CONSTRANT ON LIGHT DIPOLE DARK MATTER FROM HELIOSEISMOLOGY

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ABSTRACT

We investigate the effects of a magnetic dipole moment of asymmetric dark matter (DM) in the evolution of the Sun. The dipole interaction can lead to a sizable DM scattering cross section even for light DM, and asymmetric DM can lead to a large DM number density in the Sun. We find that solar model precision tests, using as diagnostic the sound speed profile obtained from helioseismology data, exclude dipolar DM particles with a mass larger than 4.3 GeV and magnetic dipole moment larger than 1.6 × 10−17 e cm.

Key words: cosmology: miscellaneous – dark matter – elementary particles – primordial nucleosynthesis – Sun: helioseismology

Online-only material: color figures

1. INTRODUCTION

The universe is composed of baryons and unknown nonbaryonic particles, commonly called dark matter (DM). Although the gravitational interaction between baryons and DM is well-established, other types of interactions with the standard particles are less well known.

Several experiments seek to detect the DM particle by observing its scattering off nuclei, by detecting some by-product resulting from its annihilation into high energy particles, or by producing them in accelerators through the collision of standard particles. The goal is for one or more of these experiments to obtain a signal of the DM interaction, other than the well-known gravitational interaction. The first positive hints of direct DM observations are intriguing, although controversial: the established, other types of interactions with the standard particles which do not comply with standard explanations of weak interactions massive particle interactions. Furthermore, other collaborations, such as XENON (Aprile et al. 2012) and CDMS (Agnese et al. 2013a), can nearly exclude the positive results found by the previous experiments.

This experimental data has stimulated interest in light DM ≤ 10 GeV as a candidate. For the purpose of illustrating the potentially stringent constraints on light DM, we consider an operator which can induce large enough DM-nuclear interactions even for small momentum transfer due to a small DM mass. One of the simplest extensions of the standard model for this purpose would be the dipole operator which is the only gauge invariant operator up to dimension five, letting fermionic DM with an intrinsic dipole moment couple to the photons (Bagnasco et al. 2000; Sigurdson et al. 2006; Masso et al. 2009; Héo 2010). Such magnetic dipole dark matter (MDDM) can successfully explain recent claims of direct detections, including DAMA/LIBRA and CoGeNT (An et al. 2010; Barger et al. 2011). Moreover, several constraints have been set on MDDM using direct search data (Lin & Finkbeiner 2011; Del Nobile et al. 2012), astrophysical and cosmological observations (Fukushima & Kumar 2013) and the Large Hadron Collider data (Fortin & Tait 2012; Barger et al. 2012).

Here, we use helioseismic data to set constraints on asymmetric MDDM. In particular, we focus on the solar sound speed radial profile, for which there is a reliable inversion obtained from seismic data (Basu et al. 2009; Turck-Chieze et al. 1997).

2. PROPERTIES OF MAGNETIC DIPOLE DARK MATTER

This study focuses on the DM fermion χ which couples to the photon by the magnetic dipole interaction Lagrangian \( L_{\text{MDDM}} = \frac{\mu \chi}{2} \sigma^\mu \nu F^\mu \nu \chi \) where \( F^\mu \nu \) is the electromagnetic field strength tensor, \( \sigma^\mu \nu \) is the commutator of two Dirac matrices and \( \mu \chi \) is the magnetic dipole moment. We notice this interaction vanishes for Majorana fermions, so the fermionic DM particle has to be Dirac.

The fermionic DM particle with a magnetic dipole moment arises in many models of DM, including among others models related to technicolor (e.g., Foada et al. 2007). In particular, we are interested in the case of the interaction of DM with the baryons that takes place by means of a massless mediator to yield long-range interaction, a process quite distinct from the contact-like interaction (Del Nobile & Sannino 2012; Del Nobile et al. 2012). The photon is the obvious mediator, among more exotic candidates such as the dark photon (Fornengo et al. 2011; Chun et al. 2011).

The DM differential scattering cross section with respect to the nuclei recoil energy \( E_R \) off the nucleus with a spin \( I \) with a DM particle of spin \( S_\chi \), via the electromagnetic interaction between the nuclear magnetic moment \( \mu Z A \) (of a nucleus of mass \( A \) and charge \( Z \)) and the magnetic moment \( \mu_\chi \) of the DM particle, is described by (Barger et al. 2011):

\[
\frac{d\sigma_\chi}{dE_R} = \frac{e^2 \mu^2 Z A}{4\pi E_R} \frac{S_\chi + 1}{5S_\chi} \left[ A_E |G_E|^2 + B_M |G_M|^2 \right].
\]

where \( A_E \) and \( B_M \) are the electrical and magnetic moment terms, and \( G_E(E_R) \) and \( G_M(E_R) \) are the nuclear form factors

\[1\]
(normalized to $G_F(0) = 1$, $G_M(0) = 1$) to take into account the elastic scattering off a heavy nucleus. $A_E$ and $B_M$ read

$$A_E = Z^2 \left(1 - \frac{E_R}{2m_A v_r^2} - \frac{E_R}{m_X v_r^2}\right)$$

(2)

$$B_M = \frac{I + 1}{3I} \left(\frac{\mu_Z A}{e/(2m_p)}\right)^2 \frac{m_A E_R}{m_p v_r^2}$$

(3)

where $e$ and $m_p$ are the elementary electric charge and the mass of the proton (Barger et al. 2012). $m_A$ and $m_X$ are the masses of the baryon nucleus and DM particle, respectively. $E_R$ and $v_r$ are defined from the transfer momentum $q$ and the center-of-mass momentum $p_x$, such that $q^2 = 2m_A E_R$ and $|p| = m_v v_r$ where $m_v = m_A m_X / (m_A + m_X)$.

At first glance, it is reasonable to expect that the contribution of heavy elements for the interaction inside the Sun could be quite significant, due to the strong dependence in $Z$ and $I$ (see Equations (1)–(3)). However, because metals inside the Sun contribute to less than 2% of the total mass of the Sun, their contribution can be considered to be negligible. The electromagnetic interaction between MDDM and baryons will be important for hydrogen and helium which correspond to 98% of the total mass of the Sun, from which Helium abundance in the Sun’s core changes during its evolution from an initial abundance of 27% to 62% for the current age of the Sun. Nevertheless, this increase of helium occurs only in the very center of the Sun, the atomic number of helium ($Z = 2$) is relatively small (when compared with other chemical elements), and the helium abundance is always smaller than that of hydrogen. Furthermore, during the Sun’s evolution, to a good approximation, it is reasonable to consider only the interaction of MDDM with hydrogen to be relevant. The total elastic scattering cross section of DM with hydrogen $\sigma_{Xp}$, from Equations (1)–(3) with a uniform form factor, can then be expressed as $\sigma_{Xp} = \sigma_{Xp}^{SL} + \sigma_{Xp}^{SD}$ where $\sigma_{Xp}^{SL}$ and $\sigma_{Xp}^{SD}$ are the conventional effective scattering cross sections (Barger et al. 2012):

$$\sigma_{Xp}^{SL} = \frac{\mu_p^2 e^2}{2\pi} \left(1 - \frac{m_p^2}{2m_p^2} - \frac{m_p^2}{m_pm_X}\right)$$

(4)

and

$$\sigma_{Xp}^{SD} = \frac{\mu_p^2 e^2}{2\pi} \left(\frac{\mu_p}{e/(2m_p)}\right)^2 \frac{m_p^2}{m_p^2}$$

(5)

with $\mu_p$ being the magnetic moment of the proton. Both $\sigma_{Xp}^{SL}$ and $\sigma_{Xp}^{SD}$ contribute equally for the total scattering cross section, $\sigma_{Xp}$. However, in the case that the mass of the DM particle is much larger than the mass of the proton, i.e., $m_X \gg m_p$, it follows that $m_r \approx m_p$ and the $\sigma_{Xp}$ becomes independent of the mass of the DM particle, and $\sigma_{Xp}$ is only proportional to the square of the DM magnetic moment, $\sigma_{Xp} \approx 8.3 \cdot e^2/(2\pi) \mu_p^2$.

3. DARK MATTER AND THE STANDARD SOLAR MODEL

Our Galaxy and the Sun are assumed to be immersed in an isothermal sphere composed of MDDM particles. The observational determination of the DM density $\rho_X$ in the neighborhood of the Sun is quite uncertain, varying from 0.3 to 0.85 GeV cm$^{-3}$ (Boyr & Tremaine 2012; Garbari et al. 2012). Here we set $\rho_X = 0.38$ GeV cm$^{-3}$ (Catena & Ullio 2010).

DM particles flow through any celestial object such as the Sun. A few of these particles will occasionally scatter with the atomic nuclei of the star, mostly with protons, losing energy in the process, in some cases the energy reduction is such that the velocity of the DM particle becomes smaller than the Sun’s escape velocity, i.e., the DM particle becomes gravitationally bound to the Sun. As time passes, the DM particle undergoes more collisions, until the particle reaches thermal equilibrium with local baryons.

The accretion of DM by the Sun depends on the balance between three processes: capture of DM via energy loss of the colliding particle with the baryon nuclei; annihilation of two DM particles into standard particles; and evaporation of DM particles, important for light DM particles for which the collisions with nuclei result in escape from the Sun’s gravitational field. Therefore, the total number of DM particles inside the Sun is determined by the relative magnitude of these three processes.

At each step of the Sun’s evolution, the total number of particles $N_x$ that accumulate inside the star is computed by solving the following equation numerically (Lopes & Silk 2012a):

$$\frac{dN_x(t)}{dt} = C_c - C_a N_x(t)^2 - C_e N_x(t),$$

(6)

where $C_c$ is the rate of capture of particles from the MDDM halo, $C_a$ is the annihilation rate of particles, and $C_e$ in the evaporation rate of DM particles from the star. The capture rate $C_c$ is computed numerically at each step of the evolution from the expression obtained by Gould (1987). The cross section used in the computation of $C_c$ corresponds to the ones given by Equations (4)–(5). In the following, we will consider the asymmetric DM scenario and hence $C_a$ can be neglected. A concrete realization could include asymmetric composite DM which can induce a sizable dipole for the bound state of the particles (Foadi et al. 2007; Ryttov & Sannino 2008; Del Nobile et al. 2011).

The evaporation of DM particles is not relevant for $m_x \geq 4$ GeV, nevertheless for less massive particles, the effect of evaporation is not negligible and the capture process goes into equilibrium with the evaporation. In the regime where the Sun is optically thin with respect to DM particles, Busoni et al. (2013) have obtained an approximate expression for $C_e$, which we use in our calculations to define the lower bound of less massive DM particles. This expression reproduces the full numerical results with an accuracy better than 15% (Kappl & Winkler 2011).

The reference solar model used in our computation corresponds to the standard solar model (SSM), which has been updated with the most recent physics (Turck-Chieze & Lopes 1993). In particular, we choose to use the solar composition determined by Asplund et al. (2009), usually known as the low-metallicity (or low-Z) SSM, as discussed by Haxton et al. (2013). Figure 1 shows the sound speed difference of reference that corresponds to the sound speed difference between the low-Z SSM and the sound speed obtained by inversion of the seismic data of the Global Oscillations at Low Frequencies and Michelson Doppler Image instruments of the Solar and Heliospheric Observatory Satellite and BiSON observational network (Turck-Chieze et al. 1997; Basu et al. 2009). A detailed discussion about the physics of our SSM can be found in Lopes & Turck-Chieze (2013). This SSM is identical to others low-Z SSM published in the literature (e.g., Serenelli et al. 2013).
The solar models evolving in different MDDM halos are obtained by a similar procedure to the SSM. Likewise these models are required to have the observed solar radius and luminosity at the present age. In our description of the impact of DM on the evolution of the Sun, we closely follow recent developments in this field (Cumberbatch et al. 2010; Lopes et al. 2011; Lopes & Silk 2012b, 2012a; Casanellas & Lopes 2013). A detailed description of how this process is implemented in our code is discussed in Lopes et al. (2011).

The accumulation of MDDM particles inside the Sun reduces the temperature in the Sun’s core and, as a consequence, the sound speed drops, but is compensated for by an increase of sound speed in the radiative region and the convection zone (see Figure 1). This results from the fact that these solar models are required to have a radius and luminosity consistent with observations. The calibration follows an iterative procedure identical to the one used to compute the SSM. In principle, we could use the sound speed and density profiles obtained from inversion of helioseismology data as a diagnostic tool, however, we prefer to use the sound speed because only frequencies of acoustic modes are observed, consequently sound speed inversion is the more reliable diagnostic method. In the future, if frequencies of gravity modes are measured with success, the density profile could become an independent method to probe the Sun’s core. Figure 1 shows that the sound speed differences of the solar models computed for different values of \( m_\chi \) and \( \mu_\chi \) are quite distinct from the sound speed difference of reference. This effect is more important for DM particles of relatively low mass and high magnetic moment. In the case of particles with a very low \( m_\chi \), the impact on the sound speed difference profile becomes insignificant due to the occurrence of DM evaporation. Although the DM affects the whole internal structure of the star equally, we focus our analysis on the Sun’s core where the direct impact of DM is detected. It is reasonable to consider that for solar models for which the sound speed difference is larger than the sound speed difference of the reference model, or equivalently if this difference is larger than 2%, then these solar models can be excluded on the basis that they cannot be accommodated with our current understanding of the physics of the solar interior. It is true that in the Sun’s deep core the sound speed difference of the reference solar model still contains a few uncertainties coming either from an insufficient description of the physics of the SSM, or poor inversion of the sound speed profile due to a lack of low degree seismic data. It is believed that some of the current problems in the SSM are related to abundances and opacities below the base of the convection zone, but these localized uncertainties do not affect the core of the Sun where this diagnostic is done. Moreover, their effect on the Sun’s structure will be smaller than the observational sound speed difference. Nevertheless, this uncertainty is at most of the order of 1.5%. Alternatively, if we choose to use as reference a high-Z SSM, as the sound speed difference with observations is of the order of 0.3%, the constraint on the MDDM parameters could be stronger. Nevertheless, due to the problem related to the chemical composition in the solar interior (Serenelli et al. 2011), we take the conservative approach of using the low-Z SSM which has the largest observational uncertainty as the reference.

Figure 2 shows the MDDM exclusion plot computed for different values of \( m_\chi \) and \( \mu_\chi \). We choose as diagnostic the value corresponding to the maximum difference between the square of the sound speed of the SSM and the sound speed of the DM solar models. There is a region of the parameter space for the relatively light DM \( 4.0 \leq m_\chi \leq 20.0 \) GeV and with magnetic moment \( \mu_\chi \geq 10^{-17} \) cm for which the sound speed difference is larger than 2%. Accordingly, these models can be rejected. We find the quantitatively same exclusion limits on the MDDM parameters even if we use the density profile, rather
than the sound speed profile, as a diagnostic method for which the observational density uncertainty is considered to be of the order of 4%.

4. SUMMARY AND CONCLUSIONS

In this Letter, we use helioseismology to constrain the mass and magnetic moment of MDDM. We find that there is an important set of parameters for which the impact of MDDM is much larger than the current difference between theory and observation. We have found that solar model precision tests using the sound speed profile obtained from helioseismology data as the diagnostic exclude MDDM with \( \mu \chi \gtrsim 4.3 \) GeV and \( \mu \chi \gtrsim 1.6 \times 10^{-17} \) e cm. DM particles with the above parameters produce changes in the Sun which are much larger than the current sound speed difference between theory and observation.

Furthermore, this new constraint does not affect the results found by Del Nobile et al. (2012) for which a DM particle with \( m_\chi \sim 10 \) GeV and \( \mu_\chi \sim 10^{-18} \) e cm could accommodate the positive signal detections of DAMA, CoGeNT and CRESST experiments and simultaneously not be ruled out by CDMS, XENON and PICASSO. Our solar constraint result slightly improves the bound on the dipolar DM from the Large Hadron Collider (LHC) and Large Electron–Positron Collider (LEP): the LHC, using the mono-jet events plus missing transverse energy, puts the bound \( \mu_\chi \lesssim 10^{-15} \) e cm for \( m_\chi = 10 \) GeV and LEP using the mono-photon plus missing transverse energy events improves the bound to \( \mu_\chi \lesssim 10^{-16} \) e cm (Fortin & Tait 2012).

For the Sun, unlike in the case of other stars, the stellar parameters are very well-known. Nonetheless, there is an uncertainty in parameter determination related to the nature of the DM particles and their interaction with baryons, namely \( m_\chi \) and \( v_\theta \). Nevertheless, this uncertainty should not produce variation in the capture rate larger than 15% (Lopes et al. 2011). A major concern comes from the DM density used in the calculation, for which one of the more recent measurements predicts a value 2.2 times larger than the value used (Bovy & Tremaine 2012; Garbari et al. 2012). Accordingly, the capture rate of DM particles by the Sun increases by an order of magnitude. Therefore, it is expected that the iso-contours could change slightly.

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