Focal Points in Contemporary β Cephei Star Research

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Abstract

We review the latest results on searches for new β Cephei stars, and discuss the most recent findings from high-resolution spectrographic observations. The implications of analyses of archival data and new observations in the light of period changes, binarity, and aspects of the evolutionary state of β Cephei stars are evaluated.

1. Introduction

Attempts to find a pulsation mechanism for β Cephei stars went on since decades, and the problem of the unknown driving mechanism gradually grew to become a real challenge for stellar oscillation theory. The problem may have been solved now: the application to the β Cephei star problem of new opacity tables published by Iglesias and Rogers (1991a,b) (see Cox and Morgan 1990, Kiriakidis et al. 1992, Moskalik and Dziembowski 1992) leads to the understanding that the driving is caused by the usual κ mechanism acting in a zone with temperature near 200,000 K where there is an opacity bump. The pulsations are extremely sensitive to metal abundance. The theoretical instability strip agrees well with the observational one, and extends well above the β Cephei star region in the H-R diagram, which suggests that the same mechanism may be responsible for oscillations observed in Luminous Blue Variables (Moskalik and Dziembowski 1992, see also Sterken 1988).

For many years, the justification to carry out a specific topic of observational β Cephei star research was extracted from the state of affairs that no adequate pulsation mechanism was at hand. Now that a plausible mechanism seems to have been found, one might argue that there are much less reasons to carry on observational studies of β Cephei stars. This opinion, however, is unfounded, as is shown in the present paper.

First of all, the new pulsation mechanism needs to be tested observationally, and several papers of the 1991-1992 period deal with such measurements (see also Balona's contribution to this conference). In addition, high-precision spectrographic and photometric observations (at high time-resolution) of selected "classical" β Cephei stars have revealed hitherto unknown facts and have opened up new horizons for observational research on β Cephei stars: the last two years disclosed an outstanding element

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in observational studies of β Cephei stars, viz. the large research effort put into the observation of a couple of **bright** β Cephei stars. The stars concerned are BW Vul, σ Sco and β Cephei and were the subject of several independent investigations.

2. Searches for β Cep stars

Monitoring of β Cephei stars is still being done (see, for example, Heynderickx 1991), but few systematic searches for β Cephei stars seem to be going on. Delgado et al. (1992) carry on their systematic observations of young open clusters with the detection of β Cephei stars and related pulsating variables as primary aim. In their last paper (*uvbyβ* photometry of NGC 1502 and NGC 2169) particular attention is given to the problem of internal calibration of their *uvby* photometric system, and to possible influence of interstellar reddening in the photometric transformation procedures. They report the discovery of two new β Cephei candidates, viz. 1502-A and 1502-26, with respective pulsation periods of 0.19 and 0.10 days. The latter star has also a secondary pulsation period of about 0.06 days, and the former exhibits long-term variations that may reflect binarity. These new candidates, of course, need confirmation, and the values of their pulsation periods need to be refined.

An interesting search project for β Cephei stars in LMC clusters was initiated by Balona and Jerzykiewicz (Balona 1992a, Balona and Jerzykiewicz 1992, see also Balona 1992b). The underlying idea is that β Cephei stars should not exist in metal-poor systems such as the Magellanic Clouds. Such considerations, among others, prompted Sterken and Jerzykiewicz (1988) to initiate a first search for β Cephei stars among field stars in the LMC. Out of six programme stars they selected from among the LMC stars which fell in the same region in the $Q - M_V$ diagram where are the galactic β Cephei stars, only one star showed β Cephei star-like variations, and was classified as a candidate β Cephei star. Kubiak (1992) searched the young LMC cluster NGC 1712 for new β Cep stars, without success. Balona (1992a), and Balona and Jerzykiewicz (1992) monitored 178 stars lying in the instability strip of the young LMC clusters NGC 2004 and NGC 2100. For each star 150 observations were obtained over a period of 12 nights, but not a single star was found that is variable with a short period and with an amplitude in excess of 0.01 mag. Balona (1992b) concludes that the chance of not finding a variable among the stars surveyed is less than 0.1 per cent. As he points out, one should take into consideration that the studied clusters are older than the galactic clusters that contain β Cephei stars, so that one should await the results of a survey of younger LMC clusters. The NGC 2004 and NGC 2100 results, however, give additional evidence that there is a dependence on metallicity. In this respect, attention must be drawn to the results of Waelkens et al. (1991) who conclude that β Cephei stars in the direction of the galactic center seem to be hotter than normal, so that the blue edge of the β Cephei instability strip moves blueward, what is another point of support for the hypothesis of metallicity dependence. Conclusive evidence on this point may be obtained from similar surveys of stars in the SMC, as has been pointed out by Sterken and Jerzykiewicz (1988).

3. High-resolution spectrography

Fundamental contributions to the understanding of the atmospheres of the bright β Cephei stars σ Sco and 12 Lac have been published by Mathias et al. (1991, 1992). Hα and Si III spectra of σ Sco reveal, for the first time, the line of the 33-day companion of the star. The observed line-profile changes and radial-velocity changes are consistent with a double-shock model (as for BW Vul, see Crowe and Gillet 1989). 12 Lac resembles σ Sco and BW Vul (the two β Cephei stars which have the largest 2K-amplitudes, respectively 120 and 200 km s^{-1}), which undergo shock waves during one pulsation period and exhibit a stillstand, which is the consequence of the simultaneous combination of inward and upward motions of the atmosphere. 12 Lac, however, has a rather chaotically variable radial-velocity curve, in strong contrast to σ Sco and BW Vul. Mathias et al. (1992) understand the phenomenon as the superposition of radial and non-radial modes. In 12 Lac there is no sign of duplicity.

Kaper et al. (1992) report on new observations of strong Hα emission-activity in β Cephei characterized by a (slow) decline in strength of the emission component, and Henrichs et al. (1992) confirm a periodicity of 12 days in the equivalent widths of the ultraviolet resonance lines of $C\,IV$, $Si\,III$, $Si\,IV$ and $N\,V$. Their measurements of the variable magnetic-field support a model in which the stellar wind from the star is rotationally controlled (P = 12 days) by an asymmetric oblique magnetic field. The on-and-off appearance of emission in β Cephei is an interesting case of transition from a "normal" B star to a star of type Be. A most interesting example of reverse transition is the appearance of β Cephei-like pulsations in the Be star 27 CMa (Balona and Rozowsky 1991) with a periodicity of 2^h12^m in addition to the 1.257-day variability. This is the first time the growth of β Cephei pulsations has been witnessed, and 27 CMa is the only Be star known which shows such pulsations.

4. Period changes, pulsation and binarity

During a star's lifetime, the star changes its radius in its evolution off the main sequence, and, as is well-known, the pulsation period, which varies with the mean density, will vary as well. Other processes may cause changes in the pulsation period of a star, such as the presence of binary companions, the occurrence of discontinuous mass loss, or mixing events within the star itself. In Cepheids, for example, parabolic $O-C$ diagrams[2] are observed (see e.g. Szabados 1977, 1980, 1981), though two other kinds of period changes were observed too, viz. cyclic behaviour caused by the light-time effect, and stepwise period changes, where the period returns to its earlier value (so-called phase jumps, which always seem to occur in those Cepheids having a companion star). But, as Hall (1990) points out, most $O-C$ curves which show more than one complete cycle of period variation do not have equal amplitudes, shapes or periods for successive cycles, as would be required by Keplerian motion.

[2] i.e. corresponding to continuous period changes as a result of stellar evolution

In addition, several Cepheids with demonstrable binary companions show variable $O-C$ curves, even after the light-travel-time effect is removed. Moreover, sudden jumps can be produced by cycle miscounts, see for example the famous case of Polaris (Fernie 1984).

The large scatter in rates of period changes in β Cephei stars is not explainable by evolutionary effects alone, but if averaged over a sufficiently long time interval, one may expect to obtain a value of $\dot{P}$ that is in agreement with the calculated evolutionary rate of period change. From an analysis of photometric and radial-velocity data, Chapellier (1985) had come to the conclusion that probably no secular variations of pulsation periods do occur in β Cephei stars. In σ Sco, BW Vul and β Cep the amplitudes of the changes are largest, and a better fit to the data is obtained assuming that positive and negative period jumps occur. Hence, the large $\dot{P}$ cannot be reconciled with evolution, and from this he concludes that all β Cephei stars are in the core hydrogen burning state of evolution.

Chapellier (1990) considered that the apparent changes of the pulsation period of β Cephei can be explained by the light-time effect, induced by the orbital motion of the variable in a highly-eccentric double-star system. The high eccentricity is then responsible for the swiftness of the change of period around the time of periastron passage. Pigulski and Boratyn (1992) derived the spectroscopic orbital elements of the system from the $O-C$ diagram *assuming* that the orbital motion is the *only* cause of the observed variation of the pulsation period. The solution is supported by speckle observations that roughly cover one fifth of the orbital period of 91.6 years. The time of periastron passage coincides with the time of the "abrupt" change of period found by Chapellier (1985)[3], and the next periastron passage is to be expected in A.D. 2003. The agreement between the observed and calculated pulsation period is excellent, though discrepancies up to about 0.1 s do remain. The scatter of the observed radial velocity around the synthetic radial-velocity curve remains substantial, and it is not clear whether this difference is due to systematic errors or to a real physical phenomenon. The $O-C$ curve derived from the orbital elements leaves irregular deviations up to about 0.03 days.

In a subsequent paper, Pigulski (1992a) shows that the changes in the dominant pulsation period of σ Sco can be completely[4] explained by a superposition of two effects: an evolutionary increase of the intrinsic pulsation period, and a variation due to the light-time effect in a binary (the $O-C$ diagram reveals time intervals of increasing and decreasing period, which means that an evolutionary effect alone cannot be held responsible, and the presence of a speckle tertiary companion suggests that the light-time effect may contribute to the observed changes). He derived the spectroscopic elements of the system from radial-velocity data, and from elements obtained by Mathias et al. (1991). He finds a satisfactory explanation for the period change: *assuming* an evolutionary period increase of 3.3 s cen^{-1}, together with proper

[3] see also Chapellier 1990, p52

[4] the explanation of the changes of the period of σ Sco in terms of the light-time effect by Chapellier (1990) ceases to function for data obtained after 1955

adjustment of the ambiguous cycle-count for the time interval from 1925 to 1947 (a gap of 35000 cycles to be bridged), a resulting $O-C$ diagram is obtained that is commensurable with an orbital period of the order of 100-350 years, as was suggested by Evans et al. (1986). A complete orbit solution, of course, could not be obtained.

In a similar approach, Pigulski (1992b) explains the changes in the period of BW Vul by an evolutionary increase of the period with constant rate equal to 2.34 s cen^{-1}, and a periodic term caused by an *hypothetical* companion (as suggested by Odell 1984, who pointed out that the periodic variations in the $O-C$ residuals of BW Vul could indicate that the star is a binary with period 24.9 ± 6.5 years, see also Jiang 1985, who found P=26.3 years). The derived orbital period is 33.3 years ± 0.3 and the expected time of the next perisatron passage is A.D. 1992.3 ± 1.5. He concludes that the light-time effect, combined with an effect of evolutionary origin, may be responsible for at least some of the "unexpected" or "sudden" period changes. An alternative hypothesis, proposed by Odell (1984), is in terms of simultaneous excitation of two very closely spaced pulsation frequencies causing a beat phenomenon (the periods differ only 0.3 s and have an amplitude ratio of 1/3).

Note that, since β Cep and σ Sco are known to have distant companions, any period analysis *must* incorporate the light-time effect, whereas in BW Vul the changes seen in the $O-C$ diagram are the *only* manifestations of the presence of a companion. It should be stressed that all $O-C$ diagrams used by Pigulski and Boratyn (1992) and by Pigulski (1992a,b) are based both on photometric and on radial-velocity data, an approach that involves the assumption of constant average time difference between the times of maximum of the radial-velocity curve and the light curve (Lloyd and Pike 1984, and Chapellier 1986, demonstrated that the phase difference between light- and radial-velocity maximum is variable).

σ Sco has also been the subject of an investigation by Chapellier and Valtier (1992). From all available spectroscopic data they derive an orbital period of 33.0114 ± 0.0026 day, a value which is in very good agreement with the findings of Pigulski (1992a), Mathias et al. (1991) and Goossens et al. (1984). From their investigation Mathias et al. (1991) also concluded that, despite variations in the principal pulsation period, the value of the beat period remains constant and is strictly equal to a quarter of the orbital period. They are convinced that the secondary pulsation period does not really exist and is only an artifact of period analysis, and they conclude that σ Sco is a monoperiodic nonradial pulsator.

5. The $O-C$ diagram: its power and its deficiencies

The real power of the $O-C$ diagram lies in the fact that quasi-sinusoidal portions of it may indicate binary motion with K-values that are too small to be detected by radial-velocity observations. As was demonstrated above, such studies of $O-C$ diagrams have proven to be very useful in unveiling unknown orbital elements of binary β Cephei stars. The remaining discrepancies, if of proper magnitude, could reflect a long-term modulation in the pulsation itself, or could be explained by orbital-element variations due to mass exchange inside the system or due to stellar wind from the system, or even reflect the evolution of the binary (especially in close binary systems) through degradation of the orbit. But sometimes, the orbital period is the only one physical property known accurately for a binary system, and also then an $O - C$ study would be extremely beneficial.

However, one must also ask what is the role of observational selection in all such studies of period changes. Jerzykiewicz (1986), for example, showed that the correlation between abrupt period change and period (Hoffleit 1976) has arised as a result of observational selection and from limitations in the quality of data used to derive these quantities. One may not forget that for the evaluation of the period history, archival data are used, some of which were obtained more than half a century ago, and one must ponder whether these data may be combined with modern data as straightforwardly as is currently been done.

Before discussing the interpretation of observed period changes, one should remember that the $O - C$ diagrams have a number of inherent uncertainties and inaccuracies. In particular, *all* such representations are of non-homogeneous character, because

- data points from which the times of minimum (or maximum) light were derived have been obtained with very different time resolution, and the number (and the quality) of these underlying measurements often is insufficient
- the time distribution of the used times of maximum differs in different parts of the $O - C$ diagram
- the fact that, when one goes back in time, the uncertainties on the times of maximum are much larger than they are now (see Fernie 1990 and Sterken 1992). Times of minimum or maximum light could be routinely measured to an accuracy of better than 0.001 day. But, to quote Jerzykiewicz 1986: "No attempt is usually made to take full advantage of the precision of modern observations, the excuse being that the early ones are not so good anyway"
- the fact that, when one goes back in time, there is less and less certainty that the data have been properly corrected for the light-time effect due to the orbital motion of the earth (heliocentric correction)
- the response functions of the equipment (through unequal effective wavelength of filters, and due to the application of cooled and uncooled photomultipliers with differing response curves) deviate significantly, and multiple-periodic stars (like σ Sco, where the ratio of amplitudes varies from about 2 in y to about 5 in u, see Jerzykiewicz and Sterken 1984), will, for measurements at shorter wavelengths, yield smaller differences between time of observed maximum and time of maximum associated with the dominant pulsation period

However, assuming a homogeneous $O - C$ diagram, one should then very carefully consider the following points:

- a few scattered epochs of maximum light are sometimes used to determine a period
- a single large gap in the sequence of times may cause cycle-count errors, which induce large apparent period variations
- an improper type of extremum is sometimes used (like time of light maximum in the case of BW Vul, see Sterken et al. 1987)
- a non-uniform time system (UT instead of ET) has been used
- one should ask whether the available data are accurate enough to furnish reliable evidence on evolutionary period changes, specifically for those $O-C$ diagrams that are constructed under the assumption of constant average phase difference between the radial-velocity curve and the light curve
- $O-C$ diagrams for well-studied β Cephei stars never cover more than one full orbital cycle, and thus give us no indication of occurrence of strict repetition, so that one is not sure whether the cyclical behaviour is truly periodic or only quasi-periodic
- the separation of evolution and light-time effect is sometimes rather arbitrary, and this is even more so for stars with multiple pulsation periods with appreciable amplitudes
- Fernie (1990) makes a very pertinent remark concerning the common acceptance of the expectation that evolutionary changes necessarily yield *linear* changes of the pulsation period of a variable star. After all, changes in luminosity and temperature are nonlinear in time, and the motion along the evolutionary track has a variable rate. Fernie advocates the introduction of quartic or even higher-order polynomials in the $O-C$ diagrams of classical Cepheids, a move that would eliminate most evidence supporting sudden period changes
- dP/dt should, in fact, be computed using two independent techniques, viz. study of the $O-C$ diagram, and direct non-linear least squares fit to the entire dataset of a sine curve incorporating additional terms (linear or quadratic in time)

In BW Vul, for example, some period variability (sudden glitches or smooth changes) does remain after a linear evolutionary period change has been removed and after the effect of binarity has beeen taken into account (Sterken 1992). Thus, a nonlinear evolutionary effect could be present, since the star appears to be in the shell hydrogen-burning phase of evolution (Sterken and Jerzykiewicz 1990), where such nonlinear effects are more likely to become detectable. Such interpretation of residual variations in terms of a nonlinear evolutionary effect, or in terms of secondary aspects of binarity (is the remaining $\dot{P}$ correlated with the period, does mass transfer[5] play a role, and does this give rise to disk-like structures which might even account for some of the intermittent emission phenomena?) intricately depends on the accuracy of the available observational data. As Irwin (1952) puts it: "The problem of the determination of the light-time orbit will occur with increasing frequency as the observational data become more accurate and extend over greater stretches of time..."

6. Conclusions

Despite the discovery of a suitable pulsation mechanism for β Cephei stars, there is a surge of observational data of high quality with strong astrophysical impact. These observations make up direct tests of the proposed pulsation mechanism, and reveal new facts of fundamental importance concerning the binary nature of some of these stars. One must not forget that binary stars are the main sources of fundamental data on stellar masses and radii. Andersen (1991) presented a sample of 45 detached, double-lined eclipsing binary systems with mean errors $\leq 2\%$ in both mass and radius. These are fundamental data, of lasting value, independent of changes in temperature and flux scales, model atmospheres, abundance data and stellar models. The sample not only highlights the paucity of accurate masses and radii for normal giants, the sample also does not contain a single β Cephei star. This fact alone should be a driving force to further motivate continuous monitoring of a suitably defined sample of bright β Cephei stars.

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