DIFFUSE GAMMA RAYS

Galactic and Extragalactic Diffuse Emission

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Abstract

"Diffuse" gamma rays consist of several components: truly diffuse emission from the interstellar medium, the extragalactic background, whose origin is not firmly established yet, and the contribution from unresolved and faint Galactic point sources. One approach to unravel these components is to study the diffuse emission from the interstellar medium, which traces the interactions of high energy particles with interstellar gas and radiation fields. Because of its origin such emission is potentially able to reveal much about the sources and propagation of cosmic rays. The extragalactic background, if reliably determined, can be used in cosmological and blazar studies. Studying the derived "average" spectrum of faint Galactic sources may be able to give a clue to the nature of the emitting objects.

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Introduction

As is discussed in detail in the first Chapter of this book, the subject of γ-ray astronomy was born in 1972 when the first statistically significant results were obtained by the SAS-2 satellite. This was followed by the COS-B observatory in 1975–1982 and several low-energy missions. The Compton Gamma-Ray Observatory (CGRO) launched in 1990 had 4 instruments onboard covering the energy range from 20 keV to 30 GeV and was very successful. Besides many observations of point sources, COS-B and then COMPTEL and EGRET (two of four CGRO instruments) unveiled the spectrum of the diffuse Galactic continuum emission and thus have shown the potential of γ-ray observations to contribute to cosmic ray physics.

The diffuse γ-ray emission supposedly consists of several components: truly diffuse Galactic emission from the interstellar medium, the extragalactic background, whose origin is not firmly established yet, and the contribution from unresolved and faint Galactic point sources. The Galactic diffuse emission dominates other components and has a wide distribution with most emission coming from the Galactic plane.

Diffuse continuum γ-rays from the interstellar medium are potentially able to reveal much about the sources and propagation of cosmic rays, but in practice the exploitation of this well-known connection is not straightforward. The Galactic diffuse continuum γ-rays are produced in energetic interactions of nucleons with gas via neutral pion production, and by electrons via inverse Compton scattering and bremsstrahlung. These processes are dominant in different parts of the spectrum, and therefore if deciphered the γ-ray spectrum can provide information about the large-scale spectra of nucleonic and leptonic components of cosmic rays. In turn, having an improved understanding of the Galactic diffuse γ-ray emission and the role of cosmic rays is essential for unveiling the spectra of other components of the diffuse emission and is thus of critical importance for the study of many topics in γ-ray astronomy, both Galactic and extragalactic.

The launch in 2007 of the Gamma-ray Large Area Space Telescope (GLAST) will tremendously increase the quality and accuracy of the γ-ray data. Study of the diffuse emission is one of its priority goals. In the present Chapter, we concentrate on the high energy ($E > 100$ MeV) part of the diffuse emission.

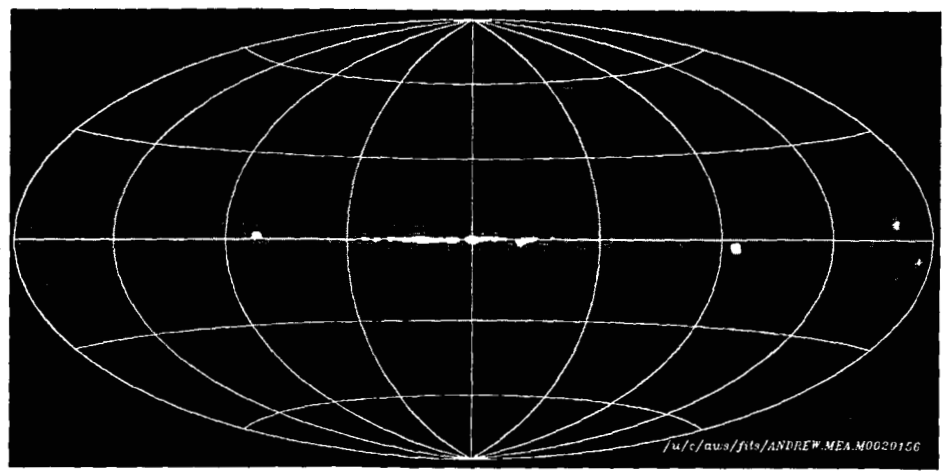

Figure 1. EGRET all-sky map in continuum γ-ray emission for energies >100 MeV (A. W. Strong, unpublished).

1. Gamma Rays and Cosmic Rays Connection

The Galactic diffuse γ-ray continuum emission, which arises from cosmic-ray proton and electron interactions with gas and interstellar radiation fields, is the dominant feature of the γ-ray sky. This emission in the range 50 keV – 50 GeV has been systematically studied in the experiments OSSE, COMPTEL, EGRET on the CGRO as well as in earlier experiments, such as SAS 2 and COS B. A review of CGRO observations was presented by Hunter et al. (1997).

The great sensivity and spatial and energy resolution of the EGRET instrument allowed for detailed spatial and spectral analysis of the diffuse emission (Fig. 1). Because the Galaxy is transparent to high energy γ-rays, the diffuse γ-ray emission is the line-of-sight integral over the emissivity of the interstellar medium. The latter is essentially the product of the cosmic ray density and the density of the gas or radiation field. The hydrogen distribution (H_2, H I, H II) is derived from radio surveys and an assumed Galactic rotation curve, where the distribution of molecular hydrogen is derived indirectly from CO radio-emission and the assumption that the conversion factor H_2/CO is the same for the whole Galaxy. The Galactic radiation field consists of contributions of stars, dust, and cosmic microwave background (CMB). Its spectrum varies over the Galaxy and (apart from the CMB) cannot be measured directly.

The first detailed analysis of the diffuse emission from the plane $|b| \leq 10°$ was made by Hunter et al. (1997). The basic assumptions of this calculation were that (i) the cosmic rays are Galactic in origin, (ii) a correlation exists between the cosmic ray density and interstellar matter in the Galaxy, and (iii) that the spectra of nucleons and electrons in the Galaxy are the same as observed in the solar vicinity. This analysis confirmed results of earlier experiments (Kniffen et al. 1973; Fichtel et al. 1975; Mayer-Hasselwander et al. 1982) that the great majority of the emission is clearly correlated with the *expected* Galactic diffuse emission. It was also shown (Strong et al. 1988) that, on average, there is a generally decreasing γ-ray emissivity per H atom, and hence a decreasing cosmic ray density, with Galactic radius.

The observations have confirmed main features of the Galactic model derived from cosmic rays, however, they brought also new puzzles. The γ-rays revealed that the cosmic ray source distribution required to match the γ-ray data apparently should be distinctly flatter (Strong and Mattox 1996) than the (poorly) known distribution of supernova remnants (SNRs), the conventional sources of cosmic rays. The spectrum of γ-rays calculated under the assumption that the proton and electron spectra in the Galaxy resemble those measured locally reveals an excess at >1 GeV in the EGRET spectrum (Fig. 2).

The puzzle of the "GeV excess" has lead to an attempt to re-evaluate the reaction of π^0-production in *pp*-interactions. However, a calculation (Mori 1997) made using modern Monte Carlo event generators to simulate high-energy *pp*-collisions has shown that the γ-ray flux agrees rather well with previous calculations.

Leaving the possibility of a instrumental artefact aside, another leading reason for the discrepancy discussed is that the local cosmic ray particle spectra (nucleons and/or electrons) may be not representative of the Galactic average. The local source(s) and propagation effects (e.g., electron energy losses) can change the spectrum of accelerated particles.

A flatter Galactic nucleon spectrum has been suggested as a possible solution to the "GeV excess" problem (Mori 1997; Gralewicz et al. 1997). Explaining the excess requires the power-law index of proton spectrum of about –2.4–2.5. A flatter electron spectrum has been proposed by Porter and Protheroe (1997) and Pohl and Esposito (1998). The average interstellar electron spectrum can be harder than that locally observed due to the spatially inhomogeneous source distribution and energy losses. The γ-ray excess in this case may be explained in terms of inverse Compton emission.

However, the average energy spectrum of the diffuse γ-ray emission alone does not tell much about the underlying processes. Instead, the

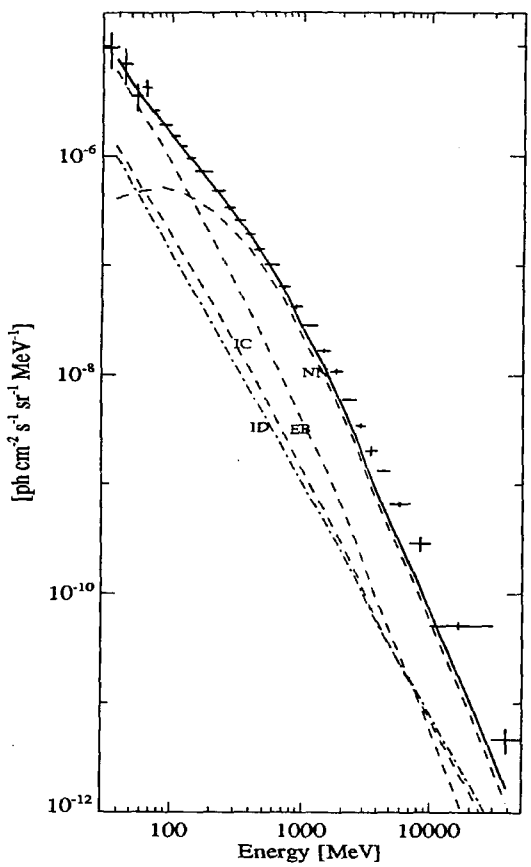

Figure 2 Average diffuse gamma-ray spectrum of the inner Galaxy region, $300° < l < 60°, |b| \leq 10°$. The contribution from point sources detected with more than 5σ significance have been removed. The individual components of this calculation are nucleon-nucleon (NN), electron bremsstrahlung (EB), inverse Compton (IC), and isotropic diffuse emission (ID). Adapted from Hunter et al. (1997).

spectrum of diffuse continuum γ-ray emission from different directions and its distribution on the sky carry unique information about the particle fluxes, mostly protons and electrons, in different locations. The π^0-decay and bremsstrahlung photons are gas related and thus should mimic the distribution of interstellar matter. In contrast, inverse Compton emission is broad since the density of background photons is high at even large distances from the Galactic plane. In practice, however, this simple picture is complicated because the H II gas distribution is broad with typical scale height $\sim$1 kpc, while the distribution of high energy electrons is narrow and concentrated near the Galactic plane due to the large energy losses. To decode the wealth of information provided to us by diffuse γ-rays from different directions one needs a proper propagation model to calculate the particle spectra and the corresponding γ-ray flux on a large Galactic scale.

A self-consistent model of particle propagation and generation of diffuse γ-rays should include cosmic-ray transport as the first step. Knowing the number density of primary nuclei from satellite and balloon observations, the production cross sections from laboratory experiments, and the gas distribution from astronomical observations, one can calculate the production rate of secondary nuclei. The observed abundance of radioactive isotopes determines then the value of the diffusion coefficient, halo size and other global parameters. The detailed procedure was described, e.g., by Ptuskin and Soutoul (1998) and Strong and Moskalenko (1998). Having fixed the propagation model and assuming some particle spectra in the cosmic-ray sources, this allows one to calculate the spectrum of the diffuse γ-ray emission (Strong et al. 2000).

2. Cosmic Rays

Cosmic rays are energetic particles, which come to us from outer space, and are measured either with satellites, balloons, or Earth based experiments. Direct measurements give the spectra in the local region of the Galaxy. For energies below 10 GeV the heliospheric modulation is large and this hinders the study of the truly interstellar spectrum.

The spectrum of cosmic rays can be approximately described by a single power law with index -3 from $\sim$10 GeV to the highest energies ever observed $\sim 10^{20}$ eV. The only feature observed below 10^{18} eV is a small change in the slope from -2.7 to -3.1 at $\sim 3\times10^{15}$ eV, known as the "knee." Because of this featureless spectrum, it is believed that cosmic-ray production and propagation is governed by the same mechanism over decades of energy; a single mechanism at least works below the knee, at $\sim 10^{15}$ eV, and the same or another one works above the knee. Meanwhile the origin of the cosmic-ray spectrum is not still understood.

Galactic cosmic rays are an important part of the interstellar medium. The energy density of relativistic particles is about 1 eV cm^{-3} and is comparable to the energy density of the interstellar radiation field, magnetic field, and turbulent motions of the interstellar gas. This makes cosmic rays one of the essential factors determining the dynamics and processes in the interstellar medium. The EGRET observations of the Small Magellanic Cloud (Sreekumar et al. 1993) have shown that the cosmic rays are a Galactic and *not* a "metagalactic" phenomenon. Observations of the Large Magellanic Cloud (Sreekumar et al. 1992), on the other hand, have shown that γ-ray emission is consistent with quasi-static equilibrium of cosmic rays and the interstellar medium.

The sources of cosmic rays are believed to be supernovae and SNRs, pulsars, compact objects in close binary systems, and stellar winds. Ob-

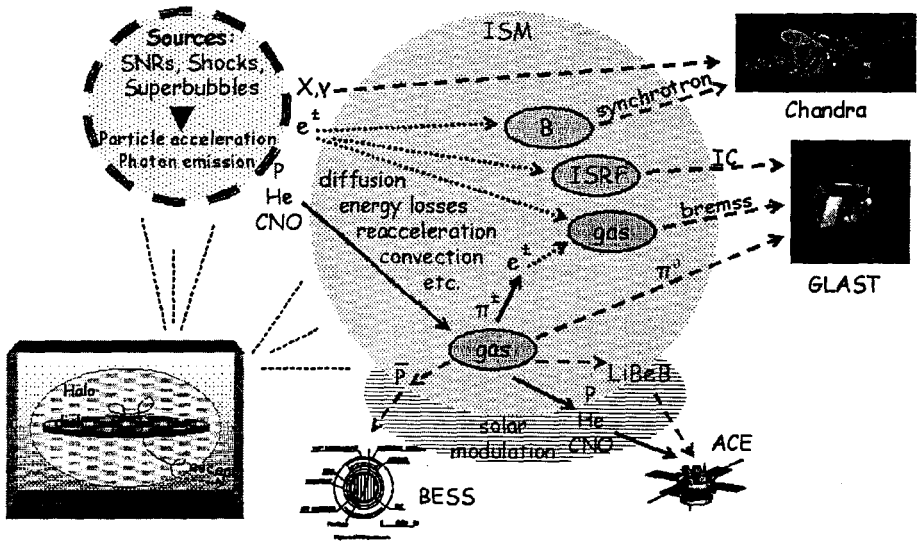

Figure 3. A schematic view of cosmic ray propagation in the interstellar medium (ISM), production of secondary nuclei, particles and γ-rays.

servations of X-ray and γ-ray emission from these objects reveal the presence of energetic particles thus testifying to efficient acceleration processes near these objects. The total power of Galactic cosmic ray sources needed to sustain the observed cosmic ray density is estimated at 5×10^{40} erg s^{-1} which implies the release of energy in the form of cosmic rays of approximately 5×10^{49} erg per supernovae if the supernova rate in the Galaxy is 1 every 30 years. This value comes to about 5% of the kinetic energy of the ejecta which is in agreement with the prediction of the theory of diffusive shock acceleration (Jones and Ellison 1991). This scenario implies that cosmic rays accelerated by the shock waves propagate further in the Galaxy where they are contained for some 10 Mys before escaping into intergalactic space.

Particles accelerated near the sources propagate in the interstellar medium (Fig. 3) where they lose or gain energy, their initial spectra and composition change, they produce secondary particles and γ-rays. The destruction of primary nuclei via spallation gives rise to secondary nuclei and isotopes which are rare in nature, antiprotons, and pions which decay producing γ-rays and secondary positrons and electrons. Because secondary antiprotons, positrons, and diffuse γ-rays (via neutral pion decay) are all products of the same *pp*-interactions, accurate measurements of the antiproton and positron fluxes, especially at high energies,

could provide a diagnostic of the interstellar nucleon spectrum complementary to that provided by γ-rays (Moskalenko et al. 1998; Strong et al. 2000).

The variety of isotopes in cosmic rays allow one to study different aspects of their acceleration and propagation in the interstellar medium as well as the source composition. Stable secondary nuclei tell us about the diffusion coefficient and Galactic winds (convection) and/or re-acceleration in the interstellar medium (2nd order Fermi acceleration mechanism). Long-lived radioactive secondaries allow one to constrain global Galactic properties such as, e.g., Galactic halo size. Abundances of K-capture isotopes, which decay via electron K-capture after attaching an electron from the ISM, can be used to probe the gas density and acceleration time scale. All these together allow us in principle to build a model of particle acceleration and propagation in the Galaxy.

The most often used propagation model, the flat halo diffusion model, has a simple geometry which reflects however the most essential features of the real system (Ginzburg and Ptuskin 1976). It is assumed that the Galaxy has the shape of a cylinder with a radius R ($\sim$20 kpc) and total height $2H$ ($H > 1$ kpc). The cosmic-ray sources are distributed within an inner disk having characteristic thickness $\sim$300 pc. The Sun is at a distance $\sim$8 kpc from the center of the Galaxy. The diffusion of cosmic rays averaged over the scale of few hundred parsec is isotropic. The particles escape freely through the halo boundaries into intergalactic space where the density of cosmic rays is negligible.

The modelling of cosmic-ray diffusion in the Galaxy includes the solution of the transport equation with a given source distribution and boundary conditions for all cosmic-ray species. The transport equation describes diffusion, convection by the hypothetical Galactic wind, energy losses, and possible distributed acceleration (energy gain). The study of transport of cosmic-ray nuclear component requires the consideration of nuclear spallation and ionization energy losses. Calculation of isotopic abundances is impossible without inclusion of hundreds of stable and radioactive isotopes produced in the course of cosmic-ray interactions with interstellar gas.

3. Galactic Structure

The Galaxy is a barred spiral with a radius of about 30 kpc (Fig. 4). From the point of view of γ-ray diffuse emission the important components are the gas and the interstellar radiation, while synchrotron emission provides restrictions on the electron spectrum. These are also relevant for the energy losses of cosmic rays. The gas content is domi-

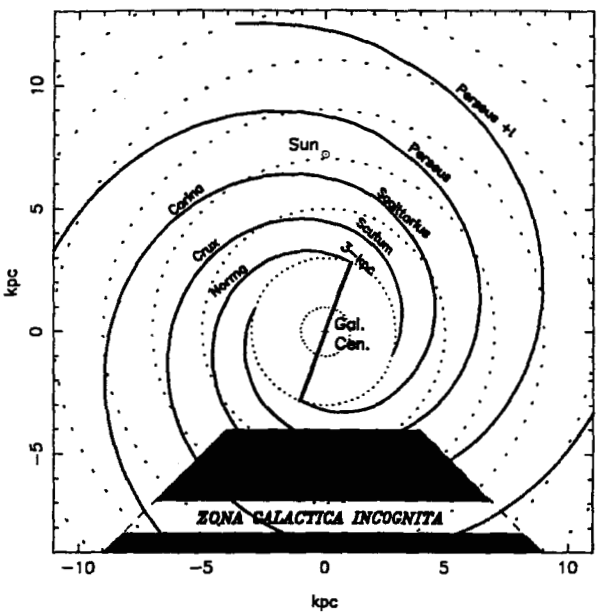

Figure 4 Model of logarithmic spiral arms. The sun is shown by the circled dot. Dots show the concentric circles at the Galactocentric radii 1, 3, 5, 7, 9, 11, 13 kpc. Adapted from Vallée (2002).

nated by atomic (H I) and molecular hydrogen (H_2), which are present in approximately equal quantities ($\sim 10^9\ M_\odot$) in the inner Galaxy, but with very different radial distributions. There is also a small fraction of low-density ionized hydrogen (H II). In addition to hydrogen, the interstellar gas contains heavier elements, dominated by helium, with a ratio of $\sim$10% by number relative to hydrogen. Helium is therefore an important contributor to the gas-related γ-ray emission.

3.1 Interstellar Gas

The molecular hydrogen H_2 is distributed within $R < 10$ kpc, with a peak around 5 kpc and a small scale height, about 70 pc (Fig. 5). It is concentrated mainly in dense clouds of typical density 10^4 atom cm^{-3} and masses $10^4 - 10^6 M_\odot$. The H_2 gas cannot be detected directly on large scales, but the 115 GHz emission of the abundant molecule ^{12}CO is a good "tracer," since it forms in the dense clouds where the H_2 resides. The derivation of H_2 density from the CO data is problematic; normally a linear relation is assumed and the conversion factor is derived from independent estimates of the mass of gas, including the assumption of virial equilibrium, and γ-ray analyses. The recent result obtained from a complete CO survey and infrared and H I maps gives average $X \equiv N_{H_2}/W_{CO} = 1.8 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s (Dame et al. 2001). The γ-ray method has the advantage of sampling large regions of the Galaxy

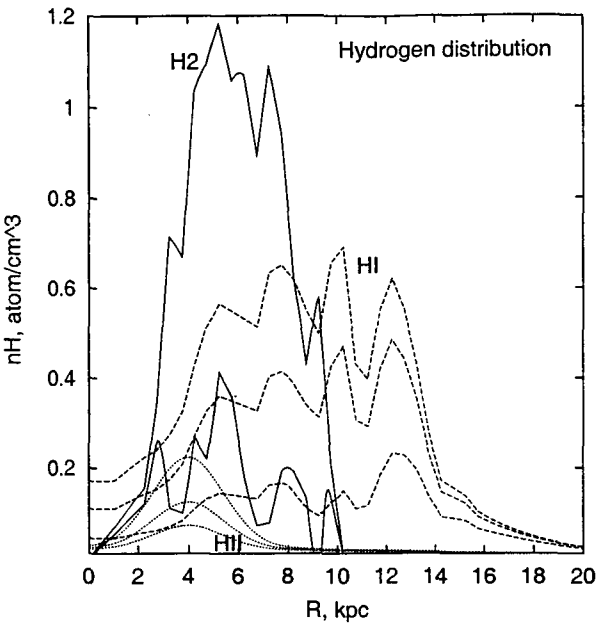

Figure 5 Number density distributions of $2{\times}H_2$ (solid), H I (dashes), and H II (dots) in the Galaxy. Shown are the plots for $z = 0, 0.1, 0.2$ kpc (decreasing density). Number density of H_2 at $z = 0.2$ kpc from the plane is very low and is not shown in the plot. Adapted from Moskalenko et al. (2002).

and requiring only the assumption that cosmic rays freely penetrate molecular clouds. An analysis of EGRET sky survey yields $X = (1.9 \pm 0.2) \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s for $E_\gamma = 0.1 - 10$ GeV (Strong and Mattox 1996) without significant energy dependence, consistent with earlier COS-B analysis (Strong et al. 1988). Observations of particular local clouds (Digel et al. 1996; Digel et al. 1999; Digel et al. 2001; Hunter et al. 1994) yield somewhat lower values $X = (0.9 \div 1.65) \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s and error bars 15–20%, but still close to the average. In the outer Galaxy X may increase. A simple parametrization of H_2 distribution is given in Bronfman et al. (1988).

The atomic gas extends out to 30 kpc, with surface density increasing with distance from the Galactic center from $1.9 M_\odot$ pc^{-2} within $R = 6$ kpc to $\sim 4 M_\odot$ pc^{-2} at 7–12 kpc, and then decreasing to $\sim 1 M_\odot$ pc^{-2} at 17 kpc (Nakanishi and Sofue 2003). The H I disk is asymmetric with warping in the outer disk, and it extends to about 1.5 kpc above the Galactic plane in the northern hemisphere and down to about 1 kpc in the southern hemisphere. The gas density is roughly uniform at 1 atom cm^{-3} and a typical scale height is about 200 pc. H I gas is mapped directly via its 21 cm radio line, which gives both distance (from the Doppler-shifted velocity and Galactic rotation models) and density information. Less studied is a cold component of H I, which does not emit at 21 cm. Its presence is detected using absorption spectra measured against bright extragalactic radio sources. A study (Kolpak et al. 2002) shows a clear

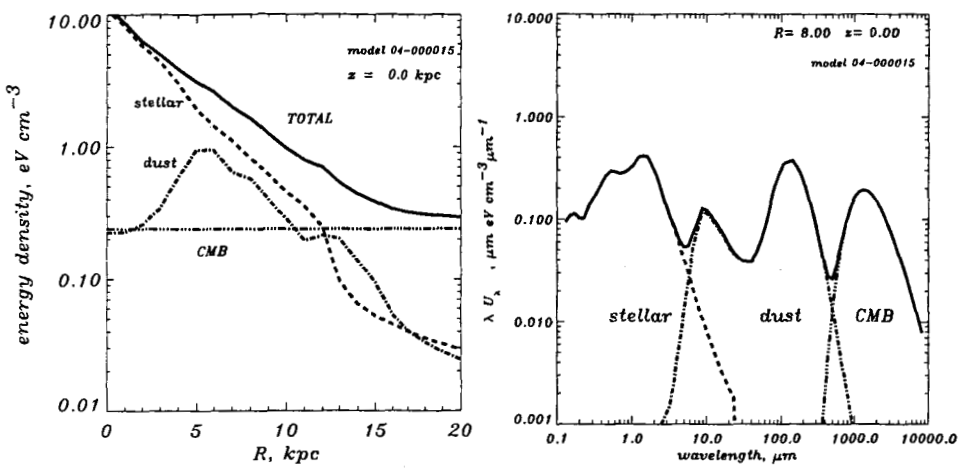

Figure 6. *Left:* ISRF energy density as function of R at $z = 0$. *Right:* The spectrum of the ISRF at $R = 8$ kpc, $z = 0$. Adapted from Strong et al. (2000).

correlation the with H_2 distribution. A simple parametrization of the H I distribution can be found in Gordon and Burton (1976) and Dickey and Lockman (1990).

Ionized hydrogen H II is present at lower densities, but with much larger vertical extent. The "warm ionized medium" has densities $\sim 10^{-3}$ atom cm^{-3} and a scale height of 1 kpc. This gas makes a small contribution to the γ-ray emission, but is nevertheless of interest because it produces a much broader latitude distribution than the neutral gas. A simple parametrization of H II distribution can be found in Cordes et al. (1991).

3.2 Interstellar Radiation Field

The interstellar radiation field (ISRF) is essential for electron propagation (energy losses) and γ-ray production by inverse Compton emission. It is made up of contributions from starlight, emission from dust, and the CMB. Estimation of the spectral and spatial distribution of the ISRF relies on models of the distribution of stars, absorption, dust emission spectra and emissivities and is therefore in itself a complex subject.

New data from infrared surveys by the IRAS and COBE (Cosmic Background Explorer) satellites have greatly improved our knowledge of both the stellar distribution and the dust emission. Fig. 6 (left) shows ISRF energy density as function of Galactocentric radius, and Fig. 6 (right) shows a recent estimate of the spectrum at $R = 8$ kpc, near the

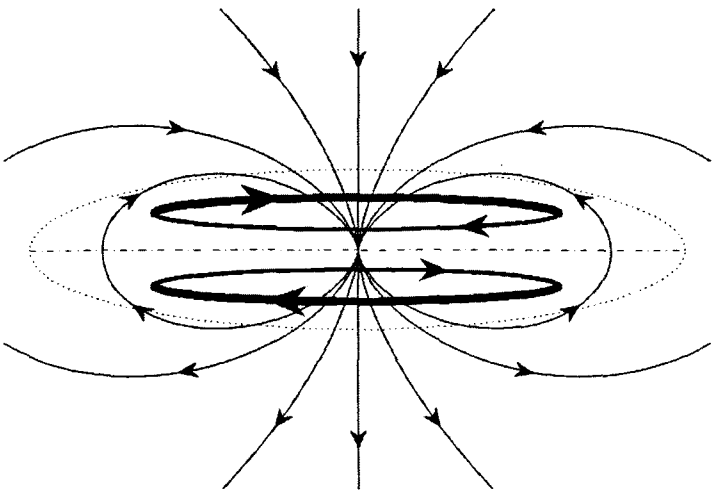

Figure 7. The rotation measures of extragalactic radio sources show the antisymmetric field structure of the Galactic halo (A0 dynamo). Adapted from Han (2003).

solar position. Stellar emission dominates from 0.1 μm to 10 μm, and emission from very small dust grains contributes from 10 μm to 30 μm. Emission from dust at $T \sim 20$ K dominates from 20 μm to 300 μm. The 2.7 K microwave background is the main radiation field above 1000 μm. The ISRF has a vertical extent of several kpc, where the Galaxy acts as a disk-like source of radius ~10 kpc. The radial distribution of the stellar component is also centrally peaked, since the stellar density increases exponentially inwards with a scale-length of ~2.5 kpc until the bar is reached. The dust component is related to that of the neutral gas (H I + H_2) and is therefore distributed more uniformly in radius than the stellar component.

3.3 Magnetic Field and Synchrotron Emission

Observations of synchrotron intensity and spectral index provide essential and stringent constraints on the interstellar electron spectrum and on the magnetic field.

The global structure of the Galactic magnetic field is currently derived from observations of rotation measures of more than 500 pulsars. It is best described by two distinct components, (i) a bi-symmetric spiral field in the disk with reversed direction from arm to arm, and (ii) an azimuthal field in the halo with reversed directions below and above the Galactic plane (Figs. 7, 8).

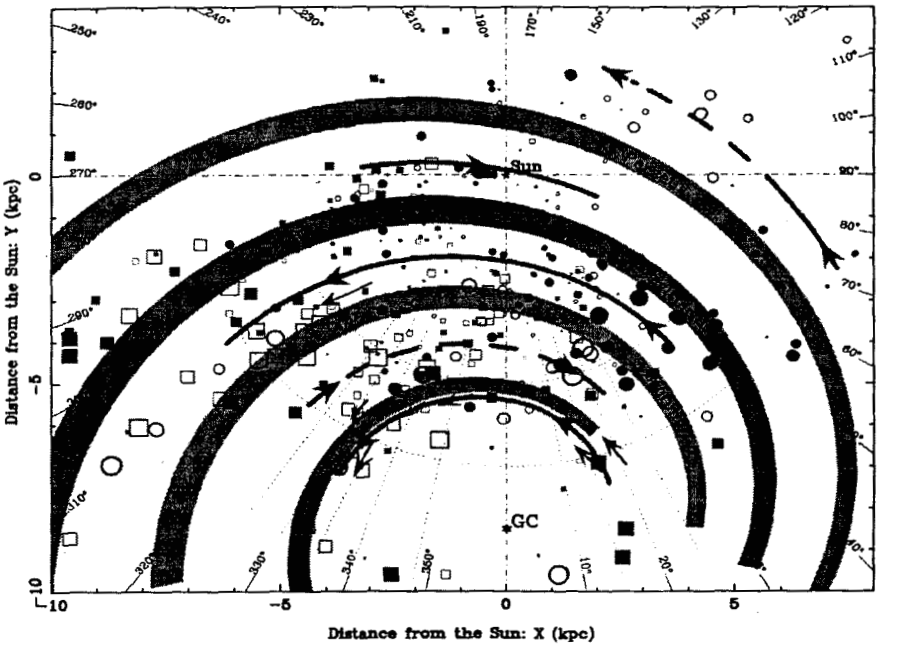

Figure 8. The distribution of pulsar rotation measures projected onto the Galactic plane reveals the field structure in the Galactic disk, which has direction reversals from arm to arm. The well-determined field structure is illustrated by thick lines and arrows. The thick dashed lines indicate structures which need further confirmation. The symbols are the rotation measures. Adapted from Han (2003).

The average strength of the *total* field derived from radio synchrotron data, under the energy equipartition assumption, is 6 ± 2 μG locally and about 10 ± 3 μG at 3 kpc from the Galactic center (Beck 2001). For comparison, Heiles (1996) gives $\sim$5 μG for the volume and azimuthally averaged *total* field at the solar position. Vallée (1996) gives similar values. Optical and synchrotron polarization data yield a strength of the local *regular* field of 4 ± 1 μG, which is probably an upper limit. Pulsar rotation measures give a lower value: 1.4 ± 0.2 μG. The strength of the turbulent magnetic field is $\sim$5 μG on typical scale $\sim$50 pc (Ohno and Shibata 1993).

The strength of the *total* field thus has a radial scale $R_B = 10$ kpc, while a reasonable value for scale height is $z_B = 2$ kpc, consistent with radio observations of edge-on spiral galaxies. Such a magnetic field reproduces well the absolute magnitude and profiles of the 408 MHz emission as shown in Fig. 9. The thermal contribution in the plane at this frequency is only about $\sim$15% (Broadbent et al. 1989). A significantly

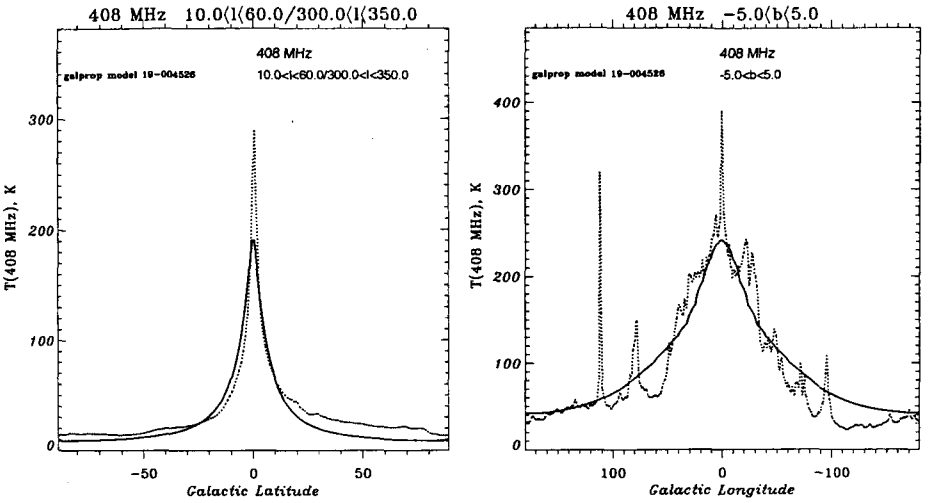

Figure 9. Intensity profiles of synchrotron emission at 408 MHz in latitude ($10° \leq l \leq 60°, 300° \leq l \leq 350°$) and longitude as calculated in "hard electrons and modified nucleons" (HEMN) model. Data: Haslam et al. (1982). Adapted from Strong et al. (2000).

smaller field would give too low synchrotron intensites as well as a spectral index distribution which disagrees with the data. R_B is constrained by the longitude profile, and z_B by the latitude profile of synchrotron emission. A more detailed fit to the profiles, involving spiral structure as well as explicit modelling of random and non-random field components, is given in Phillipps et al. (1981), Broadbent et al. (1990), Beuermann et al. (1985).

The synchrotron emission in the 10 MHz – 10 GHz band constrains the electron spectrum in the ~1–10 GeV range (see e.g. Webber et al. 1980). Out of the plane, free-free absorption is only important below 10 MHz (e.g., Strong and Wolfendale 1978). In particular the synchrotron spectral index ($T \propto \nu^{-\beta}$) provides information on the ambient electron spectral index γ in this range (approximately given by $\beta = 2 + \frac{\gamma-1}{2}$).

While there is considerable variation on the sky and scatter in the observations, and local variations due to loops and spurs, it is agreed that a general steepening with increasing frequency from $\beta = 2.5$ to $\beta = 2.8 - 3$ is present. A reanalysis of a DRAO 22 MHz survey (Roger et al. 1999) finds a rather uniform 22 – 408 MHz spectral index, with most of the emission falling in the range $\beta = 2.40 - 2.55$. Recent new experiments give reliable spectral indices up to several GHz (Platania et al. 1998); they used a catalogue of HII regions to account for thermal

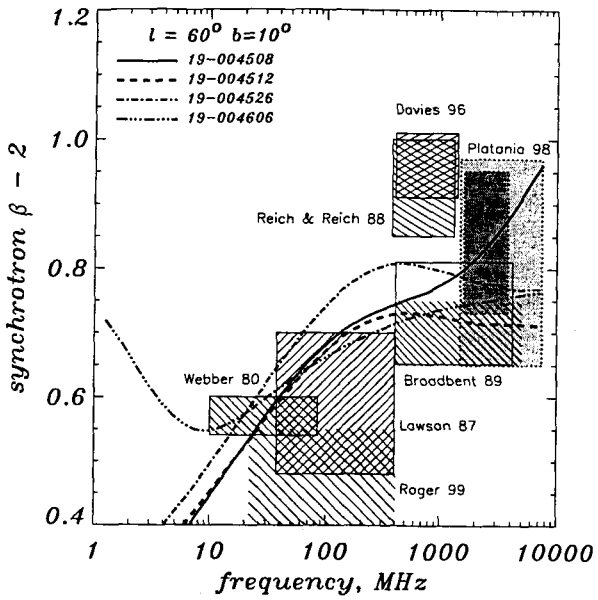

Figure 10 Synchrotron spectral index for selected propagation models. Measurements by different authors are shown by boxes. Adapted from Strong et al. (2000).

emission. Fig. 10 summarizes these estimates of the Galactic nonthermal spectral index as a function of frequency.

4. Diffuse Galactic Gamma-Ray Emission

The Galactic diffuse continuum γ-ray emission dominates other components and has a wide distribution with most emission coming from the Galactic plane. Its study is important for cosmic ray physics and lays the ground for other studies such as extragalactic background emission. It is rather easy to get agreement with data within a factor of $\sim$2 from a few MeV to $\sim$10 GeV with a "conventional" set of parameters, but the data quality warrant considerably better fits.

An extensive study of the Galactic diffuse γ-ray emission in the context of cosmic ray propagation models has been carried out by Strong et al. (2000). This study confirmed that models based on locally measured electron and nucleon spectra and synchrotron constraints are consistent with γ-ray measurements in the 30 MeV – 500 MeV range, but outside this range excesses are apparent. Attempts were made to explain the observed excess by a harder nucleon spectrum in the distant regions (Mori 1997; Gralewicz et al. 1997); however, it seems that a harder nucleon spectrum is inconsistent with other cosmic ray measurements such as antiprotons and positrons (Moskalenko et al. 1998). The GeV excess appears in all latitude/longitude ranges (Strong et al. 2003a). This implies that the GeV excess is not a feature restricted to the Galactic ridge

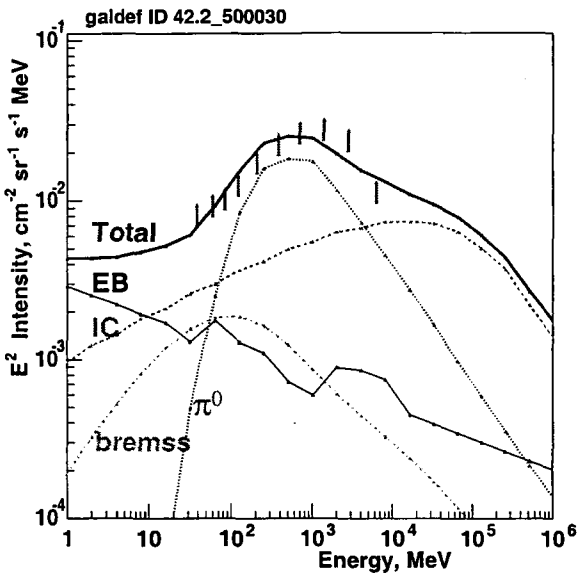

Figure 11 Spectrum of the Galactic diffuse γ-ray emission from the Galactic plane excluding the inner Galaxy ($30° < l < 330°$, $|b| < 5°$). The components shown are inverse Compton (IC), electron bremsstrahlung (bremss), π^0-decay (π^0), extragalactic diffuse emission (EB). EGRET data are shown by error bars. Adapted from Strong et al. (2003a).

or the gas-related emission. A simple re-scaling of the components (π^0, inverse Compton) does not improve the fit in any region, since the observed peak is at an energy higher than the π^0-peak. This is an argument towards a substantial inverse Compton component at high energies. We note that a population of unresolved sources can not help to explain the excess either, since the excess is also present at high Galactic latitudes.

An electron injection index of 1.9 (no breaks) is found optimal, consistent with earlier findings (Strong et al. 2000) and observations of SNRs. The *average* spectral index of the observed *flux density* of synchrotron emission from shell type SNRs is close to 0.5 ($\beta \sim 2.5$), as expected from Fermi acceleration, implying that electron spectra there are close to E^{-2} (Green 2001). It is noticeable that small young shell SNRs have steeper spectra, while older SNRs have generally flatter spectra.

In order to be consistent with EGRET data above 10 GeV, a cutoff in the electron spectrum at 3 TeV is required. The overall quality of the fit is good. Fig. 11 shows the spectrum of the Galactic diffuse γ-ray emission from the Galactic plane excluding the inner Galaxy ($30° < l < 330°$, $|b| < 5°$). At low latitudes in the inner Galaxy the peak around 1 GeV is not reproduced. To be consistent at all latitude/longitude ranges, the model required an adjustment of inverse Compton component via the electron injection spectrum and a hard spectrum γ-ray compact source population in the inner Galaxy. As an example, the Geminga pulsar does exibit the required hard spectrum making pulsars a candidate source population.

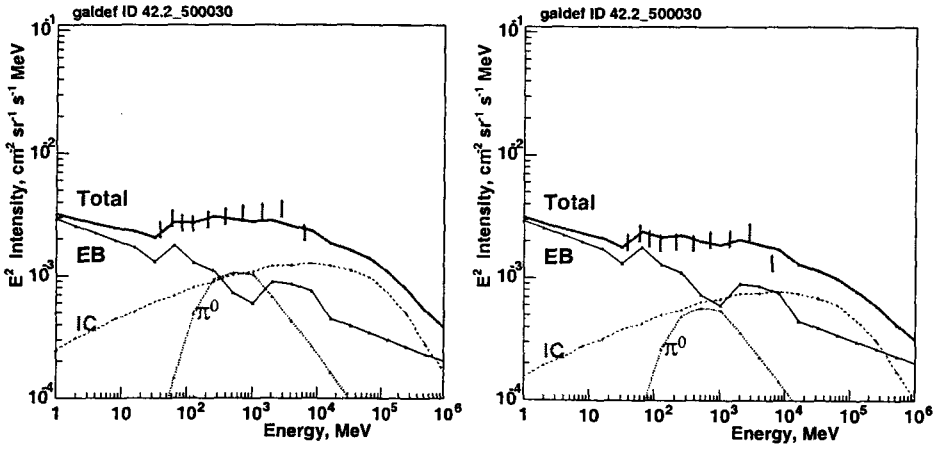

Figure 12. Spectrum of the Galactic diffuse γ-ray emission from high latitudes $0° < l < 360°$. Left: $20° < b < 60°$. Right: $60° < b < 90°$. The lines are coded as in Fig. 11. EGRET data are shown by error bars. Adapted from Strong et al. (2003a).

The large size of the Galactic halo (4–6 kpc, Moskalenko et al. 2001, 2003) implies that the electron population in the halo is considerable. Inverse Compton scattering of photons from the Galactic plane and CMB provide a major contribution to the Galactic diffuse emission from mid- and high-latitudes. Fig. 12 shows the energy spectrum of the diffuse emission from the high Galactic latitudes. The effect of anisotropic scattering in the halo (Moskalenko and Strong 2000) increases the contribution of Galactic γ-rays even further and thus reduces the extragalactic component.

Fig. 13 shows longitude and latitude profiles of the diffuse γ-ray emission in the energy range 300–500 MeV. Because the Galactic plane is relatively narrow, in latitude the agreement is always quite good. In longitude the model appears to be able to account for the peaks and dips apparently connected with details of the Galactic structure such as spiral arms.

The observations of diffuse TeV emission from the Galactic plane by Whipple (LeBohec et al. 2000), Tibet (Amenomori et al. 2002), and HEGRA (Aharonian et al. 2002) provide only unrestrictive upper limits so far. A detection of the Galactic plane has been claimed by Milagro Collaboration (Fleysher et al. 2003). Interestingly, diffuse TeV γ-rays have been detected from the nearby (2.5 Mpc) normal spiral starburst galaxy NGC 253 (Itoh et al. 2002).

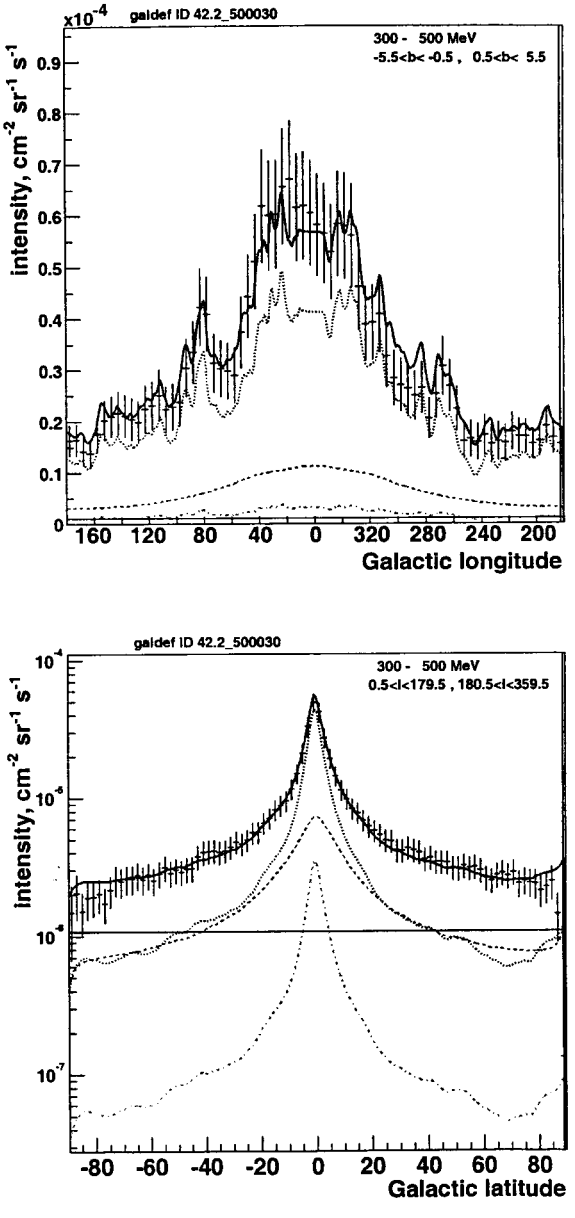

Figure 13. Profiles in longitude along the Galactic plane (top) and latitude (bottom) of the Galactic diffuse γ-ray emission in the energy range 300–500 MeV. The components shown (from top to bottom) are total flux (blue), π^0-decay (red), inverse Compton (green), electron bremsstrahlung (cyan). The horizontal line is the extragalactic diffuse emission. EGRET data are shown by error bars. Adapted from Strong et al. (2004).

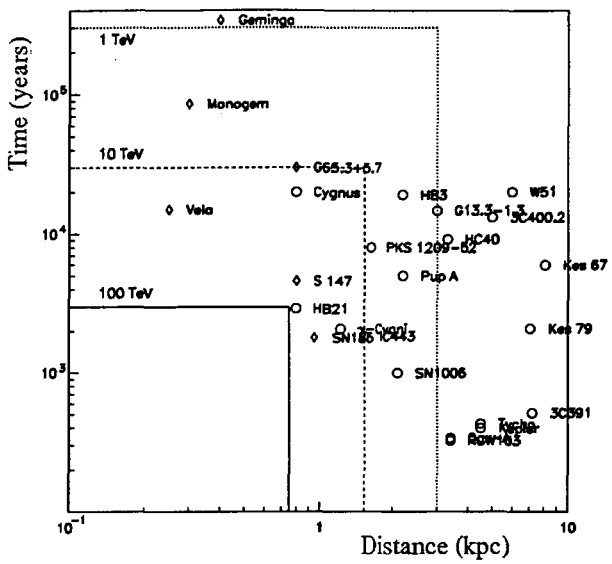

Figure 14 Compilation of nearby shell-type and plerion SNR distances and ages. Line boxes represent limiting energies for electrons to reach Earth (Swordy 2003).

4.1 Analysis of Cosmic Ray Spectral Fluctuations

In studies of cosmic-ray propagation and diffuse continuum γ-ray emission from the Galaxy it has usually been assumed that the source function can be taken as smooth and time-independent. However, especially for electrons at high energies where energy losses due to synchrotron and inverse Compton emission are rapid, the effect of the stochastic nature of the sources becomes apparent. For the typical energy density of Galactic radiation and magnetic fields of 1 eV cm^{-3}, the energy loss timescale is $\sim 3 \times 10^5$ yr at 1 TeV, and becomes as short as $\sim 3 \times 10^3$ yr at 100 TeV. A cutoff in the electron spectrum at very high energies is thus unavoidable because of both large energy losses and a discrete nature of the sources. This is similar to the GZK effect for ultra high energy cosmic rays, where the cutoff in the proton spectrum appears due to the energy losses on photopion production. The analysis of nearby shell-type SNRs predicts that the electron spectrum should have a cut off between 30 TeV and 100 TeV as measured near the solar system (Fig. 14). Studies of the propagation of very-high-energy electrons from local sources (Nishimura et al. 1997) has shown that some nearby SNRs are possibly capable of producing unique identifiable features in the cosmic-ray electron spectrum at 1–30 TeV, where the important parameters are the distance and the age of a SNR. The most promising candidate sources of TeV electrons are Vela, Cygnus Loop, and Mono-

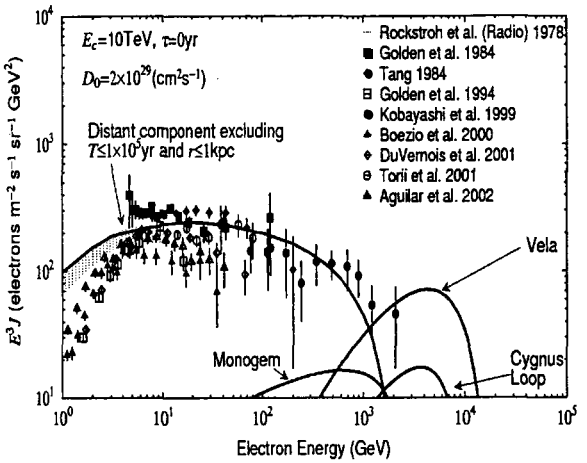

Figure 15 Absolute differential energy spectrum of electrons in comparison with calculated results for a diffusion model assuming a power law index of the injection spectrum 2.4. The contribution of individual sources is labeled as Vela, Cygnus Loop, and Monogem. Adopted from Kobayashi et al. (2003).

gem (Fig. 15). Very-high-energy electron measurements give a direct test of SNR origin of cosmic rays, but also an important test of our local environment. The features in the electron spectrum and the cut-off energy would immediately signal which SNR(s) is/are affecting the local cosmic-ray flux and to what degree, with implications for Galactic cosmic-ray propagation models and predictions of the diffuse γ-ray emission.

The fluctuations of electron spectra *for different sources* has been invoked to explain the GeV excess in the diffuse emission observed by EGRET. In particular, Pohl and Esposito (1998) allowed the electron injection index in individual sources to fluctuate around 2.0, which would lead to a flatter electron spectrum at high energies and produce more inverse Compton emission. In order to include fluctuations in the source spectra in the cosmic ray propagation code GALPROP, a model with explicit time-dependence and a stochastic SNR population has been developed by Strong and Moskalenko (2001a), which follows the propagation in three dimensions. The important parameters here are the mean time between the events $t_{\rm SNR}$ in a 1 kpc^3 unit volume, and the time of the active phase $t_{\rm cr}$ during which an SNR produces cosmic rays. Apparently, the inverse-Compton emission becomes increasingly clumpy at high energies due to the effect of individual SNRs as shown in longitude distributions obtained from the model (Fig. 16). The effect is already visible at 1 GeV and will be an important signature for the GLAST γ-ray observatory, which will measure up to 300 GeV.

The results, however, indicate that although the inhomogeneities are large they are insufficient to easily explain the GeV excess. Fig. 17 shows the simulated distribution of electrons of 1 TeV for a "standard" Galac-

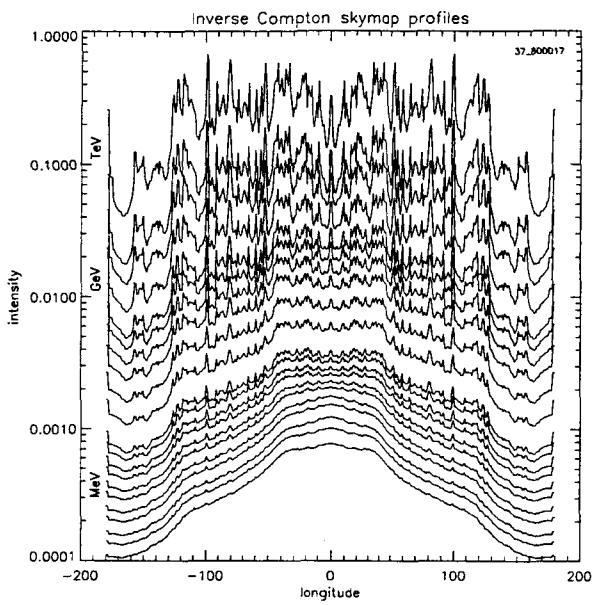

Figure 16 Modeled inverse Compton γ-ray longitude distributions for γ-ray energies from 1 MeV (bottom) to 1 TeV (top). Adopted from Strong and Moskalenko (2001c).

tic SN rate 3/century ($t_{\rm SNR} = 10^4$ yr). At GeV energies the distribution shows only small fluctuations, the particle density being dominated by the long storage times. At higher energies the losses increase and the fluctuations become significant as the individual SNR events leave their imprint on the distribution. The TeV electron distribution is quite inhomogeneous, but still none of the spectra around $R = R_\odot$ resembles even remotely that observed locally. For the Galactic SN rate 0.3/century ($t_{\rm SNR} = 10^5$ yr) the simulated distribution above 100 GeV is even more inhomogeneous and the spectrum fluctuates even more (Fig. 18). Some of the spectra resemble that observed locally within a factor of a few, although still none is fully compatible with the local spectrum.

In the case of protons, the fluctuations are also evident, but much smaller than for electrons (Strong and Moskalenko 2001b). Fig. 19 shows the distribution of protons in the Galactic plane ($z = 0$) for a representative quadrant, at two energies. For illustration we show results for a model with reacceleration based on Strong et al. (2000), and a Galactic SN rate of 3 SN/century. The stochastic SNR source produce fluctuations, which are a minimum around 1 GeV and increase at low energies due to energy losses and at high energies where the storage of particles in the Galaxy is much reduced so that the effect of sources manifests itself on the distribution. Note that the nature of the fluctuations is different at low and high energies. However, large fluctuations of the

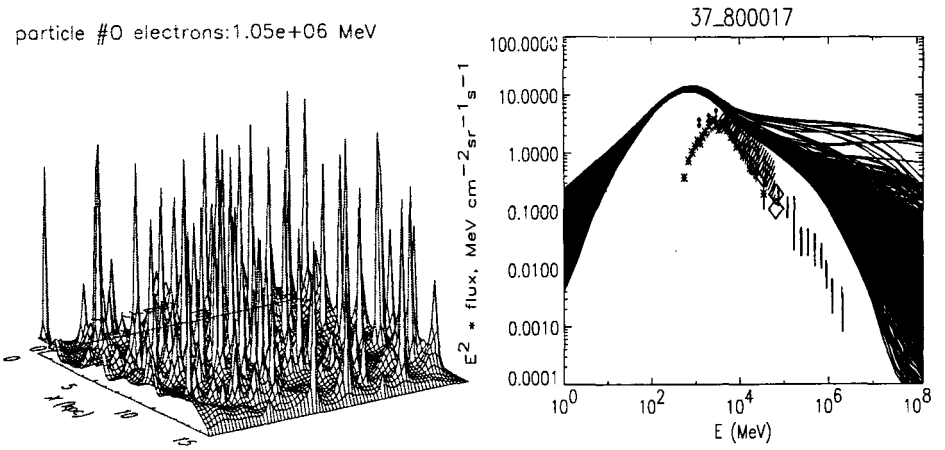

Figure 17. Simulated distribution of 1 TeV electrons at $z = 0$ (left) and spectral variations in $4 < R < 10$ kpc (right) for $t_{\rm SNR} = 10^4$ yr. Data points: locally measured electron spectra. Adopted from Strong and Moskalenko (2001a).

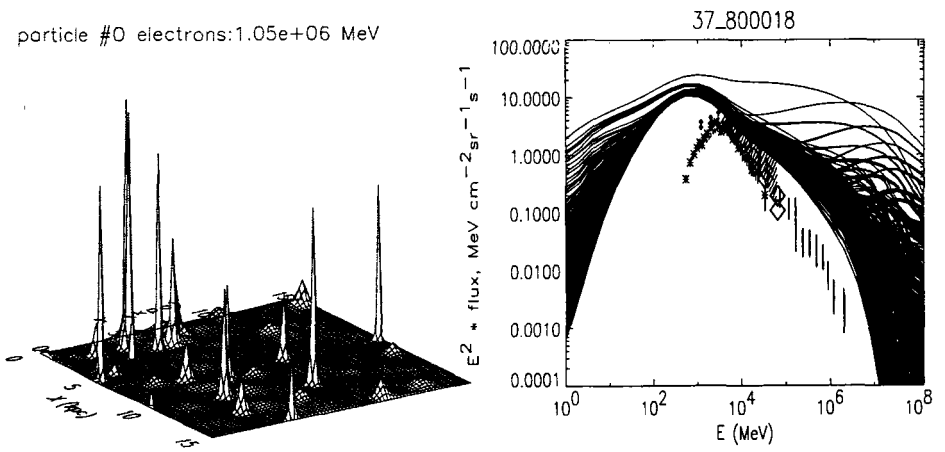

Figure 18. Simulated distribution of 1 TeV electrons at $z = 0$ (left) and spectral variations in $4 < R < 10$ kpc (right) for $t_{\rm SNR} = 10^5$ yr. Data points: locally measured electron spectra. Adopted from Strong and Moskalenko (2001a).

average nucleon spectrum are ruled out on the basis of the "antiproton test" proposed by Moskalenko et al. (1998) and confirmed by recent measurements of the high energy antiproton flux (Beach et al. 2001).

The effect of nearby SNRs on the cosmic-ray anisotropy at 1–1000 TeV has been studied by Ptuskin et al. (2003). It has been shown that inclusion of nearby SNRs improves the agreement of the reacceleration model with the data, while the most important contributions come from Vela and S 147. The very young and close SNR RX J0852.0–4622 (0.2

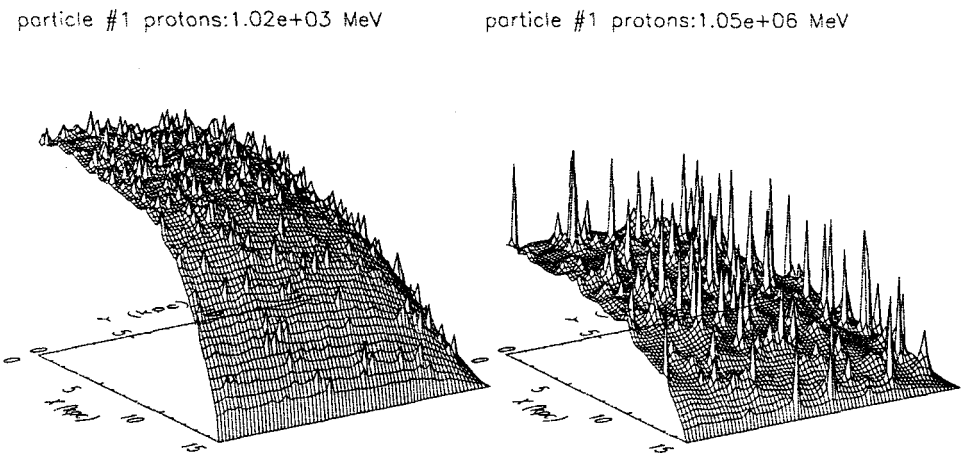

Figure 19. Simulated distribution of 1 GeV (left) and 1 TeV (right) protons at $z = 0$. Adopted from Strong and Moskalenko (2001b).

kpc, 700 yr) would dramatically change the predicted anisotropy, but the source is probably still in a free expansion stage with accelerating particles confined inside the remnant.

4.2 Local Clouds

Some nearby molecular clouds lie at latitudes outside the intense Galactic plane and hence can be detected as separate extended sources. The position and distances of clouds observed with EGRET are given in Table 1. The γ-ray intensity in these clouds was found consistent with that found for the solar circle in large-scale studies of diffuse emission (Fig. 20). The differential γ-ray emissivity is consistent with electron and proton cosmic ray spectra approximately the same as in the solar vicinity. This suggests that the density of cosmic ray protons does not

Table 1. Local clouds.

Name	*Longitude*	*Distance*	X, 10^{20} cm^{-2} K^{-1} km^{-1} s
Ophiuchus (Hunter et al. 1994)	336°– 10°	125 pc	1.1 ± 0.2
Cepheus (Digel et al. 1996)	100°–130°	250 pc	0.92 ± 0.14
Orion (Digel et al. 1999)	195°–220°	500 pc	1.35 ± 0.15
Monoceros (Digel et al. 2001)	210°–250°	830 pc	1.64 ± 0.31
Taurus/Perseus (Digel and Grenier 2001)	150°–185°	140/300 pc	1.08 ± 0.10

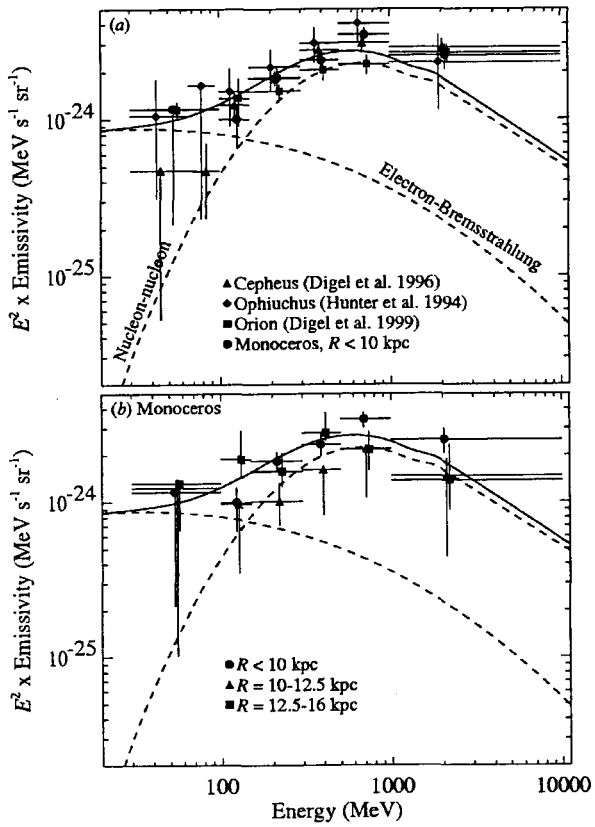

Figure 20 (a) Comparison of differential emissivities for the local gas in Monoceros (circles) with emissivities from other studies of local clouds: Ophiuchus (diamonds; Hunter et al. 1994), Orion (squares; Digel et al. 1999), and Cepheus (triangles; Digel et al. 1996). (b) Differential emissivities in the three inner annuli in Monoceros. Circles: local ($R < 10$ kpc) range; triangles: interarm ($R = 10 - 12.5$ kpc) range; and squares: Perseus arm ($R = 12.5 - 16$ kpc) range. Also plotted are the nucleon-nucleon and electron-bremsstrahlung emissivities and their sum for the solar vicinity. Adopted from Digel et al. (2001).

vary significantly on scales $\lesssim 1$ kpc. Interestingly, the Cepheus, Orion, and Monoceros clouds exibit a "GeV excess" similar to that found in the Galactic plane.

5. Extragalactic Diffuse Emission

The extragalactic diffuse γ-ray background emission (EGB) is the component of the diffuse emission which is most difficult to determine. Its spectrum depends much on the adopted model of the Galactic background which itself is not yet firmly established. It is not correct to assume that the isotropic component is wholly extragalactic, because even at the Galactic poles it is comparable to the Galactic contribution from inverse Compton scattering of the Galactic plane photons and CMB. The size of the halo, the electron spectrum there, and the spectrum of low-energy background photons are all model dependent and must be derived from many different kinds of observations.

Potentially, if reliably derived, the EGB can provide very important information about the phase of baryon-antibaryon annihilation (Gao et al. 1990; Dolgov and Silk 1993), evaporation of primordial black holes (Hawking 1974; Maki et al. 1996), annihilation of so-called weakly interacting massive particles (WIMPs) (Jungman, Kamionkowski, and Griest 1996), extragalactic IR and optical photon spectra (Stecker 1999), and/or unresolved sources (AGNs?) and their cosmological evolution.

Extensive work has been done (Sreekumar et al. 1998) to derive the spectrum of the EGB based on EGRET data. The relation of modelled-Galactic-diffuse-emission vs. total-diffuse-emission was used to determine the EGB as the extrapolation to zero Galactic contribution. The derived index -2.10 ± 0.03 appears to be close to that of γ-ray blazars.

A new approach to the determination of the EGB is based on cosmic ray propagation model (Strong et al. 2003a). This model reproduces successfully diffuse γ-ray emission from the entire sky (see previous Sections.) To reduce the effects of Galactic structure the fits are made excluding the plane ($b > 10°$). The model gives a good linear prediction for observed vs. predicted γ-ray intensities. The spectrum derived appears to be steeper than -2.10 and is a smooth continuation of the extragalactic spectrum at lower energies (Fig. 21). There is an indication of a possible upturn at $\sim$10 GeV. The positive curvature in the newly determined EGB is interesting, and is to be expected in the "unresolved blasar origin hypothesis" of the EGB (Salamon and Stecker 1998).

6. Faint Sources

From the known populations of high-energy γ-ray sources the contribution from faint sources can be deduced. Faint sources discussed here include sources below the detection threshold as chosen during source catalog compilations as well as unresolved sources in the γ-ray sky.

Clearly, most directly accessible is the dominant class of γ-ray emitters, the Active Galactic Nuclei (AGN). Known to emit up to the highest energies, a significant number of not-yet-discovered or unresolved AGN is expected to contribute to the γ-ray sky. Depending on the luminosity function of the detected AGN, considerations of high activity vs. low activity states, and the applicability of a blazar classification/unification scheme quantitative assessments of the contribution of AGN to the extragalactic background have been made (Stecker and Salamon 1996; Mücke and Pohl 2000; Mukherjee and Chiang 1999; Chiang and Mukherjee 1998). There is a consensus that blazars should contribute significantly to the observed extragalactic diffuse emission, however the predictions range from 25% up to 100%. Also, contributions from other extragalac-

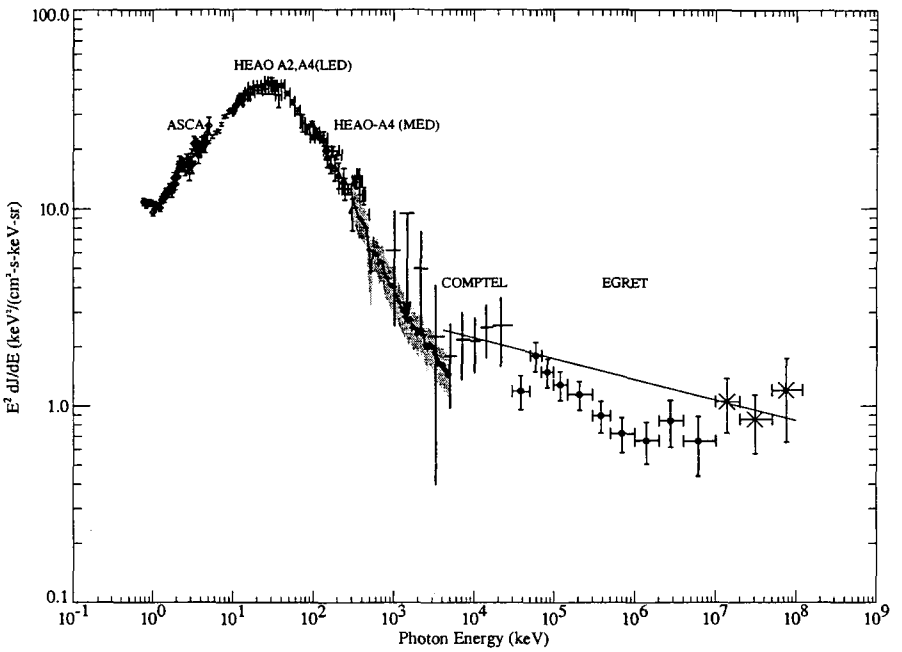

Figure 21. Spectrum of the extragalactic diffuse γ-ray emission. The solid line (a power-law fit with index -2.1) and three data points marked by cross in the EGRET energy range is the EGB as derived by Sreekumar et al. (1998). The closed circles with error bars below the line show our new determination of the EGB. Adapted from Strong et al. (2003b).

tic sources have been suggested: galaxy clusters might contribute to the extragalactic γ-ray background either as point-like or extended sources below our current instrumental detectability, distant γ-ray burst events, or a result of large scale cosmological structure formation.

Faint sources will likely contribute also to the diffuse Galactic emission. The inner Galactic ridge is known to be an intense source of diffuse continuum hard X- and soft γ-ray emission. The hard X-ray emission was discovered in 1972 (Bleach et al. 1972) and has subsequently been observed from keV to MeV energies by ASCA, Ginga, RXTE, OSSE, COMPTEL, Chandra, and most recently by INTEGRAL (Strong et al. 2003c). While the physical process (e^+e^- annihilation) producing the positron line and positronium continuum is clear, the source of the remaining continuum is not, although nonthermal bremsstrahlung is most likely (Dogiel et al. 2002a). The implied photon luminosity of a few 10^{38} erg s^{-1} is remarkable (Dogiel et al. 2002b). An origin in a point-source population seems unlikely (Tanaka et al. 1999; Tanaka 2002) since there

are no known candidate objects, and high-resolution imaging with Chandra shows a truly diffuse component (Ebisawa et al. 2001). An analysis of RXTE data in the inner Galaxy (Revnivtsev 2003) indicates that, after accounting for detected sources, only 10% of the plane emission in the 3–20 keV band can be attributed to undetected faint point sources, the rest being diffuse.

In the 1–30 MeV range, it appears difficult to account for all the emission observed by COMPTEL in terms of interstellar processes (bremsstrahlung/inverse Compton), and hence a significant source contribution has been proposed (Strong et al. 2000). There is no prediction available for how the classes represented by unidentified γ-ray sources might contribute to the observed Galactic diffuse emission. The contribution of pulsars to the Galactic diffuse emission is supposedly very little at MeV-energies, but might be in the order of 20% at GeV's (Pohl et al. 1997). Only a few pulsars have been detected in γ-rays, and the nature of the majority of Galactic γ-ray sources is still unknown.

7. Tracers of Exotic Physics ?

The nature and properties of the dark matter that may constitute a significant fraction of the mass of the universe have puzzled scientists for more than a decade. Among the favoured dark matter candidates are WIMPs, whose existence follows from supersymmetric models. In most models these particles are stable, electrically neutral, lightest neutralino χ^0, which has appropriate annihilation cross section and mass to provide suitable relic density.

A number of methods have been proposed to search for evidence for such particles. These include direct searches for scattering off a nucleus in a detector, indirect searches to detect the annihilation products, and collider experiments (for a review and references, see Bergström 2000). The indirect searches (Jungman, Kamionkowski, and Griest 1996) include antiprotons and positrons in cosmic rays, γ-rays from the Galactic center and halo (diffuse emission), and neutrinos from massive bodies like the Galactic center, the sun, and the earth.

In γ-rays the signal could be a relatively narrow line with energy far beyond that of ordinary particles, or a broad feature appearing as a result of a decay chain. The current accelerator limit is $m_\chi \gtrsim 50$ GeV (Ellis et al. 2000). GLAST observations will be able to provide a "smoking gun" or to put new limits on supersymmetric models.

The GeV excess in the EGRET data relative to that expected is intensively discussed in the literature (see Section 1). Is it a key to the problems of cosmic-ray physics, a signature of exotic physics (e.g., WIMPs

annihilation, primordial black hole evaporation), or just a flaw in the current models? This also has an immediate impact on the extragalactic background radiation studies since its spectrum and interpretation are model dependent.

Because of the complicated input (see Sections 1, 4), the excess can be the result of incomplete knowledge of the source distribution, the injection spectra of primary species, the production mechanisms of secondaries, the interstellar radiation field, or a combination of these. Some part of the excess can be associated with cosmic ray sources where freshly accelerated particles interact with nearby gas particles, producing harder γ-ray spectra. Therefore, further deep study of cosmic-ray propagation in a detailed model is necessary. Re-evaluation of the interstellar radiation field and the gas distribution including details of Galactic structure (e.g., spiral arms) are desirable. The goal is to develop a model which is consistent with cosmic-ray data and simultaneously with diffuse γ-ray data *or* clearly indicate the reason for the discrepancy.

8. Broader Picture and Future Perspective

Astrophysics of cosmic rays and γ-rays depends very much on the quality of the data, which become increasingly accurate each year and therefore more constraining. While direct measurements of cosmic rays are possible in only one location on the outskirts of the Milky Way, the Galactic diffuse γ-ray emission provides insights into the spectra of cosmic rays in distant locations, therefore complementing the local cosmic-ray studies. This connection, however, requires extensive modeling and is yet to be explored in detail. The GLAST mission, which is scheduled for launch in 2007 and is capable of measuring γ-rays in the range 20 MeV – 300 GeV, will change the status quo dramatically. The detailed spectra and skymaps of the Galactic diffuse γ-ray emission gathered by GLAST will require adequate theoretical models. The efforts will be rewarded by the wealth of information on cosmic ray spectra and fluxes in remote locations. In its turn, a detailed cosmic ray propagation model will provide a reliable basis for other studies such as search for dark matter signals in cosmic rays and diffuse γ-rays, spectrum and origin of the extragalactic γ-ray emission, theories of nucleosynthesis and evolution of elements (Fields et al. 2001) etc. In addition, GLAST will be able to detect γ-rays from other normal galaxies, which enable us to model cosmic-ray intensities there, study the intensity evolution and its dependence on the supernova rate, gas density etc., and, therefore, to understand the *history* of cosmic rays in the Milky Way galaxy. GLAST with its high sensitivity and resolution should also provide a final proof

of proton acceleration in SNRs – long awaited by the cosmic-ray community. This will provide insight into the processes of acceleration of protons and electrons by SNR shocks and shed light on the puzzle of the low e/p-ratio in cosmic rays.

Among other goals, new accurate measurements of cosmic-ray nuclei, positrons, and antiprotons are desirable. Produced in the same pp-interactions as γ-rays and positrons, antiprotons with their unique spectral shape are seen as a key link between physics of cosmic rays and diffuse γ-rays and could provide important clues to such problems as Galactic cosmic-ray propagation, possible imprints of our local environment, heliospheric modulation, dark matter etc. In a few years, several high resolution space and balloon experiments are to be launched. PAMELA (launch in 2004) is designed to measure antiprotons, positrons, electrons, and isotopes H through C over the energy range of 0.1 to 300 GeV. Future Antarctic flights of a new BESS-Polar instrument will considerably increase the accuracy of data on antiprotons and light elements. AMS will measure cosmic-ray particles and nuclei $Z \lesssim 26$ from GeV to TeV energies. This is complemented by low energy missions, ACE, Ulysses, and Voyager which will continue to deliver excellent quality spectral and isotopic data $Z \leq 28$, and TIGER capable of measuring heavier nuclei $Z > 29$. Several missions are planned to target specifically the high energy electron spectrum, which could provide unique information about our local environment and sources of cosmic rays nearby.

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