicted by models using a cosmic ray proton spectrum of index -2.7 (near Earth measurements yield an index of 2.70±0.02). Two of the more likely possibilities include

a) a harder cosmic ray proton source spectrum

b) an enhanced contribution from inverse Compton processes above 1 GeV

Assuming that the dominant contribution above 1 GeV arises from π^0-decay process, Mori (1997) showed that a harder proton spectrum of index -2.45 provides a much improved fit to the data. This could come about if the measured cosmic ray proton spectrum is greatly influenced by local sources of cosmic rays and hence deviant from the mean spectral shape elsewhere in the Galaxy. Alternatively, energy-dependent diffusion effects are expected to alter the source spectrum as it propagates through the ISM. A good test to determine differences between the local and galactic-averaged spectra is to examine the diffuse emission spectrum at high latitudes. At high latitudes the galactic emission is expected to be less intense due to the small scaleheight of H1 and H_2 distribution. However, for a reasonable scale height of cosmic rays of $\sim$ 1 kpc, much of the emission is produced locally and hence indicative of the local cosmic ray spectra. Detailed analysis by Sreekumar *etal.* (1998) showed the high-latitude galactic emission also show deviations from the $E^{-2.7}$ proton spectrum similar to that observed in the plane.

Another test of a harder proton spectrum to explain the GeV excess was pointed out by Moskalenko, Strong & Reimer (1998). They developed a cosmic ray propagation model that attempts to reproduce various observational parameters related to cosmic ray propagation in a self-consistent manner. The calculation includes diffusion and reacceleration for a given injection spectrum. A by-product of this calculation is the anti-proton flux prediction. Since a harder cosmic ray proton spectrum yields more anti-protons, the ratio of protons to anti-protons is a sensitive indicator of a harder spectrum. Recent anti-proton measurements by Bergström *etal.* (2000) are inconsistent with a harder proton spectrum, further weakening this explanation for the GeV excess. New experiments including AMS on the International Space Station should better constrain this conclusion.

Inverse Compton contributions are inherently uncertain due to the large uncertainties in the soft photon distribution and scale heights of seed photons and cosmic ray electrons. However, the resulting upscattered spectrum is naturally hard ($\sim$ 1.8-2.0) and can be used to explain the harder gamma-ray spectrum above 1 GeV (Pohl & Esposito 1998). Such an explanation solves easily the GeV excess seen in the galactic plane as well as at galactic latitudes. A close examination of the residual emission, where

$$\text{residual emission} = \text{total diffuse emission} - (\text{galactic}_{calculated} + \text{extragalactic})$$

shows the presence of an extended excess emission centered about the Galactic center (Sreekumar *etal.* 1998). This excess spectrum has a power law spectral index similar to inverse Compton emission. The spatial and spectral evidence for additional inverse

Compton contribution to the diffuse model estimates can be strengthened only with a refined soft photon distribution in the Galaxy as well as from more constrained estimates of the Galactic cosmic ray electron halo size. Major improvements are expected with the next generation gamma-ray mission (GLAST : launch ~2005) being designed to provide higher throughput spectrum beyond 1 GeV.

5. Conclusion

CGRO observations have provided new evidences for a galactic origin of cosmic ray protons in our galaxy. Though galactic supernovae remain ideal candidates for the source of cosmic rays, uncertainties remain due to deviations from the observed radial distribution of SNRs and in the derived spectral shapes. The detection of a few steady gamma-ray sources coincident with SNRs with no characteristic spectral signatures (such as the "pion-bump") is insufficient evidence to clearly establish the primary origin of cosmic rays from supernovae in our galaxy. New missions such as GLAST, with enhanced spectral capabilities especially above 1 GeV, are necessary to resolve this long standing question of cosmic ray origin.

References

Aharonian, F.A., Drury, L.O'C., & Völk, H.J., 1994, A&A, 285, 645

Arzoumanian, Z., Yusef-Zadeh, F., & Lazio, T.J., 2001, astro-ph/0107145

Bertsch, D.L., *etal.* 1993, ApJ, 416, 587

Bhat, C.L., Issa, M.R., Houston, B.P., Mayer, C.J., & Wolfendale, A.W., 1985, Nature, 314, 511

Bignami, G.F., & Fichtel, C.E., 1974, ApJ, L65

Bignami, G.F., Fichtel, C.E., Hartman, R.C., & Thompson, D.J., 1979, ApJ, 232, 649

Bloemen, J.B.G.M., *etal.* 1986, A&A, 29, 469

Claussen, M.J., *etal.* 1997, ApJ., 489, 143

Cowsik, R. & Voges, W., 1975, 14th Int. Cosmic Ray Conf. (Munich), 1, 74

Digel, S.W., *etal.* 1996, ApJ, 463, 609

Digel, S.W., *etal.* 1997, Proc. 4th Compton Symp., ed. C.D Dermer, M.S.Strickman, & J.D.Kurfess, 1188

Esposito, J.A., Hunter, S.D., Kanbach, G., & Sreekumar, P. 1996, ApJ,461, 820

Fichtel, C.E., *etal.* 1975, ApJ, 198, 163

Fichtel, C.E., Simpson, G.A., & Thompson, D.J., 1977, ApJ, 222, 833

Fichtel, C.E., Özel, M.E., Stone, R.G., & Sreekumar, P., 1991, ApJ, 374, 134

Gehrels, N., Fichtel, C,E., Fishman, G.J., Kurfess, J.D., & Schönfelder, V., 1993, Sci. Am. 269, 68

Haslam, C.G.T., *etal.* 1982, A&AS, 47,1

Hartman, R.C., et al., 1979, ApJ, 230, 597

Hayakawa, S. 1952, Progr. Theoret. Phys. 8, 571

Hunter, S.D., *etal.* 1994, ApJ, 436, 216

Hunter, S.D., *etal.* 1997, ApJ, 481, 205

Hunter, S.D., Kinzer, R.L. & Strong, A.W., Proc. 4th Compton Symp., ed. C.D Dermer, M.S.Strickman, & J.D.Kurfess, 192

Hutchinson, G.W. 1952, Phil. Mag., 43, 847

Kniffen, D.A., Fichtel, C.E., & Thompson, D.A., 1977, ApJ, 215, 765

Kraushaar, W.L., et al., 1972, ApJ, 177, 341

Mayer-Hasselwander, H.A., et al., 1980, Ann. NY Acad. of Sci. Np 336, 9th Texas Symp. on Rel. Astrophysics (Munich), 211

Mayer-Hasselwander, H.A., et al., 1982, A&A, 105, 164

Moskalenko, I.V., Strong, A.W. & Reimer, O., 1998, A&A, 338, L75

Paul, J., Casse, M., & Cesarsky, C.J., 1976, ApJ, 207, 62

Pohl, M. & Esposito, J.A., 1998, ApJ, 507, 327

Schlickeiser, R., and Thielheim, K.O., 1974, Phys. Letters, 53B, 369

Sreekumar, P., *etal.* 1992, ApJ, 400, L67

Sreekumar, P., *etal.* 1993, ApJ, Phys. Rev. Lett., 70, 127

Sreekumar, P., *etal.* 1998, ApJ, 494, 523

Strong, A.W., *etal.* 1988, A&A, 207, 1

Strong, A.W., *etal.* 1997, Proc. 4th Compton Symp., ed. C.D Dermer, M.S.Strickman, & J.D.Kurfess, 1198

Strong, A.W., Moskalenko, I.V., & Reimer, O., 2000, ApJ, 537, 763

Sturner, S.J., & Dermer, C.D., 1995, A&A Let. 293, 17

Stecker, F.W. 1975, Phys. Rev. Letters, 35, 188

Stecker, F.W. 1979, ApJ, 228, 919

Thielheim, K.O. 1975, in Origin of Cosmic Rays, ed J.L.Osborne and A.W.Wolfendale (Dordrecht: Reidel), 165