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IDENTIFICATION OF SH $\Delta v = 1$ RO-VIBRATIONAL LINES IN R ANDROMEDAE

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ABSTRACT

We report the identification of SH $\Delta v = 1$ ro-vibrational lines in the published high-resolution infrared spectrum of the S-type star R Andromedae. This is the first astronomical detection of this molecule. The lines show inverse P Cygni profiles, indicating infall motion of the molecular layer due to stellar pulsation. A simple spherical shell model with a constant infall velocity is adopted to determine the condition of the layer. It is found that a single excitation temperature of 2200 K reproduces the observed line intensities satisfactorily. SH is located in a layer from 1.0 to ~1.1 stellar radii, which is moving inward with a velocity of 9 km s^{-1}. These results are consistent with the previous measurements of CO $\Delta v = 3$ transitions. The estimated molecular abundance SH/H is 1×10^{-7}, consistent with a thermal equilibrium calculation.

Subject headings: infrared: stars — line: identification — stars: AGB and post-AGB — stars: atmospheres — stars: individual (R Andromedae)

1. INTRODUCTION

The chemistry of sulfur-containing species in space is especially interesting because of their chemical activity and relatively high abundance (Duley, Millar, & Williams 1980). It is known that abundances of sulfur-bearing molecules are strongly influenced by the presence of shocks (Hartquist, Oppenheimer, & Dalgarno 1980). So far, 14 sulfur-bearing species have been identified in space; CS, SO, NS, SiS, SO^+, SH_2, OCS, CCS, C_3S, H_2CS, HNCS, SO_2, HCS^+, and CH_3SH. However, the simplest sulfur compound, SH, has not been detected in spite of radio astronomical searches using the Λ-type doubling transitions (Meeks, Gordon, & Litvak 1969; Heiles & Turner 1971).

While sulfur chemistry in the circumstellar envelope of red giant stars has been studied extensively (e.g., Omont et al. 1993), that in the atmosphere has been regarded as in the thermal equilibrium state (Tsuji 1964, 1973). In the atmosphere of oxygen-rich giants, SH is the molecule first formed from the sulfur atom, at a temperature of about 2000 K. The SH abundance decreases when the temperature is below ~1500 K, and H_2S and SiS become the dominant species. On the other hand, Yamamura et al. (1999a) report the detection of the ν_3 infrared band of SO_2 in the spectra of oxygen-rich Mira variables obtained by the Short-Wavelength Spectrometer (SWS: de Graauw et al. 1996) on board the *Infrared Space Observatory* (*ISO*: Kessler et al. 1996). Their model analysis indicates that the molecules are located in the extended atmosphere at about 5 $R_\star$. The abundance of SO_2 is 5–10 orders of magnitude larger than the values in thermal equilibrium (Tsuji 1973; Woitke et al. 1999). The result strongly suggests the presence of non-equilibrium processes in the extended atmosphere, probably related to shocks due to stellar pulsation (Beck et al. 1992; Duari, Cherchneff, & Willacy 1999).

In this Letter, we report the detection of SH ro-vibrational transition lines in the published high-resolution infrared spectrum of the S-type star R And. We discuss the physical and chemical conditions of the SH layer in the star.

2. IDENTIFICATION OF SH LINES

The data used in this study were obtained with the Fourier-transform spectrometer at the Kitt Peak National Observatory 4 m telescope and were published in Ridgway et al. (1984). R And is a Mira variable with a period of 409 days and a visual amplitude of 9.1 mag (Kholopov et al. 1988). The spectral type is in the range S3,5e–S8,8e. The observation of R And was performed at the optical variable phase of $\phi = 0.82$. Unfortunately, the reduced data were lost after several updates of archive formats at the observatory. Therefore, we redigitized the data from the printed spectrum. The results may be as accurate as the original within ~0.02 cm^{-1} in wavenumber and a few percent in intensity. The spectrum was shifted by 5.2 km s^{-1} to longer wavelengths to adjust the absorption minimum of HCl lines at their rest frequencies (Ridgway et al. 1984). No correction for terrestrial motion was applied. In their original paper, Ridgway et al. (1984) give identifications of OH, NH, CH, SiO, CS, HCl, and atomic lines. The spectrum of R And, especially in the wavelengths shorter than the SiO first-overtone bandheads, is dominated by HCl lines. OH and NH lines are detected, but much less prominently than in the oxygen-rich stars like α Ori and α Tau. There are many strong lines left unidentified. Figure 1 shows the spectrum of R And between 2700 and 2750 cm^{-1}. The positions of SH and HCl ro-vibrational transitions are indicated. The frequencies are calculated from the molecular constants given by Ram et al. (1995) for SH and are taken from the HITRAN database 1996 edition (Rothman et al. 1992) for HCl. It is obvious that many unidentified strong lines are attributed to SH transitions. We as-

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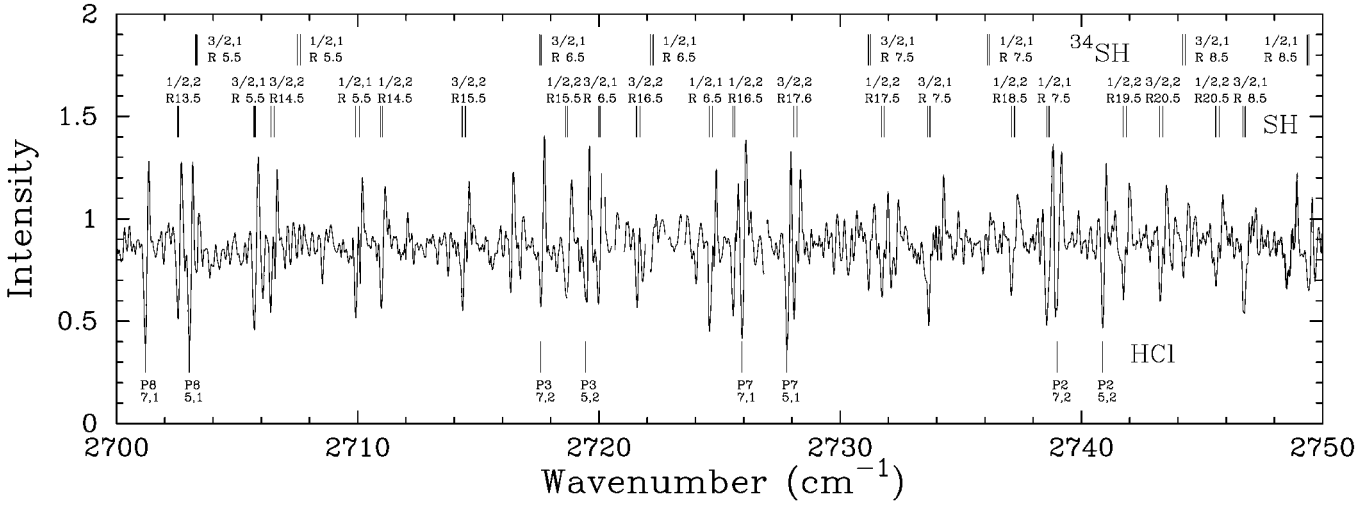

FIG. 1.—Part of the spectrum of R And obtained by Ridgway et al. (1984). The positions of $\Delta v = 1$ transitions of SH and ^{34}SH (*upper*) and HCl (*lower*) are indicated by tick marks. The notation of the transitions is the electronic angular momentum, the upper vibrational level, and the rotational line index for SH, and the rotational line index, the isotope index (5: H^{35}Cl, 7: H^{37}Cl), and the upper vibrational level for HCl, respectively.

signed 39, 41, and 11 transitions in the $v = 1$–0, 2–1, and 3–2 bands, respectively, between 2500 and 2778 cm^{-1}. The lower state energies of these transitions are up to 7000 cm^{-1}, indicating that the molecules are highly excited. The isotope ^{34}SH may also be detected. The frequencies of ^{34}SH lines are estimated from the molecular constants of SH using the relation of reduced mass (Herzberg 1950).

3. MODELING

We analyze the observed SH line profiles with a simple model. The SH (and also HCl) lines in R And show inverse P Cyg profiles, indicating that the molecular layer is moving inward toward the star due to stellar pulsation. We therefore apply a spherical shell model with a constant infall velocity.

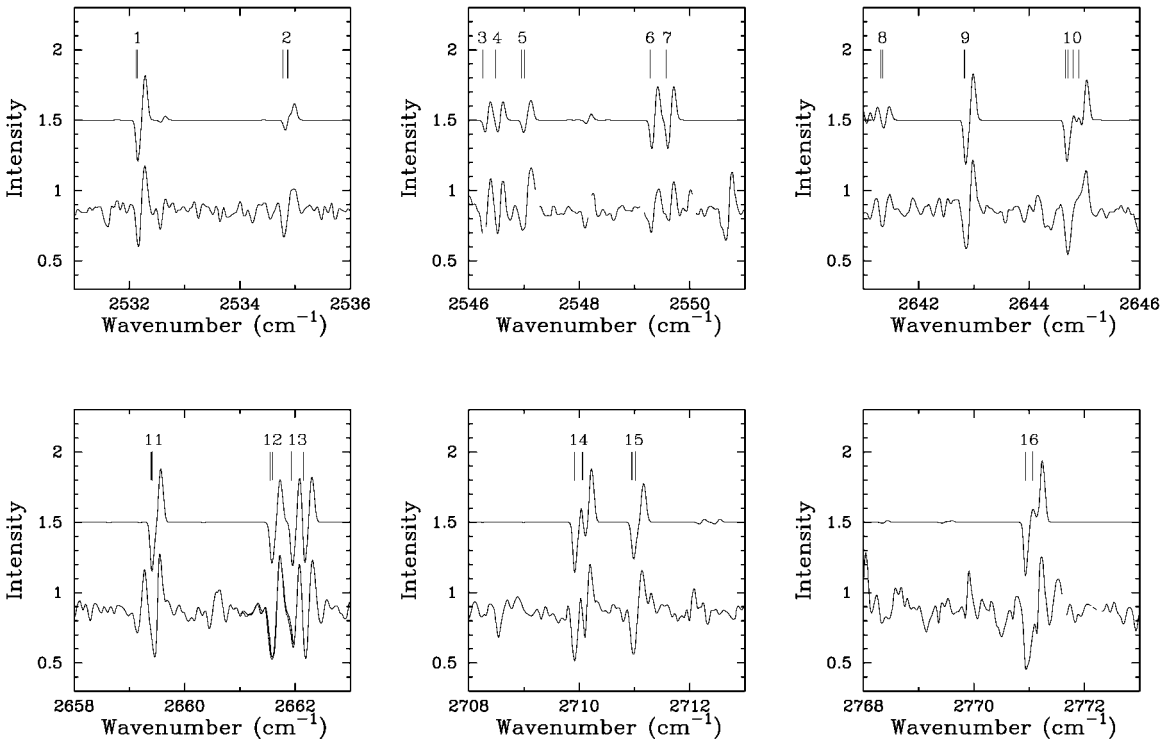

FIG. 2.—Synthesized model spectrum (*upper*) compared with the observation in six wavelength regions. The regions are chosen so that contamination of other spectral lines is minimized and that a wide range of energy levels is covered. The model assumes a spherical shell falling toward the stellar surface with a velocity of 9 km s^{-1}. The molecules are distributed from 1.0 $R_\star$ with a scale height of 0.08 $R_\star$. The model assumes constant excitation temperature of 2200 K, column density of 4.0×10^{20} cm^{-2}, and Doppler broadening velocity of 6 km s^{-1}. The model spectrum is shifted by -14 km s^{-1}. Lines indicated by tick marks are listed in Table 1.

TABLE 1
SH Lines Indicated in Figure 2

Number[a]	Frequency (cm^{-1})	Ω[b]	Transition[c]	E_l[d] (cm^{-1})
1	2532.1257	3/2	1–0 P 3.5ff	110.7175
	2532.1486	3/2	1–0 P 3.5ee	110.6810
2	2534.7858	1/2	3–2 R 7.5ee	6038.9539
	2534.8657	1/2	3–2 R 7.5ff	6040.7705
3	2546.2628	1/2	2–1 R 1.5ee	2994.8376
4	2546.4908	1/2	2–1 R 1.5ff	2995.3755
5	2546.9511	1/2	3–2 R 8.5ee	6192.1858
	2547.0067	1/2	3–2 R 8.5ff	6194.1577
6	2549.2843	1/2	1–0 P 2.5ff	446.0913
7	2549.5750	1/2	1–0 P 2.5ee	445.2626
8	2641.3159	3/2	3–2 R 24.5ee	10354.2802
	2641.3458	3/2	3–2 R 24.5ff	10358.7197
9	2642.8296	3/2	1–0 R 1.5ee	0.0000
	2642.8395	3/2	1–0 R 1.5ff	0.0037
10	2644.6568	1/2	1–0 R 1.5ee	396.9951
	2644.7048	3/2	2–1 R 8.5ee	3286.0606
	2644.7949	3/2	2–1 R 8.5ff	3286.4309
	2644.8958	1/2	1–0 R 1.5ff	397.5540
11	2659.3953	3/2	1–0 R 2.5ee	46.1293
	2659.4143	3/2	1–0 R 2.5ff	46.1440
12	2661.5489	1/2	2–1 R 9.5ee	3889.9056
	2661.5866	1/2	2–1 R 9.5ff	3892.0848
13	2661.9331	1/2	1–0 R 2.5ee	445.2626
	2662.1518	1/2	1–0 R 2.5ff	446.0913
14	2709.9111	1/2	1–0 R 5.5ee	705.7060
	2710.0575	1/2	1–0 R 5.5ff	707.2638
15	2710.9529	1/2	2–1 R 14.5ff	5042.3624
	2711.0189	1/2	2–1 R 14.5ee	5039.8647
16	2770.9408	3/2	1–0 R 10.5ee	1074.9261
	2771.0636	3/2	1–0 R 10.5ff	1075.6188

[a] Numbers in Figure 2.
[b] Electronic angular momentum index.
[c] Vibrational and rotational transition indices.
[d] Lower state energy relative to $v = 0$, $J = 1.5$, $\Omega = 3/2$.

The molecules in front of the star cause absorption, while those extended in the blank sky contribute as emission. Considering that the shell may be in the atmosphere, we adopt an exponential density law $n(r) \propto \exp(-r/r_0)$, where r_0 is the scale height. The star is assumed to be a 3000 K blackbody. For simplification, a constant excitation temperature is adopted, and the energy population of the molecule is calculated by assuming local thermodynamic equilibrium. This may be justified if the molecular shell is thin and in the high-density region near the photosphere. The line intensity of SH is calculated based on Benidar et al. (1991), which takes account of the Herman-Wallis effect. The spectrum is normalized by the stellar continuum. No smoothing is applied.

The excitation temperature can be determined from the relative intensities of the lines at different energy levels; higher temperatures excite the molecules to higher energy levels and increase the line strength from these levels. We find that 2200 K is most reasonable for the present case. A turbulent velocity of 6 km s^{-1} and infall velocity of 9 km s^{-1} reproduce the line profiles. The model spectrum is shifted by -14 km s^{-1}. Considering the terrestrial velocity of -2.7 km s^{-1} at transit of the observation and the shift applied by Ridgway et al. (1984), $+5.2$ km s^{-1}, a radial velocity of -16.5 km s^{-1} is obtained. The inner radius and the scale height of the SH shell is 1.0 and 0.08 times the stellar radius, respectively. The SH column density in the shell is 4.0×10^{20} cm^{-2}. The uncertainties of the parameters, which changes the model spectrum by about 10%, are ± 100 K for excitation temperature, a factor of 2 for column density, ± 0.01 $R_\star$ for scale height, and ± 1 km s^{-1} for the velocities. The radial velocity has an error of ± 2 km s^{-1} due to the redigitization process. The model spectrum is compared with the observation in Figure 2. The wavelength regions are selected so that the contamination of other spectral lines is minimal and that a wide range of energy levels is covered. Strong lines in Figure 2 are listed in Table 1. The fit is satisfactory in most of the lines. Fitting of ^{34}SH lines results in an isotopic abundance ratio of 5%–10%. We note that the same parameters also give reasonable fits for the HCl lines with a column density of 3.0×10^{19} cm^{-2}.

4. DISCUSSION

Why are SH lines so prominent in R And, an S-type star? S-type stars are characterized by their chemical anomaly of similar carbon and oxygen abundances. This leaves few C and O atoms for further chemical processes after formation of CO molecules at 4000–5000 K. SH should be quite abundant in the atmosphere of oxygen-rich stars but a minor product in a carbon-rich environment (Tsuji 1973). Since we do see SiO lines, but no CS line, in the spectrum of R And, the star is slightly oxygen rich. Nevertheless, it is not expected that SH is much more abundant in S-type stars than O-rich stars. This also holds for HCl, which is the most abundant Cl-bearing molecule in an oxygen-rich environment, although the absolute abundance is by 1 order of magnitude lower than SH. Ridgway et al. (1984) suggested that the atmosphere of S-type stars is more transparent than O-rich stars, so that the lines of minor species could be stronger due to larger path length. We especially emphasize the contribution of the H_2O molecules. In the same paper, Ridgway et al. reported that an enormous number of lines heavily blanket the 2400–2800 cm^{-1} region of the *o* Ceti spectrum. They suspected that these are highly excited water lines. This is supported by the *ISO*/SWS observation of *o* Ceti (Yamamura, de Jong, & Cami 1999b). Despite the relatively poor resolution of the SWS spectrum, they demonstrate that the star shows highly excited H_2O lines in the 3.5–4.0 μm region, arising from a hot (2000 K) and optically thick molecular layer. Probably, in O-rich stars, SH (and HCl) lines are weaker because of the shorter path length and also heavily contaminated by the hot water lines. On the other hand, H_2O molecules are not favored in the atmosphere of S-type stars. The thermal equilibrium abundance of H_2O in S-type stars is 3–4 orders of magnitude lower than in O-rich stars (Tsuji 1964).

The derived infall velocity and the excitation temperature of the SH layer are consistent with the measurement of CO $\Delta v = 3$ lines by Hinkle, Scharlach, & Hall (1984) at $\phi = 0.80$, indicating that the SH molecules are in the same region as hot CO near the photosphere. Comparison with the CO column density 2.6×10^{24} cm^{-2} given by Hinkle et al. (1984) leads to SH/H = 1×10^{-7}. In thermal equilibrium at the temperature of 2200 K and gas pressure of $\log(P_g) = 1.0$, the SH abundance is 2×10^{-7} (Tsuji 1973; T. Tsuji 1999, private communication). This value is insensitive to the C/O ratio as long as C/O < 1. The present estimate of SH abundance in R And, although it is rather crude, is consistent with this calculated value. The sulfur chemistry in the SH layer still follows thermal equilibrium because of its high density and high temperature.

We see no clear evidence of distinct velocity and/or different temperature components of SH lines in the spectrum. This implies that the SH molecules are distributed only in a thin layer in the atmosphere. In thermal equilibrium, SH is most abundant around 1800 K and then is rather quickly transformed to H_2S or SiS below ~1500 K (Tsuji 1973). Otherwise, nonequilibrium chemical reactions may lead to completely different compo-

sitions in the extended atmosphere, e.g., the enhancement of SO_2 in oxygen-rich stars (Yamamura et al. 1999a; Beck et al. 1992). We could not find any clear indications of H_2S or SO_2 in the spectrum of R And. The upper limit of the H_2S column density is at least a factor of 10 larger than the observed amount of SH. A dioxide molecule SO_2 may not be abundant in the atmospheres of S-type stars. Other possible candidates—SO and SiS—have no transition in the present wavelength coverage.

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