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Cosmic-ray electron signatures of dark matter

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There is evidence for an excess in cosmic-ray electrons at about 500 GeV energy, that may be related to dark-matter annihilation. I have calculated the expected electron contributions from a pulsar and from Kaluza-Klein dark matter, based on a realistic treatment of the electron propagation in the Galaxy. Pulsars younger than about 10^5 years naturally cause a narrow peak at a few hundred GeV in the locally observed electron spectrum, similar to that observed. On the other hand, if electron production by dark matter is predominantly occurring in high-mass clumps ($\gtrsim 10^3 M_\odot$), the sharp cutoff in the contribution from Kaluza-Klein particles is sometimes more pronounced, but often smoothed out and indistinguishable from a pulsar source, and therefore the spectral shape of the electron excess is insufficient to discriminate a dark-matter origin from more conventional astrophysical explanations.

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I. INTRODUCTION

Only about 1 percent of galactic cosmic rays are electrons, but their properties are of particular interest because they are very radiative at high energies and thus quickly lose their energy. The cosmic-ray electron spectrum is therefore softer than that of cosmic-ray nucleons, and high-energy electrons are few. For a long time only emulsion-chamber data of the electron flux above 100 GeV were available [1], which were well represented by a power law $N(E) \propto E^{-3.2}$, but the energy resolution and statistical accuracy were limited. Recently data obtained with the advanced thin ionization calorimeter (ATIC) balloon experiment were published, which show an excess of galactic cosmic-ray electrons at energies between 300 and 700 GeV [2]. At TeV energies the electron flux appears to drop off rapidly [3]. This excess is indicative of a previously unknown source of high-energy electrons, which could be a nearby supernova remnant [4], a pulsar [5], a microquasar [6], or an annihilation site of dark-matter particles of the Kaluza-Klein type [7].

The dark-matter interpretation is particularly appealing, because the PAMELA collaboration has reported an increase in the cosmic-ray positron fraction above 20 GeV, suggesting the existence of a local source of both positrons and electrons [8]. Dark-matter annihilation resulting in electron-positron pairs is possible in a number of models [9–12], and will produce a spectrum dominated by a delta functional at the mass of the dark-matter particle [13]. Indeed, the ATIC team finds that a Kaluza-Klein particle with mass 620 GeV fits their electron data just fine, when the expected electron source spectrum is propagated in the Galaxy using the GALPROP code [14]. Hall and Hooper suggest that high-precision measurements of the electron spectrum be conducted with atmospheric Cherenkov observatories such as VERITAS and HESS, that would permit a discrimination between the dark-matter and pulsar hypotheses [15].

If dark-matter annihilation is responsible for the excess in 600-GeV electrons, then a substantial boost factor is required to match the observed electron flux which requires that the dark matter be concentrated in dense clumps. Alternative models involving a $1/v$-correction to the annihilation cross section face severe constraints from measurements of the extragalactic radiation background and the ionization and heating rate of the intergalactic medium [16]. Here we concentrate on the conventional boosting scenario involving numerous dark-matter clumps. The electrons would then be injected into the Galaxy only at the location of those clumps, which introduces substantial variations in the electron flux throughout the Galaxy and can significantly modify the observed electron spectrum, as was shown in similar studies of electron propagation from supernova remnants [17–19]. The GALPROP code implicitly assumes a smooth source distribution on account of its using a finite-difference algorithm on a coarse grid, and therefore it will not properly describe those fluctuations.

II. THE PROPAGATION OF RELATIVISTIC ELECTRONS

The effects of the spatial structure of the electron sources appear only at higher particle energies, at which the radiative loss time is short. Therefore we may treat the propagation of electrons at energies above 50 GeV with a simplified transport equation,

$$\frac{\partial N}{\partial t} - \frac{\partial}{\partial E}(bE^2 N) - DE^a \nabla^2 N = Q \qquad (1)$$

with which we consider continuous energy losses by synchrotron radiation and inverse Compton scattering (in the Thomson limit), a diffusion coefficient DE^a dependent on energy, and a source term Q. We ignore reacceleration and convection in a galactic wind. Throughout this paper the propagation parameters have the values

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$$\frac{1}{bE} = (2.6 \cdot 10^{15}\ \mathrm{s})\left(\frac{E}{\mathrm{GeV}}\right)^{-1}, \tag{2}$$

corresponding to synchrotron losses in a 11μG galactic magnetic field and Compton scattering of the CMB. The diffusion coefficient is chosen as required in cosmic-ray propagation without continuous reacceleration [20,21]

$$DE^a = (10^{28}\ \mathrm{cm^2\ s^{-1}})\left(\frac{E}{\mathrm{GeV}}\right)^{0.6}. \tag{3}$$

Green's function for this problem is [22]

$$G = \frac{\Theta(t-t')\delta(t-t'+\frac{E-E'}{bEE'})}{bE^2(4\pi\lambda)^{3/2}}\exp\left(-\frac{(\mathbf{r}-\mathbf{r}')^2}{4\lambda}\right), \tag{4}$$

where Θ is a stepfunction and

$$\lambda = \frac{D(E^{a-1} - E'^{a-1})}{b(1-a)}. \tag{5}$$

In the case of discrete sources the injection term Q is a sum over all such sources. For an individual source we can write

$$Q_i = q_0 f(E) g(t) \delta(r) \tag{6}$$

and obtain the current ($t = 0$) contribution of that source to the electron density at distance r as

$$N_i = \frac{q_0}{bE^2(4\pi)^{3/2}}\int_{-\infty}^{0} dt' g(t')\delta\left(-t' + \frac{E-E'}{bEE'}\right) \times \int dE' \frac{f(E')}{\lambda^{3/2}}\exp\left(-\frac{r^2}{4\lambda}\right). \tag{7}$$

A. Electrons from pulsars

The spectrum of electron escaping from a pulsar is not well- known. A simple parametrization may be in order [15] that describes the differential production rate of electrons by a pulsar

$$f_p(E) = E^{-1.5}\exp\left(-\frac{E}{E_c}\right), \tag{8}$$

$$g_p(t) = \Theta(t + \tau), \tag{9}$$

where we use a step function to account for the finite age, τ, of the pulsar, and could add another step function for pulsars that have already ceased to produce pairs. Obviously, the spectrum of the excess electrons depends chiefly on the scaling parameters $\xi = bE_c\tau$ and $\rho = (r^2[1-a]b)/(4DE_c^{a-1})$, which compare the age, τ, with the energy-loss time scale, $1/(bE_c)$, and the distance, r, with the diffusion length within one energy-loss time. At time $t = 0$ and distance r we observe the differential density of electrons as

$$N_p = \frac{C}{E^{1+1.5a}}\left(\frac{\rho}{r^2}\right)^{3/2}\int_1^{x_{\max}} dx \frac{x^{-1.5}}{[1-x^{a-1}]^{3/2}} \times \exp\left(-x\frac{E}{E_c} - \left(\frac{E}{E_c}\right)^{1-a}\frac{\rho}{1-x^{a-1}}\right), \tag{10}$$

where C absorbs all constants and

$$x_{\max} = \begin{cases} \infty & \text{if } \frac{E}{E_c}\xi \ge 1, \\ \frac{1}{1-\frac{E}{E_c}\xi} & \text{if } \frac{E}{E_c}\xi < 1. \end{cases} \tag{11}$$

In Fig. 1 we show possible electron spectra near Earth, that may result from a pulsar that produces electrons with spectrum (8), indicated by the thin dotted line. To be noted from the figure is the sharp peak in the electron spectrum that is entirely a propagation effect. The distance to the pulsar is assumed as $r = 700$ pc; for our propagation parameters the distance parameter is then $\rho = 0.23$, meaning electrons observed at 600 GeV can well reach Earth within one energy-loss time, whereas electrons beyond a few TeV cannot. Increasing ρ would make the peak in the electron spectrum sharper.

The thin, solid curve is derived for the same parameters as is the thick, solid curve, except that a more shallow energy dependence of the electron diffusion coefficient was chosen, name $a = 0.4$. The spectral changes imposed by varying a are substantially smaller than those effected by varying ρ or ξ, showing that the choice of diffusion coefficient is not a decisive parameter.

If $\xi = 1$, the pulsar age is the same as the energy-loss time at 600 GeV, 140 000 years for our propagation pa-

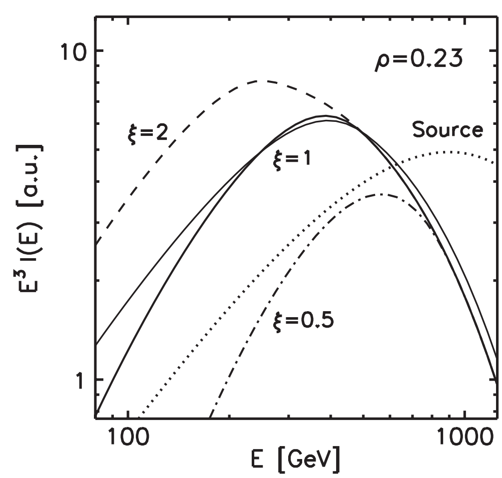

FIG. 1. Examples of electron spectra ($I = \frac{c}{4\pi}N$) measured near Earth for different ages of the pulsar [cf. Eq. (10)]. The thin dotted line denotes the assumed pulsar source spectrum as power law with exponential cutoff at 600 GeV [cf. Eq. (8)]. The three thick lines give the particle spectra for three different values ages parameter ξ, but the same distance parameter, ρ. The thin solid line is also for $\xi = 1$, but smaller energy dependence of the diffusion coefficient, $a = 0.4$. The stated $\rho = 0.23$ corresponds to a distance of 700 pc. The pulsars are assumed to have continuously released pairs for the last $\xi \cdot 140,000$ years.

rameters. For $\xi = 0.5$, the pulsar age is only 70 000 years. Subtracting the curve for $\xi = 0.5$ from that for $\xi = 1$, one would obtain the electron spectrum for a pulsar than began producing pairs 140 000 years ago and stopped doing so 70 000 years ago. Electrons at lower energy may not have enough time to not reach Earth because their propagation range scales $\propto E^{a/2}$, thus causing a sharp low-energy cutoff in the observed spectrum. Given the local supernova rate we expect about one pulsar born within 1 kpc and 10^5 years, so given the energy-loss time at 600 GeV one pulsar at $r = 700$ pc is realistic. However, the pulsars need a few million years to propagate 1 kpc above or below the galactic plane, and so electron injection by the pulsar must taper off after about 10^5 years to avoid a high flux of 100-GeV electrons.

III. ELECTRONS FROM DARK MATTER

I will now discuss electron spectra that may arise from dark-matter annihilation. As substantial boosting factors of a few hundred are needed [23], the dark matter is most likely organized in a number of individual high-density clumps. The size of the clumps is not relevant for us, as long as it is much smaller than the propagation range of 600-GeV electrons, a few hundred parsec. Likewise, the large-scale distribution of the clumps in the Galaxy does not matter, unless the clump density varies on scales similar to the electron propagation range. I will therefore assume the clumps to be randomly distributed in space with constant density n_c. Dark-matter annihilation should proceed at a constant rate and can, in the case of Kaluza-Klein particles, produce electrons with a source spectrum that is dominated by a delta-functional at the particle mass. For each clump, the differential source rate of electrons can then be described by the functions [cf. Eq. (6)]

$$f_{\rm dm} = \delta(E - E_c), \qquad g_{\rm dm}(t) = 1 \tag{12}$$

The electron spectrum observed at distance r from the clump is then

$$N_{\rm dm} = \frac{C\Theta(E_c - E)}{E^2 \lambda^{3/2}} \exp\left(-\frac{r^2}{4\lambda}\right), \tag{13}$$

where C absorbs the constants, Θ is a step function, and

$$\lambda = \frac{DE_c^{a-1}}{b(1-a)}\left[\left(\frac{E_c}{E}\right)^{1-a} - 1\right]. \tag{14}$$

The total electron spectrum is obtained by summing the contributions from all clumps. If the clump density n_c is high, the dark-matter distribution is effectively homogenous. Then the total electron spectrum is governed by a cooling tail.

$$N_{\rm dm,tot} = n_c \int_0^\infty dr 4\pi r^2 N_{\rm dm} = C' \frac{\Theta(E_c - E)}{E^2}. \tag{15}$$

This is the case implicitly (and tacitly) assumed when using the standard GALPROP code, and it is presented in many publications (e.g. [2]).

The question arises at what density the spectra start deviating from that for the homogeneous case [Eq. (15)] and what the observed spectral shape might be.

Simulations suggest that dark-matter clumps are formed over a very wide range of masses, and their density distribution is well described by a power law

$$\frac{dn(M)}{dM} = n_0 M^{-f}, \tag{16}$$

where the index may be $f = 2$ between $10^{-6} M_\odot$ and $10 M_\odot$ [24], and possibly somewhat smaller, $f \simeq 1.8$ around $10^6 M_\odot$ (e.g. [25]). In any case, the number density of clumps, n_c, is determined by the location of the low-mass cutoff in the mass distribution, the calculation of which requires a careful assessment of the survival probability of such microhaloes (e.g. [26]). We expect about one clump above $10^6 M_\odot$ within 1 kpc from us, and about one clump above $10^3 M_\odot$ within 100 pc from us.

For a dark-matter clump of characteristic size, r_c, and density, ρ_c, the source rate of pairs can be written as

$$Q_c \propto \rho_c^2 r_c^3 \propto M^d, \tag{17}$$

where the constant of proportionality and the scaling index depend on cuspyness of the clump [27,28]. Different estimates for the scaling index d have been published for the high-mass end of the mass spectrum of clumps [29,30], but here we are more concerned with the mass range $10^{-6} M_\odot$ to $10^4 M_\odot$ because the higher-mass clumps have a small density anyway. Obviously, if Q_C increases faster than linearly with mass, i.e. $d > 1$, then the pair-production rate per mass interval peaks at the high-mass end of the distribution.

$$\frac{dQ}{d\ln M} = Q_c M \frac{dn(M)}{dM} \propto M^{d+1-f}. \tag{18}$$

If the power-law index in Eq. (18) is negative, $d + 1 - f < 0$, the electron production is dominated by the numerous low-mass clouds, and we can indeed treat the dark matter as a homogeneous source of electron. On the other hand, if $d + 1 - f > 0$, then the few massive clumps dominate electron production, and the local electron spectrum will deviate from that expected in the homogeneous case.

I have randomly placed in the Galaxy dark-matter clumps with a power-law density spectrum as given in (16), and a power-law scaling of the electron source rate with mass following (17). Then, I have summed the electron contribution from all clumps according to Eq. (13), using $E_c = 600$ GeV. The resulting electron spectrum from dark matter is added to the generic galactic electron flux, for which a spectrum $\propto E^{-3.2}$ is assumed. On average, the dark-matter component at 600 GeV has twice the flux of the galactic electron background.

Figure 2 shows the resulting total electron spectra for two parameter combinations, for which the pair-production rate per logarithmic mass interval is marginally increasing with mass, $d + 1 - f = 0.05$. In all panels the dotted line indicates the mean spectrum according to Eq. (17), and the dash-dotted line denotes a randomly selected spectrum out of the 5000 that were calculated. To be noted from the figure is that the dark-matter hump often does not look different from the hump a pulsar would produce. It can be fairly roundish and lack the sharp cutoff at E_c. The reason is that electrons at an energy very close to E_c must be very young, because they have not lost a significant fraction of their energy, and can therefore only come from a very close dark-matter clump. There may not be one of the few high-mass clouds within 300 pc, that are so important for the global pair production, and thus electrons at $E \simeq E_c$ may not reach us. On the other hand, a very close dark-matter clump would produce a dominant spike at $E \simeq E_c$. The shaded areas indicate the range of flux for three different probabilities. In 68% of all cases the electron flux is within the dark gray region, the medium gray area corresponds to 90% and the light gray to 99% probability.

We can compare the dark-matter case and the pulsar case in more detail. For that purpose I have taken an electron spectrum for dark matter with homogeneous source distribution (Eq. (15)), the example spectrum shown in the lower panel of Fig. 2 to represent an inhomogeneous source distribution, and a spectrum expected from a pulsar super-

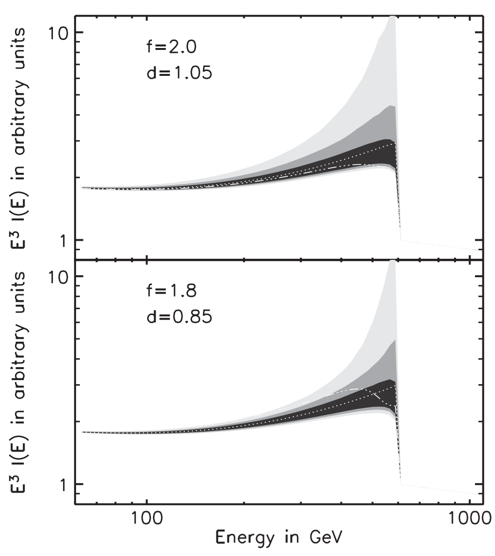

FIG. 2. The range of electron spectra measured near Earth, added onto the galactic electron background with spectrum $\propto E^{-3.2}$. The dotted line indicates the mean spectrum [cf. Eq. (15)]. The dash-dotted line denotes a randomly selected spectrum as an example of what may be observed. The shaded areas indicates the range in which we find the electron flux in 68% (dark gray), 90% (medium gray), and 99% (light gray) of all cases. Two models are shown, and the parameters for the mass-spectrum of clumps and the source-rate scaling are given in the panels.

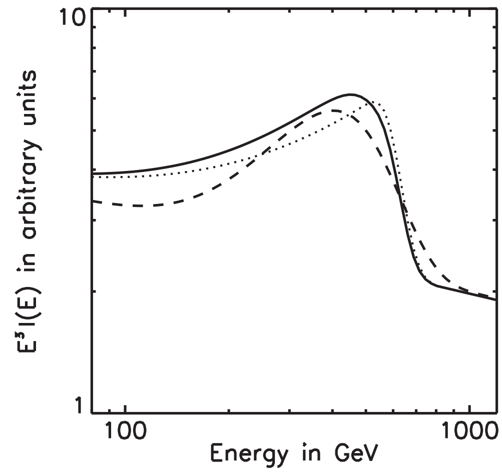

FIG. 3. A comparison of the local electron excess from a pulsar (dashed lines) with that expected from the annihilation of Kaluza-Klein particles. The dotted curve is for a homogeneous dark-matter distribution, whereas the solid line is an example for a clumpy dark matter as in Fig. 2. All spectra are added to a generic galactic electron background and smoothed with 8% energy resolution.

imposed on an $E^{-3.2}$ generic galactic electron background. The pulsar is assumed at 1.1 kpc distance, and to have produced pairs between 70 000 and 14 000 years ago. All spectra have been smoothed with a Gaussian of dispersion $\delta E = 0.08E$ to simulate the finite energy resolution of a real electron detector. The resulting electron spectra are shown in Fig. 3. To be noted from the figure is how small the difference between the three spectra is, in particular, considering the uncertainty in the underlying galactic electron background, in which spectral bumps are expected [18] and a high-energy turnover observed [5]. For example, if we choose for the galactic electron background a somewhat harder power law with soft cutoff at a few hundred GeV instead of the single powerlaw assumed here, the dashed curve representing the pulsar contribution will change to more closely resemble the solid or dotted curves. It appears that the observed electron excess alone cannot be unambiguously identified with a dark-matter signal.

IV. SUMMARY AND DISCUSSION

The ATIC collaboration has measured an excess in cosmic-ray electrons at about 500 GeV energy [2], which may be related to dark-matter annihilation. In this paper I have calculated the expected electron contributions from a pulsar and Kaluza-Klein dark matter. My emphasis is on a realistic treatment of the electron propagation in the Galaxy, for which I use analytical solutions to the electron transport equation. The commonly employed GALPROP code implicitly assumes a smooth distribution of the electron sources, because it uses a finite-difference algorithm on a grid.

The findings can be summarized as follows:

(i) Pulsars younger than about 10^5 years naturally cause a narrow peak at a few hundred GeV in the locally observed electron spectrum. A single pulsar could therefore explain both the electron excess measured with ATIC and a similar excess in positrons, evidence for which at 50 to 100 GeV was obtained by the PAMELA experiment [8]. The pulsar hypothesis does require that pulsars with ages beyond 10^5 years leak significantly fewer electron/positron pairs, otherwise they would provide a very strong contribution in the 50 to 300 GeV band that is not observed.

(ii) Dark-matter annihilation occurring predominantly in massive, dense clumps will produce a feature in the local electron spectrum, that deviates from that expected if the dark matter were smoothly distributed. The sharp cutoff in the contribution from Kaluza-Klein dark matter is often smoothed out, and the spectral feature would be indistinguishable from a pulsar source, even if the energy resolution of the electron detector were good. The spectral shape of the electron excess is insufficient to discriminate a dark-matter origin from more conventional astrophysical explanations, contrary to a recent claim [15].

The electron source rate is determined by the density profile of clumps, in particular, its scaling with clump mass. We have demonstrated that the clump density structure and density spectrum are the decisive parameters determining the amplitude of spectral variations in the electron excess from dark-matter annihilation. It is therefore of prime interest to better estimate these quantities.

Dark-matter clumpyness provides the boost factors required by the ATIC data, which may be further increased by Sommerfeld corrections [31,32]. Simulations of structure formation in cold-dark-matter cosmologies show clumping on a variety of scales, but the boost factors are generally very moderate [33,34] which may be due to limited numerical resolution.

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