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HD 101065 – Przybylski's Star: A Most Peculiar Star

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Abstract. The story of HD 101065, Przybylski's star, is one of a forty-year controversy over the nature of what is arguably the most peculiar star in the sky, a controversy that is only now being resolved fully. Our current understanding is that HD 101065 is the coolest ($T_{\rm eff} \approx 7400$ K) and the most peculiar of the Ap SrCrEu stars. The existence of this most peculiar star, and other Ap stars, has been the source of some very interesting stellar astrophysics with applications far wider than the understanding of just the stars themselves.

1. HD 101065 – Przybylski's Star

HD 101065 was classified as a B5 star in the Henry Draper catalogue. Przybylski (1961) discovered it *not* to be a B star. He found that the strongest lines in the spectrum are from Ho II, Dy II, Sm II, and Nd II. He said the spectral type from the continuum is K0 and the spectral type from H lines is F8 or G0. Thus was born a forty-year controversy over the nature of what is arguably the most peculiar star in the sky.

Wegner (1976) published a visible-light spectrum of HD 101065 traced from a photographic spectrum taken by Brian Warner with the Radcliffe 1.9-m telescope when it was still in Pretoria, South Africa (it is now at the Sutherland station of the South African Astronomical Observatory). An arresting feature of that spectrum is that the depth of many of the metal lines is greater than that of the Balmer lines! The spectrum is so heavily line-blanketed that it has been vigorously debated whether there is anything that can be reasonably called a continuum to be seen. Fig. 1 reproduces part of the spectrum as published by Wegner.

Kron & Gordon (1961) measured *UVBGRI* photometry of HD 101065 and concluded that, "[it is] very likely an F8 or G0 dwarf with very strong line blanketing." Their argument was based on the similarity of the magnitudes of HD 101065 in *BGRI* to a late F dwarf standard star, but they noted that the *U* and *B* magnitudes were depressed by line blanketing. I believe HD 101065 to have an effective temperature near to that of an F0 star, about 7400 K. So I argue that line-blanketing has also depressed the *BGRI* magnitudes, and proper correction for this would show a continuum close to that of an F0 star.

From an abundance analysis Przybylski (1966) concluded that HD 101065 has *no* Fe and little Ca. From the *BGRI* observations he found $T_{\rm eff} = 5900\,{\rm K} = {\rm T}_\odot$! The spectral type implied by this is G2Vp, so Przybylski deduced that

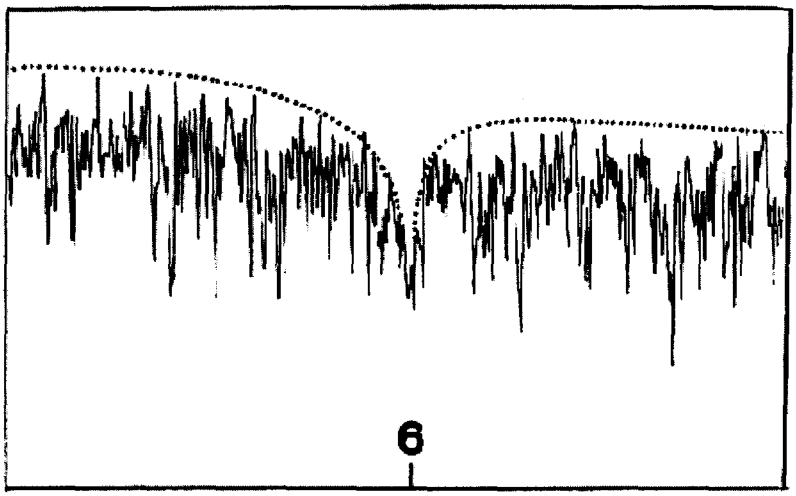

Figure 1. One panel of a triptych of an intensity spectrum of HD 101065 published by Wegner (1976) from a photographic plate taken by B. Warner, reproduced with kind permission. Blue is to the right in this spectrum. The dotted line is Wegner's estimate of the *lower* limit to the continuum. The "6" marks H6=Hδ at 4101Å. Note the many metal lines with depths greater than Hγ. The complexity of this spectrum is striking.

HD 101065 is unique. From another abundance analysis Wegner & Petford (1974) concluded that the Rare Earths are overabundant by a factor 10^5, the Fe peak elements are *normal*, the excitation temperature is $T_{\rm exc} = 6300 \pm 120$ K, and the effective temperature is $T_{\rm eff} = 7000$ K. Therefore, the equivalent spectral type is F0Vp. They pointed out that the heavy line blanketing increased the temperature gradient to cause backwarming which, if unaccounted for, results in a low estimate of $T_{\rm eff}$.

Typically, $T_{\rm eff}$ can be determined for F and G stars to an accuracy of ±150 K from spectral classification or colour index. That the dispute over $T_{\rm eff}$ in HD 101065 ranges over 1000 K attests to the extreme peculiarity of this star. The claim of *no* Fe by Przybylski and of *normal* Fe by Wegner & Petford attest to the vigour of the controversy over this star.

Jones et al. (1974), discovered that the Ap star HD 51418 is rich in Ho II and Dy II and commented that, "the star that most nearly resembles HD 51418 ... is HD 101065." The spectral type of HD 51418 is late B or early A, and it has a measured magnetic field which ranges from $-200\,{\rm G} \le B_{\rm eff} \le +750\,{\rm G}$ with a rotational period of $P_{\rm rot} = 5.4379$ d. HD 51418 is obviously an Ap star – one rich in Ho and Dy. Jones et al. suggested that, "an attempt should be made to determine whether HD 101065 in any way resembles the Ap stars." They warned that, "the temperature of HD 101065 should be carefully reconsidered." By this they meant the low, solar-like $T_{\rm eff}$. And, reasonably, they pointed out that, "measurements of magnetic field strength [in HD 101065] would be important."

This is because Ap stars have global magnetic fields; solar type stars have tangled magnetic fields. The incidence of globally organized magnetic fields stops at about F0 because that is where the surface convective envelope starts to grow (with decreasing $T_{\rm eff}$). By mid-F convection drags and entangles whatever global field is present. Hence Jones et al. were suggesting that the discovery of a dipole-like field in HD 101065 would argue strongly for the higher temperature.

2. Ap stars

On and near the main sequence for $T_{\rm eff} > 6600\,{\rm K}$ there is a plethora of spectrally peculiar stars and photometric variable stars with a bewildering confusion of names. There are Ap, Bp, CP and Am stars; there are classical Am stars, marginal Am stars and hot Am stars; there are roAp stars and noAp stars; there are magnetic peculiar stars and non-magnetic peculiar stars; He-strong stars, He-weak stars; Si stars, SrTi stars, SrCrEu stars, HgMn stars, PGa stars; λ Boo stars; stars with strong metals, stars with weak metals; pulsating peculiar stars, non-pulsating peculiar stars; pulsating normal stars; non-pulsating normal stars; δ Sct stars, δ Del stars and ρ Pup stars; γ Dor stars, SPB stars, β Cephei stars; γ Cas stars, λ Eri stars, α Cyg stars; sharp-lined and broad-lined stars, some of which are peculiar and some of which are not. There are pre-main-sequence Ae and Be stars, collectively called HAeBe stars; there are Oe and Be stars which are not pre-main-sequence stars. For the purposes of this paper you do not need to know about all these stars (see Kurtz 2000a, though, if you do want to know). All you do need to know about are the magnetic Ap stars. For understanding the arguments about Przybylski's star, it is useful to know that the Ap stars:

- have strongly anomalous abundances with overabundances of heavy elements up to a factor of 5 dex and over abundances of the Fe-peak elements of $0 - 1$ dex typically, but with some stars showing a slight deficiency of Fe (Weiss et al. 2002; Richard et al. 2001);
- lie between, but not on, the zero age main sequence and the terminal age main sequence (Hubrig et al. 2000);
- have abundance anomalies that are confined to a thin surface layer;
- rotate slowly, $v \sin i \leq 125\,{\rm km\,s^{-1}}$;
- have strong, global, approximately dipolar magnetic fields with strengths of a few hundred G to a few tens of kG;
- have magnetic fields that vary on a time-scale of days to decades;
- have spectra that vary synchronously with the magnetic variations;
- have mean brightnesses (ignoring short-period pulsation) that vary synchronously with the magnetic and spectrum variations.

These properties are understood in the framework of radiative diffusion theory and the oblique rotator model.

2.1. Radiative Diffusion Theory and the importance of HD 101065 to stellar astrophysics

Diffusion was developed by Praderie (1967), Schatzman (1969) and Michaud (1970) to explain the Ap stars. See Vauclair et al. (1978) for explanation and discussion, see Michaud & Proffitt (1992) for a review, and, in particular, see Richard et al. (2001) to see how quantitative the predictions of the theory have become. The idea is simple in principle: If there are layers in a star which are stable against turbulent mixing, then elements heavier than H will tend to sink gravitationally, unless they have many absorption lines near the local flux maximum, in which case the asymmetry in the intensity of the flux arising from the temperature gradient will mean that ions absorb more radiation from below than above, hence are radiatively driven towards the surface. These two competing effects can cause some elements to sink and other to rise, thus producing peculiar atmospheric abundances. In the Ap stars the diffusion hypothesis accounts for the overabundances of the Fe-peak, Rare Earth and Lanthanide elements, the position of the Ap stars between the ZAMS and TAMS with the disappearance of anomalies in more evolved stars, the slow rotation Ap stars, and the concentration of elements in spots near the magnetic poles in Ap stars. Diffusion is also now part of the standard solar model, with He settling included by Bahcall & Pinsonneault (1995); helium and some metal settling has also been included in calculations of Li and Be mixing in the Sun (Richard et al. 1996; Vauclair & Richard 1998). Diffusive concentration of Fe is thought to drive the pulsations in the sdBV EC 14026 stars (Charpinet et al. 2001). There has also been discussion of He settling shortening the ages of globular clusters (Stringfellow et al. 1983; Chaboyer et al. 1996), and Li settling may be part of the explanation of the Li-gap in F-stars (Chaboyer 1998; Boesgaard & Tripicco 1986). Radiative diffusion will eventually be a standard part of all stellar structure and evolution codes. Given the wide-spread application of diffusion theory in stellar astrophysics, that the Ap stars are the best test-bed for the theory, and that HD 101065 is the most extreme test, the study of HD 101065 has repercussions in stellar astrophysics far beyond the understanding of the Ap stars themselves. *In this sense, Przybylski's star is a challenge to stellar evolution theory.*

3. Back to the HD 101065 story

Przybylski (1977a) responded to Wegner & Petford by estimating the backwarming correction to be −460 K, and concluding that $T_{\rm eff} = 6075 \pm 200$ K and the spectral type is F8.

Hyland et al. (1975) found from infrared photometry that $T_{\rm eff} \approx 6300 \pm 150$ K and the spectral type is F5 – F6. HD 101065 is much less line blanketed in the infrared, so it was hoped that the controversy could be settled by studying that part of its spectrum. Hyland et al. did not observe their own standards, however. They compared their observations of HD 101065 to standards observed by Ian Glass, a point I will return to below. Wolff & Hagen (1976) discovered a −2200 G global magnetic field in HD 101065. They pointed out that the presence of the field supported Wegner's higher T_{eff} and they suggested that, "...the same mechanism that is responsible for the overabundances of the rare earths in the Ap stars may also be effective in HD 101065..." This is incompatible with the low T_{eff} estimates, since the coolest Ap stars are about F0 and the incidence of globally organized magnetic fields stops at about F0. I used to argue against the Fe deficiency, too, since Fe is very difficult to destroy and, until recently, I thought that diffusion would almost always levitate it in stellar envelopes because it has such a rich absorption spectrum. Recent observations (see Weiss 2002; see also Gelbmann et al., 2000, and previous papers in that series) show that some Ap stars do have mildly deficient Fe, and now diffusion theory also shows that this is expected at certain times in an Ap star's evolution (Richard et al. 2001). I now accept that Fe is probably mildly deficient in HD 101065.

3.1. IAU Colloquium 32

In 1975 IAU Colloquium 32, "The Physics of Ap Stars", was held in Vienna. The controversy about HD 101065 boiled over there. Fortunately, the conference organizers taped the discussion and included it verbatim in the proceedings, so it is possible to get the real flavour of the discussion. Przybylski (1975) presented a paper in which he claimed for HD 101065 that $T_{\text{eff}} = 6075 \pm 200$ K and that Fe is deficient by 2.5 dex. Let's look at some of the discussion which follows Przybylski's paper (I quote from the proceedings):

Wolff: "Hagen and I ... find that this star has a magnetic field of -2200 G. This strengthens the identification of the star as an Ap star."

Przybylski: "The presence of a strong magnetic field is not restricted to hot stars. Therefore, it is not proof that HD 101065 is hotter than I assume. The photometry of HD 101065 leaves little room for any speculation on the effective temperature of the star ($T_{\text{eff}} = 6075$ K)."

During the discussion Przybylski made another presentation on HD 101065:

Przybylski: "The third slide shows tracings of HD 101065 and Procyon (dashed line) in the interval λ3820 Å to λ3835 Å. Both stars have the same continuum temperature of 6500 K... The second strongest line in the solar spectrum at λ3820 Å... in HD 101065 this line, if present at all, cannot have a depth exceeding 30% and in this case its equivalent width would be about 100 mÅ..."

Kodaira: "Isn't it possible that the strong Fe lines are masked, because the other lines are so strong? You show that one line coincides with a peak. But even this peak could be the local continuum level."

Przybylski: "The continuum of Procyon can be drawn confidently. On the other hand, some doubts exist about the continuum of HD 101065... Masking of the lines is, of course, a very serious problem ...investigation of the spectrum is an extremely difficult task."

Cowley: "Do you agree that this spectrum shows that the Fe is weak or missing? Yes or no? ... O.K. You don't want to commit yourself."

Dworetsky: "It would seem difficult to agree about anything in that spectrum as it is incredibly blended and looks like random noise!"

Cowley: "You have some lines, and if Fe had its normal strength you ought to see it."

Dworetsky: "I am not sure in a star this severely blanketed if our usual idea of what we mean by effective temperature has much meaning..."

Cowley: "...I can tell you that in HR465 and HD 51418, which have extraordinarily rich spectra and are hot, the Fe lines are strong and stand out and I am not unmoved by this picture of Dr. Przybylski, which fails to show any real evidence of Fe I."

Shore: "When you are working on these stars one of the problems is that if you look in the blue, you can find anything you want to and you can mask almost anything you want to."

Przybylski: "Let us return to the third slide. From the fact that any Fe line at λ3820 Å, if present at all, ..."

Cowley: "If I can beg your indulgence. I think we are going over the same ground."

Michaud: "At this meeting I sometimes have the impression of being at a museum of horrors or perhaps errors... it does not seem inconceivable that diffusion would produce HD 101065."

Przybylski: "The results of the six-colour photometry and infrared photometry leave very little room for speculation about the effective temperature of the star ..."

Wolff: "I would just like to say that this discussion is essentially fruitless. It is clear that this star is cooler than most Ap stars, whatever its temperature is. It is clear to me that the Fe lines are inconspicuous, at best, and Fe might not be there at all. And since there is only one of us, so far as I know, who owns a red plate, I don't see how we can resolve this issue. This is a case where you have to see it to believe it."

3.2. Back to the literature

The next year Wegner (1976) found that the backwarming effect is only about −150 K (but might even be positive). From modelling the Hydrogen lines he found from Hα that $T_{\rm eff} \approx 7500$ K and from Hβ that $T_{\rm eff} \approx 7100$ K. He reported that Ian Glass had obtained IR photometry of HD 101065 using his own standard stars, and that from Glass's new IR photometry $J-K$ implied that $T_{\rm eff} \approx 7000$ K and $J-L$ implied $T_{\rm eff} \approx 7500$ K – much hotter than Hyland et al.'s 6300 ± 150 K obtained from IR photometry using Glass's standards. Wegner put the spectral type in the range A8–F1.

The controversy continued: Przybylski (1977b) found that Fe is underabundant by 2.4 dex. Cowley et al. (1977) used a technique called line-coincidence statistics, which is more objective than typical line identification procedure to find that Fe is underabundant by at least 2.4 dex. They stated: "... the strongest Fe lines lie near the plate limit, with equivalent widths of a few tens of milliangstroms. The equivalent widths for these lines range up to 3 Å in the Sun!" And they say, hopefully, "The current study has, we hope, resolved the outstanding question concerning the spectrum of HD 101065: iron peak elements are present, although ... their spectra are unusually weak."

Resolve the question of Fe? Not at that time. No such luck! Wegner and I were not about to leave that question alone. More on this below.

4. Discovery of the 12-min pulsation

In 1978 Wegner and I were privately discussing HD 101065 and I pointed out that if HD 101065 is as hot as he believes, then it is within the instability strip. In 1978 everyone thought that Ap stars and magnetic stars could not pulsate. This belief was because diffusion theory predicted at that time that He sinks from the He II ionisation zone sufficiently to quench the κ-mechanism that drives δ Scuti pulsation. We have a much more sophisticated understanding of the interaction of diffusion and pulsation now, so that the pulsation of some Ap and Am stars is no longer a mystery (Turcotte et al. 2000).

Also, in 1978 it was believed that the magnetic field would stabilize the star against pulsation – that it would be difficult for the large scale motions of δ Scuti pulsation to cross the field lines of a strong global magnetic field, or to drag those field lines along with the pulsation. It is only now that there is substantial progress in our theoretical understanding of the interaction of pulsation and magnetic fields; see Cunha & Gough (2000), Bigot et al. (2000) and Bigot & Dziembowski (2002) for the latest developments.

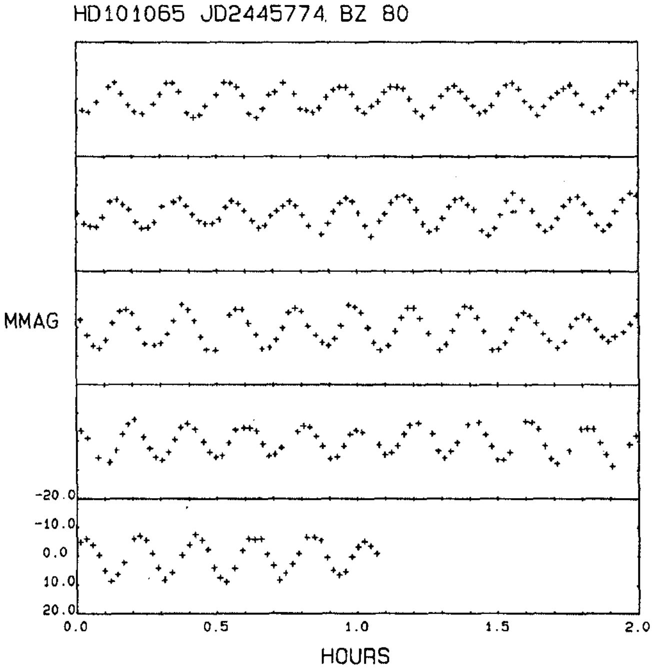

Figure 2. A light curve of HD 101065 taken with the SAAO 1.9-m telescope. Low frequency transparency variations have been filtered from the data to level it only. This has no effect on the 12-min oscillations. This 9-hr long light curve obtained under superb photometric conditions shows what high signal-to-noise can be obtained on a variable star with a peak-to-peak amplitude of only 0.01 mag.

In 1978 I was observing 12–14 weeks per year, so had the freedom to pursue unlikely observational projects. I decided to test HD 101065 for δ Scuti pulsation by spending a few hours doing differential photometry on it with the South African Astronomical Observatory (SAAO) 0.5-m telescope at Sutherland. I used two comparison stars and 100-s integration times through a Johnson V filter. The results were that HD 101065 was constant over the hours of observation to a standard deviation per observation of $\sigma = 0.003$ mag. But it was a perfect Sutherland photometric night – the kind of night where the stars blink out when they set against a sharp horizon; the kind of night when $\sigma = 0.003$ mag is unexpectedly large.

I checked the two comparison stars against each other. They had a standard deviation a bit less than $\sigma = 0.002$ mag – closer to what I expected. A visual look at the light curve of HD 101065 gave the impression that the points were alternating: up-down, up-down, up-down. I showed this the next afternoon to the other astronomers and everyone agreed that there was no signal, and that HD 101065 was constant to $\sigma = 0.003$ mag on the time scale of 8 min which was the cycle time to observe both comparison stars and HD 101065 itself for 100 s each.

That turns out to be true, but it is not true that the star is constant. The next night I decided to observe it through a Johnson B filter with no comparison stars and an integration time of 20 s. The system was old-fashioned: a teletype, punch paper tape, and no on-line plotting. So I plotted the points by hand. In only 30 min the 12.15-min pulsation with its 0.01-mag amplitude was obvious (Kurtz 1978), and I had discovered the first of the rapidly oscillating Ap stars. Fig. 2 shows a beautiful high-precision light curve for HD 101065 I obtained with the SAAO 1.9-m telescope in 1984.

Wegner and I considered the pulsation suggestive that HD 101065 lies in the instability strip, hence has $T_{\rm eff} \geq 7400\,K$; Przybylski saw it as one more bizarre behaviour in a unique star.

5. Wegner and Kurtz stir the pot

In 1979 Wegner and I (Kurtz & Wegner 1979) performed a new spectroscopic study of the equivalent widths of the Paschen lines, found $W_\lambda(\mathrm{P12}) = 4.04$ Å and concluded that this implied $T_{\rm eff} = 7400 \pm 300$ K. We also pointed out that the Fe I λ4045 is expected to have $W_\lambda = 300$ mÅ at this $T_{\rm eff}$, not the 3 Å Cowley et al. (1977) were expecting by comparing to the Sun. We thus doubted the claim that Fe is deficient, frustrating Cowley et al.'s hope that this question was finally resolved. We suggested instead that HD 101065 is an Ap star – the most extreme Ap star – and we suggested that searches for similar pulsation in other magnetic Ap stars should be made. Przybylski was provoked by the above paper; he then found (Przybylski 1982) that the equivalent width of P12 was $W_\lambda(\mathrm{P12}) < 300$ mÅ, implying $T_{\rm eff}(\mathrm{P12}) = 6140$ K. He stated, "the attempt by Kurtz and Wegner to revive the controversy about the abundance of iron seems rather unconvincing." I was not convinced by his paper. One reason was that, even as the non-anonymous referee, I could not persuade Przybylski to publish tracings of his spectra of either HD 101065 or his control star.

In 1983 Wegner et al. (1983) found from IUE UV spectra that the energy distribution of HD 101065 is greatly distorted. They said that the presence of flux below 1900 Å suggests $T \gg 6000\,\mathrm{K}$ and gave a crude estimate of $7500 \leq T_{\mathrm{eff}} \leq 8000\,\mathrm{K}$, commenting that, "this estimate could be too low." They found lines of Fe II, Cr II, Mn II, and Ti II are strongly represented in the 1900 – 3200 Å range and concluded that "[p]revious reports of the underabundance of iron and the absence of iron-peak elements cannot be supported." They considered all of this to be, "... evidence for the classification of HD 101065 as a magnetic Ap star."

I had hopes that asteroseismology would resolve the issue. The asteroseismology of HD 101065 leads to a predicted luminosity (Matthews et al. 1999). The seismic prediction for an assumed $T_{\mathrm{eff}} = 7400\,\mathrm{K}$ is $\pi = 7.80 \pm 0.24$ mas; for an assumed $T_{\mathrm{eff}} = 5900\,\mathrm{K}$ it is $\pi = 10.4 \pm 0.2$ mas. Alas, the Hipparcos parallax is $\pi = 8.0 \pm 1.1$ mas, and nothing is resolved by this.

However, continuing work on the abundances in HD 101065 supports the contention that this is the most extreme Ap star. Cowley & Mathys (1998) now find that the iron group abundances are mildly deficient in HD 101065. They point out the fact that the Hα line wings match $T_{\mathrm{eff}} = 7500\,\mathrm{K}$, but the narrow core does not fit any model. Most interestingly, Cowley et al. (2001) have now shown that there is a Core-Wing anomaly in the H-line profiles in many of the coolest, most peculiar of the Ap stars, HD 101065 included. The line wings match temperatures of around $T_{\mathrm{eff}} \approx 7400$ K, but the line cores are anomalously narrow and are better matched by much lower temperatures around 5500 K. This indicates strongly abnormal T-τ structure with much steeper temperature gradients than in normal stars of the same effective temperature. That is yet to be fully modelled, but there is active work on this problem. Years ago Shibahashi & Saio (1985) argued for such a steep temperature gradient to understand the high frequencies of pulsation seen in some of the roAp stars, HR 1217 in particular. Standard A-star models have critical cut-off frequencies lower than the observed frequencies, but a steeper temperature gradient sharpens the outer boundary of the pulsation cavity and increases the critical frequency.

6. roAp stars - where HD 101065 has led us

The discovery of the 12-min pulsation in HD 101065 then led to my discovery of the class of rapidly oscillating Ap stars, cool Ap SrCrEu stars which pulsate with periods from just under 6 min to about 16 min, although the upper limit is not well-defined. Some of the stars are non-linear pulsators and have harmonics present in their amplitude spectra at periods as short as 4 min, but there is no pulsation period shorter than that of HD 134214 at 5.6 min. The photometric semi-amplitudes through a Johnson B filter in some cases (HD 101065, HD 60435 sometimes) can be over 5 mmag, but most stars have much lower amplitudes than that. They range in temperature from $6800\,\mathrm{K} \leq T_{\mathrm{eff}} \leq 8400\,\mathrm{K}$. There are 32 known members of the class (as of this writing in April 2002).

Frequency analyses of the light curves of the roAp stars have yielded rich asteroseismic information on the degrees of the pulsation modes, distortion of the modes from normal modes, magnetic geometries, luminosities, and the interaction of the magnetic field with the pulsation modes (Cunha & Gough 2000;

Bigot et al. 2000; Bigot & Dziembowski 2002). There have been many reviews of the roAp stars: see, e.g., Weiss (1986), Kurtz (1990), Shibahashi (1987, 1990), Matthews (1991), Martinez (1993), Martinez & Kurtz (1994a,b), Kurtz (2000a,b,c,d) and Kurtz & Martinez (2000). Here I will just highlight some recent developments – the important point being that it was HD 101065 that was the start of all this work.

6.1. A predicted and confirmed frequency in HR 1217

The roAp stars have stimulated some very interesting new theoretical and observational work. For example, HR 1217 is a prototypical rapidly oscillating Ap star that has been a challenge to the theory of nonradial stellar pulsation for over a decade. Observations by Kurtz et al. (1989) showed a clear pattern of five modes with alternating frequency spacings of 33.3 μHz and 34.6 μHz, with a sixth mode at a problematic spacing of 50.0 μHz (which equals $1.5 \times 33.3\,\mu$Hz) to the high-frequency side. Asymptotic pulsation theory allowed for a frequency spacing of 34 μHz, but HIPPARCOS observations ruled out such a spacing. Theoretical calculations of magnetoacoustic modes in Ap stars by Cunha (2001) predicted *that there should be a previously undetected mode 34 μHz higher than the main* group, with a smaller spacing between it and the highest, problematic frequency. Recently, Kurtz et al. (2002) discovered this predicted frequency from a multi-site photometric campaign on the rapidly oscillating Ap star HR 1217 using the Whole Earth Telescope. With the detection of this new frequency, and support for the new theory, we haves hopes that we may soon be able to probe the magnetic field structure below the surfaces of these stars through their pulsation frequencies – a new application of asteroseismology to probing stellar interiors.

6.2. The new oblique pulsator model

Since I first introduced the oblique pulsator model (Kurtz 1982), it has been the framework within which we have thought about the pulsations in roAp stars. The idea is that the roAp stars pulsate in non-radial modes (mostly dipole modes) with their pulsation axes aligned with their magnetic axes, both of which are inclined to the rotation axes. This idea has worked well, especially giving a good explanation of the amplitude and phase modulation of the pulsation of HR 3831 with rotation (see Kurtz et al. 1997). Now Bigot & Dziembowski (2002) have used a non-perturbative treatment including the dynamical effects of both the strong magnetic field and rotation on the pulsations of roAp stars to predict what the oblique pulsator should look like based on fundamental astrophysical principles. They find a very different picture to that previously accepted. In my simple oblique pulsator model the pulsation modes are usually $\ell = 1, m = 0$ axisymmetric modes with the pulsation axis and the magnetic axis coinciding. In Bigot & Dziembowski's improved oblique pulsator model the picture is much more complex: The oscillation axis is *not* coincident with the magnetic axis, and the pulsation modes are combinations of $\ell = 1, m = -1, 0, +1$ modes with strong non-axisymmetric components. This new model can match the observed amplitude and phase variations well in three roAp stars, HR 3831, α Cir, and HD 6532 (Bigot, private communication). It appears to have excellent prospects and will soon be tested more rigorously against new spectroscopic data.

6.3. New spectroscopic results

For some years measurements of radial velocities on roAp stars led to highly discrepant results from different groups. Baldry et al. (1999) and Baldry & Bedding (2000) were able to show from studies of pulsation velocity as a function of depth in the Hα line that the vertical wavelength of the pulsation modes is short and that there is substantial variation in pulsation velocity as a function of depth in the observable atmospheres ($\tau \leq 1$) of roAp stars. This had been predicted to be the case by Medupe & Kurtz (1998) from photometric multicolour studies. Baldry & Bedding (2000) were unable to reconcile their results for HR 3831 with the standard oblique pulsator model. Tests are now underway to see if the improved model of Bigot & Dziembowski can explain their results.

There is now spectacular confirmation of the vertical resolution of the pulsation in roAp stars in the high resolution spectroscopic work of Kochukhov & Ryabchikova (2001a,b) and Ryabchikova et al. (2002). They show that pulsation velocity is highly variable, depending on the lines studied. Intriguingly, lines of Nd III give the highest pulsation velocities. This is almost certainly an effect of the vertical stratification of the elemental abundances caused by radiative diffusion. Mathys et al. (2002, in preparation) are extending this work with high resolution, high time resolution VLT spectra of an roAp star with magnetically split lines to attempt the first three dimensional model of a stellar magnetic field. Ultimately these studies may lead to, or allow: 3D pulsational mode identification; determination of the depth of the outer radial pulsation node; 3D studies of magnetic field geometry; depth information on diffusive element separation; studies of the interaction of turbulence and pulsation; resolution of the adiabatic and non-adiabatic layers in the outer atmospheres of Ap stars; higher s/n asteroseismic frequency determinations than for broad band photometry; constraints on the abnormal T–τ structure of Ap star atmospheres; studies of the magnetoacoustic outer boundary layer of the pulsation cavity; and abundance analyses in unprecedented detail.

7. Conclusion

HD 101065 has been a star of great controversy. As can be seen from the many recent references given here, it continues to stimulate new astrophysical discoveries, many of which have impacts in other fields of stellar astrophysics. HD 101065 really is a challenge to stellar evolution theory.

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Discussion

Griffin: Is there any evidence at all of radial velocity variations? Has the possibility that HD 101065 has a composite spectrum been completely ruled out?

Hubrig: There is no evidence of radial velocity variations caused by binary motions in the small amount of data that we have.

Kurtz: The peculiarities of HD 101065 are not those of a composite spectrum. None of the people working on it have suggested that, so the character of the spectrum is very different from that of a composite spectrum.

Slysh: What happened to the 160-minute solar oscillations discovered by Kotov in the Crimea?

Kurtz: Although there was an initial confirmation of the 160-min variation in the Sun from the Stanford group, that was later retracted, and no one else has been able to find it. It is now considered to be an instrumental artefact. That is too bad, since the discovery of a g-mode in the Sun would be very exciting – g-modes probe the core conditions, whereas the well-observed p-modes in the Sun are only mildly sensitive to core conditions.