Light Dark Matter and the 511 keV line

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We discuss the conditions for decaying or annihilating Light Dark Matter (LDM) particles to explain the flux and extension of the 511 keV line emission in the galactic centre.

1 Introduction

An emission line at 511 keV was detected at the galactic centre three decades ago[1]. Its identification as an electron-positron annihilation line followed as soon as high-resolution spectrometers became available[2], but the origin of low-energy galactic positrons is still a matter of heated debate. The latest observations of the annihilation emission have been performed by the SPI spectrometer aboard the INTEGRAL[a] satellite. A total flux of $\approx 10^{-3}$ photons s^{-1} cm^{-2} was measured, in agreement with previous estimates. The morphology of the galactic bulge emission could be fit by a Gaussian with $\sim 10°$ FWHM.

Several astrophysical sources have been proposed in the literature to explain the low-energy positrons, such as radioactive nuclei expelled by stars (supernovae, hypernovae, novae, Wolf-Rayet stars and red giants) and collapsed objects (neutron stars or black holes). Nevertheless, most of these sources[3] cannot account for the observed morphology, due to the large bulge-to-disc ratio of the emission, which suggests an old stellar population origin, unless rather elaborate mechanisms (e.g. jets, propagation) are invoked.

The presence of low-energy positrons could however be explained by Dark Matter (DM) annihilations[4] or decays[5,6]. The window for Light Dark Matter (LDM) particles opened when it was realized that scalar candidates with a mass from a few MeV to a few GeV, coupled to heavy fermions (F) or to light neutral particles (neutral gauge bosons Z', somewhat analogous to the Z gauge boson), could yield the observed relic density[7]. However, to avoid an overproduction of low energy gamma rays in our galaxy, it was found that the exchange of heavy fermions should be suppressed by at least five orders of magnitude (times $m^2_{\rm MeV}$, the square of the DM mass normalized to MeV) with respect to the one due to the new gauge boson[8].

Here we show that Light Dark Matter particles can explain the 511 keV line observation, provided that the radial density profile of the dark halo is as cuspy as in a Navarro-Frenk-White model. This constrains the dark matter to be a scalar rather than a fermion and has consequences for the anomalous magnetic moment of the electron (and potentially of the muon).

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[a] INTEGRAL (International Gamma Ray Laboratory) is an ESA's gamma ray observatory.

2 Theoretical positron distribution

We assume that i) most galactic positrons originate from the decays or annihilations of LDM particles, ii) they are relativistic at the moment of their creation ($E_{\mathrm{e}^+} \sim m_{\mathrm{dm}}c^2$) and iii) they can efficiently lose their energy through collisional ionization (or excitation in neutral Hydrogen and by interaction with plasma waves in ionized interstellar medium) so they do not travel long distances. The number density of positrons produced per unit of time is given by the number density of dark matter particles, n_{dm}, times Γ_{d} or $\Gamma_{\mathrm{a}} = \langle \sigma v_r \rangle n^{\star}_{\mathrm{dm}}$, with $n^{\star}_{\mathrm{dm}} = n_{\mathrm{dm}}$ and $\langle \sigma v_r \rangle$ the thermal average of the annihilation cross-section times the DM relative velocity. The latter can be written as $\langle \sigma v_r \rangle \approx a + bv^2 + O(v^4)$, where both v and v_r are expressed in units of the speed of light, c. We normalize a and b to 10^{-26} cm^3 s^{-1} and Γ_{d} to 10^{-26} s^{-1}, yielding the notation a_{26}, b_{26} and Γ_{26}. We parameterize the radial density profile as

$$\rho(r) = \frac{\rho_0}{(r/r_0)^{\gamma}\,[1 + (r/r_0)^{\alpha}]^{(\beta-\gamma)/\alpha}}, \tag{1}$$

where ρ_0 and r_0 are a characteristic density and radius of the halo, γ is the asymptotic logarithmic slope at the centre, β is the slope as $r \to \infty$ and α controls the exact shape of the profile in the intermediate regions around r_0.

Many different sets of values have been suggested for these parameters. Given the controversy, we considered four different models with (α, β, γ, r_0 in kpc, ρ_0 in GeV cm^{-3}): M99 (1.5, 3, 1.5, 29.5, 0.0536), NFW (1, 3, 1, 16.7, 0.347), BE (1, 3, 0.3, 10.2, 1.459) and a non-singular isothermal sphere, hereafter ISO (2, 2, 0, 4.0, 1.655). We also consider a family of models in which α and β are fixed to 1 and 3, respectively, while γ is varied in uniform steps $\Delta\gamma = 0.1$. The normalization of the models, ρ_0, is set by imposing a local dark matter density $\rho(r_{\odot}) = 0.3$ GeV cm^{-3}, with $r_{\odot} = 8.5$ kpc. The characteristic radius r_0 has been chosen so that the virial radius and mass are $R_{\mathrm{vir}} \approx 260$ kpc and $M_{\mathrm{vir}} \approx 10^{12}$ M$_{\odot}$. Note that the ISO model can only approximately satisfy this condition.

The characteristic velocity of dark matter particles is also a necessary ingredient in our model of the Milky Way. We derive the velocity dispersion profiles from the spherically-symmetric Jeans equation and find

$$\sigma^2(r) = \frac{3}{\rho(r)} \int_r^{\infty} \rho(r) \frac{GM(r)}{r^2}, \tag{2}$$

assuming no radial infall, an isotropic velocity ellipsoid and vanishing velocity dispersion at infinity. The total number of 511 keV photons produced per unit time[9,10,11] is given by

$$\dot{n}_{\gamma} = 2\,(0.07 + 0.93/4)\,\dot{n}_{\mathrm{e}^+} = 0.605\,\dot{n}_{\mathrm{e}^+} \quad \text{with} \quad n_{e^+} = n_{dm}\,\Gamma_{d,a}. \tag{3}$$

The predicted intensity distribution is then obtained by integrating along the line of sight, as a function of galactic longitude l and latitude b, the emissivity $\dot{n}_{\gamma}(r)$,

$$I(l,b) = \frac{1}{4\pi} \int_0^{\infty} \dot{n}_{\gamma}(r)\,\mathrm{d}s. \tag{4}$$

The spatial dependence arises through the radial density and relative velocity profiles $n_{\mathrm{dm}}(r) = \rho(r)/m_{\mathrm{dm}}$ and $v^2 \equiv v^2_{\mathrm{dm}}(r) \approx \sigma^2(r)$. The total photon flux at the earth is then simply given by:

$$\Phi = \int I(l,b)\,\mathrm{d}\Omega. \tag{5}$$

The concentration of the emission depends on the shape of the Milky Way halo as well as on Γ_a or Γ_d. Observations are mostly sensitive to the detail of the central part, where the intensity of the 511 keV line is highest. In order to compare with observational data, intensity maps

DM	MW	$\Phi_{\rm tot}\, m^2_{\rm MeV}$	$\Phi_{\rm cen}\, m^2_{\rm MeV}$
Γ_d	ISO	$0.0459\ \Gamma_{26}$	$0.0201\ \Gamma_{26}$
	BE	$0.0439\ \Gamma_{26}$	$0.0195\ \Gamma_{26}$
	NFW	$0.0478\ \Gamma_{26}$	$0.0232\ \Gamma_{26}$
	M99	$0.0512\ \Gamma_{26}$	$0.0262\ \Gamma_{26}$
a	ISO	$5.13\ a_{26}$	$3.175\ a_{26}$
	BE	$5.21\ a_{26}$	$3.325\ a_{26}$
	NFW	$9.52\ a_{26}$	$7.487\ a_{26}$
	M99	$26.6\ a_{26}$	$24.5\ a_{26}$
b	ISO	$1.92 \times 10^{-6}\ b_{26}$	$1.12 \times 10^{-6}\ b_{26}$
	BE	$1.87 \times 10^{-6}\ b_{26}$	$1.11 \times 10^{-6}\ b_{26}$
	NFW	$2.93 \times 10^{-6}\ b_{26}$	$2.10 \times 10^{-6}\ b_{26}$
	M99	$5.90 \times 10^{-6}\ b_{26}$	$4.97 \times 10^{-6}\ b_{26}$

Table 1: Theoretical photon fluxes (in $\rm cm^{-2}\ s^{-1}$) expected for different halo profiles and DM type.

$I(l,b)$ have been computed for $|l| < 60°$ and $|b| < 50°$. The total flux within this area is denoted by $\Phi_{\rm tot}$. However, a fairer comparison with the flux measured by the satellite is given by the central 33° ($\sim$ 1 steradian). We shall quote this flux as $\Phi_{\rm cen}$. The values of $\Phi_{\rm tot}$ and $\Phi_{\rm cen}$ for decaying/annihilating dark matter type and different radial density profiles are given in Table 2.

3 Comparison with SPI data

Our analysis has been performed on the December 10, 2004 public INTEGRAL data release, which consists of ≈309 days of observations. In order to reduce systematic uncertainties in the analysis, we exclude observation periods with strong instrumental background fluctuations[b]. The total effective exposure time after cleaning is 15.3 Ms. The exposure is quite uniform in the central regions of our Galaxy ($|l| < 50°$ and $|b| < 30°$). We use a maximum likelihood algorithm to compare the theoretical sky maps with the INTEGRAL/SPI data. This method has already been applied to SPI data to characterize the morphology of the annihilation. A detailed description can be found in[3].

Briefly, the normalization of each theoretical model is fitted to reproduce the measured rate in the 507.5 – 514.5 keV energy range, taking into account an instrumental background model, the pointings history and the spatial and energy response functions of SPI. Normalized maps have been convolved with the response function, providing the expected number of counts in each detector as a function of the pointing periods. We then find the intensity that maximizes the log likelihood. We subtract from this log likelihood L_1 the log likelihood L_0 that is calculated under the hypothesis that there is no 511 keV source. Multiplication by a factor of 2 provides the maximum log-likelihood ratio, $\mathrm{MLR} = 2\,(L_1 - L_0)$, which is a measure of how well the sky map of the dark matter model under study does indeed fit the INTEGRAL/SPI data.

Results of the model-fitting procedure are presented in Table 3. As in the theoretical models, $\Phi_{\rm tot}$ is the total flux of the map, integrated over the whole solid angle, while $\Phi_{\rm cen}$ is restricted to an aperture of 33°. When comparing two models, the one with the largest MLR explains the data better than the other, although differences $\Delta_{\rm MLR} < 10$ are not very significant.

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[b] These background variations are generally due to solar flares or exit and entry of the observatory in radiation belts.

DM	MW	$\Phi_{\rm tot}$	$\Phi_{\rm cen}$	MLR
Γ_d	ISO	6.82 ± 0.58	2.95 ± 0.25	135.2
	BE	7.23 ± 0.57	3.18 ± 0.25	167.3
	NFW	7.36 ± 0.46	3.53 ± 0.22	261.2
	M99	6.86 ± 0.37	3.48 ± 0.19	332.0
a	ISO	5.55 ± 0.33	3.40 ± 0.20	282.8
	BE	4.98 ± 0.27	3.16 ± 0.17	353.6
	NFW	2.49 ± 0.11	1.95 ± 0.09	459.9
	M99	0.83 ± 0.04	0.76 ± 0.04	339.2
b	ISO	6.00 ± 0.38	3.46 ± 0.22	258.3
	BE	5.76 ± 0.32	3.40 ± 0.19	305.7
	NFW	3.61 ± 0.18	2.57 ± 0.13	422.4
	M99	1.57 ± 0.07	1.32 ± 0.06	430.0

Table 2: Results of the model-fitting analysis. Fluxes in units of 10^{-3} cm^{-2} s^{-1}.

4 Results

One can readily see that the best fit to the observed spatial distribution of the 511 keV emission is provided by the model with an a-term (i.e. velocity-independent cross-section) and a NFW profile. The flux obtained for this combination is in agreement with the results of[3] for bulge or halo models (albeit a bit smaller) but it is substantially higher than that reported in[12] for a Gaussian source. Comparing with our theoretical prediction in Table 2, we obtain

$$a_{26} = (2.6 \pm 0.12) \times 10^{-4}\ m_{\rm MeV}^2, \tag{6}$$

which confirms that the LDM scenario requires both an a and b-term when $m_{\rm dm} < 100$ MeV. This implies for scalar dark matter particles:

$$\frac{m_F}{100\ \rm GeV} \simeq 6\ 10^3\ c_l\, c_r\ \left(\frac{m_{dm}}{\rm MeV}\right)^{-1}, \tag{7}$$

where the two couplings c_l and c_r are expected to be lower than unity (a few units at most).

On the other hand, we obtain $\frac{m_F}{100\ \rm GeV} \sim 0.145\ \sqrt{(c_l^2 + c_r^2)}$ for Dirac dark matter particles and $\frac{m_F}{100\ \rm GeV} \sim 0.206\ c_l\, c_r$ for Majorana candidates which indicate (for realistic values of the couplings) that the F mass should be much smaller than 100 GeV to explain the observed emission. Since the presence of charged particles much lighter than $\sim$ 100 GeV has been excluded by LEP data, one readily sees that fermionic LDM particles cannot explain the 511 keV line emission unless one considers couplings at the edge of perturbativity. Fermionic particles are therefore likely to be excluded. Our results also indicate that a Z' cross-section cannot explain the observed 511 keV emission on its own. A cross-section strictly proportional to v^2 can be ruled out by $\Delta_{\rm MLR} \geq 29.9$, suggesting that the boson-exchange channel plays only a minor role within the Milky Way halo (albeit ensuring the correct relic density).

Since we find $\gamma = 1$, other profiles suggested in the literature would be extremely hard to reconcile with the INTEGRAL/SPI data. This is at odds with[4], where a shallower profile with $\gamma \sim 0.6$ was favoured, based on a coarser comparison between the theoretical predictions and the observed flux and extension of the emission. For the density profiles considered in the present work, decaying dark matter is completely incompatible with the observed morphology of the 511 keV emission, unless maybe one considers a much steeper profile[13].

Finally, we would like to stress that the constraint we obtain for the inner asymptotic slope of the density profile is so tight that, if the Milky Way dark halo was found to follow a different shape by some independent means, the possibility that dark matter annihilations were the main source of galactic positrons would seem rather unlikely. Systematic effects would in general tend to yield values of γ below the real one, so our estimate should be regarded, to a certain extent, as a lower limit. If DM is responsible for the 511 keV emission, $\gamma > 1$. If $\gamma < 1$, galactic positrons must come from a different physical process.

F particles have important consequences on the electron/muon anomalous magnetic moment. They add a contribution $\delta a^F_{\mu} \sim \frac{c_l c_r}{16\pi^2} \frac{m_{\mu,e}}{m_{F_{\mu,e}}} > 0$ leading, in our case, to: $\delta a_e^F \sim 5.41\ 10^{-12}\ \frac{m_{dm}}{\mathrm{MeV}}$. There is a small discrepancy between the theoretical value of a_e (hereafter denotes a_{th}) and its measurement (a_{exp}):

$$\Delta a_e = (a_{exp} - a_{th}) \sim (3.44 - 3.49)\ 10^{-11}. \tag{8}$$

The first number is obtained from the positron g-2, while the second one is from the electron. To estimate Eq.8, we use $a_{th} = f(\alpha)$ with $\alpha = \alpha_{QH}$ (the fine structure constant as measured by Quantum Hall effect (QH) experiments). There are other experiments aiming at measuring α but QH experiments seem the most precise at present (see e.g. [14]).

We now readily see that δa_e^F can be of the order of Eq.8 if $m_{DM} \sim 6.4$ MeV (taking the average value of a_{th} computed with α_{QH}, see[14]). For smaller DM masses, we obtain $\delta a_e^F \leq \Delta a_e$ and for larger DM masses, we obtain $\delta a_e^F \geq \Delta a_e$. There is no direct measurement of α that is as precise as the $g-2$ as yet. Therefore, it is hard to exclude values above 7 MeV. But, this certainly places a very strong contraint and motivates further experiments measuring the value of the fine structure constant directly (and independently of QED). If these experiments find a perfect agreement with the value recommended in the CODATA, then the LDM scenario will have difficulties in explaining the 511 keV line emission. If they found a discrepancy (whether it is positive or negative) then LDM will remain a serious candidate because it would be the sign of new physics. In particular, if the value α_{QH} is confirmed, then the LDM scenario may reconcile the results from both $g-2$ and α experiments, despite the difference of sensitivity.

Taking the same couplings and the same mass m_F for F_e as for F_μ, we obtain a very large contribution to the muon $g-2$. Our prediction, in fact, exceeds the experimental value by a factor 2-3, which itself is larger than the Standard Model prediction [15]. It was found $\Delta a_\mu = (a_{exp} - a_{th}) \in [1.6, 2.7]\ 10^{-9}$. So, by using $m_{\mathrm{MeV}} \sim 6-7$ and $m_{F\mu} = 3m_{Fe}$ (or e.g. $m_{F\mu} = 2m_{Fe}$ and smaller couplings to the muons), our prediction for the muon $g-2$ becomes compatible with the experimental value. In fact, the LDM scenario would even explain the well-known discrepancy. Note that such a hierarchy exists in the Standard Model and it is very realistic to assume that it exists also in any other extensions.

Hence, the LDM scenario could in fact explain both the experimental values of the fine structure constant and the muon $g-2$ for $m_{dm} \approx 6-7$ MeV.

5 Conclusions

Convoluting the theoretical expectations of the positron distribution for different DM models and galactic density profiles with the SPI response function and using the resulting maps as a source for the INTEGRAL model-fitting analysis, we can rule out from a likelihood analysis the possibility that decaying dark matter is responsible for the observed emission, unless the density profile of the Milky Way dark halo turns out to be extremely cuspy (with inner asymptotic slope $\gamma > 1.5$). We can also exclude fermionic LDM particles.

We showed that the exchange of a heavy fermion (F_e) is required in order to fit the morphology of the 511 keV line, while the existence of a Z' boson would be necessary to satisfy the relic density criterion. The most promising signature of F particles is their contribution to the electron $g-2$ which would make the measurements of the fine structure by the Quantum Hall experiment and the electron anomalous magnetic moment compatible for $m_{dm} \sim 6-7$ MeV.

Hence, the value of α recommended in the CODATA (and used for many estimates) may not be the correct one. Assuming the existence of a spectrum (and, in particular, F_μ particles), we also find a non-negligible contribution to the muon $g-2$. Both F_e and F_μ could then explain the discrepancy between the Standard Model predictions and the experimental values of the muon $g-2$ and the fine structure constant. Alternatively those could provide a way to constrain the LDM scenario.

Our results indicate that LDM can only explain the observed 511 keV emission if our galaxy features a cuspy density profile. The best-fitting inner asymptotic slope is found to be $\gamma = 1.03 \pm 0.04$. To sum up, the 511 keV emission line provides extremely stringent constraints on the light dark matter parameters. Observations of the density profile of the Milky Way have the possibility to rule out a dark-matter related origin of galactic positrons if the density profile of our galaxy is found to be shallow at the centre. Alternatively, the discovery of LDM particles would have a tremendous impact on the determination of our dark halo profile.

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