Possible Evidence for MeV Dark Matter in Dwarf Spheroidals

Dan Hooper,[1] Francesc Ferrer,[1,2] Céline Boehm,[1] Joseph Silk,[1,3] Jacques Paul,[4] N. Wyn Evans,[5] and Michel Casse[3,4]

[1]*Astrophysics Department, University of Oxford, Oxford, United Kingdom*
[2]*Theoretical Physics, University of Oxford, Oxford, United Kingdom*
[3]*Institut d'Astrophysique de Paris, France*
[4]*CEA-Saclay, DSM/DAPNIA/Service d'Astrophysique, F-91191 Gif-sur-Yvette, France*
[5]*Institute of Astronomy, University of Cambridge, Cambridge, United Kingdom*

The observed 511 keV emission from the galactic bulge could be due to very light (MeV) annihilating dark matter particles. To distinguish this hypothesis from conventional astrophysical sources, we study dwarf spheroidals in the region observed by the International Gamma-Ray Astrophysics Laboratory/SPI such as Sagittarius. As these galaxies have comparatively few stars, the prospects for 511 keV emission from standard astrophysical scenarios are minimal. The dwarf spheroidals do, however, contain copious amounts of dark matter. The observation of 511 keV emission from Sagittarius should be a ''smoking gun'' for MeV dark matter.

Introduction.—Although particle dark matter is generally thought to be in the 10 GeV–1 TeV mass range [1], it has been shown that a 1–100 MeV candidate is, in fact, possible [2]. Recent observations of a bright 511 keV γ-ray line from the galactic bulge may be the first experimental evidence for light (1–100 MeV) annihilating dark matter particles [3].

Such particles could annihilate throughout the galactic bulge and inner halo into positrons (and electrons) which, after losing energy, annihilate into 511 keV gamma rays. The observations of 511 keV emission from the galactic bulge, made by INTEGRAL (International Gamma-Ray Astrophysics Laboratory) [4], and previously by Compton Gamma-Ray Observatory [5], could possibly be explained by a wide variety of astrophysical scenarios. Proposed sources include neutron stars or black holes [6]; radioactive nuclei from supernovae, novae, red giants, or Wolf-Rayet stars [7]; cosmic ray interactions with the interstellar medium [8]; pulsars [9]; and stellar flares.

A popular class of possible sources is type Ia supernovae. The frequency of such events required to produce a sufficient number of positrons is ∼0.6 per century (assuming an escape fraction of 4% [10]), however, well above the prediction of current models (0.03 per century within a factor of 3) [11–13]. Alternatively, massive Wolf-Rayet stars (hypernovae) of the SN 2003dh type [14], exploding in the galactic center are possible candidates [11], but their rate is unknown. Also, even if a very large flux of positrons were injected into the galactic center, it is not likely that the whole galactic bulge could be filled, even if a bipolar galactic wind is produced by star bursts [15]. If a "galactic positron fountain" were to exist [16], the annihilation rate at high altitude is too low, due to the small density of the wind, to explain the extension of the 511 keV source [17].

Despite these arguments, it is difficult to be confident that none of these more standard astrophysical explanations are responsible for the observed 511 keV line from the galactic bulge. To more strongly motivate the light dark matter annihilation scenario, further evidence is needed.

Dwarf spheroidal galaxies are environments in which high densities of dark matter are known to be present. Thus, large dark matter annihilation rates and related gamma-ray fluxes are predicted from these regions [18]. Unlike the galactic center, the dwarf spheroidals are dark matter dominated and do not contain substantial amounts of gas or stars. Therefore, observation of bright 511 keV emission from one or more dwarf spheroidals would provide strong evidence for light annihilating dark matter.

In this Letter, we consider the prospects for the observation of 511 keV gamma-ray emission from the two closest dwarf spheroidals galaxies, Sagittarius and Draco. We find that the flux predicted from Sagittarius may be above the sensitivity of INTEGRAL/SPI. Therefore, analysis of the (existing) INTEGRAL/SPI data from this region will yield a positive signal if light dark matter particles are responsible for the observed 511 keV flux from the galactic bulge.

Halo Models.—We parameterize spherical cusped halo profiles [19] by [20]:

$$\rho(r) = \frac{A}{(r/a)^{\gamma}[1 + (r/a)^{\alpha}]^{(\beta-\gamma)/\alpha}} \quad (1)$$

where α, β, and γ are unitless parameters, a is the distance from the center of the dwarf spheroidal at which the power law breaks, and A is a normalization constant.

Alternatively, spherical cored halo models can be parameterized by [21]

$$\rho(r) = \frac{v_a^2 a^\alpha 3r^2 + a^2(1-\alpha)}{4\pi G(r^2 + a^2)^{2+\alpha/2}} \quad (2)$$

where α is a unitless parameter, a is the core radius, and v_a is the velocity scale. Within the radius a, the halo has a nearly constant density core.

The velocity dispersion of the dwarf spheroidals is largely controlled by the dark matter density distribution and only weakly affected by tidal forces (even in the case of the disrupting Sagittarius) [22]. So, the observational data can be used to constrain the free parameters in the dark halo profiles [23]. For Draco, the behavior of the velocity dispersion with distance is known [24]. Retaining γ (for the cusped models) and α (for the cored models) as arbitrary, the remaining parameters are fixed by requiring that the velocity dispersion profile of Draco be reproduced. For Sagittarius, the velocity data are less complete and the morphological structure more complicated. However, the central line of sight velocity dispersion of Sagittarius is similar to that of Draco. Therefore, we assume that the shape of the halo of Sagittarius is similar to that of Draco [23]. This simple assumption may be questionable because tidal disruption has probably distended Sagittarius' dark matter halo [25] and is relaxed below.

The effect of the dark matter distribution on the annihilation rate can be described by a single quantity:

$$\overline{J}(\Delta\Omega) \times \Delta\Omega = \int_{\Delta\Omega} J(\Psi) d\Omega \quad (3)$$

where $\Delta\Omega$ is the solid angle observed, Ψ is the angle from the center of the halo, and $J(\Psi)$ is given by

$$J(\Psi) = \left(\frac{1}{0.3 \text{ GeV/cm}^3}\right)^2 \frac{1}{8.5 \text{ kpc}} \int_{\text{los}} \rho(r)^2 ds \quad (4)$$

where $\rho(r)$ is the dark matter density at a distance r from the dwarf spheroidal's center and the integral is performed over the line of sight of the observation. The rate of annihilations in an angular region is proportional to $\overline{J}(\Delta\Omega) \times \Delta\Omega$ and is otherwise independent of the properties of the halo.

Table I shows the values of $\overline{J}(\Delta\Omega) \times \Delta\Omega$ for Sagittarius and Draco calculated for several choices of halo profile, using $\Delta\Omega = 0.0038$, consistent with the 2° angular resolution of INTEGRAL/SPI. These quantities were computed following Ref. [23]. Although the details of these calculations are beyond the scope of this Letter, rough comparisons of these values can be estimated with simple scaling relationships. Comparing the fluxes from a dwarf spheroidal and from the galactic bulge, we estimate

$$\frac{\Phi_{\text{ds}}}{\Phi_{\text{gb}}} = \frac{\overline{J}(\Delta\Omega)_{\text{ds}}\Delta\Omega_{\text{ds}}}{\overline{J}(\Delta\Omega)_{\text{gb}}\Delta\Omega_{\text{gb}}} \sim \left(\frac{M_{\text{ds}}}{M_{\text{gb}}}\right)^2 \left(\frac{r_{\text{gb}}}{r_{\text{ds}}}\right)^3 \left(\frac{d_{\text{gb}}}{d_{\text{ds}}}\right)^2, \quad (5)$$

where M is the mass within a radius r, d is the distance from Earth, and ds and gb denote a dwarf spheroidal and the galactic bulge, respectively. In this estimate, we have assumed a fairly flat density within a radius r. Using the quantities $r_{\text{gb}} \sim \text{kpc}$, $r_{\text{ds}} \sim 0.25 \text{ kpc}$, $M_{\text{gb}}(r < \text{kpc}) \sim 10^9 \text{ M}_\odot$, $M_{\text{ds}}(r < 0.25 \text{ kpc}) \sim 10^8 \text{ M}_\odot$, $d_{\text{gb}} \sim 8.5 \text{ kpc}$, and $d_{\text{ds}} \sim 25 \text{ kpc}$, we very roughly estimate $\Phi_{\text{ds}} \sim 0.1 \Phi_{\text{gb}}$.

The numbers in Table I are reasonably certain for Draco, but can plausibly be either an order of magnitude larger or smaller for Sagittarius. Tidal disruption is likely to have distended the Sagittarius dark halo by a factor of ~ 10. For the same light profile, this causes the values for Sagittarius in Table I to be increased by a factor of ~ 30.

Annihilation and positron propagation.—If dark matter particles of ~ 1–100 MeV mass annihilate into electron-positron pairs, the resulting positrons then travel, gradually slowing by ionization losses. This energy loss rate is approximately given by [26]

$$\frac{dE}{dt} \sim 2 \times 10^{-12} \left(\frac{N_H}{10^2 \text{ m}^{-3}}\right)(\ln\Gamma + 6.6) \text{ eV/s}, \quad (6)$$

where Γ is the positron's Lorentz factor and N_H is the number density of target atoms. In the galactic bulge, where we estimate $N_H \sim 10^5 \text{ m}^{-3}$, this rate can yield stopping distances of $\sim 10^{24}$ and $\sim 10^{26}$ cm for positrons of MeV and 100 MeV energy, respectively. No gas has ever been detected in any of the Local Group dwarf spheroi-

TABLE I. Values of $\overline{J}(\Delta\Omega) \times \Delta\Omega$ for Sagittarius and Draco calculated using a variety of profiles and $\Delta\Omega = 0.0038$, consistent with the 2° angular resolution of SPI.

Halo Profile	$\overline{J}(\Delta\Omega) \times \Delta\Omega$ Sagittarius	$\overline{J}(\Delta\Omega) \times \Delta\Omega$ Draco
$\gamma = 1$ Navarro-Frenk-White (NFW)	0.063	0.0057
$\gamma = 0.8$	0.063	0.0056
$\gamma = 0.6$	0.062	0.0056
$\gamma = 0.4$	0.056	0.0050
$\gamma = 0.2$	0.054	0.0049
$\alpha = 0.2$	0.029	0.0026
$\alpha = 0$	0.031	0.0029
$\alpha = -0.2$	0.034	0.0035

dals. So, the stopping distance is likely to be significantly longer.

Although no magnetic fields have been measured in Sagittarius or Draco, low surface brightness galaxies, which are somewhat similar, indicate that fields of 2–4 μ G may be expected [27]. For microgauss scale magnetic fields, a positron's Larmor radius is on the order of 10^{11} or 10^{9} cm for energies of 100 MeV and 1 MeV, respectively. Considering a simple random walk, the positrons are roughly confined to a distance of $\sim \sqrt{R_{\text{stop}} \times R_{\text{Larm}}}$. Even if we conservatively estimate magnetic fields with 0.01 μ G strength and 10^{2} atoms/m^{3}, we find that positrons are stopped within 100 pc or less of their generation, a distance much smaller than could be resolved, given the angular resolution of INTEGRAL/SPI ($\sim 2°$).

The energy loss rate (6) leads to a thermalization time for positrons, as a function of energy, of

$$t(E) \sim 10^{9} \text{yr} \left(\frac{E}{\text{MeV}} \right) \left(\frac{10^{2} \text{ m}^{-3}}{N_e} \right) \left(\frac{0.5}{f_g} \right), \qquad (7)$$

where N_e is the electron density and f_g is the dust fraction. Multiplying this by the speed of light, we see that a positron's stopping distance is typically shorter than its mean free path. Annihilations are, therefore, expected to occur primarily for thermalized positrons, producing a 511 keV line. If the dark matter particles are heavier than 50 MeV or so the annihilation time for the positrons produced may exceed the age of the dwarf spheroid and equilibrium may not be reached, diminishing the 511 keV emission, but probably by less than a factor of 2, or so.

If the electron temperatures are too low, positronium formation may dominate, resulting in a narrow line (25% of the time) or a three-photon continuum (75% of the time), depending on the spin state of the positronium. Although positronium formation dominates in the galactic bulge, as the Oriented Scintillation Spectrometer Experiment and INTEGRAL data suggest [28,29], this may not be the case in a dwarf spheriodal. It is likely, for example, that the Draco dwarf galaxy is pervaded by diffuse galactic halo gas at $T \sim 10^{6}$ K and $N_e \sim 10^{2}(10^{6}$ K/$T)$ m^{-3}, as inferred from the Far Ultraviolet Spectroscopic Explorer observations of high velocity Oxygen VI absorption [30]. At this temperature, direct annihilations are important. If dust is present at even half of the standard interstellar gas-to-grain ratio, the annihilation line remains narrow (less than about 2 keV for a grain fraction greater than one tenth of the local interstellar medium value) [31]. Hence the 511 keV line flux should be approximately 4 times greater than in the case of annihilation through positronium formation, as in the case of the galactic bulge where the dominant component of the diffuse interstellar gas is assumed to be at $T \sim 10^{4}$ K.

Given that each annihilating pair of dark matter particles form a single positron which eventually annihilates producing two 511 keV gamma rays, the flux of this gamma-ray line is given by

$$\Phi \cong 5.6 \times 2 \times P \left(\frac{\sigma v}{\text{pb}} \right) \left(\frac{1 \text{ MeV}}{m_{\text{dm}}} \right)^{2} \overline{J}(\Delta\Omega) \times \Delta\Omega \text{ cm}^{-2}\text{s}^{-1},$$

$$(8)$$

where m_{dm} is the mass of the dark matter particle, σv is the annihilation cross section multiplied by the relative velocity in units of c. The quantity P is equal to 0.25 for the galactic bulge (positronium formation) and one for dwarf spheroidals (direct annihilation).

In Ref. [3], it was shown that to explain the angular distribution of events, as observed by INTEGRAL/SPI, the galactic halo is best fit to a mildly cusped profile ($\gamma \sim 0.6$) in the inner kiloparsecs. The full width, half maximum of the observed INTEGRAL/SPI signal is 9.0^{+9}_{-3} degrees, with 2-σ confidence intervals [4]. This corresponds to a value of $\overline{J}(\Delta\Omega) = 37.6^{+42.1}_{-18.2}$ for $\Delta\Omega \simeq 0.02$, the angular extent of INTEGRAL's detection. Combining this with the previous equation, and using the flux of 9.9×10^{-4} photons cm^{-2} s^{-1}, as seen by INTEGRAL, we see that

$$\left(\frac{\sigma v}{\text{pb}} \right) \left(\frac{1 \text{ MeV}}{m_{\text{dm}}} \right)^{2} \simeq 4.8^{+4.4}_{-2.4} \times 10^{-4}, \qquad (9)$$

again with 2-σ confidence intervals. We can now combine this result with values of $\overline{J}(\Delta\Omega) \times \Delta\Omega$ for specific dwarf spheroidals to calculate the flux predicted from such sources.

Considering the range of values for $\overline{J}(\Delta\Omega) \times \Delta\Omega$ for Sagittarius shown in Table I (0.029 to 0.063, for $\Delta\Omega = 0.0038$ sr), we can estimate the flux of 511 keV emission from this region:

$$\Phi \simeq 3.4^{+3.1}_{-1.7} \times 10^{-4} \quad \text{to } 1.6^{+1.5}_{-0.8} \times 10^{-4} \text{cm}^{-2}\text{s}^{-1}. \quad (10)$$

The flux from Draco is approximately a factor of 10 smaller. Sagittarius is also near the galactic plane, and within the region of the sky, which has been extensively surveyed by INTEGRAL/SPI. For a 3–σ detection after an exposure of 10^{6} s, the sensitivity of this experiment to 511 keV line emission in this region is estimated to be $\simeq 4 \times 10^{-5}$ cm^{-2} s^{-1} [32], below our predicted range of fluxes. We can, therefore, conclude that if the $\sim 10^{-3}$ cm^{-2} s^{-1} flux of 511 keV gamma rays observed from the galactic bulge is the result of light dark matter annihilations, then analysis of INTEGRAL/SPI's data from the Sagittarius region of the sky will reveal an observable signal of 511 keV emission. If no such signal is observed, we should consider other sources for the observed emission from the bulge.

Of course, other potential sources may exist. For example, M31 may produce a signal similar to that ob-

served from the galactic bulge. As M31 is a factor of ~100 further away than the galactic center, however, we expect fluxes ~500 times smaller than from Sagittarius.

Conclusions.—If light (1–100 MeV) dark matter particles, annihilating to electron-positron pairs, are responsible for the observed 511 keV gamma-ray emission from the galactic bulge, then we expect that potentially observable fluxes of 511 keV emission would also be produced in other regions with high dark matter density, particularly the nearby dwarf spheroidals such as Sagittarius and Draco. Furthermore, alternative explanations of the galactic bulge emission involve exotic stellar objects (hypernovae, etc.), which are minimal in the direction towards the dwarf spheroidals. Thus observation of 511 keV emission from such an object would provide a smoking gun for annihilating light dark matter scenarios.

We find that if the observed 511 keV emission from the galactic bulge is the product of light annihilating dark matter, then the Sagittarius dwarf galaxy may provide a 511 keV gamma-ray flux of $\Phi \simeq 3.4^{+3.1}_{-1.7} \times 10^{-4}$ to $1.6^{+1.5}_{-0.8} \times 10^{-4}$ cm^{-2} s^{-1}. If the dark halo of the Sagittarius has been distended by tidal forces, then these numbers could be larger by a factor of ~30. Such a flux is above the sensitivity of INTEGRAL/SPI. If such a signal is seen upon analysis of the (existing) INTEGRAL/SPI data, it would favor the existence of light scalar dark matter. The absence of such a signal would suggest that the 511 keV emission observed from the galactic bulge is not likely to be related to particle dark matter annihilations.

Very recently, a new candidate dwarf spheroidal in the direction of Canis Major has been suggested. Its mass and tidal radius have been estimated to be similar to that of the Sagittarius dwarf ($5 \times 10^8 M_\odot$ and 2.5 kpc) [33], however, it is considerably closer and may produce a flux an order of magnitude larger than Sagittarius.

[1] B. . Lee and S. Weinberg, Phys. Rev. Lett. **39**, 165 (1977); D. Hooper and T. Plehn, Phys. Lett. B **562**, 18 (2003); A. Bottino, F. Donato, N. Fornengo, and S. Scopel, Phys. Rev. D **68**, 043506 (2003).

[2] C. Boehm, T. A. Ensslin, and J. Silk, J. Phys. G **30**, 279 (2004); C. Boehm and P. Fayet, Nucl. Phys. B **683**, 219 (2004).

[3] C. Boehm, D. Hooper, J. Silk, M. Casse, and J. Paul, Phys. Rev. Lett. **92**, 101301 (2004).

[4] J. Knodlseder *et al.*, astro-ph/0309442; P. Jean *et al.*, Astron. Astrophys. **407**, L55 (2003).

[5] P. A. Milne, J. D. Kurfess, R. L. Kinzer, and M. D. Leising, New Astron. Rev. **46**, 553 (2002) and references therein.

[6] R. E. Lingenfelter and R. Ramaty, in *Positron-Electron Pairs in Astrophysics*, edited by M. L. Burns, A. K. Harding, and R. Ramaty, AIP Conf. Proc. No. 267 (AIP, New York, 2004).

[7] R. Ramaty, B. Kozlovsky, and R. E. Lingenfelter, Astrophys. J. Suppl. Ser. **40**, 487 (1979); P. . Milne, L. S. The, and M. D. Leising, astro-ph/0104185.

[8] B. Kozlovsky, R. E. Lingenfelter, and R. Ramaty, Astrophys. J. **316**, 801 (1987).

[9] P. A. Sturrock, Astrophys. J. **164**, 529 (1971).

[10] P. A. Milne, L. S. The, and M. D. Leising, Astrophys. J. **559**, 1019 (2001).

[11] M. Casse, B. Cordier, J. Paul, and S. Schanne, Astrophys. J. **602**, L17 (2004).

[12] F. Matteucci, D. Romano, and P. Molaro, Astron. Astrophys. **341**, 458 (1999).

[13] F. Matteucci, A. Renda, A. Pipino, and M. della Valle, Astron. Astrophys., **405**, 23 (2003).

[14] S. E. Woosley and A. Heger, astro-ph/0309165.

[15] J. Bland-Hawthorn and M. Cohen, Astrophys. J. **582**, 246 (2003).

[16] C. D. Dermer and J. G. Skibo, astro-ph/9705070.

[17] M. Pohl, astro-ph/9807268.

[18] J. Silk and M. Srednicki, Phys. Rev. Lett. **53**, 624 (1984).

[19] J. F. Navarro, C. S. Frenk, and S. D. White, Astrophys. J. **462**, 563 (1996); J. F. Navarro, C. S. Frenk, and S. D. White, Astrophys. J. **490**, 493 (1997).

[20] L. Hernquist, Astrophys. J. **445**, 359 (1990).

[21] N.W. Evans, Mon. Not. R. Astron. Soc. **260**, 191 (1993); N.W. Evans, Mon. Not. R. Astron. Soc. **267**, 333 (1994).

[22] K. S. Oh, D. N. C. Lin, and S. J. Aarseth, Astrophys. J. **442**, 142 (1995); S. Piatek and C. Pryor, Astron. J. **109**, 1071 (1995); R. S. Klessen and P. Kroupa, Astrophys. J. **448**, 143 (1998).

[23] N.W. Evans, F. Ferrer, and S. Sarkar, Phys. Rev. D **69**, 123501 (2004).

[24] J.T. Kleyna, M. I. Wilkinson, N.W. Evans, and G. Gilmore, Astrophys. J. **563**, L115 (2001).

[25] I. G. Jiang and J. J. Binney, Mon. Not. R. Astron. Soc. **314**, 468 (2000).

[26] M. S. Longair, *High-Energy Astrophysics* (Cambridge University Press, Cambridge, England, 1981), Vol. 2, Chap. 19.

[27] U. Klein, G. Giovanardi, D. R. Altschuler, and E. Wunderlich, Astron. Astrophys. **255**, 49 (1992); K. T. Chyzy *et al.*, Astron. Astrophys. **405**, 513 (2003).

[28] R. Kinzer, P. Milne, D. Kurfess, M. Strickman, W. Johnson, and W. Purcell, Astrophys. J. **559**, 282 (2001).

[29] A.W. Strong *et al.*, Astron. Astrophys., "Diffuse Continuum Emission from the Inner Galaxy: First Results from INTEGRAL/SPI" (to be published).

[30] K. R. Sembach, B. P. Wakker, B. D. Savage, P. Richter, M. Meade, J. M. Shull, E. B. Jenkins, H.W. Moos, and G. Sonneborn, Astrophys. J. Suppl. Ser. **146**, 165 (2003).

[31] P. von Ballmoos, N. Guessoum, P. Jean, and J. Knodlseder, Astron. Astrophys. **397**, 635 (2003).

[32] J. P. Roques *et al.*, Astron. Astrophys. (to be published).

[33] N. F. Martin, R. A. Ibata, M. Bellazzini, M. J. Irwin, G. F. Lewis, and W. Dehnen, Mon. Not. R. Astron. Soc. **348**, 12 (2004).