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Signals of WIMP Annihilation into Electrons at the Galactic Center

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Photons from the annihilation of dark matter in the center of our Galaxy are expected to provide a promising way to find out the nature and distribution of the dark matter itself. These photons can be either produced directly and/or through successive decays of annihilation products, or radiated from electrons and positrons. This ends up in a multi-wavelength production of photons whose expected intensity can be compared to observational data. Assuming that the Lightest Supersymmetric Particle makes the dark matter, we derive the expected photon signal from a given dark matter model and compare it with present available data.

1. Introduction

Progress in cosmology [1] has identified a concordance model where 26 % of the energy density of the universe is made up of an unknown type of non-baryonic dark matter (DM). Weakly interacting massive particles (WIMPs) are regarded as good particle candidates for cold dark matter (CDM) scenarios, which are favorite to obtain a structure distribution as it is observed today. WIMP candidates naturally arise in extensions of the standard model of particle physics, such as in supersymmetry [2] or in Kaluza-Klein theories [3].

One of the methods that have been proposed to identify the DM matter relies on detecting photons, from gamma-rays, X-rays, optical photons, infrared, to radio waves [4]. These photons would be generated in DM annihilation in the halo of the galaxy, in particular near the galactic center (GC), where a $10^6 M_\odot$ super massive black hole (SMBH) resides.

In this work we reproduce the spectrum of photons radiated from electrons and positrons produced in the annihilation chain.

2. Electron diffusion and energy loss

We define the electron density function $N(E,r) = \frac{dn(E,r)}{dE}\,\mathrm{cm}^{-3}\,\mathrm{GeV}^{-1}$ and we consider relativistic electrons.

The diffusion-loss transport equation for $N(E,r)$ in the proximity of the black hole at the center of the Milky Way reads as

$$- \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 K(E,r)\frac{\partial}{\partial r}N(E,r)\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 v(r) N(E,r)\right] - \frac{1}{3r^2}\left[\frac{\partial}{\partial r}\left[r^2 v(r)\right]\right]\left[\frac{\partial}{\partial E}E N(E,r)\right] + $$
$$+ \frac{\partial}{\partial E}\left[N(E,r)\dot{E}(E,r)\right] - \frac{\partial}{\partial E}\left[\beta^2 E^2 K_{pp}(E,r)\frac{\partial}{\partial E}\frac{N(E,r)}{E^2}\right] = Q(E,r) \quad (1)$$

The first two terms define the diffusion in physical space. This is due to the diffusive mass flux which tends to move the particles from higher to lower concentration zones (the term proportional to $K(E,r)$ and to the advective mass flux due to the motion of the fluid in which the particles are (term proportional to $v(r)$). The third term in Eq. 1 describes the change of momentum due to adiabatic advection onto the black hole. The term proportional to $\dot{E}(E,r)$ describes the loss of energy due to synchrotron emission and inverse Compton scattering (ICS). The last term of the left hand side describes the re-acceleration due to diffusion in the momentum space. Finally, $Q(E,r)$ is the source term in units of $\mathrm{cm}^{-3}\,\mathrm{GeV}^{-1} s^{-1}$ and includes the injection distribution function of electrons and positrons, as they are produced in dark matter annihilation.

The equation has been solved in the range $m_e < E < m_\chi$ where m_e is the electron rest mass and m_χ the WIMP mass which we chose to be 1 TeV, and $10R_{BH} < r < 0.01\,\mathrm{pc}$, where R_{BH} is the SMBH gravitational radius and 0.01 pc is the outer radius at which the assumption of a spherically symmetric accreting gas starts to become invalid [5].

The GMRES iterative solver on piecewise linear triangular finite elements on an unstructured grid was used and elements were refined using logarithmic scalings. The robustness of the solutions was tested by using different grid spacings and through the switching on and off of adaptive grids with varying error criteria. The results changed little under these tests.

3. Model Parameters

The following parameters were chosen for Eq. 1:

We have assumed the presence of a $M_{BH} = 2.5 \times 10^6 M_\odot$ SMBH at the GC with Schwarschild radius given by $R_{BH} = 7.4 \times 10^{11}\,\mathrm{cm}$. The accretion velocity of the fluid onto the black hole is then simply $v_{acc}(r) = \sqrt{2GM_{BH}/r} = 1.46 \times 10^8 (\frac{r}{0.01\,\mathrm{pc}})^{-\frac{1}{2}}\,\mathrm{cm\,s^{-1}}$.

We have taken the simplest model of Melia corresponding to a sub-Eddington spherical accretion flow [7]. The magnetic field around the black hole is given by equipartition between magnetic and kinetic energy density which leads to $B_{eq}(r) = 3.9 \times 10^{-2} \left(\frac{r}{0.01\,\mathrm{pc}}\right)^{-\frac{5}{4}}$ G.

Although there is no definitive answer to the question about the central slope of the DM density around the SMBH at the GC, we have so far obtained spectra for the Navarro, Frenk and White (NFW) profile $\rho_\chi = \rho_s\,(r/r_s))^{-1}$ and for the steeper Moore profile $\rho_\chi = \rho_s\,(r/r_s))^{-1.5}$ [8] obtained through N-body simulations. For our Galaxy the parameters for the two models are, $r_s = 21.746, 34.52\,\mathrm{kpc}$ and $\rho_s = 5.376 \times 10^6, 1.060 \times 10^6 M_\odot\,\mathrm{kpc}^{-3}$ respectively. An inner constant density core is imposed, corresponding to the physical radius at which which the self-annihilation rate equals the dynamical time of formation of the cusp.

The diffusion coefficient $K(E)$ was computed following the prescriptions given in [9]. Assuming a Kolmogorov spectrum for the power spectrum of the density fluctuations of the magnetic field, it is equal to $K(E,r) = \frac{1}{3} c d_0^{\frac{2}{3}} \left(\frac{E}{eB_{eq}(r)}\right)^{\frac{1}{3}}$, where $d_0 = 2\,\mathrm{pc}$ is the distance from the GC at which the interstellar value $B = 1\mu G$ is reached, e is the electron charge and c is the speed of light. Numerically, it is $K(E,r) = 1.48 \times 10^{25} \left(\frac{r}{0.01\,\mathrm{pc}}\right)^{\frac{5}{12}} \left(\frac{E}{1\,\mathrm{GeV}}\right)^{\frac{1}{3}}\,\mathrm{cm^2\,s^{-1}}$.

The coefficient $K_{pp}(E,r)$ which governs the diffusion in momentum space, is related to $K(E,r)$ through the relation: $K_{pp}(E,r) = \frac{4}{3\delta(4-\delta^2)(4-\delta)} \frac{v_A^2 p^2}{K(E,r)}$, where v_A is the Alfvén velocity, defined as $v_A = \frac{B}{\sqrt{4\pi\rho}}$ where ρ is the density of the ions which carry the wave. In the accretion onto a black hole the temperature of the plasma is typically 10^6 eV so that we can consider the plasma totally ionized and put $\rho = \rho_{acc}$. From this follows that, in our model, $v_A = v_{acc}$. In numbers, $K_{pp}(E,r)\beta^2 = 4.04 \times 10^{-10} \left(\frac{M_{BH}}{2.5\times10^6 M_\odot}\right) \left(\frac{r}{0.01\,\mathrm{pc}}\right)^{-\frac{17}{12}} \left(\frac{E}{1\,\mathrm{GeV}}\right)^{\frac{5}{3}}$ $\mathrm{GeV^2\,s^{-1}}$.

Although the diffusion region is much smaller than the emitting region so that the energy loss could be considered to happen before any significant movement has occurred, we would like to execute a complete study which involves the re-acceleration terms because of the very peculiar environment we are considering.

The electrons and positrons lose energy through synchrotron emission and inverse Compton scattering (ICS). The energy loss due to synchrotron radiation is given by: $\dot{E}_{sync}(E,r) = \frac{4}{3}c\sigma_T \frac{B^2_{eq}(r)}{8\pi}\gamma^2$, where γ is the Lorentz factor and $\sigma_T = 6.65 \times 10^{-25}\,\mathrm{cm}^2$ is the Thomson cross section. Numerically, we have $\dot{E}_{sync}(E,r) = 3.85 \times 10^{-9} \left(\frac{r}{0.01\,\mathrm{pc}}\right)^{-\frac{5}{2}} \left(\frac{E}{1\,\mathrm{GeV}}\right)^2 \,\mathrm{GeV\,s^{-1}}$ The energy loss due to ICS is given by a term which controls the ICS off background starlight and CMB photons $\dot{E}^{bck}_{ICS}(E) = \frac{4}{3}c\sigma_T U_{bck}\gamma^2$ and a term which gives the contribution of ICS off synchrotron photons $\dot{E}^{sync}_{ICS}(E,r) = \frac{4}{3}c\sigma_T U_{sync}(r)\gamma^2$

While the energy density of CMB photons and starlight is known and equal to $U_{CMB} = 0.25\,\mathrm{eV\,cm^{-3}}$ and $U_\star \sim 1\,\mathrm{eV\,cm^{-3}}$, respectively, the energy density of synchrotron radiation is not known $a-priori$, and must be determined through the relation $U_{sync}(r) = \left[\frac{1}{r^2}\int_{r_{min}}^{r} dr' r'^2 \int d\nu j_{sync}(\nu, r') + \int_r^\infty dr' \int d\nu j_{sync}(\nu, r')\right]$ where $j(\nu, r)$ is the synchrotron emissivity $j_{sync}(\nu, r)d\nu = N(E,r)\dot{E}_{sync}(E,r)dE$.

The source term is determined by the particle physics assumption for the DM nature and by astrophysics assumptions for its distribution, in lack of observational constraints. Generally $Q(E,r)$ has the form $Q(E,r) = \left(\frac{\rho_\chi(r)}{m_\chi}\right)^2 \frac{\langle\sigma v\rangle_{ann}}{2}\frac{dn_{ann}(E)}{dE}$ where $\frac{dn_{ann}}{dE}$ is the energy distribution of the electrons and positrons produced in one annihilation: $\frac{dn_{ann}(E)}{dE} = 2b_{ee}\delta(E - m_\chi) + \sum_f \frac{dn^e_{ann}(E)}{dE_e}b_f$, where the sum gives the energy distribution of the electrons produced in the cascade of particles due to hadronization and decay of each final state f, while the term proportional to the δ-function takes into account the direct annihilation into an electron-positron pair with branching ratio b_{ee}. Such branching ratio is negligible for SUSY particles. With the Moore profile and a SUSY WIMP we have $Q(E,r) = 6.68 \times 10^{-16}\left(\frac{r}{0.01\,\mathrm{pc}}\right)^{-3} \frac{dn_{ann}(E)}{dE}\,\mathrm{cm^{-3}\,GeV^{-1}\,s^{-1}}$.

4. Photon spectrum

The total energy emitted by the electrons is $L_{tot} = 4\pi \int\int j(\nu,r)r^2 dr d\nu = 4\pi\int\int N(E,r)\dot{E}r^2 dr dE$. The specific luminosity us given by $\nu L(\nu) = \nu\frac{dE}{d\nu}\int N(E,r)\left(\frac{B}{Gauss}\right)^2 \dot{E}4\pi r^2 dr$. An electron of energy E in a field of strength B gives synchrotron radiation centered around frequency $\nu = \gamma^2\nu_g = \left(\frac{E}{m_e}\right)^2\nu_g$, where $\nu_g = \frac{eB}{2\pi m_e} = 2.8\mathrm{Hz}|_{B=1\mu G}$. We thus end up with the following expression for the flux: $\nu L(\nu) = 1.0413 \times 10^{-15}\mathrm{ergs}^{-1}\frac{E^3}{2m_e^2}\int N(E,r)\left(\frac{B}{Gauss}\right)^2 4\pi r^2 dr$, to be calculated along the line of sight.

A similar reasoning holds for the ICS. Considering as a first approximation only ICS off stellar photons, we obtain $\nu L(\nu) = \nu\frac{dE}{d\nu}\int N(E,r)\dot{E}4\pi r^2 dr = \frac{E}{2}\int N(E,r)\dot{E}4\pi r^2 dr = 1.12 \times 10^{-28}\mathrm{ergs}^{-1}\frac{E^3}{2m_e^2}\int N(E,r)4\pi r^2$ dr and it can be seen straight away that the inverse compton scattering is sub-dominant.

Results for the synchrotron emission due to DM annihilation are presented in Fig. 1. The diagram on the left is for the NFW profile and contains three plots showing how different terms in the diffusion-loss equation effect the spectrum. The diagram on the right is the spectrum for the steeper Moore profile.

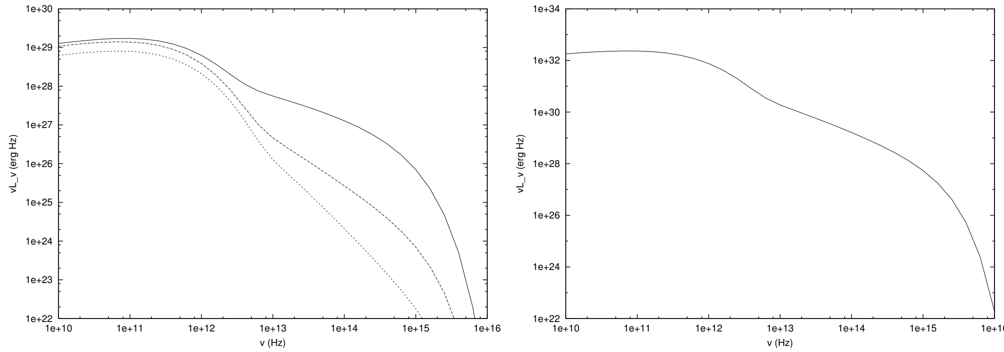

Figure 1. Left: Solution to the diffusion-loss equation for the electron density at the GC with an NFW profile. The three different curves correspond from top to bottom to i) no advection or energy loss, ii) including advection, iii) including advection and energy loss. Right: Synchrotron spectrum from dark matter annihilation at the GC for the steeper Moore Profile.

5. Discussion and conclusions

We have calculated the synchrotron photon spectrum from DM annihilation into showers of electrons at the GC. Our numerical results for the NFW profile are in good agreement with the analytic estimates of Aloisio et al [4]. We have calculated the spectra for the steeper Moore 99 Profile and although more emission occurs in this case, such a dark matter distribution cannot be rule out at this time. Simulations in progress should shed light on more spiky profiles and profiles with direct annihilation into electron-positron pairs.

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