DO SOLAR MODELS WITH WEAKLY INTERACTING MASSIVE PARTICLES REPRODUCE THE STANFORD SEISMIC DATA?

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ABSTRACT. The discrepancy between theoretical eigenfrequencies of standard solar models and the frequencies of solar modes of degree between 2 and 5 measured at Stanford is degree-independent for cyclic frequencies above about 2 mHz. Below that frequency the discrepancy for dotriacontapole modes diverges from that of the modes of lower degree. The differences between eigenfrequencies of a simple solar model containing a cloud of weakly interacting particles in its core and of one without do not reproduce this behaviour.

1. INTRODUCTION

Recent measurements by Henning and Scherrer (1986) of the frequencies of p modes of degree 2 - 5 has brought into question the structure of the energy-generating core of theoretical solar models (Gough, 1986). The data are represented in Figure 1, where the differences $\Delta\nu$ between the frequencies observed and the corresponding eigenfrequencies of Christensen-Dalsgaard's (1982) solar model 1 are plotted against frequency in the manner of Christensen-Dalsgaard and Gough (1984). For cyclic frequencies ν above $\nu_c \simeq 1.9$ mHz the discrepancy $\Delta\nu$ is independent of ℓ; as ν decreases below ν_c the $\ell = 5$ discrepancy diverges from the others. It is this feature that is the subject of our discussion.

2. EVIDENCE AGAINST THE MODEL CORE

It is the case that for high-frequency p modes the ℓ dependence of ν comes predominantly from the variation of the sound speed $c(r)$ in the vicinity of the lower turning point $r = r_1(\ell,\nu)$, which is determined by $c(r_1)/r_1 = 2\pi\nu/(\ell + \frac{1}{2})$. It is therefore immediately suggestive that there might be some interesting property of the structure of the sun at or beneath the lower turning point of the $\ell = 5$ p mode with $\nu \simeq \nu_c$: in Christensen-Dalsgaard's (1982) model 1, $r_1(5,\nu_c) \equiv r_c \simeq 0.27R$, where R is the solar radius. Modes with $\nu > \nu_c$ are oscillatory in a region beneath $r = r_c$, whereas modes with $\nu < \nu_c$ are not. Since the

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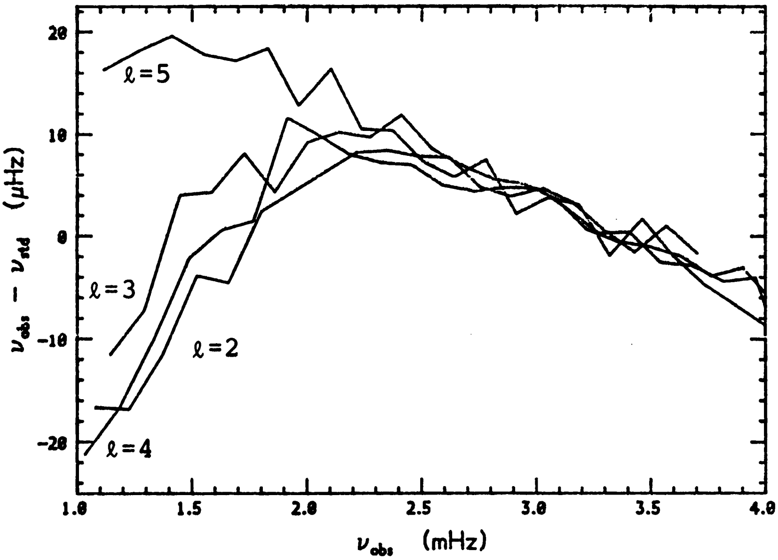

Figure 1. Differences $\Delta = \nu_{obs} - \nu_{std}$ between solar oscillation frequencies ν_{obs} measured by Henning and Scherrer (1986) and corresponding eigenfrequencies of Christensen-Dalsgaard's (1982) solar model 1, plotted against the observed frequencies. Values pertaining to modes of like degree are connected by straight lines.

decay of the amplitude of a low-degree mode in the evanescent region is not abrupt, particularly at the relatively low frequencies of interest here, it is conceivable that the discrepant region in the theoretical model is somewhat below r_c. Thus one is tempted to question the energy-generating core, which extends roughly to $r \simeq 0.2R$.

The frequency deviations Δ plotted in Figure 1 appear not to be wholly consistent with this idea, for there are other modes in the figure whose lower turning points are above r_c, namely $\ell = 4$ modes with $\nu < 1.6$ mHz and the $\ell = 3$ mode with < 1.2 mHz. However, since all these non-penetrating modes are of quite low order ($n \lesssim 10$ for $\ell = 5$, $n \lesssim 8$ for $\ell = 4$ and $n \lesssim 6$ for $\ell = 3$), our rudimentary discussion, which is based partially on asymptotic properties of modes with large n, may be inadequate. Therefore we cannot conclude immediately that so simple an explanation is incorrect. A more precise estimate of the influence of core perturbations is necessary.

3. INFLUENCE OF WIMPS

A consequence of weakly interacting massive particles (wimps) accreted by a solar model is to bring the ℓ dependence of eigenfrequencies in the range 2 - 4 mHz of p modes with $\ell \lesssim 3$ into (perhaps insignificantly) closer agreement with observation (Däppen et al., 1986; Faulkner et al., 1986). In addition, the asymptotic period separation between low-degree g modes of high order is substantially

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reduced, to a value that is consistent with evidence presented by Fröhlich (these proceedings). We have accordingly calculated the frequencies of a solar model with an accreted cloud of wimps to investigate the effect of the modification to the core on some of the lower-order p modes.

Two simplified solar models were defined by the function $\Gamma(r) = d\ln p/d\ln\rho$ which, together with the condition of hydrostatic support, completely determines the pressure $p(r)$ and density $\rho(r)$ of a stellar model of given mass and radius. For the standard model, $\Gamma(r)$ was taken to be the same as that of Christensen-Dalsgaard's model 1 in the radiative interior $r < 0.72R$, and for simplicity Γ was set at 5/3 in the convection zone $r > 0.72R$. For the wimp model, Γ was determined by subtracting from our standard the difference between the values in models A and C of Faulkner and Gilliland (1985), estimated from the computations of Faulkner et al. (1986). The two functions are shown in Figure 2.

Adiabatic eigenfrequencies ν of the two models were computed assuming an adiabatic exponent $\gamma = 5/3$ throughout. Although as a result of misrepresenting the structure of the convection zone the numerical values of ν are not precise, their ℓ dependence, which depends principally on conditions in the core, is well represented. The difference between the frequencies of the two models is plotted in Figure 3. If wimps are to be responsible for the deviant behaviour addressed at the outset of this paper, then that behaviour

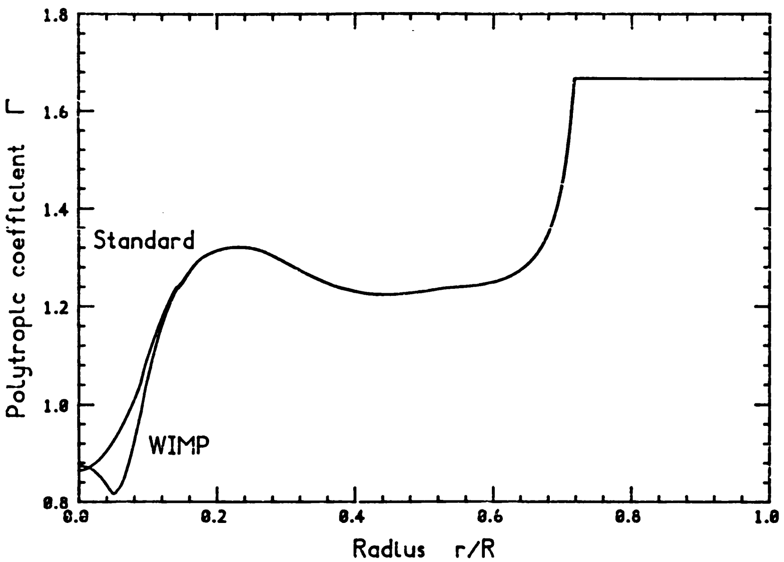

Figure 2. Stratification parameter $\Gamma(r)$ for our standard and wimp models.

must be evident in Figure 3. It is not. We therefore conclude that, provided the Stanford data are correct, there is yet another unresolved problem with our theoretical description of the solar interior.

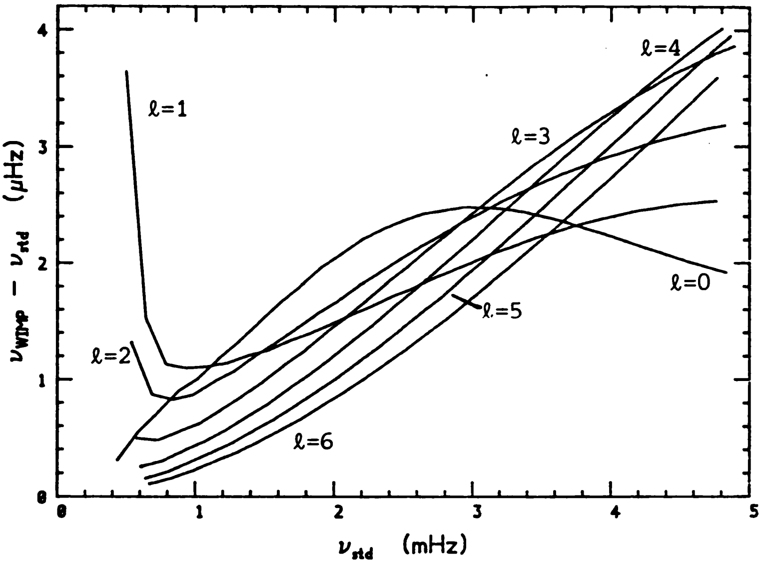

Figure 3. Differences between eigenfrequencies ν_{WIMP} of the solar model containing wimps and ν_{std} of our standard model, plotted against ν_{std}. Values from modes of like degree are connected by straight lines.

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