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The energy spectrum of cosmic ray protons in the local interstellar medium

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Abstract. A number of analyses of cosmic gamma ray data from the Compton Gamma Ray Observatory have found that the energy spectra are flatter than would have been expected if the spectra of protons in the producing regions were of the same shape as that measured at earth. Although it is true that technical artifacts could be responsible a variety of arguments - to be advanced here - make us conclude that the effect is probably genuine. Some implications of the implied spectral variations over the local region of the interstellar medium are discussed.

Key words: gamma rays: theory – cosmic rays – ISM: general

1. Introduction

A number of analyses of cosmic gamma ray data, principally from the EGRET instrument on the Compton Gamma Ray Observatory, have shown that the energy spectrum at energies above 300 MeV is somewhat flatter than expected (e.g. Fichtel et al., 1995; Fatoohi et al., 1995 - to be discussed in some detail, later). In determining the 'expected' spectrum it is assumed that the initiating particles, which are thought to be mainly protons in this energy region, have the same spectral shape as that at earth. The implication is that the average proton spectrum in the ISM is somewhat flatter than that measured at earth and, further, that it varies from place to place. Insofar as the scale height of the target HI gas is $\sim$150 pc, and much (but not all) of the analysis relates to $|b| > 10°$, by 'local ISM' we mean the region within about 1 kpc of the sun.

There are several possibilities that can be invoked to explain the discrepancy and these can be listed.
i) A technical artifact is responsible.
ii) The previous calculations of the form of the energy spectrum of gamma rays from proton - ISM gas nucleus interactions were incorrect.
iii) The Inverse Compton contribution dominates at energies above $\sim$1 GeV thus negating the assumption that protons predominate as the gamma ray progenitors and that there is a simple link between the gamma ray and proton spectra. In what follows we examine each of the possibilities in turn.

2. The evidence for a spectral anomaly and its reliability

2.1. COS B data

A number of claims for spectral variability, with respect to spatial direction, were made from analyses of COS B gamma ray data (e.g. Strong and Wolfendale, 1978, Mayer-Hasselwander, 1983, Bloemen et al., 1987, van der Walt and Wolfendale, 1988), although, some at least, of these variations could be explained in terms of changes in the electron-proton ratio. Rather dramatic latitude variations of the spectral shape above 300 MeV were reported by Bloemen and interesting hypotheses developed in order to explain the results, e.g. by Bloemen (1987) and Rogers et al., (1988).

2.2. EGRET data: Goddard Space Flight Center analysis

With the advent of new results, of higher statistical precision than hitherto, more detailed studies have proved possible.

Fichtel (1993) has given a precise Inner Galaxy spectrum ($|l| < 10°; |b| < 5°$) and compared it with expectation from the calculations of Stecker (1971) and Dermer (1986). It is evident that the fit is not good; specifically, the ratio of observed/expected is (the energies in GeV being given in brackets): 0.75 (0.25); 0.95 (0.5); 1.1 (2); 1.25 (2.5); 1.3 (4) and $\simeq$1.2 (10) a similar result has come from a more detailed study by Hunter (1995) of CGRO data for the same region.

A detailed analysis of the Rho Ophuicus region by Hunter et al. (1993) showed significant differences in spectral shape between the direction of Rho Oph - itself and an area a few degrees away.

Similarly, Digel et al. (1995) compared the spectrum of gamma rays from the 'local' region with that in part of the Outer Galaxy spiral arm in Perseus, several kpc away, and again found

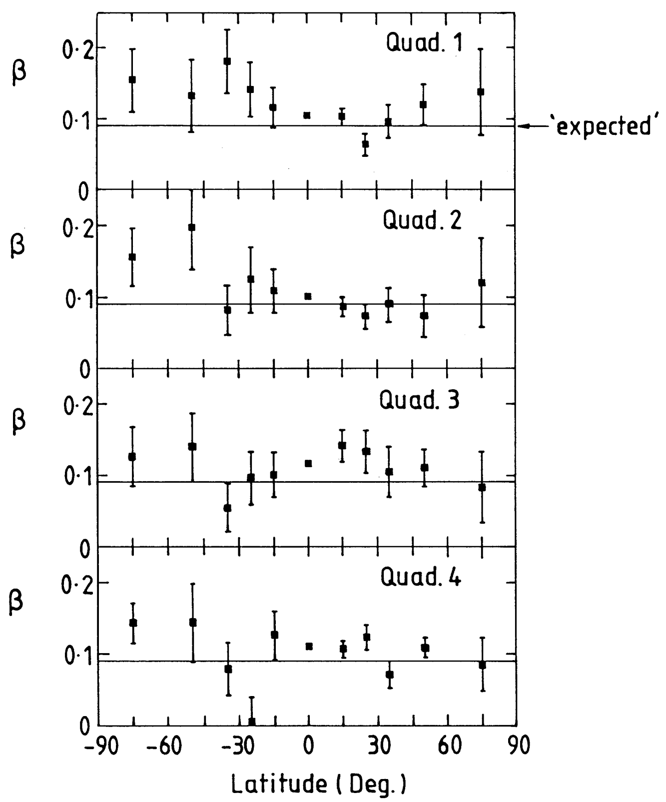

Fig. 1. Latitude dependence of the spectral shape parameter β = I(E_γ > 2GeV)/I(E_γ > 0.3GeV) for each Galactic Quadrant separately. Conventional expectation, i.e. for the p-spectrum at earth is β = 0.9 (indicated). It will be noted that the values are usually bigger than predicted, i.e. the gamma ray spectrum is flatter than expected. (After Fatoohi et al., 1995).

a difference. Perhaps the best evidence for a bad fit of experiment to theory comes from a very recent study of the Galactic Plane region by Hunter (1995). A clear excess is found above 1 GeV, at all longitudes, a result in the spirit of all the observations just referred to. These results are referred to later, in more detail.

2.3. EGRET data: Durham analysis

An independent study has been made by the Durham group and the results for the 'proton component' have been published by Fatoohi et al. (1995). Claims are made for spectral changes on a variety of scales and Fig. 1 gives a summary of the results of this work, conventional expectation being given.

The quantity β, which is I($E_\gamma > 2$GeV)/I($E_\gamma > 0.3GeV$), is clearly related to the spectrum of the initiating protons. If we assume that the proton spectrum can be represented by a power law of exponent γ_p then β can be related to γ_p (in fact, as will be demonstrated later, this may well be an oversimplification). Proceeding with a simple power law, specifically, β = 0.09 corresponds to γ_p = 2.6 and β = 0.12 corresponds to γ_p = 2.4. As described in the work of Fatoohi et al. we would expect $\gamma_p \sim 2.6$ for the proton energy range in question (3-100 GeV) when allowance is made for the (small) effect of nuclei heavier than protons (the proton spectrum itself has a rather steeper spectrum, γ_p : 2.75 ± 0.05, at the appropriate energies).

It is clear from Fig. 1 that the flatter spectrum found by Hunter (1995) for the Galactic Plane region, b $\sim 0°$, is apparent in the Durham analysis too.

Further inspection of Fig. 1 shows that the average value of β is greater than 0.9 and that the higher β (flatter proton spectrum) persists at all latitudes.

2.4. Reliability of the data

A measure of reliability of the conclusion of a flatter gamma ray spectrum than conventionally predicted - and thereby a smaller γ_p if protons predominate as progenitors - comes from a number of facts, as follows:

(i) Both the COS B and CGRO detectors found flatter spectra, although it must be admitted that the results were not always consistent. For example, Fatoohi et al.'s analysis of the spectral shape out of the Galactic Plane from CGRO data did not find the dramatic flattening seen in the COS B data by Bloemen (1987).

(ii) The independent analysis of the same data from CGRO (Sect. 2.2 and Sect. 2.3) found similar results in the common l, b region.

(iii) In principle there could be a technical fault in the EGRET instrument, or use of an incorrect collection area factor, which would give the apparent spectral flattening. We would argue against that from the fact that the spectral shapes of many disc rete gamma ray sources are 'as expected', in the sense that they are simple power laws with no evidence for upturns. Furthermore, there is general consistency between COS B and CGRO spectra for the major sources.

3. The energy spectrum of gamma rays from proton-ISM gas nucleus interactions

The basic interaction for cosmic rays in the ISM leading to gamma rays is that between protons and protons; the effect of heavier nuclei in the cosmic ray beam and elements other than hydrogen in the ISM being allowed for in a straightforward way.

We have made new calculations, the improvement over previous work being, hopefully, a more accurate representation of some of the parameters.

At low proton energies the isobar model (Stecker, 1971) of pion production in pp collisions has been used, and at high energies the geometrical one called "G2C", ("Geometrical-Two-Chain") developed by Wibig and Sobczynska (1994). The models were combined at the dN/dT_π pion energy spectra level. Fig. 2 shows examples of such spectra from G2C. Because G2C is Monte-Carlo based, this graph contains some small bumps. In fact, the spectra are histograms prepared on logarithmic scales. The bumps appear only at low energy and are due to the low statistics in the sections of smallest length. It is worth noting that they do not affect the resultant gamma spectrum.

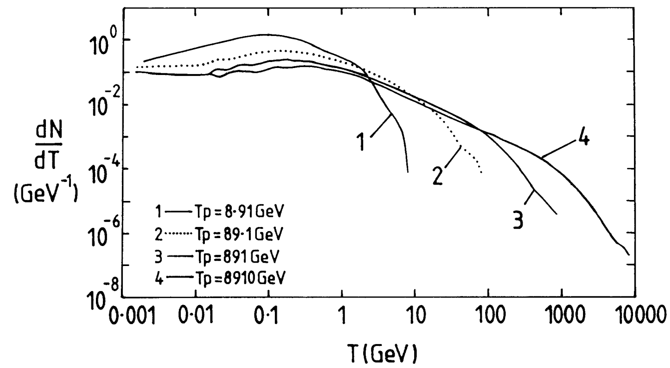

Fig. 2. Energy spectrum of pions for various initiating proton energies for the model described in the text.

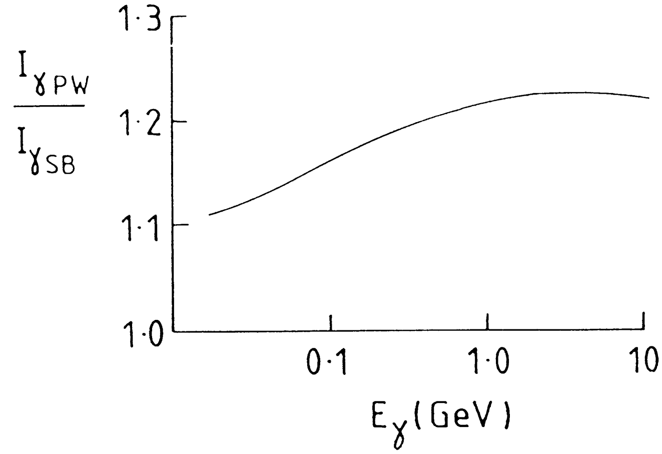

Fig. 3. a Comparison of the presently derived gamma ray spectrum with that given by Badhwar and Stephens (1977) for CR-ISM interactions (denoted SB). A proton spectrum with differential exponent γ_p = 2.75 was used in both derivations. 'PW': present work.

The dN/dT_π spectra of the two models were summed with weights:

$$w_s = \begin{cases} 1 & T_p < 3\text{GeV} \\ (10 - T_p)/(10 - 3) & 3\text{GeV} < T_p < 10\text{GeV} \\ 0 & T_p > 10\text{GeV} \end{cases}$$

$$w_{G2C} = 1 - w_s$$

where w_s and w_{G2C} are for the Stecker and G2C models, respectively, and T_p is the proton kinetic energy. The use of these parameters allows for a straightforward calculation of the differential gamma ray production rate in the standard way (see for insta nce Badhwar and Stephens, 1977). To take into account interactions other than pp, a multiplying factor of 1.45 has been adopted, after Dermer (1986). The resulting gamma ray spectrum in comparison with the calculations of Badhwar and Stephens for CR-ISM interactions is shown in Fig. 3a. A comparison has also been made with the gamma ray spectrum adopted for p-p interactions by Hunter (1995) and the results are shown in Fig. 3b normalized at 1 GeV. Also included is the spectrum for p-p collisions given by Stephens and Badhwar (1977) this differs somewhat from the Badhwar and Stephens spectrum used in Fig. 3a, the latter including heavy nuclei in both beam and target.

It will be noted from the figures that there are, in fact, significant differences in spectral shape although, as we will see, these are not big enough to negate our later claims - and indeed, for $E_\gamma > 1$ GeV, adoption of our spectrum instead of Hunter's increases the spectral flattening.

A further comparison is made in Fig. 4: the new gamma ray spectra are compared with our earlier estimates.

Fig. 4 gives a comparison of the new results with those presented by us recently (Fatoohi et al., 1995), for two values of γ_p.

It will be noted that the differences are small over most of the energy range.

It is apparent from Fig. 4 that there is little difference above 1 GeV for the important case of γ_p = 2.6. Thus, the discrepancy between observed and expected gamma ray spectra reported by Fatoohi et al. (1995) is very unlikely to be due to inaccuracies in the interaction model.

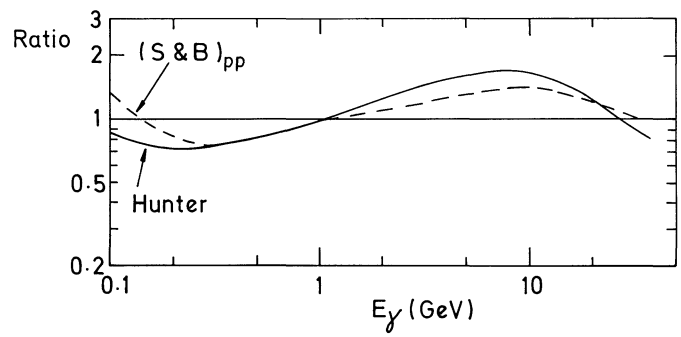

Fig. 4. Comparison of the spectra derived by Stephens and Badhwar (1977), for p-p collisions, and adopted by Hunter (1995), with ours. Their ratio to ours is plotted as a function of energy; normalisation has been carried out at 1 GeV. The initiating proton spectra has γ_p = 2.75.

4. An explanation in terms of inverse Compton interactions

At any l, b it is possible, in principle, to invoke a sufficiently high intensity of IC gamma rays so as to explain the flatter spectral shape there. This arises because the IC spectrum, as derived by most workers, is somewhat flatter than the gamma ray spectrum derived for p-p interactions (see Giller et al., 1995 for a summary). The possibility of adjusting the intensity of gamma rays is due to uncertainty in the scale height of the electrons, whose interactions with, principally, star light photons, gives rise to the IC gamma rays and, to some extent, in the intensity of the high energy electrons. It is true that we, ourselves (Giller et al., 1995) have estimated the scale height (and found Z_0 = 2.5 + 1.0 kpc) but we would be the first to admit that it is not inconceivable that Z_o is even higher.

The problem with invoking IC gamma rays concerns the expected longitude distribution. For, essentially any value of Z_0 there will be a severe dependence of the IC fraction on longitude at rather low latitudes. Thus, for a fixed γ_p (at its 'local' value of 2.6) β should be higher in the Inner Galaxy and 'normal', i.e.

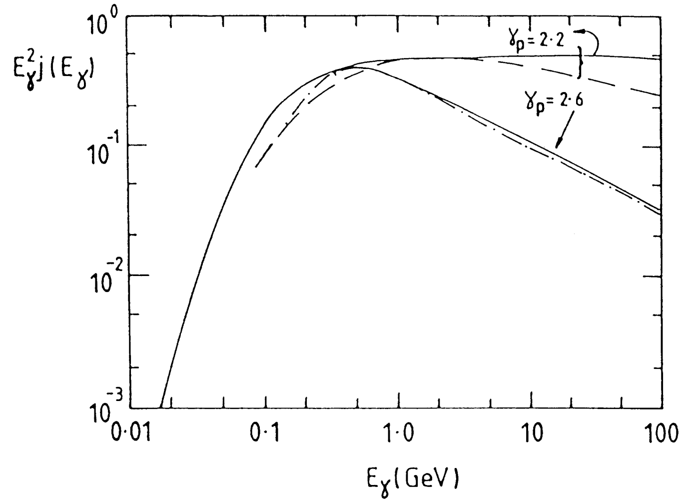

Fig. 5. Comparison of the 'new' gamma ray spectra (denoted by dashed lines) with those given by Fatoohi et al. (1995) (full lines).

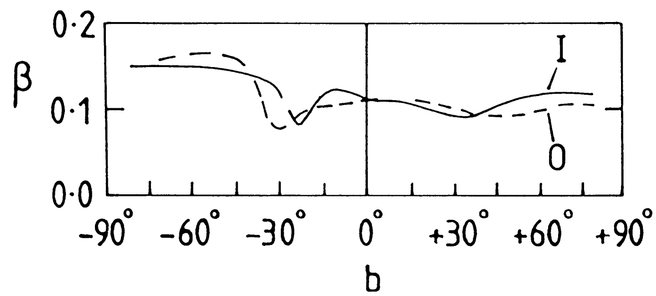

Fig. 6. Mean values of β for the Inner and Outer Galaxy (from Fig. 1). Had IC been responsible the mean for the Inner Galaxy would have been bigger than that for the Outer Galaxy particularly at low latitudes. In the figure none of the differences between I and O is significant and both differ appreciably from β = 0.1 at $b < -40°$.

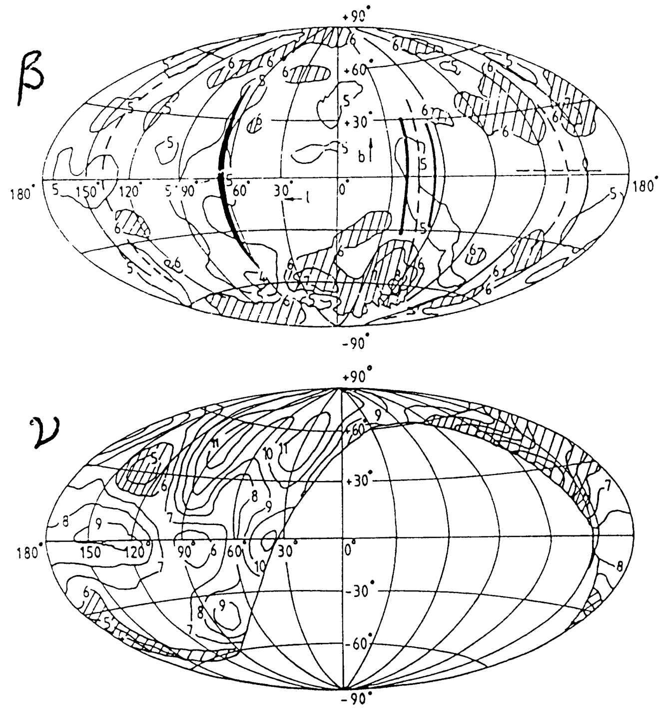

Fig. 7. Map of β for gamma rays (from Fatoohi et al., 1995) and spectral index for radio, between 408 and 1420 MHz (from Lawson et al., 1987). Gamma rays: 4,5,6 and 7 correspond to β = 0.05, 0.10, 0.15 and 0.25. The full lines represent the positions of the major interarm regions. The dashed lines represent the regions of low hydrogen column density (Paresce, 1984). Radio: 1,2,3,4 .... correspond to ν = 2.4, 2.45, 2.5, 2.55 ....

$\sim$0.9, in the Outer Galaxy. That this is not the case is apparent from Fig. 1 and Fig. 6, the latter showing the mean value of β for the Inner (Quadrants 1 and 4) and Outer (Quadrants 2 and 3) Galaxies. It is clear that there is essentially no difference between the two means; we would have expected $\Delta\beta \simeq 0.03$ for $|b| < 30°$ whereas it is < 0.01.

Over most of the range of b the overall mean is close to β = 0.11 but for b $< -30°$ it will be noted that $<\beta>$ rises to $\simeq$0.14. It is not impossible that the flat spectrum near the South Galactic Pole is associated with the well known anisotropy of cosmic rays in the range 10^{13}-10^{14} eV, the anisotropy corresponding to a flow from the general direction of the South Pole. However, it must be recognized that the distance scale of the intensity variations ($\approx$100pc) is very much bigger than the Larmor radius ($\simeq 10^{-2}$ pc) of the particles in question.

Another check of the IC explanation is afforded by examining the spectral shape of synchrotron radiation over the sky and comparing it with that of β. If the electrons producing IC were of similar energy to those producing synchrotron radiation then, since the relevant scale heights of electrons, magnetic field and starlight are not too dissimilar, the IC explanation would dictate high radio spectral exponents and apparently high γ_p (low β) regions to coincide.

One GeV gamma rays come from electrons of energy of order 1.4×10^{10} eV via IC on starlight and such electrons generate radio waves of frequency $\sim$900 H MHz in a field of H μ Gauss. In the production regions of interest, away from the Galactic Plane, we have a mean field of order 1 μ Gauss so that the operative frequency is $\sim$900 MHz. Lawson et al. (1987) have, in fact, studied the variations in the spectral index of such radio continuum emission (in the northern hemisphere) and a map of the radio spectral index between an appropriate pair of frequencies, 408 and 1420 MHz, is given in Fig. 7. Also shown in that figure, for comparison, is the map of Fatoohi et al. (1995) for β for comparison. It is evident that there is no (positive) correlation such as would be expected if IC were dominant; indeed, what correlation there is would appear to be negative.

In the β-map the high β values (flat spectra) are indicated by hatching and in the ν-map the low ν values (flat spectra) are shown hatched. If the IC contribution to the high energy γ-flux were high we would expect a correlation between the two maps; there appears to be none.

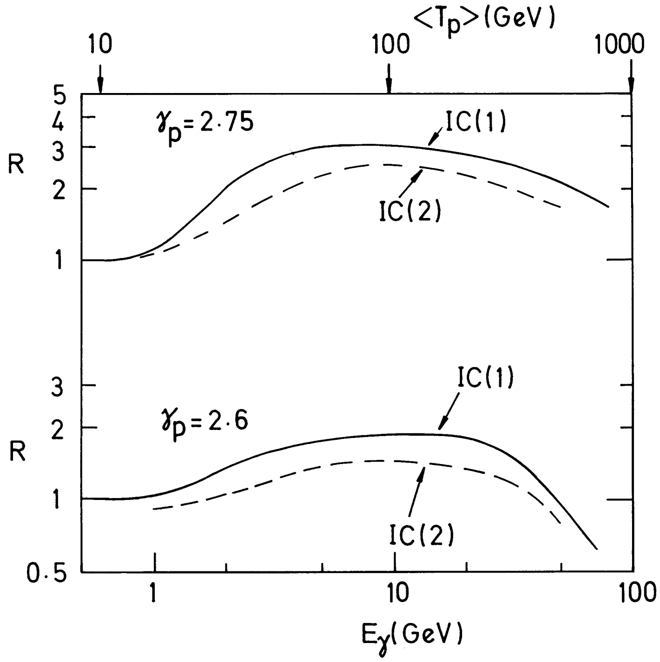

Fig. 8. Ratio of 'observed' to 'expected' proton spectrum for the l, b range $|l| < 60°$, $|b| < 10°$ using the measurements of Hunter (1995) and our own analyses. IC(1) uses the IC spectrum adopted by Hunter and IC(2) uses our own (Giller et al., 1995). There is clear evidence that the effective proton spectrum has a differential exponent somewhat smaller than 2.6. The scale of the top gives the approximate mean proton energy for the gamma ray energy scale at the bottom.

5. The Inner Galaxy: $|l| < 60°$, $|b| < 10°$

As referred to already, Hunter has published the measured spectrum (to ∼50 GeV) for the l, b region referred to. This spectrum is the most precisely known one to date and we have examined it in detail. Hunter gives the measured intensities and the adopted contributions from nuclear interactions electron bremsstrahlung, IC interactions and the extragalactic intensity.

We have analysed the results in a number of ways depending on which value of γ_p to take as a datum (2.75 or 2.6) and whether to use Hunter's estimate of IC (denoted IC(1)) or our own, as given by Giller et al. (1995) (denoted IC(2)). The other components are as given by Hunter, viz for electron bremsstrahlung and the extragalactic intensity.

Fig. 8 shows the ratio of 'proton' intensity needed to satisfy the results to that predicted by us.

The flattening of the implied proton spectrum over expectation is clearly marked; even γ_p = 2.6 is too steep unless the IC contribution is even greater than we have estimated (it is already some 2.4 times that adopted by Hunter for this l, b range). What is quite clear is that the measured spectrum is flatter than that which follows from γ_p = 2.75. As remarked previously, our own contention is that allowance for heavy nuclei causes an effective γ_p near 2.6 and thus γ_p = 2.6 is our conventional estimate. A value of γ_p less than this indicates an 'anomalous' flattening.

Taken at its face value the result in the lower half of Fig. 7, for IC(2), indicates $\gamma_p \approx 2.45$, a value not inconsistent with the result in Fig. 1.

Some further comments are necessary.

(i) Unlike regions away from the Galactic Plane there will be a significant fraction of unresolved discrete sources for $|b| < 10°$. Fatemi and Wolfendale (1995) estimate these to contribute about 10% of the total flux for $|l| < 60°$. Although the spectral shape of the detected sources is similar to that of the diffuse component that of the unresolved sources cannot be assumed to be the same and there are problems. Nevertheless, it is unlikely that they contribute much to the 'excess' in the range 1-10 GeV.

(ii) The apparent rapid fall off of R above about 30 GeV may or may not be real in the sense that the highest energy point in Hunter's plot at 39 GeV and the curves represent extrapolation.

If real then care will be needed with the correction for the Extragalactic intensity, I_{EG}. This quantity is increasing in relative magnitude as E_γ increases. Specifically, extrapolating I_{EG} and $I_{\gamma,p}$ from Hunter's work, the two meet at $E_\gamma \approx$ 100GeV.

It is not inconceivable that the EG spectrum steepens above 10 GeV; indeed, data by Osborne et al. (1994) does show signs of structure. The form used by Hunter is very similar to that advocated by Osborne et al. and has an energy independent exponent.

A further point is that the IC intensity at high energies may well fall more rapidly than we have assumed because, near the Galactic Plane there may be considerable steepening of the high energy electron spectrum

6. Conclusions

Unless the IC spectrum is itself so longitude - and latitude-dependent so of to negate the arguments given in Sect. 4, it must be concluded that the evidence for a spectral flattening of the proton spectrum away from the solar system should be accepted.

The implications are manifold. Calculations using the Leaky Box Model of cosmic ray propagation in the Galaxy will be singularly inaccurate. Thus, there will be errors in the conclusions regarding the ratios of secondary and primary nuclei (and electrons) and in the derived cosmic ray residence time. There should also be small, long term cosmic ray intensity variations visible in the cosmogenic record, caused by the solar system having moved through the regions of the ISM where the cosmic ray intensity is different. As an example of the latter, the solar system velocity of ∼20 km s^{-1} corresponds to ∼20 pc per 10^6 y. Thus, variations on a time scale of 10^6-10^7 y should occur (see Bhat et al., 1987 for an earlier discussion on this point).

Finally, some comments are in order about the likely cause of the spectral variations. Following our earlier work (Fatoohi et al., 1995) we can identify variations in the diffusion coefficient for particle propagation causing more rapid Galactic escape in some regions than others and the likelihood of effects due to Galactic winds (or enhanced convection at low Z-values) and reacceleration by old SNR. With regard to the last mentioned it can be remarked that a 'bump' in the proton energy spectrum extending to some 100's of GeV, proton energy (see top scale of Fig. 7) is not unreasonable.

References

Badhwar, G.D., Stephens, S.A., 1977, Proc. 15th Int. Cosmic Ray Conf., Plovdiv, 1, 198.

Bhat, C.L., Mayer, C.J., Rogers, M.J., Wolfendale, A.W., 1987, J. Phys. G., 13, 257.

Bloemen, J.B.G.M. et al., 1987, Astrophys. J., 317, L15.

Bloemen, J.B.G.M., 1989, Ann. Rev. Astron. Astrophys., 27 469. Dermer, C., 1986, Astron. Astrophys., 157 223.

Fatemi, J., Wolfendale, A.W., 1995, submitted.

Fatoohi, L.J., Giller, M., Wdowczyk, J., Wolfendale, A.W., Zhang, L., 1995, J. Phys. G., 21 679.

Fichtel, C.E. et al., 1993, Advances in Space Res., Pergamon Press, N.Y.

Giller, M., Wdowczyk, J., Wolfendale, A.W., Zhang. L., 1995, J. Phys. G., 21 487. Hunter, S.D. et al., 1994, Astrophys. J., 436, 216.

Hunter, S.D. (on behalf of EGRET team), 1995, Proc. Int. Cosmic Ray Conf., Rome, 2, 182.

Lawson, K.D., Mayer, C.J., Osborne, J.L., Parkinson, M.L., 1987, Mon. Not. R. astr. Soc., 225, 307.

Mayer-Hasselwander, H.A., 1983, 'Kinematics, Dynamics and Structure of the Milky Way, ed. W.L.H. Shuter, 223, Dordrecht, Reidel.

Osborne, J.L., Wolfendale, A.W., Zhang, L.J., 1994, J. Phys. G., 20, 1089.

Rogers, M.J., Sadzinska, M., Szabelski, J., van der Walt, D.J., Wolfendale, A.W., 1988, J. Phys. G., 14, 1147.

Stecker, F.W., 1971, Cosmic Gamma Rays (Baltimore: Mono Book Co.).

Stephens, S.A., Badhwar, G.D., 1981, Astrophys. and Space Sci., 76, 213.

Strong, A.W., Wolfendale, A.W., 1978, J. Phys. G., 4 1973.

Wybig, T., Sobczynska, D., 1994, Phys. Rev., D49 2268.

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