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Kaluza-Klein Dark Matter, Electrons and Gamma Ray Telescopes

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Abstract

Kaluza-Klein dark matter particles can annihilate efficiently into electron-positron pairs, providing a discrete feature (a sharp edge) in the cosmic e^+e^- spectrum at an energy equal to the particle's mass (typically several hundred GeV to one TeV). Although this feature is probably beyond the reach of satellite or balloon-based cosmic ray experiments (those that distinguish the charge and mass of the primary particle), gamma ray telescopes may provide an alternative detection method. Designed to observe very high-energy gamma-rays, ACTs also observe the diffuse flux of electron-induced electromagnetic showers. The GLAST satellite, designed for gamma ray astronomy, will also observe any high energy showers (several hundred GeV and above) in its calorimeter. We show that high-significance detections of an electron-positron feature from Kaluza-Klein dark matter annihilations are possible with GLAST, and also with ACTs such as HESS, VERITAS or MAGIC.

1 Introduction

The identity of dark matter remains one of the primary outstanding puzzles of modern astrophysics [1]. The numerous planned and ongoing searches for particle dark matter include collider experiments [2] as well as direct [3] and indirect detection efforts.

Indirect dark matter searches attempt to identify the products of dark matter annihilations produced in regions such as the galactic halo, the galactic center or the center of the Sun. Such annihilation products include gamma-rays [4], neutrinos [5], anti-protons [6, 7], anti-deuterons [7, 8] and positrons [7, 9, 10, 11, 12].

One interesting dark matter candidate are Kaluza-Klein (KK) states present in models with extra spatial dimensions. In particular, in models of Universal Extra Dimensions (UED) [13], in which all of the Standard Model fields are allowed to propagate in the bulk, it has been shown that the Lightest Kaluza-Klein Particle (LKP) can be stable and a viable dark matter candidate [14, 15, 16]. In such a scenario, the LKP may be stabilized as a result of momentum conservation in the extra dimensions (KK number conservation). For a UED model to be phenomenologically viable, however, the extra dimensions must be modded out by an orbifold, which can lead to the violation of KK number conservation. A symmetry, called KK-parity, may remain, however, which insures that the LKP cannot decay, in much the same way that R-parity stabilizes the lightest supersymmetric state in many models. A natural choice for the LKP is the first KK excitation of the hypercharge gauge boson. We will refer to this state simply as the LKP, or as Kaluza-Klein Dark Matter (KKDM).

In this article, we focus on detecting electrons and positrons which are produced in KKDM annihilations in the galactic halo. Such measurements are particularly useful for KKDM searches, as their annihilations often produce e^+e^- pairs directly, resulting in a dramatic feature in the spectrum at an energy equal to the WIMP mass [12, 16].

Measurements of the cosmic e^+e^- spectrum have been made by the HEAT experiment [17] and will be studied with much greater precision in the future with PAMELA and AMS-02 [18]. None of these experiments can accurately measure this spectrum above $\sim$200 GeV, however. Higher energy particles will be detected, but not easily identified and characterized. This is unfortunate, as KKDM is constrained by electroweak precision measurements to be heavier than about 300 GeV [19]. To look for the an injection of electrons and positrons at energies above 300 GeV, other techniques need to be pursued. In this article, we suggest using high energy gamma ray telescopes, both the planned GLAST satellite and ground based Atmospheric Cerenkov Telescopes (ACTs), to search for signatures of Kaluza-Klein Dark Matter in the cosmic electron-positron spectrum.

2 Electrons and Positrons From Kaluza-Klein Dark Matter

Kaluza-Klein Dark Matter (KKDM) annihilates through very different modes than many other WIMP candidates, such as neutralinos in supersymmetric models. Neutralino annihilations to fermions are chirality suppressed by a factor of m_f^2/m_χ^2, and thus produce essentially no e^+e^- pairs directly. KKDM, being a boson, is not similarly suppressed and can annihilate directly to e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$, each of which yield a generous number of high energy electrons and positron. The KKDM annihilation cross section is proportional to the hypercharge of the final state fermions to the fourth power, and thus most annihilations produce pairs of charged leptons (approximately 20% per generation). Other dominant modes include annihilations to up-type quarks (approximately 11% per generation), neutrinos (approximately 1.2% per generation), Higgs bosons (approximately 2.3%) and down-type quarks (approximately 0.7% per generation). The total annihilation cross section of KKDM is given by

$$\langle \sigma v \rangle = \frac{95 g_1^4}{324 \pi m_{\rm LKP}^2} \simeq \frac{1.7 \times 10^{-26}\,{\rm cm}^3/{\rm s}}{(m_{\rm LKP}/{\rm TeV})^2}. \tag{1}$$

If no other Kaluza-Klein states play a significant role in the thermal freeze-out of the LKP, Eq. 1 requires a LKP with a mass of about 700-1000 GeV in order to produce the quantity of cold dark matter measured by WMAP [20]. It has been shown, however, that if other Kaluza-Klein states are only slightly more heavy than the LKP, they may freeze-out quasi-independently, eventually decaying into LKPs and enhancing the KKDM relic density non-thermally [14]. In this case, lighter LKPs can make up all of the measured cold dark matter density.

We have used PYTHIA [21], as implemented in the DarkSUSY program [22], to calculate the e^+e^- spectrum generated in KKDM annihilations. The spectrum injected is quite different from that observed at Earth, however. Electrons and positrons travel through the galactic environment under the influence of tangled interstellar magnetic fields and lose energy via inverse Compton and synchrotron interactions. These effects can be modeled by the diffusion-loss equation:

$$\frac{\partial}{\partial t}\frac{dn_{e^\pm}}{dE_{e^\pm}} = \vec{\nabla} \cdot \left[K(E_{e^\pm}, \vec{x}) \vec{\nabla} \frac{dn_{e^\pm}}{dE_{e^\pm}} \right] + \frac{\partial}{\partial E_{e^\pm}} \left[b(E_{e^\pm}, \vec{x}) \frac{dn_{e^\pm}}{dE_{e^\pm}} \right] + Q(E_{e^\pm}, \vec{x}), \tag{2}$$

where $dn_{e^\pm}/dE_{e^\pm}$ is the number density of electrons and positrons per unit energy, $K(E_{e^\pm}, \vec{x})$ is the diffusion constant, $b(E_{e^\pm}, \vec{x})$ is the rate of energy loss and $Q(E_{e^\pm}, \vec{x})$ is the source term.

We use a diffusion constant of $K(E_{e^\pm}) = 3.3 \times 10^{28} \left[3^{0.47} + (E_{e^\pm}/{\rm GeV})^{0.47} \right] {\rm cm}^2\,{\rm s}^{-1}$ [23], and an energy loss rate of $b(E_{e^\pm}) = 10^{-16} (E_{e^\pm}/{\rm GeV})^2$ GeV s^{-1}, which is the result of inverse Compton scattering on starlight and the cosmic microwave background, and synchrotron radiation due to the galactic magnetic field [24]. We assume that the diffusion zone is a slab of thickness $2L$, taking $L = 4\,{\rm kpc}$, and we apply free escape boundary conditions.

The source term, $Q(E_{e^\pm})$, is determined by the electron-positron spectrum injected per annihilation and by the annihilation rate, which normalizes the flux. The annihilation rate depends on both the KKDM annihilation cross section (Eq. 1) and the galactic distribution of dark matter. For our halo dark matter distribution, we use an NFW profile [25], although our results are not highly dependent on this choice [9, 11]. In addition to this choice, the degree of inhomogeneity or substructure in the dark matter distribution can effect the annihilation rate. This is often parameterized by a quantity called the *boost factor*. This quantity is essentially the average of the square of the dark matter density over the square of the average of the dark matter density. Equivalently, it is the factor the annihilation rate is enhanced as a result of dark matter clumping. Typical values of the boost factor are on the scale of 2 to 5. Values much larger than this require very large amounts of dark substructure and are highly unnatural [26].

While solutions to the propagation equation are complex, it is fairly simple to understand the feature we are most interested in, namely the magnitude of the edge feature in the spectrum. We take $Q_{\rm line}(m_{\rm KKDM}, \vec{x}_\odot)$ (in cm^{-3} s^{-1}) as the rate of electron and positron injection from direct annihilation to e^+e^- locally. The spectrum near the edge is then simply

$$\frac{dn_{e^\pm}}{dE_{e^\pm}} = \frac{Q_{\rm line}(m_{\rm KKDM}, \vec{x}_\odot)}{b(E_{e^\pm}, \vec{x}_\odot)}\, \theta\left(m_{\rm KKDM} - E_{e^\pm}\right). \tag{3}$$

We show the spectrum of electrons plus positrons from Kaluza-Klein dark matter annihilations after propagation in figure 1. In the next section, we discuss the prospects for gamma ray telescopes, both ACTs and GLAST, to detect this flux.

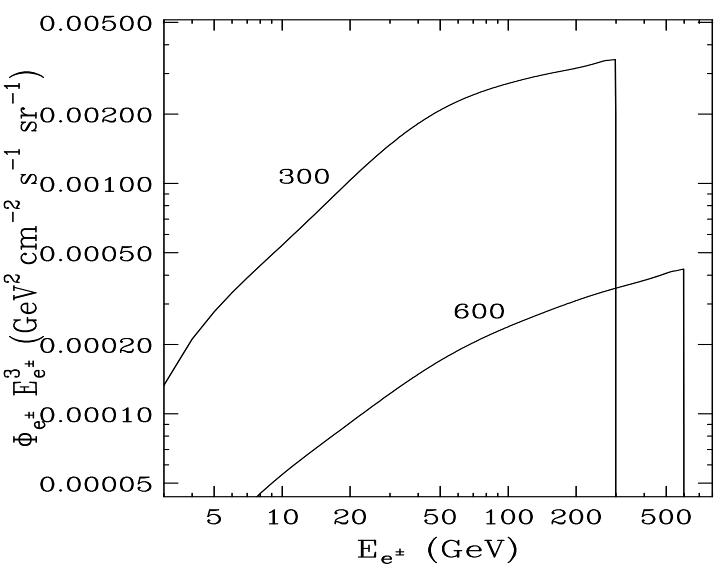

Figure 1: The spectrum of electrons plus positrons, including the effects of propagation, from Kaluza-Klein Dark Matter (KKDM) annihilations. Annihilations of KKDM produce equal fractions of $\tau^+\tau^-$, $\mu^+\mu^-$ and e^+e^- pairs (approximately 20% each) as well as up-type quarks (approximately 11% per generation), neutrinos (approximately 1.2% per generation), Higgs bosons (approximately 2.3%) and down-type quarks (approximately 0.7% per generation). Results for KKDM with masses of 300 and 600 GeV are shown. An NFW dark matter distribution with a boost factor of 5 and $\rho_{\rm local} = 0.4\,{\rm GeV/cm^3}$ was used.

3 Prospects for Gamma Ray Telescopes

Atmospheric Cerenkov Telescopes (ACTs) are ground based experiments designed to detect very high energy gamma-rays by imaging the Cerenkov light produced in air showers generated in the atmosphere. Currently, ACTs have made gamma-ray measurements in the energy range of roughly 200 GeV to 10 TeV, although thresholds as low as $\sim$50 GeV may be possible with future technology. The weakness of ACTs is in their limited ability to identify the primary particle that induced the shower. While it is usually possible (typically with better than 99% confidence) to distinguish hadronic showers (from e.g. primary protons or heavier nuclei) from electromagnetic showers, further identification of the primary cosmic ray cannot be achieved. In particular, showers caused by primary gamma-rays, electrons, and positrons are indistinguishable to ACTs. These instruments are only useful for gamma-ray astronomy because of the lack of point sources of cosmic electrons.

Modern ACTs, with effective areas on the order of 10^5 square meters and fields-of-view of a few degrees, may provide a useful window into the diffuse cosmic ray spectrum in addition to their role as gamma-ray telescopes. In this section, we assess the prospects for ACTs, such as HESS [27], VERITAS [28] and MAGIC [29], to observe a sudden drop in the electron-positron spectrum (see figure 1) which would be predicted for Kaluza-Klein dark matter.

The GLAST satellite is designed for gamma ray astronomy in the energy range between about 20 MeV and 300 GeV [30]. Higher energy photons will be measured, but the energy resolution degrades significantly (perhaps as bad as 50%). In addition, any high energy (above a few hundred GeV) showers in the calorimeter will be recorded, regardless of primary (electromagnetic or hadronic). This capability may allow a detection of the electron-positron edge.

It is expected that the flux of charged cosmic rays is (at least roughly) isotropic, thus we are searching for an all-sky signature. We propose to consider the entire datasets of ACTs or GLAST, without regard for position on the sky except where necessary for e.g. energy calibration as a function of zenith angle. Point sources (presumably of gamma-rays) may be excised from the dataset without significant effect, as the angular resolution of these instruments is typically a fraction of a degree while the field-of-view is several degrees. All other showers will be associated with the cosmic backgrounds of hadrons, electrons, positrons and gamma-rays. Considering the summed energy spectrum of all of these backgrounds, a sharp edge in the spectrum of electrons and positrons would become evident with enough exposure.

To assess the sensitivity of these gamma ray telescopes to a flux of electrons and positrons from Kaluza-Klein dark matter annihilations, we first must estimate the relevant background rates.

- The cosmic ray electron spectrum over the GeV-TeV energy range is given by:

$$\frac{dN_e}{dE_e} \simeq 0.07 \times \left(\frac{E_e}{1\,\mathrm{GeV}}\right)^{-3.3} \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}. \tag{4}$$

- The hadronic cosmic ray spectrum over the same range is:

$$\frac{dN_{\rm had}}{dE_{\rm had}} \simeq 3 \times \left(\frac{E_e}{1\,{\rm GeV}}\right)^{-2.7} {\rm GeV}^{-1}\,{\rm cm}^{-2}\,{\rm sec}^{-1}\,{\rm sr}^{-1}. \quad (5)$$

- The diffuse gamma-ray background has the same spectral shape but is considerably smaller:

$$\frac{dN_{\gamma}}{dE_{\gamma}} \simeq 4 \times 10^{-4} \times \left(\frac{E_e}{1\,{\rm GeV}}\right)^{-2.7} {\rm GeV}^{-1}\,{\rm cm}^{-2}\,{\rm sec}^{-1}\,{\rm sr}^{-1}. \quad (6)$$

Although showers (whether atmospheric, or in the GLAST calorimeter) produced by gamma-rays cannot be distinguished from electron induced showers (or vice versa), the vast majority of hadronic showers can be identified and rejected. The total background from these components is then:

$$\frac{dN_{\rm bg}}{dE_{\rm bg}} \simeq (3\times\epsilon_{\rm had}+4\times10^{-4})\times\left(\frac{E_e}{1\,{\rm GeV}}\right)^{-2.7}+0.07\times\left(\frac{E_e}{1\,{\rm GeV}}\right)^{-3.3} {\rm GeV}^{-1}\,{\rm cm}^{-2}\,{\rm sec}^{-1}\,{\rm sr}^{-1}, \quad (7)$$

where $\epsilon_{\rm had}$ is the fraction of hadronic showers which cannot be rejected. We can see that the diffuse gamma-ray component of the background is important only if the experiment's hadron rejection efficiency is greater than about 99.99%. For $\epsilon_{\rm had} = 0.01$ (appropriate to ACTs), the electron background is irrelevant. For better rejection ($\epsilon_{\rm had} = 0.001 - 0.0001$, appropriate to GLAST), the hadron / photon background dominates above a few hundred GeV.

In order for a gamma ray telescope to identify the presence of an electron-positron feature from Kaluza-Klein dark matter annihilations, there must be a statistically significant variation in the spectrum at the energy, $E = m_{\rm KKDM}$. Considering an energy bin of width corresponding to the energy resolution of the experiment, the statistical significance of the feature is $\simeq \frac{S}{\sqrt{N}}$, where S and N are the numbers of signal and background events in the bin. N is determined by integrating Eq. 7 over the energy bin width, while S is the integrated result of Eq. 2 along with the annihilation rate and injected spectrum (see Fig. 1).

Our estimate of the sensitivity of an ACT to Kaluza-Klein dark matter annihilations is shown in figure 2. We have considered an ACT with 15% energy resolution (thus a energy bin of width $\Delta E \approx 0.3\,m_{\rm KKDM}$), 99% hadronic rejection ($\epsilon_{\rm had} = 0.01$), a 0.003 sr field-of-view and 2×10^5 square meters of effective area. These are reasonable values for state-of-the-art ACTs such as HESS, VERITAS and MAGIC. We normalize the KKDM annihilation rate using a boost factor of 5, a local dark matter density of $\rho_{\rm local} = 0.4\,{\rm GeV/cm}^3$ and the annihilation cross section of Eq. 1.

We see from figure 2 that after only about 10 hours of observation, a 300 GeV KKDM particle could be detected with 5σ significance. A hundred hours would be needed to reach similar sensitivity for KKDM with a mass of about 400 GeV. To reach a 600 GeV KKDM particle, 3000 hours would be required. Due to requirements of good weather and dark (moonless or nearly so) nights, the duty cycle of an ACT is typically only 5-7%, or 450–600 hours of observation per year. We thus consider several thousand total hours of observation a plausible goal, especially if the exposure of multiple experiments can be combined.

In comparison, the capabilities of GLAST seem quite different. While we have assumed ACTs with an exposure of 600 m^2 sr and a 5% duty cycle, the GLAST calorimeter will have an exposure of 7.5 m^2 sr and an 80% duty cycle. Thus, in a given time period, the ACTs have roughly 5 times the exposure. GLAST has an advantage, in that the rejection of hadronic showers should be better than 99.9%, and perhaps as good as 99.99%, which is the useful limit as the gamma ray background comes in at this level. The signal to noise to detect the edge in the electron plus positron spectrum should improve as $S/N \propto 1/\sqrt{\epsilon_{\rm had}}$, namely GLAST should gain a factor of between 3 and 10 in sensitivity due to the improved hadron rejection. This factor roughly makes up for the fact that GLAST will have a factor of 5 less exposure. Lastly, we can assume an integration over the same energy bin, 30% wide.

Finally, we will compare the sensitivity of these experiments to those designed to observe cosmic positrons, such as PAMELA or AMS-02. PAMELA and AMS-02 will accumulate considerably smaller exposures than GLAST, 20.5 and 450 cm^2 sr, respectively. Even if they achieve their projected hadronic rejection on the order of 99.9% [31], they will not be capable of competing with GLAST or ACTs in the energy range we consider here.

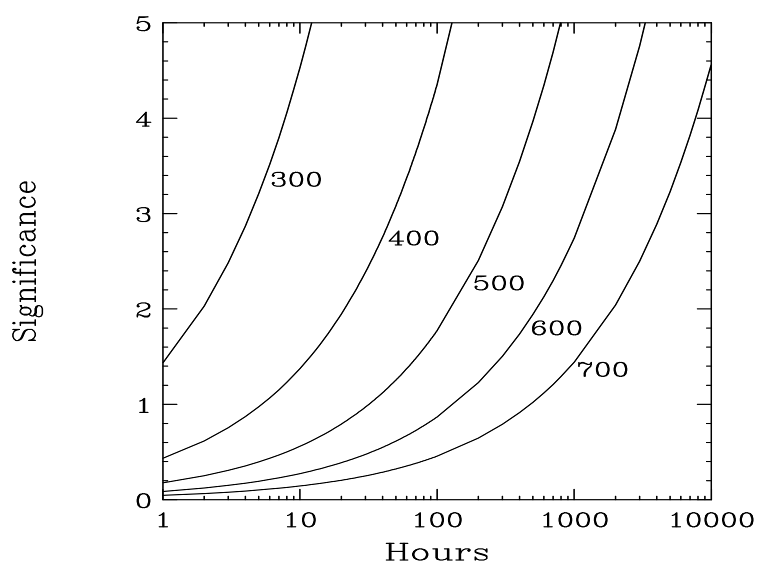

Figure 2: The significance of the $e^{\pm}$ feature from Kaluza-Klein dark matter annihilations at $E = m_{\rm KKDM}$ in a modern Atmospheric Cerenkov Telescope (ACT), such as HESS, VERITAS or MAGIC, as a function of time observed. We have considered an ACT with 15% energy resolution, 99% hadronic rejection, a 0.003 sr field-of-view and 2×10^5 square meters effective area. Results for dark matter masses of 300, 400, 500, 600 and 700 GeV are shown. An NFW dark matter distribution with a boost factor of 5 and $\rho_{\rm local} = 0.4\,{\rm GeV/cm^3}$ was used. To compare with GLAST, the exposure time axis should be multiplied by a factor of 16, thus the 600 GeV particle detected at 5σ in 3000 hours with an ACT requires 48,000 hours with GLAST. Both datasets could be collected in roughly 7 years.

4 Conclusions

Electrons and positrons produced directly in Kaluza-Klein Dark Matter (KKDM) annihilations can result in a discontinuity in the diffuse spectrum observed by gamma ray telescopes both on the ground (ACTs such as HESS, VERITAS, or MAGIC) and in space (GLAST). We have shown that this feature can be observed at statistically significant levels in either ACTs or GLAST for KKDM particles with masses of up to 600 GeV, if several years are spent accumulating data.

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