The Search for TeV-scale Dark Matter with the HAWC Observatory

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Abstract

The High Altitude Water Cherenkov (HAWC) observatory is a wide field-of-view detector sensitive to 100 GeV - 100 TeV gamma rays and cosmic rays. Located at an elevation of 4100 m on the Sierra Negra mountain in Mexico, HAWC observes extensive air showers from gamma and cosmic rays with an array of water tanks which produce Cherenkov light in the presence of air showers. With a field-of-view capable of observing 2/3 of the sky each day, and a sensitivity of ~1 Crab/day, HAWC will be able to map out the sky in gamma and cosmic rays in detail. In this paper, we discuss the capabilities of HAWC to map out the directions and spectra of TeV gamma rays and cosmic rays coming from sources of dark matter annihilation. We discuss the HAWC sensitivity to multiple extended sources of dark matter annihilation and the possibility of HAWC observations of annihilations in nearby dark matter subhalos.

1. Introduction

The evidence for dark matter comes from many varied astrophysical observations - velocity measurements of galaxies and clusters, measurements of the cosmic microwave background, large-scale cosmological structure, and gravitational lensing. However, the details of the particle physics of the dark sector are yet to be determined. The absence of a positive dark matter signal in direct-detection experiments [1] and lack of detection of dark matter production at the Large Hadron Collider [2, 3] indicate that the dark matter mass is higher than the energies probed by those experiments; the dark matter mass is increasingly likely to be heavier than 1 TeV. Furthermore, several astrophysical observations seem to be pointing toward possible observation of TeV-scale dark matter.

There is a new observatory which will be instrumental in the search for TeV-scale dark matter - the High Altitude Water Cherenkov (HAWC) observatory. The HAWC observatory is located at 4100 m above sea level, on the Sierra Negra mountain in Mexico. The experiment utilizes the water Cherenkov technique to observe the extensive air showers coming from TeV-energy gamma rays and cosmic rays incident on the atmosphere. This technique was previously used successfully in the Milagro observatory [4]. The fully completed HAWC will have 300 individual tanks and the sensitivity to detect the Crab nebula at 5-$\sigma$ significance each day [5]. The angular resolution of HAWC above ~ 30 TeV is better than 0.1°, with better than 1°...
resolution down to $\sim 500$ GeV. The HAWC observatory has a large field-of-view, covering $\sim 2$ sr, and it can observe about 2/3 of the sky per day. With its sensitivity to high-energy gamma rays and large field-of-view, HAWC should be able to search multiple objects for the signals of annihilation from TeV-mass dark matter.

2. Signals of TeV-mass Dark Matter

Observations of TeV cosmic rays have shown a surprising feature - small-scale anisotropies in the arrival directions of cosmic rays on angular scales of $\sim 10'$ [6, 7]. The Larmor radius of a 10 TeV proton in the local $2 \mu G$ magnetic field is only 5 mpc and the decay length of a 10 TeV neutron is only 100 mpc, so it would be expected that any signal coming from a source even a few parsecs away would be completely isotropized. The lack of particle diffusion from a source could be explained by a locally-coherent magnetic field propagating the source cosmic rays to the Earth [8, 9]. However, the nearest known source which could supply the cosmic rays is hundreds of parsecs away. Also, the emission prefers a spectrum much harder than that from typical astrophysical sources. Cosmic rays from dark matter annihilations in a local subhalo could naturally explain both the hardness of the observed spectrum and the proximity of the source to the Earth [10]. The best-fit dark matter candidate would have a mass of $\sim 50$ TeV which annihilates into $W$ or $Z$ bosons and has a cross-section nearly one thousand times the cross-section of $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm$^3$s$^{-1}$ for thermally-produced dark matter. This non-thermal cross-section is naturally explained by the process of “Sommerfeld enhancement”, as is discussed in Ref. [1]. Such a dark matter signature should be observable by HAWC within its first year of observations.

Observations with the H.E.S.S. observatory have shown high-energy gamma-ray emission coming from the Milky Way Galactic center (GC) [11]. The energy spectrum of this emission is fairly hard, with a spectrum consistent with that of annihilating dark matter of mass greater than $\sim 10$ TeV [12, 13, 14]. The cross-section of this annihilating dark matter would need to be a few thousand times the thermal value in order to explain this signal. It is interesting, however, that the best-fit annihilation channels and annihilation cross-sections found in Ref. [14] are nearly identical to those needed to explain the TeV cosmic-ray anisotropy.

The IceCube collaboration has recently measured a population of TeV and PeV neutrinos above those found in the atmosphere [15, 16]. The evidence for a hard neutrino spectrum and strong energy cutoff would be unusual for many source classes expected to produce neutrinos. Dark matter is expected to have just this spectral shape and has therefore been postulated as the source of these astrophysical neutrinos [17, 18, 19]. The dark matter mass necessary to explain these neutrinos must be larger than 1 PeV, which is too large to be explained naturally by the annihilation of thermally-produced dark matter. However, decaying PeV dark matter can explain the observed neutrino signal with a decay rate that is consistent with other astrophysical observations. For many dark matter decay channels, the gamma rays produced in these decays could be observable to HAWC as well.

Several experiments have detected an excess in positrons in the local neighborhood above what is predicted in standard astrophysical models. This effect was first seen with PAMELA [20] and later confirmed and expanded to higher energies by the Fermi-LAT [21] and AMS-02 collaborations [22]. The source of these excess local positrons is currently unknown. One possible explanation is that the positrons are emitted from nearby pulsars, such as Geminga [23, 24]. Another interesting explanation, however, is that the positrons are coming from dark matter annihilations in a nearby subhalo [25, 26, 27, 28, 29]. Because the experiments do not see a corresponding excess in the local antiproton population, the dark matter annihilations would have to have a large branching fraction into low-mass particles, such as muons or pions, as heavier states such as bottom quarks tend to create antiprotons as they decay. In order to produce the high-energy positrons seen by AMS-02, which sees the excess rising up to at least 350 GeV, the dark matter particles would have mass greater than $\sim 1$ TeV [29]. As with the other signature discussed above, dark matter annihilating with a flux large enough to reproduce the observed positrons excess would need to have a cross-section hundreds of times larger than thermal, in the range where HAWC is sensitive.
Fig. 1. The projected dark matter limits from HAWC after five years, for the $b\bar{b}$, $\tau^+\tau^-$, and $W^+W^-$ dark matter annihilation channels. From top to bottom, the curves are for the Segue 1 dwarf galaxy (magenta), the Galactic center using an Einasto profile (red), the substructure-boosted Virgo cluster (blue), and the substructure-boosted M31 galaxy (orange). In the $W^+W^-$ plot, the dashed curves are the limit when natural Sommerfeld enhancement is included (with $v_{\text{rel}} = 300$ km s$^{-1}$). The dotted purple line shows the expected cross-section for thermally-produced dark matter. All limits are at 95% CL.

3. Simulation of Dark Matter with HAWC

The spectral flux of the dark matter was calculated as in Ref. [30], with the gamma-ray spectrum for each dark matter annihilation channel calculated with the software PYTHIA [31]. The spatial profile of each dark matter source was assumed to be either an Einasto profile [32, 33] (for Segue 1 [34] and the GC [35]) or NFW profile [36] (for M31 [37] and the Virgo cluster [38]). For M31 and the Virgo cluster, which are expected to have much of their dark matter contained in substructures rather than the smooth dark matter halo, we also include the conservative substructure “boost factors” of 15 (M31) and 35 (Virgo cluster), as detailed in Ref. [39].

The detector response of the HAWC observatory was done using standard Monte Carlo simulation of the HAWC detector [5]. The one modification made to the standard HAWC point-source simulation algorithms was to account for the spatial extent of the dark matter halos [30]. For further details on the HAWC detector response simulation used in this analysis, see Refs [5, 30].

4. HAWC Dark Matter Sensitivity

The HAWC observatory is sensitive to multiple sources which are expected to have large amounts of annihilating dark matter. The dwarf spheroidal galaxies provide a good search region for HAWC because with its wide field-of-view, HAWC can observe multiple dwarf spheroidals at once. A joint likelihood of these multiple sources could be to improve the HAWC limits over those of a single dwarf spheroidal. HAWC is also sensitive to annihilating gamma rays in the GC. However, because HAWC is situated at 19° North latitude, it will not be able to observe dark matter annihilation in the GC as well as the H.E.S.S. observatory [35], which is in the Southern hemisphere.
Fig. 2. The projected 5-year HAWC dark matter limits for the Segue 1 dwarf galaxy, compared to the Segue 1 limits from the Fermi-LAT (red) and VERITAS (blue) collaborations. Though the published Fermi-LAT and VERITAS limits cut off at 1 TeV and 20 TeV, respectively, the HAWC limits on hadronic-channel dark matter should be competitive with the Fermi-LAT above ~ 5 TeV and competitive with VERITAS above ~ 50 TeV. For leptonic-channel dark matter, the HAWC limits should be competitive with the Fermi-LAT above ~ 700 GeV and competitive with VERITAS above ~ 5 TeV. The dotted purple line shows the expected cross-section for thermally-produced dark matter. All limits are at 95% CL.

Galaxies and galaxy clusters, which have large dark matter mass, are expected to have a fair amount of dark matter clustering as well. However, this clustering is mostly found in the outer regions of the dark matter halo [40], so the gamma-ray emission from dark matter annihilation in these sources is expected to be spatially extended. The HAWC observatory is sensitive to extended gamma-ray sources, so the HAWC search for gamma rays from dark matter annihilations should benefit from this spatial clustering when observing galaxies and clusters. HAWC can also improve its sensitivity to galaxy clusters by performing a joint likelihood analysis of multiple clusters.

HAWC also has the ability to search for gamma-ray emission from dark matter subhalos which have not yet been observed. The largest of the Galactic dark matter subhalos have been observed as dwarf galaxies, but there are expected to be many subhalos which have little star-formation and therefore could not be observed from their stellar content. Because these subhalos have little astrophysical background, the dominant gamma-ray signal should be from annihilating dark matter. With the HAWC wide field-of-view, it can scan the sky for such previously-unknown subhalos, which may be the cause of astrophysical signals discussed in section 2.

Similarly, HAWC can search for isotropic gamma-ray emission coming from dark matter annihilation in unresolved sources. Because most galaxies are far from the Milky Way, they cannot be resolved as individual point sources. Therefore, the gamma-ray emission from dark matter annihilation in those galaxies would be observable as an isotropic gamma-ray flux. Additionally, there should be isotropic gamma-ray emission from dark matter annihilations in the Milky Way. Though the flux of dark matter-induced gamma rays should peak toward the GC, there should be a fair amount of flux even toward the Galactic anti-center. This minimum amount of gamma-ray flux should be observable in all directions and therefore should also contribute a dark matter component to the isotropic gamma-ray flux. By searching the sky for this isotropic flux, HAWC may be able to constrain the nature of the dark matter.

As is shown in figure 1, HAWC is most sensitive to dark matter with mass greater than 500 GeV to over 100 TeV. For hadronic dark matter channels, HAWC should be sensitive to dark matter cross-sections of \( \langle \sigma v \rangle \approx 3 \times 10^{-23} \text{ cm}^3\text{s}^{-1} \), one thousand times larger than the thermal value. For leptonic dark matter, HAWC should be roughly ten times more sensitive, able to detect dark matter with cross-sections of \( \langle \sigma v \rangle \approx 3 \times 10^{-24} \text{ cm}^3\text{s}^{-1} \). Because of the Sommerfeld enhancement expected for TeV-mass dark matter annihilating into bosons, HAWC should be sensitive to dark matter annihilating into W bosons down to within an order of magnitude of thermal, \( \langle \sigma v \rangle \approx 3 \times 10^{-25} \text{ cm}^3\text{s}^{-1} \), above 4 TeV. For the \( W^+W^- \) channel, HAWC should also be sensitive to the thermal cross-section for particles between 4-5 TeV in mass.
5. Conclusions

HAWC is an excellent observatory for the search for multi-TeV dark matter. As shown in figure 2, the HAWC observatory will provide bounds on multi-TeV mass dark matter from individual sources which are competitive with comparable experiments. It should also be noted that the limits discussed herein are conservatively based on the current understanding of the HAWC detector performance. The operation of HAWC should lead to greater understanding of the HAWC detector which may improve its sensitivity. With the current interest in multi-TeV dark matter, HAWC observations will be able to search the high-energy gamma-ray sky with greater sensitivity than ever before.

References