Session VI

Binarity

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Archaeological site of the ancient city of Perge, less than 20 km from Antalya. Columns date from the Roman period.

Conference participants listening attentively to their guide at the thermal baths of Perge. In the foreground are Robert McClure, Steve and Irene Little, and Sophie Van Eck.

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THE ROLE OF BINARIES IN THE CARBON STAR PHENOMENON

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Abstract. This presentation reviews the role that binaries play in the production of Barium, CH, and S stars. New radial velocity observations confirming the binary nature of subgiant CH stars are also discussed. Evidence is presented that the early R–type carbon stars exhibit **no** binaries. It is suggested that they were once **all** binaries, but having small separations, a coalescing companion has caused them to mix near the helium core flash.

1. Introduction

In a review of the roles of the various carbon stars, Scalo (1976) pointed out that the classical carbon stars lie above the luminosity of the onset of helium shell flashing on the asymptotic giant branch (AGB), as shown by Crabtree et al. (1976). But he noted that most Barium stars are too faint to be identified with double-shell models. Along with CH stars, their population II equivalents, they did not fit into the AGB scenario for production of carbon stars, even though they exhibit many of the same abundance characteristics. It seemed that they must be associated with the helium core flash, but standard stellar models did not predict mixing of the core flash material.

2. The Barium, CH, and S stars

2.1. EVIDENCE FOR BINARIES

My own involvement with this subject began in 1979 with a program to measure radial velocities of Barium stars using the new radial velocity spec-

R.F. Wing (ed.), The Carbon Star Phenomenon, 249-257.

trometer in Victoria, and within a year it was obvious that Barium stars are mostly binaries (McClure, Fletcher & Nemec 1980). Over the course of the next few years, it was found that the CH stars as well as the Barium stars are likely all binaries (McClure 1983, 1984; McClure & Woodsworth 1990). It was suggested that the Barium and CH stars have received material contaminated with carbon and *s*-process elements from a companion star undergoing helium shell flashes on the AGB. The companion has since become a non-visible white dwarf.

The CORAVEL group proved beyond doubt that the binary nature of the Barium stars could not be ignored. Jorissen & Mayor (1988) found that in a sample of 27 southern Barium stars, 89% exhibited variable radial velocities above the 3σ level. But in addition they showed that eight out of a sample of nine non-variable S stars are also binaries.

The discovery of the binary nature of a subset of the S stars is one of the true success stories in the investigation of the carbon star phenomenon. The possibility of an evolutionary link between Barium and S stars has been suggested, going back as far as Burbidge & Burbidge (1957), on the basis of the spectral similarity between the coolest Barium stars and the hottest S stars. However, the S stars were thought to be undergoing helium shell-flashing in a sequence going from M to S to C stars.

Interest in duplicity among the S stars stemmed from surveys for the presence or absence of the radioactive *s*-process element Tc. Beginning with a spectral survey by Little–Marenin & Little (1979), and discussed by Scalo & Miller (1981), it was shown that some 30% of S stars exhibit no Tc lines. This quickly led several groups to suggest that the Tc-poor S stars may be binary analogs to the Barium stars (Iben & Renzini 1983; Johnson & Ake 1984; Perry 1985; Smith & Lambert 1986, 1988; Little et al. 1987). Tc, which has a half-life of 2×10^5 years, a good fraction of the star's lifetime on the giant branch, should be present if the S stars are thermally pulsating AGB stars in the M–S–C evolutionary sequence.

Thus it appears that the S stars can be divided into two groups: the "intrinsic" S stars are true AGB stars undergoing thermal pulses, whereas the "extrinsic" S stars are just binaries that have undergone a mass exchange process like the Barium stars. Brown et al. (1990), Johnson et al. (1993), and Jorissen et al. (1993) presented further evidence which fully supports this dual nature of the S stars.

2.2. PRECURSORS TO THE BARIUM STARS

The mass-transfer hypothesis for the origin of Barium and CH stars was not without difficulties, as pointed out in papers by Luck & Bond (1982), Dominy & Lambert (1983), and Luck & Bond (1991). Although evidence had been found from IUE spectra for white-dwarf companions to one or two Barium stars (Böhm–Vitense 1980; Dominy & Lambert 1983; Böhm–Vitense et al. 1984), in fact, these programs had met with very limited success. Dominy & Lambert (1983) and Bond (1984) found no additional evidence for white dwarfs among numerous Barium and subgiant CH stars. Since the time-scale for white dwarfs to cool below the IUE detection limit exceeds the evolutionary time-scale for red giants by a considerable factor, then mass transfer must have occurred while the present visible star was on the main sequence. The paucity of dwarf Barium stars, except for G77–61 (Dahn et al. 1977) and perhaps some of the sgCH stars in a limited spectral range near G0, did not favour this. So just where were the precursors to the Barium stars?

Slowly, the evidence has been accumulating that indeed, we do find these stars if we search hard enough. Besides the sgCH stars near spectral type G0, more difficult to detect F–type counterparts were observed by Tomkin et al. (1989), North & Duquennoy (1991), and North, Berthet & Lanz (1994). Despite the previous apparent lack of late-type dwarf analogues to the Barium and CH stars, it now appears that they too exist in abundance (Green & Margon 1994; de Kool & Green 1995; Green 2000).

2.3. MASS EXCHANGE MECHANISM

Webbink (1986) and McClure & Woodsworth (1990) pointed out that the eccentricities of Barium star orbits are lower on average than for normal giants. This orbital dissipation suggested that mass exchange may have taken place onto barium stars through Roche lobe overflow. After examining orbits for a good sample, however, Boffin & Jorissen (1988) suggested that wind accretion rather than Roche lobe overflow must account for the mass exchange.

The mass exchange mechanism has been discussed further by Jorissen & Boffin (1992), who point out several problems with the Roche lobe overflow scenarios. Začs (1994) finds a correlation between orbital period and *s*-process abundance anomalies for barium star binaries. Boffin & Začs (1994) show that this correlation agrees with predictions of wind accretion models. Recently, Han et al. (1995) have concluded from a theoretical investigation that mass transfer was likely accomplished in about 70% of Barium stars through a stellar wind, but that RLOF and common envelope evolution are important for the remaining significant fraction of cases. They successfully explain the distribution of orbital periods, mass functions, and numbers of observed Barium and CH stars.

3. Binaries among the sgCH Stars

For the rest this presentation, I will report on further radial velocity observations of my own for sgCH stars and early R stars. Smith & Demarque (1980) first suggested a binary mass-transfer origin for the sgCH stars on the basis that they were difficult to explain by mixing of helium core flash material. Very preliminary velocity results have been published for these stars in several conference proceedings (e.g. McClure 1985, 1989). The conclusion was reached that a large fraction of sgCH stars are binaries, but this was based on very limited data, and in the intervening years, I have collected enough velocities to set this result on a much firmer basis. In eight out of ten stars there is definitely evidence for duplicity, and perhaps evidence for velocity variations in one further star. It is reasonable to conclude that all sgCH stars are binaries, and that Luck & Bond's suggestion that they are the precursors to the Barium and CH stars is correct.

4. The R Stars – Carbon Stars of a Different Kind!

The R stars, I believe, represent the outstanding problem today in the subject of the origin of carbon stars. It is interesting, however, that the study of these stars has been almost completely ignored in the last decade, and as far as I can tell, there are no other papers at this conference that deal with them. This is despite the observation that the spectrum exhibited on all the advertisements for the conference appears to be that of an R star! [The spectrum shown on the conference poster and T-shirts is indeed that of the R star HD 156074, classified C–R2 by Barnbaum et al. (1996) – Ed.] Dominy (1984) summarizes the characteristics of R stars, and Lloyd Evans' (1986) paper is very informative. Many are not bright enough to be on the AGB, and they do not exhibit significantly enhanced *s*-process elements, signatures of carbon-related stars that have received their peculiar abundances on the AGB or from mass transfer from an AGB star. Dominy suggests that the carbon likely has to come from the helium core flash, but it is not obvious how this carbon can be conveyed out to the surface of the star.

As for the case of the sgCH stars, I have drawn preliminary conclusions in previous conferences concerning the frequency of binaries among the R stars. However, in this case, these conclusions may not have been accurate! I have suggested that the incidence of binaries among the R stars is low, but that it is probably normal for giant stars. With velocity data covering up to 16 years, I have now taken a more careful look at this question in preparation for the present conference.

When I first picked my sample years ago, I was not concerned about including stars which might turn out not to be true R stars. I intended

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to study mostly R0–R4 stars, since these are more normal, intrinsically fainter, and less likely to have unstable atmospheres; however, I included a few later R5–R8 stars. Some stars in the sample have turned out to be N stars according to more modern classifications and better data (e.g. the spectral atlas of Barnbaum, Stone & Keenan 1996). Still others have been classified as CH or CH–like stars (Yamashita 1975). Of course all CH stars were classified as R under the old HD classification.

In my original sample of 38 stars, five are N stars, and seven are R5–R8 stars. All these show velocity variations considerably larger than the observational errors, but no evidence for binary motion. This velocity "jitter" is not unusual for very high luminosity giants.

The problem of misclassification of R stars versus CH stars is a very difficult one, the differences sometimes being subtle at low dispersion. Those with strong CH bands that have high velocity can be assumed to be CH stars. However, Yamashita (1975) has suggested that there are some low velocity CH stars also, which he refers to as "CH–like". It is very important that these low velocity CH stars be removed from the sample, since CH stars appear to be binaries (McClure 1984), whereas the frequency of binaries for the R stars (which we are trying to determine here) is low.

HD 16115 has been classified as a CH–like star by Yamashita (1975) and by Keenan (1993). I have kept it in the R star sample because Dominy's (1984) analysis shows that the *s*-process element abundances are near normal, which is a primary distinction separating the R stars from the CH stars. Four other CH–like stars, however, have been excluded from my final sample. HD 85066, although classified by Yamashita (1972) as R, has a very strong CH index and more recently has been classified as a CH star by Hartwick & Cowley (1985). This star is a definite binary with a period of 2902 days. There is evidence for duplicity in BD +2°3336, for which I have determined a good orbit with a 446-day period. BD +29°95 exhibits very erratic velocities; it may be a binary, but this is uncertain. Although HD 197604 has been classified by Yamashita (1975) as a CH–like star, there is no evidence for radial velocity variations.

Finally, Figure 1 shows velocities for the 22 remaining R0–R4 stars in the sample. There is no evidence whatever for duplicity in any of these observations. This seems very surprising, given that significant numbers of normal G and K giants are binaries. For example, Gunn & Griffin (1979) comment that in their velocity data about 30% of field giants exhibit multiplicity. The largest program of velocity monitoring among giants is that by Mermilliod & Mayor (1992), who find 187 binaries among 905 giant stars in open clusters, or a frequency of ~21%. I have monitored a much smaller sample of 39 randomly picked field K giants and found six binaries. Our finding of zero binaries in a sample of 22 R stars can be compared with this

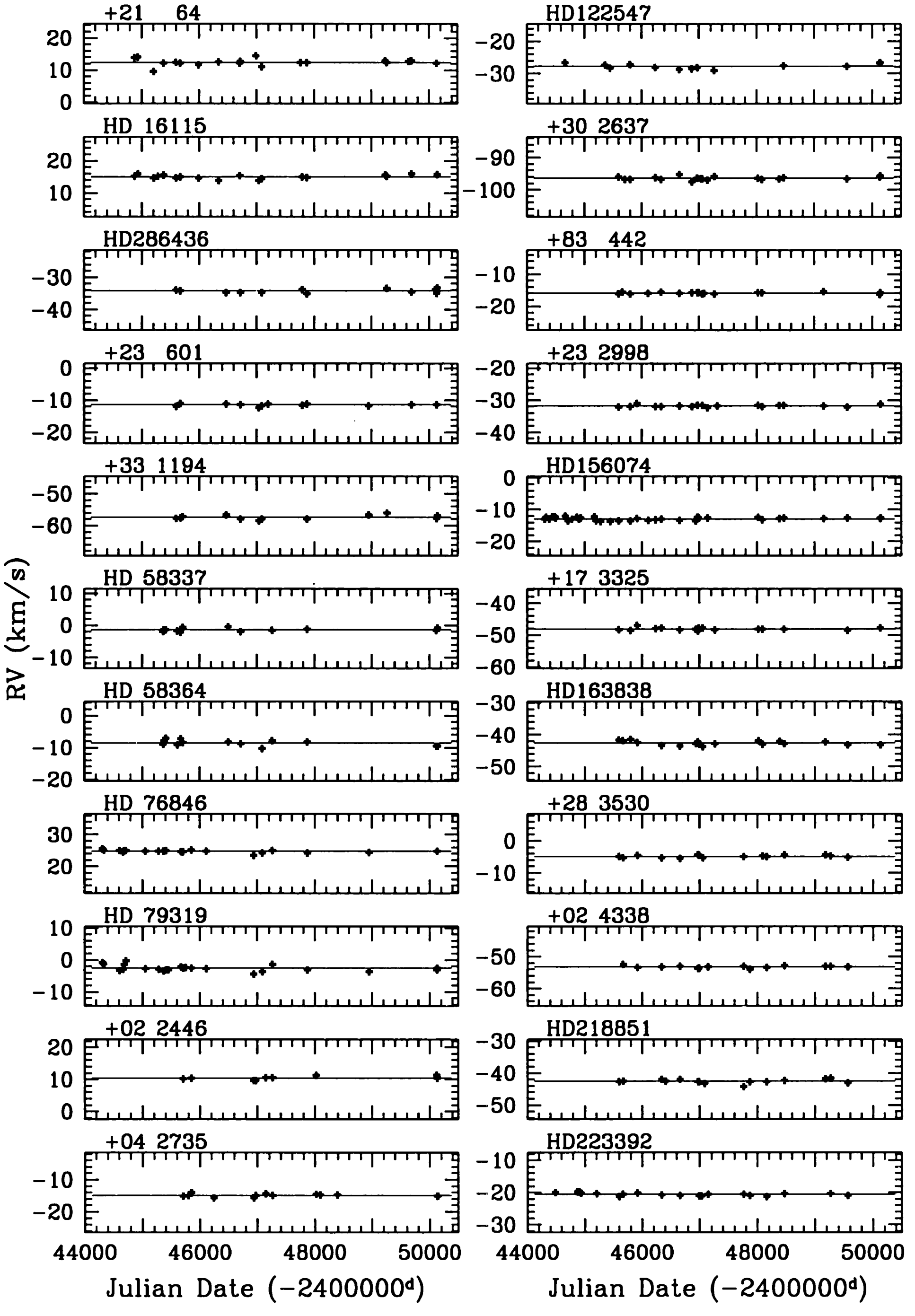

Figure 1. Velocities versus Julian Date for R0–R4 stars.

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large combined sample of normal giant stars. A χ^2 test in a 2×2 contingency table indicates that the possibility that the R stars have a normal binary frequency can be rejected at the 98% significance level!

Now, it is much more difficult to prove that a class of stars has *no* binaries, than it is to prove that a class of stars such as the Barium stars are *all* binaries. In the latter case, if a star or two are found to have constant velocity, this can be reconciled by a high orbital inclination and/or large separation, for example. In contrast, normal giants have a rather low frequency themselves (~15–25%). Therefore, it only takes two or three binaries to turn up amongst R stars to remove the significance of the result. However, suppose we take the statistics at face value. How can we reconcile the result that the R stars appear to lack binaries? A possibility is that the R stars were once all close binaries, with separations too small to survive the expansion as the star evolved up the giant branch. We have talked a lot about binary mass-transfer from an AGB star to form a Barium or a CH star. What happens, however, to binaries that have separations that are too small? Various authors have discussed common-envelope evolution. It could be that a companion spiraling into the center of an evolving giant star, either during the helium core flash or afterwards, could cause this material to be mixed to the surface.

The assumption that the carbon that is polluting the atmospheres of the R stars came from the helium core flash (e.g. Dominy 1984) is reasonable. The R stars do not show the enhanced *s*-process material that is a signature of all other types of carbon stars originating on the AGB. The R stars, it appears, were created in some other way. In addition, there do not seem to be main-sequence precursors to R stars. The Barium and CH stars appear to be just evolved sgCH stars. Green & Margon (1994) have reported enhanced abundances for *s*-process elements in all six dwarf carbon stars that they observed. The R stars appear to be ones that are polluted with carbon at a more evolved state, therefore, and it is very reasonable that this might be at the helium core flash. It appears difficult to comprehend, however, just how this carbon can be mixed out to the surface under conventional stellar evolution.

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Discussion

Feast: Is it possible that the R stars are very wide binaries which have undergone only a small amount of mass transfer?

McClure: We can observe binaries with periods of 15 years or so. I don't think you will get much mass transfer with so widely separated stars.

Frogel: From Ba star orbits you can probably set limits on the size of orbits needed to get mass transfer. You can also make estimates for sizes of R stars. Then you can see if these two numbers are consistent with the hypothesis that R stars engulf their stellar companions.

McClure: I have only done all this analysis of my velocities very recently while preparing for this meeting, so I haven't looked into details such as you mention.

Lloyd Evans: Perhaps it is time to consider alternatives to nuclear astrophysics, such as chemical fractionation in circumstellar material (such as exists around the J-silicate stars), to explain the properties of the R stars.

Zhigang Gong, who single-handedly represented the PRC at the symposium, ponders the ruins of Perge.

This stork calls Perge home.