Signature of Solar Axions

Kenneth J. H. Phillips[1]

[1]Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, United Kingdom

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A summary of the standard solar model for the solar interior is given, with the present state of observational confirmation of the model from neutrinos and helioseismology. If there is a sizable flux of axions or axion-like particles from the solar core, it might result in the heating of magnetic rope structures in the tachocline in the interior or subtle X-ray signatures in the Sun's corona, or outer atmosphere. The intensities of certain X-ray lines with magnetic dipole transitions may also be affected.

1 The solar interior

Great strides in our understanding of the interior of the Sun have been made in the past thirty or so years through a number of developments. First, improved cross sections for nuclear reactions occurring at the Sun's core, where the temperature is approximately 15×10^6 K (15 MK), now give us fairly precise values for reaction rates. There is a complex series of such reactions, but the end result is the fusion, in a step-wise fashion, of four protons to form a single helium nucleus with energy released in the form of positrons, neutrinos, and thermal energy: $4p \rightarrow ^4\mathrm{He} + 2e^+ + 2\nu + 25$ MeV. The thermal energy generated is transported by photon diffusion through the inner part of the solar interior, out to a radius of about $0.7R_\odot$ (1 solar radius = $1R_\odot = 696\,000$ km) where models predict a temperature of about 5 MK. At this level, there is an increase in the opacity of the gas, and the energy transfer is then by convection.

The structure of the solar interior has been modelled by applying known physical laws to the material of the Sun, in particular hydrostatic equilibrium and energy transfer (by both radiative and convective processes). The Sun is assumed to have been created by the collapse of an interstellar gas cloud with element abundances like those measured in the photosphere (Sun's surface layer where the energy escapes as radiation). The cloud is allowed to evolve, with hydrogen slowly converting to helium in the core region. After a time equal to the Sun's present age, the modelled Sun should resemble the actual Sun through its present radius and luminosity. Any deviations can be corrected by adjusting the Sun's chemical composition. Such is the *standard solar model* (SSM), long associated with the name of John Bahcall whose work on this subject has been well documented.

2 Testing the standard solar model: the tachocline

Since nothing can be directly observed below the photosphere (the opacity rapidly increases with depth), it might seem that the standard solar model cannot be easily observationally tested. However, there are two means available to solar physicists. The first is the observed flux of solar neutrinos at the Earth. The first experiments, particularly the Homestake mine experiment of Raymond Davies, indicated a roughly factor-of-three discrepancy between the predicted and observed neutrino flux, the observed being smaller. This has now been explained through the MSW effect.

The second test of the SSM is supplied by helioseismology: observations with spectrometers viewing Doppler shifts in sharp absorption lines in integrated sunlight show that there is a series of oscillations, identified as acoustic modes occurring over the whole Sun. These oscillations are due to sound waves travelling in the solar interior, generated by stochastic turbulence, with wave fronts moving through the solar interior in arc-like patterns. A cluster of modes is observed with frequencies of about 3 mHz. Each mode probes the interior at various depths, so giving a test of the radial variation of temperature and density predicted by the SSM. There was until 2005 highly impressive agreement of the observed mode frequencies with those predicted, but the adjustment of some element abundances [1] has vitiated this somewhat. This is still being investigated, but possibly fine adjustment of the abundances of other elements might restore the agreement.

The Sun is observed to rotate differentially (the photospheric period varies from 25 days near the equator to 34 days near the poles). Modes in the same direction as the solar rotation have a frequency that is slightly higher than those in the opposite direction: like spectral lines, then, there is a "rotational" splitting of the azimuthal mode frequencies. It provides a powerful way of examining the rotational speed of the solar interior at different depths. It is found that at a particular depth, near the boundary of the Sun's radiative and convective zones, there is a strong shear zone, with layers above rotating differentially but layers below rotating as a rigid body. This is the *tachocline*, and corresponds to where cooler material sinking down "overshoots". Helioseismology indicates that the tachocline is only 15 000 km thick, or $0.02R_\odot$.

3 Magnetic field in the tachocline

The Sun's magnetic field is manifested in particular structures, notably sunspot groups and associated regions above them in the high-temperature corona (temperature up to 5 MK), and in a general field most obvious near the poles at times of few sunspots. Zeeman splitting of spectral lines shows that sunspot fields can attain 0.4 T, but there are also field concentrations all over the Sun's surface, with strengths of up to 0.1 T. The continual generation of the magnetic field every eleven years (the solar cycle) is attributed to a dynamo operating in the solar interior. It is deduced that the dynamo cannot operate in the convective zone since the rope-like structures that the field takes on will rise by magnetic buoyancy. On the other hand, the radiative zone is practically isolated from the convective zone so any magnetic field there is not likely to appear at the Sun's surface. The seat of the dynamo is therefore thought to be the tachocline, which is convectively stable apart from the overshoot of convective currents above this level. The strength of the field in the tachocline has been much discussed: previous estimates from theoretical models indicated around 1 T. However, fields of this magnitude do not explain the latitude distribution of sunspots. Choudhuri [2] and others have persuasively argued for much larger fields, up to 10 T, in the tachocline; only then do model calculations reproduce the observed distribution of sunspot locations.

4 Implications for solar axions

The case has been made for large numbers of axions or axion-like particles (ALPs) to be produced in the solar core [9, 10]. The probability of conversion to X-ray photons by the inverse Primakoff effect is proportional to $g^2B^2l^2$ where g is the coupling constant, B the magnetic field strength, and l a length scale. For laboratory measurements, l is of order meters, but if there is interaction with solar magnetic fields l is in the range $100 - 10\,000$ km. Thus, if axions are produced at the Sun's core, with average energy ≈ few keV, interactions with the Sun's magnetic field could proceed resulting in observable X-ray signatures and this in turn might give a useful upper limit to g. Zioutas et al. [9] suggested there might be a halo of axions gravitationally captured resulting in X-ray emission. Carlsson & Tseng [3] discuss the possibility of axions interacting with the Sun's general field and strong sunspot fields by the inverse Primakoff effect. They predict that there would be an observable modulation in the X-ray emission as a large sunspot rotates across the solar disk; the field orientation does not seem to be considered by them, but this is important as the sunspot field below the photosphere is largely radial, and so the as the axion–magnetic field interaction will be reduced.

Interaction of axions with the field in the tachocline region, now considered to be 10 T and so much larger than sunspots or the general field, might produce some perturbation in the SSM. There would be substantial heating of this region and so possibly an increase of convective activity. The field in the tachocline would most likely be in the form of rope-like structures, with the length of the rope parallel to the solar equator, so the convective activity may appear in bands of latitude near where sunspots occur. The length scales l are likely to be around 10 000 km. The general field of the Sun is most apparent during solar minimum and is approximately dipole-like. Interaction of axions with the general field above the equator, which is almost parallel to the Sun's surface and so perpendicular to the axion flow, might lead to patches of dim X-ray emission near the apparent Sun's centre. Such effects have been looked for with the Soft X-ray Telescope on *Yohkoh* (operational 1991–2000), but so far nothing resembling this has been found [6]. The flux of 3–6 keV X-rays calculated on the assumption of $g \approx 10^{-10}$ GeV^{-1} and light ($\lesssim 2 \times 10^{-6}$ eV) axions, viz. ≈ 400 photons m^{-2} s^{-1} keV^{-1} [3], is close to measured estimates [4] from the *RHESSI* solar X-ray spacecraft during periods of low activity between 2005 and 2006. However, solar X-ray activity has been considerably less since then [5]. The SphinX instrument on the Russian *CORONAS-PHOTON* spacecraft [8] measured 1–15 keV X-ray flux levels 20 times less than the flux in an equivalent band in 2005–2006. It may therefore be possible to constrain the axion fluxes to much lower limits when the SphinX results are fully analyzed.

Other signatures for solar axions or ALPs include nuclear and atomic M1 (magnetic dipole) transitions. The most widely-cited in this context has been the 14.4 keV line formed when ^{57}Fe nuclides are thermally excited inside the Sun ([7]). Upper limits to the flux of this line can be set from solar X-ray spectrometers such as *RHESSI*. No feature has ever been observed at 14.4 keV, imposing an upper limit to the line flux of ≈ 10 photons m^{-2} s^{-1}. Some lines due to M1 atomic transitions are notable in the solar X-ray spectrum. They include lines emitted by flares of He-like ions such as Fe^{+24} and Ca^{+18}, with transitions $1s^2\,{}^1S_0 - 1s2p\,{}^3P_2$, close to an intercombination line ($1s^2\,{}^1S_0 - 1s2p\,{}^3P_1$). Anomalies in the intensities of these lines have been noted but are thought to be due to the intercombination line rather than the M1 line. However, the M1 line at 1.7096 nm emitted by active regions due to Ne-like Fe (Fe^{+16}), transition $2p^6\,^1S_0 - 2p^6 3d\,^3P_2$, has an intensity that varies with time compared with the nearby $2p^6\,^1S_0 - 2p^6 3d\,^3P_1$ (wavelength 1.7050 nm). The changes with time are subtle but are unexplained (for example by high densities). An axion explanation is unlikely but detailed calculations must be done to see what the possible effects are.

5 Conclusions

The possible flow of axions or ALPs from the solar core might give rise to observable effects that could lead to useful limits on the coupling constant, the length scales being much larger than are obtainable in the laboratory. These effects include the heating of magnetic rope-like structures in the tachocline (region of convective overshoot just beneath the convective zone of the solar interior) and X-ray emission in and around the solar corona. There are also possibly interesting anomalies in observed X-ray spectral lines due to magnetic dipole transitions: axion explanations are unlikely but calculations need to be done that assess their likelihood.

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