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The RV Tauri phenomenon and binarity*

H. Van Winckel[1,], C. Waelkens[1], J.D. Fernie[2], and L.B.F.M. Waters[3]**

[1] Instituut voor Sterrenkunde, K.U. Leuven, Celestijnenlaan 200B, B-3001 Heverlee, Belgium
[2] David Dunlap Observatory, University of Toronto, Box 360 Richmond Hill, Ontario, L4C 4Y6, Canada
[3] Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

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Abstract. We present accurate radial velocity measurements on the pulsating extremely iron-deficient post-AGB object HD 52961 and the RV Tauri star EN TrA (HD 131356) proving them to be binaries. Our long-term photometric monitoring campaign shows that the RV Tauri photometric class "b" phenomenon in HD 52961 is due to variable circumstellar extinction during orbital motion.

By comparing carefully the observational characteristics of RV Tauri stars and the class of extremely iron-deficient post-AGB objects we conclude that binarity is a widespread phenomenon in the RV Tauri class of objects. The observed chemical depletion patterns, weak circumstellar CO emission, peculiar spectral energy distribution and the difference in photospheric class of the RV Tauri objects can all be naturally explained by assuming that the circumstellar material is not freely expanding, but trapped in the binary system.

Key words: stars: oscillations – stars: AGB and post-AGB – stars: individual: HD 52961, En TrA (HD 131356), HR 4049 – stars: evolution – stars: binaries: spectroscopic

1. Introduction

RV Tauri stars are rare variable supergiants of spectral type F, G or K characterised by alternating deep and shallow minima in their light curves. The formal periods between two successive deep minima are in the range between 30 and 150 days and the amplitude may reach up to 4 magnitudes in V (see the General Catalogue of Variable Stars, Kholopov et al. 1985). A wide spectrum of photometric behaviour exists, ranging from a strict alternation of the two stable photometric minima to an almost random distribution of amplitudes. There is as yet no general agreement as to the nature of the pulsations, and several theories have been put forward (Pollard et al. 1997).

With their high luminosity and often large IR-excesses due to thermal radiation from circumstellar dust, there is general agreement that RV Tauri stars are low mass objects in a post-AGB evolutionary stage (Jura 1986).

For historical reasons, the classification of RV Tauri stars is confusing. The photometric classification system distinguishes two sub categories: objects with a constant mean magnitude are labeled "a" while those with a long term variation of their mean magnitudes are labeled "b". The secular variations have timescales between 600 and 1500 days (or more) and amplitudes of up to two magnitudes. Preston et al. (1963), on the other hand, introduced a spectroscopic classification distinguishing three subclasses labeled "A", "B" and "C". Objects of class "A" have spectral type G to K and sometimes display TiO bands at minimum light. They are generally strong-lined objects. The "B" type class stars have spectral type Fp(R) and are generally weak-lined objects showing strong CN and CH bands indicative of a high C abundance. The "C" class comprises variables of spectral type Fp, without enhanced CN and CH, which also display a weak-lined spectrum. The RV Tauri objects discovered in globular clusters tend to be "C" type stars. There is no correlation between the spectroscopic and photometric classes. Throughout the paper we will use capital letters to refer to the spectroscopic classification.

In a series of papers, Giridhar et al. (1994, 1998) and Gonzalez et al. (1997a,b) have shown that the chemical composition of the field RV Tauri stars of spectroscopic groups A and B resembles the gas phase composition of the interstellar medium (ISM): refractory elements are depleted while species with a low dust-condensation temperature probably show the initial abundance, which for some species may eventually be altered by stellar chemical evolution. The initial metallicity of these objects cannot be deduced from the actual Fe abundance, but only inferred from the abundance determination of elements like S and Zn with a low condensation temperature. The actual metallicities observed range between [Fe/H] = -0.5 and -2.3 but reflect an efficiency difference of the depletion process rather than an initial metallicity spread. The initial metallicity is estimated to be larger than [Fe/H] = -0.7 in all A and B objects studied up to now. The C-type RV Tauri stars in the field and in globular clusters do *not* show depletion patterns and the low metallicity ([Fe/H] ≤ -1.0) of these objects does reflect the ini-

Send offprint requests to: H. Van Winckel
(Hans.VanWinckel@ster.kuleuven.ac.be)

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** Postdoctoral fellow of the Fund for Scientific Research, Flanders tial composition, which may indicate that the depletion process is not efficient at these low initial metallicities (Giridhar et al. 1998).

Similar but even more strongly depleted photospheric abundance patterns are observed in the extremely iron-deficient *binary* post-AGB stars (Venn & Lambert 1990; Bond 1991; Van Winckel et al. 1992). This group consists of HR 4049 (Lamers et al. 1986; Lambert et al. 1988; Waelkens et al. 1991a), HD 52961 (Waelkens et al. 1991b), HD 44179 (Waelkens et al. 1992), BD$+39^{\circ}$4926 (Kodaira et al. 1970) where the observed iron abundances range from [Fe/H] = -4.8 to -3.0, and the less extreme cases HD 46703 (Bond & Luck 1987) and HD 213985 (Waelkens et al. 1995). The fact that all these extremely deficient stars proved to be binaries (Van Winckel et al. 1995) with the observed presence of dust discs around some of them (Waelkens et al. 1991a; Roddier et al. 1995; Bond et al. 1997), and the similar patterns observed in λ Bootis stars (Venn & Lambert 1990) led Waters et al. (1992) to suggest that the gas-dust separation needed to account for the depletion pattern is likely to take place in a disc. The fact that the central dust-torus in the famous C-rich Red-Rectangle nebula is oxygen rich indicates that such a torus can be extremely stable (Waters et al. 1998).

Although HR 4049, HD 44179 and HD 213985 are not pulsating stars, they do show a long-term photometric variability. In those three stars, the fundamental period of the photometry is the *orbital* period and the photometric behaviour can be understood as caused by variable circumstellar extinction in the case of HR 4049 and HD 213985 (Waelkens et al. 1991b; Waelkens et al. 1995) or in terms of a changing scattering angle during orbital motion for HD 44179 (Waelkens et al. 1996). The photometric extrema occur at conjunction.

Recently AC Her, one of the prototypes of the RV Tauri stars, was found to be a member of a wide binary system as well (Van Winckel et al. 1998). AC Her also displays the photospheric chemical depletion pattern and there is strong observational evidence from CO rotational line measurements, sub-mm continuum measurements and from a full 2.3–40 μm SWS ISO spectrum that AC Her is also surrounded by a long-lived dust disc (Van Winckel et al. 1998) similar to the oxygen-rich dust disc observed in the Red Rectangle (Waters et al. 1998), thus strengthening further the fact that binarity is a necessary condition for the depletion process to occur. Since the depletion patterns are observed in all field RV Tauri stars of type A and B studied so far (Gonzalez et al. 1997b), the binary nature of all these stars should be addressed together with the absence of the depletion patterns in C-type RV Tauri stars (Gonzalez & Lambert 1997; Giridhar et al. 1998).

In this paper we will discuss the possible binary nature of RV Tauri stars in more detail. In Sect. 2 we focus on the extremely metal deficient object HD 52961: this pulsating star is very similar to an RV Tauri object of photometric class b (Waelkens et al. 1991b). Thanks to our long multicolour photometric campaign we could determine that the long-term secular change in the mean magnitude is also caused by variable circumstellar extinction during orbital motion. In Sect. 3 we treat our radial velocity data of EN TrA (HD 131356), another RV Tauri binary where the orbital period could be determined. Finally we compare all the observational evidence for the binary nature of the RV Tauri objects, review the RV Tauri stars where the binary nature is observed and discuss the few objects where the period and orbital elements could be identified. We discuss our findings in the broader context of stellar evolution by comparing several observational characteristics of RV Tauri stars with hotter post-AGB binary objects and suggest the possibility that the binary fraction of RV Tauri stars is very high. The photometric classification could then be understood, not as a physical difference between the objects, but as a geometric projection effect. We suggest that the viewing angle onto the circumstellar dust torus determines the photometric class.

2. HD 52961

HD 52961 is the only extremely iron-deficient post-AGB star showing clear radial pulsations (Waelkens et al. 1991b). Although there are significant cycle-to-cycle variations (see Sect. 2.2.1) the photometric period of 70.8 days is stable and conforms to the interpretation that HD 52961 is an old evolved low-mass object with a high luminosity (M_V=–4.6) (Fernie 1995). The infrared excess due to thermal radiation of circumstellar dust (Waelkens et al. 1991b) further strengthens this interpretation, and although the characteristic shallow and deep minima of the light-curve are missing, the period of the pulsations, the effective temperature, the IR-excess and evolutionary stage are very similar to those of the RV Tauri objects.

2.1. Radial velocities

The binary nature of HD 52961 was documented by Van Winckel et al. (1995), but we have enlarged our dataset of radial velocities since then and are now able to deduce the orbital period and orbital elements. The radial velocity changes are certainly not due to the pulsations since there is no correlation with the stable pulsation period of 70.8 days. Moreover, integrating the large amplitude over half the period would give an increase in radius of about one stellar radius which is certainly not compatible with the spectra at different epochs nor with the photometry.

The radial velocities are all based on high-resolution spectra since the object is so metal depleted (Waelkens et al. 1991b) that no cross-correlation velocity measurements were possible due to the scarcity of lines. We obtained the spectra over several runs on the CES spectrograph fed by the 1.4m CAT telescope of the ESO La Silla Observatory in Chile and on EMMI mounted on the 3.5m NTT telescope of the same observatory. We used mostly the C I multiplet lines around 4770, 7115 Å or the C I line at 6587.622 Å for the velocity determination. The radial velocities were found to be periodic with a period of 1310 $\pm$ 8 days which we interpret as the orbital period. The radial velocities folded on the 1310 day period are shown in Fig. 1 and the orbital elements are listed in Table 1. The complete dataset covers a total time span of 3255 days which is 2.5 cycles, but unfortunately the radial velocity curve is not well sampled in or-

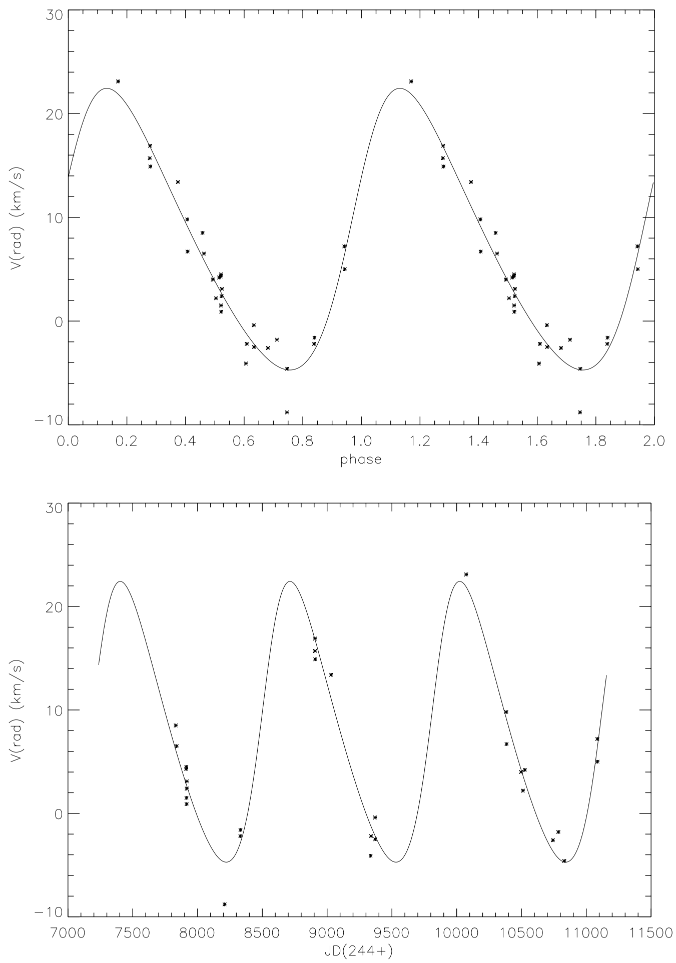

Fig. 1. The *top panel* shows the radial velocity measurements of HD 52961 (asterisk) folded on the 1310 days period, together with the best fit as discussed in the text. Perihelium passage is phase 0 (JD 2449851) The *bottom panel* shows the complete data set in the time-domain. The Julian date is given from JD 2440000 onwards as in other figures of this paper.

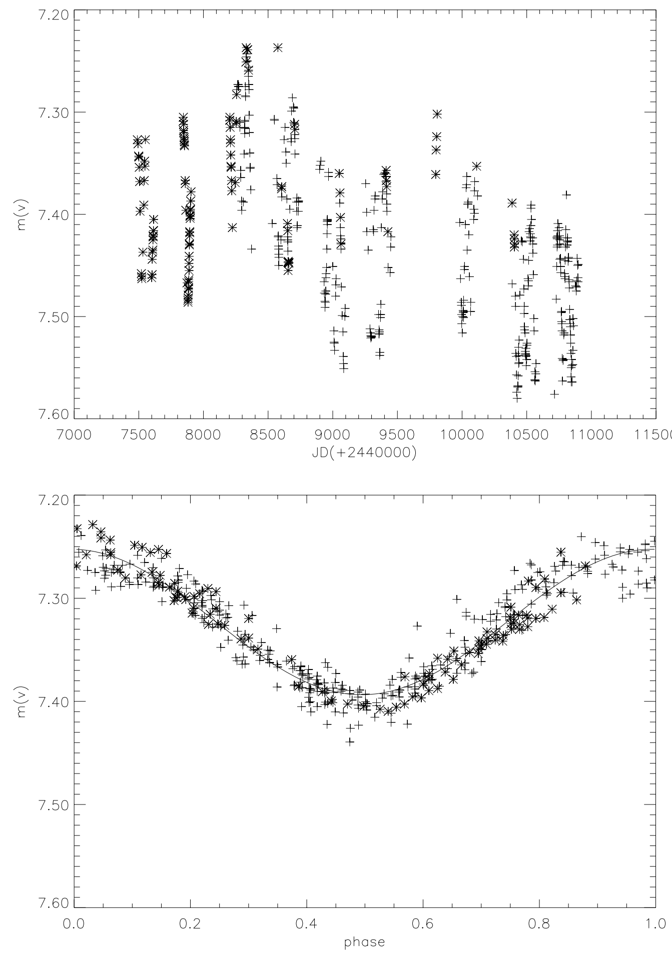

Fig. 2. The *top panel* shows the complete photometric dataset. The asterisks are the Geneva photometric measurements, the crosses the Johnson V-band. The *bottom panel* shows the V-magnitudes folded on the 70.8 days period but corrected for the secular variability. The full line is the sine representation of one pulsational cycle.

bital phase because the period is so close to 3 years: data points are scarce when the supergiant moves from the ascending node to the descending, thus limiting the accuracy of the eccentricity determination. The Lucy & Sweeney (1971) test gave a significance level of only 1% for the orbit to be circular so we can conclude that the non-zero eccentricity is real.

2.2. Photometry

2.2.1. Pulsation and secular variation

The photometric lightcurve of HD 52961 was analysed by Waelkens et al. (1991b) and Fernie (1995): on top of the stable pulsation period of 70.8 days, a secular change in the photometric behaviour on a much longer timescale was observed. To investigate this secular change in detail, we combined these two photometric sets with different pass-bands, supplemented with new measurements since then. The Geneva photometric dataset (112 measurements between JD 2447488 and 2450405) was obtained with the Geneva Photometric telescope at La Silla, Chile, while the Johnson set (336 measurements between JD 2448257 and 2450897) was obtained with the Automatic Photoelectric Telescope (APT) on Mount Hopkins. The long-term photometric behaviour is illustrated in the upper panel of Fig. 2 where the complete photometric V-band dataset is shown in the time-domain. The star brightened till about JD 2448350 and then faded till about JD 2449100. Unluckily the sampling is very poor in between JD 2449500 and JD 2449950 but the star recovered between JD 2449100 and JD 2449800 and afterwards started to fade again. Since the relation between the two different colour systems is not well calibrated in the spectral domain of an F supergiant (Cramer 1984), we only used the complete dataset of the V-band magnitudes, which is very similar is both systems, and did not combine the colours.

To determine the pulsation curve we corrected the individual cycles for the secular change by shifting every pulsation cycle such that the mean magnitude corresponded to the mean magnitude of a well sampled reference cycle. This mean mag-

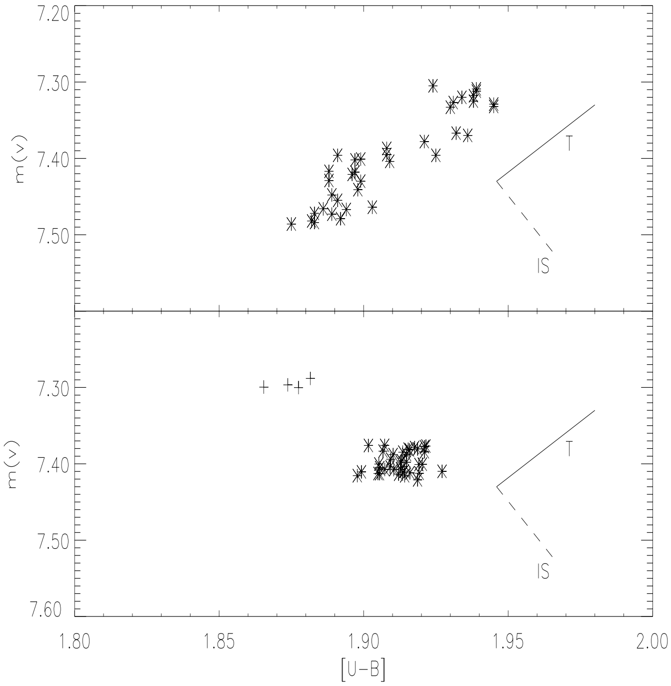

Fig. 3. The colour-magnitude diagrams of the Geneva photometry. The *top half* gives the uncorrected magnitudes and colours of one well-sampled pulsation cycle. The full line indicates the expected slope of an effective temperature variation in a star with the same atmospheric parameters as HD 52961. The broken line gives the slope of the mean interstellar extinction law. The temperature change during one pulsation cycle is clear. The *bottom half* shows the pulsation-corrected magnitude and colour measurements during two different pulsation cycles (two different symbols). The sampling of the two cycles was not equal.The difference in mean magnitude of the two pulsation cycles can best be explained by a change in reddening.

nitude of the individual cycles was determined by a sine-fit with a fixed amplitude of 0.07 mag and a zero phase-shift. We used the ephemeris of Fernie (1995)

$$JD_{max} = 2448267.28 + 70.798E$$

for the pulsation phase definition. On the lower panel of Fig. 2 the V-band photometry is shown, corrected for this secular change together with the sine-fit through the folded and corrected data.

Next, we corrected the total dataset for the pulsation amplitude using this sine fit with an amplitude of 0.07 mag as a representation of the mean pulsation cycle. In Fig. 6 we display the mean V-magnitude for every measured pulsation cycle. Since the cycle-to-cycle pulsational variations amount to 0.05 magnitudes peak-to-peak (see the width of the folded lightcurve in the lower panel of Fig. 2), there remains scatter of that order of magnitude per pulsation cycle, but one can see that the total secular photometric amplitude measured so far is certainly significant and amounts to about 0.22 mag. in V.

Fernie (1995) discovered that the fading of the mean light from JD 2448200 to 2449000 was accompanied by a reddening with a ratio of the V magnitude and the B-V colour of 3.8 ± 0.5, similar to the interstellar reddening law. The complete APT Johnson dataset discussed here conforms to these findings. Our 7 colour Geneva photometric dataset also points to the same phenomenon. The best primary colour to test the occurrence of variable circumstellar reddening is the [U-B] Geneva colour: a change in the effective temperature of HD 52961 will lead to a negative gradient of $dm_v/d[U-B]) = -2.9$ in the colour-magnitude diagram while variable circumstellar reddening will lead to a positive gradient with a slope of 4.7. One can see the effect of the pulsation correction in Fig. 3. On the top panel the main trend during one pulsation cycle in the uncorrected V-[U-B] magnitude-colour plot is one of a temperature change and the slope coincides with the estimated one on the basis of the tables published by Allen (1973). The bottom panel shows the pulsation-corrected magnitude-colour diagram of the same pulsation cycle together with the data of another pulsation cycle with a different mean magnitude. It is apparent that the variation of the mean magnitude is due to variable reddening with a slope which is very similar to the ISM extinction law. We can conclude that there is good observational evidence that the secular variability in the light curve of HD 52961 is caused by variable circumstellar extinction.

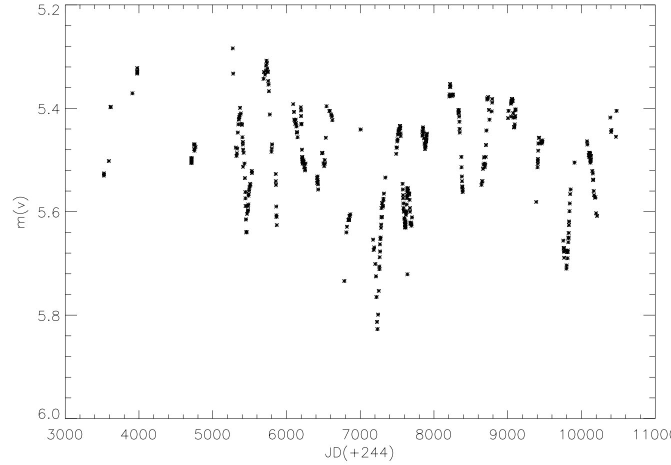

Fig. 4. The total lightcurve in the Geneva V filter of HR 4049 obtained with the Swiss Telescope at La Silla, ESO. Besides the variation with the orbital period (429 days), variation on a much longer time-scale is also observed.

2.2.2. Variable circumstellar extinction

We compared in detail the secular photometric variability of HD 52961 with the variability of another extremely iron-deficient post-AGB star HR 4049, which was the first such object where variable circumstellar extinction was detected (Waelkens et al. 1991a). We have accumulated much more data on this star since 1991, so we display some of the plots again here. The Geneva V-band magnitudes in the time-domain are shown in Fig. 4 while the folded light, [U-B]-colour and radial-velocity curves are shown in Fig. 5. The orbital period is 429 days.

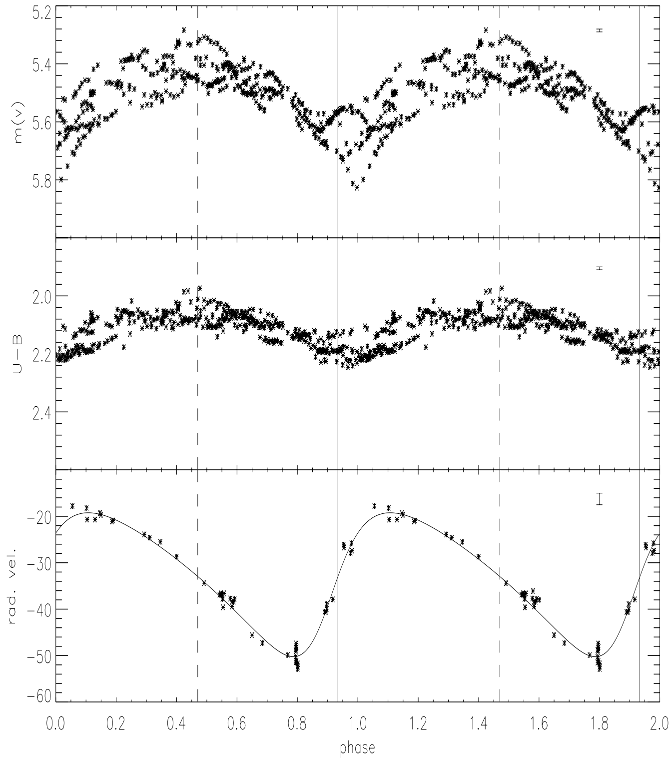

Fig. 5. The Geneva V-band photometric lightcurve, [U-B] colour curve and radial velocity curve folded on the 429 days binary period of HR 4049. The phase of inferior (superior) conjuction is marked with a full (dashed) line. HR 4049 is faintest and reddest at inferior conjunction and brightest and bluest at superior conjunction. A typical error-bar for an individual measurement is shown in the upper-right corner of each panel.

There is a clear photometric variability on two different time-scales in this non-pulsating binary: the first corresponds to variable circumstellar extinction during orbital motion. The correlation with the orbital period is shown in Fig. 5: light maximum occurs at superior conjunction while light minimum occurs at inferior conjunction. This behaviour can best be explained as due to an aspect angle of the binary where the circumstellar material is located in a thick circumbinary dust disc: when the star is in inferior conjunction, the circumstellar extinction is maximal in the line-of-sight to the supergiant while at superior conjunction the extinction is minimal (Waelkens & Waters 1993). This geometric model was also founded on the spectral energy distribution (SED) analysis where a broad IR-excess points to a wide range in temperature of the circumstellar material (e.g. Waters et al. 1997 and references therein).

On top of this periodic variation, there is a photometric variability on an even longer timescale (see Fig. 4). The Geneva colours point, also for this variability, to variable circumstellar extinction. This long trend is probably caused by inhomogeneities in the dust disc around the system.

Since HD 52961 is a pulsating star, the photometric behaviour is more complex. In Fig. 6 we plotted the radial velocity curve on top of the pulsation corrected mean V-band magnitude defined in previous sections. For every observed pulsation cycle we only plotted the mean of the corrected V-band magnitudes. Although the amplitude of the variations is much smaller than in the case of HR 4049, one can see that also in HD 52961, with a much longer orbital period of 1310 days, the variable circumstellar extinction appears to have the same time scale as the orbital motion. A local maximum near JD 2448400 seem to occur near inferior conjunction. Unfortunately the region between JD 2449500 to 2450000, where a rapid change was to be expected, is not sampled, but the bright photometric point on JD 2449802 is based on four high quality Geneva photometric measurements and there is thus no reason to doubt the bright stage of HD 52961 at that epoch, again at inferior conjunction. The epochs of local minima are less clear but seem to occur around superior conjuction at JD 2447792 and somewhat after superior conjunction at JD 2449102. HD 52961 was faint between JD 2450300 and 2450900. Continuous well-sampled monitoring of HD 52961 should be pursued but it seems that the basic time-scale of the secular photometric variations in HD 52961 coincides with the orbital period of 1310 days. If correct, HD 52961 should become brighter again after JD 2450900. Since the SED of HD 52961 also points to a broad temperature range of the circumstellar material (Waelkens et al., 1991b) there are good reasons to assume that the model for HR 4049 applies to HD 52961 as well: the variations of the mean light are due to variable circumstellar extinction during orbital motion.

However, while HR 4049 is faintest at inferior and brightest at superior conjunction, the reverse is true for HD 52961: light maximum occurs near inferior and light minimum near superior conjunction. The location of at least part of the obscuring dust must therefore be different in both systems. The fact that light minimum for HD 52961 occurs when the companion star is between the observer and the supergiant suggests that the obscuring dust is located around or near this companion. It is not unlikely that the different geometric location of the dust disc in both systems is linked with the different orbital periods. In the closer binary HR 4049, the disc has been formed after mass loss through the external Langrangian point L_2, while for the wider system HD 52961 the mass transferred through the inner Langrangian point L_1 has settled in a disc surrounding the companion.

Mass estimates for the companion star can be seen in Fig. 9: adopting a typical post-AGB mass of 0.6 $M_\odot$, the companion has a minimal mass of 0.9 $M_\odot$ while for an inclination of 60^o the companion has a mass of 1.1 $M_\odot$. As in HR 4049, there is no observational evidence that the companion is a compact degenerate object.

It is important to note that the detailed SED of HD 52961 also indicates the presence of circumstellar dust with a wide range of temperatures (Waelkens et al., 1991b). The broad IR-excess is expected for a system where the circumstellar material is trapped in a dusty disc (Waters et al., 1997).

We can conclude that the pulsating star HD 52961 is a member of a binary system with an orbital period of 1310 days. The long-term secular photometric variations can best be understood as due to variable circumstellar extinction during orbital motion with the star faintest and reddest at superior conjunction.

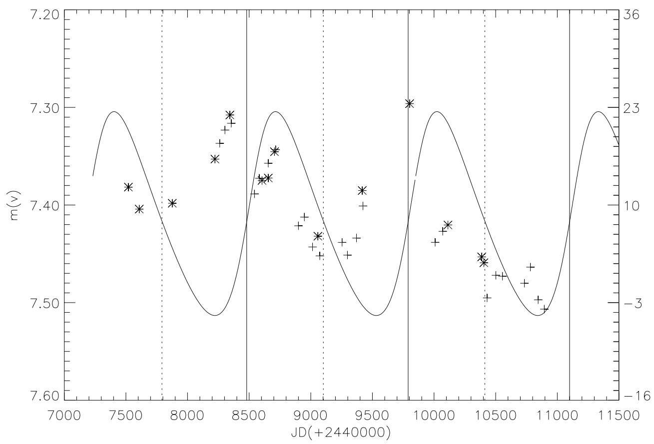

Fig. 6. The mean V-band magnitude for every pulsation cycle of HD 52961. The asterisks are the Geneva photometric measurements, the crosses the Johnson V-band. The full line gives the radial velocity curve (right-hand axis). The full (dotted) vertical line indicates phases of inferior (superior) conjunction.

3. EN TrA

EN TrA (HD 131356) is a poorly studied variable star that was originally classified as a classical Cepheid, but the photometric study of Pel (1976) revealed the RV Tauri nature of the object. His complete data set gives a timescale of 80 days in-between two deep minima. A photometric period of 34.54 days was given by Grayzeck (1978), but this was based on only 13 photometric points obtained in two observing runs, so the period has only an indicative value and gives the timescale between two successive minima. The radial velocities in that paper have only an accuracy of 10 $\mathrm{km\,s^{-1}}$ and are unfortunately not useful as a supplement to our data set. The IR-properties were discussed by Lloyd Evans (1985) who found a fairly large excess at K and L and typical RV Tauri far-IR colours. Since the object has a large broad IR-excess it was also identified in the systematic search for optically bright post-AGB stars on the basis of the IRAS point-source catalogue by Oudmaijer et al. (1992).

Our photometric data-set contains 68 measurements with a total time-span of 2244 days (see Fig. 7). We could not find a significant photometric period in our data. Our radial velocity data set contains measurements obtained with the cross-correlation CORAVEL radial-velocity spectrometer (Baranne et al., 1979) mounted on the Danish 1.5m telescope at ESO, La Silla, supplemented with radial velocities obtained from high-resolution spectra obtained by the CES spectrometer mounted on the 1.4m CAT telescope at ESO La Silla. The complete set is given in Fig. 7. In the 29 CAT+CES spectra we obtained in the period between 12/3/1991 and 25/3/1996 we did not observe line-splitting but only equivalent width variations (Van Winckel 1997).

Unfortunately the sampling of the radial velocity measurements is such that we cannot exclude the possibility that we only see pulsational variations. There are, however, observational indications that the large velocity amplitude is indeed due to orbital motion. First is the large velocity amplitude of 43 $\mathrm{km\,s^{-1}}$ compared to the small photometric amplitude of 0.6 magnitudes

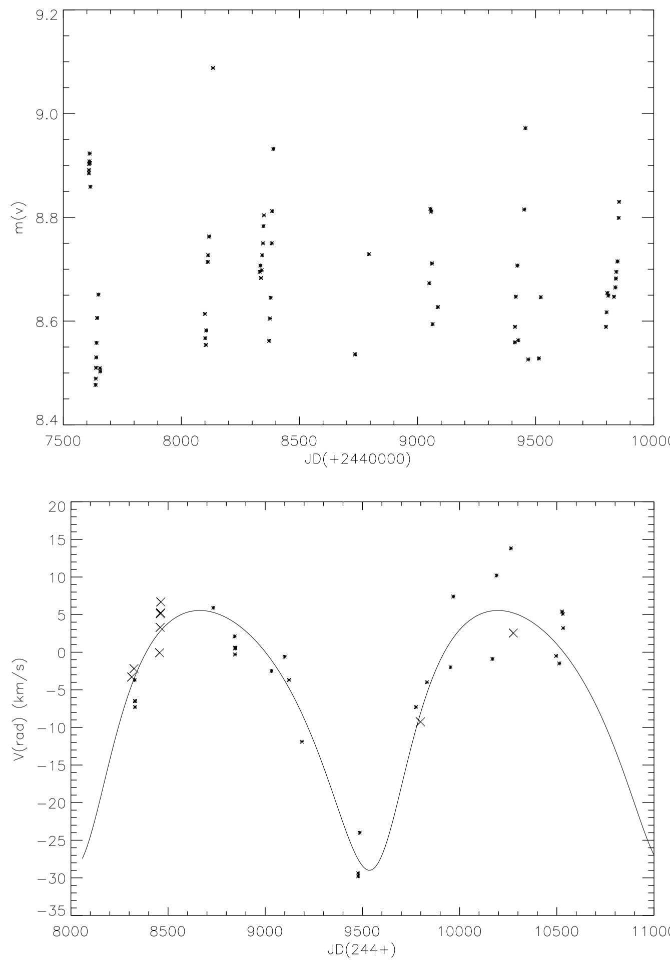

Fig. 7. The *top panel* shows the photomectric data of EN TrA in the V-band of the Geneva system. The *bottom panel* shows the radial velocity measurements of EN TrA. The crosses are the CORAVEL measurements, the asterisks the CES datapoints. The full line gives the tentative fit discussed in the text.

in the V-band. Indeed, in an extensive study of RV Tauri stars Pollard et al. (1996; 1997) give in Table 3 of the 1997 paper a list of RV Tauri stars with measured radial velocity and light curve amplitudes. Stars with comparable period and velocity amplitude tend to have a much larger photometric amplitude (see Fig. 8). A notable exception is IW Car, where the large velocity amplitude is determined by the long-term trend (see Fig. 27 of that paper) and we estimate the radial velocity variations due to the pulsations alone to be of the order of 10 $\mathrm{km\,s^{-1}}$. Another exception is AD Aql where the velocity amplitude is obtained from the H-alpha line absorption component. Note that in the literature bigger photometric amplitudes are given for some objects, but since the work of Pollard et al. treats quasi simultaneous photometric and radial velocity measurements we only took those values into account.

Second, if the large velocity amplitude were due to pulsation, the long period of 80 days would indicate a total radius increase of the order of 67 $R_{\odot}$. This is not in agreement with our spectra nor with the photometry. A detailed analysis of the

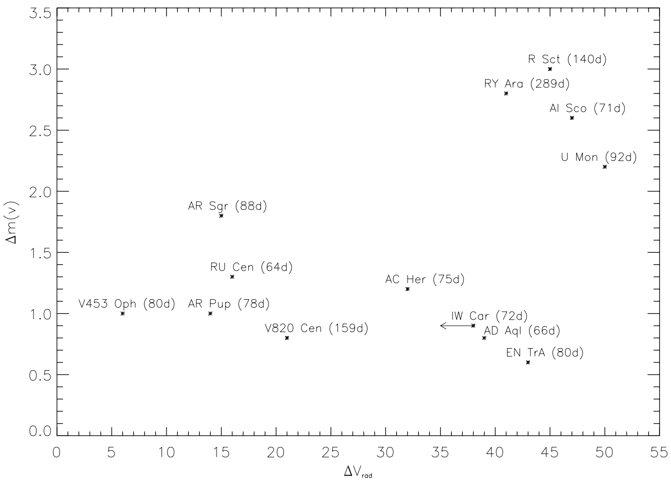

Fig. 8. The radial velocity peak-to-peak amplitude against the photometric amplitude in the V-band. The IW Car velocity amplitude is determined by the long-term trend. EN TrA shows a small photometric amplitude with respect to the velocity amplitude. Data are from Pollard et al. (1996,1997) and Gillet et al. (1992)

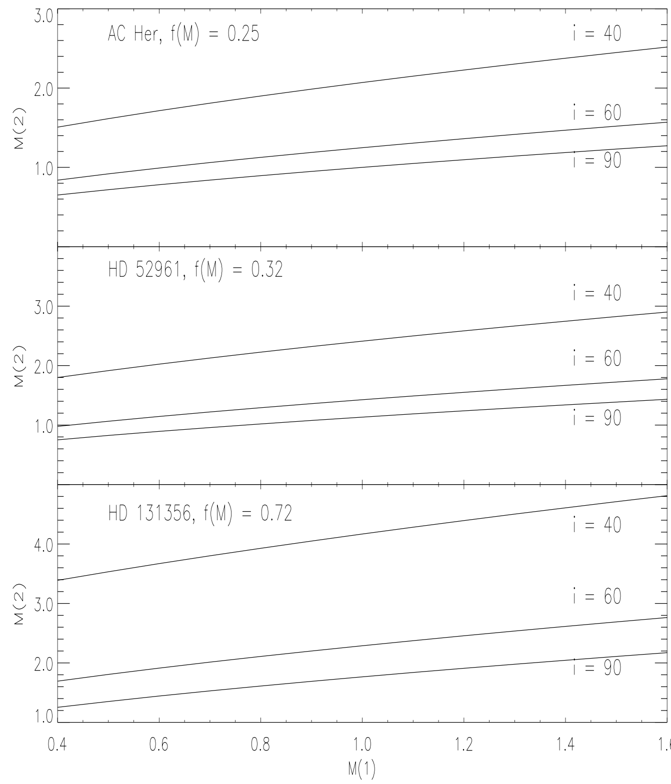

Fig. 9. The mass of the companion in function of the primary mass and the inclination for, from top to bottom, AC Her, HD 52961 and HD 131356. The mass is given in solar units.

C I line at 658.7622nm at 9 different epochs gave a mean equivalent width of 99 mÅ and an rms of 18 mÅ. The line is blended with a telluric line and we used multiple gaussian fitting to extract the C I equivalent width. The extreme values observed are 126 mÅ and 80 mÅ. Such an equivalent width change corresponds in the temperature domain of EN TrA to a temperature change of 1000 K at most, taking into account the surface gravity change. This is much smaller than expected for the estimated radius change. The photometry also points to a small temperature change. The reddening was estimated from the Geneva photometry by using the calibration of Bersier (1996) and was found to be E(B-V) = 0.19 $\pm$ 0.03. The de-reddened colour index $(B2-V1)_0$ of the Geneva photometry changes from 0.16 to 0.40 which corresponds, following the calibration of Meynet & Hauck (1985), to a spectral type change of F5 to F9 adopting a Ib luminosity class, again pointing to a relatively small temperature change during the pulsation.

We are therefore confident in interpreting the observed long term trend in the radial velocity data as due to orbital motion and find an orbital period of 1534 $\pm$ 21 days. Other orbital elements are listed in Table 1 and the complete velocity data set is shown in Fig. 7.

4. Discussion

Our long-term radial velocity and photometric monitoring programmes revealed that: 1) the RV Tauri star EN TrA and the RV Tauri-like object HD 52961 are binary stars; 2) the RVb photometric phenomenon of HD 52961 has the same time-scale as the orbital period and is probably caused by variable circumstellar extinction during orbital motion. The relation between the extremely iron-deficient post-AGB stars and the RV Tauri stars showing the same photospheric depletion patterns is therefore further strengthened. We will discuss these new findings by comparing the observational characteristics of both groups in more detail.

4.1. Radial velocities

The binary nature of the extremely iron-deficient post-AGB stars is well established and there is ample observational evidence that the circumstellar dust in these objects is not located in a slowly expanding shell but trapped in a thick circumbinary torus. Waters et al. (1992) suggested that this dust disc is the likely place for the gas-dust separation to take place in evolved stars and that such a dust disc is probably formed by binary interaction during previous evolutionary phases of high mass loss.

Since the RV Tauri stars of spectroscopic groups A and B show the same, albeit less extreme, abundance patterns as the extremely iron-deficient post-AGB stars, the binary nature of these RV Tauri stars should also be addressed. If indeed binarity is a necessary condition for the depletion process to occur, these RV Tauri stars are also surrounded by a stable dust disc; if not, such a dust disc only makes the process more efficient and there are also other mechanisms depleting RV Tauri photospheres. These other mechanisms could be intimately related to the pulsation characteristics of the RV Tauri stars (Giridhar et al. 1998 and references therein) or to the history of the mass loss (Mathis & Lamers, 1992). The fact that HD 52961, the object common to both groups, is a binary star where the dust is

Table 1. The known orbital elements of RV Tauri stars AC Her, EN TrA, U Mon and the highly similar objects HD 52961 and ST Pup. The data for AC Her are from Van Winckel et al. (1998); for U Mon from Pollard & Cottrell (1995) and for ST Pup from Gonzalez & Wallerstein (1996)

	AC Her		EN TrA		U Mon		HD 52961		ST Pup	
		σ		σ		σ		σ		σ
Period (days)	1194	8	1534	21	2597	6	1310	8	410	3
a $\sin i$ (AU)	1.39		2.34		3.6	0.9	1.60		0.65	0.03
F(M) ($M_\odot$)	0.25		0.72		0.92	0.02	0.32		0.22	0.03
K ($\mathrm{km\,s^{-1}}$)	12.7	0.3	17.2	1.3	17	1	13.6	0.8	17.2	0.7
e	0.12	0.02	0.28	0.07	0.43	0.05	0.21	0.05	0.03	0.02
ω (°)	114	12	202	11	191	6	292	9	141	47
T_0 (JD24+)	47129	35	49586	58	27573	58	49851	34	48779	5
γ ($\mathrm{km\,s^{-1}}$)	-33	0.2	-7.1	0.5	$+34.9$	0.7	$+7.8$	0.5	$+16.1$	0.6

trapped in the system strengthens the binarity model. The binary nature of ST Pup, the only W Vir star known till now to display depletion patterns in the photospheric abundances (Gonzalez & Wallerstein 1996), also favours the first suggestion.

To our knowledge, the only binary RV Tauri stars where the orbital elements have been determined till now are AC Her (Van Winckel et al. 1998), U Mon (Pollard & Cottrel 1995) and in this paper EN TrA (see Table 1). They are by no means the only ones where orbital motion is detected: others are IW Car (Pollard et al. 1997) and EP Lyr (Gonzalez et al. 1997a). Moreover, long period trends in the radial velocity data other than of pulsational origin have been measured in most RV Tauri stars of photometric class b (Pollard et al. 1997). This latter observational fact has been used by Percy (1993) and Fokin (1994) to propose a binary origin of the RVb objects. This was investigated in the the spectroscopic and photometric monitoring programmes of Pollard at al. (1996, 1997). They found that in most RVb stars in their sample, the periodic fading of the mean light is accompanied by a reddening of the colours. A noticeable exception is AR Pup where no significant colour variation was observed. Pollard et al. (1997) suggest that RVb objects are indeed binaries but since some of the objects of class b show a damping of the pulsational amplitude during long-term minimum, they propose a qualitative model where the companions interact during some orbital phases to cause a damping of the pulsation.

That binarity of RV Tauri objects is not limited to those of photometric class b was discovered as early as 1931 by Sanford (1931), who suggested that AC Her is a single-lined binary. This was confirmed recently by Van Winckel et al. (1998) who found an orbital period of 1200 days.

4.2. SED

Since large-amplitude pulsational radial-velocity varations, strong line-asymmetries and even line-splitting at some pulsational phases render direct detection of orbital motion cumbersome, alternative tracers of the possible binary nature of pulsating evolved stars should be explored.

One possibility is a detailed analysis of the SED. Indeed for the class of optically bright post-AGB stars, there is a tight correlation between the presence of a broad IR excess, indicating the presence of hot (T_{dust} = 500–1300 K) as well as cool dust (T_{dust} = 100–200 K), and binarity (Waters et al. 1997 and references therein). The hot dust in these systems is not due to recent mass-loss, but indicates that the dust is stored somewhere in the binary system, close to the central stars (Waters et al. 1993). The mass loss and mass-loss history can therefore not be deduced from the SED of these systems by applying models of a spherically symmetric expanding dust-shell. Good examples are the SED of HR 4049 (Waelkens et al. 1991a), where the cool dust component is very small and only a hot dust component is present, and HD 44179, the central star of the Red-Rectangle, where the broad IR excess is huge and the IR-luminosity is 33 times stronger than the optical luminosity (Leinert & Haas 1989; Waelkens et al. 1996). Within the class of extremely iron-deficient post-AGB objects, there is a wide range in the strength of the total IR-excess, but the shape of the IR-excess indicates that the circumstellar shell is not freely expanding (Waters et al. 1997; Van Winckel et al. 1996). This correlation between binarity and the shape of the IR-excess was enlarged and further strengthened by the discovery of the binary nature of the pulsating star ST Pup with its broad IR-excess (Gonzalez & Wallerstein 1996), and in this paper by the binaries HD 52961 and EN TrA which also display a hot dust component.

The IR excesses of RV Tauri stars also display a wide variety in strength. The far IR colours detected by IRAS were discussed by Jura (1986) and Raveendran (1989), while ground based near-IR measurements were compiled by Gehrz (1972), Gehrz & Ney (1972) and Lloyd Evans (1985). First, in most RV Tauri stars a considerable near-IR excess is observed at K and even in some cases at H (Lloyd Evans 1985; Gehrz & Ney 1972; Gehrz 1972), indicating the presence of dust with a temperature of about 900 K. There seems to be no correlation between the strength of the near and far IR excesses (Lloyd Evans, 1985). Assuming a freely expanding dust-shell, Jura (1986) computed a typical post-AGB age of 500 years for the RV Tauri stars detected by IRAS and Alcolea & Bujarrabal (1991) found an even smaller value of 100 years. This is uncomfortably short since the historical record of the brightest RV Tauri stars (see e.g. Zsoldos 1993) is about 150 years. Raveendran (1989), on the other hand, did not find evidence for a considerably reduced mass-loss rate during the recent past in RV Tauri stars, as suggested by Jura (1986).

The presence of hot dust is usually attributed to recent mass-loss events, but enlarging the correlation between binarity and the presence of hot dust in optically bright post-AGB stars, another possibility is that the dust is not freely expanding but stored in a disc.

4.3. CO microwave emission

Detailed studies revealed that the physical and chemical conditions in a circumbinary disc are quite different from those in a slowly expanding dust shell. Comparison between the well-studied disc in the Red-Rectangle nebula and the RV Tauri star AC Her (Van Winckel et al. 1998) revealed that both stars display non-typical dust-characteristics having (1) oxygen-rich crystalline silicates (Waters et al. 1998), (2) remarkably weak CO rotational line emission with a small velocity width (Jura et al. 1995; Bujarrabal et al. 1988), suggesting that the gas is depleted and not freely expanding, and (3) very strong millimeter continuum flux from large dust grains.

We are not aware of a systematic (sub-)mm continuum survey of RV Tauri stars, but a few individual objects are covered in the literature. Shenton et al. (1995) conclude from a detailed study of the millimetre continuum flux that the circumstellar environment of AC Her contains a component of large (≥ 1 μm) grains and concluded that those grains are confined in the circumstellar environment and do not participate in an outflow. Van der Veen et al. (1994) concluded that RV Tauri itself also displays an important sub-mm excess and the total SED of this object does not conform to a simple outflow. Clearly a detailed homogeneous study of the (sub)-mm continuum radiation of RV Tauri stars should be pursued.

Bujarrabal et al. (1988) and Alcolea & Bujarrabal (1991) have shown than the CO rotational microwave emission in RV Tauri stars is completely independent of the 60 μm flux. They observed that not only is the expansion velocity of 4–5 $\mathrm{km\,s^{-1}}$ small compared to a typical expansion velocity of a AGB star, but also that RV Tauri stars are in general very weak CO emitters compared to their 60 μm flux. To illustrate this, we compiled from the literature all the CO (1,0) line measurements of RV Tauri stars and compared them with the CO/60μm relation of mass-losing AGB stars determined by Nyman et al. (1992). To account for differences in beam dilution between the different telescopes we transformed all the measurements to the SEST beam (15 meter telescope).

Fig. 10 clearly shows that the circumstellar environment around RV Tauri stars is deficient in CO while other known and suspected single post-AGB stars like the 21 μm objects or HD 161796 do follow the CO/60μm relation. A similar and even greater CO deficiency is observed in the Red Rectangle where the CO (1–0) line is 100 times smaller than expected from the 60 μm flux (Jura et al., 1995). The photosphere of the central star of the Red Rectangle, HD 44179, is also strongly depleted and the deficiency of the circumstellar CO gas together with the small expansion velocity of 2 $\mathrm{km\,s^{-1}}$ is interpreted as the evidence for a long-lived dusty disc in this system. A similar narrow spike is observed in the type-J carbon star BM Gem where a an orbiting disc is also thought to be present (Kahane et al. 1998). The CO deficiencies observed in the RV Tauri stars therefore mean that the cool envelope seen around RV Tauri stars is not the freely expanding AGB wind as is generally assumed and is observed in single post-AGB stars!

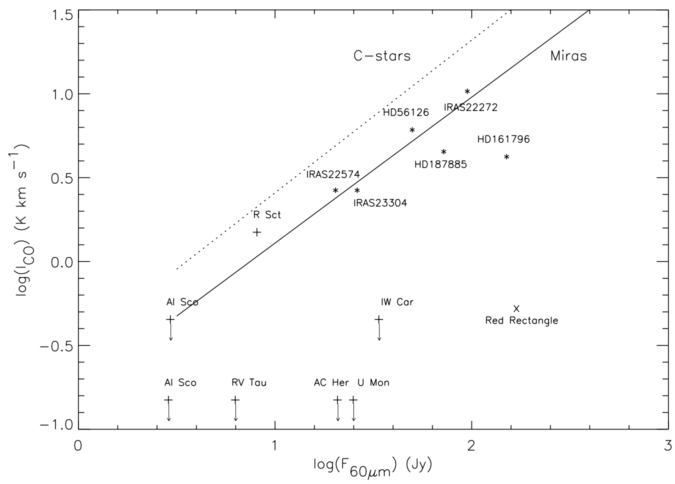

Fig. 10. The log of the integrated line-emission from the CO (1–0) line versus the 60 μm flux. The full and dashed lines indicate the observed relation for AGB Miras and Carbon stars from Nyman et al., 1992. The asterisks indicate clear detections of the 21 μm post-AGB stars together with the well studied oxygen-rich post-AGB star HD 161796. The RV Tauri stars are indicated with +-signs. Only R Sct follows the relation of the AGB objects while the circumstellar material around other RV Tauri stars is clearly deficient in CO as indicated by the upper-limits (non-detections). The same CO deficiency is observed in the Red Rectangle nebula. Data are from Bujarrabal et al., 1988; Alcolea et al. 1991; Loup et al. 1993; Van der Veen et al. 1993 and Jura et al. 1995

Moreover, since the depletion of gas is seen in the cool circumstellar dust envelope, the chemical depletion patterns observed in the photospheres of the RV Tauri objects do not have their origin in the actual pulsations but were acquired during the formation of the cool envelope. This would indicate again that the depletion process is intimately related to the special geometry of the circumstellar material.

It is interesting to note that the only RV Tauri star showing a normal CO line flux compared to the 60 μm flux is R Sct. Also the FWHM of the CO detection indicates a normal outflow velocity. The SED conforms to a freely expanding dust-shell. Since this star does not show a near-IR excess (Lloyd Evans 1985; Shenton et al. 1994) but does show high-amplitude, albeit extremely irregular pulsations, the postulated relation between the near-IR excess and recent mass-loss due to the pulsations is weakened. In the picture described above, R Sct might be a good example of a single RV Tauri star.

4.4. Photometric class

Assuming that the circumstellar material is not located in a spherically symmetric expanding shell but trapped in the system, the viewing angle onto the binary orbit will determine the observational characteristics of the system. It is then quite well possible that the aspect determines the photometric class of an RV Tauri star: objects with a low binary inclination would be the class "a" objects, while those with a high inclination so that the disc is seen nearly edge-on would be the class "b" objects. We have shown that the photometric behaviour of HD 52961 points to this direction since the photometric variations follow the binary orbit. The photomertic behaviour of U Mon (Pollard et al. 1997) also strengthens this suggestion. The photometric classification therefore distinguishes not a physical difference between the objects but a geometrical one which is entirely compatible with other observational characteristics such as the lack of a clear difference in SED (Lloyd-Evans 1985; Raveendran 1989), spectral behaviour (Pollard et al. 1997) and chemical composition (Giridhar et al. 1998) of the objects of different photometric classes. Moreover the fact that in most RVb objects long-term radial velocity variations are observed (Pollard et al. 1997) and the observational indication that RVb stars are generally redder than RVa objects (Lloyd Evans 1985) are compatible with this suggestion. A detailed and homogeneous study of the SED of RV Tauri stars over a broad spectral range from UV to mm-continuum radiation should test this suggestion further.

5. Summary

In this paper we determined the orbital elements of the RV Tauri star EN TrA (HD 131356) and the similar pulsating extremely iron-depleted post-AGB star HD 52961. The RVb photometric phenomenon observed in HD 52961 is due to variable circumstellar extinction and has the same time-scale as the orbital motion. We reviewed the binary studies of RV Tauri stars in the literature and argued that binarity may very well be a common phenomenon among RV Tauri stars. The commonly observed photospheric chemical depletion pattern, the peculiar SEDs and the generally weak and, if detected, narrow microwave CO emission all fit into a picture where the circumstellar dust is not freely expanding, but is trapped in the binary system. The RV photometric class is than determined not by a physical difference, but by the viewing angle onto the flattened circumstellar material.

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