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SHOULD roAp STARS GET WET AND WILL THEY MAKE A SPLASH?

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Abstract. The one attempt (in 1989) to monitor a rapidly oscillating Ap (roAp) star with the WET network was a failure, but for reasons which are now clearly recognized and correctable. In the meantime, roAp research has blossomed to the point that we are better able to extract astrophysical information about these magnetic stars from WET-quality data. The time is ripe for a WET campaign on a multi-mode roAp pulsator.

Key words: stars: chemically peculiar, magnetic, oscillations, asteroseismology

1. CATCHING AN ACOUSTIC WAVE WITHOUT SINKING TO OBLIVION

Fig. 1 illustrates the past and future of roAp stars as WET targets (and also illustrates why I'm an astronomer and not an artist). In this review, I'll describe some of the conditions and safety precautions which are necessary to ensure that a WET campaign on an roAp star will be successful, as well as the scientific rewards that make that effort worthwhile.

One immediate attraction of roAp stars for WET is that they are the only targets other than white dwarfs whose oscillations can be described by asymptotic theory (see Table 1), promising almost immediate diagnostic results from their eigenspectra. At the same time, they represent new territory for WET: high-overtone p-mode pulsation.

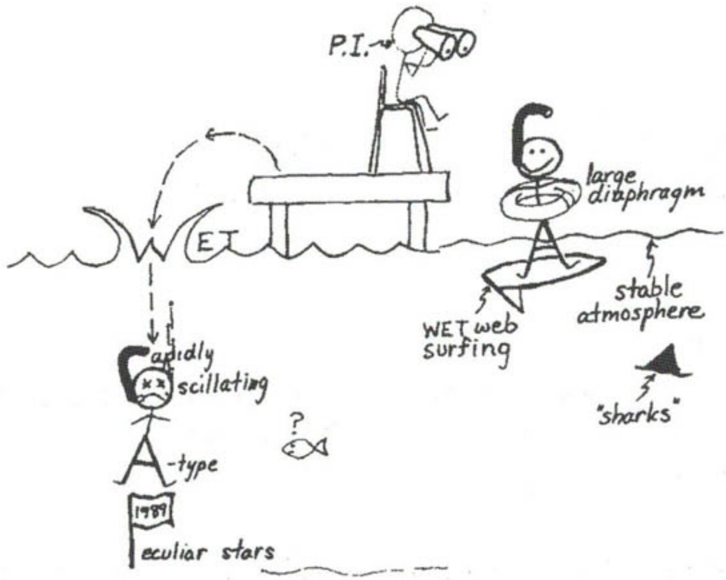

Fig. 1. The harsh realities of roAp stars and WET: Sink or swim! A few basic safety measures (described in Section 7) can save an roAp campaign from the observational "sharks".

The roAp stars vary with short periods (5–15 min) and low amplitudes (ΔB $\sim$ a few mmag; ΔRV $\sim$ a few 100 m/s). A light curve (of relatively large amplitude) for the roAp star HR 1217 is shown in Figure 2. For stars whose masses and radii are similar to δ Scuti stars, such short periods detectable in integrated light indicate high overtone p-modes of low degree ℓ.

Table 1. Pulsational regimes.

Modes	Degree ℓ	Overtone n	Stars	Asymptotic?
g	$\sim$1	$\gg \ell$	white dwarfs	yes
p	$\sim$1	$\sim \ell$	δ Scuti stars	no
g?	$\sim$10	low	γ Doradus stars	no
p	$\sim$1	$\gg \ell$	Sun	yes
			roAp stars	yes

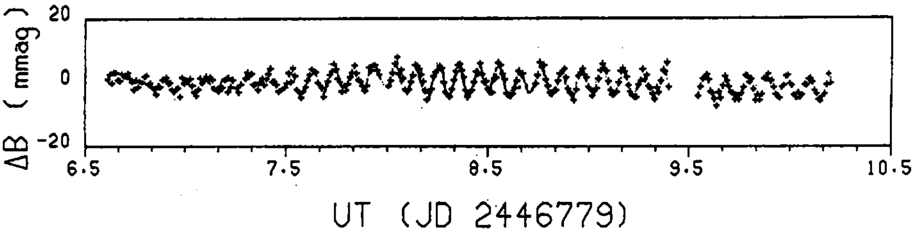

Fig. 2. A light curve of the roAp star HR 1217, obtained by the author from atop Mauna Kea. Note the amplitude modulation, which is due to beating of the multiple frequencies in this star (see Fig. 7).

2. WHY STUDY PECULIAR STARS?

The "p" in roAp means that these stars show strong spectroscopic peculiarities (enhanced Fe-peak elements and rare earths, but no or little helium). The peculiar spectra are believed to be the result of radiative diffusion of ions (and gravitational settling of He) in atmospheres stabilized by intense global magnetic fields (typically $\sim$ 1 kG). Why should other astrophysicists be interested in weird magnetic stars?

Well, for one thing, the weirdness may only be skin deep. For example, a cool Ap star like HD 101065 (Przybylski's star) has a spectrum dominated by strong holmium lines. If the Ho enhancement was not confined to the outer atmosphere, then Przybylski's star would contain almost all the holmium in the known Universe! Diffusion, regulated by the magnetic field lines, has concentrated elements like holmium in a narrow layer of the star. Globally, the star is expected to have relatively normal composition. The p-mode eigenfrequencies of roAp stars are sensitive to the global characteristics of the stars' acoustic cavities, so asteroseismology of roAp stars will give us information about the masses, radii and luminosities of "normal" late-A to early-F stars on or near the main sequence.

The magnetic fields, and possibly the atmospheric peculiarities, do have second-order effects on the eigenspectra, so we can also use these stars as laboratories to test theories of stellar magnetism and chemical diffusion. Gravitational settling of helium is a subtle but significant effect in the Sun, so a better understanding of such a processes through roAp stars may have a broad impact on astrophysics.

3. ASTEROSEISMOLOGY OF roAp STARS

Because the roAp stars pulsate in the high-overtone regime ($n \gg \ell$), their eigenfrequency spectra can be described by Tassoul's (1980, 1990) asymptotic theory. The frequencies are approximated by:

$$\nu_{\ell,n} \simeq \Delta\nu \; (n + \frac{\ell}{2} + \epsilon_1) + \delta_{02} \; [\ell(\ell+1) - \epsilon_2] \; \frac{\Delta\nu^2}{\nu},$$

where

$$\Delta\nu = \left[2 \int_0^R \frac{dr}{c} \right]^{-1}$$

and

$$\delta_{02} \propto \left[\frac{c(R)}{R} - \int_0^R \frac{dc}{dr} \frac{1}{r} dr \right]^{-1} .$$

The terms ϵ_1 and ϵ_2 are small terms which depend on the detailed structure of the star, and c is the local sound speed. $\Delta\nu$ is the inverse of the sound travel time across the diameter of the star, which is proportional to the star's mean density $< \rho > \propto M/R^3$.

To first order, the complete eigenfrequency pattern would be a comb of equally spaced peaks, spaced by $\Delta\nu/2$, such that modes of (ℓ, n) are degenerate with those of $(\ell+2, n-1)$. The overall spacing is very sensitive to the radius of the star. Such a pattern is seen in the solar oscillation spectrum observed in integrated light, and in the multiperiodic roAp stars (see Figs. 3 and 7).

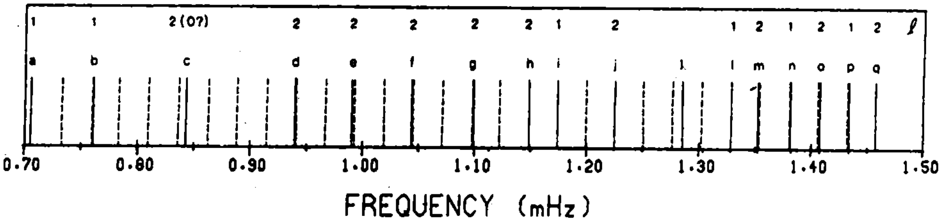

Fig. 3. Schematic of the eigenfrequency spectrum of the roAp star HD 60435, including tentative mode identifications (from Matthews et al. 1987).

In a nonmagnetic star, the degeneracy is broken by the second-order term δ_{02}, which is weighted toward the center of the star by $1/r$ and depends on the sound speed gradient dc/dr there. Since the thermonuclear core is essentially isothermal, especially the convective core of a $2M_{\odot}$ Ap star, the sound speed gradient depends almost solely on the composition gradient. The fine structure in a roAp eigenspectrum is therefore a potential clock of the star's main sequence age, as the central hydrogen supply is gradually exhausted.

There is a wrinkle in the fine structure of an roAp eigenspectrum, introduced by the strong magnetic field. The Lorentz forces are expected to perturb the eigenfrequencies by as much as a few μHz, according to the theory of Dziembowski & Goode (1996). If we can disentangle the various contributions, we have a probe of the internal properties of Ap stars.

The oblique pulsator model

The effect of the global magnetic field on the pulsations is so strong that the nonradial modes are forced to align with the magnetic dipole axis, not the rotation axis. This Oblique Pulsator Model was proposed by Kurtz (see Kurtz 1990) and is a powerful diagnostic tool unique to roAp stars. As the star rotates, its mode rotates obliquely, producing amplitude modulation and phase shifts which can be used to infer the star's rotation period and aspects of its magnetic geometry.

4. HIPPARCOS AND THE roAp STARS

The Hipparcos parallaxes represent one of the first opportunities to test independently the predictions of roAp asteroseismology. We can use the observed fundamental *p*-mode spacings in the eigenspectra of multiperiodic roAp stars to estimate their radii. Combining those results with independent estimates of effective temperature from Strömgren photometry gives luminosities (and distances) which can be compared with the Hipparcos values. Such a comparison is shown in Fig. 4 for twelve roAp stars (Matthews et al. 1998).

The Hipparcos parallax for HD 166473 (available only from the less accurate Tycho catalogue) is clearly wrong, since a parallax of nearly 40 mas implies a luminosity of only $\sim 0.4L_{\odot}$ for a late-A star. Otherwise, there is encouraging agreement between seismology and astrometry. However, a notable discrepancy occurs for α Cir, the

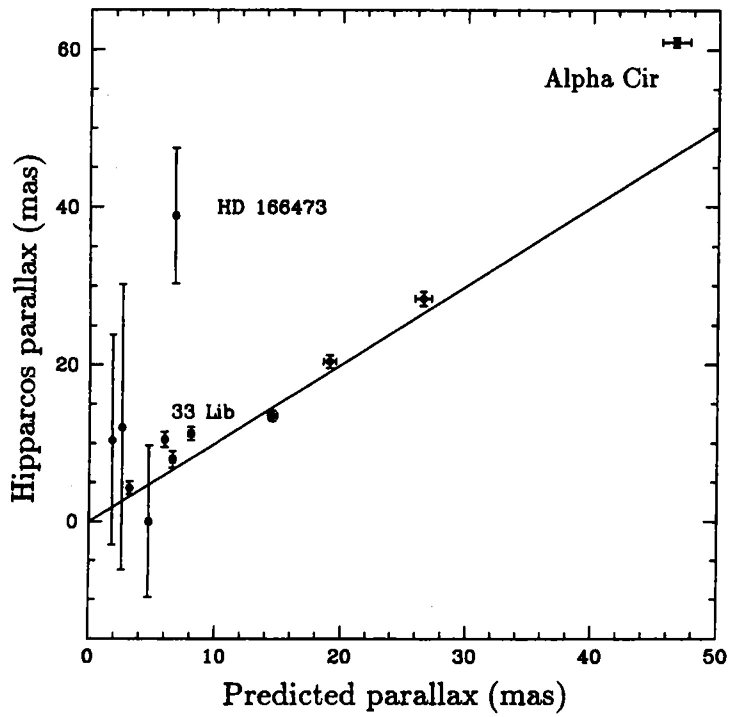

Fig. 4. Hipparcos parallaxes of roAp stars vs. the predicted values based on asteroseismology (from Matthews et al. 1998). The solid line represents 1-to-1 agreement.

brightest known roAp star and the one with the largest parallax in this sample. Also, there is a tendency for the Hipparcos parallaxes to be systematically larger than the seismic predictions. What is the source of these discrepancies?

Are the Ap stars cooler than expected from Hβ photometry? If so, some of them would lie well beyond the cool border of the classical instability strip. This would have important implications for the driving mechanism. The new temperatures could also seriously affect abundance estimates for these stars. *Are Ap stars globally metal-poor* ($Z \gg 0.02$)*?* Perhaps by enriching the upper atmosphere, diffusion has depleted the interior of metals. The lower metallicity would lead to lower Rosseland mean opacity, making solar-abundance models too large for a given $T_{\rm eff}$ and giving higher internal sound speeds. *Are there unrecognized systematic errors in* *the Hipparcos data?* Although this seems unlikely, it cannot be ruled out at this time. *Are the fundamental spacings in error?* This can be tested by obtaining a long baseline of rapid photometry with a high duty cycle. Sound familiar? In other words, a WET campaign.

5. WET MULTICOLOR PHOTOMETRY AS AN ATMOSPHERIC PROBE

Matthews et al. (1990, 1996) demonstrated that the oscillation amplitudes of roAp stars drop off far more steeply with increasing wavelength than expected for a pulsating blackbody (see Fig. 5). They argued that this wavelength dependence could be used as a probe of atmospheric structure with depth. Medupe (1997) suggests that the steep drop is due to a gradient in pulsation amplitude with depth in the outer $\sim$ 2000 km of the star – indicative of a radial node very high in the stellar atmosphere (see Fig. 6). If this idea can be rigorously tested, it would be a powerful tool for mode identification.

The problem is that existing multi-bandpass studies have deliberately focused on monoperiodic roAp stars, to avoid confusion caused by beating between several frequencies and aliasing in the single-site data. However, a global campaign of rapid multicolor photometry on a multiperiodic roAp star would have a spectral window clean enough to measure the amplitudes of many modes and/or overtones at several wavelengths simultaneously and unambiguously.

If the wavelength dependence is due to the location of a node high in the atmosphere, different overtones n of a given (ℓ, m) mode should exhibit different amplitude gradients with depth. If the pulsation amplitude is relatively constant with depth in the outer layers, then there should be little or no sensitivity to the overtone of the mode. The automated filter wheels on the latest generation of WET photometers offer an opportunity to distinguish between these alternatives for the first time.

6. PROPOSED WET TARGETS: HR 1217 AND 33 LIB

I have identified two prime targets for a WET campaign. The first, HR 1217, is a well-known multiperiodic oscillator from which definitive asteroseismic results can be obtained. The second, 33 Lib, is a star which shows multiple frequencies but whose frequency spacing is not well specified from existing data.

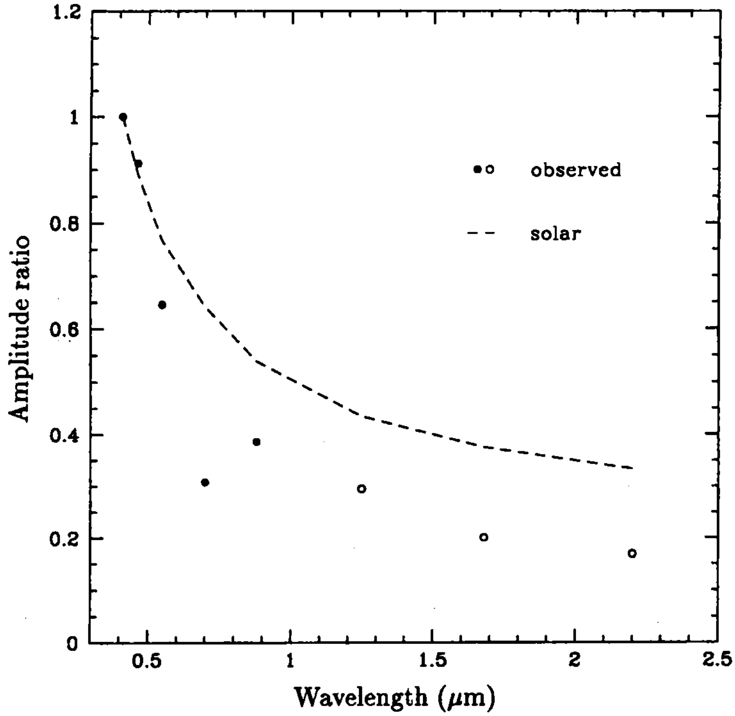

Fig. 5. Observed pulsation amplitude ratios as a function of wavelength for the roAp star HR 3831, compared to what is expected for a pulsating star with a solar-type atmosphere (from Matthews et al. 1996).

6.1. Why get WET?

Duty cycle: A high duty cycle is essential to suppress aliases, especially at ± 2 c/d ($\sim$ 23 μHz) close to the expected observed frequency spacing of $\Delta\nu/2$.
Frequency resolution: A run approximately two weeks long would yield frequency resolution of about 1 μHz, sufficient to resolve second-order and rotational splitting in these stars.
UBVR capability at some sites: Atmospheric and/or dynamical diagnosis as a function of wavelength in a multi-mode pulsator can probe various physical effects in roAp stars (see Section 5 above).

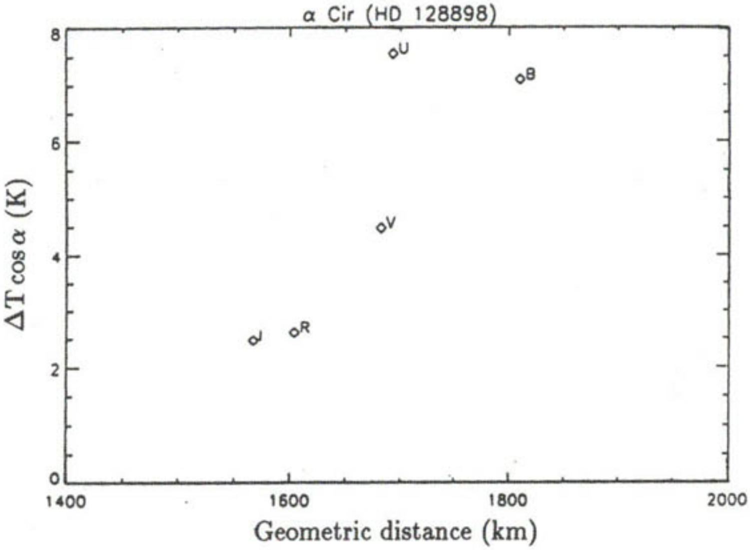

Fig. 6. The predicted temperature amplitude of the dominant dipole mode of the roAp star α Cir as a function of atmospheric depth, inferred from its observed photometric amplitudes seen in five filters (from Medupe 1997).

Table 2. Two roAp target stars.

Star	V	$<\Delta B>$ (mmag)	$\Delta\nu$ (μHz)	α (2000)	δ (2000)	$P_{\rm rot}$ (days)
HR 1217 (HD 24712)	5.99	~6	34 or 68?	$03^{\rm h}55^{\rm m}16^{\rm s}$	–12°06′	12.46
33 Lib (HD 137939)	6.67	~3	40?	$15^{\rm h}29^{\rm m}35^{\rm s}$	–17°26′	?

6.2. Science returns

1. *Unambiguous measurement of $\Delta\nu$ to better than 1 μHz.* This will provide a well-defined radius estimate, allowing us to make a comparison with the luminosity from the Hipparcos parallax (see Section 4). Even if the eigenmode spectrum is incomplete, we can use earlier frequency analyses (e.g., Kurtz 1991 for 33 Lib; Kurtz, Matthews et al. 1989 for HR 1217) to "fill the gaps". This was successful for various campaigns on the roAp star γ Equ. In the

case of HR 1217, one of the six principal frequencies observed by Kurtz, Matthews et al. (1989) is offset by $1.5\times$ the spacing of the other five frequencies (see Figure 7). This would suggest a value of $\Delta\nu \sim 34$ μHz, which makes HR 1217 uncomfortably evolved and in disagreement with the Hipparcos data on this star. New photometry will help confirm/deny the true frequency spacing.

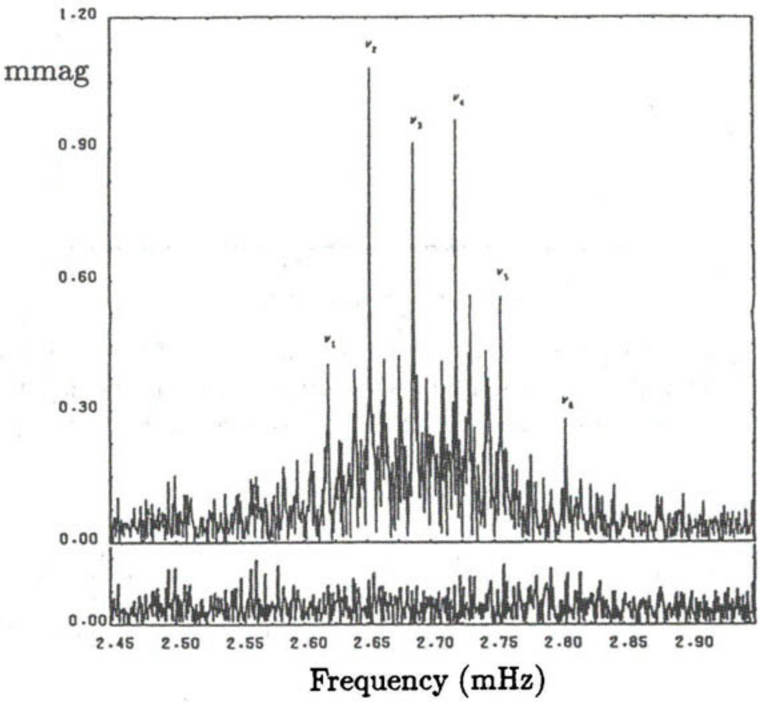

Fig. 7. Fourier amplitude spectrum of HR 1217 (*top*), based on the WET-like multi-site campaign of Kurtz, Matthews et al. (1989), and the residuals (*bottom*) after the six labelled frequencies and rotational sidelobes have been removed. The sixth frequency is difficult to interpret in terms of the p-mode spacings.

2. *Measurement of rotation frequency* $\Omega_{\rm rot}$*:* It should be possible to resolve the multiplet splitting due to rotation if the period is less than about 2 weeks. The number of sidelobes will also identify the mode independently; a triplet meaning $\ell = 1$, a quintuplet, $\ell = 2$.

3. *Second-order splitting of modes* (δ_{02})*:* These can be compared to the magnetic perturbation theory of Dziembowski & Goode (1996) to estimate internal field strengths. We can also use the models of

Audard et al. (1995) to test sensitivity to the convective core size by comparing models with and without core overshooting. This effect is of order 1 μHz, so adjoining single-site photometry may be necessary to extend the WET campaign baseline for this.

4. *Harmonics and nonlinear terms?* There is evidence of nonlinearity in Kurtz's (1991) data for 33 Lib. If frequencies exist above the acoustic cutoff for a "normal" atmosphere, these could be used to constrain the atmospheric temperature and composition profile (see Gautschy 1997; Audard et al. 1998).

5. *Frequency modulation?* There is also evidence for this in 33 Lib (Kurtz 1991). If the modulation is (quasi)periodic, this could indicate binarity or a stellar activity cycle. A monotonous value of $\dot{P}$ could be due to evolutionary effects (Heller & Kawaler 1988).

6. *Atmospheric structure and/or mode dynamics:* Measurement of the amplitude vs. wavelength for more than one mode or overtone is a diagnostic of either a radial node high in the atmosphere, nonadiabatic effects, or temperature and abundance gradients.

7. HOW TO AVOID PAST MISTAKES

The observing strategy for the bright, low-amplitude roAp stars is quite different than for the faint, higher-amplitude white dwarfs first observed with WET.

First, a *large diaphragm* ($\geq$ 20 arcsec in diameter) is recommended to avoid variable light losses from the edge of the seeing disk as the star wanders slightly due to small guiding errors of the telescope. The stars are bright enough that the sky background passing through the large diaphragm is not a serious problem, even in bright moonlight. However, when searching for oscillations at a level of 0.0001 mag, light losses from the edge of a smaller diaphragm can be disastrous.

Because the stars are bright, photon-counting statistics is generally not a problem, so it is not necessary to perform white-light photometry. A *blue filter* is preferable, since the oscillations of some roAp stars show strong phase differences with wavelength (e.g., Weiss 1986) and decreasing amplitude at longer wavelengths. Admitting a broad range of wavelengths will tend to dilute the subtle oscillation signal. Multi-filter data also have a diagnostic advantage, as described in Section 5.

Real-time communication between the P.I. and observers is essential to ensure the observing standards are being met at all sites. The WET Web site and Internet connections are already in place to ensure this will take place.

It is also important to include as many *large-aperture telescopes* as possible in the campaign. This is not for photon counting rates, but to suppress atmospheric scintillation, which is the dominant photometric noise source in roAp data from good observing sites. While it may seem counter-intuitive to ask for time on a 2 to 4 m telescope for photometry of a 6th mag star, there are strong technical and scientific arguments for doing so.

With guidelines like these, and clear lines of communication between everyone involved, there is every reason to expect that a WET campaign on an roAp star would produce excellent data leading to cutting-edge science.

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