Gamma Ray Astronomy and Baryonic Dark Matter

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ABSTRACT

Recently, Dixon et al. (1998) have re-analyzed the EGRET data, finding a statistically significant diffuse $\gamma$-ray emission from the galactic halo. We show that this emission can naturally be explained within a previously-proposed model for baryonic dark matter, in which $\gamma$-rays are produced through the interaction of high-energy cosmic-ray protons with cold $H_2$ clouds clumped into dark clusters - these dark clusters supposedly populate the outer galactic halo and can show up in microlensing observations. Our estimate for the halo $\gamma$-ray flux turns out to be in remarkably good agreement with the discovery by Dixon et al. (1998). We also address future prospects to test our predictions.

Subject headings: dark matter - diffuse radiation - Galaxy: halo - gamma rays: theory
1. Introduction and outlook

As is well known, the galactic halo chiefly consists of dark matter. A natural possibility - repeatedly considered in the past (Silk 1993, Carr 1994) - is that baryonic dark matter makes a substantial contribution. A few years ago, we recognized that the Fall & Rees theory for the formation of globular clusters (Fall & Rees 1985, Kang et al. 1990, Vietri & Pesce 1995) also leads to the existence of dark clusters - made of brown dwarfs and cold self-gravitating clouds - at galactocentric distances \( R > 10 \) kpc (De Paolis et al. 1995a-1995d, 1998a). Accordingly, the inner halo is populated by globular clusters whereas the outer halo is dominated by dark clusters. Contrary to the case of globular clusters, a large amount of residual gas should remain clumped into the dark clusters, as brown dwarfs fail to generate the strong stellar winds which expel the leftover gas from globular clusters. Moreover, although the clouds under consideration are mainly made of \( H_2 \), we expect them to be surrounded by an atomic layer and a photo-ionized “skin” (De Paolis et al. 1998a). We stress that the presence of cold self-gravitating clouds in the halo is a characteristic feature of the model in question. Remarkably enough, quite recently it has been pointed out (Walker & Wardle 1998) that cold self-gravitating clouds of the considered kind naturally explain the “extreme scattering events” associated with compact radio quasars (Fiedler et al. 1987).

Our proposal was also motivated by the discovery of microlensing events towards the LMC (Alcock et al. 1993, 1997, Aubourg et al. 1993). The first-year data were manifestly consistent with the assumption that MACHOs are brown dwarfs even within the standard (isothermal) galactic model. Unfortunately, the present situation is much less clear. An option is that the halo resembles more closely a maximal disk rather than an isothermal sphere, in which case MACHOs can still be brown dwarfs (see also Binney 1998). A more intriguing possibility has recently been suggested by Kerins & Evans (1998) and naturally fits within our model. As the initial mass function evidently changes with the galactic distance \( R \), it can well happen that brown dwarfs dominate the halo mass density without however dominating the optical depth for microlensing.

A few months ago, Dixon et al. (1998) have re-analyzed the EGRET data concerning the diffuse \( \gamma \)-ray flux with a wavelet-based technique. After subtraction of the isotropic extragalactic component and of the expected contribution from the Milky Way, they find a statistically significant diffuse emission from the galactic halo. At high-galactic latitude, the integrated halo flux above 1 GeV turns out to be \( \sim 10^{-7} - 10^{-6} \) \( \gamma \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\), which is slightly less than the diffuse extragalactic flux (Sreekumar et al. 1998).

Our aim is to show that the diffuse \( \gamma \)-ray emission from the galactic halo discovered by Dixon et al. (1998) can naturally be explained within the considered model. Basically, the idea is that cosmic-ray (CR) protons in the galactic halo scatter on halo clouds, thereby producing the observed \( \gamma \)-ray flux.

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1 Although we concentrate our attention on brown dwarfs, it should be mentioned that red dwarfs as well can be accommodated within the considered scenario.

2 Similar models have also been proposed by Ashman & Carr (1988), Ashman (1990), Fabian and Nulsen (1994, 1997), Gerhard & Silk (1996) and Kerins (1997a, 1997b).

3 It should be kept in mind that a large fraction of MACHOs (up to \( \sim 50\% \) in mass) can be binary systems, thereby counting as twice more massive objects (De Paolis et al. 1998b).

4 Notice that also the considered clouds can contribute to microlensing events (Draine 1998).
2. Cosmic ray confinement in the galactic halo

Unfortunately, neither theory nor observation allow nowadays to make sharp statements about the propagation of CRs in the galactic halo\(^5\). Therefore, the only possibility to get some insight into this issue rests upon the extrapolation from the knowledge of CR propagation in the disk. Actually, this strategy looks sensible, since the leading effect is CR scattering on inhomogeneities of the magnetic field over scales from \(10^2\) pc down to less than \(10^{-6}\) pc (Berezinsky et al. 1990) and - according to our model - inhomogeneities of this kind are expected to be present in the halo, because of the existence of gas clouds - with a photo-ionized “skin” - clumped into dark clusters\(^6\).

As is well known, CRs up to energies of \(\sim 10^6\) GeV are confined in the galactic disk for \(\sim 10^7\) yr. CRs escaping from the disk will further diffuse in the galactic halo, where they can be retained for a long time, owing to the scattering on the above-mentioned small inhomogeneities of the halo magnetic field\(^7\).

Indirect evidence that CRs are in fact trapped in a low-density halo has recently been reported. For example, Simpson and Connell (1998) argue that, based on measurements of isotopic abundances of the cosmic ratio \(^{26}\text{Al}/^{27}\text{Al}\), the CR lifetimes are perhaps a factor of four larger than previously thought, thereby implying that CRs traverse an average density smaller than that of the galactic disk.

A straightforward extension of the diffusion model (Berezinsky et al. 1990) implies that the CR escape time \(\tau_{\text{esc}}^H\) from the halo (of size \(R_H\) much larger than the disk half-thickness) is given by

\[
\tau_{\text{esc}}^H \simeq \frac{R_H^2}{3D_H(E)},
\]

(1)

where \(D_H(E)\) is the diffusion coefficient.

We recall that - for CR propagation in the disk - the diffusion coefficient is \(D(E) \simeq D_0\ (E/7\ \text{GeV})^{0.3}\) cm\(^2\) s\(^{-1}\) in the ultra-relativistic regime, whereas it reads \(D(E) \simeq D_0 \simeq 3 \times 10^{28}\) cm\(^2\) s\(^{-1}\) in the non-relativistic regime (see Berezinsky et al. 1990). As a matter of fact, radio observations in clusters of galaxies yield for the corresponding diffusion constant \(D_0\) a value similar to that found in the galactic disk (Schlickeiser, Sievers & Thiemann 1987)\(^8\). So, it looks plausible that a similar value for \(D_0\) also holds on intermediate scale lengths, namely within the galactic halo. In the lack of any further information on the energy-dependence of \(D_H(E)\), we assume the same dependence as that established for the disk. Hence, from eq. (1) - with \(R_H \sim 100\) kpc - we find that for energies \(E \lesssim 10^3\) GeV the escape time of CRs from the halo is greater than the age of the Galaxy \(t_0 \simeq 10^{10}\) yr (notice that below the ultra-relativistic regime \(\tau_{\text{esc}}^H\) gets even longer). As a consequence - since the CR flux scales like \(E^{-2.7}\) (see next Section) - protons with \(E \lesssim 10^5\) GeV turn out to give the leading contribution to the CR flux.

\(^5\)We stress that - contrary to the practice used in the CR community - by halo we mean the (almost) spherical galactic component which extends beyond \(\sim 10\) kpc.

\(^6\)Indeed, typical values of the dark cluster radius are \(\sim 10\) pc, whereas typical values of the cloud radius are \(\sim 10^{-5}\) pc (De Paolis et al. 1998a).

\(^7\)A similar idea has been proposed with a somewhat different motivation by Wdowczyk & Wolfendale (1995).

\(^8\)Moreover, we note that average magnetic field values in galactic halos are expected to be close to those of galaxy clusters, i.e. in the range 0.1 - 1 \(\mu\)G (Hillas 1984).
We are now in position to evaluate the CR energy density in the halo, getting
\[ \rho_{CR}^H \simeq \frac{3t_0L_G}{4\pi R_H^3} \simeq 0.12 \, \text{eV cm}^{-3}, \]  
(2)
where \( L_G \simeq 10^{41} \, \text{erg s}^{-1} \) is the galactic CR luminosity. Notice, for comparison, that \( \rho_{CR}^H \) turns out to be about one tenth of the disk value (Gaisser 1990).

We remark that we have taken specific realistic values for the various parameters entering the above equations, in order to make a quantitative estimate. However, somewhat different values can be used. For instance, \( R_H \) may range up to \( \sim 200 \, \text{kpc} \) (Bahcall, Lubin & Dorman 1995), whereas \( D_0 \) might be as large as \( \sim 10^{29} \, \text{cm}^2 \text{s}^{-1} \) consistently with our assumptions. Moreover, \( L_G \) can be as large as \( 3 \times 10^{41} \, \text{erg s}^{-1} \) (Völk, Aharonian & Breitschwerdt 1996). It is easy to see that these variations do not substantially affect our previous conclusions.

3. Gamma-ray emission from halo clouds

We proceed to estimate the total \( \gamma \)-ray flux produced by halo clouds clumped into the dark clusters through the interaction with high-energy CR protons. CR protons scatter on cloud protons giving rise (in particular) to pions, which subsequently decay into photons. We expect negligible high-energy (\( \geq 100 \, \text{MeV} \)) \( \gamma \)-ray photon absorption outside the clouds, since the mean free path is orders of magnitudes larger than the halo size.

An essential ingredient is the knowledge of both \( \rho_{CR}^H \) and the CR spectrum \( \Phi_{CR}(E) \) in the galactic halo. According to the discussion in the previous Section, we take \( \rho_{CR}^H \simeq 0.12 \, \text{eV cm}^{-3} \). As far as \( \Phi_{CR}(E) \) is concerned, we adopt the following power-law
\[ \Phi_{CR}(E) \simeq A \frac{1}{\text{GeV}} (\frac{E}{\text{GeV}})^{-\alpha} \, \text{particles cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \]
(3)
where the constant \( A \) is fixed by the requirement that the integrated energy flux (in the range \( 1 \, \text{GeV} \leq E \leq 10^3 \, \text{GeV} \)) agrees with the above value of \( \rho_{CR}^H \). The choice of \( \alpha \) is nontrivial. As an orientation, the observed spectrum of primary CRs on Earth entails \( \alpha \simeq 2.7 \). 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 \( \alpha \simeq 2.45 \) (Mori 1997), thereby showing that \( \alpha \) increases as a consequence of diffusion. In the lack of any direct information, we conservatively take \( \alpha \simeq 2.7 \) even in the halo, but in the Table we report for comparison some results for different values of \( \alpha \). As can be seen, the flux does not vary substantially.

Let us next turn our attention to the evaluation of the \( \gamma \)-ray flux produced in halo clouds through the reactions \( pp \rightarrow \pi^0 \rightarrow \gamma \gamma \). The source function \( q_\gamma(E) > E_\gamma, \rho, l, b \) - yielding the photon number density at distance \( \rho \) from Earth in the direction \( (l, b) \) with energy \( > E_\gamma \) - is
\[ q_\gamma(E_\gamma, \rho, l, b) = \frac{4\pi}{m_p} \rho_{H_2} \int_{E_{\pi}(E_\gamma)}^{\infty} dE_p \sigma_{in}(p_{lab}) < n_{\gamma}(E_p) > \gamma \, \text{cm}^{-3} \text{s}^{-1}, \]
(4)
where the lower integration limit \( E_{\pi}(E_\gamma) \) is the minimal proton energy necessary to produce a photon with energy \( > E_\gamma \), \( \sigma_{in}(p_{lab}) \) is the inelastic pion production cross-section, \( n_{\gamma}(E_p) \) is the photon multiplicity.

\( ^{9} \)For the inclusive cross-section of the reaction \( pp \rightarrow \pi^0 \rightarrow \gamma \gamma \) we employ the parameterization given by Dermer (1986).
and \( \rho_{H_2}(\rho, l, b) \) is the halo gas density profile \(^{10}\), which reads \(^{11}\)

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

for \( \sqrt{x^2 + y^2 + z^2/q^2} > R_{\text{min}} \), otherwise it vanishes. Here \( R_{\text{min}} \simeq 10 \) 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, \( a = 5.6 \) kpc is the core radius and \( q \) parametrizes 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\(^{-3}\).

Because \( dV = \rho^2 d\rho d\Omega \), it follows that the \( \gamma \)-ray flux per unit solid angle produced in halo clouds and observed on Earth from the direction \((l, b)\) is

\[
\Phi_{\gamma}^{\text{DM}}(> E_{\gamma}, l, b) = \frac{1}{4\pi} \int_{\rho_1(l, b)}^{\rho_2(l, b)} d\rho \ q_\gamma(> E_{\gamma}, \rho, l, b) \ \gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1},
\]

where typical values of \( \rho_1 \) and \( \rho_2 \) are 10 kpc and 100 kpc, respectively.

### 4. Discussion and conclusions

Our main result - which follows directly from eq. (6) - are maps for the intensity distribution of the \( \gamma \)-ray emission from baryonic dark matter in the halo. In order to make the discussion definite, we take \( f \simeq 0.5 \).

In Figure 1 we show the contour plots in the first quadrant of the sky \((0^0 \leq l \leq 180^0, 0^0 \leq b \leq 90^0)\) for the \( \gamma \)-ray flux at energy \( E_{\gamma} > 1 \) GeV \( \Phi_{\gamma}^{\text{DM}}(> 1 \text{ GeV}) \). Corresponding contour plots for \( E_{\gamma} > 0.1 \) GeV are identical, up to an overall constant factor equal to 8.74 (again, this follows from eq. (6)).

Figure 1a refers to a spherical halo, whereas Figure 1b pertains to a \( q = 0.5 \) flattened halo. We see that - regardless of the adopted value for \( q \) - at high-galactic latitude \( \Phi_{\gamma}^{\text{DM}}(> 1 \text{ GeV}) \) lies in the range \( \simeq 6 - 8 \times 10^{-7} \) \( \gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \). However, the shape of the contour lines strongly depends on the flatness parameter. Indeed, for \( q \gtrsim 0.9 \) there are two contour lines (for each flux value) approximately symmetric with respect to \( l = 90^0 \) (see Figure 1a). On the other hand, for \( q \lesssim 0.9 \) there is a single contour line (for each value of the flux) which varies much less with the longitude (see Figure 1b).

As we can see from the Table and the Figures, the predicted value for the \( \gamma \)-ray flux at high-galactic latitude is very close to that found by Dixon et al. (1998). This conclusion holds almost irrespectively of the flatness parameter. Moreover, the comparison of the overall shape of the contour lines in our Figures 1a and 1b with the corresponding ones in Figure 3 of Dixon et al. (1998) entails that models with flatness parameter \( q \lesssim 0.8 \) are in better agreement with data, thereby implying that most likely the halo dark matter is not spherically distributed.

\(^{10}\) As it would be exceedingly difficult to keep track of the clumpiness of the actual gas distribution, we assume that its density 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.

\(^{11}\) As usual, we use the coordinate transformation \( x = -\rho \cos b \cos l + R_0, y = -\rho \cos b \sin l \) and \( z = \rho \sin b \), where \( R_0 = 8.5 \) kpc is our galactocentric distance.
We remark that eq. (6) yields $\Phi_{\text{DM}}^{\gamma}(>0.1 \text{ GeV}) \simeq 5.9 \times 10^{-6}$ $\gamma$ $s^{-1}$ cm$^{-2}$ sr$^{-1}$ at high-galactic latitude (for a spherical halo). This value is roughly 40% of the diffuse extragalactic $\gamma$-ray emission of $1.45 \pm 0.05 \times 10^{-5}$ $\gamma$ $s^{-1}$ cm$^{-2}$ sr$^{-1}$ found by the EGRET team (Sreekumar et al. 1998). So, our result supports the conclusion of Dixon et al. (1998) that the halo $\gamma$-ray emission is a relevant fraction of the isotropic diffuse flux also for $E_\gamma > 0.1 \text{ GeV}$.

Before closing this Letter, we would like to briefly address the crucial question whether the newly discovered $\gamma$-ray halo emission really calls for a dark matter source. For, one might suspect that a nonstandard inverse-Compton $\gamma$-ray production mechanism could explain the data (owing to the large uncertainties both in the electron high scale and in the electron injection spectral index). However, this seems not to be the case. Basically, the inverse-Compton contour lines decrease much more rapidly than the observed ones. Hence, it would be impossible to explain in this manner the $\gamma$-ray flux found by Dixon et al. (1998) while still correctly accounting for the observed disk emission (Sreekumar et al. 1998). A more detailed account of this topic will be presented elsewhere.

In conclusion, we feel that - in spite of the various uncertainties - the remarkably good agreement between theory and experiment makes our model for halo dark matter worth further consideration. In particular, the next generation of $\gamma$-ray satellites like AGILE and GLAST can test our prediction, thanks to the higher sensitivity and the better angular resolution. In this respect, it might be interesting to measure whether there is an enhancement in the $\gamma$-ray flux towards the nearby M31 galaxy, since we expect a similar mechanism for the $\gamma$-ray production to hold in its halo as well.

The work of FDP is supported by an INFN grant. We would like to thank G. Bignami, P. Caraveo, D. Dixon, T. Gaisser, M. Gibilisco, G. Kanbach, T. Stanev, A. Strong and M. Tavani for useful discussions.

REFERENCES

Alcock, C. et al. 1993, Nat 365, 621
Aubourg, E. et al. 1993, Nat 365, 623
Berezinskii, V. S. et al., 1990, Astrophysics of cosmic rays (North-Holland, Amsterdam)
Binney, J., astro-ph 9809097
De Paolis, F., Ingrosso, G., Jetzer, Ph. & Roncadelli, M. 1995a, Phys. Rev. Lett. 74, 14
De Paolis, F., Ingrosso, G., Jetzer, Ph. & Roncadelli, M. 1995d, Comments on Astrophys. 18, 87
De Paolis, F., Ingrosso, G., Jetzer, Ph. & Roncadelli, M. 1998b, MNRAS 294, 283
Draine, B.T., astro-ph 9805083
Fiedler, R.L., Dennison, B., Johnston, K.J., & Hewish, A. 1987, Nature 326, 675
Hillas, A. M. 1984, ARAA 22, 425

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Fig. 1.— Contour values for the halo $\gamma$-ray flux for $E_\gamma > 1$ GeV are shown for the indicated values in units of $10^{-7} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}$, in the two cases: (a) spherical halo, (b) $q = 0.5$ flattened halo.
Table 1. Halo γ-ray intensity at high-galactic latitude for a spherical halo evaluated for $R_{\text{min}} = 10$ and 15 kpc at energies above 0.1 GeV and 1 GeV for different values of the CR spectral index $\alpha$ (see eq. (3)).

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<tr>
<th>$R_{\text{min}}$ (kpc)</th>
<th>$E_\gamma$ (GeV)</th>
<th>$\alpha$</th>
<th>$\Phi_\gamma^{\text{DM}}(b = 90^0)$ ($\gamma \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$)</th>
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