Limits on supersymmetric dark matter from EGRET observations of the Galactic center region

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In most supersymmetic models, neutralino dark matter particles are predicted to accumulate in the Galactic center and annihilate generating, among other products, gamma rays. The Energetic Gamma Ray Experiment Telescope has made observations in this region, and is sensitive to gamma rays from 30 MeV to ~30 GeV. We have used an improved point source analysis including an energy dependent point spread function and an unbinned maximum likelihood technique, which has allowed us to lower the limits on gamma ray flux from the Galactic center by more than 1 order of magnitude. We find that the present Energetic Gamma Ray Experiment Telescope data can limit many supersymmetric models if the density of the Galactic dark matter halo is cuspy or spiked toward the Galactic center. We also discuss the ability of the Gamma ray Large Area Space Telescope to test these models.

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I. INTRODUCTION

Observations by a variety of experiments have revealed that a great deal of the mass of our Universe is dark and cold [1]. Despite this growing body of evidence, we are still ignorant of the nature of dark matter.

One of the most promising dark matter candidates is the lightest neutralino in supersymmetric models [2]. In most models, the lightest supersymmetric particle (LSP) is stable by the virtue of R-parity [3]. Often, this particle is a neutralino χ^0, the partner of the photon, Z-boson and neutral higgs bosons. This candidate is attractive due to the fact that it is electrically neutral, not colored and naturally has the appropriate annihilation cross section and mass to provide a cosmologically interesting relic density.

Many methods have been proposed to search for evidence of supersymmetric dark matter. These include experiments which hope to measure the recoil of dark matter particles elastically scattering off of a detector (direct searches) [4], experiments which hope to observe the products of dark matter annihilation (indirect searches) and, of course, collider experiments [5]. Indirect searches include searches for neutrinos from the Sun, Earth or Galactic center [6], positrons [7] or antiprotons [8] from the Galactic halo and gamma rays from the Galactic center and halo [9].

Methods of indirect detection which involve the Galactic center depend strongly on the distribution of dark matter in the Galaxy. At this time, there is a great deal of debate and speculation over the merits of various Galactic dark matter halo models. Numerical simulations favor models with strong cusps in the central region, such as the Navarro, Frenk, White (NFW), and Moore, *et al.* models [10]. These models predict increasing dark matter density as one approaches the Galactic center, $\rho \propto 1/r^\gamma$, where γ is 1.0 for the NFW case and 1.5 for the Moore case.

There have been arguments made, based on observations, in the favor of flat density core models. These distributions, although possible, are probably not capable of producing observable signals from dark matter annihilation, and are not discussed in this paper for this reason.

Models with strong density spikes at the center of the halo have recently received some attention [11]. In these models, cuspy halos generate spikes as a result of adiabatic accretion of matter into the central Galactic black hole.

Finally, if halo distributions are clumpy, rather than smooth, it would be possible that less dark matter would be present in the central region, and the dark matter signal diminished.

In this paper, we will show results for smooth, cuspy halo distributions of the NFW and the Moore profiles. These distributions (as well as spikey models) are especially interesting to gamma ray experiments, as they provide signals from dark matter annihilation which appear as point sources. The angular distribution of events is proportional to the dark matter density squared integrated over the line of sight. A strongly cusped distribution produces the vast majority of the annihilation signal in an angular region much smaller than the point spread function of EGRET, and hence are indistinguishable from a point source.

II. EGRET POINT SOURCE LOCATION ANALYSIS

EGRET, the Energetic Gamma Ray Experiment Telescope, launched on the Compton Gamma Ray Observatory in 1991, is sensitive to gamma rays in the range of approximately 30 MeV to 30 GeV. During its operation, EGRET's observations included an exposure of approximately 2×10^9 cm^{2}sec in the direction of the Galactic center. This paper presents an analysis of only the gamma rays >1 GeV because the continuum spectrum of gamma rays from neutralino annihilation peaks at higher energies and because the point spread function of EGRET improves with energy.

Previous searches for point sources in EGRET data, such as the 3EG [12], used a single mean point spread function for each observed gamma ray above 1 GeV and spatially binned the data in square bins of sides 0.5 degrees. However, the EGRET point spread function significantly improves with increasing gamma ray energy with 68% of 1 GeV gamma rays reconstructed within 1.3 degrees of the true direction as compared to 68% of the 10 GeV gamma rays within 0.4 degrees. Our analysis uses the point spread function as determined in the preflight calibration [13] for six energy bins above 1 GeV, and does not degrade the reconstructed gamma ray direction to the nearest 0.5° bin. We use a spatially unbinned maximum likelihood analysis to determine the best localization of a point source.

A spatially unbinned likelihood analysis is analogous to the standard binned analysis described by Ref. [14], but the bins are infinitesimally small so that all bins have either no events or one event. The Poisson probability of detecting zero or one event when R events are expected is e^{-R} or Re^{-R}, respectively. The likelihood is the product of these Poisson probabilities for all of these infinitesimal bins, so the logarithm of the likelihood is the sum of R over all bins (or the total number of events predicted by the model in the region of interest) plus the $\ln(R)$ for all bins with one event.

This logarithm of the likelihood is maximized by adjusting the parameters in the model which gives the value of R at all spatial coordinates. The model contains a source plus background. The spatial extent of the source is determined by the point spread function, and the background spatial distribution is determined from the diffuse emission from the Galaxy as obtained from the same model [15] used for the production of the 3EG catalog. At higher energies, such as those discussed in this paper, the localization of a point source is less dependent on the shape of the diffuse background because of the narrowing of the point spread function with increasing energy.

The events are divided into the six energy intervals for which the point spread function was calibrated before launch [13]. The model of the source assumes either a power law energy spectrum or the spectral shape expected for neutralino annihilation. The spectrum is convolved with the effective area of EGRET which decreases with energy E, and is proportional to $E^{-0.4}$ from 1–10 GeV [13] and proportional to e^{-E/E_0} above 10 GeV with $E_0 = 36$ GeV [16]. While the point spread function does not vary with the angle of the incident gamma ray with respect to the spacecraft [17], the effective area varies slightly with changes of less than 0.07 of the power law index. In addition the effective area above 10 GeV was not measured by calibration, but determined later from Monte Carlo. The analysis presented here is not affected by changes in the effective area power law index of this magnitude or with changes of E_0 by ± 10 GeV. This is understandable given the limited number of gamma rays from an individual source detected by EGRET.

In order to maximize the logarithm of the likelihood, the normalization of the background is determined by requiring the total number of events predicted by the model to be the total number of events detected in the region of interest. The region of interest is 16 square degrees, much larger than the point spread function, and is chosen so that the likelihood value is rather insensitive to this choice.

A test statistic is determined from twice the difference of the logarithm of the likelihood for two different models. In order to determine the location of a point source, the likelihood is calculated for different source locations, and the 68%, 95%, and 99% confidence intervals of the location are where the test statistic drops by 2.3, 6.0, and 9.1, respectively, from the maximum value. In each of the six energy intervals a map of the test statistic is computed and then all six maps are added to give the combined test statistic. This is similar to the method used in the 3EG catalog where four energy intervals were combined to give the confidence interval.

This method was checked by a Monte Carlo with a known source location of similar flux to the sources examined in this paper, and the method confirmed the appropriateness of these confidence intervals. In addition, we tested our method on the EGRET data from the well known Galactic sources of the Vela pulsar and the Crab pulsar.

We found the position with maximum likelihood for the EGRET source near the Crab pulsar to be $l = 184.52$, $b = -5.79$. The known location of the Crab is $l = 184.56$, $b = -5.78$ which is within the 95% confidence region as determined by our analysis. The 3EG catalog lists the location of this source as $l = 184.53$, $b = -5.84$, with the known location well outside of the 95% confidence contour.

The results for the Vela pulsar are similar. We found the maximum likelihood at $l = 263.53$, $b = -2.82$ with a known location of $l = 263.55$, $b = -2.79$ again within the 95% contour. The 3rd EGRET catalog lists Vela at $l = 263.52$, $b = -2.86$ and the known location is well outside of the 99% confidence contour.

When our technique is applied to the Galactic center region, we find a point source located at $l = 0.19$, $b = -0.08$. The location of Sag A^*, the black hole at the dynamical center of the Galaxy, is at $l = 359.94$, $b = -0.05$ and is excluded as the gamma ray source beyond the 99.9% confidence level, see Fig. 1. We find that if this source, modeled with a differential power law spectrum with slope determined by the maximum likelihood technique to be -2.2, is included in the model with the diffuse background of this region, the 95% confidence upper limit on the number of gamma rays from a point source at the location of Sag A^* is 10 to 100 (depending on the spectrum of the source). By contrast, the source at $l = 0.19$, $b = -0.08$ is a bright EGRET source of 370 gamma rays. The identification of this source is unknown [18], but this new localization agrees well with a postulated source of inverse Compton gamma rays from the electrons which create the Galactic center radio arc [19].

III. CALCULATING THE GAMMA RAY FLUX FROM THE GALACTIC CENTER

We calculated, for a variety of supersymmetric models, the number of events EGRET would have been expected to have observed, as a function of the halo model. We only consider those models which do not violate accelerator limits [5,20], including b to s_γ [21] and invisible Z decay width measurements. Furthermore, we require that the relic density of the LSP be $0.05 < \Omega_\chi h^2 < 0.2$. We calculate the neutralino relic density using the full cross section, including all resonances and thresholds, and solving the Boltzmann equation numerically [22]. Coannihilations with charginos and neutralinos are included. We then calculate the LSP annihilation cross section, mass, and resulting gamma ray spectrum, for a given halo model. The results are shown in Figs. 2 and 3.

The general supersymmetric parameter space, even for the minimal supersymmetric standard model, consists of more than 100 free parameters and, therefore, must be simplified to do any practical calculations. We considered a 7-dimensional parameter space consisting of the gaugino mass parameter M_2, the non physical mass μ, the ratio of higgs vacuum expectation values $\tan\beta$, a universal supersymmetry (SUSY) mass scale M_{SUSY}, the pseudoscalar higgs mass m_A, and the couplings A_t and A_b. We varied each parameter up to 10 000 except for $\tan\beta$, which we varied between 1 and 50. We considered both positive and negative values of μ, A_t, and A_b.

We parametrized the continuum gamma ray spectrum as a function of the LSP mass and calculated the 95% exclusion confidence levels which could be placed by the EGRET data. Although this parametrization can vary depending on the annihilation properties of the LSP, we have tested our result against a large number of SUSY models and found that for the vast majority of cases, our parameterization is in good agreement with the resulting spectrum. The exclusion contour is shown in Figs. 2 and 3 as a solid line. We did not consider the $\gamma\gamma$ or γZ line emission as these are generally above the energy range sensitive to EGRET.

We also considered the ability of the future experiment, Gamma ray Large Area Space Telescope (GLAST), to probe the galactic center for dark matter annihilations.

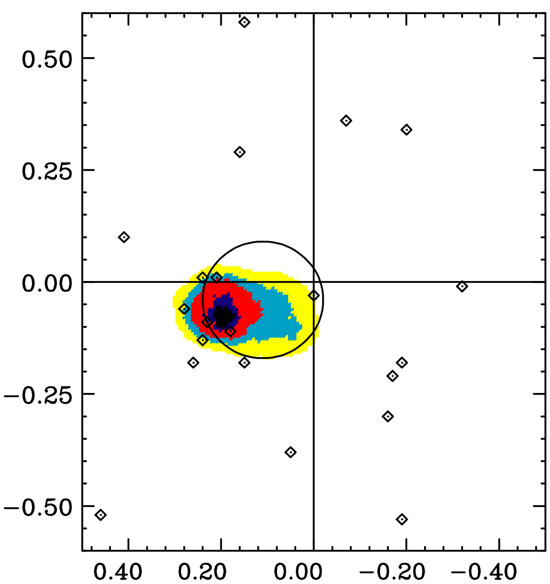

FIG. 1 (color online). Unbinned maximum likelihood point source analysis of the Galactic center region. 50, 68, 95, 99, and 99.9% confidence intervals on the point source position are shown. Note that the location of Sag A^* at $l = 359.95$, $b = -0.05$ is excluded beyond the 99.9% confidence level as the location of the source. The 95% confidence contour of the 3EG catalog position is shown as a circle for comparison. Also shown are all gamma rays above 5 GeV.

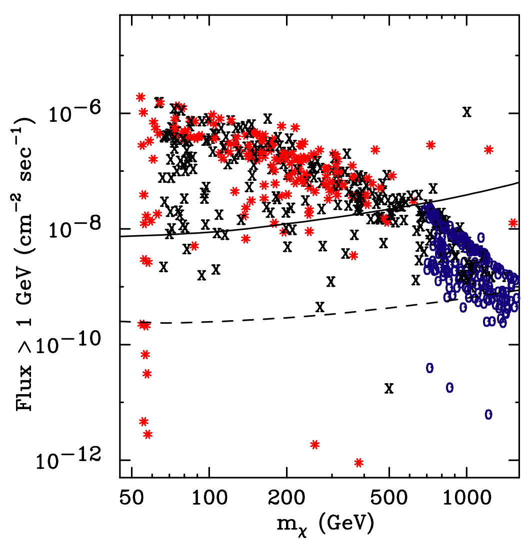

FIG. 3 (color online). SUSY model predicted fluxes for a Moore *et al.* halo profile. Also shown are the 95% confidence upper limit of EGRET (solid line) and the expected GLAST sensitivity (dashed line). (Blue) circles represent models with a LSP which is more than 95% higgsino, (red) stars represent models with a LSP which is more than 95% gaugino and (black) x's are models with mixed neutralinos.

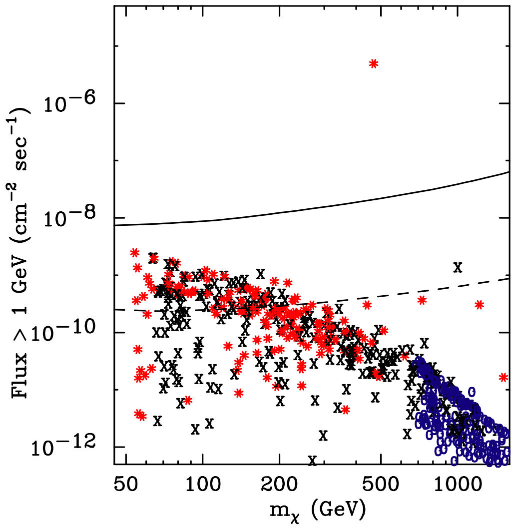

FIG. 2 (color online). SUSY model predicted fluxes for an NFW halo profile. Also shown are the 95% confidence upper limit of EGRET (solid line) and the expected GLAST sensitivity (dashed line). (Blue) circles represent models with a LSP which is more than 95% higgsino, (red) stars represent models with a LSP which is more than 95% gaugino and (black) x's are models with mixed neutralinos.

With larger area and better angular resolution, GLAST, will be capable of testing many more models than EGRET. Furthermore, GLAST, with sensitivity to energies as high as ~1 TeV, can test models with heavier LSP neutralinos somewhat more easily than EGRET. In Figs. 2 and 3, the expected sensitivity of GLAST, after three years of observation, is shown as a dashed line.

IV. CONCLUSIONS

Our analysis of the EGRET data in the Galactic center region indicates an off-center point source, excluded beyond 99.9% as the Galactic center. Considering this source as background, we found no evidence of a point source at the Galactic center and determined the 95% confidence upper limits on the flux of gamma rays as a function of the WIMP mass. The new limit we find is more than 1 order of magnitude below the previous limits.

We compared these limits to the flux predicted for a variety of supersymmetric models and galactic halo models. We find that for very cuspy (or spikey) halo models, such as the Moore *et al.* profile, the majority of viable supersymmetric models are excluded by our limit. We show that the GLAST experiment will have the sensitivity to further constrain the Galactic halo profile of neutralino dark matter.

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