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Upper limit on TeV gamma-rays from neutralino annihilation in the galactic center

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Abstract. We present results of recent observations of the galactic center (Sagittarius A*) with the Whipple High Energy Gamma-Ray Telescope. The new high resolution camera and a new data analysis technique which is re-optimized to include zenith angle corrections, provide improved sensitivity at large zenith angles. The upper limit presented here can be used to give a new constraint on the flux of TeV gamma-rays produced by neutralino annihilation near the galactic center. A preliminary upper-limit on the gamma-ray line flux is $1.86 \cdot 10^{-12}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

1 Introduction

Mounting evidence from Cosmic Microwave Background measurements and Big Bang nucleosynthesis shows that a large fraction of the critical density of the universe ($\Omega \approx 0.3$) is composed of cold, non-baryonic dark matter. The composition of this dark matter is unknown, but astrophysical data suggest that any weakly interacting massive particle (WIMP) could provide a natural explanation. The current best-guess comes from Supersymmetry, a theoretical extension of the Standard Model, which predicts a new stable, weakly-interacting particle known as the *neutralino* (if R-parity is assured as in the *Minimal Supersymmetric Standard Model*). Calculations of the relic abundance and the mass of the neutralino suggest that they would also provide a natural dark matter candidate.

Any weakly interacting, stable, massive Majorana particle would have a relic density that is an appreciable fraction of the closure density of the universe and would annihilate to gamma-rays. Gamma-rays from annihilation may be detectable here on Earth using atmospheric Cherenkov telescopes if the halo density is sufficient and the energy threshold of the telescope is low enough. Recent models of structure formation indicate a cusp in cold dark matter halo near the center of the galaxy, (Bergström, Ullio, Buckley , 1998), which may produce enough gamma-rays to be detectable.

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The most probable neutralino mass range is from 60 GeV to ~ 1 TeV, placing much of the allowed parameter space below the large zenith angle energy threshold of the Whipple gamma-ray telescope in southern Arizona (Petry et al., 2001). While it is unlikely that Whipple would be able to detect a neutralino annihilation signature in the most likely part of parameter space, we can place an upper limit on the flux of gamma-rays from this process for very massive Higgsino-like neutralinos. Next-generation gamma-ray telescopes will have lower energy thresholds and better sensitivity to place better constraints.

2 Analysis Technique

The galactic center (Sagittarius A*) transits at a large zenith angle (near $60°$) at the latitude of the Whipple telescope on Mount Hopkins. The usual Whipple analysis technique had to be modified to take into account the additional geometric factors imposed by large zenith angle (LZA) observations. While our group is currently studying other LZA analysis techniques (e.g. Petry et al. (2001)), our goal was to develop an improved two-dimensional analysis technique which is less sensitive to zenith angle and to use data taken from the Crab nebula at a range of zenith angles for optimization. Applying this new analysis to data from the galactic center, we then calculated a gamma-ray flux upper limit normalized to the Crab Nebula flux.

2.1 Zenith Angle Corrections

Our preliminary analysis is identical to the current technique, except that the zenith angle dependence of several of the standard parameters has been taken into account using approximate scaling laws. The distance to the shower maximum increases with increasing zenith angle and the light pool spreads out over a larger area on the ground. The energy threshold of an Atmospheric Cherenkov Telescope increases like:

$$E_{\rm thresh} \propto \frac{1}{\cos^2(\theta)} \quad (1)$$

where θ is the zenith angle. At $\theta \approx 60^\circ$ for the galactic center, the energy threshold increases by a factor of 4 (neglecting a significant additional factor from atmospheric absorption). Fortunately, effective area scales in the same way, which is advantageous.

The elliptical Cherenkov light image of a gamma-ray induced air shower can be characterized by several geometric parameters such as the $width$, $length$ and $distance$ (originally defined by Hillas (1985)). The parameters $width$ and $length$ are defined as the variance of the angular distribution of the Cherenkov image in the directions of the minor and major axes of the ellipse, while $distance$ is defined as the angular distance from the centroid of the ellipse to the center of the camera. Using first-order scaling laws, the effects of zenith angle distortions can be effectively removed from these parameters by several considerations. First, we assume that the intrinsic extent ($\sigma_{\rm int}$) of a gamma-ray shower is approximately the same for all showers of the same energy, but the observed angular size of the shower (e.g the $width$ and $length$ of the light pool) is proportional to $\sigma_{\rm int}\cos\theta$. Secondly, the measured shower size—the total detected Cherenkov light—is proportional to the primary energy times $\cos^2\theta$ due to the spread of the light pool over a larger area. Finally, the current spectral analysis (*Extended SuperCuts*) shows that length and width also scale as the logarithm of the energy, which is proportional to the shower $size$ (Mohanty et. al., 1998).

Combining these results, and removing the effects of the finite pixel size of the camera ($\sigma_{\rm pix} \approx a/\sqrt{2}$, where a is the pixel radius) and the point spread function of the telescope ($\sigma_{\rm psf}$), the measured $length$ and $width$ can be converted to the *intrinsic* $length$ and $width$ by the following equations:

$$({\rm width})_{\rm int} = \frac{\sqrt{({\rm width})^2 - \sigma_{\rm psf}^2 - \sigma_{\rm pix}^2}}{\cos(\theta)} - \frac{0.023}{\cos^2\theta}\ln\left[\frac{\rm size}{\langle {\rm size}\rangle}\right] \quad (2)$$

$$({\rm length})_{\rm int} = \frac{\sqrt{({\rm length})^2 - \sigma_{\rm psf}^2 - \sigma_{\rm pix}^2}}{\cos(\theta)} - \frac{0.020}{\cos^2\theta}\ln\left[\frac{\rm size}{\langle {\rm size}\rangle}\right] \quad (3)$$

From these, we can get the zenith angle corrected parameters $zwidth$, $zlength$, and $zdistance$ by adding back in the systematic variances in quadrature:

$$\begin{aligned} {\rm zwidth}^2 &= ({\rm width})_{\rm int}^2 + \sigma_{\rm psf}^2 + \sigma_{\rm pix}^2 \quad (4)\\ {\rm zlength}^2 &= ({\rm length})_{\rm int}^2 + \sigma_{\rm psf}^2 + \sigma_{\rm pix}^2 \quad (5)\\ {\rm zdistance} &= \frac{\rm distance}{\cos(\theta)} \quad (6)\end{aligned}$$

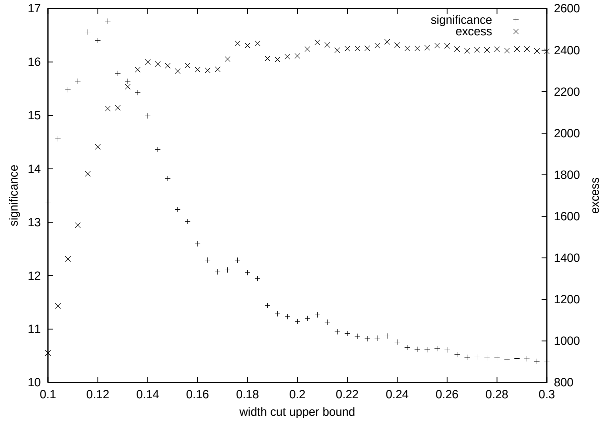

Fig. 1. Optimization curve for $width$ upper limit. The optimization data consists of 19.6 hours on-source exposure time of the Crab nebula (42 on/off pairs) at varying zenith angles.

To verify the scaling laws, we showed that the large zenith angle and small zenith angle distribution of $zlength$ and $zwidth$ for cosmic ray showers agreed if we took the full-width at half-max value of the point spread function to be 1.3 (close to the measured value).

The two-dimensional analysis must also be corrected for zenith angle. In the standard two-dimensional analysis, the point-of-origin of a gamma ray is calculated from the elongation factor, the shower orientation and asymmetry. The distance along the axis of the ellipse from the centroid is equal to $\epsilon_\theta(1 - {\rm width}/{\rm length})$, where ϵ_θ is the elongation factor correction due to zenith angle. The optimum ϵ_θ was found to be 1.25. Asymmetry is used to break the degeneracy in the two points of origin since showers tend to be systematically skewed toward the true point of origin (Lessard et al., 2001).

After applying these modifications to the data analysis, we then re-optimized the data cut values using a set of 42 on/off source pairs of twenty-eight minute runs taken of the crab nebula at a range of low and high zenith angles. The off-source runs were used as a noise source to "pad" the on-source data to reduce systematic effects from differences in on and off source star fields. An example of the optimization curve for the $width$ upper-bound cut is shown in Figure 1. The results for our zenith corrected cut values (*ZCuts*) are shown in Table 1, which can be compared to the standard SuperCuts 2001 cuts (on the non-corrected) data shown in Table 2

Parameter	ZCuts
$zlength$	$0.125 - 0.35$
$zwidth$	$0.06 - 0.35$
$zdistance$	$0.3 - 2.5$
$zlength/size$	< 0.00043
$max2$	40
$alpha$	< 15.0

Table 1. Cut values for zenith corrected data (*ZCuts*)

Parameter	Cuts
$length$	$0.09 - 0.26$
$width$	$0.05 - 0.13$
$distance$	$0.4 - 1.0$
$zlength/size$	< 0.0004
$max2$	40
$alpha$	< 15.0

Table 2. SuperCuts 2001 cut values

With these cuts on the Crab nebula optimization data, an excess of 3204 events and a significance of 15.82σ was obtained. For the subset of this data at very large zenith angle ($> 50°$, 13 on/off pairs), an excess of 331 events and significance of 4.7σ was obtained. From the two-dimensional analysis, we determine a higher peak significance of 6.68σ (see Figure 2.1), which is an indication that the two-dimensional analysis improves at large zenith angle. This is due perhaps to reduced image truncation near the edge of the camera, and hence implies a greater utility of the asymmetry and elongation parameters. Using SuperCuts 2001 on the non-zenith-corrected Crab data, we get an excess of 2336 events and significance of $14.4\ \sigma$ for the full data set and an excess of 306 events with $3.35\ \sigma$ significance for the LZA subset. Some of the improved sensitivity could come from optimization on the data—the same analysis on non-optimized data gives a slightly smaller improvement. The same analysis was applied to a new set of 14 Crab nebula on-source/off-source run pairs over a large range of zenith angles (6.5 hours on-source exposure time); these were runs *not* used during the optimization process. For the crab, the excess was 726 counts with $7.56\ \sigma$ significance. For comparison, *SuperCuts 2001* gives a $7.0\ \sigma$ significance and 783 excess counts. A plot of the Crab *non-optimized* data is shown in Figure 3.

2.2 Flux Upper Limit Calculation

Given the incomplete state of simulations of the new GRANITE III camera and our new *ZCuts*, the flux upper-limit for the galactic center was found relative to the Crab nebula flux. The integral flux for the Crab nebula is:

$$F(E > E_{\rm thresh}) = \frac{R_{\rm crab}}{A'_{\rm eff}} \tag{7}$$

Where $R_{\rm crab}$ is the gamma-ray rate for the Crab nebula, and $A'_{\rm eff}$ is the spectrally weighted effective area. The Crab nebula flux for $E_{\rm thresh} = 1{\rm TeV}$ is $2.1 \pm 0.2 \cdot 10^{-7}{\rm m}^{-2}{\rm s}^{-2}$ (Hillas et al., 1998). At a zenith angle of $60°$, the peak Crab nebula count rate for the Whipple telescope is 3.1 TeV (Petry et al., 2001). Given the Crab spectral index of 1.49, the flux above 3.1 TeV can be found by:

$$\begin{aligned} F(E > 3.1\ {\rm TeV}) &= \left(\frac{2.1 \cdot 10^{-7}}{{\rm m}^2\ {\rm sec}}\right)\left(\frac{3.1\ {\rm TeV}}{1\ {\rm TeV}}\right)^{-1.49} \\ &= \frac{R_{\rm crab}}{A'_{\rm eff}} \end{aligned} \tag{8}$$

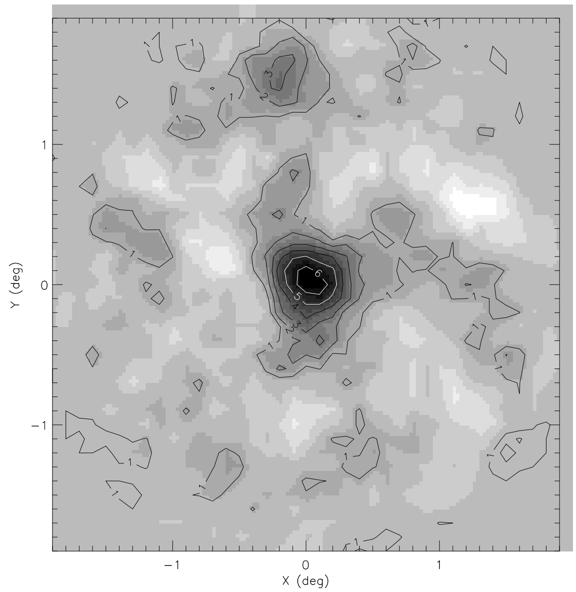

Fig. 2. A de-rotated 2-d gammma-ray image of the Crab nebula at large zenith angle. The sum of 13 pairs of on/off source runs are shown, for a total on-source exposure time of 6 hours. The image shows gamma-ray excess, and the contours indicate significance. The peak 2D significance is 6.61σ at the center of the camera.

Our observations of the Crab nebula at large zenith angle (7 hours on-source exposure padded with 7 hours off-source) show a rate of $0.347\ \gamma/{\rm min}$, giving an effective collection area $A'_{\rm eff} = 1.5 \cdot 10^5\ {\rm m}^2$. From the Sagittarius A* data, we can calculate the Helene upper-limit on the rate, $R_{\rm SgrA*}$ (Helene, et al, 1983). The flux upper-limit for the galactic center is then,

$$F_{\rm SgrA*} = \frac{R_{\rm SgrA*}}{A'_{\rm eff}}. \tag{9}$$

3 Results

Over the 2000 and 2001 observing seasons, 8.9 hours of on-source data for Sagittarius A* was taken—a total of 19 on-source observation runs with 19 off-source runs. This data was analyzed with our zenith-angle corrected technique (*ZCuts*). The result was a total excess of -58 events and -1.3σ significance. A two-dimensional image of the source is shown in Figure 3.

Based on the Sagittarius A* data, the Helene upper limit for the gamma-ray rate from the galactic center is $0.17\ \gamma/{\rm min}$. The flux upper-limit on gamma-rays from the galactic center (Equation 9) is then $1.86 \cdot 10^{-12}\ {\rm cm}^{-2}{\rm sec}^{-1}$ At $3.1\ {\rm TeV}$. (making the unrealistic assumption of a power-law spectrum.) A better upper limit would fold the expected line profile with the effective area curve. This work is in progress and will be published in a subsequent paper.

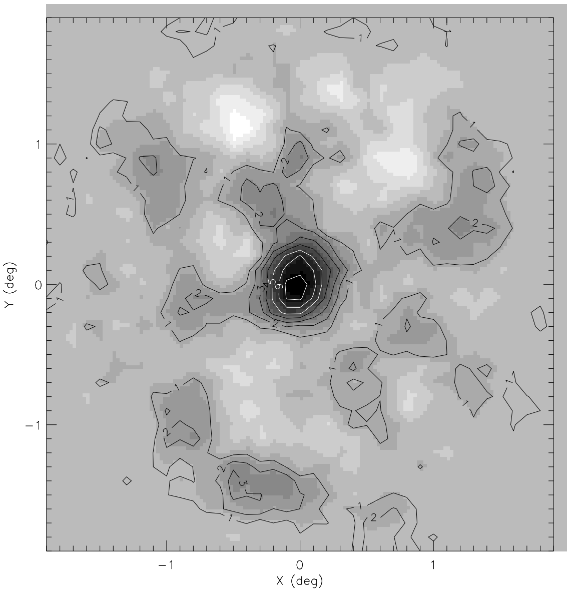

Fig. 3. A de-rotated 2-d gamma-ray image of the Crab nebula taken at a range of zenith angles. The image is of gamma-ray excess and the contours show significance. The position is relative to the center of the camera. The total on-source exposure time was 6.5 hours, in 14 runs. The peak 2-D significance is 7.72σ at the center of the camera.

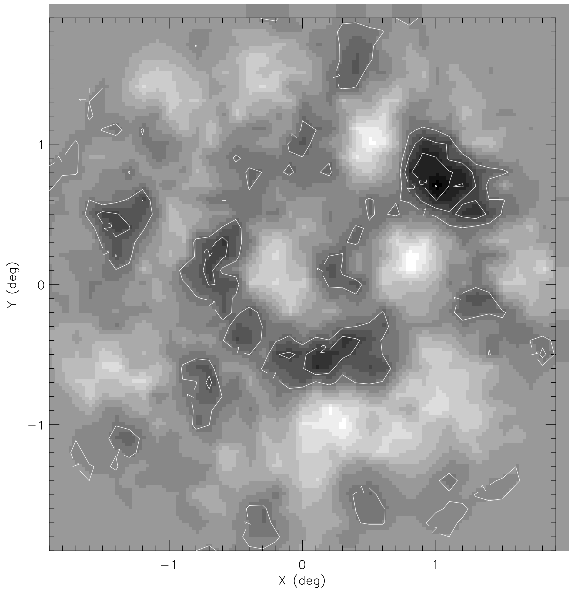

Fig. 4. A de-rotated 2-d image of gamma-ray-like events around the position of Sagittarius A*. The image shows gamma-ray excess and the contours show significance. The position is relative to the center of the camera. The total on-source exposure time was 8.9 hours (in 19 runs). No significant excess is present at the position of Sagittarius A*.

4 Conclusions

No signal was detected from the location of Sagittarius A* with the Whipple telescope. Next-generation instruments in the northern hemisphere such as VERITAS will have the advantage of a high sensitivity at energies above 300 GeV using the LZA technique for the Galactic Center. HESS will have a lower energy threshold to cover more parameter space, but may have less sensitivity above 300 GeV for the same observing time at large zenith angles. Significant uncertainties in dark-matter halo models and particle physics theory currently limit further conclusions.

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