DARK MATTER AND GAMMA RAYS FROM THE
GALACTIC HALO

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The nature of the dark matter in the halo of our Galaxy is still largely unknown. The microlensing events found so far towards the Large Magellanic Cloud suggest that at most about 20% of the halo dark matter is in the form of MACHOs (Massive Astrophysical Compact Halo Objects). The dark matter could also, at least partially, consist of cold molecular clouds (mainly $^{12}$C). Another possibility is that WIMPs (Weakly Interacting Massive Particles) make up the dark matter and that, due to annihilation processes, they show up through gamma-ray emission.

1 Introduction

Dixon et al.\cite{Dixon} analysed the EGRET data concerning the diffuse $\gamma$-ray flux with a wavelet-based technique, using the expected (galactic plus isotropic) emission as a null hypothesis. Although the wavelet approach does not allow for a good estimate of the errors, they find a statistically significant diffuse emission from an extended halo surrounding the Milky Way. This emission traces a somewhat flattened halo and its intensity at high-galactic latitude is

$$\Phi_\gamma(E_\gamma > 1\text{GeV}) \approx 10^{-7} - 10^{-6} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}. \quad (1)$$

There are several possible explanations for the observed halo $\gamma$-ray emission. One possibility is that it is due to the annihilation of WIMPs in the halo, which would produce monoenergetic $\gamma$-rays and also $\gamma$-rays from the decay of neutral pions generated in the particle cascades following the annihilation. Moreover, also positrons, neutrinos and in particular antiprotons would be produced, which could lead to an excess over cosmic-ray produced antiprotons at moderately high energies (above a few GeV). Several authors have analysed in detail some models which predict a $\gamma$-ray flux consistent with the one observed by EGRET. In particular, Gondolo\cite{Gondolo} considered a few GeV Majorana fermion in a model with an extended Higgs sector. The candidate has a mass of 2-4 GeV, a relic density $\Omega \approx 0.1$ and a scattering cross section off nucleons in the range $10^{-5}$ - $10^{-1}$ pb. The proposed model satisfies present observational and experimental constraints. The possibility that the $\gamma$-rays are due to pair annihilation of neutralinos, which is the lightest supersymmetric particle in the Minimal Supersymmetric Standard Model, has also been
extensively investigated. To explain the observed $\gamma$-ray flux a moderate amount of clumping of the neutralinos in the halo is required, which implies also a measurable excess of antiprotons at low energies. Similarly, it has been argued that neutralino annihilation could lead to an excess of positron production, which has indeed been measured. However, this requires a rather clumpy halo, since the annihilation cross section is small. Clearly, more measurements are required to test these models.

2 Dark clusters and cold clouds in the galactic halo

Another possibility is that a fraction of the dark matter is in the form of cold molecular clouds. Indeed, a few years ago we proposed a scenario, which relies on the Fall-Rees theory for the formation of globular clusters, and which predicts that dark clusters made of brown dwarfs and cold $H_2$ clouds should lurk in the galactic halo at galactocentric distances larger than $10 - 20$ kpc. Accordingly, the inner halo is populated by globular clusters, whereas the outer halo is dominated by dark clusters. In spite of the fact that the dark clusters resemble in many respects globular clusters, an important difference exists. Since practically no nuclear reactions occur in the brown dwarfs, strong stellar winds are presently lacking. Therefore, the leftover gas - which is ordinarily expected to exceed 60% of the original amount - is not expelled from the dark clusters but remains confined inside them. Thus, also cold gas clouds are clumped into the dark clusters. Although these clouds are primarily made of $H_2$, they should be surrounded by an atomic layer and a photo-ionized “skin”. Typical values of the cloud radius are $\sim 10^{-5}$ pc.

An important prediction of the present model is that high-energy cosmic-ray (CR) protons scattering on the clouds should give rise to a detectable diffuse $\gamma$-ray flux from the halo of our galaxy. Last but not least, the issue of the origin of MACHOs detected since 1993 in microlensing experiments towards the Magellanic Clouds remains controversial. Although the events detected towards the SMC (Small Magellanic Cloud) seem to be a self-lensing phenomenon, a similar interpretation of all the events discovered towards the LMC (Large Magellanic Cloud) looks unlikely. Yet – even if most of the MACHOs are dark matter candidates lying in the galactic halo – their physical nature is unclear, since their average mass strongly depends on the still uncertain galactic model, ranging from $\sim 0.1 \, M_\odot$ for a maximal disk up to $\sim 0.5 \, M_\odot$ for a standard isothermal sphere. At first glance white dwarfs

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\(^a\) Already in 1959 Zwicky suggested that there might be considerable amounts of $H_2$ in the Universe.
look as the best explanation, but the resulting excessive metallicity of the halo makes this option untenable, unless their contribution to halo dark matter is not substantial. So, some variations on the theme of brown dwarfs have been explored.

Finally, we remark that ISO observations of the nearby NGC891 galaxy have detected a huge amount of molecular hydrogen, which might account for almost all dark matter, at least within its optical radius.

3 γ-ray production in the galactic halo

In the following, we estimate the halo γ-ray flux produced by the clouds clumped into dark clusters through the interaction with high-energy CR protons. CR protons scatter on cloud protons giving rise (in particular) to neutral pions, which subsequently decay into photons.

As far as the energy-dependence of the halo CRs is concerned, we adopt the same power-law as in the galactic disk:

\[
\Phi_{CR}^H(E) \simeq \frac{A}{\text{GeV}} \left( \frac{E}{\text{GeV}} \right)^{-\alpha} \text{ particles cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.
\]  

(2)

The constant \( A \) is fixed by the requirement that the integrated energy flux agrees with the estimated value of CR energy density in the galactic halo \( \rho_{CR}^H \simeq 0.12 \text{ eV cm}^{-3} \). Another nontrivial point concerns the choice of \( \alpha \). As an orientation, the observed spectrum of primary CRs on Earth would yield \( \alpha \simeq 2.7 \). However, this conclusion cannot be extrapolated to an arbitrary region in the halo (and in the disk), since \( \alpha \) crucially depends on the diffusion processes undergone by CRs. For instance, the best fit to EGRET data in the disk towards the galactic centre yields \( \alpha \simeq 2.45 \), thereby showing that \( \alpha \) gets increased by diffusion. In the lack of any direct information, we conservatively take \( \alpha \simeq 2.7 \) even in the halo, but we checked that the flux does not vary substantially.

We now proceed with the evaluation of the γ-ray flux produced in halo clouds through the reactions \( pp \rightarrow \pi^0 \rightarrow \gamma \gamma \). Accordingly, the source function \( q_{\gamma} (E_{\gamma}, \rho, \ell, b) \) - yielding the photon number density at distance \( \rho \) from Earth \( (\ell, b \text{ are galactic coordinates}) \) with energy greater than \( E_{\gamma} \) - is

\[
q_{\gamma} (E_{\gamma}, \rho, \ell, b) = \frac{4\pi}{m_p} \rho_{H_2} (\rho, \ell, b) \times
\sum \int_{E_{\gamma}(E_{\pi})} \int dE_p dE_{\pi} \Phi_{CR}^H (\vec{E}_p) \frac{d\sigma_{p \rightarrow \pi}^n(E_{\pi})}{dE_{\pi}} n_{\gamma}(\vec{E}_p),
\]  

(3)
where the lower integration limit $E_p(E_\gamma)$ is the minimal proton energy necessary to produce a photon with energy $> E_\gamma$, $\sigma_{\gamma p \rightarrow n\pi^0}(E_\pi)$ is the cross-section for the reaction $pp \rightarrow n\pi^0$ ($n$ is the $\pi^0$ multiplicity), $\rho_{H_2}(\rho, l, b)$ is the halo gas density profile and $n_\gamma(E_p)$ is the photon multiplicity.

Unfortunately, it would be exceedingly difficult to keep track of the clumpiness of the actual gas distribution in the halo, and so we assume that its density is smooth and goes like the dark matter density - anyhow, the very low angular resolution of $\gamma$-ray detectors would not permit to distinguish between the two situations. Accordingly, the halo gas density profile reads

$$\rho_{H_2}(x, y, z) = f \rho_0(q) \frac{a^2 + R_0^2}{a^2 + x^2 + y^2 + (z/q)^2},$$

for $\sqrt{x^2 + y^2 + z^2/q^2} > R_{\text{min}}$, ($R_{\text{min}} \simeq 10$ kpc is the minimal galactocentric distance of the dark clusters in the galactic halo). $f$ denotes the fraction of halo dark matter in the form of gas, $\rho_0(q)$ is the local dark matter density, $R_0 = 8.5$ kpc is the distance of the Sun from the galactic center, $a = 5.6$ kpc is the core radius and $q$ measures the halo flattening. For the standard spherical halo model $\rho_0(q = 1) \simeq 0.3$ GeV cm$^{-3}$, whereas it turns out that e.g. $\rho_0(q = 0.5) \simeq 0.6$ GeV cm$^{-3}$.

At this point it is convenient to re-express $q_\gamma(> E_\gamma, \rho, l, b)$ in terms of the inelastic pion production cross-section $\sigma_{\gamma n}(p_{\text{lab}})$. Since

$$\sigma_{\gamma n}(p_{\text{lab}}) < n_\gamma(E_p) = \sum_n \int dE_\pi \sigma_{\gamma p \rightarrow n\pi^0}(E_\pi) \frac{d\sigma_{\gamma p \rightarrow n\pi^0}(E_\pi)}{dE_\pi} n_\gamma(E_p),$$

eq.(3) becomes

$$q_\gamma(> E_\gamma, \rho, l, b) = 4\pi \rho_{H_2}(\rho, l, b) \times$$

$$\int_{E_p(E_\gamma)}^{\infty} d\bar{E}_p \Phi_{C,R}(\bar{E}_p) \sigma_{\gamma n}(p_{\text{lab}}) < n_\gamma(\bar{E}_p) >,$$

where $\rho_{H_2}(\rho, l, b)$ is given by eq.(4) with $x = -\rho \cos b \cos l + R_0$, $y = -\rho \cos b \sin l$ and $z = \rho \sin b$. For the inclusive cross-section of the reaction $pp \rightarrow \pi^0 \rightarrow \gamma\gamma$ we adopt the Dermer parameterization [24].

Because $dV = \rho^2 d\rho d\Omega$, it follows that the observed $\gamma$-ray flux per unit solid angle is

$$\Phi_{\gamma DM}(> E_\gamma, l, b) = \frac{1}{4\pi} \int_{\rho_1(l, b)}^{\rho_2(l, b)} d\rho \ q_\gamma(> E_\gamma, \rho, l, b).$$

(7)
So, we find

$$\Phi_{\gamma}^{DM}(> E_\gamma, l, b) = f \frac{\rho_0(q)}{m_p} I_1(l, b) I_2(> E_\gamma),$$

(8)

where $I_1(l, b)$ and $I_2(> E_\gamma)$ are defined as

$$I_1(l, b) \equiv \int_{\rho_1(l, b)}^{\rho_2(l, b)} d\rho \left( \frac{a^2 + x^2 + y^2 + (z/q)^2}{a^2 + R_0^2} \right),$$

(9)

$$I_2(> E_\gamma) \equiv \int_{E_p(E_\gamma)}^{\infty} d\bar{E}_p \Phi_{CR}(\bar{E}_p) \sigma_{in}(p_{lab}) < n_\gamma(\bar{E}_p) >,$$

(10)

and $m_p$ is the proton mass. According to our model typical values of $\rho_1(l, b)$ and $\rho_2(l, b)$ in eqs. (8) and (9) are 10 kpc and 100 kpc, respectively.

4 Discussion

Regardless of the adopted value for the halo flattening parameter $q$, $\Phi_{\gamma}^{DM}(E_\gamma > 1 \text{ GeV})$ lies in the range $\simeq 6 - 8 \times 10^{-7} \gamma \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ at high-galactic latitude. Thus the predicted value for the halo $\gamma$-ray flux at high-galactic latitude is very close to that found by Dixon et al. This conclusion holds almost irrespectively of the flatness parameter. Moreover, the comparison of the overall shape of the contour lines with the corresponding ones of Figure 3 in Dixon et al. suggests that models with flatness parameter $q \sim 0.8$ are in better agreement with the data, thereby implying that most likely the halo dark matter in form of $H_2$ clouds is not spherically distributed.

Nevertheless, given the large uncertainties both in the data and in the model parameters one might also explain the observations with a nonstandard Inverse Compton (IC) mechanism, whereby $\gamma$-ray photons are produced by IC scattering of high-energy CR electrons off galactic background photons. Our calculation, however, points out that the corresponding IC contour lines decrease much more rapidly than the observed ones for the halo $\gamma$-ray emission (see Figure 3 in Dixon et al.). Of course, more precise measurements with a next generation of satellites are certainly needed in order to settle the issue.

As M31 resembles our galaxy, the discovery of Dixon et al. naturally leads to the expectation that the halo of M31 should give rise to a $\gamma$-ray emission as well. Clearly, a good angular resolution of about one degree or less is necessary in order to distinguish between the halo and disk emission from M31. So, the next generation of $\gamma$-ray satellites like GLAST will hopefully be able to test the predictions of our model and to discriminate among the
various proposed explanations for the γ-ray flux observed in the halo ranging from WIMP annihilation to a nonstandard IC mechanism.

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