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Dark matter signals in cosmic rays?

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Abstract. The flux of the diffuse gamma-ray background radiation (GBR) does not confirm that the excess in the flux of cosmic ray electrons between 300-800 GeV, which was measured locally with the ATIC instrument in balloon flights over Antartica, is universal as expected from dark matter annihilation. Neither does the increase with energy of the fraction of positrons in the cosmic ray flux of electrons in the 10-100 GeV range that was measured by PAMELA imply a dark matter origin: It is consistent with that expected from the sum of the two major sources of Galactic cosmic ray positrons, hadronic production in the cosmic ray sources and secondary production by cosmic rays in the ISM.

Key words. Gamma-ray Bursts – Dark Matter — Cosmic Rays

1. Introduction

The spectrum of the diffuse γ background radiation (GBR) that was measured by EGRET aboard the Compton Gamma Ray Observatory (CGRO) (Hunter et al., 1997) showed an excess above 1 GeV in comparison with the flux expected from interactions of cosmic ray (CR) nuclei and electrons in the Galactic interstellar medium (ISM) (Strong & Moskalenko, 1998). The origin of this GeV excess has been unknown. Among its suggested origins was decay or annihilation of weakly interacting dark matter particles (for reviews, see e.g., Bergstrom, 2001; de Boer et al., 2005). However, recent measurements with the Large Area Telescope (LAT) aboard the Fermi observatory have yielded preliminary results (Johannesson et al., 2009) that do not show a GeV excess at small Galactic latitudes and agree with the flux expected from CR interactions in the Galactic ISM. Moreover, by comparing the spectra of gamma-rays around GeV from nearby Galactic pulsars, which were measured by EGRET and LAT, the Fermi collaboration confirmed (Johannesson et al., 2009) previous conclusions (Stecker et al., 2008) that the origin of the EGRET GeV excess is instrumental and not a dark matter annihilation/decay signal. In this letter we show that an absence of a GeV excess in the GBR also challenges the reported excess in the flux of CR electrons at energies between 300-800 GeV that was measured with the Advanced Thin Ionization Calorimeter (ATIC) aboard balloon flights over Antartica (and was also suggested to arise from annihilation of dark matter particles such as Kaluza-Klein particles with a mass of about 620 GeV/c^2 (Cheng et al., 2009). We also demonstrate that the reported increase in the fraction of positrons in the flux of CR electrons above 10 GeV, which was measured with the satellite-borne Payload for Antimatter Exploration and Light Nuclei Astrophysics (PAMELA) (Morselli & Moskalenko, 2008), and was interpreted as a

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dark matter signal, is that expected from the main source of Galactic cosmic rays - the non-relativistic shells and the highly relativistic jets ejected in supernova explosions.

Practically all CR acceleration mechanisms invoke an ionized medium that is swept by a moving magnetic field, such as would be carried by the rarefied plasma in a supernova shell or a plasmoid of a jet (Dar & Plaga, 1999, Dar & De Rújula, 2008). The swept-in ionized particles, which enter the plasma with $\gamma = E/m\,c^2$ equal to the bulk motion Lorentz factor of the plasma, are isotropized and Fermi accelerated by its turbulent magnetic field. The deceleration of the jets/ejecta by the swept-in particles and their isotropic emission in the jet/ejecta rest frame determine their spectrum. To the extent that particle-specific losses (such as synchrotron radiation) can be neglected, all source fluxes roughly have the same power-law spectrum $dF_s/dE \sim E^{-\beta_s}$ with $\beta_s \approx 2.2$ (Dar & De Rújula, 2001). This injected spectrum of Galactic CR nuclei is modulated mainly by their accumulation during their residence time in the Galaxy, $\tau_{gal}(E)$, before they escape into the intergalactic space by diffusion in the Galactic magnetic field. Observations of the nuclear abundances of secondary CRs produced in the interstellar medium (ISM) as functions of energy indicate that $\tau_{gal}(E) \propto E^{-0.5\pm0.1}$ (Swordy et al., 1990). Thus, in a steady state, the observed Galactic flux of CR nuclei below the knee is predicted to have a spectrum $dF/dE \propto \tau_{gal}\, dF_s/dE \propto E^{-2.7\pm0.1}$ in good agreement with observations, while CRs which escape into the intergalactic space have the source spectrum $dF/dE \sim E^{-2.2}$ (e.g., Dar & De Rújula, 2008).

High energy CR electrons can also be produced by the interaction of CR nuclei with matter and radiation, mainly through production and decay of charged pions: $\pi \to \mu + \nu_\mu$, $\mu \to e + \nu_e + \nu_\mu$. Due to Fynman scaling, they also have a power-law source spectrum with a spectral index $\beta_s = 2.2$, if produced in/near the source of CR nuclei or in the inter galactic medium (IGM), or $\beta_s = 2.7$ if produced by CR interactions in the Galactic ISM (Dar, 1983). But, unlike CR nuclei, CR electrons in the ISM above a few GeV lose their energy by inverse Compton scattering (ICS) of starlight and cosmic microwave background radiation (MBR) and by synchrotron radiation in the ISM magnetic field, in a time shorter than the Galactic confinement time (Dar & De Rújula, 2001,2008).

$$\tau_{cool}(E_e) = \frac{3\,(m_e\,c^2)^2}{4\,\sigma_T\,c\,E_e\,[\rho_\gamma + \rho_B]}, \tag{1}$$

where $\sigma_T \approx 0.665 \times 10^{-24}\,\mathrm{cm^{-2}}$ is the Thomson cross section, $\rho_\gamma = 0.47\,\mathrm{eV\,cm^{-3}}$ is the mean energy density of starlight and MBR, and $\rho_B = B^2/8\,\pi \approx 0.62\,\mathrm{eV\,cm^{-3}}$ is the mean energy density of the magnetic field ($B \sim 5\,\mu$Gauss) in the Galactic disk. This implies a spectrum of high energy CR electrons, $dF_e/dE \propto E^{-\beta_s-1} = E^{-3.2}$ (Dar & De Rújula, 2001,2008). Radio and X-ray observations of synchrotron radiation emitted by CR electrons accelerated by the major cosmic accelerators such as supernova remnants, gamma ray bursts, microquasars and active galactic nuclei, confirm this predicted universal spectrum of high-energy CR electrons. Indeed, the energy spectrum of CR electrons with $E_e > 5$ GeV that was measured directly near Earth (Aguilar et al., 2002; Kobayashi et al., 2004; Torii et al., 2001,2008) is well described by:

$$\frac{dF_e}{dE} = 1.5 \times 10^5 \left[\frac{E}{\mathrm{MeV}}\right]^{-3.2} \frac{1}{\mathrm{cm^2\,s\,sr\,MeV}}. \tag{2}$$

Inverse Compton scattering of MBR photons and stellar light by these electrons give rise to a diffuse GBR with a power-law spectrum $dF_\gamma/dE \sim E^{-\beta_\gamma}$ and a power-law index $\beta_\gamma = (\beta_e + 1)/2 \approx 2.1 \pm 0.05$. It dominates the diffuse GBR at large Galactic latitudes and contributes significantly to the diffuse GBR at small Galactic latitudes.

The intensity and spectrum of the diffuse GBR was measured by EGRET aboard the Compton Gamma Ray Observatory (CGRO). An extragalactic GBR was inferred (Sreekumar et al., 1998) from the extrapolation of these measurements in directions away from the Galactic disk and center to zero column density, in order to eliminate the Galactic contributions of bremsstrahlung from CR electrons, and π^0 production by CR nuclei

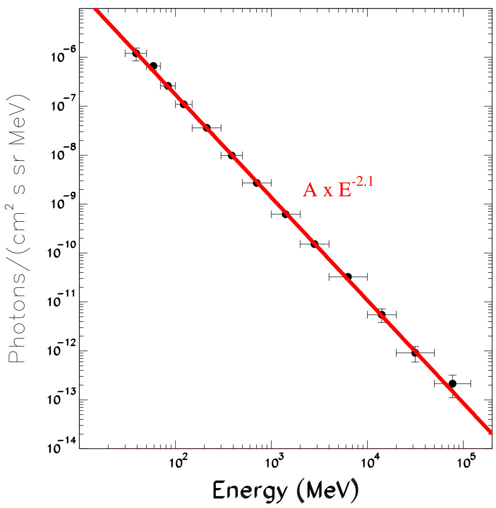

Fig. 1. The GBR spectrum, inferred by EGRET (Sreekumar et al., 1998). The line is the best power-law fit.

in the ISM. Fig. 1 shows that this GBR flux in the 30 MeV-120 GeV energy range is well described by a single power-law:

$$\frac{dF_\gamma}{dE} \simeq 2.7\times10^{-3}\left[\frac{E}{\rm MeV}\right]^{-2.1} \frac{1}{\rm cm^2\ s\ sr\ MeV} \,.\quad(3)$$

The spectral index of the GBR inferred by EGRET is the same, 2.1 ± 0.03, in all sky directions away from the Galactic disk (Sreekumar et al., 1998). But the data show a significant deviation from isotropy, clearly correlated with the structure of the Galaxy and our position relative to its center (Dar & De Rújula, 2001). This advocates a large Galactic contribution to the EGRET GBR arising from ICS of MBR photons and starlight by Galactic CR electrons (Dar & De Rujula, 2001). The uniformity of the spectral index of the diffuse GBR over the whole sky, despite a large Galactic contribution correlated with the structure of the Galactic CR halo and our position relative to its center, suggests a CR origin of both the Galactic and extragalactic diffuse GBR (Dar & De Rújula, 2001; Dar, 2007).

Below ~ 100 GeV the spectrum of Galactic CR electrons measured by ATIC agrees with that measured in other experiments and is well represented by Eq. (2). Above ~ 100 GeV the ATIC results show an excess in flux of CR electrons that peaks around ~650 GeV and drops rapidly to zero around 800 GeV. Consider ICS of MBR photons whose present temperature and mean energy are $T_0 = 2.725$ K and $\epsilon \approx 2.7\,k\,T_0 \approx 0.635$ meV (Mather et al,, 1993; Fixen et al., 1993). The mean energy of these upscattered photons by CR electrons with $E_e \sim 650$ GeV is:

$$E_\gamma(\epsilon) \approx \frac{4}{3}\left(\frac{E_e}{m_e\,c^2}\right)^2 \epsilon \approx 1.37\ {\rm GeV}\,. \quad (4)$$

This relation holds for the observed E_γ independent of the redshift where the ICS took place because the blueshift of the MBR temperature compensates the redshift of the observed energy of the scattered photons. Inverse Compton scattering of stellar photons ($\epsilon \sim 1$ eV) by 650 GeV electrons boosts the energy of the stellar photons to ~2 TeV, but this process is strongly suppressed by the energy dependence of the Klein-Nishina cross section.

The GBR flux produced by ICS of MBR photons at Galactic latitude b and longitude l is given to a good approximation by (Dar & De Rújula, 2001):

$$\frac{dF_\gamma}{dE_\gamma} \simeq N_e(b,l)\,\sigma_T\left[\frac{dE_e}{dE_\gamma}\,\frac{dF_e}{dE_e}\right]_{E_e=E_{eff}}, \quad (5)$$

where $N_e(b,l)$ is the column density of CR electrons at latitude b and longitude l and $E_{eff} = m_e c^2\sqrt{3\,E_\gamma/4\,\epsilon}$. The ATIC flux excess between 500-800 GeV and the smooth CR electron flux without it are comparable. Thus, if the ATIC excess between 500-800 GeV is ‘universal’ and not a local excess, such as that expected from dark matter annihilation in the entire universe, it should have produced an excess in the GBR between 0.8-2 GeV (i.e., a ‘GeV excess’) comparable with the contribution from ICS of MBR photons by a CR electron flux without the ATIC excess. This ‘GeV excess’ in the GBR should be observable mainly at large Galactic latitudes where ICS scattering of MBR photons dominates over photons from the decay of π^0 produced in collisions of high energy CR nuclei in the ISM. An

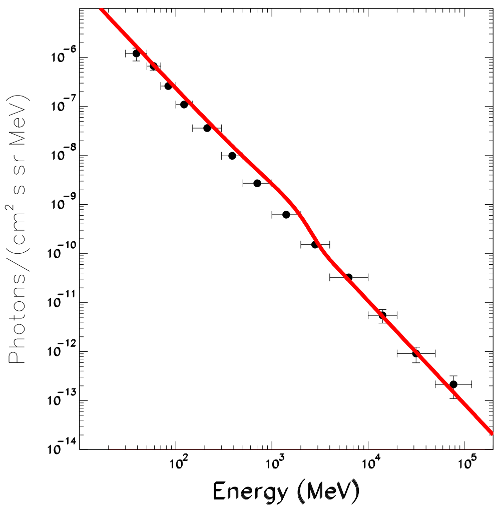

Fig. 2. Comparison between the spectrum of the GBR which was measured by EGRET (Sreekumar et al., 1998) and that produced by ICS of MBR photons by CR electrons with a power-law spectrum with an index $\beta_e = 3.2$ plus an excess such as that measured by ATIC (Chang et al., 2008) between 300-800 GeV.

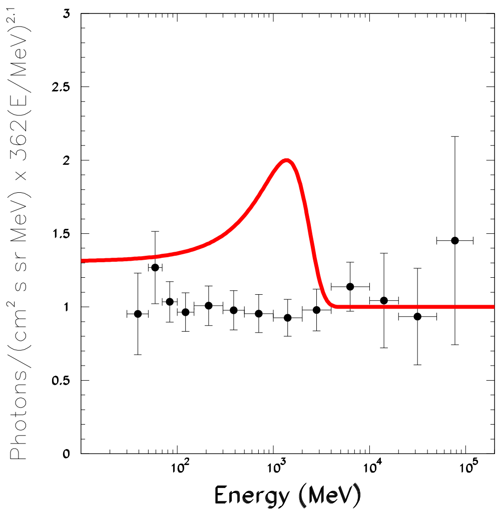

Fig. 3. Comparison between the GBR spectrum measured by EGRET (Sreekumar et al., 1998) and a GBR spectrum produced by ICS of MBR photons by a universal CR electrons power-law spectrum plus an excess such as that measured by ATIC (Chang et al., 2008) between 300-800 GeV. Both spectra were divided by the best fitted power-law to the EGRET GBR spectrum (Sreekumar et al., 1998).

estimate of the expected GBR at large Galactic latitudes, which is based on Eq. (5) and the universality of the ATIC excess, is shown in Figures 2 and 3.

These Figures show that the EGRET GBR does not support a 'universal' ATIC excess ($\chi^2/dof = 14.6$ for an ATIC-like flux compared to $\chi^2/dof = 0.27$ for the power-law fit in Figure 1.)

Very bright local point sources of CR electrons with $E_e \sim 650$ GeV could produce the ATIC excess (Profumo et al., 2008). But, such sources must also be extremely bright in GeV and TeV γ-rays due to ICS of the MBR and stellar light near the sources. Ultra-bright nearby steady sources of γ rays were not observed either with EGRET aboard the CGRO satellite and LAT aboard the Fermi satellite in the GeV range or with the H.E.S.S., MAGIC and VERITAS air shower Cherenkov telescopes in the TeV range. Moreover, steady or transient bright sources of Galactic CRs such as gamma ray bursts that are beamed away from Earth (Dar & Plaga, 1999), which could have produced a local CR excess like the ATIC excess, would have also produced such a universal excess that is ruled out by the observed GBR.

The increasing positron fraction in the 10-100 GeV range which was measured by PAMELA is at odds with the expected decrease from the decay of π's and $K's$ produced in the collisions of the primary CR nuclei with ISM nuclei (Moskalenko & Strong, 1998). The observed increase may result from misidentified hadrons by PAMELA (whose fraction may increase with energy due to a more rapid decline with energy of the positron flux than the flux of protons and secondary hadrons (Schubnel, 2009). However, the flat positron fraction between 5-50 GeV that was measured by HEAT (Barwick et al., 1998; DuVernois et al., 2001) with the record hadron rejection ($\geq 10^{-5}$) is consistent within errors with the PAMELA result but is also inconsistent with the slow decrease with increasing CR energy from secondary meson production in the ISM calculated from a Leaky Box Model (Moskalenko & Strong). It suggests that another positron source begins to dominate the CR positron flux around 10 GeV. Positrons of 10-100 GeV energy Compton upscatter starlight ($\epsilon \sim 1$ eV) to $E_\gamma \sim 0.5 - 50$ GeV. But, unlike the ATIC excess, the small positron fraction measured by PAMELA (Figure 4) have too small a signature which can be resolved from the GBR with current instrumentation aboard gamma-ray satellites.

The increaing positron fraction measured by PAMELA could be either local or global. The sources which can enhance the positron fraction locally could be: (i) a local environment with a higher density than that of the ISM; (ii) nearby luminous sources of CR nuclei (such as supernova remnants) which can enhance local production of CR electrons and positrons in the ISM; (iii) nearby astrophysical point sources of CR positrons such as pulsars which are believed to be producers of high energy e^+e^- pairs (Profumo et al., 2008). Global sources include gamma ray bursters whose jets can transport ballisticly primary CRs to Galactic distances (Dar & Plaga, 1999; Dar & De Rújula, 2008) and annihilation/decay of dark matter particles (Cheng et al., 2009).

Consider the combination of primary electrons produced by the CR sources and the secondary CR electrons produced in the ISM. At low energies, the observed positron fraction near minimum solar activity decreases like $\sim E^{-0.8}$ because of the effects of the geomagnetic field, which are not fully understood, and because multi-meson production becomes more symmetric in charge with increasing energy. At high energies the electrons and positrons which are produced in the CR sources are injected into the ISM with $\beta_s = 2.2$ and a positron fraction ~ 0.7, and cool to a power-law $\propto E^{-3.2}$, while the secondary electrons that are injected with a spectrum $\propto E^{-2.7}$ cool to a steady state

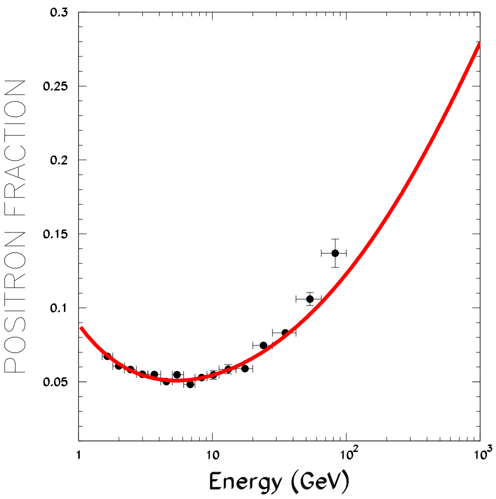

Fig. 4. Comparison between Eq. (6), which follows from CR acceleration by both, non relativistic spherical ejecta and highly relativistic jets from supernova explosions (Dar & Plaga, 1999; Dar & De Rújula, 2008), and the PAMELA positron fraction (Morselli & Moskalenko, 2008).

spectrum $\propto E^{-3.7}$. Thus, the positron fraction can be described effectively by:

$$\frac{e^+}{e^+ + e^-} \approx \frac{E^{-4.5} + a\,E^{-3.2}}{b\,E^{-3.7} + (a/0.7)\,E^{-3.2}}\,, \tag{6}$$

which interpolates between the expected decrease at low-energy and the increase towards ~ 0.7 at higher energies. In Figure 4 we compare Eq. (6) and the PAMELA positron fraction (Morselli & Moskalenko, 2008). The values of a and b, which depend on the phase of the solar cycle and on many other not well known astrophysical parameters, were treated as adjustable parameters. For E in GeV units, their best fitted values are, $a = 0.19$ and $b = 13.1$. Eq. (6) seems to fit well the positron fraction measured by PAMELA without invoking positron production by dark matter annihilation. It is consistent with the fact that the antiproton flux measured by PAMELA (Morselli & Moskalenko, 2008) and in other experiments agrees with that expected from CR production of these antiprotons in the ISM.

In conclusion, the measured GBR rules out a universal source, such as dark matter annihilation, as the origin of the ATIC excess. Positron production in/near source plus production in the ISM can explain the behaviour of the positron fraction measured by PAMELA.

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