RAPID OSCILLATIONS OF CP2-STARS

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1. INTRODUCTION

With the announcement in 1978 (Kurtz, 1978) of short periodic photometric variations of HD 101065, the first member of a subgroup of CP2 stars was found. This gained attention due to the possibility of applying the methods of stellar seismology to late A to early F type stars. However, the extremely low photometric amplitude of these stars, which is typically few millimagnitudes in B, and the short periods, ranging from few minutes to about 15 minutes, make these stars difficult to discover and a considerable amount of telescope time is required to accumulate sufficient data for a reliable analysis of the frequency spectrum. As a consequence aliasing imposes serious problems. Synchronous observations from observatories well separated in longitude could overcome this dilemma, and have indeed proven to be sucessful (Kurtz and Seeman, 1983; Kurtz and Bàlona, 1984; Kurtz, Schneider and Weiss, 1985; Kurtz and Kreidl, 1985).

Presently, only speculations exist concerning the excitation mechanism for the oscillations. Insights in the stellar structure and in the magnetic field characteristics of the stellar interior are posssible from modelling rapidly oscillating CP2 stars.

Two remarks may be allowed in this context. First, as it is evident from the publications, it is possible even for small telescopes in the 0.5 m to 1 m class to contribute significantly to new astrophysical aspects. Second, as the history of the detection of rapidly oscillating CP2 stars demonstrates, one always should be open to the unexpected (and a word to the observers: do not trust

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theoretical results too much). In the case of HD 101065, indications for rapid photometric variations were already found in 1975 by Heck and Manfroid (Heck et al., 1976), but not followed up by the authors. For HD 24712, Weiss (1980) found some evidence for a variability in the order of 1 hour, but these observations were planned to detect periods expected for radial modes. These modes were the only ones considered possible for this group of stars by theoreticians, who, in any case, thought that main sequence stars in this temperature range would be dynamically stable. The spurious observations can be explained as interference of the pulsation and data taking frequency.

2. THE OBLIQUE PULSATOR MODEL

Not only did Don Kurtz discover the group of rapidly oscillating CP2 stars, he also provided the first and hitherto most successful model to explain the complex frequency pattern (Kurtz, 1982). According to this model, non-radial p-modes of low degree (i.e. a small l) are aligned to the magnetic field in such a way that the pulsation and magnetic field axes coincide. Generally, the magnetic field axis is inclined to the rotation axis, which gives rise to an amplitude-modulation of the pulsation light curve.

Some difficulties immediately arise for the theoretical understanding, among which are the questions why only very few modes (compared to the sun, e.g.) are excited and how the precession of the standing wave pattern about the axis of rotation can be suppressed. Dolez and Gough (1982) deal with this problem and they present arguments, based on a very simple model, that nonradial standing modes grow preferentially with a particular orientation to the magnetic field and decay after precession has destroyed the initial alignment. Their calculations give evidence that the required growth (decay) time of aligned (misaligned) modes is indeed short relative to the rate of precession, namely on a timescale of only few hours, depending only on the relative orientation to the magnetic field.

The most elaborated discussion of the oblique pulsator model is published by Dziembowski and Goode (1985). These authors criticize the model of Dolez and Gough (1982, op.cit.) because it does not account for the long-term coherence of the oscillation frequencies observed for most of the rapidly oscillating CP2 stars (exceptions might be HD 60435 and HD 201601). In their opinion, Dolez and Gough, as well as Mathys (1985, see later in this review), introduce unnecessary complications. Dziembowski and Goode (1985, op.cit.) treat the problem of a non-axisymmetric perturbation of the pulsation due to a rotating oblique magnetic field in a self-consistent way. They argue that magnetic field effects may dominate those of rotation.

$$\omega^{rot}/\,\omega_o \cong m\cdot C(l,m)\cdot\Omega/\omega_o \cong 10^{-2}\cdot\Omega/\omega_o \cong 10^{-5} \div 10^{-6} \qquad (1)$$

with ω_o being the unperturbed oscillation frequency, ω^{rot} the

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frequency splitting due to advection, C(l,m) the rotational splitting constant depending on the internal structure of the star and Ω its rotation frequency. Because these rotation effects will be quite small for oscillating CP2 stars the dominance of magnetic effects even can hold true for a fairly small ratio of magnetic pressure, p^{mag}, to the gas pressure, p, (Dziembowski and Goode, 1984) and thus for fairly weak magnetic fields.

$$\langle \omega^{mag}/\omega_o \rangle \cong \langle p^{mag}/p \rangle \qquad (2)$$

Dziembowski and Goode's model reduces to Kurtz's simple oblique pulsator, if the effect of magnetism fully dominates that of rotation. An increasing ratio of rotational to magnetic frequency splitting results in an increasing contamination from other spherical harmonics and thus in a reduced degree of symmetry in this mode relative to the magnetic field axis and finally in an increasing deexcitation. The measure for the importance of rotation is the (observable) amplitude ratio of the prograde and retrograde frequencies, which have equal amplitudes in Kurtz's model. With the assumption of an approximately rigid rotation the authors even can estimate the strength of the magnetic field in the stellar interior.

Based on Kurtz's (1982) frequencies for HD 24712 an impressive numerical example is given by Dziembowski and Goode to illustrate the general properties of the model. However, the significance of the results largely depends on a correct identification of the pulsation modes.

As already mentioned, Mathys (1985, op.cit.) investigated in his so-called spotted pulsator model another possibility to explain some features which are typical of the frequency spectra observed for rapidly oscillating CP2 stars. He assumes aligned rotation and pulsation axes and explains the amplitude modulation of the oscillations due to inhomogeneities of the surface with a cylindrical symmetry about the magnetic-field axis. To account for the magnitude of the observed effects, Mathys also has to assume an inhomogeneous distribution of the ratio of the flux to radius variations and of the phase lag between these parameters. The frequency spacing in his model consequently is exactly equal to the stellar rotation frequency, which is indeed observed to a high degree of significance. The unequal amplitudes of the outer frequency peaks, observed for example in HD 83368, are a natural consequence of the model. One obviously can criticize that the number of introduced free parameters, most of which are presently unmeasurable, is too large to allow a conclusive test of the spotted pulsator model.

While Dziembowski and Goode have demonstrated that the heuristically established oblique pulsator model can be consistently derived and generalized, Shibahashi and Saio (1985) calculate frequencies for different realistic stellar models in analogy to the solar oscillations. They neglect, however, the effect of rotation and the magnetic field on the stellar equilibrium and atmospheric structure. In particular the authors study the influence of the T-τ relation, of an eventual helium depletion due to diffusion, and of the initial chemical composition on the eigenfrequencies for equilibrium models in the range of 1.3 to 2.4 solar masses.

It turns out that the ratio of the critical frequency above which no standing wave is stable, f(crit), and the characteristic frequency,

$$f_o \equiv 1/(2\cdot\int_o^R (1/c)dr) \cong (GM/R^3)^{1/2} \qquad (3)$$

is quite sensitive to T_{eff}/T_{surf} and thus to the particular peculiarities of CP2 stars. For frequencies higher than the critical frequency the surface becomes transparent and wavepatterns cannot be maintained stable. Shibahashi and Saio show that

- o $f(crit)/f_o$ is almost independent of the stellar mass and
- o only very weakly dependent on the stellar evolution.
- o $f(crit) - f_o$ keeps the homologous relation to the standard models over a large variety of chemically inhomogeneous envelopes and for models with different initial chemical composition.

With the relation $f_o/(GM/R^3)^{1/2} \cong 0.20$, derived by Gabriel et al. (1984) for main sequence models in the range of 1.5 to 2 solar masses, it is possible to estimate the radial order of the highest overtone, n(crit), to be about 30. It is worth mentioning that the ratio of 0.2 is very similar to the solar value of 0.216 which illustrates that many oscillation parameters scale indeed homologuous for a large range of different stellar models.

Shibahashi and Saio also discuss the problem of the rotational splitting of frequencies and calculate the coefficient C(n,l). This coefficient decreases with increasing n and is about 0.001 for l = 1 and n = 40, which is comparable with the upper limit determined by Kurtz and Seeman (1983, op.cit.) for HD 24712. A consequence of this small value is a lifetime of the wavepattern of more than 1000 days for a rotation period of the order of few days. This lifetime would be considerably longer than the growth and decay time for oscillations excited by the kappa-mechanism (Dolez and Gough, 1982, op.cit.) as well as by magnetic overstability. Shibahashi (1983) and Cox (1984) calculated the characteristic timescale for the latter case to be of the order of weeks or months.

3. THE RIDDLE OF THE EXCITATION MECHANISM

Overstable magnetic convection can be understood as convective instability in a thin superadiabatic zone close to the stellar surface in the presence of a moderate magnetic field. A rising mass-element will be hotter and less dense than the environment and thus tend to continue to move upward. Magnetic lines of force which are "frozen" in such a plasma tend to inhibit this upward motion and are responsible for the restoring force. The heat exchange in a superadiabatic layer results in a motion of the mass element which is faster on the way back to the origin than as it was for the upward direction. In an appropriate environment the oscillation amplitude will grow steadily, resulting in so-called overstable oscillations.

Another mechanism is related to the resonant excitation of large-scale non-radial oscillations by turbulent convection and is considered by Dolginov and Muslimov (1984), but not explicitly applied to CP2 stars.

Dolez and Gough (1982, op.cit.) investigate the effectiveness of the kappa-mechanism for driving non-radial oscillations. Their attempt to model a typical CP2 star is based on piecing together segments of two spherical symmetric stellar models which represent the magnetic poles and the magnetic equator, respectively. Growth and decay of modes is primarily determined by the outer stellar layers where the eigenfunctions can be taken in first order to be insensitive to l. Based on the argument that in these layers all low-degree p-modes with similar frequencies look similar, Gough and Dolez restrict their calculations to radial oscillations and assume that the calculated growth and decay times are also valid for the non-radial modes under investigation. Linear nonadiabatic radial pulsations were computed by the authors taking convective perturbation of the heat flux into account. They find a sharp maximum for the growth rate of $n = 15$, corresponding to a period of about 11 min, and conclude that some modes might be therefore self-exciting. The excitation of only very few modes in pulsating CP2 stars would find a simple explanation, if the most rapidly growing mode suppresses the other unstable modes.

Presently, nothing decisive can be said about the excitation mechanism working in real CP2 stars. The mechanism of magnetic overstability is related to magnetic inhibition of convection in sunspots (Bierman, 1941), however, it would mean accepting a new pulsation mechanism in an area of the HR-Diagram where already another mechnism (kappa-mechanism) is effective.

4. THE LIST OF RAPIDLY OSCILLATING CP2 STARS

Currently, eleven rapidly oscillating CP2 stars are known. In Table 1 a list of these stars is given together with references concerning the main parameters. It is obvious that for most of the

HD HR	m (V) (28,29)	H_{eff} in gauss	Puls. period (min) amplitude (mmag)	Rotation period (days)	References
6532	8.5	-	6.922 to 6.956 0.55 to 1.01	-	1
24712 1217	6.0	+300 to +1200 (18)	5.966 to 6.361 0.44 to 2.13	12.46	2, 3, 4, 17
60435	8.9	-	3.994 to 15.141 0.5 to 6	-	5
83368 3831	6.2	-700 to +700 (19)	5.819 to 11.705 0.18 to 2.14	2.85 (1.426)	4, 17
101065	8.0	-2200 (20)	6.070 to 12.140 0.26 to 5.40	-	6, 7, 8, 9
128898 5463	3.2	-300 (var) (21,22,23)	6.825 to 6.832 0.38 to 1.91	1.004 to 12	10, 16, 17
134214	7.5	-	5.650 3.23	-	14
137949	6.7	+1400 to +1800 (24)	8.272 1.39	7.194 to 23.26	4, 17
201601 8097	4.7	+500 to -800 (25,26,27)	12.448 0.86	312 to 72^{yr}	11, 15, 17
203932	8.8	-	5.942 0.66	-	12
217522	7.5	-	13.716 2	-	13

Table 1: List of rapidly pulsating CP2 stars. Whenever several pulsation periods were known, the smallest and largest period is given in minutes and the smallest and largest pulsation amplitude is given in units of 1/1000 of a magnitude (mmag). If more than one rotation period is given, several periods within the interval presented in Table 1 are discussed in the literature.

stars many parameters which are relevant for modeling the pulsation modes are unknown and still much has to be done by the observers.

The cross references for table 1 are the following: (1) Kurtz, Kreidl 1895; (2) Kurtz, Seeman 1983; (3) Kurtz, Schneider, Weiss 1985; (4) Kurtz 1982; (5) Matthews, Kurtz, Wehlau 1985; (6) Kurtz 1981; (7) Kurtz 1980; (8) Kurtz, Wegner 1979; (9) Weiss, Kreidl 1980; (10) Kurtz, Balona 1984; (11) Kurtz 1983a; (12) Kurtz 1984; (13) Kurtz 1983b; (14) Kreidl 1984a; (15) Weiss 1983; (16) Weiss, Schneider 1984; (17) Catalano, Renson 1984; (18) Preston 1972; (19) Thompson 1983; (20) Wolff, Hagen 1976; (21) Wood, Campusano 1975; (22) Borra, Landstreet 1975; (23) Borra, Landstreet 1980; (24) Wolff 1975; (25) Babcock 1958; (26) Bonsack, Pilachowski 1974; (27) Scholz 1979; (28) Vogt, Foundez 1979; (29) Blanco et al. 1970.

The references listed above contain to the best of our knowledge all publications related to observations of rapidly pulsating CP2 stars. In another review presented by D. Kurtz (1985) the observational data are nicely summarized and the reader is referred to it. In the following section we will try to pin down some observational and theoretical problems for which a solution seems to be crucial for a further improvement of our understanding of the phenomenon of rapidly pulsating CP2 stars.

5. SOME OF THE PROBLEMS

5.1 The photometric mode identification:

Following a recipe which seems to work quite successfully for Delta Scuti stars and Cepheids (Balona and Stobie, 1979), the first attempts of a mode identification were based on a discussion of the phase shift between light and color variations. Balona (1981) included gravity effects and has shown their importance for high frequency oscillations. Stamford and Watson (1981) included in addition pressure effects. Within the uncertainties in the assumptions, the phase lag between light and radial velocity variations yield reasonable mode identifications for HD 128898 (Weiss and Schneider, 1984), if neither gravity nor pressure effects were taken into account. However, including the gravity effect results in a phase shift of more than 100° for l = 0, 1 or 2, instead of 13° to 20° which were observed (Kurtz and Balona, 1984). On the other hand, the gravity effect is required to account for the observed phase shift of 63° for HD 83368 and for l = 1. In the case of HD 101065 with an observed phase shift of 39° (Kurtz, 1980) a value of 16° would be predicted for l = 2 including the gravity effect. This difference, however, is larger than the observational uncertainties in the phase shift.

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Further evidence for a more complicated situation, hitherto unpublished, results from an observing run at ESO, La Silla. In December 1983, H. Schneider used the Walraven photometer attached to the Dutch 90cm telescope and observed HD 24712 and HD 83368. A full description of the instrument and reduction technique can be found in Weiss and Schneider (1984, op. cit.). We intended to use the wavelength dependence of the phase shifts relative to the Walraven-V channel to investigate whether or not certain frequencies originate from the same mode (Figure 1).

Within the errors for the phase determination, which are of the order of 10° to 15°, we find no systematic differences for the wavelength dependence of the phases for HD 24712. The frequency numbering corresponds to Kurtz (1982). A comparison with a similar figure obtained by Weiss and Schneider for HD 128898 yields a clearly different trend with wavelengths. The phase shifts for HD 83368 are again different. Basically, all five frequencies show a similar wavelength trend, except for the U-channel which contains the Balmer jump. For this wavelength region the low frequency triplet (f1 to f3) behaves differently to the high frequency triplet of which only f4 and f5 could be reasonably well detected in our data. This difference can be interpreted as a possible indication that the latter triplet is not just an overtone of the low frequency triplet.

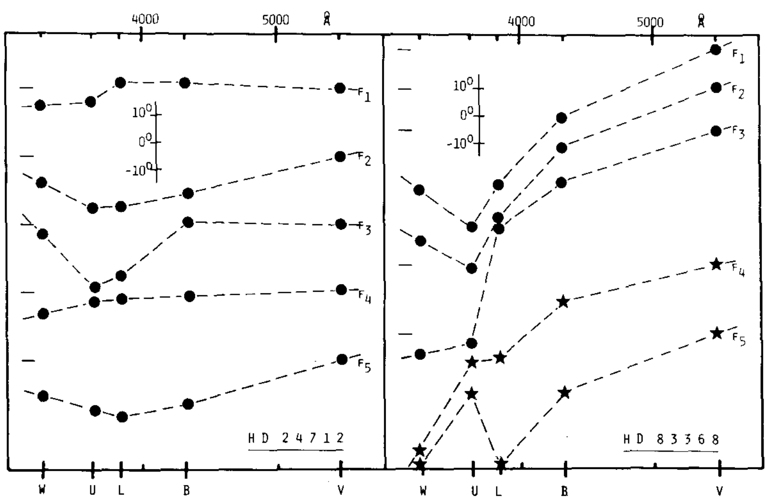

Figure 1: Phase shifts relative to Walraven - V.

Furthermore, we found that the wavelength characteristics determined for HD 128898 in May 1984 with the 4-channel Stroemgren photometer attached to the 50cm Danish telescope at La Silla, ESO, looked markedly different to what we have published earlier (Weiss and Schneider, 1984, op.cit.). Presently, we are unable to explain these observations conclusively and to use phase shifts for a mode identification based on the linearized theory.

5.2 The spectroscopic mode identification:

The negative results for a mode identification with photometric techniques motivated Schneider and Weiss (1986) to try spectral line profile variations for this purpose. They observed HD 128898 and HD 201601 with the ESO Coude-Echelle spectrometer at the 1.5m Coude-Auxiliary telescope and the Reticon detector in Chile. In Figure 2 an example is given of HD 128898 for the Ca I line profile at 6471.8 Å.

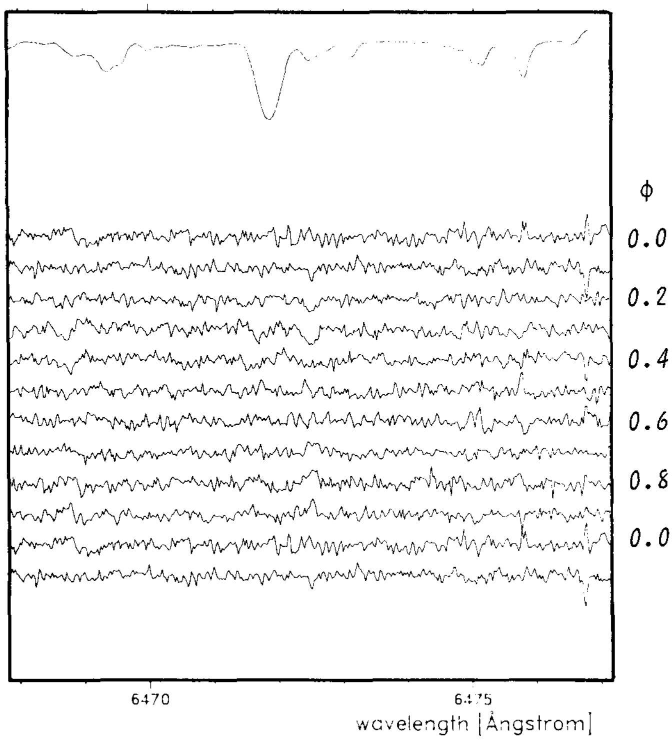

Figure 2: HD 128898 mean Ca I (6471.8 Å) lineprofile and residuals for pulsation phases 0.0 to 1.1 .

A total of 306 individual spectra were coadded according to the photometrically determined pulsation phase, binned in intervals of 0.1 in phase. The upper trace in Figure 2 shows the mean of all spectra, and below the residuals relative to this mean spectrum are plotted which were calculated for individual phase bins. The contemporaneously determined photometric amplitude was 3 mmag in Stromgren-u. No profile variations larger than 0.5% are present. A similar negative result can be reported for HD 201601. The latter star was also observed spectroscopically by Kreidl and Odell (1985) with the same negative result.

Synthetic line profiles for non radially pulsating CP2 stars are discussed by Odell and Kreidl (1984) and by Baade and Weiss (1986, abstract in this volume).

In any case, a correct mode identification is essential for a reliable discussion of the pulsation frequency spectrum and hence for a determination of several astrophysical parameters.

5.3 Temperature range for rapidly oscillating CP2 stars:

The hot and cool limits for rapidly oscillating CP2 stars are an important parameter for isolating a possible excitation mechanism. A coincidence of these limits with the instability strip known from Delta Scuti stars would lend some support to the kappa-mechanism. Superadiabaticity, on the other hand, decreases for the hotter CP2 stars and hence will be unfavorable for magnetic overstability (Shibahashi, 1983, op.cit.). In this context, the detection of a rapid variability in the slightly metal-deficient (!!!) F3Vp star HD 119288 (Matthews and Wehlau, 1985) is extremely interesting. Attempts to measure a possible magnetic field for this star are very much encouraged. The lack of any measureable field in this star would obscure things considerably.

Realizing the importance of observationally well defined temperature limits for rapidly oscillating CP2 stars, several surveys have regularly included also hotter stars. Such surveys were performed by Don Kurtz mainly at South Africa, by H. Schneider and W. Weiss mainly at ESO, La Silla, Chile, and at the Mauna Kea Observatory, Hawaii, by Tobias J. Kreidl at Lowell Observatoru, and by Jaymie M. Matthews and William H. Wehlau in Chile and Canada). However, none of these surveys verified short periodic variations reported by other observers (e.g. for 21 Com or HD 224801), nor did they detect such variations in hotter stars. These negative results do not neccessarily mean that hotter CP2 stars are pulsationally stable, as pulsation might be a transient phenomenon, and the amount of observing time might not have been sufficient. If hotter stars pulsate by some yet unknown reasons in systematically higher orders, then the already small photometric amplitude would be even smaller. These are only some of the most obvious explanations for the negative results.

5.4 $T - \tau$ relation and the frequency spectrum:

Shibahashi and Saio show that the critical frequency strongly depends on the $T - \tau$ relation. The most hitherto consistent and complete investigation of the atmosphere of CP stars is published by Muthsam (1979a,b). His models S76 and S77 give a ratio for $T_{eff}/T(\tau = 2.10^{-5})$ of 1.5 which is the value for the model series B in Shibahashi and Saio (1985, op.cit.). However, as these authors write, an even larger ratio of about 2.5 would be required to explain the observed frequencies in HD 24712 which are clearly higher than the critical frequency. Muthsam's model atmosphere, on the other hand, does not take magnetic pressure effects into account (nor do Shibahashi and Saio) and the model might be therefore still inadequate, despite its complexity. In addition, various theoretical models do not correctly reproduce the observed frequency-spacings in the cases of HD 24712 and HD 60435.

CP2 stars possibly are another example, like our sun, of contradicting results derived by astroseismology and by classical model calculations.

5.5 Long time stability of the frequency spectrum:

HD 60435 is characterized by the most complex frequency spectrum, including the highest and lowest frequencies yet observed for rapidly oscillating CP2 stars (Matthews et al, 1985, op.cit.). This star seems to provide a fairly strong case for transient oscillations, since well determined frequencies in one night can not be detected in another night. Considerably more data are necessary to prove this claim and for a reliable mode identification. As in HD 83368, resonant coupling of modes seems to be effective. For HD 60453 Matthews et al. speculate that an overtone of a very weak radial mode might excite the oscillations near 1.1 mHz. HD 201601 might be another example for transient oscillations. Although a rotation period of many years is discussed in the literature the pulsation amplitude changes much more rapidly. However, excellent photometric conditions are required to detect the oscillation which rarely exceeds the 1 mmag limit (Kurtz, 1983a; Weiss, 1983).

Dappen and Perdang (1985) investigate the theoretical implications for a non-linear, non-radial adiabatic mode coupling and raise the question for conditions under which chaotic oscillations become effective.

5.6 The group of low-harmonic pulsating CP2 stars:

It would be obvious to discuss in the context of this review the properties of the group of low-harmonic pulsating CP2 stars. Unfortunately, for most of the proposed members of this group contradicting observational evidence are found in the literature. A critical discussion of the relevant references clearly would be beyond the scope of this paper. We refer to a review presented at the Workshop on Rapid Variability of Early-Type Stars (Weiss, 1983) held at Hvar and to the references given herein. Furthermore, as discussed during this meeting, a survey program recently was finished by a group of astronomers headed by W. Schoeneich and the results are currently prepared for publication. Another group, coordinated by N. Polosukhina, investigated selected CP2 stars like 53 Cam (Burnashev et al., 1983), and they announced additional publications. T. Kreidl (1984b to 1984d) is still continuing his promising survey at Lowell Observatory. Polosukhina and Weiss currently are preparing a hopefully complete bibliography of publications related to low-harmonic pulsating CP2 stars.

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