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ON NEUTRALINO STARS AS MICROLENSING OBJECTS

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Abstract

The microlensing objects, Machos, recently observed in the halo of our Galaxy, can be interpreted as dense neutralino objects, neutralino stars, produced by the gravitational instability of neutralino gas. Taking the mass and radius of these objects from microlensing observations we calculated the diffuse gamma-ray flux produced in neutralino-neutralino annihilation inside the objects. The resulting flux is many orders of magnitude higher than the observed one.

The recent observations of microlensing objects in the halo of our Galaxy [1] show that the Macho mass is $0.46_{-0.17}^{+0.30} M_{\odot}$ at 68% CL. This large mass of lenses raises the question of how they can escape from the observations by the Hubble telescope. The fraction of the total halo mass in the form of Machos, according to the observations [1], is $\xi = 0.50_{-0.20}^{+0.30}$. If this fraction is higher than 50% a new question arises as to why the fraction of non-baryonic cold dark matter, which is needed for the large scale structure formation, is so small in our Galaxy.

In some recent papers [2] a very interesting idea about the nature of these microlensing objects was put forward. These objects can be dark matter formations around a singularity, produced during the non-linear stage of the fluctuation growth ([3] and references therein). The authors call these objects neutralino stars (NS). If this idea is correct, the microlensing phenomenon is a natural result of fluctuation growth in the neutralino gas, and the aforementioned possible difficulties connected with the baryonic nature of Machos disappear.

In this note we shall study the gamma-ray production in the neutralino stars in an approach more general than the model [2]. Namely, we shall adopt for the neutralino stars the mass, the radius and their space density in the halo being restricted by the microlensing observations. For the density distribution inside NS we shall use $\rho \propto r^{-1.8}$, which is a basic theoretical result for this kind of objects [3]. We shall consider the mass of neutralino as a free parameter, though in the work [2] the neutralino mass is restricted as $5 \text{ GeV} \lesssim m_{\chi} \lesssim 50 \text{ GeV}$.

The diffuse gamma-ray flux from neutralino stars in the halo is

$$I_{\gamma} = \frac{1}{4\pi} n_s R_h \dot{N}_{\gamma}, \quad (1)$$

where n_s is the number density of neutralino stars in the halo, R_h is the radius of the halo and \dot{N}_{γ} is the production rate of photons in the NS.

The density of NS in the halo can be estimated by assuming that the fraction ξ of the total mass of the halo, M_h , is in the form of NS:

$$n_s = \frac{3\xi M_h}{4\pi M_{\chi} R_h^3} \quad (2)$$

where M_{χ} is the mass of the NS.

Let us now estimate the production rate of photons \dot{N}_{γ} in an NS.

The density of neutralinos inside the NS depends on the distance as $r^{-1.8}$ [3] and can be expressed through the mass M_{χ} and radius R_{χ} of the NS as

$$n_{\chi} \approx \frac{1.2 M_{\chi}}{4\pi m_{\chi} R_{\chi}^3} \left(\frac{r}{R_{\chi}} \right)^{-1.8} \quad (3)$$

with a negligible correction due to a modification of the $r^{-1.8}$ dependence at very small distances. The gamma-ray production rate is

$$\dot{N}_{\gamma} = 2\eta_{\pi^0} 4\pi \langle \sigma v \rangle \int_{R_c}^{R_{\chi}} n_{\chi}^2(r) r^2 dr \quad (4)$$

where $\langle\sigma v\rangle$ is the cross-section of neutralino–neutralino annihilation and $\eta_{\pi^0}(m_\chi)$ is the multiplicity of neutral pion production in neutralino–neutralino annihilation.

We have assumed in (4) that the neutralino star has a core of radius R_c . Inside the core the neutralino density is constant or rising more slowly than $r^{-1.8}$, and we neglected the gamma-ray production there, which is 5 times smaller than outside it for the case of constant density.

Using Eqs. (1), (3) and (4) we obtain the diffuse flux as

$$I_\gamma = \frac{0.9}{4\pi^3} \eta_{\pi^0} \frac{\xi M_h M_\chi}{m_\chi^2} \left(\frac{R_\chi}{R_c}\right)^{0.6} \frac{\langle\sigma v\rangle}{R_\chi^3 R_h^2}. \quad (5)$$

To proceed further we should evaluate two parameters: core radius R_c and annihilation cross-section $\langle\sigma v\rangle$.

Let us start with the annihilation cross-section $\langle\sigma v\rangle$. This quantity is of relevance both for the determination of the flux (see Eq. (5)) and for the evaluation of the neutralino relic abundance. In the usual expression $\langle\sigma v\rangle = a + bx$, where $x \equiv m_\chi/T$, valid in the non-relativistic limit, a takes contribution from the s-wave only, whereas b contains both s and p-wave contributions. The relic abundance is given by

$$\Omega_\chi h^2 = 8.67 \cdot 10^{-11} \frac{1}{N_f^{1/2}}, \frac{\text{GeV}^{-2}}{ax_f + (1/2)bx_f^2} \quad (6)$$

where $N_f \approx 100$ is the number of degrees of freedom at the epoch of the neutralino decoupling and $x_f = m_\chi/T_f \simeq 1/20$, T_f being the temperature at the decoupling. Situations in which this approximation is not valid are discussed, for instance, in [4].

Let us note that the annihilation cross section in Eq. (5) has to be evaluated at the present temperature (T_0) and then for $x_0 \simeq 10^{-7}$. This implies that I_γ critically depends on the size of the a term in $\langle\sigma v\rangle$; any suppression effect in the a term entails a large depletion in the diffuse flux emitted by NS. As will be shown later, the flux I_γ has the tendency to largely (by many orders of magnitude) exceed the experimental bound. Thus in what follows we adopt the conservative approach of analysing with special care situations in which the term a is significantly suppressed.

The evaluation of $\langle\sigma v\rangle$ requires the inclusion of the full set of annihilation final states ($f\bar{f}$ pairs, gauge-boson pairs, Higgs-boson pairs and Higgs gauge-boson pairs), as well as the complete set of Born diagrams (Z , Higgs, squark, neutralino and chargino exchanges). Furthermore one should include loop contributions, leading to gluon final states, which may be relevant in annihilation processes at the present temperature. Analytical expressions and numerical codes for the annihilation cross section are available (for a complete set of references, see [5]).

As discussed above, the case favourable for neutralino stars as microlensing objects is the one in which the s-wave annihilation, described by a , is strongly suppressed in comparison with the p-wave contribution given by b . This occurs in the gaugino and higgsino dominated states when the neutralino is lighter than the W -boson and the final states are fermionic pairs. In the case of strong s-wave suppression ($bx_f \gg a$) one obtains from (6):

$$b \simeq 1.4 \cdot 10^{-35} \frac{0.2}{\Omega_\chi h^2} \text{ cm}^2. \quad (7)$$

Our way of writing the numerical factors in the previous expression is motivated by the observation [7] that for all cosmologically successful models the cold dark matter contribution to Ω is given by $\Omega_{CDM} h^2 = 0.2 \pm 0.1$.

Turning now to the calculation of $\langle \sigma v \rangle$ at the present time, we shall evaluate a using b as given by Eq. (7) and the ratio a/b , which is almost free from particle-physics uncertainties following the procedure suggested in Ref. [6]. Let us first consider the case when $m_b < m_\chi < m_W$, where m_b is the mass of the b -quark. The dominant contribution to the cross section is given in this case by $b\bar{b}$ final states.

For the gaugino-like case the ratio of a/b is given [6] by

$$a/b = 6.3 \cdot 10^{-4} \left(\frac{m_b/5 \text{ GeV}}{m_{100}} \right)^2 / f(y), \quad (8)$$

where $m_{100} = m_\chi/100$ GeV. The function $f(y)$, where y characterizes the neutralino composition, is given by [6]

$$f(y) = \frac{567 - 108y + 1242y^2 - 12y^3 + 2023y^4}{(9 - 6y + 5y^2)^2} \quad (9)$$

and is bounded as

$$8 \leq f(y) \leq 120. \quad (10)$$

For a higgsino-like neutralino, the a/b ratio is [6]:

$$\frac{a}{b} \approx 4.1 \cdot 10^{-6} \left(\frac{m_b/5 \text{ GeV}}{m_{100}} \right)^2. \quad (11)$$

Notice that the smallness of the a/b ratio in both the gaugino- and higgsino-like neutralinos is due to the well known suppression effect in the s -wave annihilation channel (proportional to the square of the mass of the final-state fermion) due to helicity properties [8].

We recall that for the case of a neutralino of a mixed gaugino–higgsino composition the Higgs exchange in the annihilation cross section is usually important and the size of the a/b ratio depends critically on the values of the Higgs masses. For instance, for a light A Higgs boson ($M_A \lesssim 2m_\chi$) the a term dominates, at decoupling, over the b term in the annihilation cross section. This is due to the fact that, for the Higgs exchange diagrams, also the b -term is proportional to m_b^2 because of the Yukawa couplings. The case of s -wave suppression here can occur only at the pole $M_A = 2m_\chi$ (see Ref. [6]), but in this case $\Omega_\chi h^2$ is less than cosmologically needed.

Therefore, to minimize the gamma-ray production in the NS we consider the Higgsino-like neutralino with the a/b ratio given by Eq. (11). Then using Eq. (7) we obtain, for the cross-section:

$$\langle \sigma v \rangle \approx 1.7 \cdot 10^{-30} m_{100}^{-2} \text{ cm}^3 \text{ s}^{-1}, \quad (12)$$

Note that this is the smallest annihilation cross-section we can obtain. Since b is fixed by $\Omega_\chi h^2$ (Eq. (7)), the value of the cross-section in Eq. (12) is determined by the suppression of the s-wave contribution.

For a neutralino heavier than the W -boson, the situation is different. Among many channels with weak gauge bosons and Higgses in the final states, there are those where the s-wave is not suppressed at all and those where it is strictly forbidden. Thus the average suppression is not strong.

A discussion of the core radius R_c is in order now. We shall consider first the case of a pure neutralino star, with no baryon contamination. The core radius can be estimated by equating the rate of neutralino accumulation in the core, $4\pi R_c^2 n_c u_r$, and that of neutralino annihilation there, $(4\pi/3)R_c^3 n_c^2 \langle \sigma v \rangle$, where n_c is the density of neutralinos in the core and u_r is the bulk streaming velocity of neutralinos towards the centre (we shall omit the index r in the following discussion):

$$R_c = \frac{3u(R_c)}{n_c \langle \sigma v \rangle}. \quad (13)$$

To estimate u , let us consider the Euler and Poisson equations [9], which determine the flow of the neutralino gas:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{\partial \phi}{\partial r} = 0, \quad (14)$$

$$\Delta \phi = 4\pi G \rho, \quad (15)$$

where ϕ is the gravitational potential, ρ is the gas density and G is the gravitational constant.

The solution (3) corresponds to the quasi-stationary regime, when $\partial u / \partial t$ can be neglected. Putting (3) into Eq. (15) one finds

$$\frac{\partial \phi}{\partial r} = \frac{GM_\chi}{R_\chi^2} \left(\frac{r}{R_\chi} \right)^{-0.8}. \quad (16)$$

Now it is easy to solve Eq.(14), which gives

$$u(r) = \sqrt{5} \left(\frac{r}{R_\chi} \right)^{0.1} u_{ff}, \quad (17)$$

where u_{ff} is the free-fall velocity for an NS:

$$u_{ff} = \sqrt{\frac{2GM_\chi}{R_\chi}}. \quad (18)$$

Another way to estimate $u(r)$ is just to assume that it is everywhere the free-fall velocity relative to the mass inside the radius r . In this case we obtain

$$u(r) = \sqrt{0.4} \left(\frac{r}{R_\chi} \right)^{0.1} u_{ff}, \quad (19)$$

to be compared with Eq. (17).

Now by inserting Eq. (17) into Eq. (13) one finds

$$R_c = 28 R_{14}^{-0.665} m_{100}^{-3.33} M_{01}^{0.55} \text{ cm}, \quad (20)$$

where R_{14} is the radius of the neutralino star R_χ in units of 10^{14} cm and M_{01} is M_χ in units of $0.1 M_\odot$.

We shall further minimize the flux (5) by using the following set of parameters :

$m_\chi = m_W = 80$ GeV, $\eta_{\pi^0} = 10$, taken from $e^+e^- \rightarrow$ hadrons data at $\sqrt{s} = 80$ GeV, $R_h^{max} = 200$ kpc and consequently $M_h = 10^{12} M_\odot$, $\xi = 0.1$, $M_\chi^{min} = M_{macho} = 0.1 M_\odot$, $R_\chi^{max} = 1 \cdot 10^{14}$ cm, $\langle \sigma v \rangle = 2.6 \cdot 10^{-30} \text{ cm}^3 \text{ s}^{-1}$ and $R_c = 1 \cdot 10^2$ cm.

The diffuse flux at $E_\gamma > 70$ MeV is

$$I_\gamma^{min} \simeq 1 \cdot 10^7 (10^2 \text{ cm}/R_c)^{0.6} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (21)$$

almost 12 orders of magnitude higher than allowed by observations of SAS 2 and EGRET ($I_\gamma \leq 2 \cdot 10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at $E_\gamma > 70$ MeV [10]). As was mentioned above the value of I_γ in Eq. (21) is already a conservative estimate in terms of neutralino composition. Even adopting the very extreme phenomenological assumption that in the annihilation at the present time the b term is dominant (i.e. $a/b \lesssim 10^{-7}$), the value of the gamma flux would only be reduced by a factor ~ 40 , as compared with the value in Eq. (21), and then it would still be largely above the experimental bound.

Why is the flux in Eq. (21) so large? It is because we compressed the considerable fraction of the neutralino mass in the halo in the dense NS, taking the radius of neutralino star $R_\chi \leq 10^{14}$ cm from the focusing condition [2]. It is instructive to compare the flux (5) with the case when neutralinos are distributed homogeneously in the halo. The diffuse gamma-ray flux is

$$I_\gamma^{hom} = \frac{1}{4\pi} \beta_\gamma R_h, \quad (22)$$

where the rate of gamma-ray production β_γ is

$$\beta_\gamma = (n_\chi^{hom})^2 2\eta_{\pi^0} \langle \sigma v \rangle$$

and n_χ^{hom} is the homogeneous density of neutralinos in the halo. The ratio of fluxes from NS and from a homogeneous distribution of neutralinos is

$$\frac{I_\gamma^{NS}}{I_\gamma^{hom}} = 0.8 \frac{M_\chi}{\xi M_h} \left(\frac{R_\chi}{R_c} \right)^{0.6} \left(\frac{R_h}{R_\chi} \right)^3. \quad (23)$$

This ratio can be easily rewritten as

$$\frac{I_\gamma^{NS}}{I_\gamma^{hom}} \sim \frac{\langle \rho_\chi \rangle_{NS}}{\langle \rho_\chi \rangle_{hom}} \left(\frac{R_\chi}{R_c} \right)^{0.6}, \quad (24)$$

where one can easily recognize the compression factor discussed above as the ratio of average neutralino density $\langle \rho_\chi \rangle$ in the NS and in the halo. Numerically this ratio is $\sim 10^{17}$.

The flux given by Eq. (21) is obtained for a case of a pure NS. In reality the neutralino star should unavoidably have some baryonic contamination, because dissipative baryonic gas is streaming to gravitational potential minimum created by neutralino gas and is accumulated there. This phenomenon was clearly recognized and considered by Gurevich et al. (see [3] and references therein). We would like to note here that heating of the baryonic gas due to neutralino–neutralino annihilation (which was not taken into account) is very important for the dynamics of the baryonic accretion in vicinity of a singularity. For the mass of the baryonic object M_b the ratio $M_b/M_\chi \geq 10^{-3}$ was suggested in Ref. [2]. We shall use $M_b = 0.01M_\chi$ [11]. As a simple estimate shows, for this mass the neutralino trajectories are modified by the baryonic core at distances $R_c \leq 0.03R_\chi$. However, it is questionable how the space density of neutralinos is changed. In Refs. [12, 13] it is shown that the density distribution of a non-dissipative gas with baryonic contamination is the same as for a non-dissipative gas. Even assuming that the core radius is very large, $R_c = 0.1R_\chi$ [11], the calculated flux turns out to be $I_\gamma \simeq 3 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, still 5 orders of magnitude larger than allowed by observations.

In conclusion, our analysis shows that the interpretation of the observed Machos or even of a small fraction of them as neutralino stars results in too large a diffuse gamma-ray flux, many orders of magnitudes higher than the observed one ¹.

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¹We do not analyse here the peculiar case of a very light photino considered in Ref. [14]. In this model, the neutralino relic abundance is determined by a physical process different from pair annihilation, and then the procedure presented in our paper does not apply. The cross-section of photino–photino annihilation in this case can be small, since the large mass of sfermions and thus gamma-ray flux can be further suppressed. However, we remark that in this model the photino mass is constrained within $\lesssim 2 \text{ GeV}$ and then, below the range $5 \text{ GeV} \lesssim m_\chi \lesssim 50 \text{ GeV}$, allowed for the NS model of Ref.[2].

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