Can Planck constrain indirect detection of dark matter in our galaxy?

Timur Delahaye\(^1\), Céline Bœhm\(^2,3\) and Joseph Silk\(^4,5\)

\(^1\)Instituto de Física Teórica UAM/CSIC Universidad Autónoma de Madrid Cantoblanco, 28049 Madrid, Spain
\(^2\)Inst. for Particle Physics Phenomenology, Durham University, South Road, DH1 3LE, United Kingdom
\(^3\)LAPTH, CNRS/UMR 5108, 9 chemin de Bellevue - BP 110, 74941 Annecy-Le-Vieux, France
\(^4\)Astrophysics department, Oxford University, Keble Road, OX1 3RH, United Kingdom
\(^5\)Institut d’Astrophysique de Paris, CNRS/UMR7095, 98 bis boulevard Arago, 75014 Paris, France

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ABSTRACT

We investigate the synchrotron emission (both intensity and morphology) associated with generic dark matter particles and make predictions for the PLANCK experiment using the FERMI data and a model for the astrophysical sources. Our results indicate that the morphology of the dark matter plus astrophysical source synchrotron emission is frequency-dependent. We show that a thorough comparison between LFI and HFI data can potentially provide a new tool for constraining the dark matter particle mass.

Key words: Astroparticle physics – dark matter – radio continuum: ISM.

1 INTRODUCTION

There are many indirect detection techniques that can be used to elucidate the nature of the dark matter in our Universe. Among them, the anomalous production of cosmic rays and \(\gamma\)-rays, first proposed by Silk & Srednicki (1984) in the context of self-annihilating neutralinos, has received much attention since the PAMELA experiment confirmed an excess of positrons at relatively low energies. A new type of dark matter signature has also been proposed in the form of anomalous radio emission from leptonic annihilation products (Bœhm et al. 2004; Colafrancesco et al. 2006; Zhang & Sigl 2008; Borriello et al. 2009; Crocker et al. 2010; Siffert et al. 2011; Bergstrom et al. 2009; Boehm et al. 2010). It may even be possible to discriminate decaying from annihilating dark matter scenarios using the morphology of the electromagnetic emission if a signal were detected (Ascasibar et al. 2006; Bœhm et al. 2010).

There has been recent interest in the exploitation of galactic foregrounds in all-sky CMB experiments for the detection of synchrotron light (corresponding to microwave and submillimetre radiation) emitted by a new, relativistic, population of electrons originating from dark matter annihilations or decays. It was pointed out a few years ago that the subtraction of known foregrounds (extrapolated from the Haslam data at 408 MHz and from Parkes at 2.4 GHz) to microwave frequencies showed a residual trace in the 22GHz channel of WMAP. It was then speculated that the so-called WMAP haze (Finkbeiner 2004) could be due to dark matter particles (Hooper et al. 2007; Dobler & Palomares-Ruiz 2010). Whatever the origin of the WMAP haze, this work has demonstrated that dark matter could potentially be seen in CMB experiments via galactic foregrounds.

Here, we demonstrate that exploiting PLANCK data may open up a new window for indirect searches of dark matter particles and offers a way to cross-check the results obtained from other channels. Our assumptions are the following: i) we suppose that dark matter particles annihilate or decay into electrons (and positrons) with some specified branching ratio, as in Bœhm et al. (2010) and Bernal & Palomares-Ruiz (2010); ii) we use a semi-analytical approach to solve the diffusion equation (as described in Delahaye et al. (2008)) to propagate relativistic electrons, and iii) we assume a smooth NFW dark matter halo profile, parameterized as:

\[
f_{\text{DM}}(r) = \frac{R_{\odot}}{r} \left( \frac{R_{\odot} + R_{\Gamma}}{r + R_{\Gamma}} \right)^2,
\]

with \(R_{\Gamma} = 20\) kpc and \(R_{\odot} = 8.5\) kpc.

2 METHOD

In order to estimate the synchrotron emission from dark matter particles, we first need to determine the electron/positron production rate by dark matter (\(Q_n\)) for each adopted particle mass \(m_{\text{dm}}\). For this purpose, we exploit the fact that the same population of relativistic electrons is expected to produce both synchrotron radiation relevant for CMB experiments and a measurable cosmic ray flux at the Sun’s position relevant for balloon or satellite experiments such as FERMI.
For a given dark matter mass, one cannot arbitrarily increase the value of $Q_n$ because this would lead to an excess of electrons and positrons in the Fermi data. Before evaluating the “dark” synchrotron emission, we thus need to determine the maximal allowed dark matter pair annihilation cross-section which is compatible with the Fermi data for specific values of the dark matter mass $\nu$

This, however, requires knowledge of the background emission. I.e. one has to estimate the electron and positron flux expected from galactic astrophysical sources. Unfortunately there is no exhaustive catalogue of high energy electron emitters in the galaxy. Hence, a technique, used in particular by WMAP to remove the synchrotron emission, assumes that radio (low frequency synchrotron) maps and access the cosmic microwave background (CMB), as-needed there is no exhaustive catalogue of high energy electron fluxes expected from galactic astrophysical sources. Unfortunately such variations and embed them into a semi-analytical approach, we will assume that the field is constant over the entire diffusion zone and consider the same set of propagation parameters whatever the source of high energy electrons. Finally, we neglect the reacceleration of cosmic rays while this may actually be important for low mass dark matter particles.

We can now estimate the synchrotron emission from dark matter particles in a smooth dark halo. The surface brightness is given by:

$$I_r(l, b) = \frac{N_e Q_n}{\eta_n b(E)} \int ds(l, b) \int d^3x \left( \frac{\rho(x)}{m_{dm}} \right)^n \times G(\odot, x \leftarrow E_{inj})$$

(2)

the electron flux at an energy $E$ and in a given direction (integrated along the line of sight). The term $G(\odot, x \leftarrow \epsilon, E_{inj})$ represents the Green’s function. It encodes the propagation of the electrons (spatial diffusion and losses) from their place of “birth” to a position $x$ and from an injection energy $E_{inj} = n \times m_{dm}/2$ to a lower energy $E_{min} = \epsilon$. $N_e$ is a multiplicity factor. Since dark matter always produces both an electron and a positron simultaneously, $N_e = 2$. The term $b(E)$ accounts for the energy losses (inverse Compton and synchrotron) and $b_{sync}(E)$ for those due to synchrotron only.

The convention displayed in Eq.2, i.e. $n = 1, 2$, denotes the decaying and annihilating DM cases respectively. The term $Q_1$ is the decay rate (expressed in $s$), $Q_2$ is the annihilation cross section (expressed in $cm^3/s$), $\rho$ is the dark matter mass distribution and $m_{dm}$ is the dark matter mass. The term $\eta_n$ is equal to unity when dark matter is decaying ($\eta_{n=1} = 1$). It is equal to 2 or 4 if dark matter is annihilating ($\eta_{n=2} = 2$ if dark matter is a Majorana and $\eta_{n=2} = 4$ if dark matter is a Dirac particle).

1 Note that maximising the annihilation cross-section (or the decay rate) may actually lead to some structures in the cosmic ray flux but this is not in conflict with observations. Besides, local sources may induce similar effects.
Following this procedure, we find that for 40 GeV particles, the annihilation cross section can be as large as $\sigma v \simeq 1.5 \times 2.5 \times 10^{-26} \text{cm}^3/\text{s}$ in our galaxy without being in conflict with the FERMI data. This suggests that annihilations in the primordial Universe were either occurring mostly into particles other than electrons (and positrons) or the velocity-dependent term in the pair annihilation cross section into electrons is important ($\sigma v = a + bv^2$ with $a > b$). For 100 GeV particles, the annihilation cross section is about $\sigma v \simeq 7 \times 10^{-26} \text{cm}^3/\text{s}$. This is somewhat larger than the canonical thermal annihilation value required to explain all the dark matter today (namely $3 \times 10^{-26} \text{cm}^3/\text{s}$) but is still compatible with the FERMI measurement of the electron + positron flux in the Milky Way. Such a $\sigma v$ value could suggest scenarios in which the annihilation cross section is enhanced in the galaxy due to the small velocity dispersion of the dark matter particles in the halo (c.f. the Sommerfeld enhancement). Hence constraints from spheroidal dwarf galaxies (dSph) may apply.

Although the FERMI limits on dark matter candidates obtained from dSph are stringent, they do depend on the dark matter mass and most notably on the adopted dark matter profile. Using PLANCK data would therefore provide additional constraints and a means to cross check the FERMI results.

3 “DARK” SYNCHROTRON EMISSION

In what follows, we will display the most significant synchrotron map predictions. We focus on annihilating dark matter particles. We use the “MED” (corresponding to $L = 4 \text{ kpc}$, $\delta = 0.7$, $K_0 = 0.0112 \text{kpc}^2/\text{Myr}$) and “MAX” (corresponding to $L = 15 \text{ kpc}$, $\delta = 0.46$, $K_0 = 0.0765 \text{kpc}^2/\text{Myr}$) set of propagation parameters. As demonstrated in our previous work Boehm et al. (2010), a smaller diffusion zone (corresponding to the “MIN” set of parameters) will lead to a more confined “dark matter” synchrotron emission (brighter in the centre and fainter outside) while a more optimistic model of propagation (“MAX”) would lead to a brighter emission at larger latitude and longitude. Of course, the relative brightness of the emission at each frequency is affected by the choice of propagation parameters but, in this Letter, we do not attempt to perform a detailed analysis of the propagation parameters. We only point out that if propagation of cosmic rays in our galaxy is correctly described by the “MED” and “MAX” parameter sets, PLANCK may have the ability to constrain the dark matter mass.

To produce the dark matter-related synchrotron maps, we assume a monochromatic emission (i.e., one frequency corresponds to a single value of the electron energy). The relation between injection energy and frequency then reads:

$$\nu_{\text{max}} = 16 \text{ MHz} \times \left( \frac{E}{100 \text{ eV}} \right)^2 \times \left( \frac{N_{\text{dm}}}{10^{12} \text{ particles}} \right)^2 \times \left( \frac{B}{\mu \text{G}} \right).$$

This well-known relation indicates that small dark matter masses cannot “shine” at high frequencies unless the magnetic field is very strong. Although obvious, this property turns out to be very important for dark matter searches. In Fig. 1, we show that 10 GeV dark matter can shine at 33 GHz if the magnetic field is about 25 $\mu$G. However, no signal is expected at higher frequencies unless the magnetic field is stronger. The intensity of the emission is large enough to be within the reach of PLANCK sensitivity. The dark matter signal is very bright at the centre, as can be expected from the large value of the magnetic field (the latter indeed confines the electrons in the centre). However the sum of the two contributions is bright enough at high latitudes to have a chance of being detected by the LFI. This is consistent with previous dark matter analyses performed in the context of the WMAP haze (Hooper & Linden 2011). Interestingly enough, for such parameters one also expects a radio signature in the galactic centre. As shown in Boehm et al. (2001); Boehm et al. (2010), one expects the radio emission to be about ten times smaller than the emission attributed to the central black hole. Therefore, in principle, the estimate of the radio emission should set a stronger limit on the cross-section. I.e. it is likely to constrain cross-sections greater than $\sigma v \simeq 2 \times 10^{-27} \text{cm}^3/\text{s}$. Nonetheless, one still expects a visible signal in PLANCK/LFI and no signal in HFI.

When the mass is about 40 GeV and the magnetic field is close to the average value in the whole galaxy (cf. Fig. 2), one observes an extinction of the dark matter contribution is stronger. The intensity of the emission is large enough to be within the reach of PLANCK sensitivity. The dark matter signal is very bright at the centre, as can be expected from the large value of the magnetic field (the latter indeed confines the electrons in the centre). However the sum of the two contributions is bright enough at high latitudes to have a chance of being detected by the LFI. This is consistent with previous dark matter analyses performed in the context of the WMAP haze (Hooper & Linden 2011). Interestingly enough, for such parameters one also expects a radio signature in the galactic centre. As shown in Boehm et al. (2001); Boehm et al. (2010), one expects the radio emission to be about ten times smaller than the emission attributed to the central black hole. Therefore, in principle, the estimate of the radio emission should set a stronger limit on the cross-section. I.e. it is likely to constrain cross-sections greater than $\sigma v \simeq 2 \times 10^{-27} \text{cm}^3/\text{s}$. Nonetheless, one still expects a visible signal in PLANCK/LFI and no signal in HFI.

When the mass is about 40 GeV and the magnetic field is close to the average value in the whole galaxy (cf. Fig. 2), one observes an extinction of the dark matter contribution.
Figure 4. Synchrotron maps for 200 GeV dark matter particles, \(B = 3\mu G\). We use the MED parameter set and assume annihilating particles.

Figure 5. Synchrotron maps for 200 GeV dark matter particles, \(B = 6\mu G\). We use the MED parameter set and assume annihilating particles.

teresting effect: namely extinction of the dark synchrotron emission at the lowest frequencies. Unlike what is shown in the previous figures, we see that the signal is fainter at low frequencies than that at high frequencies. The emission becomes clearly visible in the 857 GHz channel while still present at lower frequencies. One could therefore cross-correlate all channels to constrain the dark matter mass. The same feature can be seen in Fig. 5 when one increases the magnetic field. However, the signal is brighter and slightly more concentrated towards the galactic centre. Again, this was to be expected since a large value of the magnetic field confines the electron in the galactic centre. As a result, the synchrotron emission is brighter but also more confined towards the centre.

The emission is easier to observe when the propagation parameters correspond to the MAX set. In this case, it is broader (cf Fig. 6). However, in terms of intensity, it is quite similar to the MED set of parameters.

Finally, it is interesting to note that the extinction of the dark synchrotron emission at low frequencies is particularly visible when the dark matter mass is about 800 GeV (cf Fig. 7). In this case, the LFI should not see any signal while HFI could in principle have a detection. The emission at 857 GHz should be about \(7 \times 10^{-2}\) Jy. This is quite faint but the synchrotron emission associated with astrophysical sources is comparable. Hence, the ability for HFI to determine whether there is a “dark” synchrotron signal depends on the level of accuracy required to remove the other foregrounds. These figures demonstrate that extrapolating radio maps to high frequencies can lead to the wrong conclusions since very high energy electrons can, depending on their injection energy, shine at the highest frequencies only.

Concerning decaying dark matter, the emission is spatially much broader and because the decay rate is constrained by local cosmic-ray fluxes to be quite low \((1-10 \times 10^{-28} \text{ s}^{-1})\), it appears to be very difficult to distinguish from the astrophysical background. Nearby galaxy cluster observations by Fermi (Dugger et al. 2010; Ke et al. 2011) provide strong constraints on gamma rays from \(b\) and \(\mu\) channels for decaying dark matter because of the relatively broad emission profile, and it might be of interest to reexamine the implications of Planck data for constraining dark matter via leptonic decays in these systems.
4 CONCLUSION

In this Letter, we have investigated the synchrotron emission from annihilating and decaying dark matter particles and predict the morphology and the intensity of the emission at PLANCK frequencies. To avoid considering unrealistic scenarios, we have required that the sum of the dark matter and astrophysical source contributions to the electron plus positron flux observed at Earth position be compatible with the FERMI data. By comparing the different LFI and HFI frequency channels, we found that the dark matter (synchrotron) signature has very specific features that could be used to find such a signal if it exists. For reasonable values of the magnetic field (and assuming it is uniform), we find that heavy dark matter particles illuminate high frequencies but do not shine in the lowest frequencies. Alternatively, light particles “illuminate” the lowest frequencies (rather than the highest frequencies) for small values of the magnetic field.

Although this is somewhat obvious, this characteristic indicates that the combined analysis of both LFI and HFI could help in determining the dark matter mass if an anomalous synchrotron emission were detected by the LFI at high latitude and absent from HFI data, or vice versa. This confirms that the PLANCK experiment has the capacity to compete with dark matter direct (as well as other indirect) detection experiments. Such an analysis would be particularly useful in light of the recent claims of signals in several direct detection experiments (Aalseth et al. 2011; Bernabei et al. 2008, 2010; CDMS II Collaboration et al. 2010; EDELWEISS Collaboration et al. 2011) whose (highly speculative) interpretation as dark matter inelastic scattering events would favour relatively light dark matter particles and could therefore be within reach of PLANCK sensitivity.

Disentangling the dark matter signal from astrophysical sources would be rather difficult. For example a 10 GeV dark matter particle would contribute to both the radio and submillimeter frequency ranges. However, a combined analysis of all the different frequency channels together with improved modelling of known astrophysical sources and the propagation of cosmic rays may actually help to discriminate among various scenarios. In any case, performing such an analysis using PLANCK data, would certainly complement the constraints on the dark matter parameter space already obtained by several dark matter experiments, including FERMI searches for γ-rays from dSph.

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