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LETTER

Letter to the Editor

H_2 dark matter in the galactic halo from EGRET

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Abstract. We present a model for the interpretation of the γ-ray background emission from the Galactic halo, which we attribute to interaction of high-energy cosmic rays with dense molecular clumps. In a wide range of clump parameters we calculate the expected γ-photon flux, taking into account for the first time optical depth effects. This allows us to derive new constraints on masses and sizes of possible molecular clumps and their contribution to the galactic surface density.

The observed γ-ray distribution can be explained best by models with a flattened halo distribution of axis ratio ~ 0.3. If optical depth effects are important, the clumps must have radii of ~ 6 AU and masses of $\sim 10^{-3}\mathrm{M}_\odot$. This would result in a total mass of $\sim 2\cdot 10^{11}\mathrm{M}_\odot$ for such clumps and contribute with $\Sigma \sim 140\ \mathrm{M}_\odot\ \mathrm{pc}^{-2}$ to the local surface density.

Key words: Galaxy: halo – gamma rays: observations – cosmology: dark matter

1. Introduction

Recent observational results of the anisotropy of the cosmic microwave background, deuterium abundance from cosmological nucleosynthesis, dynamics of clusters of galaxies and the data from the Supernova Cosmology Project provide evidence for the distribution of mass in the universe in the proportion: $\Omega_\mathrm{b} \simeq 0.05$ for baryons, $\Omega_\mathrm{m} \simeq 0.35$ for non-baryonic matter, and $\Omega_\Lambda \simeq 0.6$ for the cosmological constant (Turner, 1999). Since luminous baryons contain only $\Omega_\mathrm{b}^\mathrm{L} \simeq 0.007$, more than 85% of the baryonic mass is still undetected. Pfenniger & Combes (1994) and more recently Walker & Wardle (1998) have suggested that a considerable fraction of baryonic mass can be contained in dense molecular clumps of AU sizes and about a Jovian mass, which in turn may manifest themselves through extreme scattering events (ESEs) – dramatic flux changes of compact radio quasars over several weeks (Fiedler et al., 1987). However, estimates of this fraction are uncertain because the existing statistics of the ESEs sets a wide range for the covering factor of the radio-refracting regions: $f \sim 10^{-4}$ to $5\cdot 10^{-3}$ (Walker & Wardle, 1998). From this point of view γ-rays produced via interaction of high energy cosmic rays (CR) with nucleons of dense clumps through the process $p+p \rightarrow p+p+\pi^0 \rightarrow p+p+2\gamma$ are a unique probe of baryons hidden in dense H_2 clumps.

Recently several groups have studied the γ-ray emission from H_2 clumps in detail using EGRET ($E > 100$ MeV photons) data (Chary & Wright 1999, De Paolis et al. 1999, Dixon et al. 1998, and Sciama 1999). An essential assumption of all these attempts is that the dark matter in the halo is optically thin to both, the exposing high-energy protons, and the resulting γ-ray photons. However, as we will argue below, most of the possible baryonic dark matter candidates are dense and compact enough to allow γ-ray emission only from thin external skin layers, and thus the existing EGRET data can trace a small fraction f_T of baryons in the halo only. In this *Letter* we determine the γ-ray background emission from small optically thick H_2 clouds.

2. γ-ray emission from dense clumps

At present, no direct observations of cold, $T \sim 3\,K$, dense molecular clumps which might carry a considerable fraction of baryonic dark matter do exist, and their parameters, such as masses and radii, may vary in a wide range. Pfenniger & Combes (1994) have argued that a considerable fraction of baryonic dark matter in galaxies can be accounted for by dense clumps of predominantly molecular hydrogen of Jovian masses and radii of 30 AU. Gerhard & Silk (1996) estimated masses of $\sim 1\ \mathrm{M}_\odot$ and radii of ~ 0.03–0.1 pc. Walker & Wardle (1998) have shown that the extreme scattering events might be naturally explained if the clumps have radii of ~ 3 AU. Larger radii, ~ 10 AU, are proposed by Draine (1998) from consideration of optical lensing of stars by dense gas clouds. Quite different arguments, based on the analysis of turbulent motions of HI gas in the halo, lead Kalberla & Kerp (1998, KK98) to conclude that a significant fraction of the dark matter in the halo can be in form of gas clouds with masses of $\lesssim 2\times 10^{-3}\ \mathrm{M}_\odot$ and radii of ~ 10 AU. To distinguish between these different proposals, we need to check whether optical depth effects might affect the observed γ-ray emission. High energy (> 100 MeV) CR protons in H_2

are attenuated by a factor e for $\Sigma_{\rm CR} \simeq 40\,{\rm g\,cm^{-2}}$ (Salati et al., 1996). The mass column density of a clump along the radius is $N_{\rm c} = 4.2 \times 10^6 M/r_{\rm c}^2\,{\rm g\,cm^{-2}}$, where $r_{\rm c}$ is the clump radius in AU, M, its mass in ${\rm M_\odot}$. Using the parameters as proposed by Walker & Wardle (1998) we find from this crude estimate that $N_{\rm c}$ exceeds $\Sigma_{\rm CR}$ by two orders of magnitude. γ-photons produced inside the clumps suffer from absorption. According to Salati et al. (1996), an optical depth of one in H_2 is reached at $\Sigma_{\rm p} \simeq 80\,{\rm g\,cm^{-2}}$, twice as big as $\Sigma_{\rm CR}$.

After this first estimate we define $f_{\rm T}$ as the fraction of γ-ray emission from a dense clump relative to the emission from an optical thin cloud. We derive $f_{\rm T}$ by integrating the γ-ray emission from the sphere assuming that the in-falling cosmic rays are distributed isotropically. This in turn results in an isotropic distribution for the π^o-photons. We assume that the density ρ of the clump is constant and derive

$$f_{\rm T} = \frac{3L_{\rm CR}^2 L_{\rm p}^2}{4r_{\rm c}^5} \int_0^{r_{\rm c}} dr F_{\rm CR}(r) F_{\rm p}(r), \quad (1)$$

where $L_i = \Sigma_i/\rho$, $i = {\rm CR,\ p}$,

$$F_i(r) = e^{-(r_{\rm c}-r)/L_i}[1 + (r_{\rm c} - r)/L_i] - e^{-(r_{\rm c}+r)/L_i}[1 + (r_{\rm c} + r)/L_i]. \quad (2)$$

$f_{\rm T}$ is an approximation only, since we use frequency averaged attenuation lengths $\Sigma_{\rm CR}$ and $\Sigma_{\rm p}$, we neglect also electron Bremsstrahlung.

In Fig. 1 we display $f_{\rm T}$ as a function of the clump radius $r_{\rm c}$ for clumps with masses 10^{-4} to $10^{-2}{\rm M_\odot}$. There is significant absorption for radii $r_{\rm c} \lesssim$ 30 AU. Clouds described by Pfenniger & Combes (1994) and by Gerhard & Silk (1996) are transparent and therefore in these models the γ-ray intensity is proportional to the total mass contained in dense clouds and clumps. On the contrary, dense clumps in models described by Walker & Wardle (1998), Draine (1998), and KK98 are optically thick. In this case the determination of the mass of a baryonic dark matter halo from the observed γ-ray emission depends on $f_{\rm T}$.

The γ-ray emission is caused by nuclear interactions between cosmic rays and matter (most prominent the π^0-decay), by electron Bremsstrahlung, and by inverse Compton interactions. We used the source functions for nucleon-nucleon interactions and Bremsstrahlung as published by Bertsch et al. (1993). For the inverse Compton interaction we have used the "galprop" database according to Strong & Moskalenko (1997). The total γ-ray flux observed on Earth is a superposition of fluxes produced by dark matter halo clouds and diffuse components of the interstellar gas: the extra-planar diffuse ionized gas (Dettmar, 1992), the H I disk, and the gaseous halo with H I gas and plasma (KK98). The density $\rho_i(R_{\rm g}, z)$, ($R_{\rm g} = \sqrt{x^2 + y^2}$), of the various gaseous components is given by

$$\rho_i(R_{\rm g}, z) = n_i g_1(R_{\rm g}) \exp\left[\frac{-\Phi(z)}{\sigma_i^2\ (1 + \alpha_i + \beta_i)}\right] \quad (3)$$

with n_i, the local midplane density of the individual component, $\Phi(z)$ the gravitational potential, σ_i the corresponding velocity

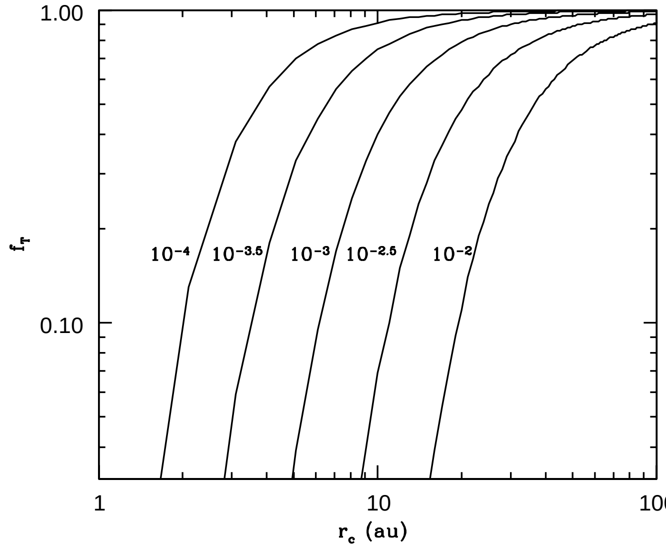

Fig. 1. $f_{\rm T}$, the fraction of the γ-ray emission from a clump with radius $r_{\rm c}$ relative to the emission from an optical thin H_2 cloud. The curves are for clump masses 10^{-4} to $10^{-2}{\rm M_\odot}$.

dispersion, and α_i and β_i according to Parker (1966) quotients which determine the pressure of the magnetic field and cosmic rays relative to the gas pressure. According to KK98 *all* gaseous components have a common radial density distribution according to

$$g_1(R_{\rm g}) = {\rm sech}^2(R_{\rm g}/A_1)/{\rm sech}^2(R_\odot/A_1), \quad (4)$$

with a radial scale length $A_1 = 15$ kpc. This relation was introduced by Taylor & Cordes (1993) to describe the diffuse ionized gas component. The scale height of the gaseous halo according to KK98 is $h_{\rm z} = 4.4$ kpc.

A widely used standard expression to describe the density distribution in the galactic halo is (e.g. De Paolis et al., 1999)

$$\rho_{\rm H_2}(x, y, z) = \rho_0(q) \frac{a^2 + R_0^2}{a^2 + x^2 + y^2 + (z/q)^2}, \quad (5)$$

where $x,\ y,\ z$ are the galactocentric coordinates, R_0 is the Solar distance, $\rho_0(q)$, the local dark matter density.

3. Model calculations

We discuss here several models for the distribution of diffuse gas components and the dark matter clumps in detail:

1) the disk, the extra-planar diffuse ionized gas and the (observed) gaseous halo with parameters as in KK98 model according to Eq. (3) and (4). The local midplane density of the γ-ray emitting gas is $n_0^{\rm h} = 0.0025\,{\rm cm^{-3}}$, and the CR density is derived from the pressure equilibrium with the observed gas. In this model there is *no* significant γ-ray emission from the halo.
2) same as the previous model with the best fit local midplane density of the halo γ-ray gas $n_0^{\rm h} = 0.065\,{\rm cm^{-3}}$. In this model the flat rotation curve demands a local total midplane

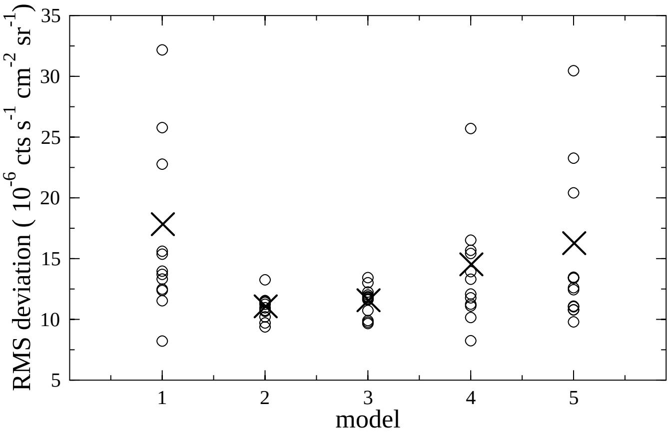

Fig. 2. RMS deviations between observations and model calculations as described in Sect. 3. The RMS scatter derived for individual scans at constant longitudes is displayed as circles, the total RMS deviation between model and data is given by the crosses.

density $n_0^{\rm d} = 0.7\,{\rm cm}^{-3}$ (KK98). Assuming that the total dark matter in the Milky Way is contained in H_2 clumps, we obtain $f_{\rm T} = 0.09$.

3) the dark matter halo with a distribution in the form (5) with $a = 5.6$ kpc, $q = 0.3$, $R_0 = 8.5$ kpc, and a constant CR energy density in the halo of 0.12 eV cm^{-3}. This model is similar to the model of De Paolis et al., however without a central hole in the dark matter distribution at $R < 10$ kpc. We fit a local midplane density $n_0^{\rm h} = 0.55\,{\rm cm}^{-3}$. For a rotation velocity of $v_\odot = 220\,{\rm kms}^{-1}$ we derive $n_0^{\rm d} = 0.5\,{\rm cm}^{-3}$, hence $n_0^{\rm h}/n_0^{\rm d} = 1.1$. According to Eq. (1) $f_{\rm T} \le 1$, and within the errors we obtain for this model $f_{\rm T} = 1$.
4) same as the previous model but with $q = 1$ and $n_0^{\rm h} = 0.18\,{\rm cm}^{-3}$, we derive $n_0^{\rm d} = 0.24\,{\rm cm}^{-3}$ corresponding to $f_{\rm T} = 0.75$.
5) same as the model 4, but with a central hole for $R < 10$ kpc. We determine $n_0^{\rm h} = 0.35\,{\rm cm}^{-3}$. This is the model proposed by De Paolis et al. (1999) with $n_0^{\rm d} = 0.32\,{\rm cm}^{-3}$. This model cannot reproduce the rotation velocity observed in the inner galaxy; $f_{\rm T}$ is undefined.

We estimate the errors in the determination of $n_0^{\rm h}$ and $n_0^{\rm d}$ to about 10%. The isotropic γ-ray background was fitted to $5(\pm1)\cdot10^{-6}{\rm cts\ s}^{-1}\,{\rm cm}^{-2}{\rm sr}^{-1}$, in good agreement with the rate of $4(\pm1)\cdot10^{-6}{\rm cts\ s}^{-1}\,{\rm cm}^{-2}{\rm sr}^{-1}$ due to blazars as determined by Mukherjee & Chiang (1999).

4. Discussion and conclusions

For all models we calculated the RMS deviation between data and model, individually for each of the scans at constant longitude and further for all of the data under consideration (Fig. 3). We found that the RMS values derived this way were for all of the models biased by a number of positions with significant deviations between model and data. Predominantly the deviations were due to γ-ray excess from point sources, but also from extended regions like the Orion complex which are not part of the model (see Fig. 3 at longitude $l = 180°$). At a few positions the emission was found to be systematically low. We decided to disregard these isolated regions and excluded 6% of the data, identical for all models, from the RMS determination.

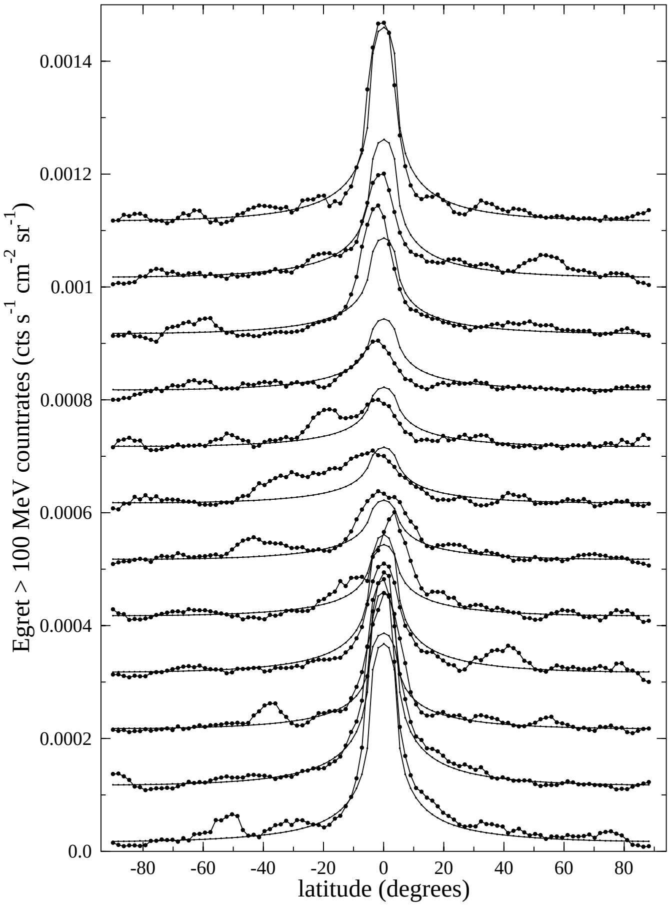

Fig. 3. The EGRET diffuse γ-ray emission ($E_\gamma > 100$ MeV) observations – lines with dots, and best fit model 2 – solid lines. The longitude l varies from 0° (bottom) to 300° (top) in steps of $\Delta l = 30°$.

Fig. 2 presents the derived RMS deviations for our models. Model 1 is not a fit but gives the residual γ-ray emission after subtracting the γ-ray emission from disk and diffuse ionized gas. For the models 2 to 5 the additional emission originating from a baryonic halo has been calculated. Model 2 represents the best fit. The RMS deviation between data and model (crosses) as well as the scatter between individual scans at constant longitudes (circles) is minimal. In Fig. 3 we plot model 2 in comparison with the observations.

The models which have been represented in Fig. 2 have been supplemented by additional calculations with various core radii a and flattening parameters q according to (5). We found $0.2 \lesssim q \lesssim 0.4$ and $a \sim 5.6$ kpc to fit the observations well, however, in no case we could recover the best fit results of model 2. A flattening parameter $q = 0.3$ corresponds to the flattening of model 2, which has no free parameters concerning the shape of the halo.

Halos with a flattening parameter $q \gtrsim 0.4$ barely fit the observations. In particular, spherical halo models, as represented by model 4 and 5, result in very poor fits. Flat dark matter models with $q \lesssim 0.2$ or models with a scale height $h_z \lesssim 1$ kpc for the CR distribution (Combes & Pfenniger 1996) also do not fit the EGRET data in a satisfactory way.

Concerning the question, whether the γ-ray emission from H_2 clumps suffers from obscuration as defined by f_T in Eq. (1), we need to distinguish two cases, the transparent and the opaque model. For model 3 we derive $f_T = 1$. From Fig. 1 it is obvious that the radii of the clumps must be large, $r_c \gtrsim 20$ AU. Such models have been detailed by Pfenniger & Combes (1994), by Combes & Pfenniger (1996), and by Gerhard & Silk (1996). For model 2 we derive $f_T = 0.09$, the opaque case. The clumps have masses of $\sim 10^{-3}M_\odot$ and radii $r_c \sim 6$ AU. For masses of 0.3–$3 \cdot 10^{-3}M_\odot$ we derive radii between 3 and 10 AU respectively. The lower values are close to the radii estimated by Walker & Wardle (1998) from their explanation of extreme scattering events. Our upper limit corresponds to the estimates by Draine (1998) and by KK98.

The major difference between model 3 and 2 is the assumption concerning the distribution of cosmic rays on large scales. Models 3 to 5 are based on a constant energy density of 0.12 eV cm^{-3} out to distances of 100 kpc (De Paolis et al. 1999). In model 2 it is assumed that the cosmic rays are in pressure equilibrium with the observed gaseous halo. This results in a rather narrow distribution with an exponential scale height of $h_z \sim 4.4$ kpc. According to current diffusion models, the distribution of cosmic rays is restricted to z-scales of 2–4 kpc (Webber & Soutoul 1998) or to 4.9^{+4}_{-2} kpc (Ptuskin & Soutoul 1998). Similar parameters were used by Salati et al. (1996). Their conclusion, that only about 3% of the γ-ray flux which is expected for a gaseous dark matter halo can be observed is in good agreement with our determination of f_T. Strong et al. (1999) favor CR re-acceleration and determine z-scales of 4–10 kpc. In this case also the inverse Compton emission at high latitudes would be affected. Using parameters as proposed by Strong et al. (1999) for z-scales of 4–10 kpc leads to an increase of the RMS deviation between model and data. Clump radii, however, are affected by $\lesssim 10\%$ due to the steep gradient of f_T (Fig. 1).

Since there is no observational evidence for a cosmic ray halo at z-scales exceeding 10 kpc, we adopt our best fit model 2. We interpret the residual observed γ-ray emission after subtraction of the emission from disk and diffuse ionized gas layer as due to H_2 clumps with masses of $\sim 10^{-3}M_\odot$ and characteristic radii of $r_c \sim 6$ AU. Such clumps, exposed to cosmic rays, are optical thick and emit γ-rays only close to their surfaces. The Milky Way dark matter halo may contain $\sim 10^{14}$ such H_2 clumps with a total mass of $\sim 2 \cdot 10^{11}M_\odot$. The local surface column density of these clumps then is $\Sigma \sim 140\ M_\odot\,\mathrm{pc}^{-2}$ (KK98).

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