PROBING THE EXISTENCE OF A DARK MATTER ISOTHERMAL CORE USING GRAVITY MODES

ILÍDIO LOPES1,2 AND JOSEPH SILK3,4

1 Centro Multidisciplinar de Astrofísica, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal; ilidio.lopes@ist.utl.pt
2 Departamento de Física, Universidade de Évora, Colégio Luís António Verney, 7002-554 Évora, Portugal; silk@astro.ox.ac.uk
3 Department of Physics, University of Oxford, Beacroft Institute for Particle Astrophysics and Cosmology, UK
4 Institut d’Astrophysique de Paris, France

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ABSTRACT

Although helioseismology has been used as an effective tool for studying the physical mechanisms acting in most of the solar interior, the microscopic level and the dynamics of the deep core are still not well understood. Helioseismological anomalies may be partially resolved if the Sun captures light, non-annihilating dark matter particles, a currently discussed dark matter candidate that is motivated by recent direct detection limits. Once trapped, such particles (4–10 GeV) naturally fill the solar core. With the use of a well-defined stellar evolution code that takes into account an accurate description of the capture of dark matter particles by the Sun, we investigate the impact of such particles in its inner core. Even a relatively small amount of dark matter particles in the solar core will leave an imprint on the absolute frequency values of gravity modes as well as the equidistant spacing between modes of the same degree. The period separation for gravity modes could reveal changes of up to 3% for annihilating dark matter and of up to 20% for non-annihilating dark matter. This effect is most pronounced in the case of the gravity dipole (l = 1) modes.

Key words: dark matter – elementary particles – stars: evolution – stars: interiors – Sun: helioseismology – Sun: interior

Online-only material: color figures

1. INTRODUCTION

Evidence for the existence of dark matter in the universe is well established by cosmological observations (Komatsu et al. 2009), and its influence is also necessary in order to explain the formation of the structure of the current epoch universe (Springel et al. 2005). Various studies suggest that dark matter is constituted of massive, neutral, weakly interacting non-baryonic particles. Furthermore, independent considerations from particle physics also propose the existence of such particles (Bertone et al. 2005).

Recently, the results from several particle physics detection experiments (Bernabei et al. 2010; Ahmed et al. 2010; Aalseth et al. 2010; Fitzpatrick et al. 2010) have been interpreted in terms of weakly interacting massive dark matter particles (WIMPs) with a mass smaller than 10 GeV and with spin-dependent elastic scattering cross-sections with baryons as large as $10^{-32}$ cm$^2$ (Angle et al. 2008; Behnke et al. 2008) or spin-independent elastic scattering cross-section with baryons of the order of $10^{-40}$ cm$^2$ (Ahmed et al. 2009). The relatively weak experimental limits on spin-dependent interactions of dark matter particles are especially of interest for the Sun with its large abundance of protons, for which both self-annihilating cold dark matter particle scenarios (Bergström 2009) and non-annihilating (Frandsen & Sarkar 2010) have previously been studied.

Investigation of the effects of the accumulation of dark matter particles by the Sun may therefore be an important complement to direct detection searches for light WIMPs. These particles are trapped in the Sun’s interior when they collide with nuclei and lose (linear) momentum, and drift into the Sun’s core. Collisions of captured particles with the local baryons transfer and redistribute thermal energy and lower the central temperature by a few percent. In thermal equilibrium, the kinetic energy of dark matter particles is balanced by the local gravitational potential (Spiegel & Press 1985). An estimation of the radius of the dark matter core is given by $r_c \sim (9kT_c/4\pi G\rho_{\odot} m_p) \sqrt{m_p/m_\chi}$, where $m_p$ and $m_\chi$ are, respectively, the mass of the proton and the mass of the dark matter particle, $T_c$ and $\rho_{\odot}$ are the central temperature and the central density of the Sun’s core, and $k$ and $G$ are, respectively, the Boltzmann and Newton gravitational constants. This expression approximately gives the radius of the dark matter core in the Sun’s interior. It follows that the more massive a dark matter particle, the smaller is the radius of the dark matter core, and the less important is the impact of dark matter in the evolution of the Sun.

The Sun shows a complex pattern of surface oscillations whose restoring forces are produced either by compressibility or buoyancy. The pressure perturbations give rise to acoustic sound waves in the high-frequency part of the spectrum, and buoyancy variations drive gravity waves in the low-frequency range of the spectrum. The small amplitude surface perturbations observed in the Sun can be described as a sum of eigenstates. Each eigenstate has a spatial counterpart that is defined by a spatial eigenfunction that depends on the thermodynamical structure of the background state (the Sun’s internal structure) and a time-dependent eigenfunction that is characterized by the frequency $\nu_{l,n}$. The numbers $l$ and $n$ are positive integers, known as the degree and radial order of the mode (e.g., Gough 1993), respectively.

During the last 50 years, accurate measurements of frequency values were obtained for more than 5000 acoustic mode frequencies $\nu_{l,n}$. This achievement is the result of the combined efforts of several observational networks, such as BISON (Chaplin et al. 1996) and GONG (Harvey et al. 1996), followed by the helioseismic experiments from the Solar and Heliospheric Observatory (SOHO) mission: GOLF (Gabriel et al. 1995), VIRGO (Fröhlich et al. 1995), and Michelson Doppler Imager
Seismology has provided the most powerful tool to probe the Sun’s interior to date. Accurate frequency measurements of the large numbers of acoustic modes have been made, including the radial and dipole global acoustic modes, which penetrate more deeply into the core. Unfortunately, the diagnostics of the Sun’s core provided by these acoustic modes are still insufficient. However, the possible discovery of gravity modes by current ongoing experiments (García et al. 2007) or future ones could be a breakthrough toward fully understanding the physics of the Sun’s core and establishing the possible existence of dark matter. The impact of dark matter particles in the Sun’s core (Cox et al. 1990; Dearborn et al. 1990; Kaplan et al. 1991) and its consequences on the acoustic spectrum were previously analyzed by Lopes et al. (2002b) among others, and more recently by Cumberbatch et al. (2010) and Taoso et al. (2010).

In this Letter, we have computed a series of solar models evolving within dark matter halos for which we have estimated the impact of dark matter particles in the present-day Sun. As a reference, we use an updated solar standard model that provides a seismic diagnostic similar to other solar standard models found in the literature. Furthermore, we have computed the gravity mode oscillation spectrum for such dark matter scenarios.

2. HELIOSEISMOLOGY AND THE SUN’S EVOLUTION IN DARK MATTER HALOS

The capture rate of dark matter particles in the Sun was computed in detail by taking into account their scattering with the different chemical species of the solar plasma (Gould 1987; Gondolo et al. 2004; Casanellas & Lopes 2010a). The presence of dark matter inside the star can change its evolution by two mechanisms: (1) by changing the transport of energy inside the star (Spiegel & Press 1985; Gould & Raffelt 1990a) and (2) by contributing to the energy production that sustains the gravitational collapse of the star (Jocco et al. 2008; Freese et al. 2008; Casanellas & Lopes 2009, 2010b). In the case of the Sun, the latter mechanism is negligible (Lopes et al. 2002b). The efficiency of the energy transport by dark matter particles depends, among other factors, on the scattering cross-sections of dark matter particles on baryons.

Dark matter particles might have a total scattering cross-section $\sigma_t$ with several components: spin-independent interactions with all chemical elements in the Sun and spin-dependent interactions with hydrogen. The presence of such particles contributes to the local energy transport. The efficiency of the heat transport by dark matter particles is dependent on the value $\sigma_t$, relative to the fiducially critical cross-section $\sigma_c = (m_p/M) R^2 \sim 8 \times 10^{-36}$ cm$^2$, where $m_p$ is the proton mass and $M$ and $R$ are the mass and radius of the Sun. The optimal heat transport depends on the dark matter particle scattering cross-section $\sigma_t$. For particles with small mean free paths (diffusion regime) or with large cross-sections ($\sigma_t > \sigma_c$), the conductivity falls as $\sigma_t/\sigma_c$. Similarly, for particles with large mean free path (Knudsen regime) or lower cross-sections ($\sigma_t < \sigma_c$), the conductivity falls as $\sigma_t/\sigma_c$. Furthermore, a suppression factor is required in this latter transport regime (Gould & Raffelt 1990a, 1990b). Both regimes are included in our stellar evolution code (Lopes et al. 2002b; Casanellas & Lopes 2009). The numerical computation of such effects on the transport of energy can be accomplished by means of changing the production of energy or by changing the coefficient for radiative transfer. We have implemented both methods. The results obtained in both cases are similar. In this work, the transport of energy by dark matter is computed as a coefficient for the radiative transfer. This seems to be more realistic and is numerically more stable.

Several models of evolution of the Sun were computed in different dark matter scenarios of suppressed and non-suppressed annihilation dark matter particles. Our reference model is an updated solar standard model (Turck-Chièze & Lopes 1993; Asplund et al. 2005) that shows an acoustic seismic diagnostic similar to other solar standard models (Turck-Chièze et al. 2004a, 2010; Bahcall et al. 2005; Guzik & Mussack 2010). We include self-annihilating and non-annihilating massive particles with the following masses: self-annihilating particles from 3 to 10 GeV and non-annihilating particles from 4 to 100 GeV.

Figure 1. Comparison of temperature profiles between the solar standard model and models of the Sun evolving in different dark matter halos. The halos are constituted of self-annihilating and non-annihilating massive particles with the following masses: (i) self-annihilating particles (colored curves): 3 GeV (red), 4 GeV (blue), 5 GeV (green), 6 GeV (cyan), 8 GeV (magenta), 10 GeV (dashed-red), and 12 GeV (dashed blue); (ii) non-annihilating particles (black curves, from low to higher temperature): 5 GeV, 7 GeV, 10 GeV, and 50 GeV. The particles interact with baryons with a spin-dependent scattering cross-section of the order of $3 \times 10^{-33}$ cm$^2$ (i) colored curves) or $2 \times 10^{-33}$ cm$^2$ (ii) black curves), and spin-independent scattering cross-sections of the order of $10^{-40}$ cm$^2$ (negligible). The product of the self-annihilation cross-section and the relative velocity of colliding particles is of the order of $3 \times 10^{-33}$ cm$^2$ s$^{-1}$ (i) colored curves) or $10^{-30}$ cm$^2$ s$^{-1}$ (ii) black curves; suppressed annihilation). The black curve with the highest central temperature corresponds to the solar standard model.

(A color version of this figure is available in the online journal.)
12 GeV and non-annihilating particles from 5 to 50 GeV. The particles interact with baryons with a spin-dependent scattering cross-section $3 \times 10^{-33}$ cm$^2$ or $2 \times 10^{-35}$ cm$^2$, and a spin-independent scattering cross-sections of $10^{-40}$ cm$^2$ (in fact, this is negligible). The product of the self-annihilation cross-section and the relative velocity of colliding particles taken to be $3 \times 10^{-33}$ cm$^3$ s$^{-1}$ or $10^{-50}$ cm$^3$ s$^{-1}$ (for the case of suppressed annihilation).

In the case of non-annihilating particles, the numerical model shows a 2% reduction of the central temperature of the Sun’s core due to the lightest massive particles (Figure 1). This temperature reduction seems to be stronger than that obtained by Taoso et al. (2010). Additionally, the square of the sound speed and density profiles incur a variation of between 0.8% and 2% (Figure 2). In the case of non-annihilating particles, the decrease in the central temperature is of the order of 8% for a particle with a mass of 12 GeV and even larger for lighter particles.

Figure 2 shows the profiles of sound speed and density in the case of annihilating dark matter scenarios compared with the inverted profiles. The inversion of the sound speed and density profiles were done using the seismic data of the BISON and GONG networks (Basu et al. 2009). This seismic data is consistent with the previous high accuracy measurements done by the GOLF and MDI instruments of the SOHO mission (Turck-Chièze et al. 2001). It is evident that the present acoustic seismology is not able to probe the inner core of the Sun accurately. In summary, our knowledge about the Sun’s interior is quite accurate up to 10% of the Sun’s radius (Turck-Chièze et al. 2004b; García et al. 2007). The dark matter is expected to accumulate in the inner core of the Sun. An accurate description of such deep layers of the Sun’s interior can be obtained if gravity modes are observed.

3. GRAVITY MODES AND THE EXISTENCE OF A DARK MATTER CORE

An additional probe of the Sun’s interior, capable of finding small dark matter effects occurring in the Sun’s core, can be performed through gravity modes. We have computed the gravity modes of oscillation of the present Sun for different dark matter halo scenarios (Christensen-Dalsgaard 2008). The changes in the spectrum of gravity modes, due to the existence of dark matter in the Sun’s core are visible even in the case of very small amounts of dark matter accumulated in its core. In the case of self-annihilating dark matter scenarios, the period for gravity dipole ($l = 1$) mode changes is from a few tens of seconds up to 10 minutes (see Figure 3). In non-annihilating dark matter scenarios, the effect is much stronger. For very light particles, the gravity dipole modes could have their periods reduced by 80 minutes.

This existence of a dark matter core also affects the period spacing of gravity modes, a quantity identical to the large separation for acoustic modes. In principle, this should provide the first clear indication of the existence of a gravity oscillation pattern in the observed spectrum. A qualitative expression for the
This was computed for dipole gravity modes (Tassoul 1980). Large separation for gravity modes: the large separation was computed from periods $P_{l,n}$, $\delta P_{l,n} = P_{l,n} - P_{l,n-1} \approx P_o/\sqrt{l(l+1)}$ shown in Figure 3. This was computed for dipole gravity modes ($l = 1$). These dark matter halos are constituted of self-annihilating massive particles (case (i): colored curves). See the caption of Figure 1 for the details of the self-annihilating scenario.

(A color version of this figure is available in the online journal.)

Large separation can be obtained for the case of gravity modes with low degree $l$ and high-order $n$ modes, where the period $P_{l,n}(= \nu_{l,n})$ is given by

$$P_{l,n} = \frac{P_o}{\sqrt{l(l+1)}} \left( n + \frac{l}{2} + \phi \right) + \mathcal{O} \left( \frac{1}{P_{l,n}} \right),$$

(1)

with

$$P_o = 2\pi^2 \left[ \int_0^R \frac{|N| \, dr}{r} \right]^{-1},$$

(2)

where $N$ is the buoyancy and $\phi$ is a phase term sensitive to the layers below the base of the convective zone (Tassoul 1980). This expression, and in particular $P_o$, tells us that gravity mode frequencies are determined by the density stratification of the core, through the buoyancy. The value of $P_o$ is of the order of 34.10 minutes in the case of our solar standard model. Usually, the value of $P_o$ is computed from the large period separation, $\delta P_{l,n} = P_{l,n} - P_{l,n-1}$. In the case of dipole modes ($l = 1$), it reads $\delta P_{l,n} = P_o/\sqrt{2}$. In the case when the dark matter core becomes isothermal, the value of $P_o$ is strongly affected. The structure differences between the solar standard model (ssm) and different dark matter scenarios (dm) can be estimated by computing large separation period differences, which is equivalent to measure period differences, $\Delta P_{l,n} = P_{l,n}^{\text{dm}} - P_{l,n}^{\text{ssm}}$ ($l$ and $n$ fix). It follows that $\Delta P_{l,n}/P_{l,n}^{\text{ssm}} \approx \Delta P_o/P_o^{\text{ssm}}$.

The structure differences produced by the presence of dark matter in the Sun’s core lead to a significant change in the period separation. Figure 4 shows the large period separation for several self-annihilating dark matter scenarios in the case of gravity dipole modes ($l = 1$). The period spacing in such models can experiment changes of up to 3%. In the case of non-annihilating scenarios the period spacing can be reduced by as much as 20%.

4. CONCLUSION

The possible existence of a dark matter core, even in the case of non-annihilating dark matter scenarios of low-mass particles, will be always contained within the first 5%–10% of the solar radius. Such a dark matter core will very likely have a small temperature gradient where dark matter particles are present and, in the case of strongly interacting dark matter scenarios, it will form a fully isothermal core. Such an isothermal core will produce two distinct signatures in the gravity modes: (1) by changing the frequency values of gravity modes and (2) by changing the large period separation between gravity modes of the same degree and consecutive radial order.

The impact of the dark matter in the evolution of the Sun and its impact in the helioseismology acoustic data as well as in the solar neutrinos observables have been addressed by several authors (e.g., Dearborn et al. 1990; Kaplan et al. 1991; Lopes et al. 2002a, 2002b; Lopes & Silk 2002, 2010). More recently a specific study has been done to explore a new class of fundamental particle candidates which are able to produce significant changes in the structure of the core of the Sun (Cumberbatch et al. 2010; Frandsen & Sarkar 2010; Taoso et al. 2010). In this study, we have explored in more detail how the gravity spectrum could be modified by the presence of such types of dark matter particles in the Sun’s core.

Nevertheless, other physical processes participating in the evolution of stars need to be better understood in order to take full account of the effects caused by dark matter in the Sun’s core. In particular, the new CNO composition has led to a smaller central temperature than the one required by neutrino detection (e.g., Guzik & Mussack 2010; Turck-Chièze et al. 2010). The inclusion of well-known physical processes in the Sun’s evolution, such as differential rotation, meridional circulation, magnetic breaking, formation and evolution of the solar tachocline layer and solar dynamo (e.g., Charbonneau 2005; Passos & Lopes 2008), as well as the transport of angular momentum by gravity waves and/or magnetic fields (among other dynamical processes) will lead to minor structure changes throughout the evolution of the star (e.g., Turck-Chièze et al. 2010). In some cases, such dynamical processes will increase the discrepancy between solar neutrino measurements and acoustic seismology. In other cases, hydrodynamical processes will lead to reductions of the (small) differences between the solar model and observations (e.g., Garaud & Bodenheimer 2010). Nevertheless, a full quantitative account of the physical processes involved in the evolution of the star is fundamental to finding the signature of the dark matter in the Sun’s core.

The possible discovery of gravity modes by current space missions such as SOHO or the next generation experiments Solar Dynamics Observatory and PICARD will be of major importance in the search for dark matter inside the Sun. In addition to these, the GOLF-NG instrument is specifically designed for a future solar mission. The goal of this instrument is to probe the very central region of the Sun, around 0.5% of the solar radius, the most likely place to find dark matter.

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