Annihilation Radiation from a Dark Matter Spike at the Galactic Centre

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ABSTRACT
We study annihilation radiation of neutralinos in the Galactic centre, assuming the existence of a ‘spike’ in the dark matter density profile, due to adiabatic accretion onto the massive black hole lying at the Galactic centre. Under this assumption we find that it is possible to reproduce the observed SgrA* emission at radio and gamma-ray frequencies in a consistent scenario with a magnetic field close to the equipartition strength and with values of $\gamma$ (the density profile power law index) around 0.1.

Key words: Galaxy: centre – dark matter

1 INTRODUCTION
In a recent paper, Gondolo and Silk (2000) showed that the existence of a massive black hole in the Galactic centre would produce a ‘spike’ in the dark matter density profile due to the adiabatic accretion of dark matter particles. It has subsequently been argued that such a spike may be destroyed by mergers (Ullio, Zhao and Kamionkowski, 2002; Merritt et al., 2002). We point out here that such dynamical destruction processes are unlikely to have occurred for the Milky Way. However our knowledge of black hole formation is so uncertain that we cannot make this assertion with any real confidence, and we therefore propose a new means of observing the central spike via gamma ray emission. Both the flux and spectrum of the galactic centre annihilation gamma ray source are consistent with EGRET observations (as long as the initial cusp profile is rather shallow, $\propto r^{-\gamma}$ with $\gamma \approx 0.1$) and if this interpretation is correct, will potentially enable us to deduce the magnetic field in the vicinity of SgrA*.

Supermassive black holes (SMBH) are ubiquitous in galactic nuclei. Their formation remains a mystery. However circumstantial evidence points strongly towards formation in the highly dissipative environment of the forming galaxy. This is based on the remarkably tight correlation between black hole mass and bulge velocity dispersion (Ferrarese and Merritt, 2000; Gebhardt et al., 2000; Merritt and Ferrarese, 2002) that attests to a common origin, which, given the fact that our bulge formation preceded that of the disk some 12 Gyr ago, places black hole formation at an epoch when our galaxy was extremely gas-rich. Now dynamical formation of the SMBH by stellar collisions and mergers is an extremely slow process, as also would be formation by black hole mergers. Theory supports a dissipative origin, and the protogalactic origin provides the ideal environment. Thus, the SMBH formed early in the protogalaxy, which in turn condensed in a dark halo of weakly interacting particles that constitute cold dark matter (CDM).

A spike would inevitably have developed in the CDM halo core as the SMBH formed by dissipation of gas infall. The critical issue is: were there subsequent mergers that destroyed the spike and boosted the SMBH mass? The answer is yes and no. Yes for ellipticals and for early type galaxies with massive bulges. But no for the Milky Way, and presumably for similar late-type galaxies with small bulge-to-disk ratios.

There is little doubt that massive spheroids formed by mergers, and most likely by a series of mergers. Observations point to a drastic increase in the merger rate associated with starbursts in the early universe, and the inferred formation rate of dust-shrouded spheroids. The phenomenological case for merger-driven spheroid formation is strong (Sanders and Mirabel, 1996). Theory, for those who take it seriously, indicates that mergers were common in the past (e.g. Steinmetz and Navarro, 2002). SMBH fit into the merger scenario by virtue of the fact that a major merger provides a dramatic means for channeling gas into the central regions of the merged galaxy (e.g. Barnes and Hernquist, 1996), thereby instigating the formation of the SMBH. Possibly later mergers enable the central SMBH to merge and thereby develop and maintain the observed correlation between SMBH mass and bulge central velocity dispersion.

But what can be stated with considerable confidence is that our Milky Way galaxy underwent one significant merger 12 Gyr ago. This resulted in the formation of the bulge, and presumably therefore of the SMBH, and of the thick disk. Gas disk formation is a consequence of a gas-rich merger, and such disks commonly characterize merger remnants (Barnes, 2002). The chemical evidence for a unique
merger origin in the case of our Milky Way’s thick disk is compelling (Wyse, 2001). The thick disk amounts to as much as 20 percent of the thin disk, so that this one merger was indeed a major merger. But the continuity between thin disk, thick disk, and bulge would have been destroyed had anything significant happened since in the way of a merger. In particular, the bulge was formed then, and therefore the SMBH formed shortly afterwards if we accept a dissipative protogalactic origin. The spike developed in the halo core when the SMBH formed by gas infall, and no subsequent major dynamical merging event occurred that could have destroyed it.

We note that an alternative theory for bulge formation in Milky Way-type galaxies has no recurrence at all to a merger (e.g. Emsellem, 2001). Gravitational instability of a cold disk and secular evolution is capable of forming the bulge, and such a process would also be capable of driving in the gas to form the SMBH. Only small bulges are presumably formed in this manner, the massive bulges forming via mergers. Hence theory and phenomenology of the Milky Way formation support our contention that the CDM spike presents a primordial feature that developed as the SMBH formed and has not subsequently been destroyed.

Other dynamical effects, such as the influence on the dark halo of the formation of the galactic stellar nucleus bulge disc (Klypin, Zhao & Somerville, 2001), have been neglected here. The consequent enhancement of dark matter density in the Galactic centre would further reduce the portion of dark matter parameter space we showed to be consistent with observations.

The SMBH acts as an amplifier of the CDM, locally enhancing the annihilation rate. The enhancement of the particle number density and self-annihilation rate in the proximity of the central black hole provides a means of probing the nature of CDM by indirect detection of the various annihilation signatures. There are three such signatures: high energy neutrinos, synchrotron emission from high energy positrons and electrons, and high energy gamma rays. We have previously discussed the observability of neutrinos and of synchrotron emission from the spike at the GC. Here we discuss the gamma ray signature for our favoured dark matter candidate, the so-called neutralino, arising in the framework of supersymmetric theories (for an extensive review of dark matter candidates see e.g. Bergstrom, 2000).

In particular, we have previously estimated (Bertone, Sigl and Silk, 2001) the corresponding enhancement of annihilation signals, such as synchrotron radiation originating from the propagation of e+e− pairs in the galactic magnetic field. We were able to constrain neutralino mass and cross section, the constraints being strongly dependent on the slope of the density profile. Here we extend this analysis to continuum gamma-ray emission, which, in absence of the central spike, has previously been evaluated by several authors (see e.g. Berezinsky et al., 1994).

When considering neutralinos annihilating in a halo with a power-law density profile, even with an index as high as 1.0, a deficit of gamma-rays is found, with respect to the flux measured by EGRET (see Mayer-Haesselwander, 1998). An explanation for this excess has been proposed in terms of 'clumpiness' of the halo by Bergstrom et al. (1999). However rather extreme clumpiness factors are required, and it is not clear that the halo substructure has survived at least as judged by counting the number of dwarf satellites and by theoretical arguments pertaining to excessive loss of angular momentum by clumpy protogalactic gas (e.g. Silk, 2001).

In the present case, the gamma-ray flux is enhanced by the presence of the central spike at the Galactic Centre. We will show that a consistent scenario can be developed that simultaneously reproduces the observed SgrA* radio spectrum as well as the high energy gamma ray emission observed from the Galactic Centre by EGRET if the initial cusp profile, before adiabatic accretion onto the SMBH, is rather shallow, with power law index $\gamma \approx 0.1$.

Although some astrophysical processes may flatten considerably the cusps respect to conventional $\gamma \approx 1$ profiles (see Katz & Weinberg, 2002 and Valenzuela & Klypin, 2001) and lead to the formation of shallow cusps, we prefer here to treat $\gamma$ as an unknown parameter.

Alternative models exist in literature, to explain the spectrum of SGR A*, suggesting that high energy emission could have an origin in pulsars or around a supermassive black hole (e.g. Mayer-Haesselwander et al., 1998).

In section 2 we give details about the supersymmetric scenarios used to make detailed estimates of expected fluxes. Section 3 is devoted to the description of the halo model with a central spike. The detailed analysis of synchrotron and gamma-ray emission is presented in section 4. The final section contains results and conclusions.

2 NEUTRALINOS AS DARK MATTER CANDIDATES

There is convincing evidence that a large part of the dark matter is non-baryonic. Here we focus on the lightest supersymmetric particle, which in most supersymmetric scenarios turns out to be the neutralino (e.g. Jungman et al., 1996, and references therein).

One of the best reasons to consider neutralinos as dark matter candidates is that SUSY was not introduced to solve cosmological or astrophysical problems: rather, its motivations are related to some fundamental problems of theoretical physics, such as the fundamental difference between bosons and fermions, the mass hierarchy problem and Grand Unification (e.g. Jungman et al., 1996).

Despite its success in solving some of these problems, it is still not very predictive, containing a huge number of free parameters. This is mainly due to the fact that SUSY is not an exact symmetry of nature, and should be broken at some scale (otherwise we would observe superpartners of ordinary particles with the same masses, and we do not).

It is possible, however, to reduce the number of free parameters by making several reasonable assumptions. The definition of a SUSY scenario thus corresponds to specifying a set of assumptions that aim to reduce and constrain the parameter space. The results discussed in this paper are obtained in the framework of the Minimal Supersymmetric Standard Model (see Haber&Kane, 1985, or Jungman et al., 1996) as implemented by Gondolo et al (2000) in the Dark-SUSY code, in which there are seven free parameters: one scalar mass parameter $m_0$, the mass of the pseudo-scalar Higgs $m_A$, one universal gaugino mass $M_{3/2}$, $\tan\beta$ (ratio of the VEVs of the two Higgs fields) and two trilinear parameters $A_b$, $A_t$. 

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

$$R_{\text{core}} = R_{sp} \left( \frac{\rho(R_{sp})}{\rho_{\text{core}}} \right)^{(1/\gamma_{sp})}. \quad (4)$$

This result is obtained neglecting dynamical effects of hierarchical merging. If one takes into account the former effects, then shallower dark matter profiles are formed, with power law index as low as $\gamma \approx 0.5$ or even flatter (see Merritt et al., 2002, Nakano & Makino, 1999, and Ullio, Zhao & Kamionkowski, 2001).

However, as stressed in the introduction, post-merger black hole formation, as seems to be the case for our galaxy, means that the spike will still form, albeit with a reduced value of $\gamma_{sp}$ that however is always larger than 7/4 and hence gives a large annihilation flux enhancement. An interesting effect arises if the massive black hole does not lie exactly at the centre of the dark matter halo, as may be the consequence of being embedded in a central massive star cluster of size $a < 0.01 \, \text{pc}$. According to Chatterjee, Hernquist and Loeb (2002), for solar mass stars, stochastic motions of the SMBH occur in a harmonic potential of scale $\sim 10^{-2} \, \text{pc}$, and this would have the effect of further softening the spike; note that annihilation softening occurs at $\sim 10^{-3} \, \text{pc}$ (Gondolo and Silk 1999).

4 ANNIHILATION RADIATION

The neutralino self-annihilation rate is very sensitive to the neutralino number density, namely

$$\Gamma = \frac{\sigma v}{m_\chi^2} \int_0^\infty \rho_{\text{dm}}^2 4\pi r^2 \, dr, \quad (5)$$

We therefore expect the annihilation signals coming from the neighborhood of the central black hole to greatly exceed the signals from other regions of the halo.

Among secondary products of neutralino annihilation, we study high energy photons, originating via neutral pion decays, and the synchrotron radiation of electron-positron pairs (originating from the decays of charged pions) in the Galactic magnetic field.

4.1 Synchrotron radiation

In the region of interest, the Galactic magnetic field can be roughly approximated using the ‘equipartition assumption’ (see Melia, 1992), such that

$$B_{eq}(r) = 1 \mu G \left( \frac{r}{pc} \right)^{-5/4}. \quad (6)$$

This value is obtained assuming equality between magnetic and gravitational energy density. In the case of accretion with conservation of mass flux $\rho vr^2 = \text{constant}$, hence, for keplerian velocities, $r \rho \sim r^{-3/2}$ and the gravitational energy $\epsilon_{\text{GR}} \sim r^{-5/2}$ (for more details see also Shvartsman, 1971).

In paper I, we estimated the synchrotron luminosity at a given frequency $\nu$ in such a magnetic field to be

$$L_\nu \approx \frac{9}{8} \left( \frac{1}{0.29\pi} \right)^{1/2} \frac{m_\chi^3 c^5}{e} \left( \frac{\Gamma_{\nu}(> E)}{\sqrt{\nu}} \right) I \quad (7)$$
persymmetric models and \( \gamma = 0.05 \) (triangles), \( \gamma = 0.1 \) (diamonds), \( \gamma = 0.2 \) (dots), \( \gamma = 1.0 \) (squares), along with EGRET data (Narayan et al, 1998) and expected sensitivities for GLAST (1 month observation time) and MAGIC (50 hours).

Figure 2. Expected gamma-ray flux for the same set of supersymmetric models and \( \gamma = 0.05 \) (triangles), \( \gamma = 0.1 \) (diamonds), \( \gamma = 0.2 \) (dots), \( \gamma = 1.0 \) (squares), along with EGRET data (Narayan et al, 1998) and expected sensitivities for GLAST (1 month observation time) and MAGIC (50 hours).

\[
I = \int_0^{\infty} 4\pi r^2 f_\nu(r) B^{-1/2}(r) \, dr
\]
and the function \( f_\nu(r) \) is defined as
\[
f_\nu(r) = \frac{\rho_{\nu}^s}{\int_0^1 \rho_{\nu}^s 4\pi r^2 \, dr}
\]

Eq. 7 may appear to be counterintuitive, due to the presence of the factor \( B^{-1/2} \) in the integral defined in eq. 8. Indeed an increase of the magnetic field would produce a decrease of the expected flux for a given frequency, simply because the full spectrum would be 'shifted' towards higher energies. The synchrotron flux (see e.g. Bertone, Sigl and Silk, 2001) is a growing function of frequency, roughly following a power law, until the cut-off frequency, which is the critical synchrotron frequency (see Rybicki & Lightman, 1979) of photons produced from the highest energy electrons (of energy \( \approx m_e \)). The cut-off frequency can be expressed as
\[
\nu \approx 408 \left( \frac{B}{\mu G} \right) \left( \frac{m_e}{100 \text{GeV}} \right) \text{GHz}
\]

An increase of the magnetic field would thus move the photons originated by the same electron population towards higher frequencies, thus reducing the flux for any given frequency, but extending it at higher frequencies, due to the increase of the cut-off frequency.

To obtain the observed radiation, one should multiply the luminosity \( L_\nu \) for the synchrotron self-absorption coefficient, defined as (see Rybicki & Lightman, 1979)
\[
A_\nu = \frac{1}{a_\nu} \int_0^{\infty} \left( 1 - e^{-\tau(b)} \right) 2\pi b \, db
\]
where \( \tau(b) \) is the optical depth as a function of the cylindrical coordinate \( b \)
\[
\tau(b) = a_\nu \int_{d(b)}^{\infty} f_\nu(b, z) \, dz
\]

and the coefficient \( a_\nu \) in our case is given by
\[
a_\nu = \frac{1}{4\pi} \frac{\gamma^2}{\nu^3}. \tag{13}
\]

(see paper I for details about lower limit of integration in eq.12 and approximations introduced).

We found that synchrotron self-absorption can reduce the predicted radio flux by several orders of magnitude. We evaluated the synchrotron luminosity for a wide set of supersymmetric models (using the DarkSUSY code) and for different values of \( \gamma \). We used, in particular, the expected luminosity at \( \nu = 408 MHz \) to estimate the magnetic field required to reproduce the observed flux.

In figure 1 we show the value of the magnetic field, relative to the equipartition field of eq. 6 for a wide set of supersymmetric model and 4 different values of \( \gamma \).

A value of \( \gamma \) between 0.05 and 0.1 seems to reproduce the right normalization at radio wavelengths, if combined with a magnetic field close to equipartition. Other values of the density profile power law index would instead require unacceptable values of \( B \).

4.2 Gamma-ray emission

As discussed above, neutralino annihilation produce a continuum \( \gamma \)-ray spectrum, originating from the decay of neutral pions, which in turn come from the hadronization process of quark-antiquark pairs.

Referring to the paper of Gondolo and Silk (1999) we write the contribution of the spike as
\[
\Phi_{\text{spike}} = \frac{\rho_\gamma^2 Y_\gamma \sigma_{\gamma}\nu D}{m^2} \left( \frac{R_{\text{sp}}}{R_{\text{in}}} \right)^{3-2\gamma} \left( \frac{R_{\text{sp}}}{R_{\text{in}}} \right)^{2\nu - 3}, \tag{14}
\]
where \( R_{\text{in}} = 1.5 \left[ (20 R_{\text{sp}})^2 + R_{\text{core}}^2 \right]^{1/2} \) and \( Y_\gamma \) is the number of photons produced per annihilation.

This formula is valid in the case of adiabatic accretion from an initial power law density profile. If one considers an initial isothermal profile (i.e. a profile with a flat central core), the enhancement of the flux in the Galactic Center...
would be negligible compared to radiation from annihilations along the line of sight (see Gondolo and Silk, 1999).

We show in figure 2 the expected fluxes for a subset of supersymmetric models and the same values of $\gamma$ as in figure 1. A value of $\gamma$ between 0.05 and 0.1 can reproduce the normalization of the observed flux. This is fully consistent with the result found in the previous section.

Larger values of $\gamma$ are also able to reproduce the EGRET normalization, as shown in figure 3. In particular we found that even if most of the models would require a $\gamma$ of the order of 0.1 or lower, some of them could go as high as $\gamma \approx 1$. These models correspond to very low predicted fluxes, and are thought to require an important level of fine-tuning of the seven input parameters. For comparison we also show the expected results in a scenario without the central spike, in which case a range of $\gamma$ between 1 and 2 is required.

Finally in figure 4 we show the required cross sections to reproduce the EGRET data normalization for all the supersymmetric models and four different values of $\gamma$ (in the case of presence of the central spike). Here again it is possible to read out the range of values of $\gamma$ which can reproduce the observed EGRET normalization with cross sections close to those predicted in our supersymmetric scenario.

5 RESULTS AND CONCLUSIONS

In the framework of a halo model with a spike around the central black hole, we showed that a consistent scenario can be built, reproducing at the same time both the radio and gamma-ray emission.

Observed radio emission can be explained by synchrotron emission of secondary e-e+ pairs in the Galactic magnetic field. The enhancement of annihilation rate due to the central spike and synchrotron self-absorption were the two main ingredients of our calculation.

Despite the lack of distinctive features of continuum gamma-ray emission, we find full consistency of the results obtained with the radio emission, the EGRET flux normalization being reproduced with values of $\gamma \approx 0.1$, when assuming profiles with a central spike.

The argument can also be turned the other way round and interpreted as a 'measure' of the Galactic magnetic field: we can in fact decide to select the values of $\gamma$ reproducing the normalization of the observed gamma-ray emission (figure 3), and go back to figure 1 to read out the corresponding value of $B^*$, which for most of the models is indeed of order the equipartition value, thus confirming the consistency of our scenario.

Forthcoming experiments, such as GLAST, will probe energies well above the EGRET measurements, up to 300 GeV. A sharp cutoff around the neutralino mass is predicted for this scenario, if the annihilation radiation gives the dominant contribution to normalization. Furthermore other 'smoking gun' signatures, such as narrow high energy gamma ray lines could give further information and constraints on neutralino properties or halo profiles.

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