is much more complicated that in the Sun. In particular, some of the stars pulsate in multiple modes which are not consecutive overtones; intermediate modes are missing, or have undetectable amplitude. An extreme case of this is HD 217522. Between 1982 and 1989 (when the star was not observed) the principal frequency changed by 15 μHz; in 1989 a mode which was undetectable in 1982 appeared separated by 802 μHz from the principal frequency. Since $\delta\nu_0$ is in the range of 20 to 80μHz for the roAp stars, there are many intermediate overtones not excited in this star. We have looked at HD 217522 again in 1993 and find it unchanged from 1989.

HD 119027 has five pulsation modes with frequencies separated by about 26 μHz consistent with alternating even- and odd-l modes. HD 203932 has four pulsation modes with nearly equal spacing of about 33 μHz. Most of the studies of these stars have been limited to single-site observations, or, at best, a short multi-site campaign. What is needed are much more extensive multi-site observations.

New multi-site observations of α Cir show that its principal pulsation mode is a pure oblique dipole mode with a frequency of 2442 μHz. A rotationally split triplet shows the rotation period to be $P_{rot} = 4.4790 \pm 0.0001$ day. Four low-amplitude secondary frequencies are present with separations that are multiples of 25 μHz suggesting that $\delta\nu_0 = 50$ μHz. The asteroseismological luminosity inferred from this agrees with the luminosity determined independently from the parallax.

An interesting new result for the roAp stars is that many of them show frequency variability on a time scale of months to years. This variability appears to be cyclic and has an amplitude similar to that seen in the Sun over the solar cycle of about 0.1 mHz. We have suggested that this may be evidence for magnetic cycles in Ap stars, but that is theoretically difficult to understand, since the Ap stars are rigid rotators without extensive surface convection zones.

The cyclic frequency variability, the seismology, the geometric information contained in the frequencies, the mystery of the pulsation mechanism, the unknown overtone and degree selection mechanisms, the extreme abundance peculiarities, and other properties of the roAp stars make them fascinating subjects to study.

14. Asteroseismology of white dwarf stars (R.E. Nather)

Perhaps the hardest scientific problems to solve are those most scientists believe have already been solved, but which have not. Any model we make of an astronomical process is doomed to be incomplete at some level; the "broad–brush" picture of stellar structure and evolution is often accepted as a solved problem, but in fact many discrepancies exist between our models

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and the observations.

For example, the "standard solar model" fails to predict the observed neutrino flux from the Sun, and its insistence that the Sun's luminosity increased by 30% over geological time is not in accord with the evidence. White dwarf stars were thought to be stable against pulsation because the models did not pulsate, and it took a long time to improve them to the point where they did, and could then begin to match our observations of pulsating white dwarfs. For several years their outer hydrogen layers were thought to be extremely thin because models with thicker layers did not pulsate; once the zoning problem was found and solved in the models they could begin to match observations better. These past difficulties illustrate a common danger: it is very easy to confuse our models with the observed reality they try to mimic, and to assume they match better than they do. In what follows I will try to keep the observations and our models of them separate.

Since Don Winget's review six years ago (Winget, 1988), observations of variable white dwarfs have caught up with, and now seriously challenge, pulsation models designed to describe them. In 1988 Winget reported that the prototype DOV pulsator "...has over 8 separate periods" [the number has now risen to over 125 (Winget *et al.*, 1991)] and that the brightest DBV (helium atmosphere) pulsator GD 358 "...has over 25." [We have identified over 180 to date, (Winget *et al.*, 1994) and there may well be more.] This matters, since our ability to model their interior structure depends on the number of separate frequencies we can identify, as each one probes a slightly different region.

We have developed, and have placed into routine operation, an instrument that allows the rich frequency spectrum present in the white dwarfs to be fully resolved: the Whole Earth Telescope (WET, Nather *et al.*, 1990). Resolution of the closely-spaced frequencies requires 200 hours or more of continuous observations, which we achieve by locating our observers at different longitudes around the globe, so that one or more of them are always in darkness. We have learned how to merge data thus obtained into a single light curve, which we can then transform into a detailed spectrum of the oscillations present. We call this kind of measurement "temporal spectroscopy."

Pulsation theory (*e.g.* Unno *et al.*, 1979) offers us an excellent basis for interpreting the temporal spectra are able to obtain. The observed frequency patterns can now be identified unambiguously with the model quantum parameters k, ℓ, m. We find that the lowest pulsation order $\ell = 1$ is the most popular, with $\ell = 2$ a distant second, and $\ell = 3$ and above undetectable. The radial overtones are represented from $k = 1$ in the coolest (DAV, hydrogen atmosphere) white dwarfs to $k = 37$ in the hottest (DOV,

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C/O atmosphere). Rotation causes the azimuthal pulsation frequencies to have slightly different values, so their indices are all found, showing a triplet of closely–spaced frequencies for $\ell = 1$ and a quintuplet for $\ell = 2$.

Our pulsation models (Bradley, 1993) are designed to have parameters which correspond one–to–one with important physical quantities in the observed objects, so we can derive values for these quantities when we find a model that fits the observations in detail. This gives us the illusion of understanding. These derived quantities are shown in Table 1 for three individual stars, and similar results will be forthcoming for all of the variable white dwarfs, and their immediate progenitors, as observations accumulate. Notice that the mass of the object can be determined to about 1%, and its derived absolute luminosity allows us to determine its seismological distance with gratifying precision.

Somewhat to our surprise we find that the DOV star PG1159-035 exhibits solid body rotation, within our ability to detect it, but the DBV GD358 shows differential rotation, with its envelope rotating almost twice as fast as its core. The likely presence of shear effects may explain the sub–surface discontinuity at $10^{-6} M_{\star}$, evident as a pattern of triplet spacings that deviate from uniformity; the discontinuity might also be a composition–transition zone between the helium outer envelope and the expected C/O core. Our models will have to be refined before we can tell the difference between them.

In his thesis, Clemens (1994) showed that all the hot DAV stars, taken as a group, showed the same basic pulsation patterns, which could then be matched very closely with a single model. The small differences were significantly reduced when the model was adjusted for small differences in mass, centered on 0.6 $M_{\odot}$. This confirmed the observational evidence that the deviation in mass for white dwarfs is remarkable small (Weidemann, 1990), and the remarkable uniformity in the pulsation properties strongly suggests that they all have the same hydrogen layer thickness of about $10^{-4} M_{\odot}$, the maximum amount that evolutionary models allow: any hydrogen added would burn to helium at the base of the hydrogen layer.

Lest we get complacent with this success, however, I must mention that there are still significant mysteries surrounding the details of the temporal spectra of all the white dwarfs. We see amplitude changes from one year to the next, and even during the 200 hours or so a WET run lasts. Some frequencies come and go, although the overall pattern remains stable, and we find sum and difference frequencies that cannot be normal modes of the star, but arise as non–linear combinations of the large amplitude pulsations. Our current (linear) models have nothing to say about these obvious effects. Although we include neutrino luminosities in our models, as we must — in our DOV models, the plasmon neutrino luminosity is greater than the pho-

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ton luminosity (Kawaler, 1986) — we still are not able to model correctly the way the overall frequency pattern changes with time as the star cools, although we seem to have the timescale about right.

We still have a lot to learn from the white dwarf stars, particularly about the history of nucleosynthesis in our galaxy. That record is written there, and we now have the tools with which we can examine it. We might even be able to understand, at long last, the mysterious process by which a red giant becomes a white dwarf — a problem "solved" long ago.

SEISMOLOGICAL RESULTS ON INDIVIDUAL STARS

	PG-1159	PG-2131	GD 358
Mass	0.59 ± 0.01	0.593 ± 0.006	0.61 ± 0.03
He layer	4×10^{-3}	6×10^{-3}	2×10^{-6}
Rot. per.	1.38 ± 0.01 d	0.42d	0.89-1.6d
Rot. type	solid body	differential	differential
Mag. Field	< 200 G	~5,000 G	1300 G
Abs. Lum.	200 ± 5	~30.5	0.05 ± 0.01
Seis. Dist.	440 ± 40 pc	~1200 pc	42 ± 3 pc

15. Seismology of δ Scuti stars in stellar clusters (Y. Lebreton, E. Michel)

Several δ Scuti stars (A/F stars) have been observed during multi-site campaigns of observations and have been found to be multiperiodic pulsators. They are thus good candidates for asteroseismology from ground based observations. Observations provide the position of the star in the H-R diagram and some frequencies (about 5 for the STEPHI campaigns). Comparisons with models should then allow to identify the oscillation modes of the star and then give information on the unknown parameters of the star (mass, age, chemical composition). However the situation is complicated, since stellar models are based on a physical description of the stellar material, which is not well known in many respects. In particular A/F stars have convective cores, the extent of which depends on the amount of overshooting considered and on the description of this process.

The observation of several δ Scuti stars in the *same* stellar cluster in principle simplifies the problem. All the stars have, in that case, the same chemical composition and their age is the age of the cluster which can be determined by means of comparison with theoretical isochrones. Then, when one more star is observed in the same cluster, this brings several new observable quantities but only one more unknown quantity, the mass of that particular star.

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