The Crystal Method: Asteroseismology of BPM 37093

T.S. Metcalfe,1 M.H. Montgomery,2 and A. Kanaan3

1Harvard-Smithsonian Center for Astrophysics
2Department of Astronomy, University of Texas-Austin
3Departamento de Física, Universidade Federal de Santa Catarina

Abstract. More than 40 years have passed since Ed Salpeter and others predicted that the carbon/oxygen cores of the coolest white dwarf stars in our Galaxy will theoretically crystallize. This effect has a dramatic impact on the calculated ages of cool white dwarfs, but until recently we have had no way of testing the theory. In 1992, pulsations were discovered in the massive potentially crystallized white dwarf BPM 37093, and in 1999 the theoretical effects of crystallization on the pulsation modes were determined. Observations from two Whole Earth Telescope campaigns in 1998 and 1999, combined with a new model-fitting method using a genetic algorithm, are now giving us the first glimpse inside of a crystallized star.

1. Crisis in the Cosmos

In 1994, Ed Nather was reading the newspaper and came across a headline which read, “Crisis in the Cosmos - stars older than the universe”. Reading through the accompanying article, he learned that a group of astronomers had fit cosmological models to new observations from the refurbished Hubble Space Telescope and had concluded that the Universe was between 8 and 12 billion years old. Meanwhile, another group of astronomers had used stellar models to fit main-sequence isochrones to observations of a globular cluster and had derived an age of about 18 billion years. When presented with these details, Ed’s reaction was: “Where’s the crisis? Either the cosmological models are wrong, the stellar models are wrong, or both!” As we now know, the age estimates from these two methods later met somewhere in between.

The lesson here is that it is always useful to have independent methods of measuring a quantity, because it gives us a chance to improve our models. In the context of asteroseismology, if we restrict the range of our search for pulsation models to be consistent with the spectroscopic determinations of the surface gravity and effective temperature, we will never find a disagreement between the models. A global search allows the pulsation periods to speak for themselves, and lends more credibility to the final results.

2. Theory

There is a very simple explanation for how crystallization affects the derived ages of cool white dwarfs: the process releases latent heat. This is familiar to anyone
who has ever used a small packet of super-saturated sodium-acetate solution (see Fig. 1) to keep their hands warm—the transition from liquid to solid changes the entropy of the substance, and the difference is released as thermal energy. In a white dwarf, this new source of thermal energy causes a delay in the gradual cooling of the star (e.g., see Fontaine, Brassard, & Bergeron 2001).

In addition to the latent heat from crystallization, there is another source of energy that can delay the cooling even further. When a mixture of carbon and oxygen crystallizes, the two elements are expected to make the transition from liquid to solid at slightly different rates (Lamb & Van Horn 1975). So, the concentration of oxygen in the resulting solid will be greater than in the liquid (Segretain & Chabrier 1993). This leads to a net redistribution of oxygen inward and carbon outward (phase separation) during the crystallization, releasing gravitational potential energy as additional heat (Segretain et al. 1994; Salaris et al. 1997; Montgomery et al. 1999).

Together, crystallization and phase separation produce a total delay of 2-3 Gyr in white dwarf cooling. So if we want to use cool white dwarfs to date stellar populations, we need to model these processes accurately. Ideally, we could use observations of pulsating white dwarfs to probe the interiors and determine the size of the crystallized core empirically—allowing us to calibrate the models.

3. Observations

The trouble is, typical white dwarfs with masses near 0.6 $M_\odot$ don’t theoretically begin to crystallize until they cool down to about 6000-8000 K (depending on their core composition), and this is well below the temperatures where they are observed to pulsate. More massive white dwarfs have higher internal pressures, so they can begin to crystallize at higher temperatures. Prior to the Sloan Digital Sky Survey data, only one pulsating white dwarf was known that was theoretically massive enough to be at least partly crystallized: BPM 37093.

BPM 37093 was discovered to be pulsating by Kanaan et al. (1992). The peak to peak variation in total light is about 1 percent on a timescale of about 600 seconds, but we also see the signature of beating between closely-spaced
Figure 2. Changes to the crystallized mass fraction and the thickness of the hydrogen layer have similar effects on the mean period spacing in models. This degeneracy can be lifted by matching the individual periods.

pulsation modes. To resolve the pulsation modes from each other unambiguously we need to observe the star continuously for a week or more. So a multi-site campaign of the Whole Earth Telescope (Nather et al. 1990) was necessary, and in fact there have been two such campaigns—one in 1998 and another in 1999 (Kanaan et al. 2000, 2004). In the Fourier Transforms of the long light curves from these campaigns, we clearly resolve a total of about 8 distinct pulsation modes, which is what we are attempting to fit with our theoretical models.

4. Model Fitting

In chemically uniform white dwarf models, the pulsation periods are almost evenly spaced. But abrupt changes in the interior composition cause large spikes in the buoyancy frequency which can selectively shift some of the periods from this simple pattern (mode trapping). The effect of crystallization is distinct because it alters the pulsation modes by basically moving the inner boundary from the center of the star out to the edge of the crystallized core. So, for example, if the star is 50 percent crystallized, the modes will be confined to the outer half of the mass—and this will change all of the periods.

4.1. Simple Treatment

The adjustable parameters in our models include the total mass, the effective temperature, the masses of the helium and hydrogen layers, the core composition and the crystallized mass fraction. To make the problem computationally tractable, early attempts to fit the observations fixed many of these parameters and tried to match the average spacing between consecutive $\ell=2$ modes (Montgomery & Winget 1999). This approach quickly ran into the difficulty that changes to the crystallized mass fraction and the thickness of the surface hydrogen layer had very similar effects on the mean period spacing (see Fig. 2).
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Figure 3. Systematic errors in the measurement of $M_{cr}$ can arise when fixing some parameters (like the mass, temperature, and core composition) incorrectly, allowing secondary minima to become locally optimal.

To break the degeneracy between these model parameters, we need to use the individual periods in addition to the period spacing. When we do so, one of the models stands out as the best. But this is just a simple analysis—since we have fixed so many of the other model parameters, we have most likely found a locally optimal match to the periods, rather than the true global solution.

4.2. Initial Results

We have recently published our first steps towards a global solution (Metcalfe, Montgomery, & Kanaan 2004). To keep the computing time reasonable, we initially did a series of fits with masses fixed near the spectroscopic values, and we tried core compositions of pure C and pure O just to test the extreme limits. Also, for each combination of parameters we examined only 10 values of the crystallized mass fraction, from 0 to 90 percent. All of our fits reproduced the periods observed in BPM 37093 at the level of about 1 second, and in every case we found solutions with a large crystallized mass fraction. But it’s important to put these numbers into context by noting the large uncertainties that come about just from the way we did the fitting.

We passed artificial data through the same process to estimate the systematic errors in the crystallized mass fraction that we should expect from our limited exploration of the models. We found that because of our low resolution in the crystallized mass fraction, fixing the mass or composition incorrectly could lead to systematic errors of at least ±0.2 (on top of the statistical errors of ±0.1). We can understand this by looking at a model that is 80 percent crystallized, and trying to match its pulsation periods with models that are anywhere from 0 to 99 percent crystallized (see Fig. 3). What emerges is a series of secondary minima spaced about 0.2 apart. When we fix one of the other parameters incorrectly, the minimum at 0.8 can get shallower and one of the nearby secondary minima can become the locally optimal “best fit”.
So, these initial fitting results tell us two important things: (1) BPM 37093 is substantially crystallized, so it’s worth spending more computing time to try to pin down the exact fraction, and (2) we should probably fit to the nearest 0.01 in the crystallized mass fraction to reduce the systematic errors, and we should avoid fixing as many parameters as we possibly can.

4.3. Latest Results

Our next step has been to treat the crystallized mass fraction as a completely adjustable parameter to the nearest 0.01. Again, the computational demands of the problem forced us to fix the mass and the core composition, but we are performing fits over a broad range of fixed masses to minimize the systematic errors. The best fit we have found so far (fixed $M_\star = 1.03 \, M_\odot$, 50:50 C/O core) is significantly better than any of the initial fits we published:

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\begin{align*}
T_{\text{eff}} &= 11,200 \, \text{K} \\
\log(M_{\text{He}}/M_\star) &= -2.54 \\
\log(M_{\text{H}}/M_\star) &= -4.56 \\
M_{\text{cr}} &= 0.56 \, M_\star \\
\sigma_P &= 0.52 \, \text{sec}
\end{align*}
\]

Because of the limited sampling of models with different fixed masses, the systematic uncertainty on the crystallized mass fraction is still about ±0.1, but when we have finished we expect to measure this parameter to within a few percent. There are still secondary minima in the crystallized mass fraction (see Fig. 4), but we hope to rule these out unambiguously as the model-fitting continues. Recently, our mode identification and a comparable set of best-fit parameter values were independently found by Fontaine & Brassard (2005).
5. Summary

To summarize the main conclusions of this work:

- Crystallization delays white dwarf cooling by 2-3 Gyr, but we can calibrate the effect on their ages through asteroseismology.
- BPM 37093 is currently the only pulsating white dwarf massive enough to be crystallized, but others are expected from the Sloan Digital Sky Survey.
- Surface layers cause “mode trapping”, changing the pulsation periods selectively; crystallization squeezes the resonant cavity to change all of the periods.
- Initial fitting suggests that BPM 37093 is substantially crystallized, and work in progress will measure the crystallized mass fraction to ±3 percent.

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