SOLAR COSMIONS

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ABSTRACT. Two of the outstanding problems in astrophysics are the solar neutrino problem and the missing mass problem. The "solar cosmion", a weakly interacting massive particle, could solve both problems. Several particle physics models have been suggested for the solar cosmion.

The solar cosmion may have other interesting astrophysical effects. It will alter the predicted helioseismology spectrum, effect horizontal branch evolution and may alter the mass-radius relationship in low mass stars. These considerations constrain solar cosmion properties.

Several laboratories have begun an active experimental search for the solar cosmion. The UCSB-UCB-Saclay silicon experiment in the Oroville mine has already placed stringent limits on solar cosmions that couple to matter through spin-independent interactions. A planned Saclay experiment may either detect or rule out the existence of "solar cosmions".

The Sun is an powerful laboratory for exploring particle physics beyond the standard model. Even if "solar cosmions" do not exist, the Sun can help "illuminate" the search for other weakly interacting particles posited as solutions to the missing mass problem.

1. Solar Cosmions and the Solar Neutrino Problem

For over 20 years, Ray Davis' solar neutrino experiment has been hinting that something is missing in our basic understanding of either solar or neutrino physics (for review, see Bahcall 1989).

In recent years, it has been popular to blame the neutrino as the cause of the solar neutrino problem (Wolfenstein 1979, Mikheyev and Smirnov 1985, Okun *et al.* 1986). However, the fault may lie not with the neutrino but inside the Sun. The solar models are based on standard physics: the atomic and ionic cross-sections are either measured in the laboratory or calculated from well-established theory; the nuclear reaction rates are derived from experimental values. However, a new physical assumption could alter the Sun's thermal profile and change the predicted SNU flux.

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My collaborators and I suggested that a mechanism for altering energy transport in the stellar interior. We posited the existence of a new particle that carried much of the energy in the core of the Sun. Bill Press and I suggested that a weakly interacting particles could be extremely efficient at energy transport (Spergel and Press 1985). After publication, we learned that John Faulkner and Ron Gilliland had considered this possibility several years earlier, but were dissuaded from publishing their results. [Most of their conclusions were summarized in Steigman et al. (1978). Their full paper finally appeared seven years later (Faulkner and Gilliland 1985)].

Particles with cross-sections of order 10^{-36} cm^2 are ideal for transporting energy in the Sun. In the conductive (large cross-section) regime, energy transport scales as the mean free path. As the cross-section decreases, the cosmion travels through a larger temperature gradient between collisions and is thus more effective at transporting energy. In the small cross-section regime, collisions are so rare that the energy transport scales as the collision rate. The cross-over between these two regimes occurs at the optimal cross-section for energy transport: when $\sigma \approx 6 \times 10^{-36}$ cm ^{2} and the cosmion's mean free path is its orbital radius. The cosmion can deposit a large fraction of its kinetic energy at aphelion and can increase its kinetic energy at perihelion.

The cosmions are extremely efficient at energy transport. The timescale for the cosmion to transfer energy from the center of the Sun to a scale height, the free fall time ($\approx$ 100 s), is much shorter than the timescale for photons to diffuse the same distance, the Kelvin-Helmholtz time ($\approx 10^6$ years). In fact, only 10^{-11} cosmions per baryon is sufficient to significantly alter energy transport in the solar core and lower the predicted SNU flux to the observed value.

The net effect of the cosmion on the temperature distribution in the Sun is to cool the central core of the Sun while heating the region near the aphelion of the typical orbit (Spergel and Press 1985, Nauenberg 1986 and Gould 1987a, Gould 1989). The scale height of the cosmion distribution can be estimated by equating the cosmion's thermal energy with its potential energy,

$$r_x = 0.13 \left(\frac{m_p}{m_x}\right)^{1/2} R_\odot$$

Most of the B^8 neutrinos are produced in the inner 0.05 $R_\odot$, while most of the Sun's luminosity is produced in the inner 0.2 $R_\odot$. Thus a cosmion with mass between 2 and 10 GeV will reduce the B^8 neutrino production rate without reducing the solar luminosity or affecting the production rate of pp neutrinos. Hence the predicted count rate from a solar model cum cosmions for the pp-neutrino sensitive ^{71}Ga experiment does not differ significantly from a standard model. Cosmions more massive than 10 GeV will be too centrally concentrated to affect the thermal

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structure in most of the ^{8}B neutrino producing region (Gilliland, Faulkner, Press and Spergel 1986).

The Sun will capture weakly interacting particles from the galactic halo. The escape velocity from the Sun's surface is 617 km/s, while the escape velocity from the core is over 1000 km/s. A halo cosmion with typical velocity 30 km/s will fall into the Sun where it can be captured through a single collision as long as its mass is less than ~ 50 proton masses. Thus the solar capture rate is approximately the cross-sectional area of the Sun, $\pi R_\odot^2$, divided by the typical cosmion halo velocity, times the escape velocity squared, since gravitational focusing is always important in any elastic capture processes. Press and Spergel (1985) discuss these effects and find that the capture rate is sufficient for the Sun to accumulate a significant number of cosmions in the solar lifetime. If we multiply the capture rate by the lifetime, we find that we can achieve a significant concentration of cosmions relative to baryons,

$$\frac{n_x}{n_b} \simeq 3 \times 10^{-10} \left(\frac{\rho_x}{1 M_\odot/pc^3}\right) \left(\frac{v_{esc}}{\bar{v}}\right) \left(\frac{m_p}{m_x}\right) \min\left[\left(\frac{\sigma}{\sigma_{crit}}\right), 1\right]$$

Recall that a concentration of 10^{-11} of cosmions with cross-section of 4×10^{-36} cm^2 will resolve the solar neutrino problem. If the cosmions compose the halo ($\rho_{\rm HALO} \approx 10^{-2} M_\odot/{\rm pc}^3$, $v_{\rm HALO} \approx 300$km/s), then their cross-section must be within a factor of 2 of σ_{crit}. If cosmions compose the disc ($\rho_{\rm DISC} \approx 10^{-1} M_\odot/pc^3$ and $v_{\rm DISC} \approx 50 km/s$), then they can resolve the solar neutrino problem, if their baryon scattering cross-section is between 10^{-37} and 10^{-34} cm^2.

Since cosmions alter the solar thermal structure, they affect the seismology of the Sun. Solar seismology, which measures the sound speed as a function of radius, might detect the variations in density and temperature induced by cosmion energy transport. Däppen *et al.* (1986) and Faulkner *et al.* (1986) suggest that cosmions can eliminate the discrepancy between the observed p-wave spectrum and the standard solar model. Bahcall and Ulrich (1988) argue that this discrepancy may not be not significant. Cosmions would have more dramatic effects on the still unobserved g-wave spectrum, which is more sensitive to the core conditions. (For more details, see J. Faulkner's paper in the same proceedings).

Most of the cosmions in the Sun are tightly bound: their typical velocities, $\sqrt{3kT/2m_x} \approx 300$ km/s, are much less than the escape velocity from the core $v_{esc}^2 =$ 1400 km/s, so scatterings that produce $v \geq v_{esc}$ are rare. In the conclusion of Spergel and Press (1985), the evaporation rate is estimated as the fraction of cosmion distribution with energy sufficient to escape divided by the time to repopulate the tail. More detailed calculations show that evaporation is negligible for cosmions with $m_x > 4m_p$ (Griest and Seckel 1987, Gould 1987a). Since the core is optically thick for cosmions with larger cross-sections ($\sim 10^{-34}$ cm^{-2}) , they do not evaporate unless their mass is less than 2 m_p (Gilliland *et al.* 1986).

Annihilation can also reduce the number of cosmions in the core of the Sun. If the cosmion is a Majorana particle, it is its own anti-particle and will self-annihilate. If the cosmion is a Dirac particle and the Sun contains both it and its anti-particle in equal numbers, annihilation will also reduce its solar abundance. The cosmion annihilation timescale in the Sun can be estimated,

$$t_{ann} = (n_x \sigma_{ann} v)^{-1} = \left(\frac{n_p}{n_x}\right)\left(\frac{\sigma_{ann}}{\sigma_{bx}}\right) t_{coll} \quad ,$$

where σ_{ann} is the cosmion annihilation cross-section and σ_{bx} is the cosmion-baryon scattering cross-section. If the cosmion is to resolve the Solar neutrino problem,. $t_{coll} \approx t_{dynamical} \approx 100$ seconds and $n_p/n_x \approx 10^{11}$. Most of the attractive particle physics cosmion candidates, photinos, scalar neutrinos, massive and Dirac neutrinos, have scattering cross-sections less than or on the order of their annihilation cross-sections; this implies $t_{ann} < 10^{13}$ seconds, much shorter than the age of the Sun (Krauss, Freese, Spergel and Press 1986). Cosmions are more centrally concentrated than baryons; this enhances their annihilation rate and exacerbates the problem.

There are several possible ways of avoiding this annihilation problem. If there is a net asymmetry between cosmions and anti-cosmions (perhaps, equal to the asymmetry between baryons and anti-baryons), or if $\sigma_{ann} << \sigma_{b,x}$, then cosmion annihilation is suppressed.

Several particle physics models have been proposed for the solar cosmion (Gelmini *et al.* 1986; Raby and West 1988, Ross and Segré 1988). In these models, the cosmion couples to baryons through either a higgs, Z or some new exchange particle. The effects of the cosmion on stellar evolution depends upon the nature of this interaction. If the cosmion couples to nucleons through a spin-dependent interaction, then it will be difficult to detect in the laboratory and have minimal effects on the later stages of stellar evolution. If the cosmion has a spin-independent interactions, then it has a much larger scattering cross-section with helium and heavier nuclei than with hydrogen. As we will see in the next two sections, this leads to observable effects in the later stages of stellar evolution.

2. Solar cosmions in other stars

Solar cosmions will be captured not only by our Sun, but also by other stars moving through the galactic halo (see e.g. Bouquet and Salati 1987). Massive stars accumulate very few cosmions during their brief lives, however, in low mass stars, cosmion energy transport produces subtle, but potentially observable effects.

DeLuca *et al.* (1989) found that solar cosmions slightly alter the mass-radius relationship in low mass stars. Careful observations of a low mass binary system could potentially confirm or contradict the solar cosmion solution to the solar neutrino problem.

Faulkner and Swenson (1988) followed the evolution of low mass stars with modified energy transport. The solar cosmions isothermalized the core of these stars during the end of their main sequence evolution. These isothermal cores could no longer support themselves and began to collapse, driving the star off the main sequence. Faulkner and Swenson (1988) concluded that solar cosmions could reduce estimates of globular cluster ages.

Renzini (1986) suggested that cosmions would significantly alter energy transport in the cores of horizontal branch(HB) stars. Horizontal branch stars burn helium to carbon in their convective cores. Renzini claims that cosmions will isothermalize the cores of HB stars, thus suppressing core convection. Without core convection and semi-convection, the core would rapidly exhaust its supply of Helium and evolve off of the horizontal branch. Shortening the horizontal branch lifetime relative to the asymptotic giant branch lifetime would produce a discrepancy with star counts.

Spergel and Faulkner (1988) made analytical estimates of solar cosmion capture, survival and energy transport in an HB star. They noted that solar cosmions with spin-dependent couplings do not interact with the helium and are ineffectual at energy transport. Cosmions with spin-independent interactions have their numbers depleted through evaporation during the helium flash and the subsequent HB phase. For most parameters, these cosmions have too large a cross-section to efficiently transport energy in HB stars.

Dearborn *et al.* (1989) investigated the effects of solar cosmions on HB star evolution. They assumed that the solar cosmion parameters were optimal for altering HB evolution and used a numerical code to simulate cosmion energy transport. They found that an HB star with solar cosmions can not be in thermal equilibrium: the core oscillates between two phases. During the active phase, it rapidly burns helium and expands on a dynamical timescale. The expansion overshoots and turns off core helium burning. Without helium burning, the core contracts until it achieves the high density needed to re-enter the active phase. These oscillations do not alter HB lifetimes, however, in their simulations, HB stars with cosmions burn $\sim 1/2$ magnitude brighter than standard HB stars.

3. Experimental WIMP searches

3.1. DETECTING WIMPs IN THE LABORATORY

Solar cosmions share the epithet "WIMP" (Weakly Interacting Massive Particles) with several other particles including heavy neutrinos and supersymmetric relics.

Heavy neutrinos have the oldest pedigree of the WIMP candidates. They arise in four generation models: if the heaviest neutrino is stable and its mass is ~ 2 GeV, then it can comprise the missing mass. LEP and SLC will soon test the viability of these models.

Supersymmetry offers a particularly attractive dark matter candidate. In supersymmetry, there is a new conserved quantum number: R- parity. This implies that there will be a lowest mass particle with charge R=1 and that charge conservation will imply that it is stable. In most theories, this lightest supersymmetric particle (LSP) is a linear combination of photino, higgsino and zino interaction eigenstates. The photino is the fermionoic supersymmetric partner of the photon. The higgsino is the partner of the Higgs and the zino is the partner of the Z-boson. In minimal supersymmetry models, there is a large range of parameter space within which the LSP can close the universe (Ellis *et al.* 1984).

WIMPs are potentially detectable through their direct interactions in the laboratory. (Goodman and Witten 1985, Wasserman 1986, Drukier *et al.* 1986). If WIMPs comprise the halo, then their number density is ~ 0.1 cm^{-3} and their flux is $\sim 10^7$ cm^{-2} s^{-1}. A tiny fraction of this incident flux will collide with a nucleus in an experiment and deposit ~ 1 keV of kinetic energy. The experimental challenge is detecting this rare event.

Germanium spectrometers, originally designed for double β decay experiments, provided the first limits on weakly interacting halo dark matter (Ahlen *et al.* 1987, Caldwell *et al.* 1987). These experiments, with their low energy threshold and ultra-low backgrounds, are well suited for WIMP detection. Silicon detectors can push these limits to lower masses and cross-section (Sadoulet *et al.* 1988). The Saclay-UCB-UCSB silicon experiment may soon either rule out or detect solar cosmions with spin-independent interactions.

Detecting cosmions with spin-dependent coupling will require new technologies. These particles have their largest interaction rate per gram with hydrogen and couple extremely weakly to silicon and germanium. Rich and Spiro have suggested that a hydrogen-filled time-projection chamber (TPC) could be used search for these elusive solar cosmion candidates.

3.2. DETECTING WIMPs IN THE SUN

Even if WIMPs do not solve the solar neutrino problem, the Sun's interior may still be an important particle physics laboratory. Any WIMP in the halo, not just the solar cosmion, can be captured by the Sun. The WIMP number density will accumulate until balanced by WIMP annihilation.

When WIMPs annihilate, their annihilation products are likely to include high energy neutrinos. These GeV neutrinos will stream towards the earth, where they can be detected in underground experiments (Silk, Olive and Srednicki 1986). The Frejus, IMB and Kamiokande detectors have all searched for these high energy neutrinos. So far, they have failed to detect an excess number of events coming from the direction of the Sun.

The current limits on WIMPs from non-detection of high energy (GeV) neutrinos from the Sun already constrain several particle physics candidates (Roulet and Gelmini 1988). Detectors, coming on line in the next few months, may rule out several solar cosmion candidates. In the coming years, sensitivities are likely to improve and WIMPs may be either detected or ruled out.

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