Long-Term Spectroscopic Monitoring of Pulsating B Stars: a Tribute to the CAT

C. AERTS, P. DE CAT and L. EYER, Instituut voor Sterrenkunde, Leuven, Belgium*

1. Asteroseismology

Asteroseismology is a modern term for the study of the internal structure of multiply-periodic pulsating stars. If a large number of pulsation modes occurs, then the stellar interior can be probed from oscillation studies because the modes penetrate to various depths inside the star. The first very successful application of asteroseismology was presented for white dwarfs (Winget et al. 1991), which pulsate in high-order gravity (g-) modes.

Seismological studies of main-sequence stars are in a sense more interesting compared to those of white dwarfs, because they can provide us with important issues about the internal structure of stars that still have a long and interesting evolution ahead. Especially massive main-sequence stars are worth investigating, since accurate evolutionary tracks for the latter are still lacking.

Good candidates to perform asteroseismology of massive stars are the multiperiodic B-type pulsators, i.e. the β Cep stars and the slowly pulsating B stars. These two groups of stars provide us with the opportunity to study accurate masses, the extent of convective overshoot, and the internal rotation law observationally. The β Cep stars pulsate in pressure (p-)modes, which have a large amplitude at the stellar surface. The slowly pulsating B stars, on the other hand, can be viewed as main-sequence analogues of pulsating white dwarfs in the sense that they also pulsate in many high-order g-modes which penetrate deep into the star.

2. Monitoring Pulsating B Stars with the CAT

A nice recent review on the observational status of OB-type variables is presented by Baade (1998). We have been involved in numerous observing programmes of pulsating B stars. It concerns both photometric and spectroscopic runs with various telescopes (e.g. Aerts 1994).

2.1 β Cep Stars

While the first efforts of asteroseismology of β Cep stars are at hand (Dziembowski & Jerzykiewicz 1996, 1999), they have not been very successful up to now. The reason is that unambiguous mode identifications are not available. This is especially the case for the rapid rotators among the β Cep stars. In 1997, we have obtained the most extensive continuous data sets of high-quality spectra for the β Cep stars κ and λ Sco with the CAT. For each star, we obtained more than 400 profiles spread over 8 consecutive nights, each having a S/N ratio of over 500. Both stars were classified as β Cep stars in the seventies and rotate rapidly ($v \sin i > 100$ km/s). A detailed spectroscopic study is not available yet. We show in Figure 1 one night of our data for λ Sco in a grey-scale representation. The spectra reveal the presence of absorption dips that move partly through the profile from blue to red. Such moving patterns are not yet often found for β Cep stars for the simple reason that few rapid rotators among this group of variables have been the subject of detailed spectroscopic monitoring. Striking is the fact that the bumps do not move across the whole profile. Moreover, the line-profile variability is somewhat different during each of the 8 nights of the mission. This seems to suggest that multiperiodicity is present. On the other hand, the moments of the line profiles are clearly dominated by one period of 0.2137 days. This period is in full agreement with the result derived from photometric data by Lomb & Shobbrook (1975). The grey-scale representations point out that the pulsation mode must be of a complicated tesseral nature, contrary to Lomb & Shobbrook's suggestion that the star pulsates radially. The detection of tesseral modes in β Cep stars is scarce and is important in view of a confrontation of observational

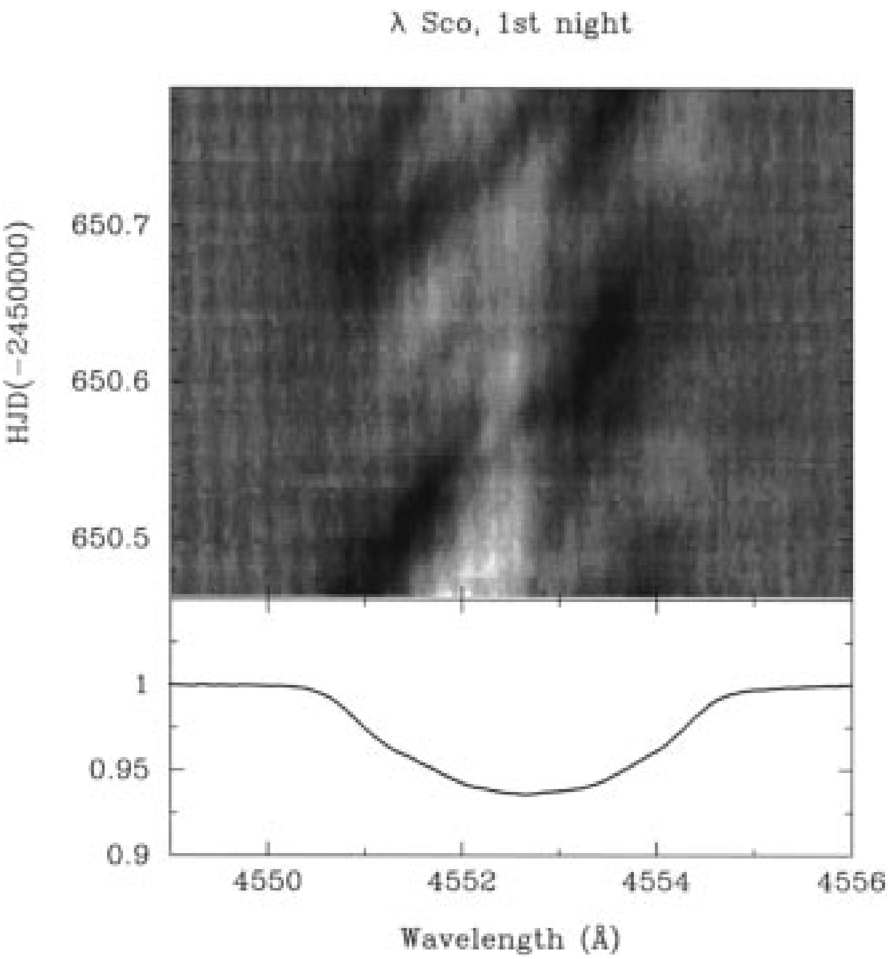

Figure 1: Grey-scale representation of the first night of our obtained line-profile variations of λ Sco. Each wavelength bin of the residual spectra with respect to the average profile of the entire run (8 nights) is given a grey value. White denotes local flux emission and black local flux absorption compared to the average profile, which is given in the lower panel.

*Postdoctoral Fellow, Fund for Scientific Research, Flanders.

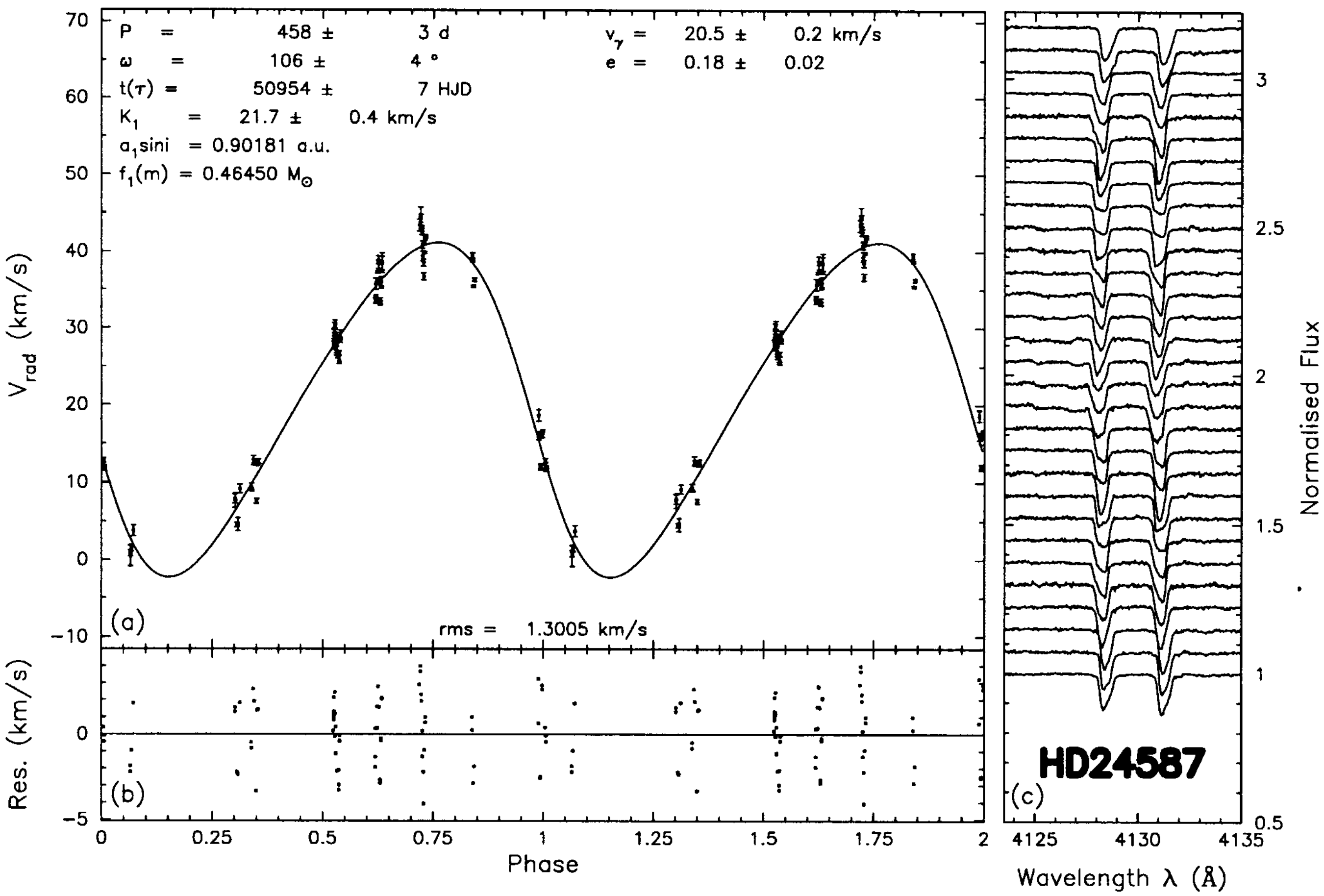

Figure 2: (a) The radial velocity variations of the slowly pulsating B star HD 24587. The dots represent the observations, and the full line is the orbit for the parameters that are listed. (b) The residuals after prewhitening with the orbital solution given in panel (a). (c) The line-profile variations of the main component of the system.

results with the recent theoretical pulsation models for β Cep stars proposed by e.g. Dziembowski & Pamyatnykh (1993). Although we still have to complete a detailed mode identification for this star, this example clearly shows that dedicated high-resolution spectroscopy is needed in order to derive accurate velocity parameters. The CAT was perfectly suited to obtain such data.

2.2 Slowly pulsating B stars

The slowly pulsating B stars, being confirmed high-order g-mode pulsators, are the most promising early-type stars to apply asteroseismology. During a first CAT observing run more than 10 years ago, Waelkens (1987) could prove the existence of line-profile variability in two such stars. The data were not numerous at that time because the Reticon worked markedly slower than current CCDs. We recently re-addressed the study of line-profile variations in slowly pulsating B stars because of the possibility to apply seismology. Also, Hipparcos provided us with a large sample of new members of this class of variables (Waelkens et al. 1998). Many of them are sufficiently bright to be observed spectroscopically.

The observational study of these stars remains very challenging, despite the instrumental improvements. Indeed, the long beat periods (months/years) have to be covered with a sufficient amount of data to unravel all the beat phenomena. Nonetheless, we have started a systematic photometric and spectroscopic study of some 20 bright slowly pulsating B stars in 1996. The photometric data were obtained with the Swiss photometric telescope at La Silla in the course of 1997. The spectroscopic observations were performed with the CAT. Both telescopes were closed in the meantime. In total, we have gathered CAT data during more than 10 weeks, spread over more than two years. The most important results so far derived from our spectra are:

- the detection of line-profile variations on the expected time scales in all target slowly pulsating B stars,
- the finding that slowly pulsating B stars are not necessarily slow rotators, as was thought before our missions,
- the discovery that about half of the monitored slowly pulsating B stars are spectroscopic binaries.

Concerning the latter point, we show in Figure 2 the orbit derived for the star HD 24587. This star was not known to be a binary and has the longest orbital period among the sample. Several weeks of monitoring, spread over more than one year, were necessary to derive the orbital parameters. Besides the orbital motion, line-profile variability is clearly present in the observed profiles.

The first results of our long-term project are encouraging, since they suggest that our observations fulfil the expectations we had when starting this study. We refer to Aerts et al. (1998a, b, 1999) for subsequent reports on the progress of the analysis of the data. Much work still remains to be done and we expect to report on the definite results in a few years from now.

It is our intention to select the most interesting targets for very-long-term spectroscopic monitoring with CORALIE, the accurate spectrograph mounted on the new 1.2-m Swiss telescope at La Silla. Our first test runs with CORALIE were completed recently and our data show that this instrument is indeed a suitable alternative to continue our long-term project now that the CAT is no longer available. In Figure 3, we compare a CORALIE line profile of the Si II 4130Å line and the corresponding cross-correlation function for the slowly pulsating B star HD 215573 with a CAT/CES spectrum of the same spectral line. The integration times for both exposures were 17 (CORALIE) and 25 (CES) minutes. At present, we still have to work out a better mask (typical for a B-type star) to cross-correlate in a more efficient way, but it is clear that working with the cross-correlation profile instead of with the true spectrum will be better to identify the pulsation modes.

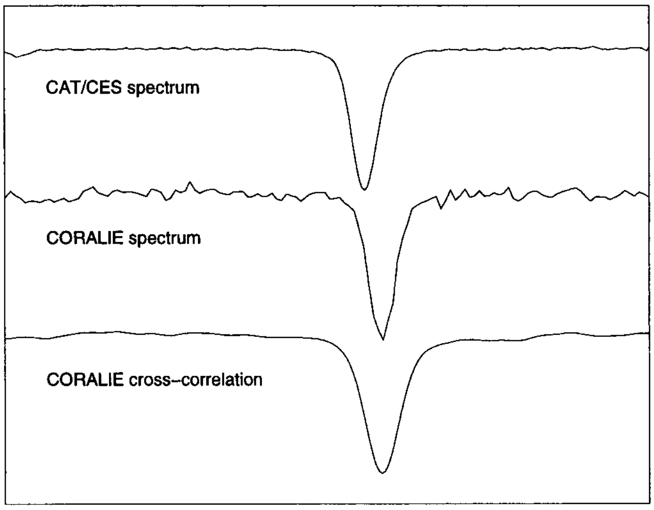

Figure 3: A Si II 4130Å line profile obtained with the CAT/CES is compared with one obtained with CORALIE and a cross-correlation profile derived from the CORALIE spectrum. Integration times were 25 minutes for the CAT spectrum and 17 minutes for the CORALIE spectrum.

For a previous application of mode identification in a pulsating star by means of cross-correlation functions we refer to Mathias & Aerts (1996). Another possibility to continue our monitoring is by means of FEROS. Up to now, we did not yet observe slowly pulsating B stars with this instrument, but we expect to find results comparable to those obtained with CORALIE.

3. Many Thanks

As already mentioned, a study as the one that we are undertaking is very challenging from an observational point of view. On the other hand, long-term monitoring is the only way to obtain meaningful results in the field of asteroseismology of early-type stars. Obviously, the OPC members judged that the scientific rationale of our proposals is important. We would like to thank both ESO and the Geneva Observatory for the generous awarding of telescope time to our long-term project.

We realise that the spectroscopic study of pulsating stars, one of the main subjects of our work in astronomy during the past 10 years, would not have been possible without an instrument like the CAT/CES. This combination of telescope and spectrograph was a cornerstone for the observational research performed at our institute, and several other astronomers, who now occupy key positions in important astronomical institutes, also made largely use of the CAT to develop their careers.

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A Procedure for Deriving Accurate Linear Polarimetric Measurements[1]

*H. LAMY and D. HUTSEMÉKERS**

Institut d'Astrophysique, Université de Liège, Belgium; e-mail: lamy@astro.ulg.ac.be, hutsemek@astro.ulg.ac.be

We present here a procedure written within the ESO MIDAS reduction package with the aim of deriving semi-automatically linear polarisation data from CCD images obtained with beam-splitters such as those available at the ESO 3.6-m telescope equipped with EFOSC2 or at the VLT equipped with FORS1. This method is adequate for point-like objects and was used for measuring quasar polarisation (cf. Hutsemékers et al. 1998). We also report on the detection of a significant image deformation effect, most probably due to the recent addition to EFOSC2 of a rotatable half-wave plate.

Polarimetry with EFOSC2

With EFOSC2, polarimetry is performed by inserting in the parallel beam a Wollaston prism which splits the incoming light rays into two orthogonally po-larised beams separated by a small angle (typically 20″). Every object in the field has therefore two images on the CCD detector (see Figure 1). In order to avoid any overlapping of different images and to reduce the sky contribution, an aperture mask is put at the focal plane of the telescope. The normalised Stokes parameters (NSPs), q and u, fully describing the linear polarisation, are then computed from the fluxes measured in the two orthogonally polarised images. Two frames with the Wollaston prism rotated by 45° are necessary to determine the NSPs. Additional frames may be considered although the quasi-perfect transmission of the Wollaston generally makes two orientations sufficient (Serkowski 1974; di Serego Alighieri 1989). Usually the orientations at 270° and 225° are taken and

$$q = \frac{I^{u}_{270} - I^{l}_{270}}{I^{u}_{270} + I^{l}_{270}}, \quad u = \frac{I^{u}_{225} - I^{l}_{225}}{I^{u}_{225} + I^{l}_{225}}, \qquad (1)$$

[1] See note on page 31.

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