Some recent results for the roAp stars

D. W. Kurtz

Department of Astronomy, University of Cape Town, Rondebosch 7700, South Africa

Abstract. Three topics are discussed: 1) Photometric observations of the rapidly oscillating Ap stars have shown that the pulsation amplitude drops dramatically as a function of wavelength from the blue to the red. A theoretical derivation, plus modelling, indicates that this is because the vertical wavelength of the pulsation mode is short compared to the scale height of the atmosphere; in fact, it indicates that we are seeing a pulsation node in the observable atmosphere. Radial velocity observations, and theoretical calculations now support this. The implication for other research on CP stars is that this can provide observational constraints on the atmospheric structure independent of traditional spectral analysis. 2) Luminosities of roAp stars can be determined from asteroseismology. A recent comparison of such asteroseismic luminosities with HIPPARCOS luminosities is shown. This suggests that roAp stars have lower temperatures and/or smaller radii than previous models have used, or that the magnetic fields in these stars alter the frequency separations. 3) The latest results of our long-term monitoring of the pulsation frequencies in certain roAp stars are discussed. There is a clear cyclic variability to the pulsation cavity, hence the sound speed and/or sound travel time (radius) of these stars. This might be indicative of magnetic cycles at a level that magnetic measurements cannot currently detect, although there is no theoretical support for such an idea.

Key words: Stars: chemically peculiar – Stars: oscillating

1. Introduction: Of snakes and fish

High in the mountains of Angola arises the Kavango river. It flows down across the deep sands of the Kalahari desert in Botswana where it spreads out over 200 km to form the Okavango Swamps - one of the greatest wildlife refuges in Africa. In the Swamps the water meanders through papyrus-choked channels dotted with small desert islands. The sand filters the water to spectacular clarity and purity. Hippos wallow in the main channels; crocodiles are common. On the biggest island, Chief's Island, the "real" Africa of the imagination comes alive: There are elephants, lions, cape buffalo, impala, warthogs, and the "Swamp Specials", Tssessebe and Lechwe - buck specially adapted to swamp living.

Many years ago five friends and I from Cape Town flew deep into the Swamps where we joined three Batswana guides in dugout canoes (called Mekoros) for a 10-day camping trip through the Swamps. We had no one common language

Contrib. Astron. Obs. Skalnaté Pleso **28**, (1998), 264– 271.

between our three guides and the six of us, but amongst us all we spoke enough of a mixture of Tsetswana, Zulu, Xhosa, Fanikalo, English and Afrikaans to communicate. Each night, around the campfire over a shared dinner, we told stories of Africa.

On our first night we six from Cape Town all crawled into warm, goose-down sleeping bags - the latest and best in Western camping gear - snug against the sub-freezing cold of a winter's cold snap. We lay on our groundsheets oriented radially away from the fire with our feet at a safe distance from the sparks which might damage the expensive sleeping bags, and our heads out in the darkness where we could see the spectacular African Sky through the foliage of the bushveld trees. Our three guides had only two blankets for the three of them. One they put down in the sand to sleep on; they then curled up together for warmth and put the other blanket over them. Their heads were almost in the fire, and a stack of wood for stoking the fire during the night was nearby.

Even with the cold we asked them, "Why do you sleep with your heads so close to the fire? Aren't you afraid of being burned by the sparks?" And they explained, "We have lived here all our lives. When a hyena or lion comes out of the night and tries to bites us, we would rather it bit at our feet, than our heads. We will then sit up and hit it with this Panga [machete] to scare it off." "Ha, ha, ha", we laughed, "Listen to our guides trying to scare us city-slickers; well, you can't scare us! We are experienced campers."

As we were trying to go to sleep there came the nearby roar and clatter of a train approaching! How could this be? There are no trains in the Okavango Swamps. Our guides patiently explained that it was a herd of Lechwe fleeing at high speed through the shallows of the swamp, possibly being chased by lions. We fell asleep thinking "there they go - trying to scare us again. Ha Ha."

But then, in the night, the lion roars came. They sounded like they were just beyond the shadows of the firelight - very near to our exposed heads. When you hear lions roar nearby, there is a louder-than-possible, low-frequency, or even sub-sonic, rumble which shakes your insides and turns them to jelly. It says, "Be Frightened!" And you are frightened. When we awoke the next morning all six Capetonians were sleeping with feet away from the fire and heads nearly in it; and that is how we slept the rest of the trip.

One night around the campfire we were exchanging our multiglottal stories. Our guides told us of a giant snake which lives far up near the headwaters of the Kavango River in Angola, a snake so big that it can swallow a Mekoro and its three occupants whole in a single swallow! When I recovered from laughing uproariously at this ridiculous claim, I asked "Have *you* ever seen one of these snakes?" "Wellllll, actualllllly, hmmmm, no we haven't! .... BUT! We have reliable friends who have seen them, and we *know* they are there."

I just poo-pooed the idea. I said it was absurd. There is no snake in the world anywhere near that big.

Then I decided to tell the guides about the Great White Sharks of False Bay near Cape Town. In the Okavango Swamps lives the terrifying and terrific

Tigerfish, with its razor teeth and mouth big enough to take off the hand of an unwary or foolish fisherman. Our guides knew this fish well; they all knew about the huge sea, too, although they hadn't seen it. False Bay is famous for its 5-m Great Whites. So I told our guides that in the sea near Cape Town we have fish so big that it can swallow a person in only two bites!

"Hahahahahahahahahahahahahahahahahahahahahahahahahahaha!!!!!!!!!!!!"

All three guides were rolling on the ground in the sand with tears streaming down their faces. When they finally recovered from laughing uproariously at this ridiculous claim, one looked at me, trying to control involuntary outbreaks of more laughing, and asked "Have *you* ever seen one of these fish?"

I was rather taken aback by the question. I thought about it, then said in all honesty, "Wellllll, actualllllly, hmmmm, no I haven't! .... BUT! I have reliable books! I have seen reliable films! I have reliable friends who have seen them, so I *know* they are there."

They just poo-pooed the idea. They said it was absurd; there is no fish in the world anywhere near that big.

Both "the fish" and "the snake" were undoubtedly-real and obviously-absurd, depending on our preconceptions and viewpoints. In science a major task is to discriminate between the fish and the snake. Either may seem plausible - indeed, may seem probable - and either may turn out to be absurd in the end. Great care and hard work are needed to learn which is true, and which absurd.

2. Atmospheric nodes in rapidly oscillating Ap stars

I was very excited by the announcement by Jaymie Matthews (Matthews *et al.* 1990, 1996) that atmospheric T-τ in roAp stars could be determined from the amplitude of their pulsations at different wavelengths. A problem much discussed for the roAp stars is that of the critical frequency: Many of them seem to pulsate with frequencies so high that their vertical wavelength should be of order of the thickness of the surface boundary layer. In that case the mode should become evanescent; without very large driving there is not enough energy for modes with frequencies above the critical frequency to be maintained as standing waves. This problem is discussed by Gautschy & Saio (1998) and Audard *et al.* (1998). Matthews found that the T-τ gradient in HR 3831 was much steeper than in a normal A star model; this steepness sharpens the surface boundary and increases the critical frequency. It also results in the derivation of smaller overabundances of the rare earths and lanthanides for a given observed line strength.

Because this looked such a fruitful field, Thebe Medupe and I decided to begin a large project to observe many roAp stars in *UBVRI* colours to apply Matthews' technique of inferring T-τ from limb darkening affects on the pulsation amplitude. Instead of modelling this first on a computer, however, we started with a simple analytic derivation of what we expected, making some reasonable first-order assumptions, such as a black body energy distribution and the Wien approximation. To our surprise we found a "snake": We found that limb-darkening is not an important effect (Kurtz & Medupe 1996, Medupe & Kurtz 1997). The pulsation amplitude drops from the blue to the infrared by a factor of two greater than the drop expected for a simple black body. Limb-darkening can only account for about 12.5% of this. Much more sophisticated computer modelling confirms this result.

Medupe and I found that the observed amplitude is expected to be

$$A_{\lambda\mathrm{obs}} = 1.086\,\frac{1}{4}\sqrt{\frac{3}{\pi}}\,\left(\frac{4-\mu_\lambda}{3-\mu_\lambda}\right)\cos\alpha\,\frac{hc}{\lambda k T_0}\,\frac{\Delta T}{T_0} \tag{1}$$

where μ_λ is the wavelength-dependent limb-darkening coefficient, T_0 is the temperature at the atmospheric level appropriate to the wavelength observed, and ΔT is the semi-amplitude of the pulsational polar temperature variation. What is clear is that only a strong dependence on ΔT can match the observations. We suggested that we were seeing over a large fraction of the vertical wavelength of a high-overtone p-mode.

Several studies now give strong support to this suggestion; it looks like it is a "fish". Baldry *et al.* (1998) show radial velocity measures in which an atmospheric node is evident in α Cir. Pulsation phase versus equivalent width diagrams give further support in studies of α Cir (Baldry *et al.* 1997) and γ Equ (Kanaan & Hatzes 1997). Theoretical models are now also producing pulsation nodes in the observable atmospheres of roAp stars. Fig. 1 shows computations kindly provided by Alfred Gautschy which show a temperature node of just the sort hypothesised by Medupe and me in an A star model for a k=27, ℓ=1 mode. We thus have the prospect of a new asteroseismic technique for probing the atmospheres of the most peculiar stars known.

3. Asteroseismic Luminosities

The frequency spacings of 12 roAp stars allow theoretical asteroseismic estimates of their luminosities. These stars are spectroscopically so peculiar that these luminosities have been thought to be the best available. However, severe doubt was thrown on this by Dziembowski & Goode (1996) when they calculated that the magnetic perturbation to the pulsation frequencies is so large (of order tens of μHz) that perturbation theory will not work, and the development of the oblique pulsator model (*e.g.* see Shibahashi & Takata 1993; Takata & Shibahashi 1995) was on shaky ground.

With the new HIPPARCOS parallaxes Matthews *et al.* (1997) have been able to test the asteroseismic luminosities. Figure 2 is from their paper, and it shows good agreement. There are two exceptions. One is HD 166473 which, according to the HIPPARCOS parallax, has a luminosity only 40% that of the Sun. For a main sequence A star this is obviously incorrect, so we conclude

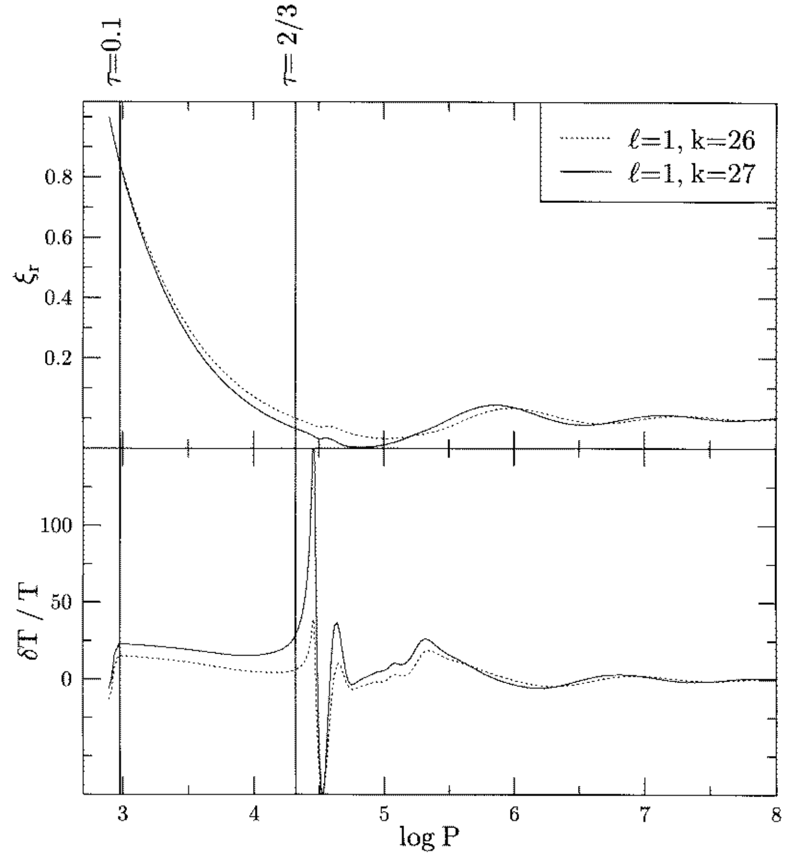

Figure 1. This diagram (courtesy of Alfred Gautschy) shows the sharp variation of $\frac{\Delta T}{T_0}$ in the observed atmosphere for an A star model. This is consistent with our explanation for the sharp drop in observed amplitude as a function of wavelength.

that the HIPPARCOS parallax is wrong. For α Cir the discrepancy is a bigger problem. The asteroseismic parallax is determined from a frequency spacing of 50 μHz (Kurtz *et al.* 1994). The secondary frequencies in this star give a strong indication that 50 μHz is the right value, but they are all of amplitude about 0.2 mmag, so this needs confirmation. In this important case another intensive study of α Cir is called for.

For the remainder it can be seen from Figure 2 that the asteroseismic parallaxes are systematically slightly smaller than the HIPPARCOS parallaxes. That means that the A star models used to predict the luminosity from the frequency separations systematically give too large a luminosity, hence the models are too hot and/or too large in radius, or the magnetic field affects the frequency *spacings*. To get an order of magnitude feel for the discrepancy: If we assume

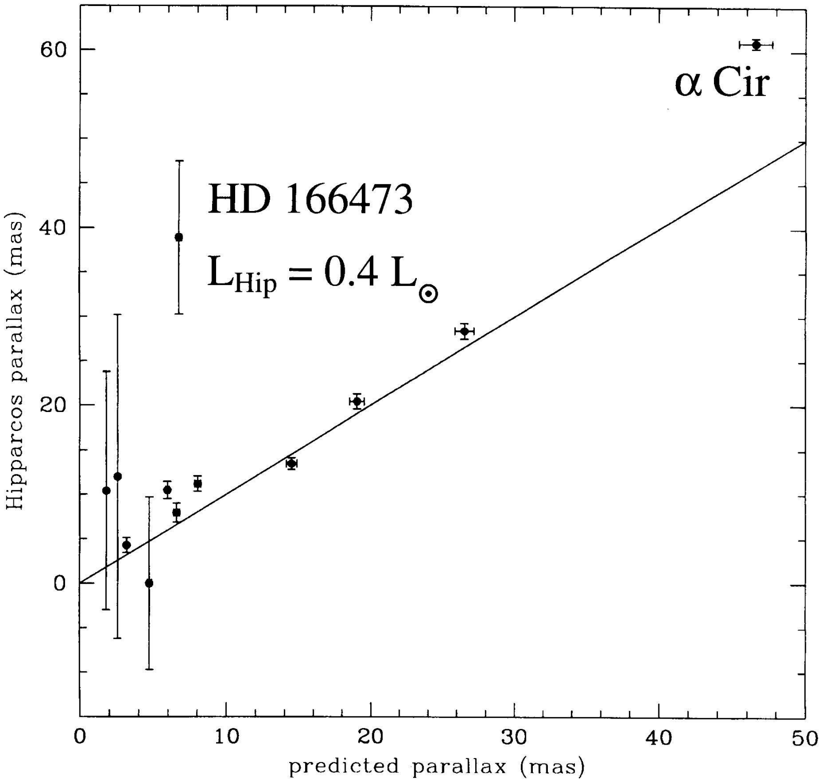

Figure 2. A comparison of the HIPPARCOS and asteroseismic parallaxes. The asteroseismic parallaxes are systematically slightly smaller, and two stars (discussed in the text) stand out. Otherwise, the agreement is remarkably good - indicating that the asteroseismic luminosities are correct.

the radii are correct, then the parallax disagreement indicates that the effective temperatures of the roAp stars are about 1000 K cooler than the A star models from which the asteroseismic luminosities were calculated.

I remind you that the atmospheres of the roAp stars are peculiar to pathological. Luminosities are notoriously difficult to determine, and even the effective temperature can lead to decades-long, acrimonious dispute. In the most extreme case, HD 101065, temperature estimates range from less than 6000 K to over 8000 K! This particular star is arguably the most peculiar in the sky. In its visible spectrum the lead role is played by singly ionised Holmium, with strong supporting roles from Dysprosium, Neodymium, Gadolinium, Samarium, Lanthanum, *etc.* (presuming you know where "*etc.*" leads with that series as a starter). Asteroseismology is providing unique constraints on the structure of the Ap stars.

4. Frequency variability in roAp stars

A group from the University of Cape Town and the South African Astronomical Observatory has been observing roAp stars on a long-term basis for frequency variability for 6 years now. In this on-going project we get one hour of observation of HR 3831 on each possible night over the approximately 8-month season when it is observable. The reason for the emphasis on this star is that it is the best-studied of the roAp stars, it has interesting rotational amplitude and phase variability which we need to remove to study the frequency variability, and the rotational variations are interesting subjects to study in their own right. We also observe for one hour once per week two other roAp stars, HD 134214 and HD 128898 (α Cir). HD 134214 is singly periodic with the shortest known pulsation period for the roAp stars, 5.65 minutes. The very bright star α Cir is nearly circumpolar, and has a single large amplitude pulsation mode with only small amplitudes for other modes and small rotational sidelobes. The frequency variability of HR 3831 is discussed in Kurtz *et al.* (1997); we have not published O-C diagrams for the other two stars recently.

It is clear that there are variations in the pulsation cavities of these stars on time-scales of years. For HR 3831 the variations can be characterised as cyclic with a time-scale of 1.6 years. For α Cir the time-scale is about 6 years, and HD 134214 is harder to characterise. The O-C diagrams can be seen in Kurtz (1998). The variations in O-C cannot be easily explained as Doppler shifts caused by companions; for HR 3831 many companions would need to be hypothesised. In addition, the Ap stars have a very low incidence of binarity, only about 20% are in short period binary systems. So the frequency variations are intrinsic, and they indicate a cyclic variability in the acoustic cavity - this may be anything which affects the sound speed. One speculation we have made is that this indicates a magnetic cycle. The time scale and amplitude of the frequency variations are similar to those which are seen in the sun over the solar cycle. Magnetic fields in Ap stars are thought to be fossil, however, rather than dynamo generated, so this suggestion has not met with much approval; a "snake" is suspected here. Whatever the physical mechanism that is at work, we have a new observational phenomenon which will eventually tell us more of the inner workings of the roAp stars via asteroseismology.

References

Audard, N., Kupka, F., Weiss, W.W., Morel, P., Provost, J.: 1998, in *New eyes to see inside the sun and stars; proceedings of IAU Symp. 185*, eds.: F.-L. Deubner, J. Christensen-Dalsgaard and D.W. Kurtz, Reidel, Dordrecht, in press

Baldry, I. K., Bedding, T.R., Viskum, M., Kjeldsen, H., Frandsen, S.: 1998, in *New eyes to see inside the sun and stars; proceedings of IAU Symp. 185*, eds.: F.-L. Deubner, J. Christensen-Dalsgaard and D.W. Kurtz, Reidel, Dordrecht, in press

Baldry, I.K., Bedding, T. R., Viskum, M., Kjeldsen, H., Frandsen, S.: 1997, *Mon. Not. R. Astron. Soc.* , in press

Dziembowski, W., Goode, P.R.: 1996, *Astrophys. J.* **458**, 338

Gautschy, A., Saio, H.: 1998, in *New eyes to see inside the sun and stars; proceedings of IAU Symp. 185*, eds.: F.-L. Deubner, J. Christensen-Dalsgaard and D.W. Kurtz, Reidel, Dordrecht, in press

Kanaan, A., Hatzes, A.P.: 1997, *Astrophys. J.* , in press

Kurtz, D.W.: 1998, in *New eyes to see inside the sun and stars; proceedings of IAU Symp. 185*, eds.: F.-L. Deubner, J. Christensen-Dalsgaard and D.W. Kurtz, Reidel, Dordrecht, in press

Kurtz, D.W., Medupe, R.: 1996, *Bull, Ast. Soc. India* **24**, 291

Kurtz, D.W., Sullivan, D.J., Martinez, P., Tripe, P.: 1994, *Mon. Not. R. Astron. Soc.* **270**, 674

Kurtz, D. W., Van Wyk, F., Roberts, G., Marang, F., Handler, G., Medupe, R., Kilkenny, D.: 1997, *Mon. Not. R. Astron. Soc.* **287**, 69

Matthews, J.M., Wehlau, W.H., Rice, J., Walker, G.A.H.: 1996, *Astrophys. J.* **459**, 278

Matthews, J.M., Wehlau, W.H., Walker, G.A.H.: 1990, *Astrophys. J., Lett. Ed.* **365**, L81

Matthews, J. M., Kurtz, D. W., Martinez, P.: 1997, in preparation

Medupe, R., Kurtz, D. W.: 1997, Mon. Not. R. Astron. Soc., submitted

Shibahashi, H., Takata, M.: 1993, *Publ. Astron. Soc. Japan* **45**, 617

Takata, M., Shibahashi, H.: 1995, *Publ. Astron. Soc. Japan* **47**, 219