NEUTRALINO DARK MATTER AND CAUSTIC RING SIGNALS

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We have studied the effects on the gamma-ray flux on Earth by neutralino annihilations in caustic rings of dark matter in the Galactic halo. The caustic ring model by Sikivie has been used where dark matter particles are assumed to possess angular momentum with respect to the Galactic centre. The computer code DarkSusy was then used to examine the supersymmetric implications on the flux. We conclude that a small signal might be detectable under very optimistic assumptions, but under these only.

1 Introduction

The overwhelming evidence for Dark Matter presents to us the intriguing questions of what it might consist of and how we can detect it. Several WIMP (Weakly Interacting Massive Particle) candidates have been suggested of which one is of particularly great interest, the Lightest Supersymmetric Particle (LSP). In most scenarios this is the neutralino. The possible properties of supersymmetric particles can be examined with the Fortran computer code DarkSusy, which has been used in this work, focusing on the (not yet discovered) neutralino.

The experimental search for dark matter is an ongoing project employing many direct detection experiments, such as CDMS and DAMA. All show null results except for DAMA which claims an annual signal modulation due to the motion of the Earth about the sun and which could be explained by WIMPs. Indirect detection experiments searching for MACHO (Massive Astrophysical Compact Halo Object)-induced microlensing events, such as MACHO and EROS conclude that MACHOs alone (of mass up to 1 $M_\odot$) cannot make up the entire halo.

Another indirect detection possibility arises when studying the properties of the neutralino. Being a Majorana particle, it can self-annihilate and produce gamma photons. The annihilation rate is proportional to the square of the particle density, implying that wherever an overdensity is formed, an increased gamma flux will result from that region. Overdensities may form in different ways and recently through N-body simulations, Calcáneo-Roldán and Moore showed that primordial fluctuation-seeded hierarchical clustering
of dark matter into clumps is a most likely scenario. They also study the effects of neutralino annihilation on the gamma ray flux on Earth. This work is also supplemented in Ref.

An almost orthogonal structure formation scenario is proposed by Sikivie, where dark matter falls more or less smoothly onto the Galaxy. The infall produces continuous regions of enhanced density, caustic rings, in the dark matter halo of the Milky Way. This model and its implications for the gamma flux is studied in greater detail in the following sections.

2 Caustic rings of dark matter

2.1 Infall model

Consider a set of particles initially positioned on a spherical shell centered around an overdensity. If the age of the Universe is small enough, their motion will be governed almost solely by the Hubble flow. Eventually they will be halted by the gravity of the overdensity (galaxy), turn around, and start falling back onto the galaxy. They will then pass through the centre of the galaxy, again reach a point of turnaround, again pass the galactic centre and so on. At turnaround, the particle density will be enhanced since the phase-space sheet on which they lie will fold back there, they create a so called outer caustic.

Assuming also that the particles have acquired angular momentum similar to that of the luminous parts of the Galaxy, only the particles lying on the axis of rotation will pass through the Galaxy centre. Particles near the “equator” will produce another caustic near their point of closest approach to the Galactic centre. These are called inner caustics or caustic rings, since they will be circular density enhancements. In fact, if the particles have vanishing initial velocity dispersion, the density will diverge. The oscillation of shells will be similar with the presence of angular momentum and several caustic rings will be produced with decreasing radii due to the deepening of the potential well from the infall. Since the infall is continuous, the caustic rings will be a persistent feature in space. It turns out that we seem to be quite close to the fifth of these rings.

2.2 Density profile

In the following we will neglect the velocity dispersion when we derive the general shape and location of the caustics, but introduce a small velocity dispersion when we consider the detailed density distribution close to the caustics.
We label the particles arbitrarily by a 3-parameter, $\alpha$ (which could, for instance, be the position of the particle at a given initial time). The flow of a particle is completely specified by giving for each time its spatial coordinate $x(\alpha, t)$. If we have $n$ different flows at $x$ and $t$, we can write the solutions of $x = x(\alpha, t)$ as $\alpha_j(x, t)$, where $j = 1, \ldots, n$. To obtain the total number of particles, $N$, we integrate the number density of particles over $\alpha$-space,

$$N = \int \frac{d^3N(\alpha)}{d\alpha_1d\alpha_2d\alpha_3} d^3\alpha.$$  

(1)

Mapping onto position space gives the number density

$$d(x, t) = \sum_{j=1}^{n} \frac{d^3N(\alpha_j(x, t))}{d\alpha_1d\alpha_2d\alpha_3} \frac{1}{|D(\alpha,t)|_{\alpha_j(x,t)}},$$

(2)

where $D(\alpha, t) \equiv \det \left( \frac{\partial x}{\partial \alpha} \right)$ is the Jacobian of the map $\alpha \rightarrow x$. Wherever $D(\alpha, t) = 0$, the density will diverge, and hence caustic surfaces are associated with zeros of $D$.

We assume that the flow of particles is axially symmetric about the $\hat{z}$-axis, coinciding with the rotation axis of the Galaxy and also reflection symmetric with respect to the $\hat{x}$-$\hat{y}$-plane, i.e. under reflection $z \rightarrow -z$. We also assume the dimensions of the cross-section of the caustic ring to be small compared to the ring radius. Cylindrical symmetry suggests using cylindrical coordinates.

In Fig. 1 we show the cross section of the fifth caustic ring (which is the one closest to us), where regions with a density larger than 1 GeV/cm$^3$ have been indicated. We see that the caustic ring resembles a ‘tricusp’.

The model of Sikivie has a set of caustic parameters that describe it. To find these we assume that the turnaround sphere is initially rigidly rotating and that it initially really is a sphere, not just an axially symmetric topological sphere. We also have to make an assumption about the distribution of the smooth component of the dark matter distribution (i.e. not associated with the caustic flows). We adopt a time-independent logarithmic potential producing perfectly flat rotation curves. To obtain the caustic parameters, we have followed the procedure in Ref. 7. The interested reader can find the result and more details about the caustic parameters in Ref. 8.

A diverging density at the caustics results from our assumption of zero velocity dispersion, which of course is an over-simplified assumption. We thus reintroduce a non-zero velocity dispersion by estimating how much a given velocity dispersion would smear the caustic. We do that by considering a particle falling into the aforementioned logarithmic potential. If we change the initial velocity of the particle with the velocity dispersion, we obtain a difference in the location of the point of closest approach (i.e. the location of
Figure 1. Plot of points where the density exceeds 1.0 GeV/cm$^3$. Note that for $R_0$ between about 7.8 and 8.8 kpc, we are situated inside the ‘tricusp’. $\rho$ and $z$ are the distances from the Galactic centre and plane respectively.

the caustic ring). We can then use this difference as an estimate of how much the caustic ring is smeared by the velocity dispersion. The simplest way to take the smearing into account is to apply a cut-off in the density whenever we are closer to the caustic than the smearing scale. For a velocity dispersion of $\delta v/c = 10^{-12}$, this corresponds to a cut-off in the density at $D_{\text{cut}} \simeq 250$ GeV/cm$^3$, which we used in the calculations. To obtain the mass density, we multiply Eq. (2) by the particle mass, $m_\chi$, and the result can be found in Fig. 1, where the cross-section of the caustic ring is plotted in cylindrical coordinates by showing all points where the density exceeds 1 GeV/cm$^3$.

3 Gamma-ray flux from neutralino annihilation

Now assume that the dark matter in the caustics is in the form of neutralinos. Self-annihilation in the overdense regions into gamma rays will increase the $\gamma$-flux from that location. A continuous gamma ray spectrum mainly coming from fragmentation of quark jets will be the most prominent gamma annihila-
Figure 2. Flux of gamma rays above 1 GeV from the caustic, the smooth halo, the diffuse background and the sum of them for $\Delta \Omega = 10^{-5}$ sr. A maximum flux SUSY model was used for the signal and the smooth part. For the smooth halo a modified isothermal sphere with the scale radius $a_c = 4$ kpc and the local density $D_0 = 0.2$ GeV/cm$^3$ was used. Our galactocentric distance was set to $R_0 = 8.2$ kpc, but the results are essentially the same for other values.

The $\gamma$-ray flux from WIMP annihilations in the galactic halo is given by

$$
\Phi_{\gamma}(\eta) = \frac{N_\gamma \sigma v}{4 \pi m_\chi^2} \int_L D(\ell) \, d\ell(\eta),
$$

(3)

where $D(\ell)$ is the halo mass density of WIMPs at distance $\ell$ along the line of sight, $\eta$ is the angle between the direction of the Galactic centre and the line of sight, in the $\hat{\rho}$-$\hat{z}$-plane. $N_\gamma$ is the number of photons produced per annihilation.

Assuming a supersymmetric model giving the largest flux, we show in Fig. 2 the expected flux from the caustic ring as a function of $\eta$. We used a
galactocentric distance of $R_0 = 8.2$ kpc and Eq. was also integrated over the angular acceptance of a telescope of $\Delta\Omega = 10^{-5}$ sr. Plotted in the figure is also a fit to the EGRET data of the diffuse background gamma flux, the expected flux from annihilations in the smooth isothermal halo and the sum of the three. A significant peak can be seen in the directions of the cusps.

4 Conclusions

As can be clearly seen in Fig. 3, there is a possibility for a signal exceeding the diffuse background. However, this is under very optimistic assumptions, such as a very small velocity dispersion and a maximum flux supersymmetric model. Relaxing these would decrease the flux by orders of magnitude and make the signal vanishingly small compared to the background. If the optimistic assumptions unlikely turns out to be true, the Gamma ray Large Area Space Telescope (GLAST) launched in 2005 would be able to detect about 330 events from the closest parts of the caustic and about 1700 events from the diffuse background during one year in the same solid angle window of $0.18^\circ \times 100^\circ$.

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