GAMMA-RAY BACKGROUND FROM NEUTRALINO ANNIHILATION IN THE FIRST COSMOLOGICAL OBJECTS

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ABSTRACT

The paradigm of the neutralino dark matter predicts that the first gravitationally bound objects are earth-mass sized microhaloes, which would emit annihilation gamma-rays. Here we show that, though the flux from individual nearest microhaloes is extremely difficult to detect, meaningful constraints on their survival probability and internal density profile can be set by requiring that the galactic and extragalactic gamma-ray background flux from the microhaloes does not exceed the existing EGRET background data. Possible disruption of microhaloes by stellar encounters does not significantly reduce the background flux. If the probability for microhaloes to survive the hierarchical clustering process of dark matter is as large as indicated by a recent simulation, they could be a significant component of the observed background flux in some photon energy range, even with the standard annihilation cross section and conservative internal density profile of microhaloes. The integrated gamma-ray flux from microhaloes in the halo of the Andromeda galaxy may also be detectable by observations in the near future.

Subject headings: dark matter — gamma rays: theory — Galaxy: halo — galaxies: haloes

1. INTRODUCTION

The neutralino predicted by the supersymmetry theory of particle physics is the most promising candidate of the cold dark matter (CDM). The theory predicts that neutralinos should annihilate and produce high energy particles such as gamma-rays, and the detectability of these particles from dense regions like the Galactic center (GC) has been discussed intensively in the literature. [See Bertone et al. 2004 for a review and references therein for the earlier papers.] The structure formation theory predicts hierarchical substructure in a dark matter halo, and this clumpiness is expected to enhance the annihilation signal. Previous investigations, however, considered substructures only to the first order (i.e., isolated subhaloes in a halo) and masses larger than $\sim 10^6M_\odot$, mainly because of the limitation of cosmological N-body simulations (Ullio et al. 2002, Taylor and Silk 2003, Elsaesser and Mannheim 2005).

Recently attention has been turned to substructures on much smaller scale, especially the first gravitationally bound objects in the cosmological evolution. If the dark matter is the neutralino, any density fluctuations of mass scales smaller than $M_{\text{min}} \sim 10^{-6}M_\odot$ are washed out by collisional damping and subsequent free streaming in the early universe. Then the first objects form as “microhaloes” with a mass $\sim M_{\text{min}}$ at $z \sim z_{\text{nl}}$, where $z_{\text{nl}} = 60 \pm 20$ is the epoch when the rms linear density fluctuation at this mass scale, $\sigma(M_{\text{min}})$, becomes unity (Hofmann et al. 2001, Green et al. 2004, 2005, Berezinsky et al. 2003, Loeb & Zaldarriaga 2004). Therefore a considerable part of the neutralino dark matter should have collapsed into these earth-mass objects, at least once in the cosmic history.

However, it is highly uncertain how much fraction of these microhaloes can survive the subsequent hierarchical structure formation until present. Berezinsky et al. (2003) estimated that only 0.1–0.5% of microhaloes survive, because of tidal disruption when they are taken into larger haloes. This is, however, a completely analytic estimate and uncertainty must be large. On the other hand, Diemand et al. (2005), based on a N-body simulation, argued that about 50% of the total halo mass $M_{\text{tot}}$ is in the form of substructure with a subhalo mass function $dN/dM \sim M^{-2}$ in the mass range $10^{-6} < M < 10^{10}M_\odot$, where $\mu \sim 2$. This indicates that the mass fraction of microhaloes is at least $M_{\text{min}}^2 [dN(M_{\text{min}})/dM]/M_{\text{tot}} \sim 1.3\%$. Furthermore, the nested nature of hierarchical structure formation predicts that microhaloes may be embedded in larger subhaloes, which may again be embedded in even larger ones. Counting microhaloes in larger mass subhaloes up to $M \sim 10^{10}M_\odot$ will further increase the true number of earth-mass microhaloes. Diemand et al. (2005) used 500 pc$^{-3}$ as the number density of such microhaloes in the solar neighborhood, which is about 7% of the standard dark matter density at the Sun’s location, $\rho(R_{\odot}) = 0.3$ GeV cm$^{-3}$ (Bertone et al. 2004). In addition to the tidal disruption by hierarchical clustering, microhaloes may also be destroyed by tidal interaction with stars in the Galactic disk (Zhao et al. 2005, Moore et al. 2005), but again estimates are controversial.

It is obvious that such microhaloes could have significant impact on the detectability of the annihilation signal. Here we show that both the galactic and extragalactic gamma-ray background radiation (hereafter GGRB and EGRB, respectively) give a strong constraint on the existence of such microhaloes. Since the microhalo survival probability is highly uncertain, we simply parametrize this quantity as $f_{\text{surv}}$, and try to estimate how much constraints can be set from existing and future observations. It has been argued that neutralino annihilation cannot be a significant component of the observed EGRB data since it would overpredict the gamma-ray...
flux from the GC beyond the observational upper bound (Ando 2003). This argument does not apply here, because the microhaloes are likely disrupted by strong tidal forces of the GC gravity field and/or interaction with stars within ~ kpc of the GC (Diemand et al. 2005) and hence the visibility of the GC is not enhanced by the microhaloes. However, the mass included within 1 (10) kpc is only 0.3 (6) % of the total mass of the Galactic halo (Klypin et al. 2002). Therefore the total gamma-ray flux from microhaloes in a galactic halo, to which the EGRB is related, is hardly affected by tidal disruption in its central region, if microhaloes trace the mass distribution.

2. GAMMA-RAY BACKGROUND FROM MICROHALOES

2.1. Estimating GGRB and EGRB Flux

In this work we assume that microhaloes are formed at redshift ~ z_{nl}, and a fraction (1 - f_{surv}) of them are immediately destroyed by tidal forces in subsequent hierarchical structure formation. After that, we assume that the number of microhaloes and their density profile are kept constant until present, except in regions very close to galactic halo centers. These are not unreasonable, since the tidal force within an object is proportional to its internal density, and the mean density within virialized objects decreases with the cosmic expansion in proportion to the mean background density. Therefore we expect that the tidal disruption at a typical location within a dark halo should occur most efficiently at redshift not very different from z_{nl}, when isolated microhaloes are first taken into larger objects.

Consider a region in the universe with the mass scale M_{mh} whose linear fractional overdensity is \delta = \delta\rho/\rho \propto (1 + z)^{-1}. According to the standard structure formation theory, the height over the rms, \nu = \delta/\sigma(M_{mh}), obeys to the Gaussian, i.e., the comoving number density of microhaloes given by d\nu_{mh}/d\nu = f_{surv}\Omega_{\chi\rho_{crit},0}\exp(-\nu^2/2)/(\sqrt{2\pi}\nu_{mh})$, where we use the WMAP values (Spergel et al. 2003) for the present-day critical density \rho_{crit,0} and the neutralino density parameter \chi = 0.22. At z ~ z_{nl} the universe is flat and matter-dominated, and the region will collapse and virialize when \delta = 1.686 at z = z_{vir}, where (1 + z_{vir}) = (1 + z_{nl})/\delta_c. The internal density of microhaloes is given as \nu_{eff}(\nu) = 18\pi^2 f_c(1 + z_{vir})^3\Omega_\chi\rho_{crit,0}. Here, f_c is the enhancement factor from the virial density, to take into account the density profile of each microhalo; we found that the mass-weighted mean density, which is proportional to the annihilation rate, is increased by f_c = 6.2 for the microhalo profile\(^3\) found in the simulation (Diemand et al. 2005).

Then, integrating over \nu, the comoving annihilation rate density is given by:

\[ N_{\chi\chi} = \int_{\nu_{eff}}^{\infty} M_{mn} \rho_{eff}(\nu) \frac{\langle \sigma_{\chi\chi} v \rangle}{2m_{\chi}^2} d\nu_{mh}/d\nu d\nu, \]

where \nu_{eff} is the neutralino mass and \langle \sigma_{\chi\chi} v \rangle being the mean velocity-multiplied cross section of neutralino annihilation. Throughout this letter we use the standard value of \langle \sigma_{\chi\chi} v \rangle = 3 \times 10^{-26} \text{cm}^3\text{s}^{-1} (Bertone et al. 2004).

and scaling for different values is obvious. The possible range of \chi is \sim 30 \text{GeV} - 10 \text{TeV} (Bertone et al. 2004), and we use \chi = 100 \text{GeV} for calculations below, unless otherwise stated. Since \rho_{eff} \propto \nu^3, the annihilation signal comes mainly from microhaloes of \sim \nu_{p} sigma fluctuation, where \nu_{p} = \sqrt{3}. Microhaloes with \nu \ll 1 may not gravitationally collapse or would be disrupted by subsequent structure formation, but the integration is not very sensitive to the lower bound, and hence we take \nu = 0. Note that, by this formulation, f_{surv} is effectively the survival probability for microhaloes having relatively high density fluctuation of \nu \sim \nu_{p}, and their mass fraction in the total dark matter, f_{m}, is related as: f_{m} \sim (1/\sqrt{2\pi})\exp(-\nu_{p}^2/2)f_{surv} \sim 0.09f_{surv}. Assuming that the spatial distribution of microhaloes traces the smoothed mass over larger scales, the number density of microhaloes with \nu \sim \nu_{p} around the solar system is n(R_S) \sim f_{m}\rho(R_S)/M_{mh} \sim 680f_{surv} \text{pc}^{-3}. This number is close to the estimate based on the simulation, ~ 500 pc^{-3} (Diemand et al. 2004), indicating that f_{surv} could be of order unity.

Now we can calculate the EGRB photon flux from microhaloes per steradian, as:

\[ \frac{dF_{\gamma}}{dE_{\gamma}} = \frac{c \dot{N}_{\chi\chi}}{4\pi} \int_{z_{nl}}^{z_{vir}} dz \frac{dt}{dz} \frac{dn_{\gamma}[(1 + z)E_{\gamma}]}{dE_{\gamma}}(1 + z), \]

where E_{\gamma} is the gamma-ray energy and its spectrum produced by an annihilation, d\nu/dE_{\gamma}, is calculated using the analytical fitting formula given in Bergstrom et al. 2001. (We consider only the continuum gamma-rays.) The integration up to the redshift z_{nl} is an approximation, but it is almost insensitive to this upper bound since annihilation at z \leq 1 is dominant to the EGRB. High energy gamma-rays may be absorbed by interaction with the cosmic infrared background. However, in this letter we consider only E_{\gamma} \leq 100 \text{GeV}, and at this photon energy the optical depth becomes unity only beyond z \sim 2 (Totani and Takeuchi 2002). Therefore our result is hardly affected by the absorption.

Next we calculate the GGRB flux. The annihilation rate per unit dark matter mass in a region smoothed over larger scales than microhaloes is given by \dot{N}_{\chi\chi} = \dot{N}_{\chi\chi}/(\Omega_\chi\rho_{crit,0}). Then we obtain the GGRB flux per steradian as:

\[ \frac{dF_{\gamma}}{dE_{\gamma}} = \frac{\dot{N}_{\chi\chi} d\nu_{\gamma}(E_{\gamma})}{4\pi} \int_{\text{l.o.s.}} d\rho_{\text{sm}} dl, \]

where the integration is over the line of sight, for the smoothed dark matter density in the Galactic halo, \rho_{\text{sm}}. It should be noted that the flux is proportional to the line-of-sight integration of \rho_{\text{sm}}^4, not \rho_{\text{sm}}^3 as in the case of diffuse matter distribution. We use two spherically symmetric models of \rho_{\text{sm}} (Klypin et al. 2002); one has the Navarro-Frenk-White (NFW, Navarro et al. 1996) profile but the other is modified from the NFW profile by adiabatic compression of dark matter responding to the baryon infall. As discussed above, microhaloes are expected to be destroyed by tidal forces in the inner region around the GC. Therefore, as a simple model, we introduce the disruption radius R_d within which microhaloes are completely disrupted, while they are all preserved outside R_d with an abundance proportional to f_{surv}.  

\(^3\) The $\alpha\beta\gamma$-profile with $(\alpha, \beta, \gamma) = (1, 3, 1.2)$ and the concentration parameter $c = 1.6$. 

2.2. Comparison to Observations

The calculated EGRB flux is shown in Fig. 1 for $m_\chi = 100$ GeV and 1 TeV. If $f_{\text{surv}} \gtrsim 0.1$, the microhaloes make a significant contribution to the observed EGRB flux [Strong et al. 2004a] in some photon energy range. The predicted flux is much higher than those in earlier studies [Ullio et al. 2002; Taylor and Silk 2003; Ando 2003], this is mainly because the microhaloes formed much earlier than galactic haloes considered in these studies ($M \gtrsim 10^{5-6} M_\odot$) and hence have much higher internal density. The GGRB flux from the microhaloes, which is the mean in the all sky except for the disk region 4, is also shown in this figure. It is found to be comparable to the EGRB, indicating that it could also be a significant component of the observed flux. It should be noted that, since the "observed" EGRB data was estimated as the residual after the subtraction of the cosmic-ray interaction model in our Galaxy, not only the EGRB but also the GGRB expected from microhaloes should be compared to the observed EGRB data.

Figure 2 shows the predicted total flux (EGRB + GGRB) as a function of the Galactic longitude. It can be seen that, if $R_\odot \gtrsim 5$ kpc, the anisotropy of the background flux is at most a factor of 2. This is acceptable, considering the precision of the EGRB measurements and possible systematic uncertainties in the foreground subtraction [Sreekumar et al. 1998; Strong et al. 2004a; Keshet et al. 2004]. Even smaller $R_\odot$ may also be allowed, since the anisotropy close to the GC would be hidden by strong background flux from cosmic-ray interactions in the Galactic disk.

In fact, evidence for a diffuse gamma-ray halo towards the GC that cannot be explained by the standard cosmic-ray interaction model has been reported [Dixon et al. 1998], at a flux level similar to the EGRB. This gamma-ray halo might be explained by the microhaloes with an appropriate choice of $R_\odot$. The GGRB sky distribution is expected to show strong small-scale anisotropy by the complicated substructures in the Galactic halo. Since annihilation signal peaks in rather narrow photon energy range, the gamma-ray energy dependence of the GGRB anisotropy may be used to examine the contribution from microhaloes.

The EGRET background data around the disk region shows so-called GeV excess over the standard prediction from cosmic-ray interaction, which is about 1–2 orders of magnitude higher than the EGRB along the Galactic disk [Hunter et al. 1997]. The flux level of the excess might be achieved by microhaloes with a large boost factor from our prediction above, which is, in fact, not very unlikely (see below). However, still the GeV excess seems difficult to explain by the microhaloes, because the spatial distribution of the GeV excess is clearly associated with the Galactic disk while distribution of microhaloes is expected to be more spherical. Note that the GeV excess can also be explained by modification of the cosmic-ray interaction models [Strong et al. 2004a; Kamae et al. 2005].

It should be noted that the internal density profile of the microhaloes used above is conservative in a sense that it predicts relatively low annihilation luminosity. Though we have used the $\alpha\beta\gamma$ profile with $\gamma = 1.2$ following the fitting by Diemand et al. [2005] ($\rho \propto r^{-\gamma}$ with $r \to 0$), their simulated microhaloes have $\gamma \sim 1.7$ to the resolution limit of the simulation. They also noticed the similarity between their simulated microhaloes and galactic haloes shortly after the formation or major mergers, showing a single power law profile with slopes of $\gamma \sim 1.5$–2. If $\gamma > 1.5$, annihilation luminosity diverges in the center, and assuming that the maximum density is limited by annihilation time scale, $\rho_{\text{max}}/(2m_\chi) < (10^{40} \text{yr}^{-1})$, we find that the enhancement factor $f_e = 6.2$ used above (for $\gamma = 1.2$) will be boosted up to $f_e = 31, 190$, and $1.4 \times 10^4$ for $\gamma = 1.5, 1.7, \text{and } 2.0$, respectively. Here we used consistently (and conservatively) a low value for the concentration parameter, $c = 1.6$, as found in the simulation [Diemand et al. 2005].

Provided that annihilation cross section is close to the standard value, the two major astrophysically uncertain parameters are $f_{\text{surv}}$ and $f_e$. We note that the background flux is only weakly dependent on $M_{\text{mh}}$. The formation redshift $z_{\text{fhl}}$ depends on $M_{\text{mh}}$, but only very weakly, because $\sigma(M)$ is only weakly dependent on $M$ in small scales under the standard CDM density fluctuation spectrum and hence fluctuations over a wide range of mass scales will become non-linear at similar redshifts. Hence we calculate the excluded region in the $f_{\text{surv}}$-$f_e$ plane in Fig. 3 by requiring that the predicted flux does not exceed any of the observed EGRB data.

3. DISCUSSION AND CONCLUSIONS

The observability of the nearest microhalo from the Earth is of great interest. The expected photon flux is given by:

$$F \sim \frac{Y_{\gamma} M_{\text{mh}\text{eff}}}{4\pi} \frac{\langle \sigma_{\chi\chi} \rangle}{2m_\chi^2} \frac{(f_e/6.2)Y_{40}m_{\chi}^{-2}}{c^2s^{-1}},$$

where $m_{\chi} = m_\chi / (100 \text{ GeV})$ and $Y_{40} \equiv 40Y_{40}$ is the photon number yield from one annihilation; typically one annihilation produces 30–50 continuum gamma-rays and more than 80% of them are above 100 MeV [Gondolo et al. 2004]. Unfortunately this flux is much smaller than the point source sensitivity of the EGRET, and even of the future GLAST mission, and hence detection of individual microhaloes is unlikely. It is impossible to greatly enhance the detectability by boosting the internal density factor $f_e$, because it would seriously overpredict the background flux far beyond the observed level.

The detectability of gamma-rays from microhaloes in the nearby extragalactic objects is also intriguing. Here we estimate the flux expected from M31, $d = 770$ kpc from the Earth. The dark matter mass enclosed within 13 kpc, corresponding to the position accuracy of EGRET ($\sim 1^\circ$), is $M_{\text{DM}} \sim 1.5 \times 10^{11} M_\odot$ [Klypin et al. 2002]. Then we expect photon flux of $Y_{\gamma} N_{AX} M_{\text{DM}}/(4\pi d^2) \sim 7.7 \times 10^{-9} f_{\text{surv}}(f_e/6.2)Y_{40}m_{\chi}^{-2} \text{ cm}^{-2}\text{s}^{-1}$, which is interestingly very close to the EGRET upper bound (1.6 $\times 10^{-8}$, Blom et al. 1993), indicating that there is a good chance of detecting annihilation flux from microhaloes in M31 by the GLAST mission or next generation air Cerenkov.
Fig. 1.— The background gamma-ray flux from neutralino annihilation in the microhaloes. The Galactic (dashed), extragalactic (dot-dashed), and the total (solid) components are shown. The two cases of $m_\chi = 100$ GeV and 1 TeV are presented, with $f_{\text{surv}} = 0.35$ and 1, respectively. The internal density profile parameter $f_c = 6.2$ is conservatively assumed. The baryon compressed NFW profile for the Galactic halo and $R_d = 5$ kpc are used for the Galactic component.

In conclusion, annihilation gamma-rays from the microhaloes could be a significant component of the observed EGRB flux. The two major uncertain parameters are $f_{\text{surv}}$ and $f_c$, and a considerable part of the parameter space has already been excluded by the observed EGRB flux level.

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Fig. 2.— The longitudinal distribution of the background flux (GGRB+EGRB), assuming $m_\chi = 100$ GeV, $f_{\text{surv}} = 1$, and $f_c = 6.2$. Three different values of disruption radius $R_d$ are used as indicated. Two different density profiles of the Galactic halo are used: the baryon-compressed NFW (upper thick curves) and the original NFW (lower thin curves). The level of the predicted isotropic EGRB from microhaloes is also indicated.

Fig. 3.— The excluded region in the space of the two parameters, the survival probability ($f_{\text{surv}}$) and the enhancement factor by the internal density profile of microhaloes ($f_c$). The microhalo mass fraction $f_m$ in the total dark matter mass is related to $f_{\text{surv}}$ as $f_m \sim 0.09 f_{\text{surv}}$. Several curves are depicted for different neutralino masses ($m_\chi$) as indicated, and the upper-right regions are excluded because the predicted background flux will exceed the observed data. The compressed NFW profile for the Milky Way halo and $R_d = 5$ kpc are assumed for the GGRB component. The values of $f_c$ corresponding to several values of the inner slope index ($\gamma$) of internal density profile of microhaloes are marked by vertical thin solid lines.