1970ApJ...161L.213G

The Astrophysical Journal, 161:L213–L217, September 1970
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# RV TAURI STARS: A NEW CLASS OF INFRARED OBJECT

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## ABSTRACT

Large excess 11-$\mu$ radiation is reported for three of five RV Tauri stars observed photometrically. It is hypothesized that matter ejected by shock waves condenses to form solids in a cool circumstellar shell about 25 stellar radii in size.

## I. INTRODUCTION

Following the discovery by R. D. Gehrz and D. W. Strecker (unpublished) of a large 11.4-$\mu$ flux for the RV Tauri star AC Her on the 30-inch O'Brien telescope at the University of Minnesota, five RV Tauri stars have been measured photometrically at effective wavelengths of 3.5, 4.9, 8.4, and 11.0 $\mu$. A four-filter photometer with an 11″ beam was used at the Cassegrain focus of the 50-inch metal-mirror telescope of the Kitt Peak National Observatory.

The $[3.5]\mu - [11.0]\mu$ color index for these objects ranges from $+1.2$ for R Sct to $+4.5$ for AC Her. The color index for AC Her is the largest that has been reported for a star. The measurements show that some RV Tauri stars have a broad emission feature extending from roughly 5 $\mu$ to beyond 13 $\mu$, with peak emission near 8.4 $\mu$. This feature differs from the silicate-emission feature identified by Woolf and Ney (1969) which contributes a negligible 8.4-$\mu$ flux and peaks at $\sim$10 $\mu$. However, the RV Tauri feature may be similar to the emission from R Aqr (Stein *et al.* 1969), which has been suggested to be a silicate feature that is optically thick at the peak.

## II. DISCUSSION

The $[3.5] - [11.0]$ color index for "normal" stars and supergiants with silicate emission has been discussed by Gehrz, Ney, and Strecker (1970). In "normal" stars earlier than about K5, the $[3.5] - [11.0]$ index is less than $+0.2$. One of the more extreme cases of optically thin silicate emission, BC Cyg, shows an index of $+3.0$. NML Cyg, which is surrounded by a cool, optically thick shell, has an index of $+3.5$, 1 mag less extreme than AC Her.

The RV Tauri stars are variable yellow supergiants whose light curves have alternating deep and shallow minima. Their spectra range from G to late K, being earliest near maximum brightness (Joy 1952; Preston *et al.* 1963). Radial-velocity measurements give a discontinuous velocity curve for RV Tauri stars, showing that their variability may be connected with atmospheric pulsations in which shock waves play an important role (Abt 1955; Preston 1962, 1964).

An infrared survey of stars (see Table 1) having some features in common with RV Tauri stars leads to the conclusion that the RV Tauri stars belong to a distinct class. Although the yellow supergiants $\delta$ CMa (F8 Ia) and $o^1$ CMa (K3 Iab) have no appreciable $[3.5] - [11.0]$ excess, some extremely luminous yellow Population I stars, RW Cep (K5 Ia), AX Sgr (G8 Ia), and W Cep (K0ep Ia), have excesses of $\sim +3.0$. Photometry

* Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.



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TABLE 1

RV TAURI AND COMPARISON STARS

| Class | Object | Spectral Type | $L$ 3.5 μ | $M$ 4.9 μ | $N'$ 8.4 μ | $O$ 11.0 μ | $L-O$ [3.5]−[11.0] | Period (Days) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| RV Tauri stars | AC Her | F2p Ib–K4e(Rp) | +4.4 | +4.0 | +0.6 | −0.1 | +4.5 | 75.5 | Carbon rich, RV type B |
| | U Mon | F8e Ib–K0p Ib | +2.4 | +1.5 | −0.7 | −1.6 | +4.0 | 92.3 | RV type A |
| | R Sct | G0e Ia–K0p Ib | +1.6 | +1.3 | +0.6 | +0.4 | +1.2 | 144 | RV type A |
| | R Sge | G0 Ib–G8 Ib | +4.5 | +3.3 | +1.6 | +1.3 | +3.2 | 70.6 | RV type A |
| | UU Her | F2 Ib–F8 | +6.4 | +5.9 | . . . | ≥+3.9 | ≤+2.5 | 90, 71 | RV type C |
| Cepheids...... | SV Vul | F7 Ia–K0 | +4.0 | +3.6 | +3.3 | +2.5 | +1.5 | 45.1 | |
| | RS Pup | F8–K5 | +3.8 | +3.8 | +4.1: | +3.1 | +0.7 | 41.4 | Circumstellar dust |
| | RU Cam | K0–R2 | +6.3 | . . . | . . . | >+3.1 | <+3.2 | 22.1 | Carbon rich |
| | W Vir | cF2e–G6e | +7.8 | . . . | . . . | >+3.5 | . . . | 17.3 | Population II |
| | AL Vir | F6–G2 | +7.6 | . . . | . . . | >+3.7 | . . . | 10.3 | Population II |
| | ζ Gem | F7 Ib–G3 Ib | +2.1 | +2.1 | +2.1 | +2.2 | +0.1 | 10.2 | No excess |
| Yellow super-giants....... | δ CMa | F8 Ia | +0.3 | +0.1 | 0.0 | −0.1 | +0.4 | Nonvariable | No excess |
| | o¹ CMa | K3 Iab | 0.0 | +0.2 | 0.0 | −0.2 | +0.2 | Nonvariable | No excess |
| | RW Cep | K5 Ia | +1.6 | +1.3 | +0.4 | −1.2 | +2.8 | . . . | Ic variable |
| | AX Sgr | G8 Ia | +2.5 | +2.3 | +1.3 | −0.7 | +3.2 | 350: | SRc variable |
| | W Cep | K0ep Ia | +1.8 | +1.0 | −0.4 | −1.7 | +3.5 | . . . | SRc variable |
| SRd variables.. | SX Her | G3e–K0(M3) | +4.5 | +4.1 | >+4.0 | <+4.0 | ≤+0.5 | 102.9 | No excess |
| | TY Vir | K5 | +5.3 | +4.2 | >+4.0 | >+3.5 | <+1.8 | (100 | |
| Late M stars.. | R Aql | M5e–8e | −1.2 | −1.4 | −1.8 | −2.9 | +1.7 | 300.3 | Mira variable |
| | S CrB | M6e–8e | −0.6 | −1.0 | −2.0 | −2.8 | +2.2 | 360.7 | Mira variable |
| | NML Cyg | Late M | −1.9 | −2.9 | −5.0 | −5.4 | +3.5 | . . . | Infrared star |
| Normal yellow star......... | α Boo | K2 IIIp | −3.1 | −3.0 | −3.2 | −3.3 | +0.2 | Nonvariable | |

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at 4.9 and 8.4 $\mu$, however, distinguished them from the RV Tauri stars. RW Cep and AX Sgr appear to have optically thin silicate emission similar to that found in most late M stars. W Cep has colors almost identical with those of the moderately optically thick object VY CMa. Even these optically thick shelled objects, however, have smaller infrared excesses than some RV Tauri stars.

SRd variables are somewhat similar to RV Tauri stars at optical wavelengths (Preston *et al.* 1963). Photometry on SX Her (G3e–K0[M3]) shows it to have a [3.5] − [11.0] index of less than +0.5. TY Vir (K5) has an index of less than +1.8.

The long-period Cepheids (yellow pulsating variables) RS Pup (F8–K5) and SV Vul (F7 Ia–K0) have [3.5] − [11.0] colors of +0.7 and +1.5, respectively. Based on 8.4-$\mu$ data, they are probably showing mild silicate emission. Westerlund (1961) has noted that RS Pup is surrounded by a dust shell. The normal Cepheid $\zeta$ Gem has no excess. RU Cam (K0–R2), a carbon-rich Cepheid with a period of 22 days, has an excess smaller than +3.2. AL Vir (F6–G2) and W Vir (cF2e–G6e), the brightest available disk-population Cepheids, were too faint to detect at 11.0 $\mu$.

Thus, the infrared characteristics of the RV Tauri stars cannot be duplicated from these possibly related groups of stars. However, the effect of increasing optical depth of a circumstellar dust shell is known for later-type stars. Figure 1 shows the energy distribution for two RV Tauri stars and six comparison stars. W Cep compared with RW Cep appears to show the effects of increasing optical depth of the circumstellar envelope for a pair of stars somewhat cooler than the RV Tauri stars. S CrB, R Aql, and the extremely thick-shelled object NML Cyg demonstrate the same phenomenon for later M stars. Arcturus ($\alpha$ Boo) is included as an example of a "normal" yellow star.

The large emission feature in the 10-$\mu$ region for the RV Tauri stars AC Her, U Mon, and R Sge does not continue to shorter wavelengths because the 4.9-$\mu$ point is relatively depressed for a blackbody curve through the other three measures. Therefore, a material of high opacity over the range of 8.4–11.0 $\mu$ is probably responsible for the emission. Alternatively, a very cool blackbody-like envelope may be present. For example, a blackbody of ~300° K roughly approximates the spectrum of AC Her through the 4.9-, 8.4-, and 11.0-$\mu$ measures. Similar arguments were used to show that dust shells were responsible for the 10-$\mu$ emission peak in late M stars (Woolf and Ney 1969). The large and variable polarization observed for some RV Tauri stars (Serkowski 1970) is possible further evidence for the existence of dust shells around these stars. Heavy-element abundance is high for all of the RV Tauri stars in which large infrared excesses were observed. Thus, dust production in their envelopes appears to be possible. Surprisingly, both AC Her, which is carbon rich, and oxygen-rich RV Tauri stars such as U Mon show similar emission peaks. Silicon carbide and other heavy-metal carbides could be responsible for the shell around AC Her, while silicates and metal oxides may occur around U Mon and other oxygen-rich RV Tauri stars.

A shell size of ~25 stellar radii results for AC Her if effective temperatures of ~4500° K for the star and ~500° K for the dust grains are assumed.

A feature distinguishing the RV Tauri stars from other stars with infrared excesses is the amplitude of the shock waves in their atmospheres (Abt 1955; Preston 1962, 1964). If, as suggested by Christy (1966), matter is ejected in these shock waves, it is by no means clear whether condensates would develop equilibrium chemical compositions. Thus, the condensates could, in fact, be a mixture of many simple solids.

## III. CONCLUSION

The RV Tauri stars are distinguished from other cool stars with excess radiation near 10 $\mu$ both by the size of their excesses and by the amplitude of the shock waves in their atmospheres. One can expect matter to be ejected by these shock waves. The condensation of solids from the ejected matter seems to be the likeliest explanation of the excess infrared radiation.

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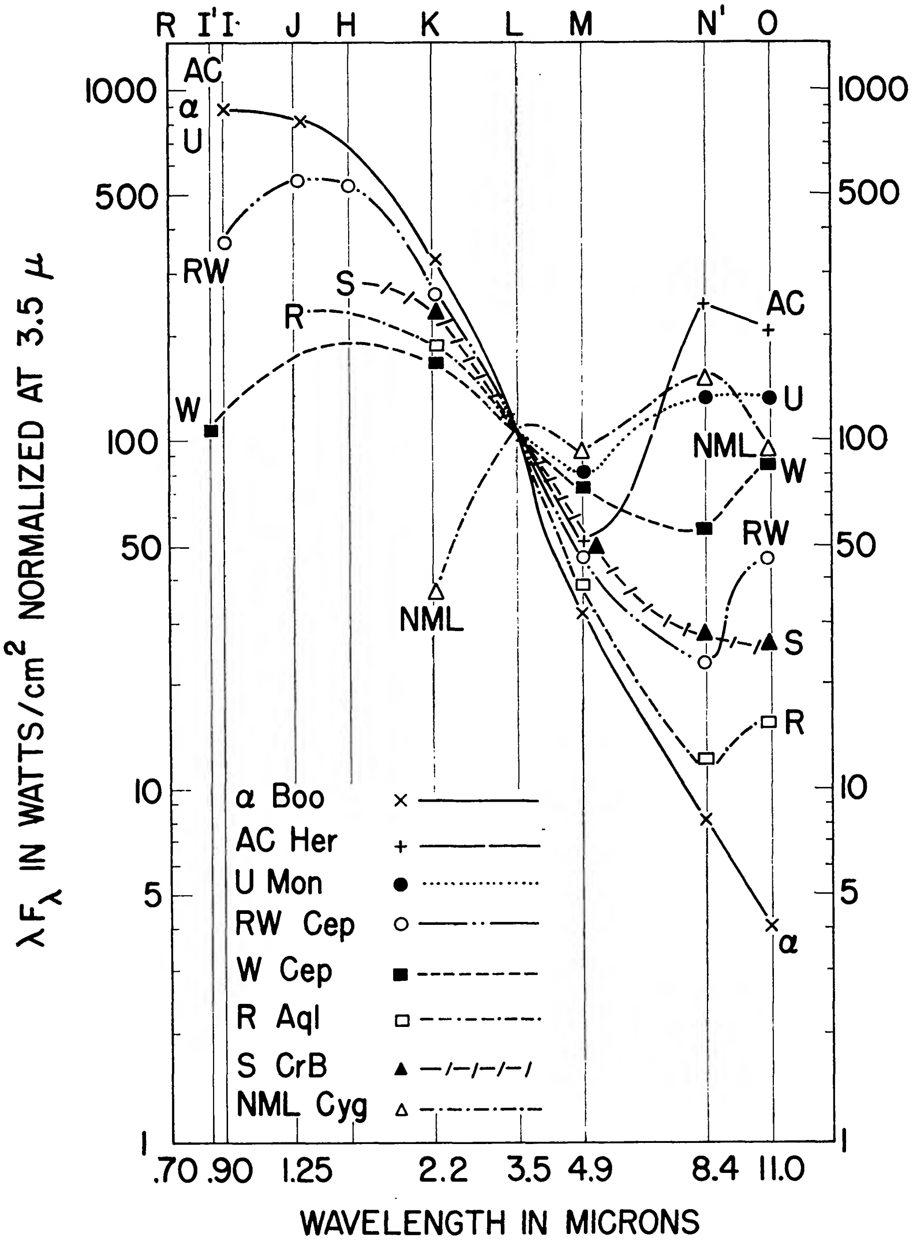


FIG. 1.—Energy distribution of two RV Tauri stars and comparison objects. Note that the ordinate is $\lambda F(\lambda)$ and the abscissa is a logarithmic scale of wavelength. AC Her and U Mon have been assumed to follow the energy distribution of α Boo in the near-infrared. This assumption is consistent with both *UBV* photometry and upper limits on the 2.2-μ flux from the CIT sky survey.

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We are indebted to D. W. Strecker for assistance with the discovery of the excess for AC Her. Dr. G. Neugebauer kindly reexamined the records of the 2.2-$\mu$ CIT survey to estimate upper limits to the flux of AC Her and U Mon. Drs. G. Wallerstein and H. Abt made helpful suggestions of objects that might be related to the RV Tauri stars.

This research was supported by the Graduate School of the University of Minnesota. R. D. Gehrz is a National Science Foundation trainee.

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