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LETTER

Letter to the Editor

γ-ray evidence for galactic in-situ electron acceleration

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Abstract. Evidence for the possible existence of a strong flux of low-energy (< 10 MeV) cosmic ray electrons in the Galaxy has been recently established by GINGA, OSSE and COMPTEL observations of the diffuse galactic gamma ray continuum emission down to photon energies below 50 keV. We explain the implied presence of many low-energy cosmic ray electrons with the existence of interstellar in-situ reacceleration of cosmic ray particles by the ambient interstellar plasma turbulence.

Key words: cosmic ray electrons – bremsstrahlung emission – stochastic acceleration – interstellar plasma turbulence

1. Introduction

The possible existence of a strong flux of low-energy ($<$ 10 MeV) cosmic ray electrons in the Galaxy has profound consequences for the heating, ionization and pressure balance of the interstellar matter. Evidence for such a component has been scarce in the past, since direct cosmic ray measurements are contaminated by solar modulation and Jovian electrons, while the nonthermal cyclotron and synchrotron radiation of these electrons in the galactic magnetic field is strongly affected by interstellar free-free absorption. However, recent observations made with the OSSE (Kurfess 1995) and COMPTEL (Strong et al. 1994) instruments on board of the *Compton Gamma Ray Observatory* provide evidence that the diffuse galactic gamma ray continuum emission extends down to photon energies below 100 keV. The diffuse origin of this radiation has been suggested by correlated SIGMA measurements to estimate the galactic point source contribution (Purcell et al. 1996) and the analysis of the GINGA measurements of the galactic ridge emission at much lower energies (Yamasaki et al. 1996). As the gamma-ray emission in this energy region is most likely electron bremsstrahlung in the interstellar medium, this implies the presence of many low-energy cosmic ray electrons in the Galaxy. Moreover, the power in cosmic ray electrons required to produce a given amount of bremsstrahlung is a fixed quantity that depends only on the spectrum of the electrons and (weakly) on the ionization state of the interstellar medium. Attributing this power input to injection in cosmic ray electron sources it has been estimated that integrated over the whole Galaxy a source power of about $\sim 4 \cdot 10^{41}$ erg s^{-1} (Skibo and Ramaty 1993) or even $\sim 10^{43}$ erg s^{-1} (Skibo, Ramaty and Purcell 1996) in low-energy (< 10 MeV) electrons is required to maintain these electrons against the severe Coulomb and ionization losses. The later estimate is significantly larger due to the GINGA analysis that the diffuse bremstrahlung may extend down to photon energies ~ 10 keV. Taking the Skibo and Ramaty (1993) estimate as a lower limit, this electron power exceeds the power supplied to the nuclear cosmic ray component by a factor ≥ 20, and represents a serious problem for the general problem of the origin of cosmic rays.

Here we show that the existence of many low-energy ($<$ 10 MeV) cosmic ray electrons can be explained by the existence of in-situ acceleration in the Galaxy due to the presence of interstellar electromagnetic turbulence. This turbulence is an important additional energy source of cosmic ray particles and thus weakens considerably the power requirements on the injection of particles in nominal cosmic ray sources. Our interpretation requires that most of the interstellar plasma turbulence is damped by accelerating cosmic ray electrons.

2. Interstellar dynamics of cosmic ray electrons

The bremsstrahlung photon intensity is calculated by the line-of-sight integral of the bremsstrahlung emissivity over the field of view scanned by the OSSE and COMPTEL instruments, and is influenced by the spatial distribution of the interstellar gas and cosmic ray electron density. Assuming that the shape of the energy spectrum of the radiating electrons is the same throughout the galaxy, the calculated bremsstrahlung photon energy spectrum is

$$\frac{dI_b}{dtd\epsilon}(\epsilon) = N \int_0^\infty dE J_e(E) \frac{d\sigma_b}{d\epsilon}(\epsilon, E) \quad (1),$$

Send offprint requests to: R. Schlickeiser where $d\sigma_b/d\epsilon$ denotes the (known) differential bremsstrahlung cross section, $J_e(E)$ the isotropic differential cosmic ray electron equilibrium intensity as a function of the electron kinetic energy E, and the constant factor N accounts for the line-of-sight and solid angle integration.

The electron equilibrium spectrum in the Galaxy is controlled by the balance of injection of particles in sources and their interactions with ambient electromagnetic, photon and matter fields. Among these by far quickest are resonant particle-wave interactions with electromagnetic fields, which in a quasilinear description give rise to spatial and momentum diffusion of the cosmic ray particles (Schlickeiser 1994). With respect to the generation of energetic charged particles, stochastic acceleration of particles, characterized by the acceleration time scale $t_A = p^2/A$, where A is the momentum diffusion coefficient, competes with continous energy loss processes $\dot{p}_{loss}$, characterized by energy loss time scales $t_L = p/|\dot{p}_{loss}|$. Below cosmic ray electron energies of 400 MeV Coulomb and ionization losses dominate in all phases of the interstellar medium, i.e. $t_L \simeq t_C$. Moreover, the Coulomb and ionization loss time scale t_C at all momenta of interest is much smaller than the escape time scale from the Galaxy, associated with both the spatial diffusion and convection of particles, so that the Galaxy at these particle momenta is a thick target for the cosmic ray electrons. The steady-state electron transport equation then simplifies to

$$\frac{1}{p^2}\frac{d}{dp}[p^2 A\frac{dF(\boldsymbol{r},p)}{dp} - p^2\dot{p}_C F(\boldsymbol{r},p)] + S_0(\boldsymbol{r},p) \simeq 0 \quad (2).$$

The equilibrium momentum (p) spectrum of cosmic ray electrons at the position $\boldsymbol{r}$ in the Galaxy $N(\boldsymbol{r},p) = 4\pi p^2 F(\boldsymbol{r},p)$ and the equilibrium differential electron intensity $J_e(\boldsymbol{r},p) = vp^2F(\boldsymbol{r},p)$ follow from the solution of Eq. (2) for given source injection spectrum $S_0(\boldsymbol{r},p)$, momentum diffusion coefficient $A(\boldsymbol{r},p)$, and Coulomb and ionization loss rate $\dot{p}_C(\boldsymbol{r},p)$. We consider each input quantity in turn.

2.1. Sources of cosmic ray electrons

It is well known that inelastic nuclear interactions and knock-on collisions of cosmic ray nuclei with ambient interstellar gas particles generate secondary electrons (Ramaty 1974). At electron momenta below 10 MeV/c the production by the knock-on process dominates, yielding the production rate of secondary electrons per unit electron momentum interval above $p \geq 0.21 m_e c$ is (Abraham, Brunstein and Cline 1966)

$$S_k(\boldsymbol{r},p) = \frac{4.9 n_g(\boldsymbol{r}) p}{4\pi m_e^2 c^2 [1+(\frac{p}{m_e c})^2]^{3/2}}$$

$$\Big[\sqrt{1+(\frac{p}{m_e c})^2} - 1\Big]^{-2.76} \; cm^{-3}\, s^{-1} (eV/c)^{-1} \quad (3).$$

An additional source of cosmic ray electrons is the acceleration of primary electrons in supernova shock fronts that gives rise to a power law source spectrum in momentum.

2.2. Coulomb and ionization interactions

Adopting an interstellar medium consisting of hydrogen and helium with a total number abundance ratio of 10:1 we obtain a reasonably accurate approximation for the momentum loss rate of energetic electrons in neutral interstellar matter (for details see Schlickeiser 1996)

$$\dot{p}_I \simeq -\frac{1.8 c\sigma_T m_e c}{\beta^2}[10.1 + \ln(\gamma - 1)] n_g(\boldsymbol{r}) \; (eV/c) s^{-1} \quad (4).$$

In the completely ionized thermal phase of the interstellar medium of temperature $T = 10^6 T_6$ K we obtain for the momentum loss rate

$$\dot{p}_C = -6.0 \cdot 10^{-13} n_c(\boldsymbol{r}) \frac{m_e c\beta}{x_m^3 + \beta^3} (eV/c) s^{-1} \quad (5),$$

which we use for electrons with momenta above $0.77 p_M$, where $p_M = 0.016 T_6^{1/2}\; m_e c$, $x_M = 0.02 T_6^{1/2}$, and $\beta = v/c$ devotes the electron velocity.

2.3. Stochastic acceleration

Stochastic acceleration rates in weakly turbulent plasmas for general plasma modes have been calculated by Schlickeiser and Achatz (1993). Leaving out any contribution from fast magnetosonic waves cosmic ray electrons with Lorentz factors below 1836 interact with weakly-damped Alfven waves and with weakly-damped right-handed circularly polarized Whistler waves. The momentum diffusion coefficient of cosmic ray electrons then consists of two parts: the first, A_A, resulting from the resonant interaction with the Alfven waves, and secondly, A_W resulting from the interaction with the Whistler-electron cyclotron plasma waves. Assuming only parallel propagating waves we use for the former (A_A) the calculation by Dung and Schlickeiser (1990), and for A_W the calculation by Steinacker and Miller (1992). In both cases we adopt a Kolmogorov-type magnetic turbulence power spectrum $I(k_\parallel) = I_0 k_\parallel^{-q}$, with $q > 1$, above $k_\parallel \geq k_{min}$. In this case

$$I_0 = (q-1)(\delta B)^2 k_{min}^{q-1} \quad (6)$$

determines the energy density in magnetic field fluctuations. Assuming further vanishing cross and magnetic helicities for the Alfven waves we derive

$$A_A(\boldsymbol{r},p) = A_0(\boldsymbol{r},p) H[p - m_p V_A][1 - (\frac{m_p V_A}{p})^q] \quad (7),$$

where $H(x) = 1(0)$ for $x \geq 0 (< 0)$ denotes the Heaviside step-function, and

$$A_0(\boldsymbol{r},p) = \frac{\pi}{4}\frac{q-1}{q}\frac{(\delta B)^2}{B_0^2}\frac{\Omega_e}{\gamma}\frac{V_A^2 p^2}{v^2}(k_{min} R_e)^{q-1} \quad (8).$$

$V_A = 2.18 \cdot 10^{11} (B_0/G)(n_e/1cm^{-3})^{-1/2}$ cm/s denotes the Alfven velocity, $\Omega_e = |e|B_0/m_e c$ the nonrelativistic electron gyrofrequency, and $R_e = pc/|e|B_0 = \gamma v/\Omega_e$ the electron gyroradius.

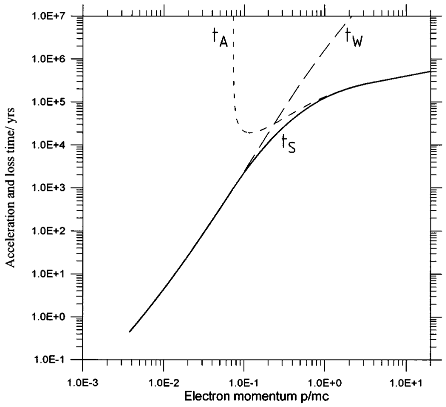

Fig. 1. Total (t_S) and individual electron acceleration time scales due to resonant interactions with Alfven (t_A) and Whistler (t_W) waves in the interstellar medium

For the Whistler momentum diffusion coefficient we obtain for electron Lorentz factors $\gamma < 1836$

$$A_W(\boldsymbol{r},p) = A_0(\boldsymbol{r},p)\frac{q}{2}(\frac{p}{m_pV_A})^{-q}J_W(p) \qquad (9),$$

where the slowly varying function $J_W(p)$ describes cut-off effects,

$$J_W = H[k_2-1]H[43-k_1]\Big(\frac{L_2^{2-q}-L_1^{2-q}}{2-q}[1+2\frac{V_A}{v}\frac{m_pV_A}{p}]$$

$$-(\frac{m_pV_A}{p})^2[\frac{L_1^{-q}-L_2^{-q}}{q}+\frac{L_2^{4-q}-L_1^{4-q}}{(4-q)k_e^4}]\Big) \qquad (10),$$

with L_1 = max $[k_1, 1]$, L_2 = min $[k_2, 43]$, $k_e = 43/\sqrt{\gamma}$ and

$$k_{1,2} = \frac{v}{2V_A}[\sqrt{1+(4\frac{V_A}{v}\frac{m_pV_A}{p})} \mp 1] \qquad (11).$$

2.4. Loss and acceleration time scales

It is convenient to introduce the dimensionless momentum variable $x = p/(m_ec)$ so that

$$A_{A,W}(p) = \frac{m_e^2c^2x^2}{t_{A,W}(x)}\ , \quad \dot{p}_{I,C} = -\frac{m_ecx}{t_{I,C}(x)} \qquad (12),$$

in terms of the characteristic acceleration and loss time scales. Evidently, the total momentum diffusion coefficient then is

$$A = A_A + A_W = \frac{m_e^2c^2x^2}{t_S(x)},\ t_S = \frac{t_At_W}{t_A+t_W} \qquad (13).$$

We treat the interstellar medium as a composite medium consisting of the well-intermixed coronal phase and atomic hydrogen layer. We therefore use the following parameters typical for the interstellar medium: $n_g = 0.3n_3$ cm^{-3}, $B_0 = 3B_3\cdot 10^{-6}$ G,$(B_0/\delta B)^2 = 10$, q=5/3, $k_{min} = 2\pi/100l_{100}$ pc $= 2\cdot 10^{-20}l_{100}^{-1}$ cm^{-1}, and $T_6 = 0.1$. For the momentum loss we assume Eq. (5) to hold with $n_c = n_g$.

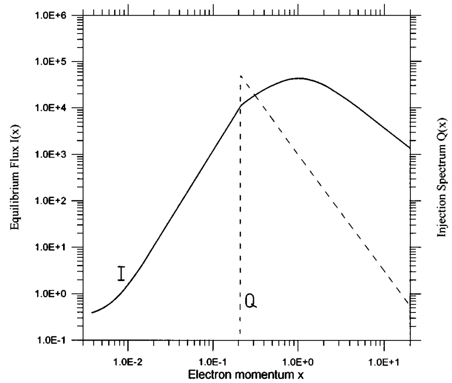

Fig. 2. Equilibrium differential electron flux in the case of no ($t_s = \infty$) stochastic acceleration for single power law injection (19) above $x_i = 0.21$ with spectral index $\alpha = 4.5$

Fig. 1 shows the resulting acceleration time scales due to Alfven and Whistler waves, respectively, as well as the total acceleration time scale t_S according to Eq. (13). We find for the acceleration time ratio apart from the slow variation of the function $J_W(p)$ that $t_W(p)/t_A(p) \propto (\frac{p}{m_pV_A})^q$, indicating that the stochastic acceleration of cosmic ray electrons is dominated by Whistler waves at small semirelativistic momentum values ($p < p_W$), and by Alfven waves at relativistic momentum values ($p > p_W$). This behaviour is clearly apparent in Fig. 1, which shows that in the interstellar medium p_W is of order $\sim 0.2m_ec$ = 0.1 MeV/c. The momentum dependence of the Alfven wave acceleration time $t_A(p) \propto t_0 \propto p^{3-q}/\gamma$ is determined by the turbulence spectral index q, while the Whistler wave acceleration time $t_W(p) \propto p^3/\gamma$, at least to leading order, is independent from the value of q.

3. Galactic electron equilibrium spectrum

In terms of the new variable x, implying $F(\boldsymbol{r},p)d^3p = f(\boldsymbol{r},x)d^3x$ and $S_0(\boldsymbol{r},p)d^3p = q_0(\boldsymbol{r},x)d^3x$, the steady-state electron transport equation (2) reads

$$\frac{1}{x^2}\frac{d}{dx}[\frac{x^4}{t_S(x)}\frac{df}{dx}+\frac{x^3f}{t_C(x)}] = -q_0(x) \qquad (14).$$

The solution of Eq. (14) is

$$f(x) = \exp[h(x)]\Big(\int_0^x dx_0x_0^2q_0(x_0)\int_x^\infty\frac{ds}{D(s)}+$$

$$\int_x^\infty dx_0x_0^2q_0(x_0)\int_{x_0}^\infty\frac{ds}{D(s)}\Big) \qquad (15),$$

where

$$h(x) = \int_x^\infty dy\ \frac{t_S(y)}{yt_C(y)} \qquad (16),$$

$$D(x) = \frac{x^4\exp[h(x)]}{t_S(x)} \qquad (17).$$

Adopting the power law injection source distribution above some x_i,

$$q_0(x) = q_sx^{-\alpha}H[x-x_i] \qquad (18),$$

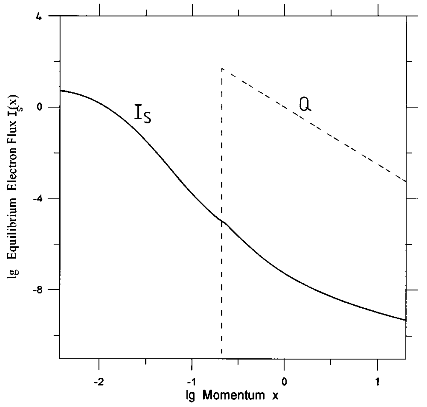

Fig. 3. Equilibrium differential electron flux in the case of finite $t_s \neq \infty$ stochastic acceleration for single power law injection (19) for q = 1.5.

which for x_i = 0.21 is consistent with Eq. (3) and reproduces well the known electron spectrum at very high (> 10 MeV) energies, we obtain from Eq. (15) after partial integration

$$f_s(x) = \frac{q_s e^{h(x)}}{\alpha - 3} \left(x_i^{3-\alpha} \int_m^\infty \frac{ds}{D(s)} - \int_m^\infty \frac{ds s^{3-\alpha}}{D(s)} \right) \qquad (19)$$

with $m = \max[x_i, x]$. For small momentum values $x \leq x_i$ implying $m = x_i$, the momentum variation of the equilibrium spectrum is simply given by $f_s(x \leq x_i) \propto \exp[h(x)]$, and thus (see Eq. (16)) solely controlled by the momentum variation of the stochastic acceleration and the Coulomb momentum loss time scales. We calculate the solution (19) for the case without ($t_s = \infty$) and with ($t_s \neq \infty$) interstellar stochastic acceleration in Figs. 2 and 3, respectively, where we show the associated equilibrium electron fluxes $I_s(x) = cx^3 f_s(x)(1 + x^2)^{-1/2}$ for a value of q = 1.5. In case of no stochastic acceleration (Fig. 2) the heavy Coulomb losses dramatically attenuate the source spectrum at low energies. In particular, it is impossible with such a source distribution to account for the spectral turn up below 200-500 keV visible in the bremsstrahlung photon spectrum. However, allowing for interstellar stochastic acceleration (Fig. 3), we obtain a different behaviour. The equilibrium spectrum in this case rises exponentially at small momenta, providing many more low-energy electrons below the minimum injection momentum x_i in the electron equilibrium spectrum. We thus have shown that the inclusion of interstellar stochastic acceleration of electrons provides an alternative explanation for the existence of many low-energy electrons. In particular, it is not necessary,to postulate the existence of a second low-energy electron source component with steep spectrum, to account for the observations.

4. Discussion and conclusions

In this work we have investigated the implications of the OSSE and COMPTEL measurements of the diffuse galactic gamma ray bremsstrahlung continuum emission for the interstellar dynamics of cosmic ray electrons. We show that the previous interpretation of the bremsstrahlung spectral upturn, as being due to the existence of a second electron source component at mildly relativistic electron energies with a total source power of $Q_s \geq 4 \cdot 10^{41}$ erg/s, is not unique. As an alternative we demonstrate that the spectral upturn can be explained by the existence of in-situ stochastic acceleration by the interstellar plasma turbulence in the Galaxy.

From careful measurements of the interstellar turbulence Spangler (1991) as well as Minter and Spangler (1997) estimated the mean of the interstellar magnetic field fluctuations due to turbulence of $\delta B \simeq 0.9\ \mu G$ which corresponds to an energy density of $\delta U \simeq 3.6 \cdot 10^{-14}$ erg cm^{-3}. Integrated over the whole Galaxy ($V \simeq 10^{67}$ cm^3) this gives a total magnetic turbulent energy of $E_B \simeq 3.6 \cdot 10^{53}$ erg. It is plausible that this turbulence is generated by supernovae and OB associations (Simonetti 1982). To account for the cosmic ray electron power input the transfer time of magnetic turbulence to electrons has to be $t_T = E_B/Q_s \leq 3 \cdot 10^4$ yrs. Since the transfer time equals the momentum-averaged electron acceleration time in the relevant momentum range ($\leq$ 2 MeV/c), this requirement is in accord with our result in Fig. 1 that the acceleration times vary between 1 and $3 \cdot 10^5$ yrs at kinetic energies below 2 MeV. Note that our stochastic acceleration calculation sofar only has covered resonant interactions with parallel propagating Alfven and Whistler waves; the extension of our analysis to fast magnetosonic waves may further reduce the values of the acceleration times. Our interpretation avoids the requirement of additional source power in cosmic ray electrons, but argues for an efficient power transfer from the interstellar turbulence to cosmic ray electrons. It also requires an acceleration mechanism of cosmic rays that preferentially accelerates electrons over hadrons.

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