ANNIHILATIONS FROM THE GALACTIC CENTRE

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A massive black hole is present at the centre of our galaxy and inevitably accretes
dark matter particles, creating a region of very high particle density. The annihi-
lation rate is enhanced with a large number of $e^+e^−$ pairs produced either directly
or by successive decays of mesons. We evaluate the synchrotron emission (and self-
absorption) associated with the propagation of these particles through the galactic
magnetic field and give constraints on the values of mass and cross section of the
dark matter particles.

1 Introduction

There is convincing evidence for the existence of an unseen non-baryonic compo-
nent in the energy density of the universe. The most promising dark matter
candidate appear to be weakly interacting massive particles (WIMPs) and in
particular the so-called neutralinos, arising in supersymmetric scenarios (for
a review of particle candidates for dark matter see e.g. [1]). The annihilation
of these X-particles would produce quarks, leptons, gauge and Higgs bosons
and gluons. In particular $e^+e^−$ pairs are produced either directly or by suc-
cessive decays of mesons, and lose their energy through synchrotron radiation
as they propagate in the galactic magnetic field. This radiation is expected
to be greatly enhanced in the proximity of the galactic centre, where the exis-
tence of a massive black hole creates a region of very high dark matter particle
density and consequently a substantial increase in the annihilation rate and
in the ensuing synchrotron radiation.

2 Dark matter distribution around the Galactic Centre

There is strong evidence for the existence of a massive compact object lying
within the inner 0.015pc of the galactic centre (see [2] and references therein).
This object is a compelling candidate for a massive black hole, with mass $M =
2.6±0.2M_⊙$. The galactic halo density profile is modified in the neighbourhood
of the galactic centre by the adiabatic process of accretion towards the central black hole. If we consider an initially power-law type profile of index $\gamma$, as predicted by high resolution N-body simulations\[4\], the corresponding dark matter profile after accretion is modified to

$$\rho' = \left[ \alpha_\gamma \left( \frac{M}{\rho_D D^3} \right)^{3-\gamma} \right]^{\gamma_{sp}^{-\gamma}} \rho_D g(r) \left( \frac{D}{r} \right)^{\gamma_{sp}}$$

(1)

where $\gamma_{sp} = (9 - 2\gamma)/(4 - \gamma)$, $D$ is the solar distance from the galactic centre and $\rho_D = 0.24\text{GeV}/c^2/\text{cm}^3$ is the corresponding density. The factors $\alpha_\gamma$ and $g_\gamma(r)$ cannot be determined analytically (for approximate expressions and numerical values see\[4\]). Expression (1) is only valid in a central region of size $R_{sp} = \alpha_\gamma D(M/\rho_D D^3)^{1/(3-\gamma)}$ where the central black hole dominates the

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**Figure 1.** Left panel: $A_\nu$ as a function of frequency for $m_\chi = 1\text{TeV}$. The two upper curves correspond to the cross section $\sigma v = 10^{-28}/m_\chi^2 \text{(GeV)} \text{cm}^3 \text{s}^{-1}$, close to the unitarity limit; the two lower curves correspond to $\sigma v = 10^{-38}/m_\chi^2 \text{(GeV)} \text{cm}^3 \text{s}^{-1}$, a cross section more typical for wimps. Results for two values of the density profile are shown in each case: $\gamma = 1$, for solid curves and $\gamma = 1.5$ for dashed ones. Right panel: $A_\nu$ as a function of the particle mass for $\nu = 408\text{MHz}$, $\sigma v = 10^{-38}/m_\chi^2 \text{(GeV)} \text{cm}^3 \text{s}^{-1}$ and two values of $\gamma$. 
gravitational potential. If we take into account the annihilation of dark matter particles, the density cannot grow to arbitrarily high values, the maximum density being set by the value

$$\rho_{\text{core}} = \frac{m}{\sigma v t_{BH}}$$

where $t_{BH} \approx 10^{10}$ years is the age of the central black hole. The final profile, resulting from the adiabatic accretion of annihilating dark matter onto a massive black hole, is

$$\rho_{dm}(r) = \frac{\rho'(r)\rho_{\text{core}}}{\rho'(r) + \rho_{\text{core}}}$$

following a power-law profile for large values of $r$, and with a flat core of density $\rho_{\text{core}}$ and dimension

$$R_{\text{core}} = R_{sp} \left( \frac{\rho(R_{sp})}{\rho_{\text{core}}} \right)^{(1/\gamma_{sp})}$$
3 Constraints from Synchrotron Emission

Among the products of annihilation of dark matter particles, there are energetic electrons and positrons, which are expected to produce synchrotron radiation in the magnetic field around the galactic centre. The pair production spectrum is determined by the quark fragmentation function and has been evaluated using the MLLA approximation (see 5 for details). The galactic magnetic field can be modeled by making the 'equipartition assumption', where the magnetic, kinetic and gravitational energy of the matter accreting on the central black hole are in approximate equipartition (see 6). In this case, the magnetic field can be expressed as

$$B(r) = 1 \mu G \left(\frac{r}{\text{pc}}\right)^{-5/4}$$  \hspace{1cm} (5)

Most of the annihilations occur at very small distances from the centre, typically at $\approx \text{min}(R_{\text{core}}, 10 R_s)$, i.e. in a region with magnetic fields of the order of $> 1G$. Under these conditions, comparable to the size of the region where most of the annihilations occur, the electrons lose their energy almost in place. To compute the synchrotron luminosity resulting from the propagation of $e^\pm$ in the galactic magnetic field, we need to evaluate their energy distribution in the magnetic field, following 7

$$\frac{dn}{dE} = \frac{\Gamma Y_e(> E)}{P(E)} f_e(r)$$  \hspace{1cm} (6)

where $\Gamma$ is the annihilation rate

$$\Gamma = \frac{\sigma v}{m_e^2} \int_0^\infty \rho_{sp}^2 4\pi r^2 \ dr,$$  \hspace{1cm} (7)

the function $f_e(r)$ is given by

$$f_e(r) = \frac{\rho_{sp}^2}{\int_0^\infty \rho_{sp}^2 4\pi r^2 \ dr}$$  \hspace{1cm} (8)

and

$$P(E) = \frac{2e^4 B^2 E^2}{3m_e^2 c^7}$$  \hspace{1cm} (9)

The quantity $Y_e(> E)$ is the number of $e^+e^-$ with energy above $E$ produced per annihilation, which depends on the annihilation modes. The energy dependence of $Y_e(> E)$ can be neglected, and we estimate $Y_e(> E)$ by the
number of charged particles produced in quark fragmentation (see [4]). We obtain a simple analytical expression for the total synchrotron luminosity

$$L_\nu \approx \frac{9}{8} \left( \frac{1}{0.29 \pi} \frac{m_e^3 c^5}{e} \right)^{1/2} \frac{\Gamma Y_e(> E)}{\sqrt{\nu}} I$$

where

$$I = \int_0^\infty dr \ 4\pi r^2 f_e(r) B^{-1/2}(r)$$

The synchrotron self-absorption coefficient is defined by

$$A_\nu = \frac{1}{a_\nu} \int_0^\infty (1 - e^{-\tau(b)}) 2\pi b \ db$$

where \( \tau(b) \) is the optical depth as a function of the cylindrical coordinate \( b \)

$$\tau(b) = a_\nu \int_{d(b)}^{\infty} f_e(b, z) \ dz$$

and the coefficient \( a_\nu \) is given by

$$a_\nu = \frac{e^{3\Gamma B(r)}}{9m_e\nu^2} \int_{m_e}^m E^2 \frac{d}{dE} \left[ \frac{Y_e(> E)}{E^2 P(E)} \right] F \left( \nu \frac{\nu_0}{\nu} \right) \ dE$$

The final luminosity is obtained by multiplying eq. (10) with \( A_\nu \) given by eq. (12). It is evident that in the limit of small optical depths the coefficient \( A_\nu \to 1 \), as can be seen by expanding the exponential. We find for \( a_\nu \) the following expression

$$a_\nu = \frac{\Gamma Y}{4\pi \nu^3} c^2$$

which can in turn be used to evaluate \( \tau(b) \) in eq. (13) and \( A_\nu \) in eq. (12).

We first evaluate the self-absorption coefficient for selected values of the mass, as a function of frequency. The coefficient (see left part of fig.) grows from very low values and then reaches the value 1, around a frequency which is strongly dependent on the cross section and the mass \( m_X \), but not very much on the profile power-law index \( \gamma \). The right part of fig. shows the self-absorption coefficient at the fixed frequency of 408 MHz as a function of the wimpzilla mass. The behaviour shown is qualitatively the same for any value of the cross-section and for different \( \gamma \).

The coefficient is evaluated for two different values of the cross section, the first one corresponding to the maximum possible value \( \sigma v \approx 10^{-28}/m_X^2 \text{(GeV)} \text{ cm}^3\text{s}^{-1} \), (the so-called unitarity bound, see [12]) and the second one corresponding to typical cross sections for supersymmetric scenarios,
Figure 3. Exclusion plot based on the comparison between predicted flux and radio observations of the galactic centre. The 3 solid curves indicate, for 3 different density profile power law index, the lower edge of the excluded regions. The dashed line shows, for comparison, the unitarity bound, \( \sigma v \approx \frac{1}{m_X^2} \). The shaded region is the portion of the parameter space occupied by cosmologically interesting neutralinos (i.e. those leading to \( 0.025 < \Omega X h^2 < 1 \); see, e.g. Bergstrom et al (1997)).

\[ \sigma v = 10^{-38} / m_X^2 \text{(GeV)} \text{cm}^3\text{s}^{-1} \] (see, e.g., [13]). In figure 2 we compare the predicted spectrum with the observations; we choose a set of parameters \( m_X \), \( \gamma \) and \( \sigma v \) in order to reproduce the observed normalisation. It is remarkable that in this way one can reproduce the observed spectrum over a significant range of frequencies. The submillimeter excess is generally attributed to processes in the accretion disk within several Schwarzschild radii of the black hole (e.g., [11]). The set of dark matter parameters for which the fluxes predicted in our model are consistent with observations is shown in the exclusion plot of fig. 3.
4 Conclusions and perspectives

We have shown that present data on the emission from Sgr A* are compatible with a wide set of dark matter parameters. The evaluation of synchrotron self-absorption has enabled us to reach an alternative conclusion to an earlier claim of incompatibility of cuspy halos with the existence of annihilating wimp dark matter. We find that the experimental data on the Sgr A* spectrum at radio wavelengths could be explained by synchrotron emission of electrons produced in the annihilation of rather massive dark matter particles, extending up to and beyond TeV masses. This is relevant to a recent study of coannihilations, which suggests that WIMPs with $\Omega X h^2 = 0.2$ can extend up to several TeV, as well as to very massive particles (wimpzillas) that are produced non-thermally in the primordial universe. We also find that the synchrotron emission tends to give somewhat sharper constraints on masses and cross sections than the observed gamma-ray fluxes and neutrino limits. This situation could change with more sensitive gamma-ray and neutrino observations anticipated from forthcoming experiments.

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