THE ASTROPHYSICAL JOURNAL, 539:372–378, 2000 August 10

THE PREDICTED SIGNATURE OF NEUTRINO EMISSION IN OBSERVATIONS OF PULSATING PRE–WHITE DWARF STARS

M. S. O'BRIEN[1] AND S. D. KAWALER[2]

Received 1999 December 14; accepted 2000 March 20

ABSTRACT

Pre–white dwarf (PWD) evolution can be driven by energy losses caused by neutrino emission in the core. Unlike the solar neutrino flux, this is not the by-product of nuclear fusion but is instead the result of electron-scattering processes in the hot, dense regions of the PWD core. We show that the observed rate of period change in cool PWD pulsators will constrain neutrino emission in their cores, and we identify appropriate targets for future observation. Such a measurement will tell us whether the theories of lepton interactions correctly describe the production rates and therefore neutrino cooling of PWD evolution. This would represent the first test of standard lepton theory in dense plasma.

Subject headings: dense matter — elementary particles — plasmas — stars: interiors — stars: variables: other — white dwarfs

1. INTRODUCTION

In general, stars are too remote—and observables too few—to make them practical experimental physics test beds: our data are spent in simply describing the dimensions of the objects under study. In many cases we must extrapolate experimental data over many orders of magnitude, or resort to untested calculations from first principles, in order to reach the regions of phase space that apply to stellar interiors.

If we hope to overcome these problems and pursue "experimental" astrophysics, we can either attempt to increase the number of observables or find simpler stars. As first realized by Mestel (1952), the evolution of white dwarfs and pre–white dwarfs (PWDs) is primarily a simple cooling problem. In general, our growing understanding of white dwarf interiors and evolution has paralleled advances in the theory of dense plasmas and the recognition of important influences like electron degeneracy (Chandrasekhar 1939), Coulomb interactions (Salpeter 1961), crystallization (Kirzhnitz 1960; Abrikosov 1960; Salpeter 1961; Stevenson 1980), and neutrino-cooling effects (Chin, Chiu, & Stothers 1966; Winget, Hansen, & Van Horn 1983; Kawaler, Hansen, & Winget 1985). Iben & Tutukov (1984) summarize the various mechanisms which dominate white dwarf evolution from the planetary nebula nucleus (PNN) stage to the coolest white dwarfs.

On the observational side, the discovery of white dwarf pulsators in the 1960s and pre–white dwarf pulsators in the 1970s greatly increased the observable parameters available for comparison with theoretical models. These are short-period, multiperiodic, g-mode variables, showing anywhere from a few to over a hundred separate periodicities on timescales of 100–3000 s. The pulsating PWD stars are divided into two classes: the planetary nebula nucleus variable (PNNV) stars, and the slightly more evolved GW Virginis (GW Vir) stars, which lack observed nebulae. With high surface gravities ($\log g \sim 6$–7.5) and effective temperatures between 80,000 K and 170,000 K, they occupy a region of the H-R diagram between the high-$T_{\rm eff}$ end of the PNN branch and the top of the white dwarf cooling track. There are eight known PNNV stars and four GW Vir stars (Ciardullo & Bond 1996).

The evolutionary timescale of PWD stars is of the order of 10^6 yr. During this short transition from PNN star to hot white dwarf, stellar radius and photon luminosity decrease by 1 and 3 orders of magnitude, respectively. High core density and temperature allow electron-scattering processes to produce a large neutrino flux which remains roughly constant during this time. As photon luminosity plummets, neutrinos constitute an increasing fraction of the total energy loss. Neutrino emission eventually comes to dominate the overall evolution of the star.

Unlike photon energy, which must diffuse relatively slowly through the entire star before emerging into space, neutrinos created near the center of the PWD escape directly. This neutrino luminosity cools the center of the star, maintaining a temperature inversion similar to that within stars at the tip of the red giant branch. Calculations of the relevant reaction rates were performed initially by Beaudet, Petrosian, & Salpeter (1967) based on the theory of weak interactions proposed by Feynman & Gell-Mann (1958). Later, Dicus (1972) and Dicus et al. (1976) recalculated these rates using the unified electroweak theory of Weinberg and Salam (Weinberg 1967; Salam 1968). All of these calculations are theoretical, however. We have no direct experimental or observational confirmation of neutrino production rates under conditions appropriate to PWD interiors.

The cooling of a GW Vir interior tends to increase the periods of each given pulsation mode. Their high luminosity ($\log L \sim 0$–3) means that they cool much more rapidly than cooler white dwarf variables. GW Vir period changes are therefore expected to be more rapid also. Winget et al. (1983) show that the e-folding time for period changes in GW Vir stars should be of the same order as the evolutionary timescale—10^6 yr; such rapid changes are measurable to within 1–3 yr. This is an exciting prospect: to measure directly, on human timescales, the rate of evolution of a star and, specifically, to place strict constraints on the mechanisms which regulate the evolution of a stellar interior. Over

---

[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; obrien@stsci.edu.

[2] Department of Physics and Astronomy, Iowa State University, Ames, IA 50011.

30 years ago, Chin et al. (1966) predicted that at some point in PWD evolution neutrino losses should dominate all other cooling processes. Asteroseismological analysis can tell us which stars are at this point, and then measurement of period changes can tell us if our neutrino physics is right.

Such a test has implications far beyond the study of PWD evolution. For instance, one of the fundamental questions of stellar astrophysics is the length of time stars spend on the main sequence. Answering this question requires precise knowledge of the *p-p* and CNO nuclear reaction rates. Currently, the best laboratory for measuring these rates is our own Sun, since terrestrial labs cannot in general reproduce the conditions of the stellar interior. However, models which successfully reproduce the known structure of the Sun predict a neutrino flux 2–3 times that measured by earthly detectors (Bahcall & Pinsonneault 1996 and references therein). For a long time, it was thought the problem might reside in our incomplete knowledge of conditions in the solar interior. Recently, helioseismology projects such as the Global Oscillation Network Group (GONG) have resulted in the measurement of millions of solar pulsation frequencies (Harvey et al. 1996). With so many parameters to constrain model properties, the possibility that the solar-neutrino problem can be solved through variations in the thermodynamics or mechanics seems to be excluded (Bahcall & Pinsonneault 1996). The problem, then, almost certainly lies in the way we handle the nuclear physics.

Under the most intense scrutiny in this regard is the standard theory of lepton interactions. Our calculations of neutrino emission from PWDs are based on this same theory. In PWDs, however, the energy-loss rate due to neutrinos is thousands of times greater than in the Sun. Measurement of the effects of neutrino interactions in PWDs would afford a critical independent test not only of the standard lepton theory but also of nonstandard theories brought forward to solve the solar-neutrino problem.

To explore this possibility, we calculated PWD evolutionary tracks using different neutrino production rates. In the next section we describe the calculation of these rates and summarize the basic interactions that lead to neutrino emission in PWD interiors. Section 3 describes PWD sequences with varied neutrino production rates and examines effects on measurable quantities such as $T_{\rm eff}$, surface gravity, and rate of period change. Finally, in Section 4 we discuss prospects for placing observational constraints on neutrino physics, and we identify appropriate targets for future observation.

2. NEUTRINO COOLING IN PRE–WHITE DWARF INTERIORS

Unlike the solar neutrino flux, neutrino emission in PWDs is not a by-product of nuclear fusion. Instead, the density and temperature in PWD cores are high enough ($\log \rho_c \sim 6$–7, $\log T_c \sim 7$–8) to produce neutrinos directly through several different scattering processes. The two most important processes are *neutrino bremsstrahlung* and *plasmon* excitation. Neutrino bremsstrahlung is much like the normal bremsstrahlung process familiar to astrophysicists, in which high-energy electrons scatter off nuclei, emitting X-rays. At the high density and temperature of PWD interiors, however, neutrinos can be produced instead. These same conditions support the existence of thermally excited photons within the plasma, analogous to phonons propagating within a metal lattice. These "plasmons" have a finite lifetime and decay to form a neutrino and an antineutrino.[3]

The possible relevance of the plasma process to stellar astrophysics was first pointed out by Adams, Ruderman, & Woo (1963), who subsequently calculated rates based on the theory of Feynman & Gell-Mann (1958). Beaudet et al. (1967) were the first to incorporate these rates into stellar-evolution calculations. Later, Dicus (1972) recalculated the rates of various neutrino processes using the unified electroweak theory of Weinberg and Salam (Weinberg 1967; Salam 1968).

The rates used in our stellar-evolution code, ISUEVO, derive from updated calculations by Itoh et al. (1996) and include the plasmon, bremsstrahlung, and several less important neutrino production processes. The evolution code ISUEVO (Dehner 1996; see also Dehner & Kawaler 1995) is optimized for the construction of PWD and white dwarf models. The models used in this investigation are based on the evolution of a 3 $M_\odot$ model from the zero-age main sequence through the thermally pulsing asymptotic giant branch (AGB) phase. After reaching a stable thermally pulsing stage (about 15 thermal pulses), mass loss was invoked until the model evolved to high temperatures. This model (representing a PNN) had a final mass of $\sim 0.6\ M_\odot$ and a helium-rich outer layer. Additional details concerning the construction of this evolution sequence (and others of different mass, discussed below in § 3) can be found in O'Brien (2000).

To study the direct effects of neutrino losses on PWD evolution, we introduced artificially altered rates well before the evolving models reached the PWD track. If we simply changed the rates beginning at the hot end of the PWD sequence, the thermal structure of each model would take several thermal timescales to relax to a new equilibrium configuration based on the new rates. Unfortunately, this relaxation time is of the same order as the PWD cooling time, and so only the models at the cool end of the sequence would see the full effects of the new rates on their evolutionary timescales. Therefore, the enhanced and diminished rates described in the next section were introduced into evolutionary calculations beginning at the base of the AGB. The resulting thermal structure of the initial PWD "seed" models was then already consistent with the neutrino rates used during the prior evolution that produced them.

3. PRE–WHITE DWARF SEQUENCES WITH DIFFERENT NEUTRINO RATES

Starting with the PWD seed models above, we evolved the models from high L and $T_{\rm eff}$ down toward the white dwarf cooling track. Three sequences were calculated. The base sequence used the normal neutrino production rates. The second sequence used rates diminished by a factor of 3 (at any given ρ and T in the stellar interior), while the third used rates enhanced by a factor of 3. This trio spans nearly 1 order of magnitude in neutrino production.

The resulting 0.6 $M_\odot$ evolutionary sequences are shown in Figure 1, from $T_{\rm eff} \sim 170{,}000$ K—equivalent to the

---

[3] Actually there are two types of plasmons. The process described here is that of the *transverse* plasmon. The other, *longitudinal*, plasmon corresponds to an oscillation in the electron gas similar to a sound wave but is usually less important as a neutrino source in hot white dwarfs (Itoh et al. 1992).

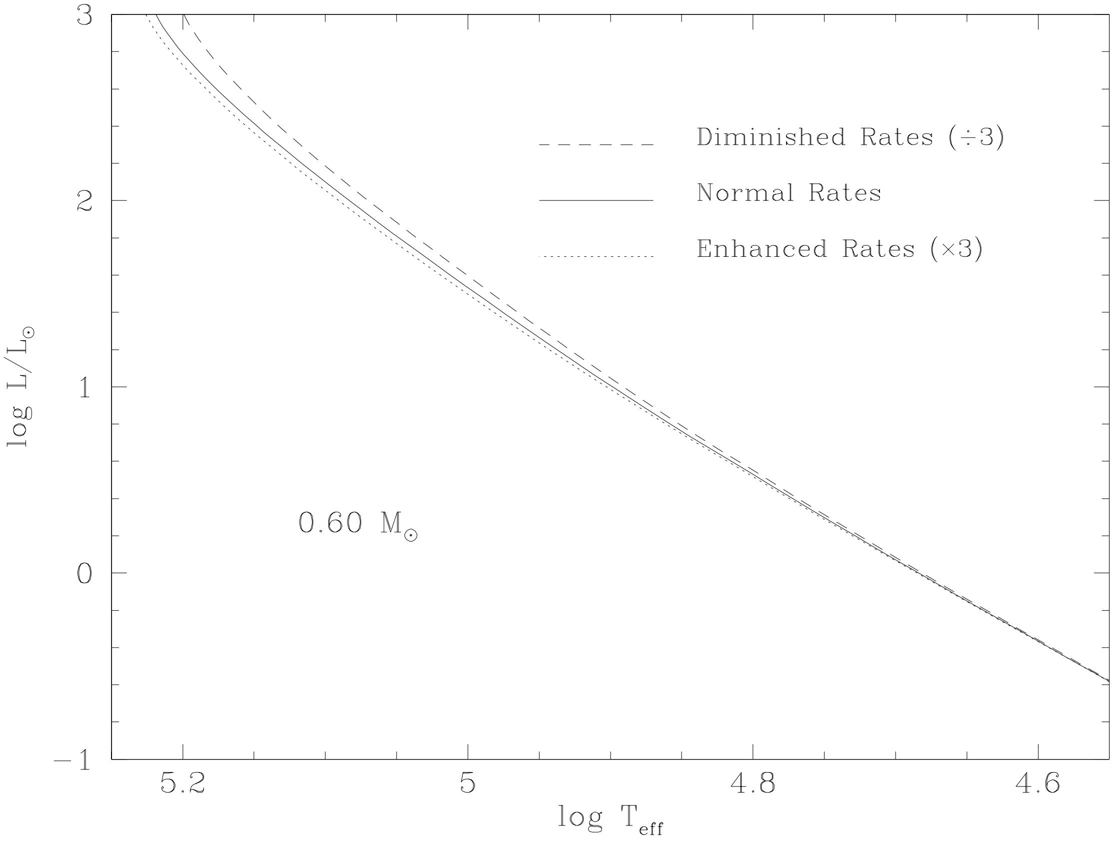

FIG. 1.—Evolutionary tracks for three 0.6 $M_\odot$ model sequences with different neutrino production rates. The upper and lower tracks were calculated with rates one-third and 3 times the normal rates (*middle track*), respectively.

hottest PWDs known—down to about 35,000 K. Luminosity decreases by almost 4 orders of magnitude in approximately 5 million yr. The GW Vir instability strip occupies the left half of the figure, above $T_{\rm eff} \sim 80{,}000$ K (log $T_{\rm eff} = 4.9$), a temperature reached by the PWD models in only 500,000 yr.

The most striking aspect of Figure 1 is the similarity of the tracks: changing the neutrino rates seems to have little effect on the luminosity at a given $T_{\rm eff}$ at *any* point in PWD evolution, despite the importance of neutrino losses as a cooling mechanism over much of this range. In Figure 2, we find that, for all three sequences, neutrino losses are the *primary* cooling mechanism over the approximate range 100,000 K > $T_{\rm eff}$ > 30,000 K. Plasmon reactions are dominant over the bremsstrahlung process for 0.6 $M_\odot$ models at all stages of PWD evolution, as shown in Figure 3.

The ratio L_ν/L_γ increases with stellar mass. In the $T_{\rm eff}$ range 80,000–100,000 K, L_ν/L_γ for a 0.66 $M_\odot$ model sequence is nearly 30% higher than for a 0.60 $M_\odot$ sequence.

Figures 1 and 2 show that the differences in L and $T_{\rm eff}$ are smallest when the neutrinos are important. This is because the primary *structural* effect of changing the neutrino rates is on the radius of the models (Fig. 4), causing the tracks to assume a position in the L-$T_{\rm eff}$ plane normally occupied by models of slightly higher mass (for enhanced rates) or lower mass (for diminished rates). However, at lower temperatures electron degeneracy becomes increasingly important as a mechanical support against gravity (and thus in determining the final stellar radius); neutrino cooling only affects the thermal processes participating in the mechanical structure. Even at high luminosity, however, different neutrino rates result in only small changes in measurable quantities such as surface gravity. Current observational techniques could not hope to resolve such small differences.

Figure 5 shows a more tangible effect of changing the rates. Even though models with different rates look much the same at a given $T_{\rm eff}$, they get there at widely differing times, since the rate of evolution along a track is directly dependent on the importance of neutrino emission as a source of cooling. For example, the model with enhanced neutrino rates cools from 100,000 K down to 65,000 K in 600,000 yr, while the model with diminished neutrino rates takes 1.3 million yr, more than twice as long, to cool by the same amount. The maximum difference in slope of the different curves in Figure 5 occurs at $T_{\rm eff} \sim 80{,}000$ K. Thus the epoch where the rate of evolution is most sensitive to the assumed neutrino physics corresponds to the position in the H-R diagram occupied by the coolest pulsators in the PWD instability strip. On the other hand, for stars in the strip hotter than 100,000 K, Figure 5 shows that evolutionary rates do not depend on neutrino rates.

Our expectations are borne out in Figure 6, which shows the rate of change in period, $\dot{\Pi}/\Pi$ [$\equiv d(\ln \Pi)/dt$], as a function of period, Π, for PWD models at 140,000 K (*lower panel*) and 80,000 K (*upper panel*), given normal, enhanced, and diminished neutrino production rates. The rate of period change $\dot{\Pi}/\Pi$ in the cooler models changes by a factor of 4 between the enhanced and diminished rates. Changing the neutrino rates has little effect on $\dot{\Pi}/\Pi$ in the hotter model, consistent with the results from Figure 5. We now turn to the exciting implications of these results and explore the possibility and practicality of measuring $\dot{\Pi}/\Pi$ in cool

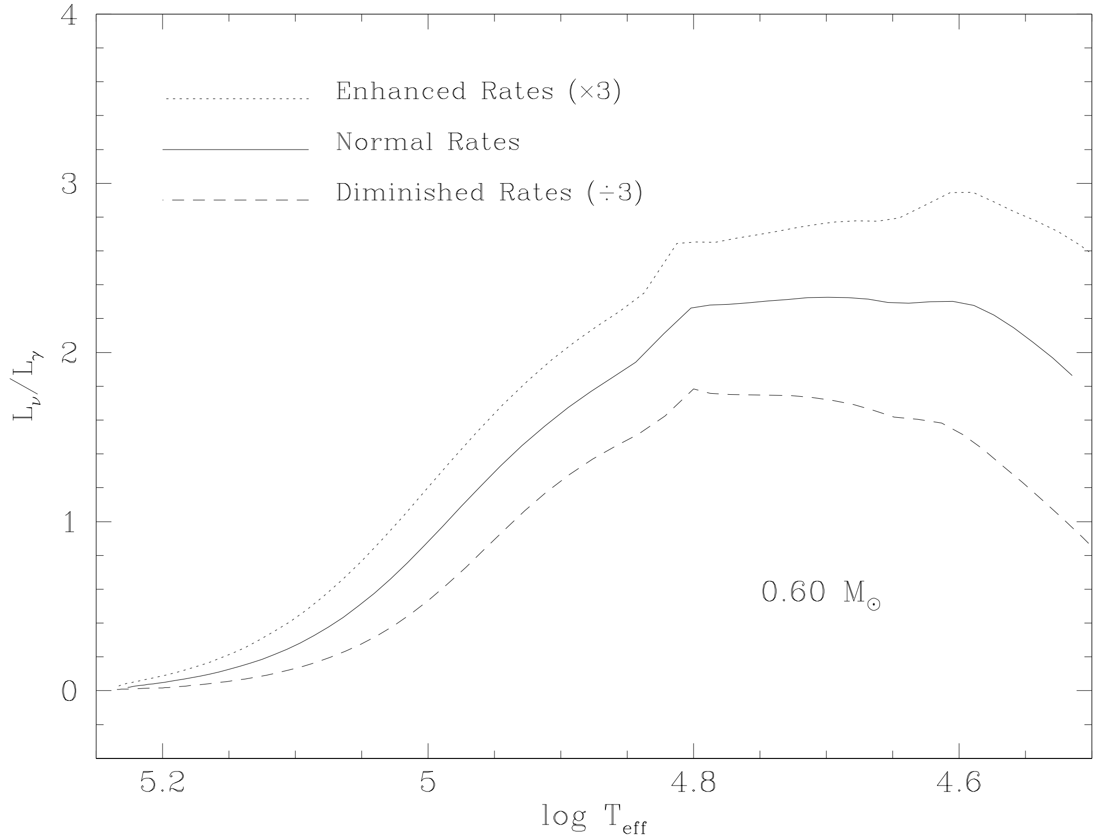

FIG. 2.—Ratio of the neutrino luminosity to the photon luminosity as a function of T_{eff}, for three 0.6 $M_\odot$ model sequences with different neutrino production rates.

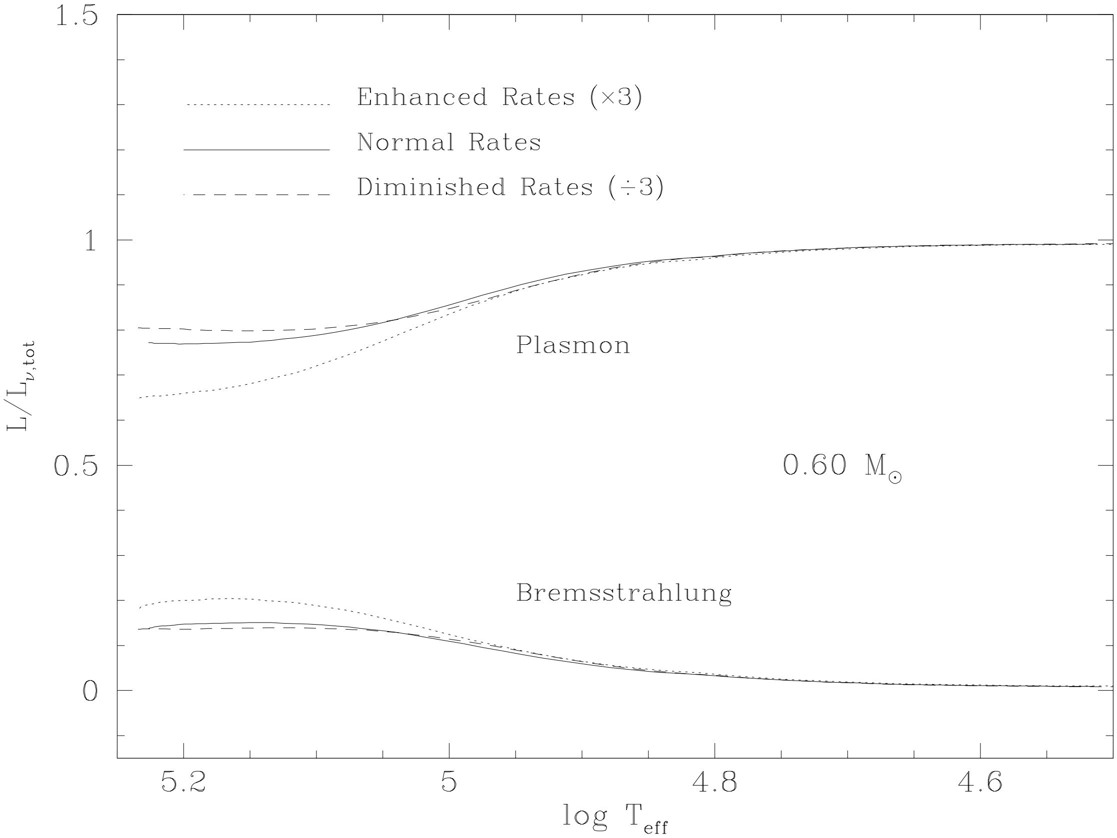

FIG. 3.—Fraction of total neutrino luminosity contributed by the plasmon and bremsstrahlung processes, as a function of T_{eff}, for three 0.6 $M_\odot$ model sequences with different neutrino production rates.

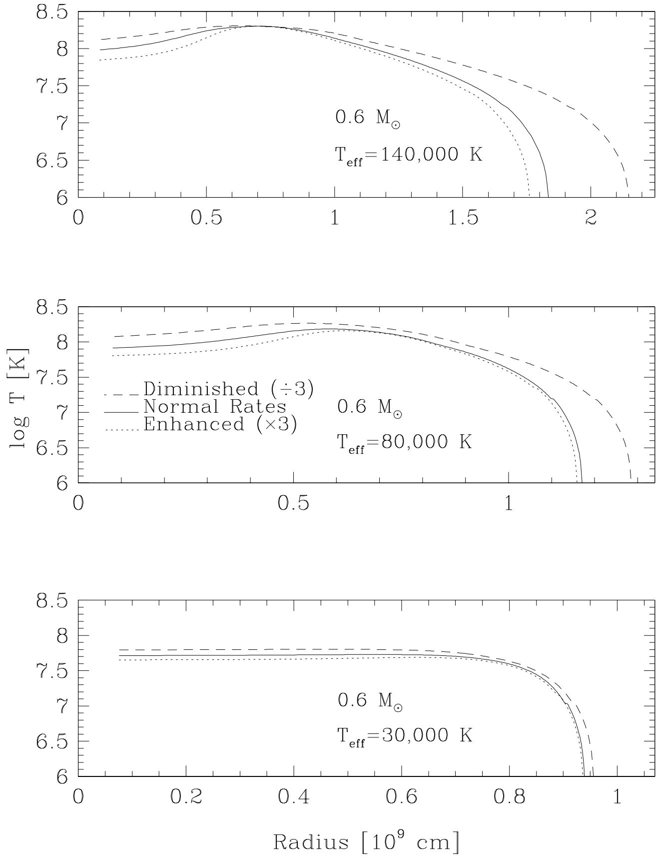

FIG. 4.—Thermal structure at three different evolutionary stages, $T_{\rm eff} = 140{,}000$ K (*upper panel*), 80,000 K (*middle panel*), and 30,000 K (*lower panel*), for 0.6 $M_\odot$ models with different neutrino production rates.

pulsating PWD stars. We can then identify likely targets for future observational campaigns.

4. PROSPECTS FOR MEASURING NEUTRINO-COOLING EFFECTS

4.1. *Determination of* $d\Pi/dt$

Unfortunately, the period changes expected to occur in PWD stars are too small to detect from simple comparison of the period from one year to that of the next. To determine $d\Pi/dt$, a better technique is to measure the cumulative phase change in a mode with a slowly changing period. This is accomplished by comparing the observed times of maxima (O) in the light curve to the times of maxima (C) calculated from an assumption of constant period. The resulting plot of $O - C$ shows the phase drift associated with a changing period. A constant rate of period change, $d\Pi/dt$, enters as a quadratic term in time:

$$O - C \approx \frac{1}{2}\frac{1}{\Pi_{t_0}}\frac{d\Pi}{dt}(t - t_0)^2 \text{ s}, \quad (1)$$

where Π_{t_0} is the period at time t_0 (see for example Winget et al. 1985, 1991; Kepler et al. 1995). To measure $d\Pi/dt$ with confidence, the star must of course have stable and fully resolved pulsation periods, with reliable phase measurements from season to season.

Kawaler et al. (1985) and Kawaler & Bradley (1994) present predicted values of $d\Pi/dt$ for models relevant to GW Vir and PNNV stars; the only observed value of $d\Pi/dt$, that for PG 1159, is consistent with these models. However, as Kawaler & Bradley (1994) demonstrated, for a star as hot as PG 1159, $d\Pi/dt$ is strongly affected by mode trapping. This is an effect whereby some modes become

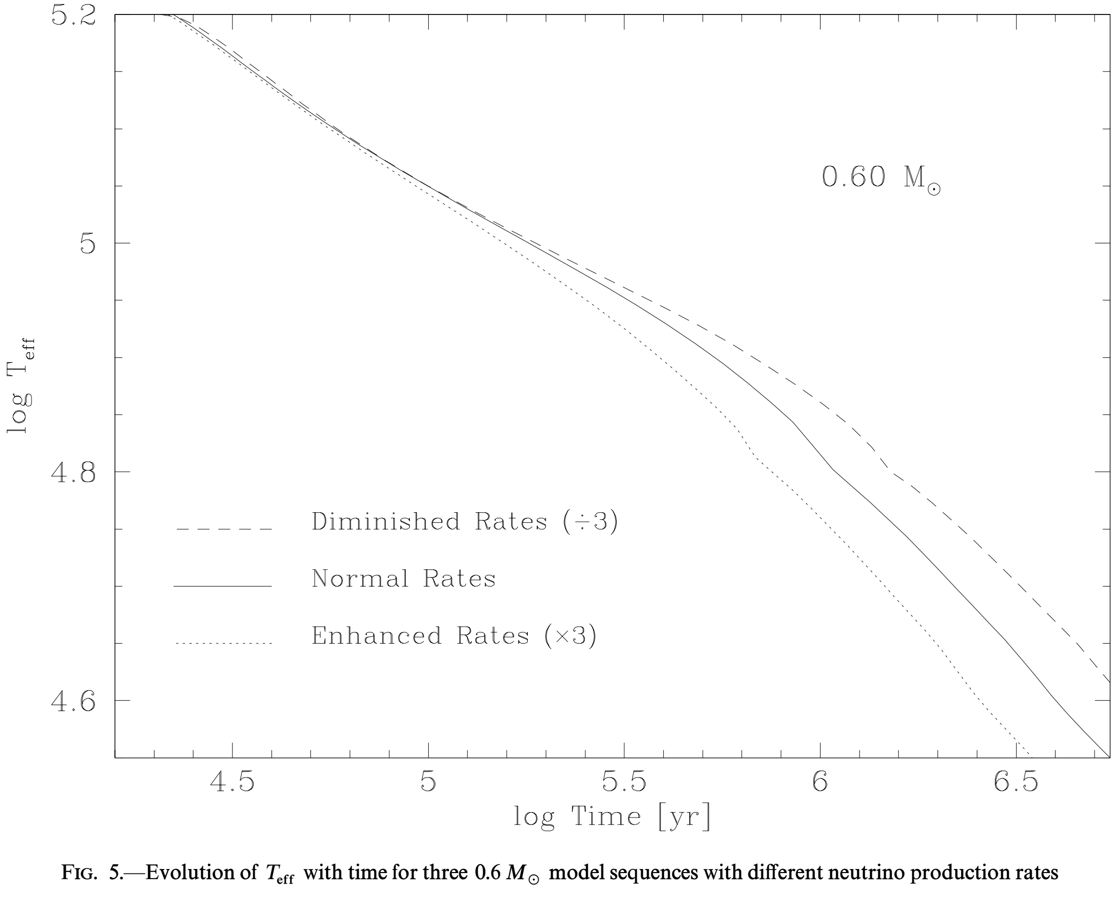

FIG. 5.—Evolution of $T_{\rm eff}$ with time for three 0.6 $M_\odot$ model sequences with different neutrino production rates

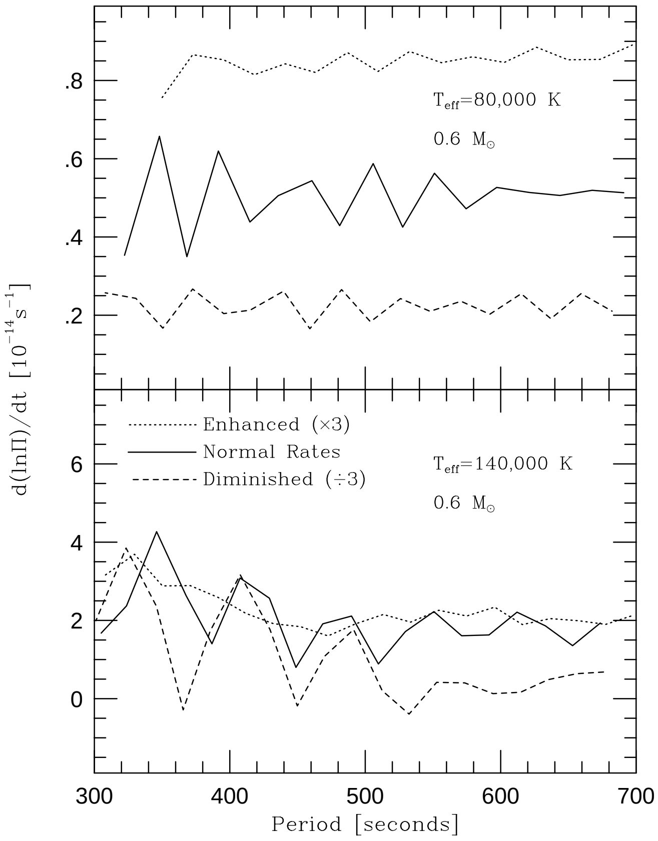

FIG. 6.—Rate of period change for 0.6 $M_\odot$ models with different neutrino production rates.

excluded from regions below subsurface composition discontinuities. Kawaler & Bradley (1994) show that, in general, $d\Pi/dt$ should be positive; this reflects the overall cooling of the model (Winget, Hansen, & Van Horn 1983). Trapped modes, however, are concentrated in the outer layers, within which contraction dominates cooling; therefore trapped modes can show periods which decrease with time. Thus, mode trapping can complicate the interpretation of measured period changes in hot PWDs. As GW Vir stars cool, the surface contraction rate decreases relative to the cooling rate of the interior. So, while mode trapping can still influence the pulsation-period distribution itself, the rates of period change become more similar from mode to mode in cooler GW Vir stars. Kawaler & Bradley (1994) found that the sign of $d\Pi/dt$ could be different for different modes in hot GW Vir models; by the time those models evolve to the cool end of the strip, the period-change rates are all positive.

4.2. *Prospective Targets*

Measurements of secular period change, $\dot{\Pi}/\Pi$, in white dwarfs have been attempted by a number of investigations, with either measurements made or tight upper limits set for the GW Vir stars PG 1159 (Winget et al. 1985, 1991; Costa & Kepler 1998) and G117-B15A (Kepler et al. 1995). Unfortunately, neutrino cooling is not expected to be an important effect for either of these stars. However, PG 0122, with a $T_{\rm eff}$ of 80,000 K, occupies the stage in GW Vir evolution most highly dominated by neutrino emission. O'Brien et al. (1998) show that PG 0122 is in addition the most massive GW Vir star, which should enhance neutrino effects as well.

As noted above, in order to measure $\dot{\Pi}/\Pi$ with confidence, a star must have a stable and fully resolved pulsation, with stable phase measurements from season to season. PG 0122 is a very stable pulsator: over the past decade, it has shown a consistent pulsation spectrum, with the large-amplitude modes present at the same frequencies during each of three intensive observing seasons in 1986, 1990, and 1996. The amplitudes of each of the dominant modes remained approximately constant as well (O'Brien et al. 1998). Therefore, PG 0122 is an excellent candidate for measurement of the rate of secular period change caused by the evolutionary cooling of its interior.

In addition to the physics governing neutrino production, PG 0122 is an ideal target for measuring neutrino-emission rates because of the minimal influence of any mode trapping on interpretation of its $\dot{\Pi}/\Pi$. As mentioned above, for stars below 100,000 K trapping no longer significantly affects $\dot{\Pi}/\Pi$ from mode to mode.

From Figure 6, we estimate the value of $\dot{\Pi}/\Pi$ for the dominant pulsation mode ($\Pi = 400$ s) in PG 0122 to be about 6×10^{-15} s^{-1}. With this rate of period change, the period should increase by about 0.001 s in 10 yr; this is smaller than the period uncertainty for a run length of several months [assuming a frequency precision of $(10 \times \text{run length})^{-1}$]. However, the accumulated phase advance over a 10 yr period should be *nearly two full cycles*.

Using the periods alone from the 1986, 1990, and 1996 data, O'Brien et al. (1998) attempted to calculate $\dot{\Pi}/\Pi$ directly. From the best least-squares periods from 1996 and 1986, they calculate a period change of -0.10 ± 0.02 s, implying $\dot{\Pi}/\Pi = -7 \times 10^{-13}$ s^{-1}, about 100 times larger in magnitude—and different in sign—than theory expects. However, as O'Brien et al. (1998) point out, this calculation is based on the formal errors from a least-squares fit to the observed periods, and the *formal* least-squares error generally underestimates the true error by an order of magnitude. In practice, the data currently available allow an upper limit to be set on the absolute magnitude of $\dot{\Pi}/\Pi$ for PG 0122 of 1.5×10^{-12} s^{-1}. In view of the importance of measuring $\dot{\Pi}/\Pi$ for this star—as well as for the other cool GW Vir stars—we must continue analysis of archival data and mount observing campaigns in the near future to monitor all the known GW Vir stars with $T_{\rm eff} < 100{,}000$ K. With frequent observation, an accumulated phase advance of half a cycle, combined with the techniques described above, could be used to determine $\dot{\Pi}/\Pi$ for the GW Vir stars PG 0122, PG 2131, and PG 1707 in 2–3 yr. In the case of PG 0122, the data presented in O'Brien et al. (1998) provide a key anchor for this investigation.

5. SUMMARY AND CONCLUSIONS

We have shown that the predicted rates of period change in GW Vir stars near the cool end of the instability strip are sensitive to the neutrino production rates used in stellar models. The persistence of the solar-neutrino problem has made the standard model of neutrino interactions one of the most intensely scrutinized theories in all of physics. Determination of $\dot{\Pi}/\Pi$ in the GW Vir stars PG 0122, PG 2131, and PG 1707 will provide an important test of the standard model and of any new theories put forward to replace it.

The authors express their appreciation to Chris Clemens for valuable editorial comments. We also thank the anonymous referee who, in particular, helped clarify our under-

standing and explanation of lepton-scattering theory as it applies to white dwarf interiors.

M. S. O'B. was supported during much of this research by a GAANN fellowship through grant P200A10522 from the United States Department of Education to Iowa State University. Support also came from the National Science Foundation under the NSF Young Investigator Program (grant AST 92-57049) to S. D. K. at Iowa State University. Finally, some support for this work came to S. D. K. from the NASA Astrophysics Theory Program through award NAG 5-4060 to Iowa State University.

REFERENCES

Abrikosov, A. 1960, Soviet Phys.–JETP Lett., 39, 1797

Adams, J. B., Ruderman, M. A., & Woo, C. H. 1963, Phys. Rev., 129, 1383

Bahcall, J. N., & Pinsonneault, M. H. 1996, BAAS, 189, 56.01

Beaudet, G., Petrosian, V., & Salpeter, E. E. 1967, ApJ, 150, 979

Chandrasekhar, S. 1939, An Introduction to Stellar Structure (Chicago: Univ. Chicago Press)

Chin, C. W., Chiu, H. Y., & Stothers, R. 1966, Ann. Phys., 39, 280

Ciardullo, R., & Bond, H. E. 1996, AJ, 111, 2332

Costa, J. E. S., & Kepler, S. O. 1998, Baltic Astron., 7, 83

Dehner, B. T. 1996, Ph.D. thesis, Iowa State Univ.

Dehner, B. T., & Kawaler, S. D. 1995, ApJ, 445, L141

Dicus, D. A. 1972, Phys. Rev. D, 6, 941

Dicus, D. A., Kolb, E. W., Schramm, D. N., & Tubbs, D. L. 1976, ApJ, 210, 481

Feynman, R. P., & Gell-Mann, M. 1958, Phys. Rev., 109, 193

Harvey, J. W., et al. 1996, Science, 272, 1284

Iben, I., Jr., & Tutukov, A. V. 1984, ApJ, 282, 615

Itoh, N., Hayashi, H., Nishikawa, A., & Kohyama, Y. 1996, ApJS, 102, 411

Itoh, N., Mutoh, H., Hikita, A., & Kohyama, Y. 1992, ApJ, 395, 622

Kawaler, S. D., & Bradley, P. A. 1994, ApJ, 427, 415

Kawaler, S. D., Hansen, C. J., & Winget, D. E. 1985, ApJ, 295, 547

Kepler, S. O., et al. 1995, Baltic Astron., 4, 221

Kirzhnitz, D. A. 1960, Soviet Phys.–JETP Lett., 38, 503

Mestel, L. 1952, MNRAS, 112, 583

O'Brien, M. S. 2000, ApJ, 532, 1078

O'Brien, M. S., et al. 1998, ApJ, 495, 458

Salam, A. 1968, in Elementary Particle Physics, ed. N. Svartholm (Stockholm: Almquist & Wiksells), 367

Salpeter, E. 1961, ApJ, 134, 669

Stevenson, D. J. 1980, J. Phys. 41, C2-61

Weinberg, S. 1967, Phys. Rev. Lett., 19, 1264

Winget, D. E., Hansen, C. J., & Van Horn, H. M. 1983, Nature, 303, 781

Winget, D. E., Kepler, S. O., Robinson, E. L., Nather, R. E., & O'Donoghue, D. 1985, ApJ, 292, 606

Winget, D. E., et al. 1991, ApJ, 378, 326