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Published in:
Astronomy & Astrophysics

Astron. Astrophys. 336, L17–L20 (1998)

ASTRONOMY
AND
ASTROPHYSICS

LETTER

Letter to the Editor

The binary RV Tauri star AC Her and evidence for a long-lived dust-disc*

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Received 16 June 1998 / Accepted 19 June 1998

Abstract. We present in this letter a homogeneous set of CORAVEL radial velocity measurements of the well studied RV Tauri star AC Her showing it to be a binary with a period of 1196 ± 6 days. The photospheric abundances are deduced using high resolution, high signal-to-noise optical spectra and prove that AC Her is another RV Tauri star displaying depletion of refractory elements, strengthening the relation between binarity and the depletion process. Our full ISO-SWS spectrum shows that the unusual broad emission feature at 8–12 μm is due to a high crystallisation fraction of the circumstellar silicates. We review all observational evidence that the circumstellar material is trapped in a long-lived disc in the system similar to what is observed in the Red Rectangle nebula.

Key words: stars: binaries: close – stars: evolution – stars: individual: AC Her, HD 44179 – stars: AGB and post-AGB

1. Introduction

The RV Tauri class of objects is characterised by photometric variations showing alternating deep and shallow minima, that are interpreted as stellar pulsations. RV Tauri stars have high luminosity and often show a large IR excess due to thermal emission from circumstellar dust grains (Jura 1986). These properties indicate that RV Tauri stars are post-asymptotic giant branch (post-AGB) objects. In a recent series of papers (Giridhar et al. 1994, 1998; Gonzalez et al. 1997a,b) is was shown that the photospheric abundances of most field RV Tauri stars are characterized by depletion of refractory elements by dust formation. The difference in metal content, labelled 'A' (strong-lined objects), 'B' (weak-lined objects with enhanced CN and CH) by Preston et al. (1963), in fact reflects a difference in efficiency of the depletion process and not in initial metallicity. The true metal deficient RV Tauri stars, not affected by depletion seem to be the 'C' class objects (weak-lined objects with absent or weak CN and CH) which include the globular cluster RV Tauri variables (Giridhar et al., 1998).

The depletion pattern of RV Tauri stars is similar to (but less extreme than) that of a small group of *binary* post-AGB stars, among which the RV Tauri star HD 52961 (Waelkens et al. 1991a; Van Winckel et al. 1992) and the Red Rectangle and its central star HD 44179 (Van Winckel et al. 1995 and references therein). The binarity of these objects and the observed presence of dust discs around some of them (e.g. Waelkens et al. 1991b; Roddier et al. 1995), and the similar patterns observed in λ Boötis stars (Venn & Lambert 1991) 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 (long-lived) disc.

In this letter we demonstrate that one of the proto-types of the RV Tauri class, AC Her, is in fact member of a wide binary system, and that it shows a pronounced depletion pattern of refractory elements in its photosphere. The previously reported C-rich nature of the star (based on the C/Fe ratio), is entirely due to this depletion. In addition, on the basis of new ISO observations, we show that the circumstellar dust is predominantly *oxygen-rich* and shows strong crystalline silicates. The dust properties of AC Her closely resemble those of the dust in the long-live disc in the Red Rectangle.

2. Radial velocities

To detect orbital motion in a highly unstable photosphere like the one of AC Her is by no means obvious since at some pulsation phases strong line asymmetries and even line-splitting is observed (e.g. Gillet et al. 1990). Our sample of radial velocities was obtained with the CORAVEL radial velocity spectrometers installed at the Swiss telecope at the Haute Provence Observatory in France and at the Danish 1.5 meter telescope at La

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* based on observations collected at the European Southern Observatory in Chile, at La Palma Spain, and with the Swiss telescope at OHP, France

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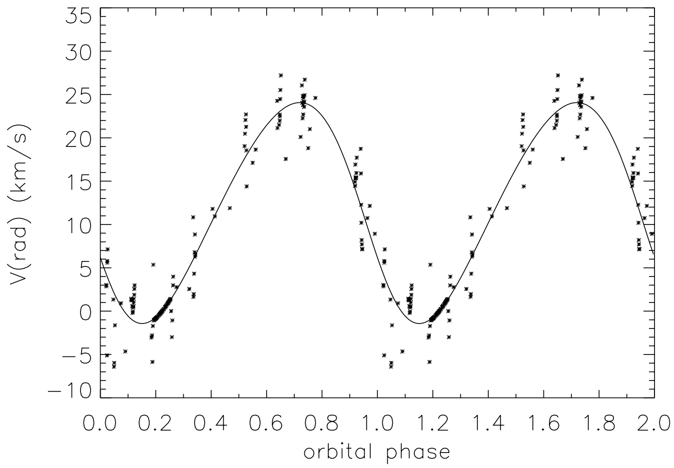

Fig. 1. The radial velocity measurements of AC Her (asterisk) folded on the 1194 days period, together with the best fit as discussed in the text. The radial velocities were corrected for the pulsation amplitude obtained in between JD+7359.4 and 7434.3. Our total dataset covers 2.8 cycles. The julian date is given from JD2440000 onwards.

Silla, Chile (Baranne et al., 1979). Since the spectrum is correlated with a hardware mask spectrum of Arcturus always the same lines contribute to the radial velocity determination which makes this sample very homogeneous. In total 144 radial velocities were obtained over a total time-span of 3329 days but 4 measurements were rejected because the line-splitting was such that no single cross-correlation function could be obtained.

Gillet et al. (1990) describe in detail one pulsation cycle observed with CORAVEL. In Fig. 4a of their work one can see that the peak-to-peak amplitude is as high as 32 $\mathrm{km\,s^{-1}}$. Thanks to the fact that AC Her is one of the stablest RV Tauri stars known we could correct the total velocity set for the pulsation amplitude by using the pulsation period determination of 75.47 days by Zsoldos (1993). The zero-point of the pulsation phase was optimized for the reference cycle and put to JD+7359. The first orbital solution was used to correct the reference pulsation cycle for orbital motion.

The final residuals were found to be periodic with a final period of 1194 ± 6 days which we interpret as the orbital period. The radial velocity curve together with the best fit is shown in Fig 1, and the obtained orbital elements are listed in Table 1. The standard deviation on the total O–C set is 2.61 and the total measured peak-to-peak amplitude of the residuals is 33 $\mathrm{km\,s^{-1}}$, which is similar to the pulsation amplitude. In total 2.8 orbital cycles are sampled. According to the Lucy & Sweeney (1971) criterion, the hypothesis that the orbit is circular can be rejected at a significance level of 0.2%. Since the rest frame velocity of the reference pulsation cycle was $-45.0\,\mathrm{km\,s^{-1}}$, the γ-velocity of the system is $-33\,\mathrm{km\,s^{-1}}$. We confirm the binary nature of AC Her which was originally proposed by Sanford (1931, 1955) who suggested a period of 1240 days with a similar amplitude.

Table 1. The orbital elements of AC Her. The $\gamma_{reduced}$ velocity is the system velocity after correction of the pulsation amplitude using one well-sampled pulsation cycle.

	AC Her	
		σ
Period (days)	1194	6
a $\sin i$ (AU)	1.39	
F(M) ($M_\odot$)	0.25	
K ($\mathrm{km\,s^{-1}}$)	12.7	0.3
e	0.12	0.02
ω (°)	114	12
T_0 (periastron) (JD24+)	47128.9	35
$\gamma_{reduced}$ ($\mathrm{km\,s^{-1}}$)	11.9*	0.2
γ ($\mathrm{km\,s^{-1}}$)	–33	
σ_{O-C}	2.61	

3. Chemical composition

We performed a chemical analysis of AC Her on the basis of high-resolution (R$\sim$50000) high signal-to-noise (S/N = 130–280) optical spectra obtained with the Utrecht Echelle Spectrograph mounted on the 4.2m William Hershel Telescope at La Palma, Spain. The spectra were obtained on two consecutive nights (23–24/2/1994; or 0.37 in phase behind deep minimum) and consist of three settings covering the entire optical range from 360nm to 1 μm. From 660nm red-wards, the orders do not overlap and the spectral domain is not not completely covered.

Our method of analysis is described in detail in Van Winckel (1997) and Decin et al. (1998), and we refer to these articles for a full description. We used the CDROM-grid of LTE model atmospheres by Kurucz (1993) in combination with his abundance calculation programme WIDTH9. The parameters of an atmospheric model are determined by forcing the computed abundances of Fe to be independent of excitation potential (T_{eff} determination), reduced equivalent width (microturbulent velocity ξ_t) and the ionization stage (gravity). In order not to compromise the result of such analysis, one has to take care that only lines with well determined oscillator strengths ($\log gf$-values) are selected. The best list of such critically compiled $\log gf$-values useful for the temperature domain of AC Her was published by Lambert et al. (1996) and we restricted the use of Fe-lines to those values. This resulted in a list of 78 Fe I and 28 Fe II lines. Our best model has T_{eff} = 5500K; $\log g$ = 0.5; ξ_t = 3.5 $\mathrm{km\,s^{-1}}$ and an overall metallicity of -1.5. Typical errors are ΔT = 250 K, $\log g$ = 0.5 and ξ_t = 1 $\mathrm{km\,s^{-1}}$.

Once the model is defined we performed a complete chemical analysis, again restricting ourselves to lines with good oscillator strengths, clear profiles and equivalent widths in-between 5 and 140 mÅ. The results are listed in Table 2 for the individual ions. The individual lines and their atomic data can be obtained from the authors (HVW) upon request.

The abundance pattern is very well correlated with the dust condensation temperature (see Fig. 2). AC Her is clearly another RV Tauri star where the photospheric abundance patterns are determined not by internal nucleosynthesis and subsequent

Table 2. Chemical analysis of AC Her. The solar abundances to compute the [el/H] ratios are taken from Grevesse (1989) except for the C,N and O abundances which are from Biémont et al. (1993). The dust condensation temperatures are from Wasson (1985) and computed using a solar abundance mix at a pressure of 10^{-4} atm.

AC Her T_{eff}=5500 K $\log g$=0.5 $\xi_t = 3.50\,\mathrm{km\,s^{-1}}$ [Fe/H]=−1.5						
ion	N	$\overline{W_\lambda}$	ϵ	σ	[el/H]	T_{cond}
C I	15	29	7.91	0.11	−0.66	90
N I	2	14	7.77	0.00	−0.22	110
O I	4	4	8.31	0.02	−0.55	200
Na I	4	32	5.42	0.24	−0.91	970
Mg I	2	69	6.26	0.01	−1.32	1340
Si I	9	9	6.30	0.12	−1.25	1311
Si II	1	45	6.21		−1.34	
S I	8	15	6.46	0.10	−0.75	648
Ca I	15	32	4.68	0.13	−1.68	1518
Sc II	2	20	1.13	0.04	−1.97	1644
Ti II	10	39	3.02	0.18	−1.97	1549
Cr I	12	22	3.99	0.16	−1.68	1277
Cr II	11	25	4.09	0.16	−1.58	
Mn I	6	27	3.78	0.09	−1.61	1190
Fe I	78	47	5.85	0.15	−1.66	1336
Fe II	28	53	5.79	0.13	−1.72	
Ni I	22	19	4.62	0.14	−1.63	1354
Cu I	1	27	2.97		−1.24	1351
Zn I	4	50	3.58	0.08	−1.02	660
Y II	4	7	−0.12	0.22	−2.36	1592
Zr II	1	14	0.68		−1.92	1780
Ba II	1	118	0.54		−1.59	?
La II	1	4	−0.48		−1.70	1520
Ce II	1	2	−0.39		−1.94	1599
Pr II	1	5	−0.89		−1.60	1532
Nd II	4	7	−0.39	0.21	−1.89	1510
Sm II	4	3	−0.56	0.34	−1.56	1515

dredge-ups but by a fractionation process in which the atmosphere became depleted of chemical elements with a high condensation temperature. Although often referred to as C-rich, AC Her does not have a chemical signature of a carbon star. The [C/Fe] of +1.0 is indeed high but does not reflect the nucleosynthetic history of the object.

It is interesting to note that also the s-process elements have high dust condensation temperatures. The determination of the s-process elements in post-AGB stars is often used as a good tracer to investigate the 3rd dredge-up effectiveness. In objects where the depletion of the photosphere was efficient, the chemical pattern mimics a dredge-up pattern by increasing the C/Fe ratio. The s-process elements are also depleted; whether the 3rd dredge-up was indeed efficient or not is then not easy to deduce from the photospheric chemical content and the circumstellar dust chemistry and molecular envelope chemistry

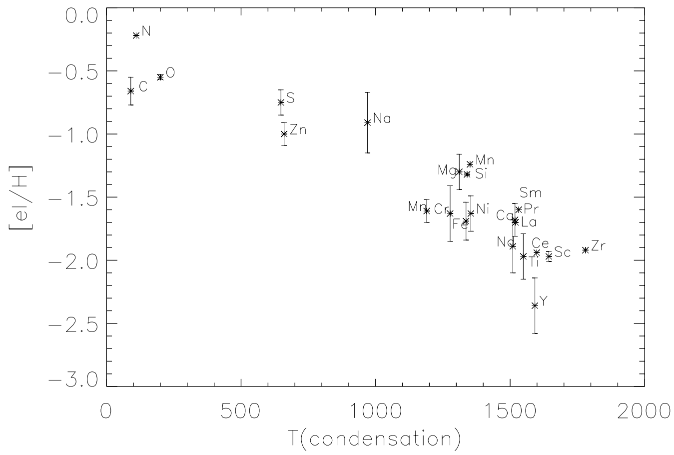

Fig. 2. The chemical deficiencies in the atmosphere of AC Her against the dust condensation temperature of the chemical element.

are much more reliable tracers in AC Her and RV Tauri stars in general.

The referee (G. Gonzalez) made us aware of a preprint (Giridhar et al., 1998) which includes also a chemical analysis of AC Her. Their abundance study give essentially the same [el/Fe] values for all chemical elements in common. The absolute abundance differences reflect the difference in atmospheric model parameters used.

4. ISO-SWS spectrum of AC Her

We obtained a full AOT1 speed 4 spectrum in the complete 2.3–45 μm window with the SWS spectrometer (de Graauw et al. 1996) on board of ISO (Kessler et al., 1996) during revolution 520. A detailed analysis of the rich spectrum is out of the scope of this letter and will be published elsewhere. We will summarize here the main results.

The silicate emission feature in the 8–12 μm window is much broader than the astronomical silicates and peaks at a redder wavelength. It can best be explained as a mixture of amorphous and crystalline silicate grains since also the crystalline olivines and pyroxene features in the 20–40 μm window are observed at 19.7, 23.7, 33.2 and 36.0. We find a prominent, broad emission feature near 9.2 μm which can be attributed to crystalline pyroxenes (Koike et al. 1993; Jäger et al. 1998), suggesting a rather high abundance of these grains. Since 10 μm feature is very similar to the one observed around young stellar objects with a high crystallisation fraction and the one of comet Hale Bopp (Malfait et al. 1998; Crovisier et al. 1997) there is no evidence for SiC contributing to the feature. Since also the mid UIR bands at 6.2, 7.7 and 8.7 are absent and only a very minor detection of a 3.3 μm feature is observed, the SWS spectrum does not reveal the presence of a large carbon-rich dust component.

5. Discussion

In this letter the binary nature of AC Her is deduced from our CORAVEL radial velocity set. The close correlation between the chemical deficiencies of the photosphere and the condensation temperature shows that the chemical patterns observed in AC Her are due to depletion rather than internal nucleosynthesis and dredge-ups. These depletion patterns are also observed in the extremely iron deficient binary post-AGB stars (Van Winckel et al., 1995 and references therein) and strengthens further the fact that binarity is a necessary condition for the depletion process to occur (Waters et al. 1992).

The properties of the circumstellar dust shell of AC Her closely resemble those of the Red Rectangle (RR): both stars have (1) prominent oxygen-rich crystalline silicates (Waters et al. 1998; Molster et al. (in preparation), (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, (3) very strong millimeter continuum flux from large dust grains (van der Veen et al. 1994; Shenton et al. 1995). These properties suggest that the dust is highly processed. In analogy with the RR, the dust in AC Her is likely also stored in a long-lived disc. This implies that no conclusion can be derived about the time that has elapsed since AC Her has left the AGB from the inner radius of the dust shell.

Since the depletion patterns are observed in all field RV Tauri stars of type A and B studied till now (Gonzalez et al. 1997b) the binary nature of all these RV Tauri stars should be addressed together with the absence of the depletion patterns in globular cluster RV Tauri stars and field RV Tauri objects of class C (Gonzalez & Lambert 1997; Giridhar et al. 1998). Since direct detection of binary motions is made difficult by the high amplitude pulsations, we propose indirect methods which include physical, geometrical and chemical studies of the circumstellar material to probe for the presence of dust discs. The very short post-AGB lifetime inferred by Jura (1986) for the RV Tauri objects detected by IRAS together with the low gas-to-dust ratio observed by Bujarrabal et al. (1988) for 4 objects give already an indication that indeed the binary fraction among RV Tauri stars might be very high but a more detailed investigation is clearly needed.

We can conclude that our radial velocity monitoring campaign confirms the binary nature of AC Her and that the photospheric chemical depletion patterns, presence of a population of large grains, low gas-to-dust ratio and the presence of crystalline silicates indicates that the circumstellar dust around AC Her is highly processed and trapped in a long-lived circumbinary disc similar to the oxygen rich dust-disc in the Red Rectangle.

References

Baranne A., Mayor M., Poncet J.L., 1979, Vistas in Astron. 23, 463

Biémont E., Hibbert A., Godefroid M., Vaeck N., 1993, ApJ 412, 431

Bujarrabal V., Bachiller R., Alcolea J., Martín-Pintado, 1988, A&A 206, L17

Crovisier J., Leech K., Bockelee-Morvan D., et al., 1997, Science 275, 1904

Decin L., Van Winckel H., Waelkens C., Bakker, E.J., 1998, A&A 332, 928

De Graauw Th., Haser L.N., Beintema D.A., et al., 1996, A&A 315, L49

Gillet D., Burki G., Duquennoy A., 1990, A&A 237, 159

Giridhar S., Rao N.K., Lambert D.L., 1994, ApJ 437, 476

Giridhar S., Lambert D.L., Gonzalez G., 1998, ApJ in press

Gonzalez G., Lambert D.L., 1997, AJ 114, 341

Gonzalez G., Lambert D.L., Giridhar S., 1997a, ApJ 479, 427

Gonzalez G., Lambert D.L., Giridhar S., 1997b, ApJ 481, 481

Grevesse N., 1989, in AIP Conferences Series 183: "Cosmic Abundances of Matter", ed C.J. Waddington, American Institute of Physics, New York, 9

Jäger C., Molster F.J., Dorschner J., et al., 1998, A&A submitted

Jura M., 1986, ApJ 309, 732

Jura M., Balm S.P., Kahane C., 1995, ApJ 453, 721

Kessler M.F., Steinz J.A., et al., 1996, A&A 315, L27

Koike, C., Shibai, H., Tuchiyama, A., 1993, MNRAS 264, 654

Kurucz R.L., 1993, CD-ROM set, Cambridge, MA: Smithsonian Astrophysical Observatory.

Lambert L.D., Heath J.E., Lemke M., Drake J., 1996, ApJ 103, 183

Lucy L.B., Sweeney, M.A., 1971, AJ 76, 544

Malfait K., Waelkens, C., Waters L.B.F.M. et al., 1998, A&A 332, L25

Preston G.W., Krzeminski W., Smak J, Williams J.A., 1963, ApJ 137, 401

Roddier F., Roddier C., Graves J.E., Northcott M.J., 1995, ApJ 443, 249

Sanford R.F., 1931, ApJ 73, 364

Sanford R.F., 1955, ApJ 121, 318

Shenton M., Evans A., Williams P.M., 1995, MNRAS 273, 906

Van der Veen W.E.C.J., Waters L.B.F.M., Trams N.R., Matthews H.E., 1994, A&A 285, 551

Van Winckel H., 1997, A&A 319, 561

Van Winckel H., Mathis J.S., Waelkens C., 1992, Nature 356, 500

Van Winckel H., Waelkens C., Waters L.B.F.M., 1995, A&A 293, L25

Venn K.A., Lambert D.L., 1990, ApJ 363, 234

Waelkens C., Van Winckel H., Bogaert E., Trams N.R., 1991a, A&A 251, 495

Waelkens C., Lamers H.J.G.L.M., Waters L.B.F.M., et al., 1991b, A&A 242, 433

Wasson J.T., 1985, Meteorites: Their Record of Early Solar System History (New York:Freeman)

Waters L.B.F.M., Trams N.R., Waelkens C., 1992, A&A 262, L37

Waters L.B.F.M., Waelkens C., Van Winckel H. et al., 1998, Nature 391, 868

Zsoldos, E., 1993, A&A 268, 149