Galactic Cosmic Rays & Gamma Rays: A Synthesis

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**Abstract.** We have developed a model which aims to reproduce observational data of many kinds related to cosmic-ray origin and propagation: direct measurements of nuclei, antiprotons, electrons and positrons, $\gamma$-rays, and synchrotron radiation. Our main results include evaluation of diffusion/convection and reacceleration models, estimates of the halo size, calculations of the interstellar positron and antiproton spectra, evaluation of alternative hypotheses of nucleon and electron interstellar spectra, and computation of the Galactic diffuse $\gamma$-ray emission. We show that combining information from classical cosmic-ray studies with $\gamma$-ray and other data leads to tighter constraints on cosmic-ray origin and propagation.

1. Introduction

We have developed a model which aims to reproduce self-consistently observational data of many kinds related to cosmic-ray origin and propagation: direct measurements of nuclei, antiprotons, electrons and positrons, $\gamma$-rays, and synchrotron radiation. These data provide many independent constraints on any model and our approach is able to take advantage of this since it must be consistent with all types of observation. Propagation of primary and secondary nucleons, primary and secondary electrons and positrons are calculated self-consistently. For cosmic rays this approach differs from most others in that the spatial transport is treated numerically. This allows us to include realistic astrophysical information such as the gas distribution and realistic data for the

2. Description of the models

A numerical method for the calculation of Galactic cosmic-ray propagation in 3D has been developed\(^2\), as described in detail in Strong & Moskalenko (1998). The basic spatial propagation mechanisms are diffusion and convection, while in momentum space energy loss and diffusive reacceleration are treated. Fragmentation and energy losses are computed using realistic distributions for the

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\(^2\)For interested users our model is available in the public domain on the World Wide Web, [http://www.gamma.mpe-garching.mpg.de/~aws/aws.html](http://www.gamma.mpe-garching.mpg.de/~aws/aws.html)
interstellar gas and radiation fields. The basic procedure is first to obtain a set of propagation parameters which reproduce the cosmic ray B/C and $^{10}$Be/$^{9}$Be ratios; the same propagation conditions are then applied to primary electrons. Gamma-ray and synchrotron emission are then evaluated with the same model.

The models are three dimensional with cylindrical symmetry in the Galaxy, and the basic coordinates are $(R, z, p)$, where $R$ is Galactocentric radius, $z$ is the distance from the Galactic plane, and $p$ is the total particle momentum. In the models the propagation region is bounded by $R = R_h$, $z = \pm z_h$ beyond which free escape is assumed. For a given $z_h$ the diffusion coefficient as a function of momentum is determined by B/C for the case of no reacceleration; if reacceleration is assumed then the reacceleration strength (related to the Alfvén speed) is constrained by the energy-dependence of B/C. We include diffusive reacceleration since some stochastic reacceleration is inevitable, and it provides a natural mechanism to reproduce the energy dependence of the B/C ratio without an ad hoc form for the diffusion coefficient (e.g., Seo & Ptuskin 1994). The distribution of cosmic-ray sources is chosen to reproduce (after propagation) the cosmic-ray distribution determined by analysis of EGRET $\gamma$-ray data (Strong & Mattox 1996).

The primary propagation is computed first, giving the primary distribution as a function of $(R, z, p)$; then the secondary source functions of nucleons and $\bar{p}$, $e^\pm$ are obtained from the gas density and cross sections, and finally the secondary propagation is computed. The bremsstrahlung and inverse Compton (IC) $\gamma$-rays are computed self-consistently from the gas and radiation fields used for the propagation.

3. Evaluation of models

In our evaluations we use the B/C data summarized by Webber et al. (1996), from HEAO–3 and Voyager 1 and 2. We use the measured $^{10}$Be/$^{9}$Be ratio from
Figure 2. Interstellar $^{10}\text{Be}/^{9}\text{Be}$ ratio for diffusive reacceleration models. (a) As function of energy for $z_h = 1, 2, 3, 4, 5, 10, 15$ and 20 kpc (from top to bottom). Data points from Lukasiak et al. (1994) (Voyager-1,2: square, IMP-7/8: open circle, ISEE-3: triangle) and Connell (1998) (Ulysses: filled circle). Note that the data points shown are at the measured, not the interstellar energy. (b) As function of $z_h$ at 525 MeV/nucleon corresponding to the mean interstellar value for the Ulysses data (Connell 1998); the Ulysses experimental limits are shown as horizontal dashed lines.

Ulysses (Connell 1998) and from Voyager-1,2, IMP-7/8, ISEE-3 as summarized by Lukasiak et al. (1994).

In diffusion/convection models with a diffusion coefficient which is a simple power-law in momentum a good fit is not possible; the basic effect of convection is to reduce the variation of B/C with energy, and although this improves the fit at low energies the characteristic peaked shape of the measured B/C cannot be reproduced. Although modulation makes the comparison with the low energy Voyager data somewhat uncertain, the fit is unsatisfactory. The failure to obtain a good fit is an important conclusion since it shows that the simple inclusion of convection cannot solve the problem of the low-energy falloff in B/C. In the absence of convection the limits on the halo size are $4 \text{ kpc} < z_h < 12 \text{ kpc}$. If convection is allowed the lower limit remains but no upper limit can be set, and $dV/dz < 7 \text{ km s}^{-1} \text{ kpc}^{-1}$.

For diffusive reacceleration models, Fig. 1 illustrates the effect on B/C of varying $v_A$, from $v_A = 0$ (no reacceleration) to $v_A = 30 \text{ km s}^{-1}$, for $z_h = 5 \text{ kpc}$. This shows how the initial form becomes modified to produce the characteristic peaked shape. Fig. 2 shows $^{10}\text{Be}/^{9}\text{Be}$ for the same models, (a) as a function of energy for various $z_h$, (b) as a function of $z_h$ at 525 MeV/nucleon corresponding to the Ulysses measurement. Comparing with the Ulysses data point, we again conclude that $4 \text{ kpc} < z_h < 12 \text{ kpc}$.

Recently, Webber & Soutoul (1998) and Ptuskin & Soutoul (1998) have obtained $z_h = 2 - 4 \text{ kpc}$ and $4.9^{+1.1}_{-2} \text{ kpc}$, respectively, consistent with our results.
4. Probes of the interstellar nucleon spectrum: $\bar{p}$ and $e^+$

Diffuse Galactic $\gamma$-ray observations $> 1$ GeV by EGRET have been interpreted as requiring a harder average nucleon spectrum in interstellar space than that observed directly (Hunter et al. 1997, Gralewicz et al. 1997, Mori 1997, Moskalenko & Strong 1998b,c). A sensitive test of the interstellar nucleon spectra is provided by secondary antiprotons and positrons.

Secondary positrons and antiprotons in Galactic cosmic rays are produced in collisions of cosmic-ray particles with interstellar matter\(^3\). Because they are secondary, they reflect the *large-scale* nucleon spectrum independent of local irregularities in the primaries and thus provide an essential check on propagation models and also on the interpretation of diffuse $\gamma$-ray emission (Moskalenko & Strong 1998a, Moskalenko et al. 1998, Strong et al. 1999). These are an important diagnostic for models of cosmic-ray propagation and provide information complementary to that provided by secondary nuclei. However, unlike secondary nuclei, antiprotons reflect primarily the propagation history of the protons, the main cosmic-ray component.

We consider 3 different models which differ mainly in their assumptions about the electron and nucleon spectra (Strong et al. 1999). In model C ("conventional") the electron and nucleon spectra are adjusted to agree with local measurements. Model HN ("hard nucleon spectrum") uses the same electron spectrum as in model C, but it is adjusted to match the $\gamma$-ray data at the cost of a much harder proton spectrum than observed. In model HEMN ("hard electron spectrum and modified nucleon spectrum") the electron spectrum is adjusted to match the $\gamma$-ray emission above 1 GeV via IC emission, relaxing the requirement of fitting the locally measured electrons above 10 GeV, and the nucleon spectrum at low energies is modified to obtain an improved fit to the $\gamma$-ray data. (Some freedom is allowed since solar modulation affects direct measurements of nucleons below 20 GeV, and the locally measured nucleon spectrum may not necessarily be representative of the average on Galactic scales either in spectrum or intensity due to details of Galactic structure.)

Our calculations of the antiproton/proton ratio, $\bar{p}/p$, and secondary positron spectra for these models (with reacceleration) are shown in Fig. 3. In the case of the conventional model, our results (solid lines) agree well with measurements above a few GeV where solar modulation is small and with the antiproton calculations of Simon et al. (1998).

The dotted lines in Fig. 3 show the $\bar{p}/p$ ratio and positron spectrum for the HN model; the ratio is still consistent with the data at low energies but rapidly increases toward higher energies and becomes $\sim 4$ times higher at 10 GeV. Up to 3 GeV it does not conflict with the data with their large error bars. It is however larger than the point at 3.7–19 GeV (Hof et al. 1996) by about $5\sigma$. Clearly we cannot conclude definitively on the basis of this one point, but it does indicate the sensitivity of this test. Positrons also provide a good probe of the nucleon spectrum, but are more affected by energy losses and propagation uncertainties.

\(^3\)Secondary origin of cosmic-ray antiprotons and positrons is basically accepted, though some other exotic contributors such as, e.g., neutralino annihilation (Bottino et al. 1998, Baltz & Edsjö 1998) are also discussed.
Figure 3. **Left panel:** Interstellar $\bar{p}/p$ ratio for different ambient proton spectra (Moskalenko et al. 1998, Strong et al. 1999) compared with data. Solid line: C, dotted line: HN, dashed line: HEMN. Data (direct measurements): see references in Moskalenko et al. (1998). **Right panel:** Intenstellar positron spectra for different ambient proton spectra (Strong et al. 1999) compared with data. Lines are coded as on the left. Data (direct measurements): Barwick et al. (1998).

The predicted positron flux in the HN model is a factor 4 above the Barwick et al. (1998) measurements and hence provides further evidence against the “hard nucleon spectrum” hypothesis.

The dashed lines in Fig. 3 show our results for the HEMN model. The predictions are larger than the conventional model but still agree with the antiproton and positron measurements.

5. Diffuse Galactic continuum gamma rays

Recent results from both COMPTEL and EGRET indicate that IC scattering is a more important contributor to the diffuse emission that previously believed. The puzzling excess in the EGRET data $>1$ GeV relative to that expected for $\pi^0$-decay has been suggested to originate in IC scattering from a hard interstellar electron spectrum (e.g., Pohl & Esposito 1998). Our combined approach allows us to test this hypothesis (Strong et al. 1999)$^4$.

A “conventional” model, which matches directly measured electron and nucleon spectra and is consistent with synchrotron spectral index data, can fit the observed $\gamma$-ray spectrum only in the range $30$ MeV – $1$ GeV. A hard nucleon spectrum (HN model) can improve the fit $>1$ GeV but as described above the high energy antiproton and positron data probably exclude the hypothesis that the local nucleon spectrum differs significantly from the Galactic average.

$^4$Our model includes a new calculation of the interstellar radiation field based on stellar population models and IRAS and COBE data.
We thus consider the “hard electron spectrum” alternative. The electron injection spectral index is taken as –1.7, which after propagation with reacceleration provides consistency with radio synchrotron data (a crucial constraint). Following Pohl & Esposito (1998), for this model we do not require consistency with the locally measured electron spectrum above 10 GeV since the rapid energy losses cause a clumpy distribution so that this is not necessarily representative of the interstellar average. For this case, the interstellar electron spectrum deviates strongly from that locally measured. Because of the increased IC contribution at high energies, the predicted γ-ray spectrum can reproduce the overall intensity from 30 MeV – 10 GeV (Fig. 4 left) but the detailed shape above 1 GeV is still problematic. Fig. 4 (right) illustrates further refinement of this scenario (HEMN model) showing that a good fit is possible (Strong et al. 1999).

Fig. 5 shows the model latitude and longitude γ-ray distributions for the inner Galaxy for 1–2 GeV, convolved with the EGRET point-spread function, compared to EGRET Phase 1–4 data (with known point sources subtracted). It shows that the HEMN model with large IC component can indeed reproduce the data.

None of these models fits the γ-ray spectrum below ~30 MeV as measured by the Compton Gamma-Ray Observatory (Fig. 4). In order to fit the low-energy part as diffuse emission, without violating synchrotron constraints (Strong et al. 1999), requires a rapid upturn in the cosmic-ray electron spectrum below 200 MeV. However, in view of the energetics problems (Skibo et al. 1997), a population of unresolved sources seems more probable and would be the natural extension of the low energy plane emission seen by OSSE (Kinzer et al. 1997) and GINGA (Yamasaki et al. 1997).
Figure 5. Distributions of 1–2 GeV $\gamma$-rays computed for a hard electron spectrum (reacceleration model) as compared to EGRET data (Cycles 1–4, point sources removed, see Strong et al. 1999). Contribution of various components is shown as calculated in our model. \textit{Left panel:} Latitude distribution ($330^\circ < \ell < 30^\circ$). \textit{Right panel:} Longitude distribution for $|b| < 5^\circ$.

6. Conclusions

Our propagation model has been used to study several areas of high energy astrophysics. We believe that synthesizing information from classical cosmic-ray studies with $\gamma$-ray and other data leads to tighter constraints on cosmic-ray origin and propagation.

We have shown that simple diffusion/convection models have difficulty in accounting for the observed form of the B/C ratio without special assumptions chosen to fit the data, and do not obviate the need for an \textit{ad hoc} form for the diffusion coefficient. On the other hand we confirm the conclusion of other authors that models with reacceleration account naturally for the energy dependence over the whole observed range. Taking these results together tends to favor the reacceleration picture.

We take advantage of the recent Ulysses Be measurements to obtain estimates of the halo size. Our limits on the halo height are $4 \text{ kpc} < z_h < 12 \text{ kpc}$. These limits should be an improvement on previous estimates because of the more accurate Be data, our treatment of energy losses, and the inclusion of more realistic astrophysical details (such as, e.g., the gas distribution) in our model, although it should be noted that the limits are strictly only valid in the context of this particular halo picture.

The positron and antiproton fluxes calculated are consistent with the most recent measurements. The $\bar{p}/p$ data point above 3 GeV and positron flux measurements seem to rule out the hypothesis, in connection with the $> 1 \text{ GeV} \gamma$-ray excess, that the local cosmic-ray nucleon spectrum differs significantly from the Galactic average (by implication adding support to the “hard electron” alternative). It therefore seems probable that the interstellar electron spectrum is
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harder than that locally measured, but this remains to be confirmed by detailed study of the angular distribution. The low-energy Galactic γ-ray emission is difficult to explain as truly diffuse and a point source population seems more probable.

References