

# A common origin of all the species of high-energy cosmic rays?

Arnon Dar<sup>a,b</sup>, A. De Rújula<sup>a</sup> and Nikos Antoniou<sup>a,c</sup>

<sup>a</sup> Theory Division, CERN, CH-1211 Geneva 23, Switzerland

<sup>b</sup> Technion, Israel Institute of Technology, Haifa 32000, Israel

<sup>c</sup> Department of Physics, University of Athens, 15771 Athens, Greece

## Abstract

Cosmic ray nuclei, cosmic ray electrons with energy above a few GeV, and the diffuse gamma-ray background radiation (GBR) above a few MeV, presumed to be extragalactic, could all have their origin or residence in our galaxy *and its halo*. The mechanism accelerating hadrons and electrons is the same, the electron spectrum is modulated by inverse Compton scattering on starlight and on the microwave background radiation; the  $\gamma$ -rays are the resulting recoiling photons. The spectral indices of the cosmic-ray electrons and of the GBR, calculated on this simple basis, agree with observations. The angular dependence and the approximate magnitude of the GBR are also explained.

PACS numbers: 98.70.Sa, 98.70.Rz, 98.70.Vc.

arXiv:astro-ph/9901004v2 31 Jul 1999

The origin and spectrum of non-solar cosmic ray hadrons, electrons and photons has been debated for almost a century. The cosmic ray (CR) nuclei have a power-law spectral flux  $dF/dE \propto E^{-\beta_i}$  with a series of break-point energies ( $\beta_{1,2,3} \sim 2.7, 3.0,$  and  $2.5$  in the intervals  $10^{10} \text{ eV} < E < E_{\text{knee}} \sim 3 \times 10^{15} \text{ eV}$ ,  $E_{\text{knee}} < E < E_{\text{ankle}} \sim 3 \times 10^{18} \text{ eV}$ , and  $E_{\text{ankle}} < E < E_{\text{GZK}} \sim 6 \times 10^{19} \text{ eV}$ ). Below  $E_{\text{knee}}$ , protons constitute  $\sim 96\%$  of the nucleon flux at fixed energy per nucleon. Their flux is [1]:

$$\frac{dF_p}{dE_p} \simeq 1.8 \left[ \frac{E_p}{\text{GeV}} \right]^{-2.70 \pm 0.05} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}. \quad (1)$$

A presumed extragalactic origin [2] of the highest-energy CRs is at variance with observations [3] of CRs above the ‘GZK cutoff’:  $\gamma$ -rays and neutrinos are not good candidate primaries [4] and, for  $E > E_{\text{GZK}}$ , the flux of protons and nuclei originating more than  $\sim 20 \text{ Mpc}$  away [5] should be quenched [6] by the cosmic background radiation (CBR). In this letter we argue that, above typical nuclear energies of a few MeV, non-solar CR electrons and the ‘diffuse’  $\gamma$ -ray background may be intimately related to hadronic CRs, whose observed spectral shape we use as input.

By assuming a common accelerating mechanism for all charged particles we deduce a power law that fits, above  $E_e = 5 \text{ GeV}$ , the CR electron flux [7] [8] shown in Fig. 1, from the hadron spectral index  $\beta_1$ . Unlike protons, electrons are significantly affected by Compton scattering on starlight and on the CBR. The up-scattered photons have a spectral index that agrees with that of the observed [9] diffuse  $\gamma$ -ray background above a few MeV, shown in Fig. 2. To obtain the observed  $\gamma$ -ray intensity, we need a scale-height of the CR electrons much bigger than the accepted  $\sim 1$

kpc minimum [10]. There is evidence for CR electrons well above galactic disks [11] from observations of synchrotron emission by galaxies seen edge-on. We envisage the possibility that the ‘box’ in which charged CRs reside be much larger than the galactic disk, and we call this box ‘the halo’ [12].

A classic argument determines the volume of a region to which CRs are confined. An abundance ratio of secondary to primary rays (e.g., Li/C) is used to deduce  $X$ : the mean column density they traverse. Ratios of unstable to stable isotopes (e.g.  $^{10}\text{Be}/^9\text{Be}$  or  $^{26}\text{Al}/^{27}\text{Al}$ ) are used to deduce the mean length,  $L$ , of their voyage. The inferred mean density [13] is  $\bar{\rho} = X/L \sim \rho(\text{disk})/5$ . The usual conclusion –that the confining volume is  $\sim 5 V(\text{disk})$ – relies on tacit assumptions that need not be right. If the halo is magnetized, as the disk is, we have a “leaky box” within a (much less dense) leaky box. If the lifetimes of  $^{10}\text{Be}$  and  $^{26}\text{Al}$  are not longer than the mean residence time in the disk, the observed ratios determine  $L(\text{disk})$ , but not  $L(\text{halo})$ . The stable isotope ratios do determine the total column density  $X(\text{tot})$ , but this may include various prolonged journeys in the halo. Without knowing  $L(\text{halo})$  the density  $\bar{\rho} = X(\text{tot})/L(\text{tot})$  of the overall confining domain cannot be estimated. The conventional tacit assumption is that the stable CRs that reach us cannot have spent long periods in a baryonically thin halo, before or between disk-crossings.

To relate the spectra of CR electrons and protons we shall need an estimate of the protons’ spectrum at their source. At  $E < E_{\text{knee}}$  a source spectrum  $dF^s/dE$  with index  $\beta_s \sim 2.2$  is obtained from collisionless-shock simulations [14] or analytical

estimates of acceleration by relativistic jets [15]. The CR spectrum is modulated by their residence time in the galaxy,  $\tau_{\text{gal}}(\text{E})$ . For a steady source of CRs the energy dependence of the observed flux is roughly that of  $\tau_{\text{gal}} dF^{\text{s}}/d\text{E}$ . Observations of astrophysical and solar plasmas and of nuclear abundances as functions of energy indicate [16] that  $\tau_{\text{gal}}(\text{E}) \propto \text{E}^{-0.5 \pm 0.1}$ , explaining  $\beta_1 \sim 2.7$ , as in Eq. (1).

The CR electron flux of Fig. 1 is well fit, from  $\sim 10$  GeV to  $\sim 2$  TeV, by:

$$\frac{dF_e}{dE_e} \simeq (2.5 \pm 0.5) \times 10^5 \left[ \frac{E_e}{\text{MeV}} \right]^{-3.2 \pm 0.10} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}. \quad (2)$$

The  $e^+$  admixture is  $\sim 7\%$  from 3 to 50 GeV [17]. To a good approximation, as we assume at all energies, CR electrons are not pair produced, nor are they secondary products of interactions, nor the result of relic-particle annihilation or decay.

Practically all CR acceleration mechanisms invoke a region of space that is swept by a moving magnetic field, such as would be carried by the rarefied plasma in a supernova shell [2] or by a ‘plasmoid’ of jetted ejecta [12]. The magnetic field acts as a moving ‘mirror’ that imparts the same distribution in velocity, or Lorentz factor  $\gamma = E/mc^2$ , to all charged particles. To the extent that particle-specific losses (such as synchrotron radiation) can be neglected at the acceleration stage, all source fluxes have the same energy-dependence. Confinement effects preserve this equality for ultrarelativistic electrons and protons: their behaviour in a magnetic maze is the same. But, unlike for hadrons, the ‘cooling’ time of electrons in their ‘inverse’ Compton scattering (ICS) interactions with starlight and the CBR is shorter than

their galactic confinement time,  $\tau_{\text{gal}}(E)$ , above a relatively low energy.

Consider electron interactions with the CBR. Let  $T_0 = 2.728$  K,  $n_0 \approx 411 \text{ cm}^{-3}$ , and  $\epsilon_0 \approx 2.7 kT_0 \approx 6.36 \times 10^{-10}$  MeV be the current CBR temperature, number density and mean energy [18]. The cross section for ICS is  $\sigma_T \approx 0.65 \times 10^{-24} \text{ cm}^2$  (for the relevant  $E_e$  range the Thompson limit is accurate, even for ICS on starlight). The mean energy  $E_\gamma$  of the upscattered photons, –or  $\Delta E_e$ , the mean energy loss per collision– is  $E_\gamma \approx \Delta E_e \approx (4/3)\epsilon_0(E_e/m_e c^2)^2$ . The single electron interaction rate is  $\sigma_T n_0 c$ . Let  $R$  (also an inverse time) be the production rate of CR electrons, assumed to be constant [1], and let  $dn_e^s/dE_e$  be their source number-density spectrum. The actual density  $dn_e/dE_e$  in an interval  $dE_e$  about  $E_e$  is continuously replenished and depleted by electrons whose energy is being degraded by ICS. This leads to a steady-state situation in which production and losses are in balance:

$$\sigma_T n_0 c \frac{d}{dE_e} \left( E_\gamma \frac{dn_e}{dE_e} \right) = R \frac{dn_e^s}{dE_e}. \quad (3)$$

For a relatively uniform galactic CR electron density, Eq. (3) also applies to the local electron flux  $dF_e \simeq (c/4\pi)dn_e$ . Substitute the spectrum  $dn_e^s/dE \sim E_e^{-\beta_s}$  into the flux version of Eq. (3) to obtain:

$$\frac{dF_e}{dE_e} = \frac{3 m_e^2 c^4 R}{4 (\beta_s - 1) c \sigma_T n_0 \epsilon_0 E_e} \frac{dF_e^s}{dE_e} \propto E_e^{-(\beta_s+1)}. \quad (4)$$

Compton scattering on starlight and synchrotron radiation on magnetic fields can be included by replacing  $n_0 \epsilon_0$  by the total energy density  $\Sigma n_i \epsilon_i + B^2/(8\pi)$ , whose local variations do not affect the spectral shape. For electrons with  $E_e < (m_e/m_p) E_{\text{knee}} \sim$

1.6 TeV we deduced that  $\beta_s \sim 2.2$ . Thus,  $\beta_s + 1 = 3.2$ , in agreement with the observed spectral index, Eq. (2) and Fig. 1. Above the ‘electron’s knee’ at  $E_e \sim 1.6$  TeV the spectrum should steepen up by  $\Delta\beta \simeq 0.25$ , like that of CR hadrons [15]. The available spectral measurements extend only to  $E_e \leq 1.5$  TeV.

The cooling time of electrons in the CBR bath is given by

$$\tau_{\text{ICS}}(E_e) \simeq \frac{E_e}{n_0 \sigma_T c \Delta E_e} \simeq \frac{3 m_e^2 c^4}{4 E_e n_0 \epsilon_0 \sigma_T} \simeq 1.2 \times \left[ \frac{E_e}{\text{GeV}} \right]^{-1} \text{ Gy}. \quad (5)$$

At our location in the Galaxy, starlight and magnetic fields have energy densities similar to that of the CBR, and  $\tau_{\text{ICS}}$  is shorter by a factor  $\sim 3$ . The galactic escape time of GeV electrons should be similar to that of CR protons  $\tau_{\text{gal}}(E) \propto E^{-0.5 \pm 0.1}$  [16], and has a weaker energy dependence than  $\tau_{\text{ICS}}$  does. At sufficiently low energy, then,  $\tau_{\text{gal}} < \tau_{\text{ICS}}$ , and processes other than ICS cooling become relevant. The slope of the electron spectrum of Eq. (4) should change as the energy is lowered. The observed spectrum of Fig. 1 shows such a change, but it occurs below  $E_e = 10$  GeV, a range in which local modulations would mask the effect.

Data from the SAS 2 satellite [19] suggested the existence of an isotropic, ‘diffuse’ gamma background radiation (GBR). The EGRET instrument on the Compton Gamma Ray Observatory has confirmed its existence. By removal of the Galactic-disk diffuse emission a uniformly distributed GBR has been found, of alleged extragalactic origin [9]. The GBR flux in the observed energy range of 30 MeV to

120 GeV is well described by a single power law:

$$\frac{dF_\gamma}{dE_\gamma} \simeq (2.74 \pm 0.11) \times 10^{-3} \left[ \frac{E_\gamma}{\text{MeV}} \right]^{-2.10 \pm 0.03} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}. \quad (6)$$

Many possible sources for the GBR have been discussed, and are reviewed in [9].

EGRET data on  $\gamma$ -rays above 1 GeV show an excess over the expectation from cosmic-ray production of  $\pi^0$ s [20]. Electron bremsstrahlung in gas is not the source of the 1–30 MeV inner-Galaxy  $\gamma$ -rays observed by COMPTEL [21], since their latitude distribution is broader than that of the gas. These findings imply that a source such as ICS may be more important than previously believed [22]. We go even further and propose that the GBR is not mainly extragalactic, but dominantly due to the ICS of CBR and of starlight photons by CR electrons in the galactic halo. It is useful to discuss the CBR and starlight contributions in turn.

Let us characterize the CR electron density in the Galaxy and its halo as a smooth spherical distribution. Assume the electron flux, Eq.(2), observed at  $E_e > 10$  GeV, to be representative of the local interstellar value. Define a ‘scale radius’ for the CR electrons,  $R_e \equiv \int dr [dn_e(r)/dr]/n_e(0)$ . Let  $\theta$  be the angle away from the direction to the galactic center, distant  $d_\odot \sim 8.5$  kpc. The CR-electron density distribution in energy and position may be convoluted with the CBR spectrum to derive the resulting flux of ICS up-scattered photons [23]. For  $R_e^2 \gg d_\odot^2$  the result is insensitive to the spatial shape of the electron distribution and very well approximated by:

$$\frac{dF_\gamma}{dE_\gamma} \simeq \frac{n_0 \sigma_T R_e f(\theta)}{2 E_\gamma} \left[ E_e \frac{dF_e}{dE_e} \right]_{E_e=\bar{E}_e}; \quad \bar{E}_e \equiv m_e c^2 \sqrt{\frac{3 E_\gamma}{4 \epsilon_0}}, \quad (7)$$

where  $\bar{E}_e$  is obtained by inverting  $E_\gamma$ . The form-factor  $f(\theta)$  reflects our excentricity:

$$R_e f(\theta) = d_\odot \cos \theta + \sqrt{R_e^2 - d_\odot^2 \sin^2 \theta}. \quad (8)$$

For the value we shall estimate,  $R_e = 30$  kpc,  $f(\theta) = 1 \pm 0.28$ , for  $\theta = 0, \pi$ .

Substitute Eq. (2) into Eq. (7) to obtain:

$$\frac{dF_\gamma^{\text{CBR}}}{dE_\gamma} \simeq (1.43 \pm 0.30) \times 10^{-3} \left[ \frac{R_e f(\theta)}{30 \text{ kpc}} \right] \left[ \frac{E_\gamma}{\text{MeV}} \right]^{-2.10 \pm 0.05} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}. \quad (9)$$

The index coincides with the measured one and, for  $R_e = 30$  kpc, the normalization is roughly half of what is observed, Eq.(6). The electron spectrum of Eq. (2) describes the data in the range  $E_e > 5$  GeV, so that Eq. (9) should be valid above  $E_\gamma \sim 100$  keV. We have predicted a steepening of the electron spectrum at  $E_e \sim 1.6$  TeV. By the same token, the spectral index  $\beta \sim 2.1$  of Eq. (9) should increase by a currently unobservable  $\Delta\beta \sim 1/8$  at  $E_\gamma \sim 10$  GeV.

It is difficult to model in detail ICS on starlight [24] [9]. We make a coarse estimate of the effect, at high latitudes, of an electron distribution with large  $R_e$ . Approximate the Galaxy's starlight, of average energy  $\epsilon_\star \sim 1$  eV, as that produced by a source at its center with the galactic luminosity  $L_\star = 2.4 \times 10^{10} L_\odot$ . Assume that  $R_e^2 \gg d_\odot^2$  and replace in Eq. (9) the halo column density of CBR photons in the  $\theta$  direction,  $n_0 R_e f(\theta)$ , by the same quantity for starlight:

$$N_\star \approx \frac{L_\star}{4\pi c \epsilon_\star} \int_0^\infty \frac{dx}{d_\odot^2 - 2x d_\odot \cos \theta + x^2} = \frac{L_\star}{4\pi c \epsilon_\star} \left[ \frac{(\pi - \theta)}{d_\odot \sin \theta} \right], \quad (10)$$



to obtain

$$\frac{dF_{\gamma}^{\text{SL}}}{dE_{\gamma}} \simeq (1.14 \pm 0.24) \times 10^{-3} \left[ \frac{2(\pi - \theta)}{\pi \sin \theta} \right] \left[ \frac{E_{\gamma}}{\text{MeV}} \right]^{-2.10 \pm 0.05} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}^{-1}. \quad (11)$$

The point source approximation is not accurate enough for directions close to the galactic disk and galactic bulge, but the GBR data [9] mask  $|b| \leq 10^{\circ}$  as well as  $|b| \leq 30^{\circ}$  for  $|l| \leq 40^{\circ}$ .

The angular average of the sum of CBR and starlight contributions to the GBR, Eqs.(9) and (11), is shown in Fig. 2. It has the observed spectral shape and, for  $R_e = 30$  kpc, the observed magnitude. The fitted value  $R_e \sim 30$  kpc is imprecise: the starlight to CBR ratio is proportional to  $\epsilon_{\star}/\epsilon_0$  raised to a poorly determined power,  $0.10 \pm 0.05$ . Our spectral index is independent of direction, as observed, see Figs. 5 and 6 of [9]. The spectral-index data are given in [9] for 36 (b,l) domains, in Figs. 3-7 we have redrawn them as functions of  $\theta$ : 9 values for each half hemisphere. The statistical test for a flat distribution is surprisingly good:  $\chi^2/\text{d.o.f.} \sim 0.5$ .

The intensity of the GBR diminishes as the angle away from the galactic center increases, see Figs. 5 and 6a of [9], which we have redrawn as functions of  $\theta$  in Figs. 8-12. Even after eliminating the four data points closest to the galactic center (at  $\bar{\theta} = 49.2^{\circ}$ ), about which the observers feel unsure [9],  $\chi^2/\text{d.o.f.} = 1.8$  for constant intensity. The sum of Eqs. (9) and (11) fits better the observed angular trend of the GBR, as shown in Figs. 8-12 ( $\chi^2/\text{d.o.f.} = 1.3$ ). This agreement would presumably further improve with a more realistic treatment of starlight.

For  $R_e = 30$  kpc, the luminosity of our galaxy in  $\gamma$ -rays of energy above  $E$  is:

$$L_E \simeq (1.5 \pm 0.5) \times 10^{40} \left[ \frac{E}{\text{MeV}} \right]^{-0.10 \pm 0.05} \text{ erg s}^{-1}. \quad (12)$$

This result is slowly converging and uncertain, but a future  $\gamma$ -ray telescope, such as GLAST, could possibly see the corresponding glow of Andromeda's halo.

To estimate the contribution of external galaxies to the GBR, some concepts and numbers need be recalled. Hubble's 'constant' is  $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ , with  $h \sim 0.65$ ;  $\Omega_m$  and  $\Omega_\Lambda$  are matter and vacuum cosmic densities in critical units;  $\Omega \equiv \Omega_m + \Omega_\Lambda$ ;  $y \equiv 1 + z$  is the redshift factor. In a Friedman model, the time to redshift relation is  $dy/dt = -H_0 f(y) y$ , with  $f(y) \equiv [(1 - \Omega) y^2 + \Omega_m y^3 + \Omega_\Lambda]^{1/2}$ . The luminosity density of the local universe [25] is  $\rho_L \simeq 1.8 \times 10^8 h L_\odot \text{ Mpc}^{-3}$ . The combination  $\rho_L/L_*$  provides an estimate of the average number density of 'Milky-Way-equivalent' galaxies. If the sources of CRs are young supernova remnants or gamma-ray bursts, the CR production rate ought to be proportional [26] to the star formation rate  $R_{\text{SFR}}$ , recently measured up to redshift  $z \simeq 4.5$  [27].

The energy of CBR photons up-scattered by electrons at 'epoch  $y$ ' is proportional to  $T(y) = y T_0$  and is subsequently redshifted by the same factor; hence the corresponding spectra from distant galaxies have the same energy dependence as from our galaxy up to  $E_\gamma \sim 10 \text{ GeV}$ , where absorption on the infrared background becomes relevant [28]. The cosmological starlight contribution is redshifted and

consequently becomes negligible. For the sum of all galaxies, we obtain:

$$\frac{dF_\gamma}{dE_\gamma} \simeq \frac{dF_\gamma^{\text{CBR}}}{dE_\gamma} \left[ 1 + \frac{4\pi R_e^2}{3} \frac{\rho_L}{L_*} \frac{c}{H_0} \int_1 \frac{R_{\text{SFR}}(y)}{R_{\text{SFR}}(0)} \frac{y}{f(y)} \frac{dy}{y^3} \right], \quad (13)$$

where the CBR flux is that of Eq. (9). For  $R_{\text{SFR}}$  we interpolate the summary values of [27]. For  $\Omega = \Omega_m = 1$  and  $R_e = 30$  kpc, the extragalactic contribution in Eq. (13) is at the 4% level (the h-dependences cancel). Other sensible values of the cosmological parameters give similar results.

We have given a simple explanation for the observed spectral index of CR electrons. We have suggested that these electrons populate a “halo” region well beyond the disk of our Galaxy and that they produce the GBR by inverse Compton scattering on CBR and starlight photons. Thus, the diffuse  $\gamma$  radiation (in directions other than those of the Galaxy’s disk and bulge) would not originate outside the Galaxy, but outside its starry domain. We have demonstrated that the predicted spectral index and angular distribution of the produced radiation agree with the GBR data, their normalization results in an estimate of the scale-height of the electron distribution. Our results can be checked in various ways. The power index  $\beta$  of the electron spectrum should steepen above  $E_e \approx 1.6$  TeV by  $\Delta\beta \sim 1/4$ . The halo of Andromeda should shine in gamma rays above a few MeV. The GBR should reflect the asymmetry of our off-center position in the galactic disk and its energy spectrum should not have the GZK-like cutoff expected [28] for cosmological sources.

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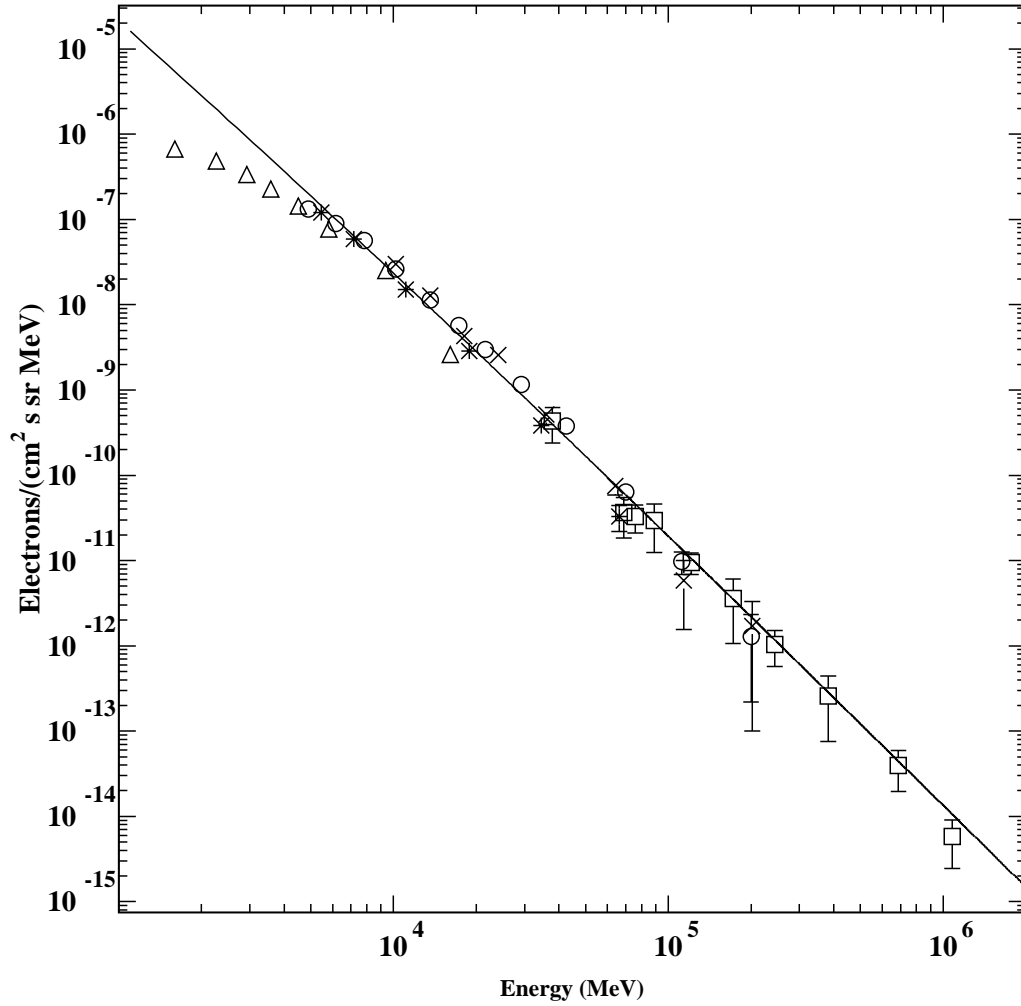


Figure 1: The primary cosmic ray electron spectrum as measured [8] by Prince [crosses], Nishimura *et al.* [squares], Tang [circles], Golden *et al.* [triangles] and Barwick *et al.* [stars]. The theoretical curve is normalized to the data.

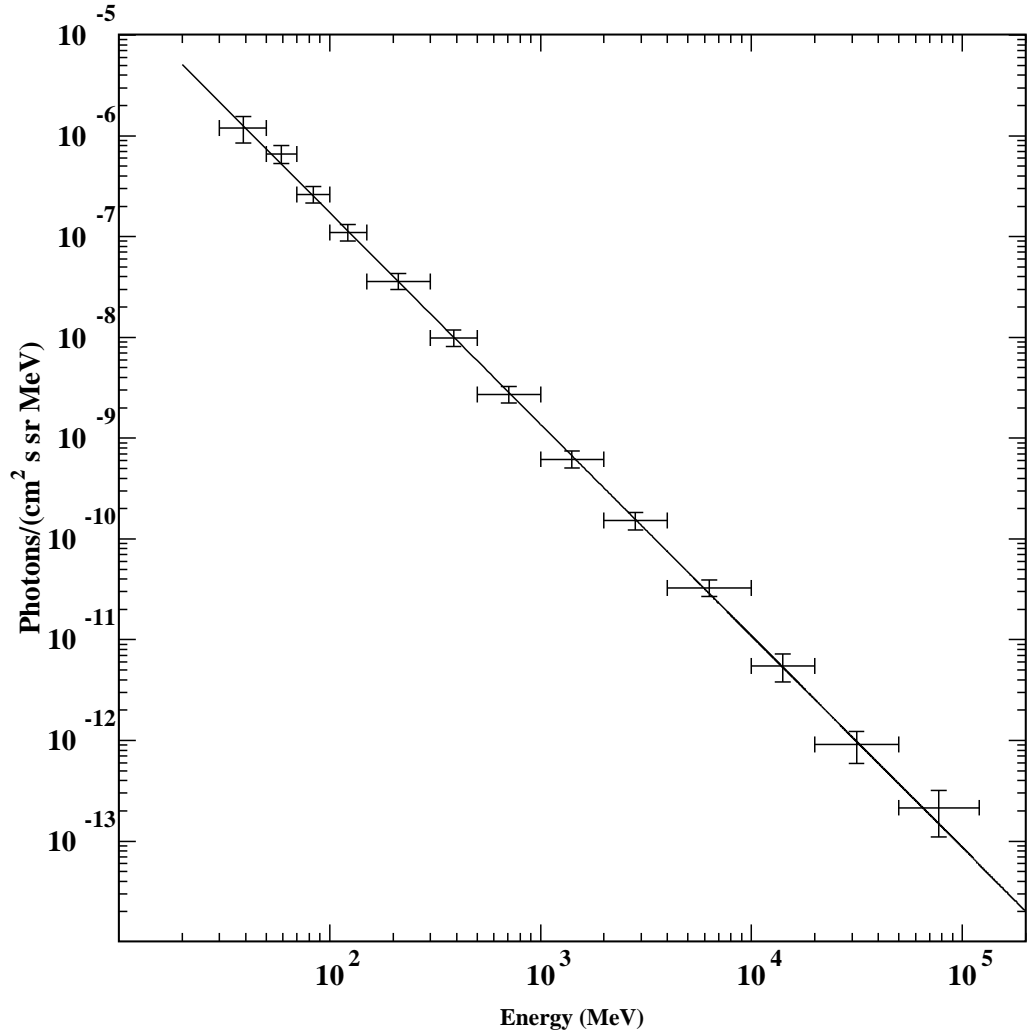


Figure 2: Comparison between the spectrum of the GBR, measured by EGRET [9], and the prediction for ICS of starlight and the CMB by CR electrons. The slope is the central prediction, the normalization is the one obtained for  $R_e = 30$  kpc.



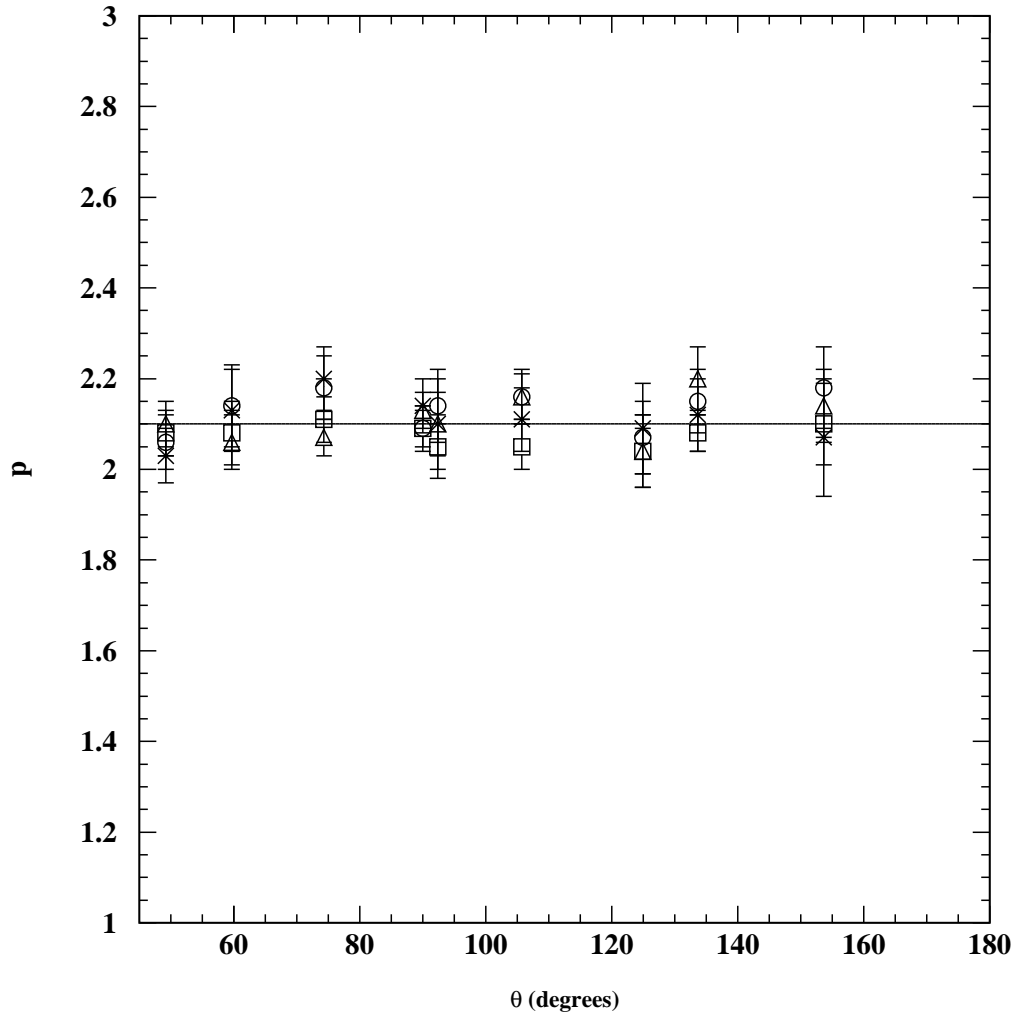


Figure 3: EGRET data for the angular dependence of the GBR spectral index as a function of direction, plotted as a function of  $\theta$ : the angle away from the direction of the galactic center. The galactic disk and galactic bulge are masked: the data are for  $|b| \geq 10^\circ$  for  $|l| \geq 40^\circ$  and  $|b| \geq 30^\circ$  for  $|l| \leq 40^\circ$ . The four points at each  $\theta$  correspond to the four half-hemispheres. The straight line is the predicted spectral index.

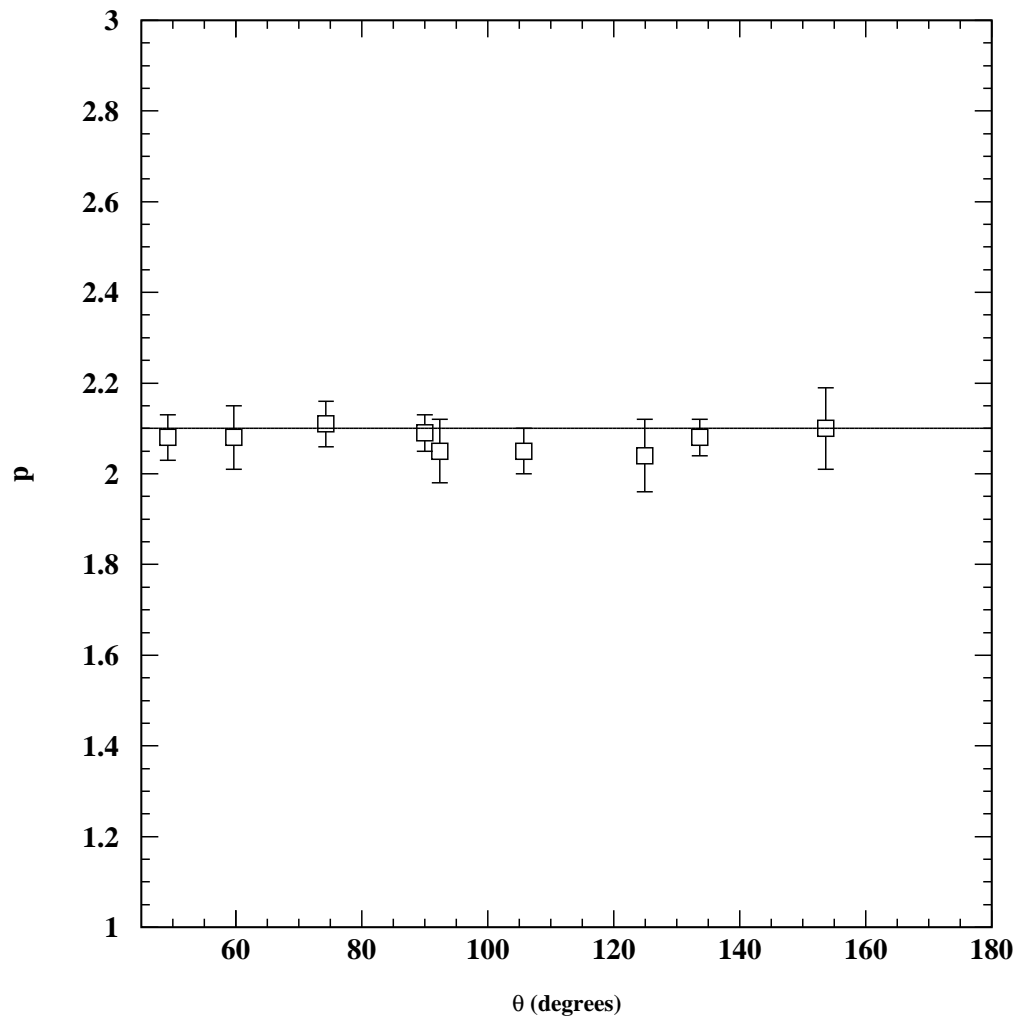


Figure 4: Same as Fig. 3 for the half hemisphere with  $b > 0, l > 0$ .

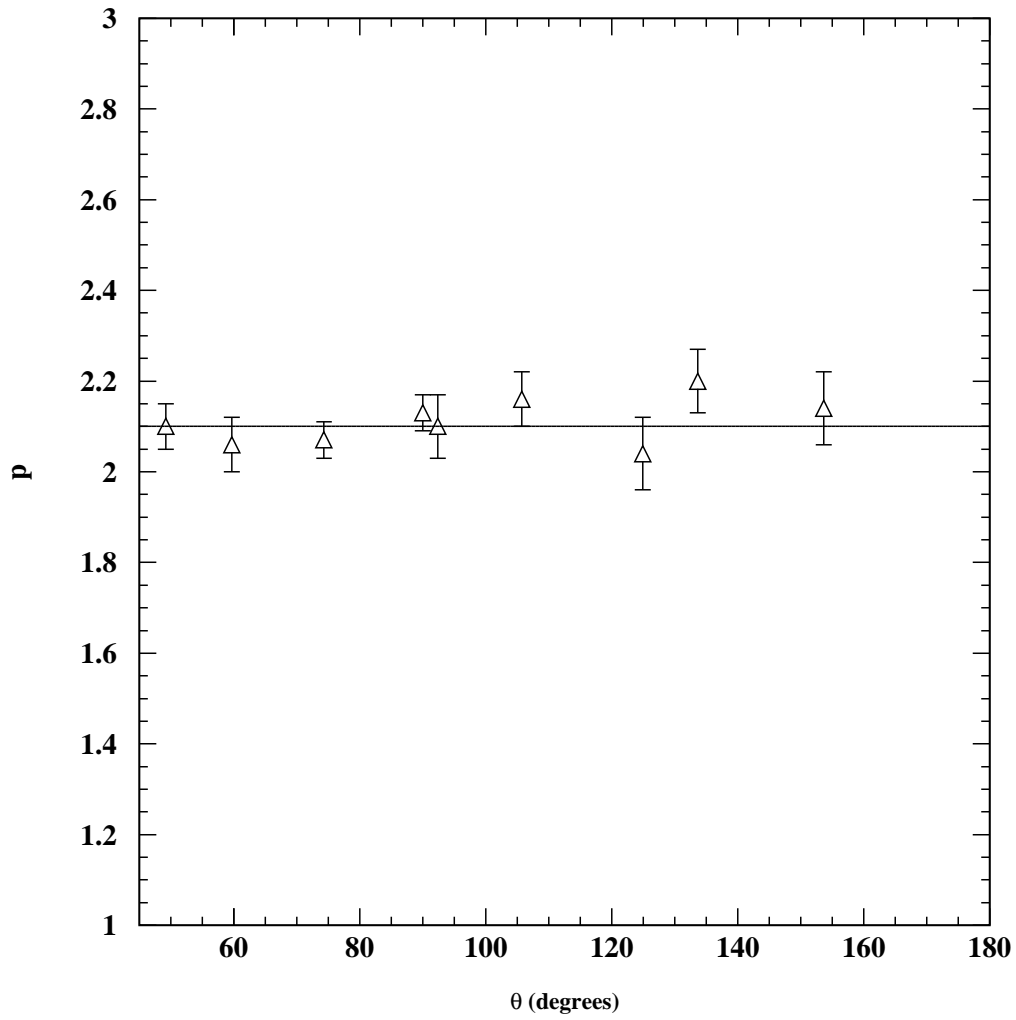


Figure 5: Same as Fig. 3 for the half hemisphere with  $b > 0$ ,  $l < 0$ .

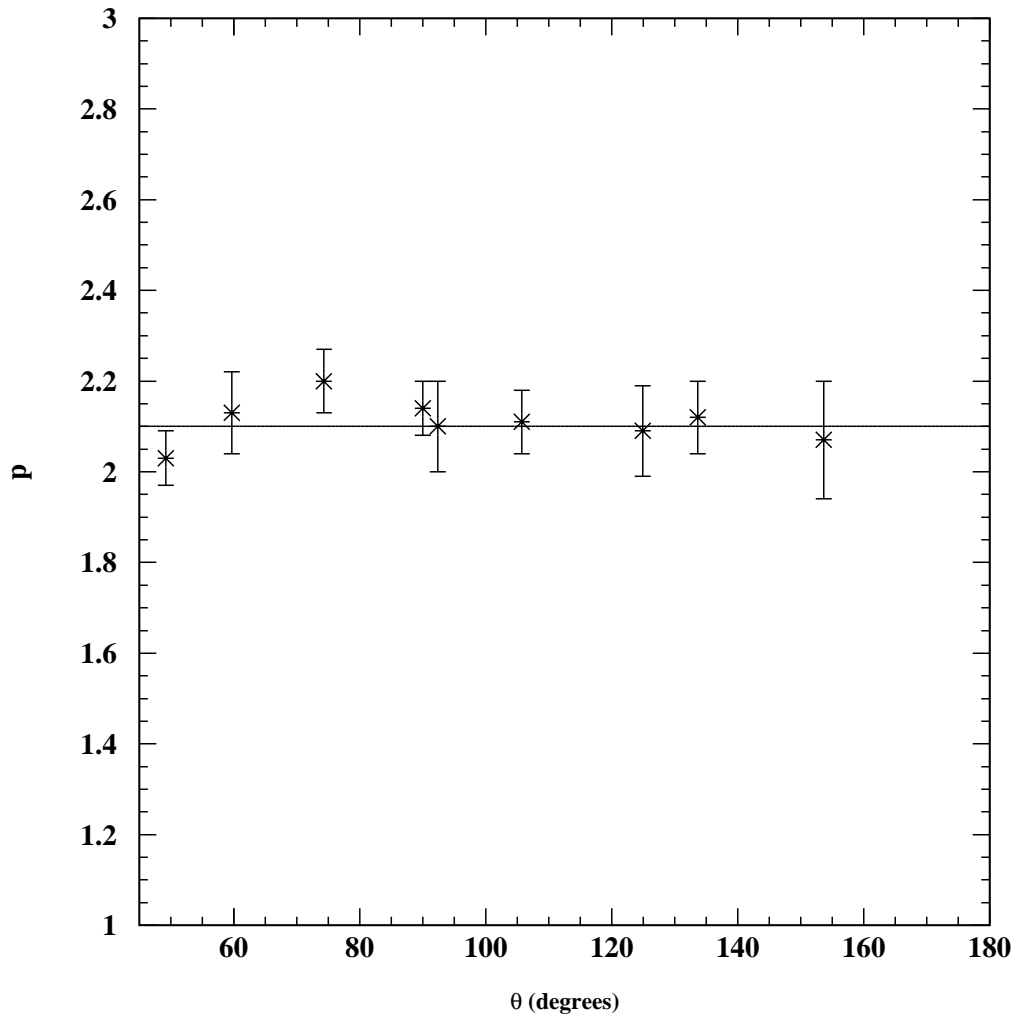


Figure 6: Same as Fig. 3 for the half hemisphere with  $b < 0, l > 0$ .

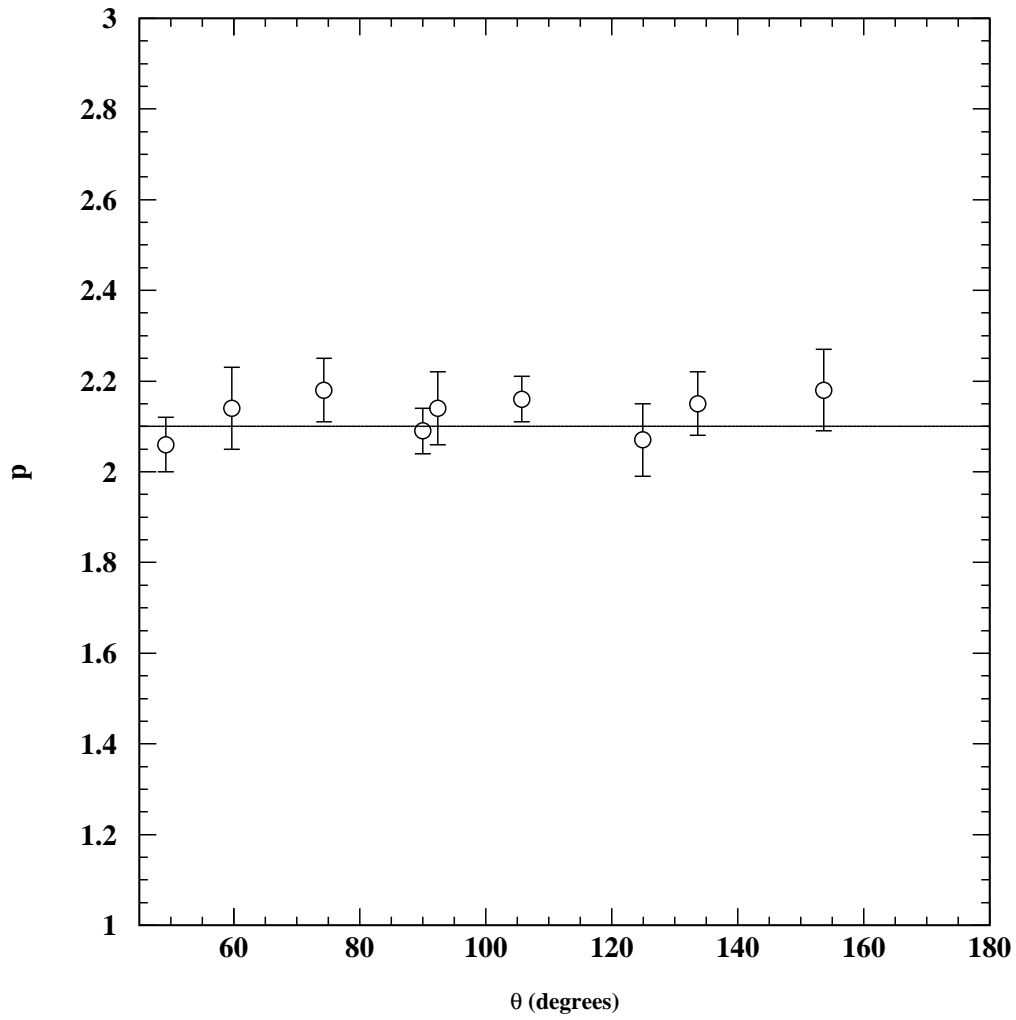


Figure 7: Same as Fig. 3 for the half hemisphere with  $b < 0$ ,  $l < 0$ .

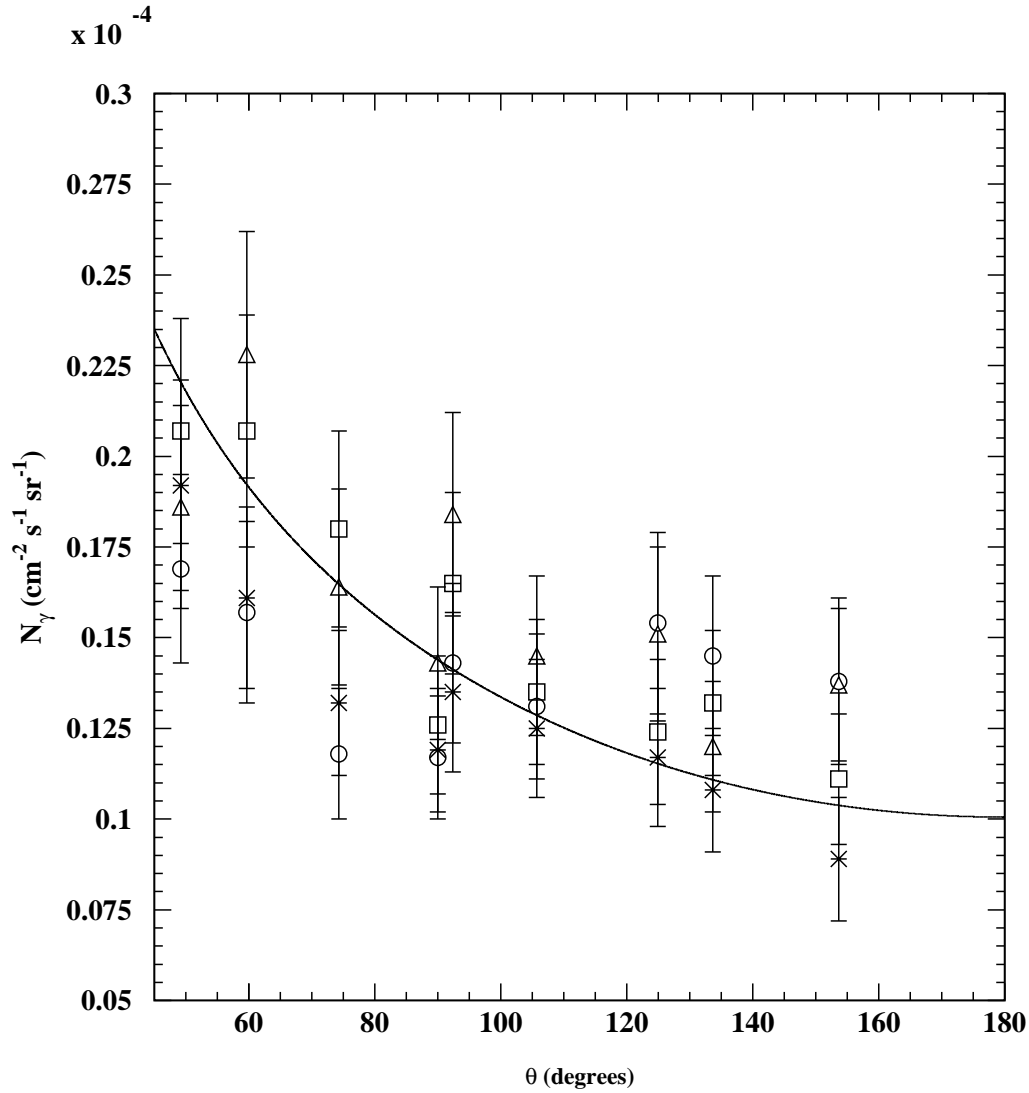


Figure 8: EGRET data, masked and organized as in Fig. 3, for the dependence of the GBR intensity on  $\theta$ . The line is the prediction for ICS of starlight and the CMB by CR electrons, for  $R_e = 30$  kpc.

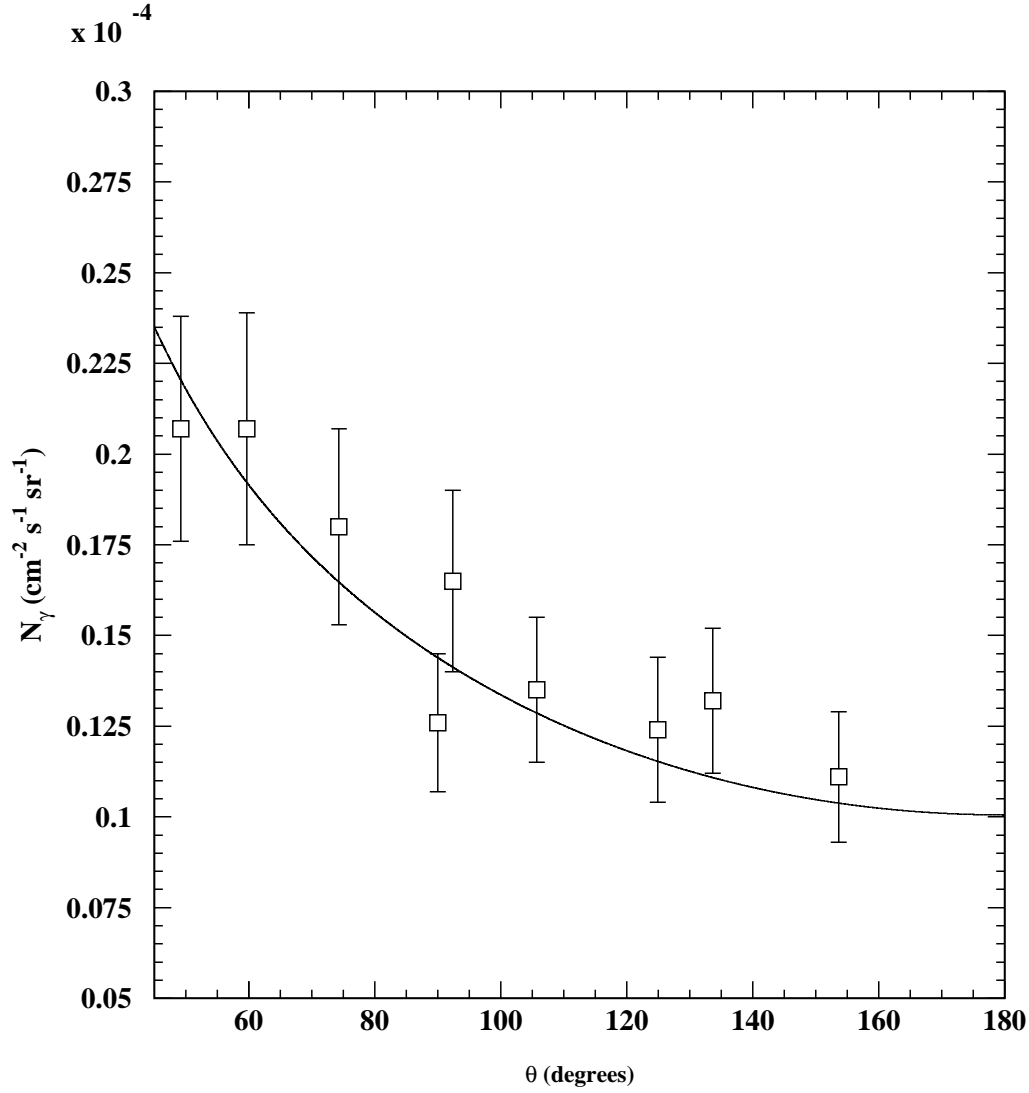


Figure 9: Same as Fig. 8 for the half hemisphere with  $b > 0$ ,  $l > 0$ .

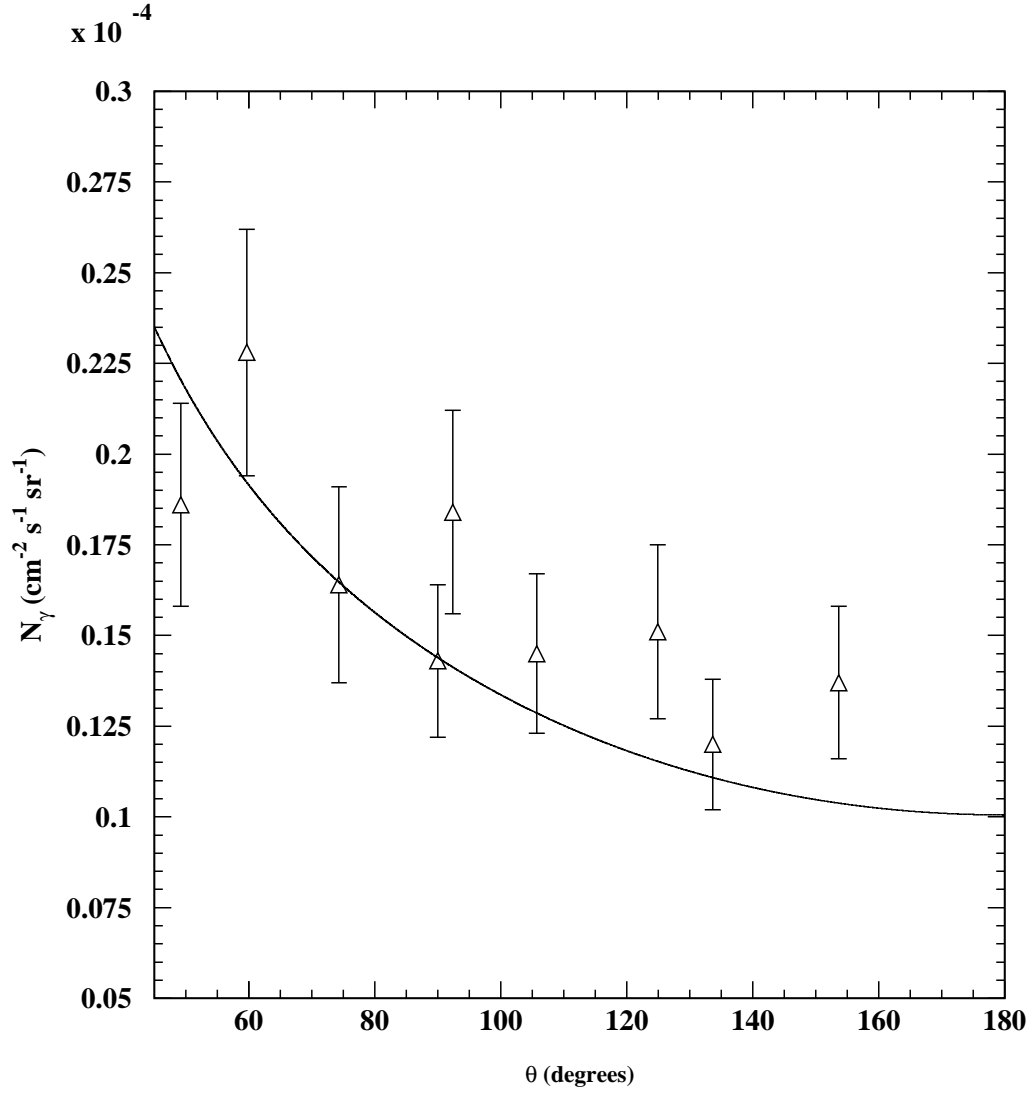


Figure 10: Same as Fig. 3 for the half hemisphere with  $b > 0$ ,  $l < 0$ .



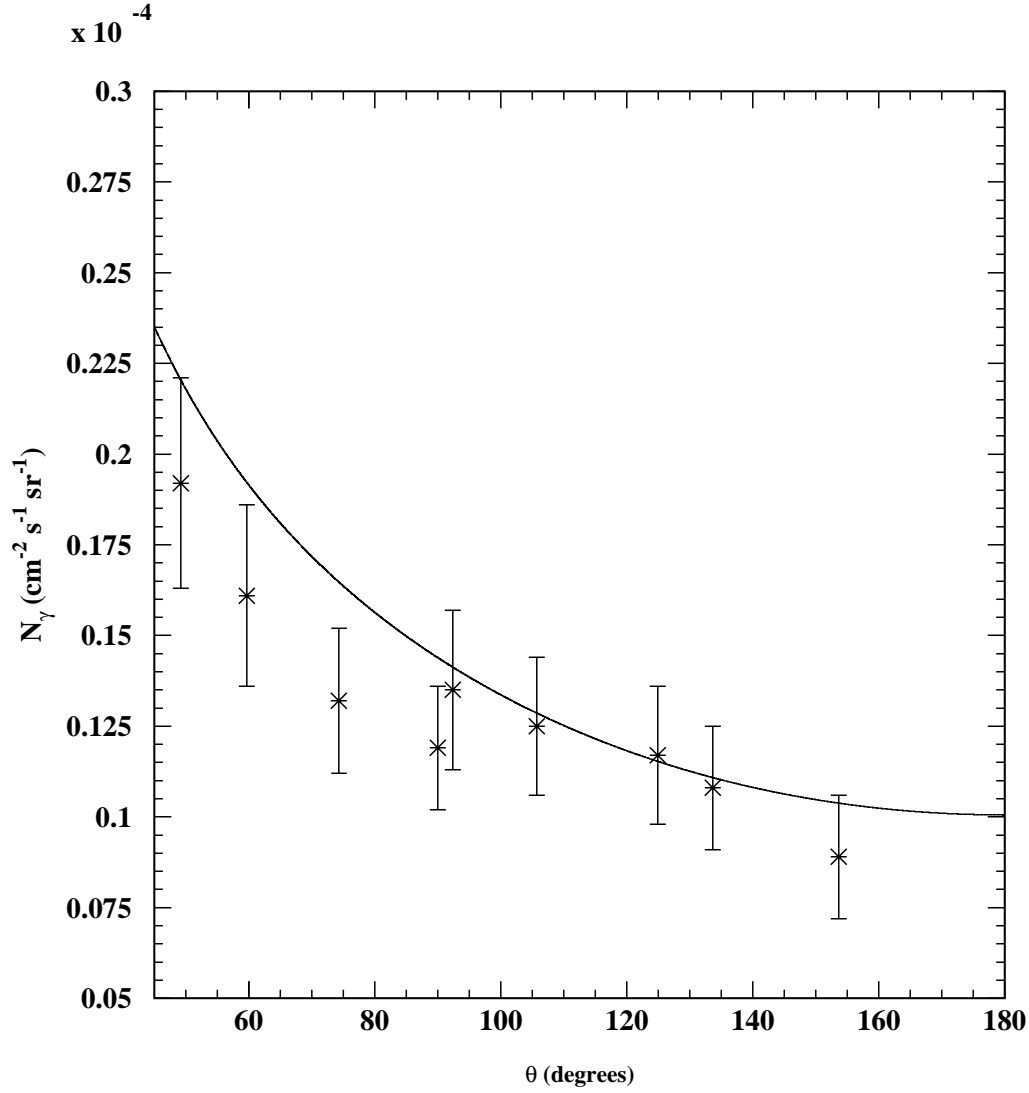


Figure 11: Same as Fig. 8 for the half hemisphere with  $b < 0$ ,  $l > 0$ .

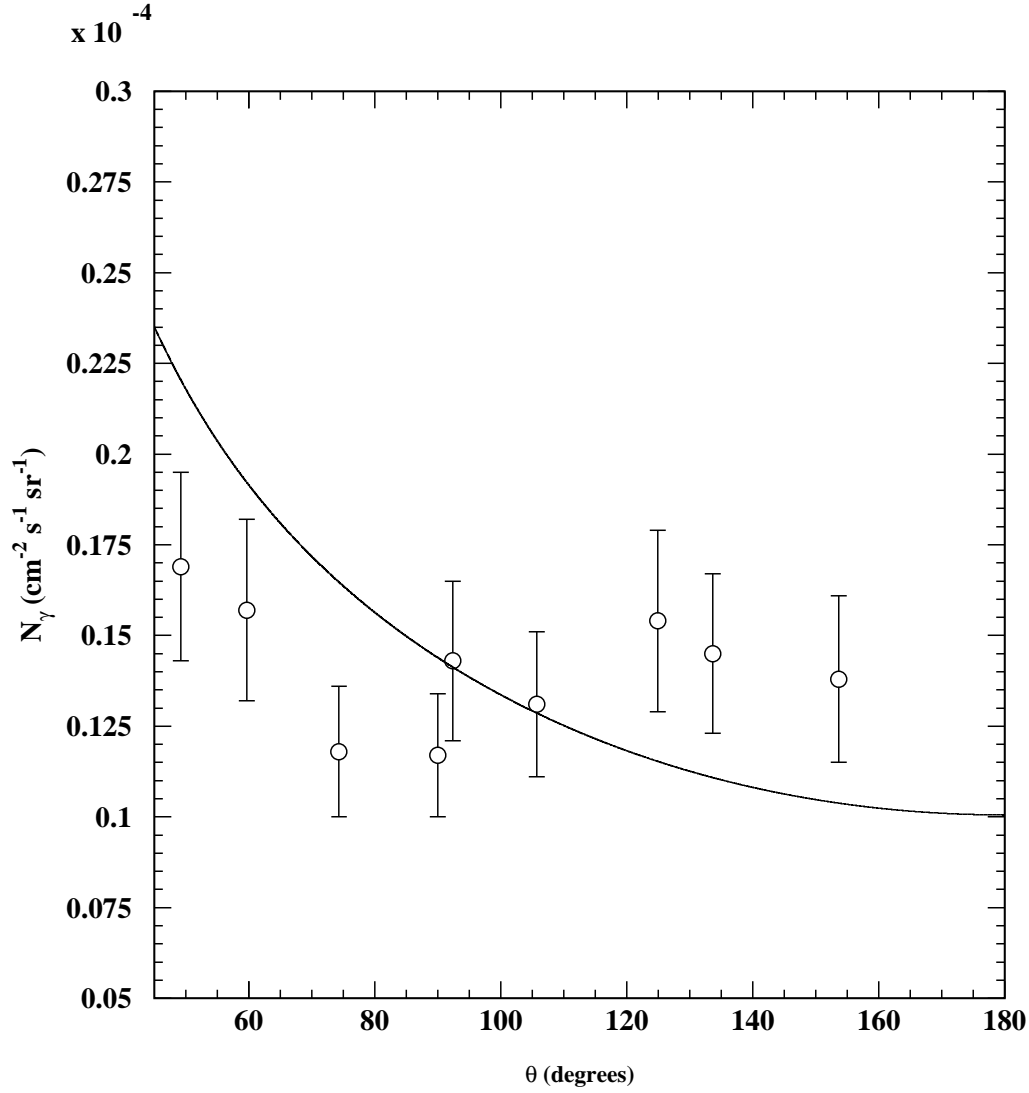


Figure 12: Same as Fig. 8 for the half hemisphere with  $b < 0$ ,  $l < 0$ .