Ultrahigh Energy Cosmic Rays, The Diffuse High Energy Gamma Ray Background and Anti-protons

David Eichler, Raz Idan, and Eyal Gavish

Physics Department, Ben-Gurion University, Be’er-Sheba 84105, Israel

Theories for the origin of ultrahigh energy cosmic rays (UHECR) may imply a significant diffuse background in secondary γ-rays from the pair cascade the UHECR initiate when interacting with background light. It is shown that, because the spectrum of these secondary γ-rays is softer than the measured diffuse γ-ray background in the 10-1000 GeV range, the addition of a hard component from the decay of TeV dark matter particles, subject to the implied constraints on its parameters, improves the fit. It is further argued that any compact astrophysical source of p~ is unlikely to be as strong as decay of TeV dark matter particles, given bounds set by neutrino observations. The diffuse γ-ray background presently sets the strongest lower bound on the lifetime of TeV dark matter particles, and hence on attendant anti-proton production, and further identification of other contributors to this background will further tighten these constraints.

I. INTRODUCTION

Dark, nonbaryonic matter is widely believed to comprise most of the matter density in the universe. Several forms of it have been proposed, including weakly interacting massive particles (WIMPs), charged massive particles (CHAMPs), and massive astrophysical compact halo objects (MACHOs). CHAMPs were strongly constrained by a variety of considerations, including sensitive rare isotope searches, and are seldom discussed these days. Unclustered MACHOs have been strongly constrained by microlensing to comprise less than 10 percent of the Galactic dark matter, and may also be constrained in the future by pulsar timing. WIMPS, if they comprise the dark matter, must have had an annihilation rate constant in the early universe of \( < \sigma_{ann} v > \) of \( 3 \cdot 10^{-26} \text{cm}^3\text{s}^{-1} \) in order that the present mass density conform the astrophysical indications. The question has been raised as to whether their annihilation products are identifiable in the cosmic radiation. For WIMP masses of less than 300 GeV, this would imply an annihilation rate in galaxies that would impact astrophysical observations such as high energy γ-ray emission from other galaxies, and failure to observe such consequence then constrains the WIMP mass to be larger than this. Large WIMP masses, on the other hand, imply that their annihilation may be undetectable and unable to account for astrophysical anomalies.

The WIMP density is only \( 10^{-4} (m_{DM}/3\text{TeV})^{-1} \text{cm}^{-3} \) so. Assuming the thermal annihilation rate constant discussed above, the annihilation rate density, at this average DM particle density, would be only \( 10^{-33.5} (m_{DM}/3\text{TeV})^{-2} \text{cm}^{-3}\text{s}^{-1} \), which is insufficient. The effective annihilation rate could be jacked up by invoking concentrated clumps of dark matter, but simulations typically do not, a priori, predict enough of an enhancement. Moreover, if such enhancement were due to clumpiness of the dark matter, then most of the prompt γ-rays that emerge from the annihilations would appear as hot spots in the high energy γ-ray background and would be detectable by Fermi and/or air Cerenkov arrays. Other enhancement mechanisms, such as Sommerfeld enhancement due to some other attractive force that pulls dark matter particles together have been proposed, but they require an additional assumption.

Decaying WIMPs were also proposed as possible contributors to the cosmic radiation e.g. \([2,3]\). A specific mass range of several TeV, in any case a likely mass range for a number of reasons, was "predicted" \([3]\) by the numerical coincidence that if the decay is via interactions on the scale of Grand Unification (GUT), then for DM particle masses of \( \sim 2 \) TeV, the decay rate could be just enough to contribute a detectable component to the Galactic cosmic radiation. This coincidence was also noticed later \([4]\). As the decay rate goes as the \( m_{DM}^3 \cos^4 \theta \), where \( \cos \theta \) is a mixing angle that establishes the coupling to any intermediate channel, the constraint of \( m_{DM} \) is rather specific, given the GUT scale. Specifically, the decay rate is about \( 10^{-26.5} (10^{12}\text{yr}/\tau_p) (m_{DM}/0.93\text{TeV})^3 (\cos^4 \theta) \text{s}^{-1} \) [where experimentally \((10^{12}\text{yr}/\tau_p) \lesssim 1\)], giving a decay rate of order \( 10^{-27} \text{s}^{-1} \) in the Galaxy for a mass of \( \gtrsim 1 \) TeV.

The trans-TeV mass for most decay modes predicts an anti-proton component that is the subject of this letter. TeV Weakly Unstable Relic Particles (TWURPs) remain both a candidate for dark matter and for a source of detectable, very energetic anti-protons and γ-rays at detectable levels. In contrast to an annihilation rate, a decay rate does not increase with density; so prior to the cosmic recombination era, less than \( 10^{-12} \) of the dark matter density would have been dumped into heat, and this would leave a negligible effect on the cosmic microwave background. As shown below and in \([5]\), many astrophysical extragalactic sources of energetic γ-rays yield softer spectra than observed, and the fit to the diffuse γ-ray background is improved when the relatively hard component from TWURP decay is added. On the other hand, accounting for the γ-ray background with yet unresolved astrophysical point sources would constrain the decay rate of dark matter (if it is TWURPs) \([6]\) and hence on \( p~ \) in the Galaxy. It is argued that astrophysical
sources of $\bar{p}s$ are unlikely to be as strong as the presently allowed signal from TWURP decay.

In figure 1 we show fits to ultrahigh energy cosmic ray (UHECR) data from HiRes and Auger, and to the extragalactic high energy diffuse gamma ray background as measured by Fermi LAT. The evolution models for the UHECRs are those of active galactic nuclei (AGN), $\gamma$-ray bursts (GRB), and star formation (SFR). The diffuse gamma rays are assumed to come from a) supernovae remnants from star-forming galaxies (SFGs) that contain cosmic rays, b) secondary $\gamma$-rays from pair-initiated electromagnetic cascades triggered by the interaction of UHECR with the CMB and with extragalactic starlight, and c) decay of TWURPs. The latter contribution assumes a TWURP lifetime of $\tau = 4.61 \times 10^{27}$ sec and decay dominated by the $W^+ - W^-$ channel. In the upper panel of this plot we show the UHECR spectra and in the lower panel we show the corresponding $\gamma$-ray fluxes (the various source evolution models color coded as in the upper panels), with the SFG contribution (magenta dashed line) and TWURP contribution (violet dashed line), and the sum of the three components (thick lines). Further calculations are presented in reference [6].

For evolutionary scenarios such as those of GRB and SFR, which were more frequent in the past, some contribution from pair cascades from UHECR is inevitable because its threshold energy was lower in the past. Even primary $\gamma$-rays are subject to pair production at high energies, so that a diffuse background from high $z$ sources is typically softer than the observed diffuse $\gamma$-ray background. It can be seen in figure 1 that a contribution from decaying TWURPs into $W^+ - W^-$ improves the fit to the observed diffuse $\gamma$-ray background, and would as a consequence give a detectable $\bar{p}$ contribution to Galactic cosmic rays.

On the other hand, if the diffuse $\gamma$-ray background is due to sources that were as or less frequent in the past, such as BL Lac objects, then there is little room either for copious $\gamma$-ray emission or for copious UHECR production in the past, as the latter generates the former. So if the UHECR and $\gamma$-ray background are generated by sources that are no less frequent now than in the past, there is less of a need for $\bar{p}$ production by decaying TWURPs. Figure 2 shows a fit to the diffuse HE $\gamma$-ray background summing all unresolved components extrapolated by [11] and the contribution of secondary $\gamma$-rays from the UHECR under the assumption that the UHECR come from a) sources whose comoving space density is constant in time (i.e. non-evolving) and b) sources that evolve as high synchrotron-peakd (HSP) BL Lac objects (comoving density proportional to $(1+z)^{-6}$, see [12]). While TWURP decay into $W^+ - W^-$ still improves the fit, it plays a smaller role and makes a weaker case for such decay.

Figure 3 shows that the constraints imposed on the TWURP decay rate by considerations of the diffuse HE $\gamma$-ray background are stronger than those presently imposed [13], [14] by measurements of $\bar{p}s$ in the Galactic foreground. FIG. 1. upper panel: The fit to the ultrahigh energy cosmic ray HiRES and recalibrated by 16% AUGER data is given for different source evolutions: active galactic nuclei (AGN) of luminosity $L = 10^{44.2}$ erg sec$^{-1}$ in the [0.5 -- 2] KeV band, gamma ray bursts (GRB), and star formation (SFR). The curves were calculated assuming a two-power law injection spectrum, with indexes $\alpha_1$ and $\alpha_2$ for $E < E_{br}$ and $\alpha_3$ for $E > E_{br}$ respectively, where $E_{br} = 8$ EeV for SFR and GRB, and $E_{br} = 9$ EeV for AGN. The power law indexes are $\alpha_1 = 2$, $\alpha_2 = 2.5$, $\alpha_3 = 3.4$, and $E_{br} = 22$ EeV. $\alpha_1 = 2$, $\alpha_2 = 3.4$, and $E_{br} = 22$ EeV.

[FIG. 1. lower panel: The contribution to the $\gamma$-ray background due to weakly unstable DM (dashed violet line) and from b) pair production of cosmic blackbody background photons against ultrahigh energy cosmic rays (thin solid lines corresponding to the UHECR spectra in the upper panel). The contribution from spiral galaxies is computed from the sum of individual supernova remnants detected in our Galaxy. The sum without the DM contribution for the SFR model is also plotted (thick dashed blue line). Further details of the computation of contribution b) are given in [6]. The DM in this plot is assumed to have a lifetime of $\tau = 4.61 \times 10^{27}$ sec.}
CRs.

Figure 4 shows the expected \( \bar{p} \) production in the Galaxy as a result of TWURP decay for lifetimes ranging from \( 3 \times 10^{22} \) to \( 1 \times 10^{26} \) s, for \( \bar{p} \) residence times in the Galactic halo (as defined by the dark matter distribution) of 10 Myr. The smallest of these residence times and longest lifetime gives a detectable \( \bar{p} \) signal in the Galaxy that barely stands out above the \( \bar{p} \) signal from cosmic ray collisions with interstellar nucleons. Because the TWURP decay gives a harder component than secondary products of CR collisions, it can give a harder overall \( p/\bar{p} \) ratio in the 100 - 300 GeV range. In calculating the secondary \( \bar{p} \) production rate we have assumed standard cosmic ray abundances and that cosmic rays traverse a grammage that is proportional to \( E^{-0.3} \) g/cm\(^2\) in the plane. The \( \bar{p} \) to \( p \) ratio is then fixed by the spallation and \( \bar{p} \) production cross sections. In computing the \( \bar{p} \) production rate we assumed that the density of TWURPs in the disk is \( 0.3 \text{GeV/cm}^3 \).

We have considered whether alternate mechanisms for \( \bar{p} \) production, e.g. from compact objects that produce energetic hadrons [15], could compete with dark matter decay in the 100 - 300 GeV energy range. The \( \bar{p}s \), for example, could a) exist in the Galaxy below 1 GeV, so that they could not penetrate the solar system, and be reaccelerated to beyond 100 GeV by supernovae remnant blast waves along with primary cosmic rays [16]. Or they could b) be accelerated directly to energies above 100 GeV, (e.g. by ultrarelativistic shocks in GRB blast waves). However, the data implies that they should not appear between 1 and 100 GeV, as there is no observed excess there. Their sources must therefore differ spectrally from the source of most cosmic rays, and also need to be anomalously rich in \( \bar{p}s \) relative to B in order not to cause an excess of the latter.

As the observed anomalous \( \bar{p} \) luminosity \( L_{\bar{p}} \) from our Galaxy is no larger than about \( 10^{35} \) erg/s, in scenario a) the actual required anomalous \( \bar{p} \) luminosity from our Galaxy would then be about \( 10^{35} l/(f_r f_p) \) erg/s, where \( l \) is the loss factor they underwent in being decelerated down to below 1 GeV from above their production threshold of 10 GeV, \( f_r \) is the fraction of low energy \( \bar{p}s \) that get reaccelerated, and \( f_p \) is the fraction of energy, after the reacceleration event, that is accelerated from below 1 GeV to beyond 100 GeV. The loss factor \( l \) is clearly at least 10. The B/C ratio, which decreases with energy over two decades of energy per nucleon, requires \( f_r \ll 1 \), and, if the reacceleration imparts a CR spectrum of \( E^{-2-\gamma}dE \), then \( f_p \leq 10^{-2p} \). The primary cosmic rays that originally produced the \( \bar{p}s \) must have required at least \( \sim 10^4 L_{\bar{p}} \). Altogether, \( 10^{35} l/(f_r f_p) \) erg/s are required in primary CR at \( E \geq 10 \) GeV in order to produce the low energy \( \bar{p}s \) that would by hypothesis be reaccelerated to beyond 100 GeV. This would exceed or come

![FIG. 2. The total flux of \( \gamma \)-rays originating from a) UHECR sources evolving as BL Lacs and b) blazars. Upper panel: Non-evolving BL Lacs. The thin blue solid line corresponds to \( \gamma \)-rays originating from UHECRs with the parameters: \( \alpha_{1,2} = 2.7, 2.5, E_{\text{min}} = 8 \times 10^{18} \text{eV}, E_{\text{max}} = 10^{20} \text{eV}, \) and \( z_{\text{max}} = 7 \). The thick dashed black line is the sum of all unresolved components (blazars, SFGs, and radio galaxies) in [11]. Figure 3 (resolved point sources have been removed). The thick dashed blue line is the sum of the dashed black line and the thin solid blue line. The thick solid blue line is the sum of the dashed black line, the thin solid blue line, and 3TeV \( W^{+}W^{-} \) decay DM with \( \tau = 1.3 \times 10^{28} \)s. Lower panel: The same as in the upper panel, but for strongly evolving high synchrotron peak (HSP) BL Lacs and for \( \alpha = 2.7, E_{\text{max}} = 10^{20} \text{eV}, \) a comoving space density proportional to \( (1+z)^{-6} \) and \( z_{\text{max}} = 7 \). The DM lifetime for this case is \( \tau = 5.9 \times 10^{27} \)s. The fits to the UHECR data with the parameters of each panel are given in [6].](image1)

![FIG. 3. Lower limits on the DM lifetimes for a \( DM \rightarrow W^{+}W^{-} \) decay as a function of the DM mass as obtained by [13] (black line) and by [14] (red line). The vertical blue line is the possible values of lifetimes for the fits that do not include the expected blazar contribution to the diffuse high energy \( \gamma \)-ray background. The vertical magenta line is the DM lifetimes for the fits that include an anticipated contribution from not-yet-resolved blazars to the \( \gamma \)-ray background.](image2)
FIG. 4. The $\bar{p}/p$ ratio is plotted as a function of energy assuming a standard secondary contribution from cosmic ray C, N, and O collisions in the Galactic disk with the traversed grammage proportional to $E^{-0.3}$ and a contribution from 3 TeV dark matter particles with the indicated lifetimes. The top two panels are for a TWURP lifetime of $1 \cdot 10^{28}$ s and for residence times in the halo of $10^{14.5}$ s (top) and $3 \cdot 10^{14.5}$ s (middle). The bottom panel is for a TWURP lifetime of only $3 \cdot 10^{27}$ s, the minimum compatible with constraints from the diffuse gamma ray background, and a residence time of $10^{14.5}$ s.

very close to the total CR output from the Galaxy and the question would arise as to why there is no evidence of this additional class of sources in the primary cosmic rays data.

In general, $\bar{p}$s from compact objects in the Galaxy would suffer adiabatic loss factors $l$ much larger than 10, and this makes scenario b) highly questionable as well. While scenarios can be arranged that favor $\bar{p}$s over other secondaries, such as anti-neutron escape from $\gamma$-ray burst fireballs, it is hard to make $\bar{p}$s at $E_\bar{p} \gtrsim 300$ GeV by cosmic ray collisions without also putting $10^{2.5}$ times as much energy into HE neutrinos at $E_\nu \sim 1$ TeV ([17] and Globus, private communication). This would imply a neutrino luminosity from our Galaxy of $10^{37.5} l$ erg s$^{-1}$, and assuming it persists for $10^{17.5}$ s, the total amount of energy per unit mass produced is then $6 \cdot 10^{9} l$ erg/g. However, the ICERCUBE-detectable HE neutrino yield [18] implies a cosmic output of $2 \cdot 10^{-20}$ erg cm$^{-3}$/$\Omega_{DM} \rho_c = 10^{10}$ erg/g, which requires $l \lesssim 2^{1}$.

Moreover, the isotropy in Galactic cosmic rays observed by ICERCUBE at $10^{15}$ eV also makes it very difficult to accommodate such a bright point source of $\bar{p}$s, even if intermittent, because it would mean that the associated primary cosmic rays from such a source would compete with the CR output, in that energy range, of the rest of the Galaxy.

We conclude that the alternative scenarios involving $\bar{p}$ production from p-p collisions do not give efficient enough $\bar{p}$ production and, at best, require extremely fine tuning. Thus observations of $\bar{p}$s by instruments such as AMS02 could provide evidence for or against the existence of slowly decaying TeV dark matter particles.

We gratefully acknowledge discussions with R. Brustein, M. Lublinsky, G. Beuf, M. Cirelli, N. Globus and P. Salati, and support from the Israel-U.S. Binational Science Foundation, the Israeli Science Foundation, and the Joan and Robert Arnow Chair of Theoretical Astrophysics. We thank D. Kaplan for technical assistance with the numerical work, and M. Cirelli for assistance in using the PPPC data.
1 unless the neutrinos have a sharp cutoff below 1 TeV and are hidden by the atmospheric background, but this would require unrealistically fine tuning.