Detecting Solar Relic Axions with ADMX

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Abstract

Axions are a hypothetical particle predicted in nuclear physics that could also be the main component of the dark matter seen in many astrophysical measurements. Experiments, such as the Axion Dark Matter Experiment (ADMX), are underway to search for dark matter axions through their conversion into microwave photons inside an RF cavity. The hot plasma in the sun would also be a source of axions. The CERN Axion Solar Telescope(CAST) and other such experiments have been made to detect high-energy solar axions. However, low energy axions produced by photon conversion in the sun may remain gravitationally bound in the solar system and build up over time. If the local density of these solar produced axions is comparable to dark matter, then ADMX would also be sensitive to them. We estimate the density of solar produced, gravitationally bound axions and axion-like-particles at earth with two simple models of axions produced from thermal photons in the sun. One is an optimistic model where the energy loss of the sun from axion like particles is as large as allowed by current solar observations, and the other is a QCD-axion inspired model. We also examine the difference in signal between dark matter axions and solar produced axions.

1   Strong CP Problem

1.1   The Emergence of the Axion

Concepts that lead physicists to believe that axions existed came from stuying CP symmetry. This symmetry deals with the relationship of matter with antimatter. If CP was conserved within the system, this would mean that matter and antimatter where intrisiclly the same. A big game changer came along when experiments showed that CP was not conserved and this observation was also backed by the weak interaction[6]. Problems arose when creating a formulation for the strong force. It conserved CP and therefore the belief was that CP symmetry would be "spontaenously broken" at some scale. One explaination that used this concept is the Pennci-Quinn mechanism[5]. It introduced a new term to the Lagrangian of the strong interaction, and the consequence was that a new particle was introduced, the axion.

The symmetry breaking scale of the strong interaction was compared to that of the weak interaction to give a rough estimate of the mass. The established range was 10keV to 1MeV[5]. These energies were easily peered into with accelerator technologies and unfortunately the axion was not found, therefore dismissing this mass range. New scales were then looked at and the most promising theoretical predictions have the mass set to about a μeV to a meV.

1.2 Dark Matter

Another complication came about when astrophysicists looked at gravitation discrepances from observation and theory[7]. One example of this is the rotation of galaxies[8]. Using Newton's laws to find the orbital speed of stars about the galactic center, the graph should go as $r^{-1/2}$ [8], but observations showed that stars exhibit a constant orbital velocity at some distance from the center. One approach to this problem was to conclude that at large distances, gravity behaved in a way that none of our current models can explain. The alternative was to introduce a new form of matter, dark matter. The latter explanation is what is being focused at ADMX.

Many particles have been brought to the table that match the properties attributed to dark matter. Weakly interacting massive particles, super symmetric particles, and low-mass axions have all been considered as dark matter candidates.

1.3 Sources of Axions

The axion has been viewed as a very good candidate for dark matter[3,4]. If we want to detect the axions, we have to look at what the possible sources would be if the axion would truly exist. Making the assumption that most of the dark matter is axions, then the big bang would be a likely source[8].

ADMX uses an RF cavity to find dark matter axions. The basis of this experiment relies on photons converting in to axions through fluctuations of electric and magnetic fields [1], and then reconverted with the same process inside the cavity with a magnetic field. The photon would then create a signal at the detector allowing ADMX to see whether we have detected an axion or not.

Inside our solar system, we have an object that has huge amounts of photons, the Sun. There is then massive amounts of axions that can be potentially created, therefore analyzing the axion spectrum emitted from the sun can allow us to see whether or not it would be feasible to detect solar axions at ADMX.

2 Flux of High Energy Axions at Earth

People from the CAST experiment did a calculation pertaining to the axion flux at the Earth in terms of the mass of an axion. The main production of axions in the model was photons interacting with electrons via Primakoff process[1]. The calculation was done with the Planck spectrum. The differential axion spectrum was show to be

$$\frac{d\Phi_a}{dE_a} = g_{a\gamma}^2 (3.821 * 10^{30}) \left(\frac{(E_a/keV)^3}{e^{E_a/1.103keV} - 1} \right) cm^{-2} sec^{-1} keV^{-1} \tag{1}$$

Our calculation is concerned with axions that stay within the solar system, limiting the velocity range and therefore also limiting the energy range. The energy of the axions are much less than 1.103keV since we are looking at axions with $m_a = 10^{-6}eV$ and the kinetic
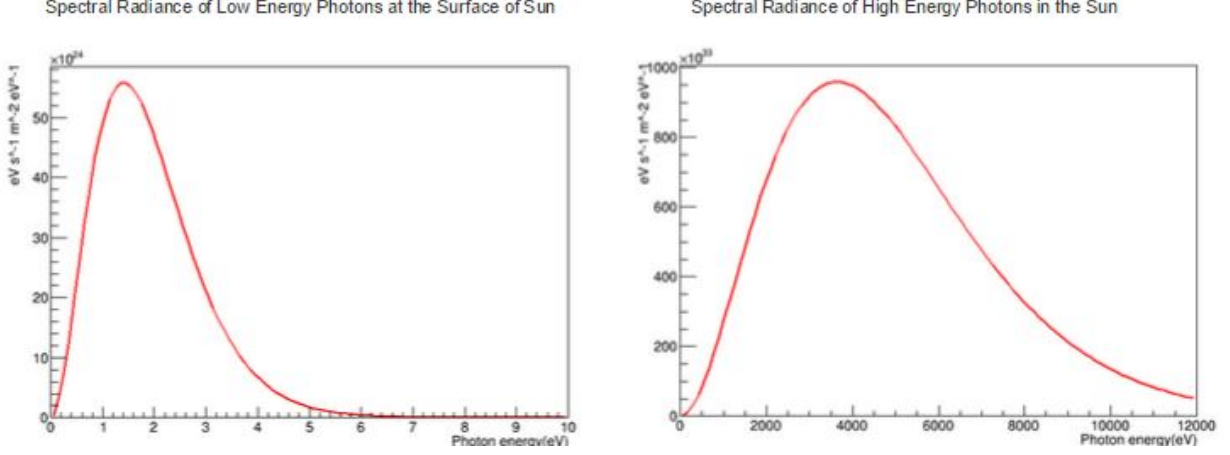
Figure 1: Equation (8) where the left graph shows the spectral radiance at the surface of the Sun(T=5800K) and the right graph is the spectral radiance around the core of the Sun(T=15,000,000), Which is where the CAST experiment get their relativistic axions from. From these two graphs, we can see that low-energy axions are more abundant at the surface of the Sun Rather than the center, which is why the CAST experiment can not peer into low-energy axions.

energy term compared with the rest mass is insignificant, so equation (1) becomes

$$\frac{d\Phi_a}{dE_a} = g_{a\gamma}^2 (3.821 * 10^{30})(1.103) \left(\frac{E_a}{keV}\right)^2 cm^{-2} sec^{-1} keV^{-1}. \tag{2}$$

The problem that arises with making this assumption is that the formulation of this spectrum does not allow us to peer into energies that are much less than 0.3eV [1]. The spectrum around the core of the Sun is not a place where μeV axions can flurish. The axion energies that are required at ADMX are on the order of 10^{-6} eV. This now requires us to make another formulation to allow the low mass, low energy axions to be considered.

3   Gravitationally Bound Axion Spectrum

The experiment at ADMX requires that the axions move at relatively slow speeds while at the same time have low mass. The first step is to look at the blackbody spectrum of the Sun in terms of frequency. The energy of a Photon with a certain frequency is quantitatively known. We can therefore make the relation

$$h\nu = m_a c^2 + \frac{1}{2} m_a v^2, \tag{3}$$

where m_a is the axion mass and h is Planck's constant. The right hand side of the equation is the axion's rest energy plus its kinetic energy. For the axion to stay within the solar system, the velocity in the kinetic energy term must not exceed the escape velocity, and for the particle to be created the energy of the photon must atleast supply the rest energy of the axion. We can then conclude that

$$\nu_{min} = \frac{m_a c^2}{h} \tag{4}$$

$$\nu_{max} = \frac{1}{h}\left(m_a c^2 + \frac{1}{2}m_a v_{esc}^2\right). \tag{5}$$

Using the spectral radiance of light, which has units of $W * sr^{-1} * m^{-2} * Hz^{-1}$, and assuming that 1% of the power created within the selected spectrum is associated with creating the axions, we can find the energy density per cubic centimeter of axions in the solar system. The power generated by the sun between ν_{min} and ν_{max} is found by evaluating

$$P = \int\int\int B(\nu,T)\,d\nu\,dA\,d\Omega \tag{6}$$

where $d\Omega$ is over the entire solid angle, dA is over the surface area of the the sun and $d\nu$ is over the frequency spectrum that allows an axion to be created while staying in the solar system which depends on the spectral radiance $B(\nu,T)$. The solid angle integral and the surface area integral are straight forward to calculate leaving the equation

$$P = 16\pi^2 R_{sun}^2 \int_{\nu_{min}}^{\nu_{max}} B(\nu,T)\,d\nu \tag{7}$$

with

$$B(\nu,T) = \frac{2}{h^3 c^2}\frac{E^3}{e^{E/kT}-1}. \tag{8}$$

Having the spectral radiance in terms of frequency to describe a axion distribution is awkward and usually we express this equation in terms of energy which becomes

$$4\pi B(E,T) = \frac{8\pi\eta E^3}{h^3 c^2}\frac{1}{e^{E/kT}-1}\,eV\,s^{-1}\,m^{-2}\,eV^{-1}. \tag{9}$$

Now, the assumption that $E << kT$ is appropriate for this calculation and therefore the spectral radiance can simply be written as

$$4\pi B(E,T) = \frac{8\pi\eta kT}{h^3 c^2}E^2. \tag{10}$$

What about axions at a particular distance from Sun? This is where we can look at more specific volumes rather than making the volume a sphere that spans the entire solar system and evenly distributing the axions that fit our specification throughout this sphere. We will still use the Planck Spectrum, but this time the kinetic energy of the axion will be put in terms of the distance the axion goes from where it was created to where it will stop and come back to the sun. We will take the case in which all axions are shot outwards from the sun perpendicular to the Sun's surface. The total energy of the axion will be

$$E = m_a c^2 + GMm_a\left(\frac{1}{R} - \frac{1}{R+r}\right) \tag{11}$$
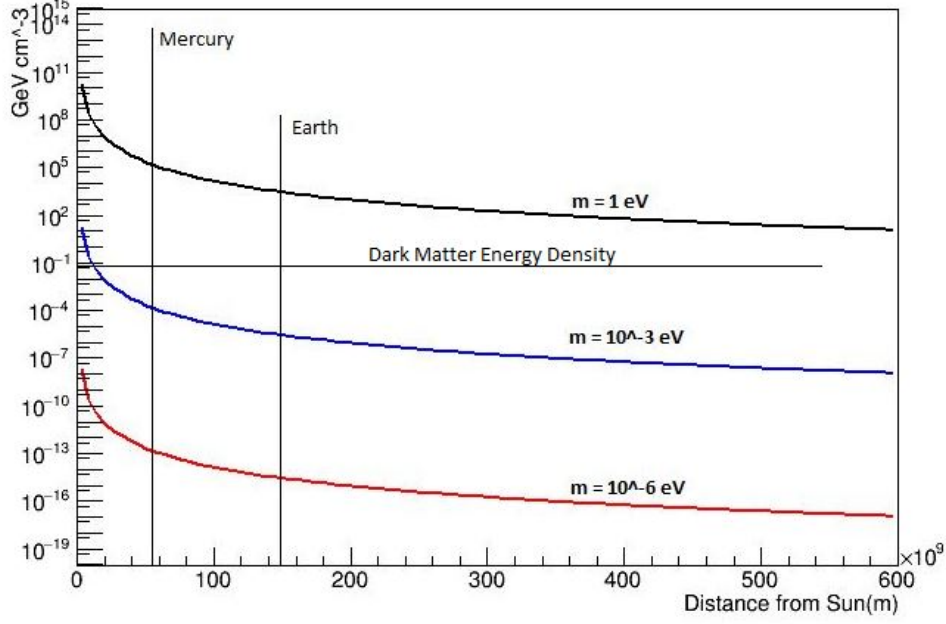
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Figure 2: Equation (14) comparing three different possible axion masses. The meV axion is the one that holds the most promise to have the axion energy density equal to that of dark matter energy density at Earth.

R will be where the axion is created(radius of the Sun), r is where the axion will go out to, G is the gravitational constant, and M is the mass of the Sun. We want to analyze the spectrum and see how many axions we will detect at the Earth. We will insert the energy of the axion in place of E in equation (10) and multiple that equation by 4π to get the differential flux at some distance away from the sun.

To reduce the complexity of this calculation we notice that the rest energy of the axion is much greater than its kinetic energy resulting the energy expression to become $m_a c^2$. We can then write

$$d\Phi = \frac{8\pi\eta kTA_{sun}}{h^3 c^2}(m_a c^2)^2 \frac{GMm_a}{r^2}\,dr \tag{12}$$

where we made the implication that $r >> R$. We will now make a conservative approximation and create a uniform energy density inside a volume of a sphere with radius that of the height in which the axions take. This will undoubtedly create a lower limit for the real energy density. The energy density turns out to be

$$\rho_a = \frac{6\pi\eta kTGM_s R_s^2 m_a^3 c^2}{h^3 R_e^4}. \tag{13}$$

Just from inspection, we can see that the energy density falls off tremendously fast as we look at axions that get further from the Sun.

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4   Conclusion

Figure (2) shows the change in energy density as we get further from the sun. Three different masses are displayed, with the μeV axion being the less dense at the Earth. Axions that have mass around the meV range have energy densities equivalent to that of dark matter around Mercury. If we make further analysis we see that axions that have mass around 20-40 meV have an energy density at Earth close to that of dark matter.

With all that being said, according to this calculation, μeV solar relic axions are irrelevant for detection at Earth. One possible improvement on the calculation is to take away the conservative approximation and take into account that the axions spend most of their time of flight at the peak of their height. This will enable us to look at a specific volume rather than uniformly distributing those axion into a sphere with a significantly larger volume. The consequence of this improvement would be an increase in energy density at Earth. Whether it be a significant increase is something that would be found out once the calculation is complete.

5   Acknowledgments

6   References

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