Galactic Positrons From Localized Sources

David Eichler\textsuperscript{1}, Irit Maor\textsuperscript{2}

ABSTRACT

The anomalous bump in the cosmic ray positron to electron ratio at 10 GeV can be explained as being a component from a point source that was originally harder than the primary electron background and degrades due to synchrotron and inverse Compton losses in the Galaxy while propagating to the Earth's vicinity. The fit is better than can be obtained with homogeneous injection and is attributed to a minimum age threshold. Annihilating neutralinos can provide a fair fit to the data if they have a mass just above 1/2 the mass of the $Z^0$ and if they annihilate primarily in distant density concentrations in the Galaxy. A possible observational consequence of this scenario would be intense inverse Comptonization of starlight at the Galactic center, with a sharp energy cutoff in the emergent photons as a possible signature of the neutralino mass.

Subject headings: cosmology: dark matter – diffusion – elementary particles – galaxy: center

1. Introduction

The possibility that weakly interacting dark matter particles (WIMP's) could annihilate into detectable cosmic radiation was suggested by Silk & Srednicki (1984). Tylka & Eichler (1987) noted a reported positron excess, curiously localized near 10 GeV [Mueller & Tang (1985, 1987); Barwick et al. (1997, 1998)] and considered whether it could be due to the annihilation of photinos (as a simple example of neutralinos) in the tens of GeV mass range. The difficulty was that this process, given the laboratory constraints on the neutralinos, seemed to fall short of providing enough positrons, and the results were not published. Various papers on this excess eventually appeared [Tylka (1989); Eichler (1989); Turner & Wilczek (1990); Coutu et al. (1999)], and some noted that the potential for positron excess

\textsuperscript{1}Physics Department, Ben-Gurion University, Beer-Sheva, Israel, eichler@bgumail.bgu.ac.il

\textsuperscript{2}Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0WA, UK, i.maor@damtp.cam.ac.uk
could be bolstered by clumpiness in the annihilating dark matter or by decay of weakly unstable dark matter particles.

The approach usually found in present literature is to try and fit the overall $e^+/(e^+ + e^-)$ ratio, without giving special attention to the curious behaviour at 10 GeV, see Hooper & Silk (2004). Baltz & Edsjo (2001) considered a whole class of minimal standard supersymmetric models and failed to get any non-monotonicity in the $e^+/ (e^+ + e^-)$ ratio. Eichler & Maor (2004) (henceforth Paper I) considered annihilation of particles through the $Z^0$-channel (which we shall henceforth refer to as virtual $Z^0$-decay) noted that non-relativistic virtual $Z^0$ decay (i.e. when the rest mass of the annihilating dark matter particle is slightly above 1/2 the $Z^0$ mass) provide a remarkably good fit to the observed $e^+/ (e^+ + e^-)$ ratio below 10 GeV mainly due to the positrons that emerge from decaying muons. At higher energies, however, the predicted $e^+/ (e^+ + e^-)$ ratio rose above the observed values within conventional assumptions about the injection and propagation. In particular, it was assumed in Paper I that the positrons and primary electrons are each injected with the same spatial profile, and that their propagation in the Galaxy is identical. The reason for this rise is that some $Z^0$'s decay directly into high energy $e^+e^-$ pairs so that the $e^+$ energy is half the $Z^0$ mass, and this gives rise to a high energy bump in the $e^+/ (e^+ + e^-)$ ratio at about 50 GeV. While this bump can be partially washed out by losses and escape, it was found that the high energy $e^+/ (e^+ + e^-)$ ratio is nevertheless apparently too high to fit the observations to within 1σ error bars. As discussed in Eichler (1989) this is a generic problem for any positron source that is significantly harder than the primary electrons above 10 GeV.

However, the dark matter annihilation scenario for explaining the positron excess in any case requires that clumping of the dark matter, and a likely place for this is near the Galactic center. This means that the positrons in our neighborhood that are dark matter annihilation products would have a minimum age, i.e. the time needed to diffuse from the source to our neighborhood, and the age distribution of the positrons that make it to the Earth’s vicinity contain fewer young positrons than the age distribution that one associates with the standard leaky box model. In this letter we consider that the positrons are injected by an effectively point source at a finite distance, and show that it greatly improves the fit over that obtained in Paper I. The positron bump at $\sim 10$ GeV can be attributed to halo-type age $\sim 3 \times 10^7$ yr for the positrons, for over such a lifetime, positrons losing energy by synchrotron and inverse Comptonization would end up at about this energy.

We will find that obtaining a good fit from a single source with a single diffusion coefficient is difficult. However, it is well known that below a certain intensity, e.g. far enough up front in a diffusion front, cosmic rays can freely stream. Such behavior is observed upstream of the Earth’s bow shock. Theoretical reasons for such free streaming include the difficulty
of resonantly scattering cosmic rays through 90 degree pitch angle in the linear wave amplitude regime. Also, a larger, counterstreaming, finitely stable component of cosmic rays would stabilize the smaller free streaming positron component. We therefore allow for the possibility that a small fraction of the positrons freely stream, and arrive at the Earth’s vicinity much younger than the rest. We find that this improves the fit still further. We find that the low energy non-monotonicity, which appears in the injection spectrum from non-relativistic $Z^0$ decay Paper I, can be produced also by using a simple power law for the injected spectrum (using the same propagation model). It can thus be produced by the combination of a harder (but monotonic) spectrum of injected positrons and propagation effects. We conclude that it is still too early to unambiguously interpret the low energy behavior of the spectrum as a signature of self annihilating dark matter.

2. Equations and Results

The steady state diffused equation for the particle number density, $n(x,r)$, is

$$\frac{\partial n}{\partial t} = 0 = \hat{D}n - Rn + \frac{1}{m_Z} \frac{\partial}{\partial x} \left( m_Z \frac{dx}{dt} n \right) + I(x)\delta (r/L)$$  \hspace{1cm} (1)

$x = E/m_Z$, $\hat{D}$ is a diffusion operator, $R = B x^{0.5}$ is the escape rate with $B \sim few \times 10^{-15} 1/s$, $m_Z \frac{dx}{dt} = Ax^2$ with $A = 8.5 \times 10^{-16} erg/s$ is the Compton loss rate, corresponding to an electromagnetic energy density in the Galaxy of $10^{-12} erg/cm^3$, $L$ is a distance scale, and $I(x)$ is the spectrum injected by a point source.

We assume as in Paper I that the primary electrons and background positrons are injected homogeneously, $\hat{D}n_b = 0$:

$$n_b(x) = \frac{m_Z}{Ax^2} exp \left[ -\frac{2m_ZB}{A\sqrt{x}} \right] \int_x^\infty I_b(x') exp \left[ \frac{2m_ZB}{A\sqrt{x'}} \right] dx'$$  \hspace{1cm} (2)

$$I_{b,e^-}(x) = Cx^{-2} \quad \text{for background } e^-$$

$$I_{b,e^+}(x) = Dx^{-2.8} \quad \text{for background } e^+$$  \hspace{1cm} (3)

For the $Z^0$ decay injected spectrum we take the diffusion to be one-dimensional with a diffusion coefficient $\mathcal{D}$, $\hat{D} = \mathcal{D} \frac{\partial^2}{\partial x^2}$, and with boundary conditions such that $\frac{\partial n}{\partial r} |_{r=L} = 0$ (conserving the number of particles except for the escape term). With these boundary conditions, the solution to eq. (1) is

$$n(x,r) = \frac{m_Z}{Ax^2} exp \left[ -\frac{2m_ZB}{A\sqrt{x}} \right] \times$$
\[ \int_x^\infty I_Z(x') \exp \left[ \frac{2m_ZB}{A\sqrt{x'}} \right] \sum_{n=-\infty}^\infty \cos \left[ \frac{\pi nr}{L} \right] \exp \left[ -\left( \frac{\pi n}{L} \right)^2 \frac{m_ZD}{A} \left( \frac{1}{x} - \frac{1}{x'} \right) \right] \, dx \quad (4) \]

While \( D \) (the diffusion coefficient) and \( L \) (the size of the leaky box) are free parameters, we took \( r = 8 \) Kpc, the distance to the galactic centre. \( K \equiv D/r^2 \) gives the inverse time for diffusion.

We have chosen a one dimensional diffusion because it gives somewhat better results than 3 dimensional diffusion. This is physically plausible if one considers magnetic fields which will confine the movement of the charged particles. So the geometry is tube-like, with an effective cross section such that the total volume is the galactic volume, \((20 \text{ kpc})^3\).

\( I_Z(x) \) is the \( Z \) decay products,

\[
I_Z(x) = N \left( 0.0344I_e(x) + 0.0344I_\mu(x) + 0.0069I_\tau(x) + 0.6916I_h(x) \right) \quad (5)
\]

\[
I_e(x) = \delta \left( x - \frac{1}{2} \right)
\]

\[
I_\mu(x) = \frac{2}{3} \left( 5 - 36x^2 + 32x^3 \right)
\]

\[
I_\tau(x) = \frac{2}{3} \left( 5 - 36x^2 + 32x^3 \right) + \frac{2}{9} \left[ \frac{95}{3} - 108x^2 + \frac{1408}{3}x^3 - (25 + 324x^2 + 128x^3) \ln(2x) \right]
\]

\[
I_h(x) = \frac{14}{9} \int_{\frac{a_2}{b_2}}^{1} \frac{dx}{x} 10^{a_2-b_2x}
\]

\[
a_1 = 3, \quad b_1 = 10 \quad 0 < \bar{x} < 0.1
\]

\[
a_2 = 2, \quad b_2 = 4 \quad 0.1 < \bar{x} < 1
\]

Each \( I_{ch} \) describes the \( ch \) channel of decay, and the pre-factors correspond to the branching ratios. The calculation was done in zeroth order, assuming 3 massless families and neglecting the top quark, for details see Paper I. Following the discussion there, we take \( N = 1.3 \times 10^{-29} \text{1/(cm}^3\text{s)} \) as the annihilation rate per unit volume.

Fig. (1) shows a fit with a single point source of \( Z^0 \) decay and a single diffusion coefficient. The good fit to the low energies from Paper I is still present, but at the price that the excess in energies toward \( x = 1/2 \) is now is suppressed by the finite age effect. As the figure shows, we are now facing a scenario which is opposite to Paper I; the finite age effect tends to suppress the high energy excess at the price of killing it off altogether.

However, there are several possibilities that avoid this problem: There may be more than
one source, and there may be more than one route (roughly guided by magnetic field lines) by which the particles diffuse or freely stream from the source to our vicinity. High energy particles diffuse much less than low energy ones because they are fewer in number and create less waves. So their self-generated scattering is less efficient. Thus, the fraction of free streaming particles should be higher at higher energy. Fig. (2) shows a combination of two $Z^0$ decay components, an older, larger one that arrives via diffusion, and a younger, smaller component that has managed more free streaming. This figure illustrates that if one takes an age distribution into account, the flexibility in adjusting the high energy spectrum becomes much larger, and can be fitted to the data.

For sake of comparison, we also include a power law injected spectrum, fig. (3) shows various power laws, and fig. (4) shows two components with different ages. We find that as long as the injected power law is hard enough, one can produce a low energy ($5−10\, GeV$) dip. The quality of the fit is almost as good for a power law as for virtual $Z^0$ decay. We consider the low energy dip to have qualitatively more significance than the higher points and have emphasized those data points accordingly in choosing the best fit. We have deliberately not quantified this with the standard statistical measures. Trying to get the statistically best parameters (for either power law or $Z^0$ decay as injected spectrums) would wash out the low energy behavior that we are focusing on.

Although we can reproduce the $7\, GeV$ dip, the peak at $E \sim 15\, GeV$ is still too big for the HEAT data (though too small for the earlier data). This seems to be a generic feature of our results, regardless of whether the injection source is virtual $Z^0$ decay or a power law. The problem would be worse if the virtual $Z^0$ had an energy well above $m_Z$.

### 3. Possible Observational Consequences

The hypothesis that the neutralino mass $m_\chi$ is only slightly more than half the $Z^0$ mass is motivated by several factors: The annihilation cross section can be resonantly enhanced by a factor of 2 or 3 more than that during annihilation in the early universe, when the thermal broadening of the $Z$ resonance somewhat exceeded its natural width, Greist and Seckel (1991). Moreover, assuming the smallest allowable mass allows the greatest annihilation rate since the annihilation reaction rate is fixed by the condition that it allows a given cosmic dark matter contribution. (Although dark matter clumping can enhance the annihilation rate, a plausible level of such enhancement is limited by observational constraints on dark matter clumping that are set by stellar distributions in galactic centers.) Making $m_\chi$ just above $m_Z$ causes the $Z^0$ resonance to be asymmetric, but this would be hard to measure
experimentally because of the weak coupling of the emerging neutralinos at CM collision energies above $2m_\chi$. On the other hand, that the annihilation cross the virtual $Z^0$ must be close to its mass shell if it is to provide a decent fit suggests that its loop corrections would be large and it might be discernable or falsifiable with particle collider data on processes that depend on such loop corrections.

In an astronomical context, a possible observational consequence of a point source of positrons at the Galactic center could be inverse Comptonization of starlight, which is far more intense than at a typical point in the Galaxy. The profile of Galactic starlight near the Galactic center is given by Kent (1992). The derived photon energy density is then $U(r) = 4.3 \times 10^{-9} (r/pc)^{-0.85}$ erg/s. Assuming the positrons are produced within a typical radius $r$ of the Galactic Center, they produce a minimum of $E_{IC}(\gamma) \equiv \int_r^{100pc} \gamma^2 \sigma_T U(r) dr$ in inverse Compton (IC) scattered starlight before escaping the central 100 pc region, and the luminosity $L(\geq \gamma m_e c^2)$ above $\gamma^2 \epsilon_{ph}$, where $\epsilon_{ph}$ is the typical energy of the pre-scattered starlight photons, is $\int_{\gamma}^{\infty} I(\gamma' m_e c^2) E_{IC}(\gamma') d\gamma'$. The most energetic $e^+e^-$ pairs alone, that is those which result directly from the $Z^0$ decay ($I_e(x)$ in eq. 6), will produce IC luminosity of $3.8 \times 10^{35}$ erg/s.

Fig. (5) shows the logarithmic derivative of the IC luminosity due to the positrons only, $-\gamma^2 L_{\gamma^2} = -dL/d\ln(\gamma^2)$, as a function of the square of the positron Lorentz factor, $\gamma^2$. Shown in the figure is the minimum IC luminosity as a function of the frequency scaled to the frequency of the pre-scattered photon (x axis). The minimum luminosity assumes that the positrons emerge from the central region in a straight line. If the mean free path $\lambda$ is less than 100 pc, then the predicted luminosity goes up by roughly a factor of $(100pc/\lambda)$.

For dark matter annihilation that yields direct monochromatic $e^+e^-$ pairs at Lorentz factor $\gamma_0$, this would translate into a sharp cutoff in the IC gamma rays of $\gamma_0^2 \epsilon_{ph}$ or about $3\gamma_0^2$ eV. In our particular example $m_\chi \simeq m_Z/2$, this would lead to a cutoff at $10^{10} \epsilon_{ph} \sim 30$ GeV. This would in principle be detectable by MAGIC, see for example Cortina (2004), if the location were suitable for observing the Galactic center. Alternatively, it could be detected by HESS if the energy threshold could be pushed to below 30 GeV. This scenario would not explain the $TeV$ photons from the Galactic center recently reported by the HESS collaboration, Aharonian et al. (2004). If, however, there is annihilation in the Galactic Center of heavier dark matter particles, then direct $e^+e^-$ pairs might be detectable via such a cutoff in the $TeV$ gamma ray spectrum at $m_\chi/2$.

In conclusion, we find that the cosmic ray positron data can be fit with more than one
hard source of positrons provided that a) they have a chance to lose energy before escaping
the Galaxy and b) they have a minimum age (e.g. they come from discrete, distant sources),
unlike the background primary electrons. They need not be from dark matter annihilation,
but a best case scenario for this is not confidently ruled out by existing data. Detection of
inverse Compton radiation with good energy resolution can in principle provide information
as to the spectrum of the positrons and their point of origin.

We thank T. Alexander, E. Baltz, and A. Dekel for helpful discussions. DE gratefully
acknowledges the support from the Israel-U.S. Binational Science Foundation, the Israel
Science Foundation and the Arnow Chair of Physics at Ben Gurion University. IM gratefully
acknowledges the support from the Leverhulme Trust.

REFERENCES

Aharonian, F. et al. [The HESS Collaboration], arXiv:astro-ph/0408145.
Baltz, E. & Edsjo, J. astro-ph/0109318 (2001)
Barwick, S. W. et al. (HEAT collaboration) Astroph. J. 482, L191 (1997)
Barwick, S. W. et al. (HEAT collaboration) Astroph. J. 498, 779 (1998)
Cortina, J. [the MAGIC Collaboration], arXiv:astro-ph/0407475.
Coutu. S. et al. (HEAT collaboration) Astropart. Phys. 11, 429 (1999)
Eichler, D. Phys. Rev. Lett. 63, 2440 (1989)
Eichler, D & Maor, I. Astropart. Phys. 21 (2004) 195.
Greist, K. and Seckel, D. Phys. Rev. D 43, 3191
Hooper, D. & Silk, J. arXiv:hep-ph/0409104.
Kent, S. M. Astroph. J. 387, 181 (1992)
Mueller, D. & Tang, J. Proc. of Nineteenth International Cosmic Ray Conference, La Jolla,
California, NASA Conf. Pub. No. 2376 (U.S. GPO, Washington, DC), 2, 378 (1985)
Mueller, D. & Tang, J. Astroph. J, 312, 183 (1987)
Silk, J. & Srednicki, M. Phys. Rev. Lett., 53, 624 (1984)
Turner, M. S. & Wilczek, F. Phys. Rev. D 42, 1001, (1990)
Tylka, A. J. & Eichler, D. University of Maryland preprint (1987)
Tylka, A. J. Phys. Rev. Lett. 63, 40 (1989)
Fig. 1.— The $e^+/(e^+ + e^-)$ as a function of $x = E/m_Z$, for a single source $Z$ decay injected spectrum. $A = 8.5 \times 10^{-16} \frac{\text{erg s}}{\text{s}}$, $B = 7.1 \times 10^{-15} \frac{\text{cm}^3}{\text{s}}$, $C = 4.0 \times 10^{-29} \frac{1}{\text{cm}^3 \text{s}}$, $D = 1.3 \times 10^{-31} \frac{1}{\text{cm}^3 \text{s}}$, and $K = 1.9 \times 10^{-16} \frac{1}{\text{s}}$. Data taken from Barwick et al. (1997) (black) and Mueller & Tang (1987) (grey).

Fig. 2.— The $e^+/(e^+ + e^-)$ as a function of $x = E/m_Z$, for a combination of 2 sources of $Z$ decay injected spectrum. $A = 8.5 \times 10^{-16} \frac{\text{erg s}}{\text{s}}$, $B = 7.6 \times 10^{-15} \frac{\text{cm}^3}{\text{s}}$, $C = 4.9 \times 10^{-29} \frac{1}{\text{cm}^3 \text{s}}$, $D = 1.3 \times 10^{-31} \frac{1}{\text{cm}^3 \text{s}}$, $K_1 = 2.8 \times 10^{-14} \frac{1}{\text{s}}$ and $K_2 = 2.8 \times 10^{-16} \frac{1}{\text{s}}$. The ratio between the two components is 1 : 5. Data taken from Barwick et al. (1997) (black) and Mueller & Tang (1987) (grey).
Fig. 3.— The $e^+/(e^+ + e^-)$ as a function of $x = E/m_Z$, for various power laws, $N x^w$, as the injected spectrum. $A = 8.5 \times 10^{-16}$ $\text{erg s}$, $B = 4.4 \times 10^{-15}$ $\frac{1}{s}$, $C = 1.7 \times 10^{-29}$ $\frac{1}{\text{cm}^3 \text{s}}$, $D = 1.1 \times 10^{-31}$ $\frac{1}{\text{cm}^3 \text{s}}$, and $K = 6.6 \times 10^{-17}$ $\frac{1}{s}$. Data taken from Barwick et al. (1997) (black) and Mueller & Tang (1987) (grey).

Fig. 4.— The $e^+/(e^+ + e^-)$ as a function of $x = E/m_Z$, for a combination of 2 sources of power law ($w = -0.3$) injected spectrum. $A = 8.5 \times 10^{-16}$ $\text{erg s}$, $B = 4.4 \times 10^{-15}$ $\frac{1}{s}$, $C = 1.7 \times 10^{-29}$ $\frac{1}{\text{cm}^3 \text{s}}$, $D = 1.1 \times 10^{-31}$ $\frac{1}{\text{cm}^3 \text{s}}$, $K_1 = 7.2 \times 10^{-17}$ $\frac{1}{s}$ and $K_2 = 1.2 \times 10^{-16}$ $\frac{1}{s}$. The ratio between the two components is 10 : 1. Data taken from Barwick et al. (1997) (black) and Mueller & Tang (1987) (grey).
Fig. 5.— Differential IC luminosity due to the positrons only, $-dL/d\ln(\gamma^2) \times (20 \text{ kpc})^3/V$ as a function of $\gamma^2$. 