Discovery of the First Eclipsing Binary Barium Star

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1. Barium Stars

Barium stars are a family of peculiar red giant stars whose envelopes exhibit overabundances of carbon as well as of elements heavier than iron. First identified by Bidelman and Keenan (1951), they represent about 1% of all red giants of types G and K. Their kinematic behaviour appears to be similar to that of A or early F main-sequence stars; accordingly, barium stars should have an average mass of about 1.5 to 2 $M_\odot$ (Hakkila 1989a).

McClure (1983) found that a large fraction of barium stars belong to spectroscopic binaries. Jorissen and Mayor (1988) showed that virtually all known southern barium stars with large barium overabundances are spectroscopic binaries, and McClure and Woodsworth, (1990) obtained orbital periods in the range 80 d to more than 10 y. White dwarf (WD) companions are inferred from the mass function distribution, although very few of them can be detected directly from their UV radiation (Böhm-Vitense, 1980, Dominy and Lambert, 1983, Böhm-Vitense, Nemec and Proffitt, 1984).

The fact that all barium stars belong to binary systems clearly means that binarity must somehow be responsible for their chemical peculiarities. It was sometimes suggested that the presence of a companion could perhaps modify the outcome of the helium flash occurring in low-mass stars, possibly triggering the extra-mixing leading to the synthesis of heavy elements (e.g., McClure, 1984). However, some barium systems are quite wide ($P > 10$ y), and it is difficult to imagine that such a distant companion could have an effect on the internal structure of the barium star.

Mass transfer from the former primary towards the barium star, when the primary was a heavy-element rich S or carbon star on the asymptotic giant branch (AGB), seems more likely. The observation of a 10 μm (N band) excess in many barium stars (Hakkila, 1989b), which is not correlated with the other atmospheric peculiarities, may point towards the presence in the system of dust left over from a former mass-loss episode. Again, many barium systems appear to be too wide for mass transfer through Roche lobe overflow (RLOF) to occur (Tout and Eggleton, 1988). Moreover, post-RLOF systems generally have circular orbits (e.g., Webbink, 1986), which is not the case for all barium stars. Boffin and Jorissen (1988) suggested instead that the accretion by the barium star of the wind from the former AGB primary may be efficient enough to account for the observed chemical peculiarities.

2. Interest of a Photometric Monitoring of Barium Stars

Since barium stars are single-lined spectroscopic binaries (SB1), only partial information can be obtained about their orbital parameters. The detection of possible photometric variations related to the binary nature of these stars could provide further insight in the characteristics of these systems. However, the relatively large orbital separation (estimated as several AU) and the low luminosity of the companion (dictated by the SB1 nature of the system) imply that photometric variations, if present, should be of rather small amplitude and have a long period.

Landolt (1983) was the first to look for photometric variability of barium stars. He obtained UBV photoelectric observations of several barium stars at KPNO and CTIO at irregular intervals over a time span of more than a decade. His photometry was basically non-differential, but included the measurements of a number of standard stars of similar brightness as the barium stars of his programme. Assuming the mean error of observations in V for standard stars to be about 0.007 magnitude, he concluded that 6 stars of the sample (which contained 17 barium stars) showed variations at or above the 3 σ level. All stars were however observed less than a dozen times under very different observing conditions and no lightcurve is provided. Our more accurate photometric monitoring, described in Section 3, does not confirm these variations in all but one case.

3. The Long-Term Photometry of Variables Programme at ESO

High accuracy and homogeneity over periods of several years are required for monitoring barium stars. Both requirements, together with the potential of extensive observing time (4 to 6 months/year), are offered by the Long-Term Photometry of Variables (LTPV) programme operating at ESO since 1982 (Sterken, 1983).

The Strömgren uvby magnitudes of a sample of 19 barium stars have been monitored since July 1984 in a differential way: for each programme star, two comparison stars were selected among nearby G or K giants. The observation frequency is about 2/week during typical one-month observing runs. That frequency was increased to one measurement/night during three observing campaigns around the predicted time of eclipse of the companion of HD 46407 by the red giant (Section 4).

Observations were performed on the ESO 50-cm telescope or on the Danish 50-cm telescope (four-channel simultaneous photometer). The reduction to the standard uvby system is performed with the "multi-night" algorithm described by Manfroid (1985), taking into account the *total set of measurements* carried out at the ESO 50-cm or Danish 50-cm telescopes *since the beginning of the monitoring*. Offsets between observing runs are avoided in that way, since there is just one colour matrix for the whole set of measurements in a given system. Checks were of course made to control the stability of the system over the whole period considered.

The accuracy of the differential magnitudes can be estimated from the standard deviations of the differences between comparison stars. For both the Danish 50 and ESO 50 systems (referred to in the following as D50 and E50-6, respectively, according to the notation of Jorissen, Manfroid and Sterken, 1991; see also Manfroid et al., 1991), 50% of the considered comparison pairs have a standard deviation in the y channel smaller than 0.003 mag for observations spanning several years. The mean value of these r.m.s. deviations is somewhat smaller for the D50 system (0.007 mag) than for the E50-6 system (0.009 mag). Colour indices in the E50-6 system are however much less accurate than in the D50 system, mainly because the latter are obtained with a four-channel photometer. In what follows, we will therefore mainly make use of the more accurate D50 measurements. More details about the observing policy, the reduction method and the resulting accuracy can be found in Manfroid et al. (1991).

A detailed discussion of the results of the photometric monitoring for the sam-

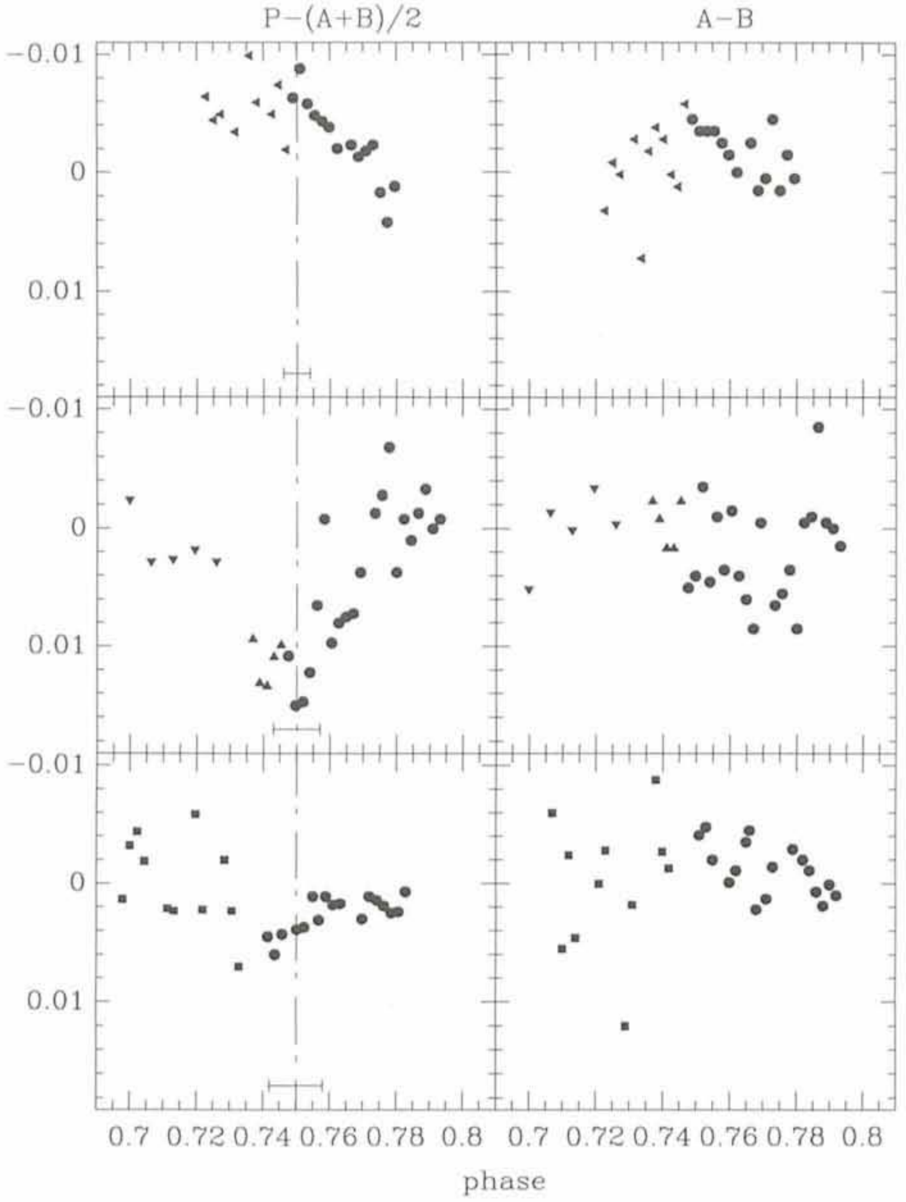

Figure 1: *Results of the three observing campaigns around the time of the predicted eclipses (φ = 0.75): February 1985 (upper panel; cycle 1), November 1988 (middle panel; cycle 4), February 1990 (lower panel; cycle 5). Phases are computed adopting the orbital elements of McClure and Woodsworth (1990). The uncertainty on the predicted time of total eclipse is displayed by the horizontal error bar around the value φ = 0.75. The left panels present the differential P-(A+B)/2 magnitude in the Strömgren y channel, whereas the right panels display the differential A-B y magnitude, where P stands for the barium star and A and B for the two comparison stars (respectively HR 2379 and HR 2367). The zero point of the magnitude scale is the mean value of the corresponding differential magnitude in a given system (● = D50 system; ◂ = E50-5 system; ▲ = E50-6 system; ▼ = ESO50-8 system; ● = E50-x system). The ordinate axis is oriented in such a way that a decrease in brightness corresponds to a dip in the curve.*

ple of 19 barium stars is presented in Jorissen, Manfroid and Sterken (1991). The main result of our monitoring is that the two barium stars with the shortest orbital periods in the sample, HD 121447 (~ 185 d, Jorissen and Mayor, in preparation) and HD 46407 (458.6 d; McClure and Woodsworth, 1990), are the only ones to present small, albeit significant, light variations. In the case of HD 121447, it is not yet clear, however, whether these variations at a level σ_y = 0.020 mag (to be compared with σ_y = 0.009 mag for the magnitude difference between the corresponding comparison stars) are specifically related to the binary nature of the star, or whether HD 121447, which is also the coolest known barium star (K7 III, Lü et al., 1983), is simply a microvariable as any other very red star.

4. HD 46407: The First Eclipsing Binary Barium Star

HD 46407 (HR 2392, y = 6.27, b − y = 0.66, K0III Ba3) has the second shortest orbital period in our sample (P = 458.6 d, McClure and Woodsworth, 1990). Its spectroscopic ephemeris was used in order to predict the times of a possible eclipse of the companion by the barium star. During the 7-year span of the monitoring, only three eclipses were predicted to occur at a time when the star was easily observable. HD 46407 was observed once a night for 20 to 40 nights during these periods (February 1985, November 1988 and February 1990).

A clear dip is seen in the lightcurve in November 1988 while the comparison pair remains stable (Fig. 1). Since this dip is exactly centred on the predicted time for the total eclipse, there is little doubt that an eclipse has actually been detected. Very accurate measurements were carried out during the February 1990 campaign at the Danish 50-cm telescope, and reveal that, if any, the eclipse was much shallower. The measurements of February 1985 are puzzling, since a statistically significant trend is indeed observed, but if it were to correspond to the eclipse ingress, there would be a > 0.03 phase lag with respect to the spectroscopic ephemeris.

Figure 2 presents the phase diagram for all D50 measurements, adopting P = 458.1 d and T = JD 2 445 296.0 (time of maximum velocity), which correspond to the lower bounds of McClure and Woodsworth's elements. The measurements of February 1985 are lagging in that phase diagram as well, so that the current uncertainty on the circular orbital elements (±0.5 d on P and ±1 d on T) cannot resolve the discrepancy. The superposition of the February 1985 eclipse ingress on the November 1988 data would require a 451.7 d period, not very different from McClure's spectroscopic period, although well outside its formal error bar.

The phase diagram of Figure 2, adopting McClure and Woodsworth's (1990) spectroscopic period, reveals that a very broad secondary eclipse may be present as well. A clear trend was in fact observed for 0.35 < φ < 0.5 in cycle 2, and the drop in brightness around phase 0.35 was confirmed by the observations of cycle 6. Again, the large scatter in that phase range indicates that the spectroscopic period is probably not the best choice for constructing a photometric phase diagram. A careful period analysis of our data remains to be done.

In summary, the lightcurve of HD 46407 derived from the currently available photometric observations in the D50 system displays a sharp "primary" eclipse (companion behind the barium star) and a possible shallow "secondary" eclipse. In November 1988, the

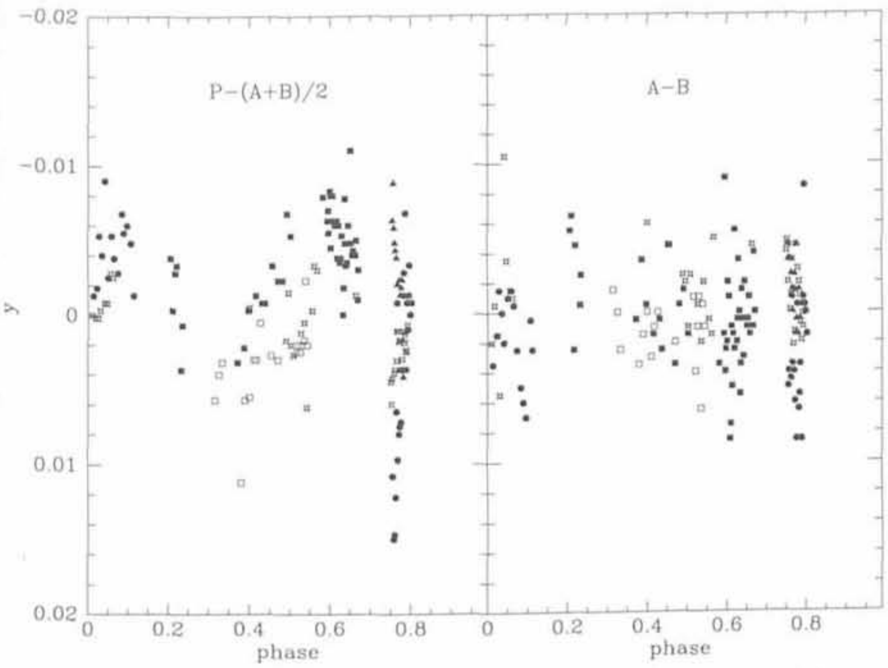

Figure 2: *Phase diagram for the whole set of y measurements in the D50 system (left panel: barium star relative to comparison pair; right panel: comparison pair), adopting the spectroscopic elements from McClure and Woodsworth (1990). The various symbols refer to the different cycles (starting from JD 2 445 296.6): ▲ = cycle 1, ▪ = cycle 2, ● = cycle 4, ☆ = cycle 5, □ = cycle 6. Note the presence of a very wide secondary eclipse (transit of the companion in front of the barium star). Note that, because P-(A+B)/2 involves the average of the two differential measurements P-A and P-B, the uncertainty on P-(A+B)/2 is $\sqrt{2}$ times smaller than the one on A-B.*

primary eclipse had a depth of ~ 0.02 mag in y and a full width of $\Delta\varphi \sim 0.05$ (i.e. about 20 d); the primary eclipse was much shallower in February 1990. The shallow secondary eclipse occurs when the companion is in front of the barium star. Its depth is at least 0.01 mag in the y band and it extends over about 50% of the orbital period. It might well be that the brightness of HD 46407 is slowly varying over the whole orbital period.

The b – y index is marginally variable, at variance with the v – b index which exhibits large variations. Quite interestingly, the variations of the v – b index and of the y magnitude appear to be roughly correlated: when the star is fainter, it is also redder, as shown by Figure 3. This behaviour is typical of light-scattering processes, so that we suggest that the eclipsed light is actually the light from the barium star itself which is backscattered by dust trapped (in a disk?) around the companion.

Dust must be present in a rather extended region around the companion, since the November 1988 eclipse was about three times longer than it would have been expected for the eclipse of a point-like source by a red giant of radius $15\ R_\odot$ (and a semi-major axis of 1.5 AU; total duration of 7 d or $\Delta\varphi = 0.015$). Moreover, there does not seem to be a flat bottom in the eclipse lightcurve, indicating that the eclipse is never total. The phase lag of February 1985 can also be accounted for by this explanation, since dust ought not to be distributed in a spherically symmetric way around the companion.

Although this model seems to account qualitatively for the observed behaviour, it remains to be tested quantitatively: the depth of the eclipse will yield an estimate of the amount of dust required and the wavelength dependence of the scattering cross-section should be compatible with the relative variations of b – y and v – b. The following questions also remain to be answered: is such an explanation compatible with the absence of IR excess for HD 46407 (Hakkila and McNamara 1987, Hakkila 1989b)? And how can dust grains remain trapped around the companion for long periods of time (Poynting-Robertson effect)?

The photometric monitoring of HD 46407 is still going on; polarimetric measurements are also in progress. Finally, a similar photometric monitoring is being carried out for the two barium stars with the shortest known orbital periods (HD 77247 and HD 121447), and it will be interesting to know whether a behaviour similar to that of HD 46407 will be observed.

In conclusion, the behaviour of HD 46407 is a clear example of a phenomenon that can only be studied as part of a carefully planned long-term project relying on service observing: (i) continuous photometric monitoring should be carried out in order to get the general light curve; (ii) each eclipse needs more than one month of daily observing; (iii) they only occur every 1.3 years and one third of them are missed because of the proximity to the Sun. In addition, we must also emphasize that only a small telescope is needed. The LTPV project

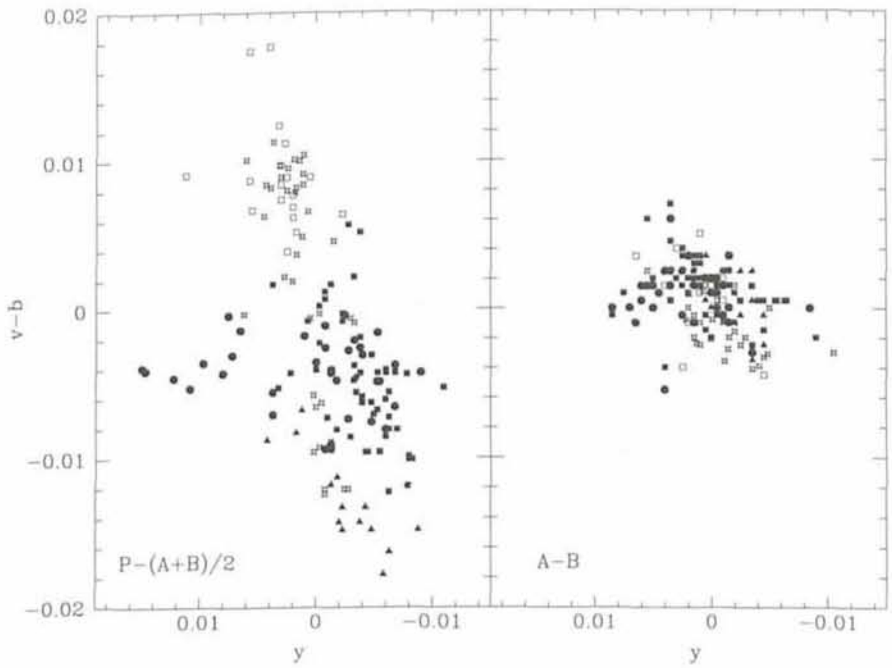

Figure 3: *The (y, v – b) diagram of the barium star (left panel) and the comparison pair (right panel) in the D50 system. Symbols and magnitude zero points are as in Figure 2. Note the triangles, which exhibit within a single observing run the general trend observed for the whole set of measurements. The filled circles standing to the left of that general trend correspond to the November 1988 eclipse.*

at ESO clearly represents the only available opportunity to address that kind of problem.

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The Rise of SN 1987 A

It is now almost five years since SN 1987 A exploded in the LMC. In the meantime, the visual brightness has decreased to about one millionth of what it was at the time of maximum. It is still being observed with large telescopes, also at La Silla, but the elusive pulsar has not yet been directly detected.

The four pictures were taken during amateur patrols in Australia at the time of the explosion by Robert H. McNaught (Plates 2, 3 and 7) and Frank B. Zoltowsky (Plate 5). They show the early rise in brightness of this famous object; the intensity and the angular scale have been rescaled to allow direct comparison. A recent, careful remeasurement of the magnitudes of SN 1987 A on these plates has shown that earlier published estimates are too faint by 0.2–0.8 magnitude (McNaught and West, to appear in *Astronomy and Astrophysics*). The new values are in better agreement with the theoretical lightcurves, but they do not by themselves permit to decide which of the two neutrino events that were observed in the morning of February 23, 1987, was the actual time-zero.