# THE EXTENDED ATMOSPHERE AND EVOLUTION OF THE RV TAURI STAR, R SCUTI

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## ABSTRACT

We analyze ISO/SWS spectra of the RV Tau star, R Scuti. The data were obtained from the ISO data archive, and processed with OLP ver.10.1 and OSIA ver.2.0. We found that the infrared spectra of this star are dominated by emission bands of $H_2O$ vapour. We also identify CO, SiO and $CO_2$ bands. Unlike the other RV Tau stars, the infrared spectra of R Sct are very similar to those of the oxygen-rich Mira variable, *o* Cet (Mira). However, 10 $\mu$m silicate band is very weak in R Sct. With these newly found properties of the star, we discuss structure and evolutionary stage of the star.

This study is an example that the uniform and high-quality data in the ISO Archive have a lot of potential to give an impact on stellar evolution.

Key words: stars: AGB and post-AGB – stars: atmospheres – stars: circumstellar matter – infrared: stars – stars: variables:general – stars: individual: R Sct

## 1. Introduction

RV Tau stars are pulsating variables showing alternating deep and shallow minima in their light curves. Their spectral type ranges from F to K supergiant, corresponding to the effective temperature ($T_{\rm eff}$) of 3000–6000 K. It has been suggested that these stars are in the post-AGB phase (Jura 1986). Abundance anomaly has been observed in some of the stars, which is interpreted by the metal depletion by the gas-dust separation in the circumbinary-discs (Waters et al. 1992; Van Winckel et al. 1999; Jura et al. 2000).

R Scuti is a bright RV Tauri star in optical to near-infrared wavelengths. Its primary period (period between deep minima) of variability is 147 days (Kholopov et al. 1988). $T_{\rm eff}$ varies in 4750–5250 K (Shenton et al. 1994) and the spectral type may become as late as M3 (Kholopov et al. 1988). CO radio observations by Bujarrabal et al. (1988) show that the star had experienced a heavy mass-loss phase in the past. The current mass-loss rate estimated from the IRAS data is smaller by two orders of magnitudes than that from CO observations (Alcolea & Bujarrabal 1991).

The ISO/SWS observations of R Sct were carried out in the program MOLBANDS (P.I. A. Heske). During systematic survey of molecular bands in the SWS spectra of evolved stars, we found that this object show interesting properties, as we describe in this paper. More detailed discussion of this star has been published in Matsuura et al. (2002b).

## 2. The SWS Spectra of R Scuti

R Sct was observed with the SWS on March 10, 1996. The variability phase (defined as phase=0.0 at deep minimum) was 0.6. The observing mode is AOT01 and the corresponding spectral resolution is $R$ =300–500.

Figure 1 shows the spectra of R Sct in 2–16 $\mu$m. The spectra of the Mira variable, *o* Cet (Yamamura et al. 1999), is also shown for comparison. The spectra of R Sct are very similar to those of *o* Cet. $H_2O$, SiO, CO, and $CO_2$ features are identified. Especially the $H_2O$ bands in R Sct are as prominent as those in *o* Cet, and dominate the infrared spectra. $H_2O$ and $CO_2$ usually appear in stars with a spectral type later than M6. In other words, stars with an excitation temperature ($T_{\rm eff}$) lower than ∼3300 K. The detection of molecular bands in the spectra of R Sct is totally unexpected from its effective temperature (4750–5250 K).

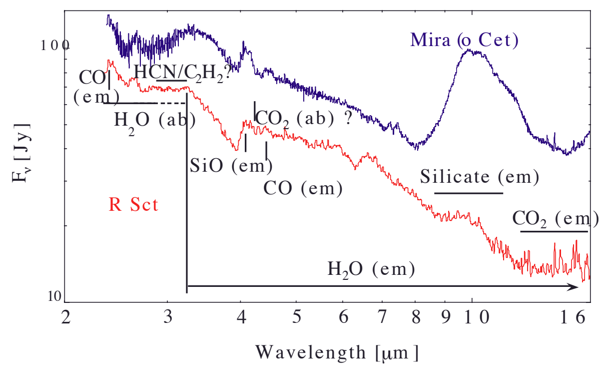


*Figure 1. The ISO/SWS spectra of R Sct. The locations of the major molecular features are indicated. The spectra of the oxygen rich Mira variable, o Cet, are shown for comparison. The spectra of o Cet are scaled for convenience. Two stars show similar spectra below ∼5 μm.*

Proceedings of the Symposium *"Exploiting the ISO Data Archive - Infrared Astronomy in the Internet Age"*,
24–27 June 2002, Sigüenza, Spain (C. Gry et al. eds., ESA SP-511)

Dust emission is also observed in the SWS spectra of R Sct. In Figure 2, the spectra of R Sct around 10 $\mu$m are compared with those of two Mira variables, *o* Cet and T Cas. There is a tiny excess around 10 $\mu$m in R Sct, probably by amorphous silicate dust. This excess is significantly weaker than that in *o* Cet, which is in contrast to the similarity in the near-infrared spectra. T Cas shows typical spectra of an AGB star with moderate mass-loss rate, with a weak silicate emission and the so called "13 $\mu$m" feature. This 13 $\mu$m feature is not found in R Sct. This feature is known to be prominent in the stars with relatively small pulsation amplitude and low mass-loss rate (Posch et al. 1999). The absence of the 13 $\mu$m feature in R Sct distinguishes this star from the "normal" AGB red-giants.

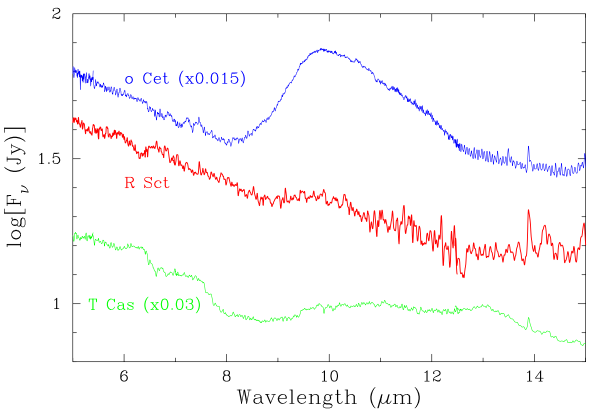


*Figure 2. The spectra of R Sct around 10 $\mu$m are compared with those of two Mira variables, o Cet and T Cas. o Cet shows a prominent silicate band at $\sim$ 10 $\mu$m, while T Cas exhibits the 13 $\mu$m feature. In R Sct, only a weak silicate band is found.*

The SWS spectra of R Sct seem to be peculiar even among those of the RV Tau stars. ISO/SWS observed five RV Tau stars, AC Her, HR Del, R Sge, SX Cen, and R Sct, in the AOT01 mode. The spectra of four out of these five stars are shown in Figure 3. Except for R Sct, the spectra of other three stars are dominated by the dust emission peaked at 10–20 $\mu$m. In AC Her, crystalline silicate features are prominent. Meanwhile, the spectra of R Sct looks like a naked red-giant star with very little dust emission in the wavelength range.

## 3. Modeling the Spectra

We model the molecular and dust features in the spectra of R Sct. We first fit the molecular bands up to 8 $\mu$m, then add the dust emission.

The synthesized molecular spectra are calculated using the *Slab* model (see, Yamamura et al. 1999). In this model, a molecular component is expressed by a plane-parallel layer, with a set of excitation temperature, column density, and relative size with respect to the central

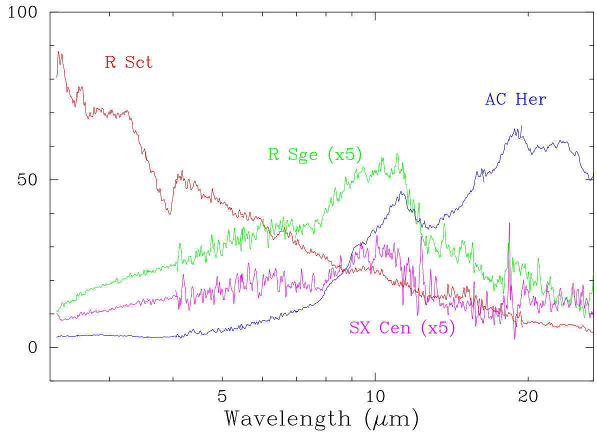


*Figure 3. SWS spectra of four RV Tau stars. R Sct shows spectra similar to those of late M-type stars with the SED peaked in near-infrared or even shorter wavelength. Other three RV Tau stars show red SED. AC Her shows prominent crystalline silicate features. The spectral resolution is degraded to be R =200 in order to improve the signal to noise ratio.*

star. The emergent spectra are obtained by solving the radiative transfer through the multiple layers overlaid along the line of sight. The slab model approach is an approximation of the real molecular envelope in the star, and it does not assume or require that the molecules are really in such layers. The synthesized spectra give reasonably good fits to the observed spectra of red giants, and help to interpret the observed spectra (Matsuura et al. 2002a).

In the calculation, we assume that the molecules are in the Local-Thermodynamic Equilibrium (LTE). Solar isotopic ratio is used for oxygen and silicon atoms, while $^{13}C$:$^{12}C= 1 : 9$ is adopted (Bujarrabal et al. 1990) for carbon. The molecules and the line lists included in the calculation are as follows: $H_2O$: Partridge & Schwenke 1997; $CO_2$: HITRAN (Rothman et al. 1998); SiO: Langhoff et al. (1993); CO: HITEMP (Rothman et al. in preparation).

The best fit synthesized spectra are compared with the observed spectra in Figure 4. The best fit parameters are summarized in Table 1. It is confirmed that following molecular bands are seen in emission in R Sct: $H_2O$ bands at longer then $\sim$3.5 $\mu$m, SiO at 4.1 $\mu$m, CO at 4.6 $\mu$m, and $CO_2$ around 15 $\mu$m.

The model fits the observed spectra well. The derived parameters are similar to those for the Mira variables except the larger numbers of layer sizes (e.g. Matsuura et al. 2002a). This is easily understood if one consider that the central star has higher $T_{\rm eff}$ and accordingly smaller radius, if the absolute luminosity is the same.

In the next step we add dust emission on the synthesized molecular spectra, to reproduce the excess in the 10 $\mu$m region. We use a spherical, optically thin dust shell model, with the density distribution being proportional to $r^{-2}$. The dust opacity table of "Case 1" in Ossenkopf et al. (1992) is adopted. In order to calculate the dust tem-

*Table 1. The parameters used for fitting the R Sct SWS spectra. In the last column, 'A' and 'E' mean absorption and emission, respectively.*

| | $T_{\rm ex}$ [K] | N [cm$^{-2}$] | $R$ [R*] | Appearance |
|---|---|---|---|---|
| CO | 4000 | $1.2 \times 10^{21}$ | 1.8 | E |
| $H_2O$-1 | 2050 | $1.4 \times 10^{21}$ | 3.5 | E |
| SiO | $=T(H_2O\text{-}1)$ | $1.0 \times 10^{21}$ | $=R(H_2O\text{-}1)$ | E |
| $H_2O$-2 | 600 | $1.0 \times 10^{19}$ | 20 | A (2.7 $\mu$m)<br>E (6.2 $\mu$m) |
| $CO_2$ | $=T(H_2O\text{-}2)$ | $5 \times 10^{17}$ | $=R(H_2O\text{-}2)$ | A (4.2 $\mu$m)<br>E (13 $\mu$m) |

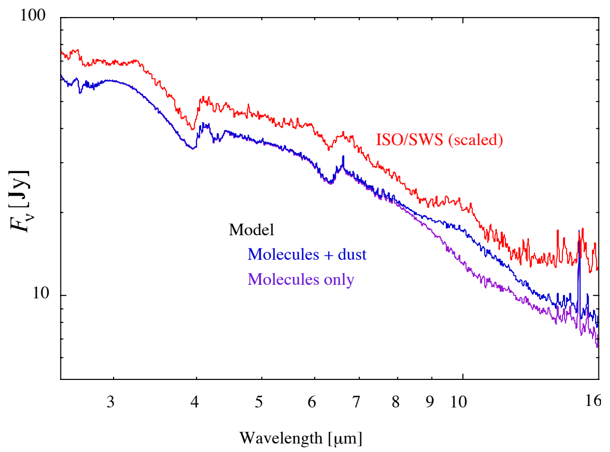


*Figure 4. The synthesized model spectra are compared with the ISO/SWS spectra of R Sct (red line). The purple line shows the model spectra considering only molecules. Blue line represents the model taking dust emission into account.*

perature, the central star is assumed to be a $T_\star = 7000$ K black body with a radius $R_\star = 3 \times 10^{12}$ cm ($L_\star = 4000$ $L_\odot$). In the calculation of the emergent spectra we use the molecular model spectra as the spectra of the central star.

Figure 4 shows the fitting result. Inclusion of dust improves the fit. The dust mass-loss rate used for this calculation is $1.5 \times 10^{-11}$ $M_\odot\,yr^{-1}$ at the expansion velocity of $10\,km\,s^{-1}$ (Bujarrabal et al. 1988).

## 4. Discussion

### 4.1. Disk or Extended Atmosphere?

The surprise in the SWS spectra of R Sct is that the spectra are dominated by the strong molecular bands, both in emission and absorption. Our analysis shows that several different bands of different molecules from different energy levels are detected in emission in the spectra of R Sct. This fact is most easily explained if the molecules are distributed beyond the size of the background continuum source (the star). Two configurations for distribution of the molecules are considered: a disc around the star, and an extended atmosphere. The presence of circumbinary-discs has been discussed in RV Tau stars (Van Winckel et al. 1999), while the atmosphere extended beyond the photosphere is though to be formed in the long-period pulsating variables of Mira or semi-regular types.

We argue that the molecular features appeared in the SWS spectra of R Sct are more likely explained by the extended atmosphere rather than the disc. There are three reasons for this conclusion. First, the temperature and column density of the molecular layers in R Sct are quite similar to those usually found in the extended atmospheres of AGB stars. Second, we found the $H_2O$ absorption bands on top of its emission bands around 2.7 $\mu$m. It is interpreted that the cool $H_2O$ layer, with a certain column density, is located in the line of sight of the warm $H_2O$ layer. If molecules are in the disc, it is only possible if the disc is in edge-on. Simply the chance that we have the edge-on configuration is small. Finally, no clear evidence of disc around R Sct has been found (Van Winckel et al. 1999).

The variable amplitude of R Sct is 2–3 mag, which is smaller than Mira variables but comparable to those of semi-regular variables. It has been a long standing problem that how the extended atmosphere (or so called *warm molecular layer* (Tsuji et al. 1997)) is formed in these relatively weak pulsators. Further studies of the extended atmosphere in this star may give a clue to understand this problem.

### 4.2. Dust Formation and Mass loss

Our analysis shows that dust mass-loss rate derived from the excess in the 10 $\mu$m region is extremely small in contrast to the presence of well developed molecular layer. Generally the mass-loss activity and the development of extended atmosphere seem to correlate each other. The mass-loss rate of $10^{-8}$–$10^{-6}$ $M_\odot\,yr^{-1}$ are expected for the AGB stars with the spectra similar to R Sct (Figure 2). However, if we assume the gas-dust mass ratio of 100, we obtain a gas mass-loss rate of only $1.5 \times 10^{-9}$ $M_\odot\,yr^{-1}$. This discrepancy implies that there must be some mechanism which currently prevent dust formation in the warm molecular gas of this star.

Heavy metal depletion has been reported in some RV Tau stars. Low abundance of metallic elements could results low dust formation efficiency and mass-loss rate. However, we think this is not the case for R Sct. The abundance analysis showed that this star is not extremely metal-poor (Giridhar et al. 2000). In addition, there are evidence that this star experienced large mass-loss rate phase in the past. Bujarrabal et al. (1988) observed CO radio lines and estimated the mass-loss rate of R Sct as $2 \times 10^{-7}$ $M_\odot\,yr^{-1}$. CO lines are sensitive to cool extended circumstellar envelope and they are often the measure of mass loss in the past. Alcolea & Bujarrabal (1991) fit the SED of R Sct with warm and cold dust components and derived dust mass-loss rate for cold dust as $2.4 \times 10^{-9}$ $M_\odot\,yr^{-1}$. If CO emission arises in the similar region with the cold dust, the two mass-loss rates are consistent with the *normal* gas-to-dust mass ratio of about 100. The mass loss in R Sct was "normal" in the past. The reason for low (dust) mass-loss rate in the current phase should be studied further.

### 4.3. The Evolutionary Stage of R Sct

Alcolea & Bujarrabal (1991) claimed that the large mass loss which produced the cold dust shell stopped about 2000 years ago. If we consider that R Sct is a post-AGB star, as generally believed for RV Tau stars, this decrease of mass-loss rate can be interpreted as that the star evolved from AGB to post-AGB phase. However, the discovery of warm molecules, probably in the extended atmosphere, discriminates R Sct from other RV Tau stars. Also the analysis of long-term pulsation period evolution over the 100 years does not fit with post-AGB scenario (Matsuura et al. 2002b). We suggest that this star could be an AGB star in quiescent helium burning phase. The large mass-loss rate in the past may occur at the last thermal pulse.

One problem is that the $T_{\rm eff}$ of R Sct is about 5000 K, which is too high for AGB stars ($T_{\rm eff}$ ~3300 K or even below). One possible explanation is that the star has just experienced a thermal pulse a few thousand years ago, and it is in the quiescent helium burning phase. (see e.g., Vassiliadis and Wood 1993).

## 5. Potential of the ISO Archive for Stellar Astrophysics

This study is a good example of serendipitous discovery in a known object using the archived SWS data. Detailed analysis of the spectra and the follow-up studies will lead us to the better understanding of the nature of this particular object and the nature of RV Tau stars.

Several hundreds of stars were observed with the SWS and other ISO instruments. These data have a lot of potential for further studies of evolved stars. The advantage of the ISO data archive from the point of view of studies of evolved stars are:

- The SWS and LWS cover enormous broad wavelength range, in total from 2.3–200 $\mu$m. Analysis of the molecular and dust features are best done with complete coverage of different transitions in different wavelengths. Large fractions of the ISO's wavelength range will not be covered again in the near future.
- The large number of uniform sample allows us to consider the common nature in the stars (see, Cami 2002).
- Thanks to the ISO data archive, we can now combine the data of the same object taken in the different programmes, and study the time variation in the spectra. (e.g. Yamamura et al. 1999; Matsuura et al. 2002a; Onaka et al. 2002).

In order to treat these large data efficiently and extract important information effectively, systematic and automatic data reduction and analysis should be considered. The SWS stellar atlas by Kraemer et al. (2002) (also this issue) and the post-Helium survey atlas by Vandenbussche et al. (2002) (also this issue), with their systematic classification are the most appreciated works. Scientific activity motivated by these atlas are encouraged.

ACKNOWLEDGEMENTS

I.Y. is supported by the Grant-in-Aid for Encouragement of Young Scientists (No. 13740131) from Japan Society for the Promotion of Science.

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