

SILANE IN IRC +10216

D. M. GOLDHABER¹ AND A. L. BETZ¹

Space Sciences Laboratory, University of California, Berkeley

Received 1983 October 25; accepted 1984 January 6

ABSTRACT

Silane has been detected in the gas surrounding IRC +10216. Thirteen absorption lines in the ν_4 band around 917 cm^{-1} were observed at 0.2 km s^{-1} resolution. A lower limit to the radial column density is $2 \times 10^{15}\text{ cm}^{-2}$, and the relative strengths of the transitions indicate an average rotational temperature of 173 K.

Subject headings: infrared: sources — infrared: spectra — interstellar: molecules — stars: carbon — stars: circumstellar shells

I. INTRODUCTION

Silane, SiH_4 , like methane, is a spherical top molecule with tetrahedral symmetry (Herzberg 1945) and consequently has only a small, rotationally induced dipole moment. The pure rotational transitions appearing at radio frequencies are therefore extremely weak, which makes the detection of silane at these frequencies a difficult prospect. By contrast, silane is an excellent candidate for observation in the infrared since the vibration-rotation transitions in the ν_4 band near 917 cm^{-1} are quite strong. Silane is extremely pyrophoric, however, so its abundance is likely to be greater in stars where $[\text{C}]/[\text{O}] > 1$. We report the detection of thirteen absorption lines of silane in the envelope of IRC +10216. These lines are the first evidence of silane beyond the Earth.

The infrared star IRC +10216 is a carbon-rich supergiant undergoing extensive mass loss. A number of molecular species have been detected in its envelope (see McCabe, Smith, and Clegg 1979 and Zuckerman 1980 for reviews). The majority of these observations are at radio frequencies where the beam size of a single antenna is typically about $1'$. With a wide beam, the emission from the large amount of gas in the outer part of the envelope dominates. However, this emission is not indicative of the conditions of the gas within a radius of about $5 \times 10^{15}\text{ cm}$. Yet, it is within this radius where the physical and chemical processes occur that largely determine the mass, velocity, and composition of the ejected matter. The significance of the observations presented here is that they provide new information on conditions in this inner region. Because the silane lines are observed in absorption, we detect mainly that gas which is along the line of sight to the small ($< 1''$) central continuum source. Furthermore, since the gas density is greatest near the star, it is to gas there that we are most sensitive.

¹Visiting Astronomer at the Infrared Telescope Facility which is operated by the University of Hawaii under contract to the National Aeronautics and Space Administration.

II. OBSERVATIONS AND RESULTS

The observations were conducted in 1983 February and April at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. The spectrometer used was the laser heterodyne system described by Betz (1981). Two banks of 64, 20 MHz filters were used to achieve a total intermediate frequency (IF) bandwidth of 2560 MHz. At 27.5 THz the resolution was 0.22 km s^{-1} and the range of observable velocities (in both sidebands) was 56 km s^{-1} . The beamwidth of the 3 m telescope was essentially the diffraction-limited value of $0''.8$.

The spectra obtained with our instrument are double sideband (DSB), each consisting typically of a silane line in absorption against the continuum in one sideband plus the unattenuated continuum from the opposite sideband. Since we do not know the relative strengths of the continuum in the two sidebands, true single sideband (SSB) spectra cannot be unambiguously determined. The best assumption we can make is that the continuum is equal in the two sidebands. This introduces an error if, for example, a broad spectral feature in the photosphere of the star gives an overall slope to the continuum. To reduce our spectra, we used the method of least squares to fit the DSB continuum with a quadratic and made the assumption of equal continuum contributions to each sideband. Six of the reduced spectra are shown in Figure 1.

In Table 1 we list the lines observed. For each line we give the frequency as measured with the spectrometer in our laboratory, the laser line used as the local oscillator, and the equivalent width (W_o) of the stellar line obtained by integrating over the entire line profile. The equivalent width for the $Q^0(8)E^{(1)} \leftarrow E^{(1)}$ line includes a contribution of an estimated 6% that fell outside the IF band. In 1983 April the stellar geocentric velocity was such that the $^{13}\text{C}^{16}\text{O}_2\text{-}P(6)I$ laser frequency fell approximately halfway between the frequencies of the $Q^0(7)F_1^{(2)} \leftarrow F_2^{(2)}$ and $Q^0(10)E^{(2)} \leftarrow E^{(2)}$ transitions in the star. These lines therefore overlapped in the IF band, and we can give only a single equivalent width including contribu-

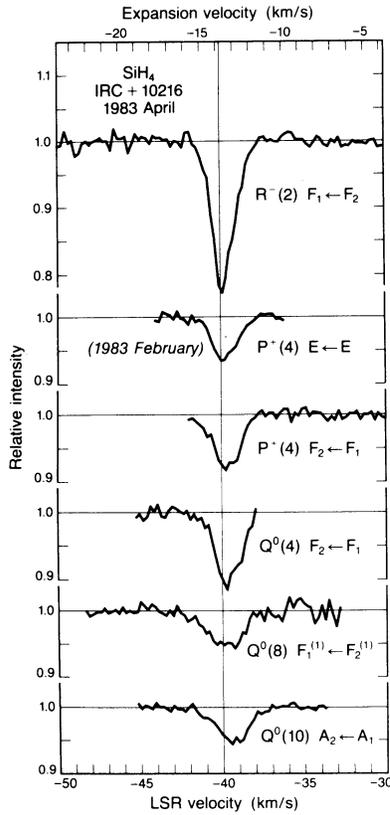


FIG. 1.—Spectra of six lines of the ν_4 band of $^{28}\text{SiH}_4$ in IRC +10216. All lines except $P^+(4)E \leftarrow E$ were observed in 1983 April. Intensities are expressed relative to the observed SSB continuum. The circumstellar expansion velocity was obtained by taking the intrinsic stellar velocity to be -26.3 km s^{-1} (LSR) as determined by Olofsson *et al.* (1982). Each line was integrated for 16 minutes except $P^+(4)E \leftarrow E$ which was integrated for 40 minutes.

tions from both lines. The same is true for the $^{13}\text{C}^{16}\text{O}_2-R(16)I$ laser and the $R^-(5)F_2^{(2)} \leftarrow F_1^{(2)}$ and $E \leftarrow E$ silane transitions. Also listed in Table 1 are four lines of higher excitation which we did not detect. For these lines, we give upper limits to W_σ at the 2σ level, where we assume line widths equal to those of the lines we did detect.

III. ANALYSIS

a) Rotational Temperature

Our analysis of the rotational temperature (T_{rot}) is presented in Figure 2. We have assumed that the relative intensities are those given by Herranz (1961) and ignored any effect of stimulated emission. Relative intensities are given by

$$I_\nu \propto g_\nu \exp\left(-\frac{E''}{kT_{\text{rot}}}\right),$$

where

$$g = \begin{cases} g_T(2J'' - 1), & \text{for } P\text{-branch,} \\ g_T(2J'' + 1), & \text{for } Q\text{-branch,} \\ g_T(2J'' + 3), & \text{for } R\text{-branch.} \end{cases}$$

The term g_T is the statistical weight due to the symmetry species of the initial state and is equal to 2, 3, and 5 for species E , F_1 (or F_2), and A_1 (or A_2) respectively. We emphasize that these formulae do not include the intensity perturbation effect arising from Coriolis mixing among the various vibrational bands. The greatest source of error in the analysis is our lack of knowledge of this effect. The analysis of Gray, Robiette, and Johns (1977) includes the interaction of the ν_4 band with the nearby ν_2 band and predicts relative intensities differing from those given by Herranz (1961) with an rms deviation equal to about 10%. Line strengths for the tetrahedral molecule CH_4 measured by Jennings (1980) are also typically 10% greater or smaller than those given by Herranz (1961). We therefore estimate a 2σ error of 20% which is shown in the figure. An experimental determination of individual line strengths would greatly improve the quality of the analysis. For our integration times, the true statistical error in the measurement of W_σ is typically 5%.

An unweighted least squares fit gives an average rotational temperature of $173 \text{ K} \pm 27 \text{ K}$ ($\pm 2\sigma$). We do not mean to say that all the silane we see is at this temperature. Since we see all the gas in the line of sight to the $11 \mu\text{m}$ continuum source, we expect to observe gas over a range of temperatures. Far from the star, where the gas is cooler, we expect that the silane is primarily in states of lower J . Closer to the star, we expect that more of the silane is in higher- J states. In fact, the relative intensities of just the $J = 2, 4,$ and 5 lines are better fitted by a rotational temperature $T_{\text{rot}} = 110 \text{ K}$, while the $J = 7, 8,$ and 10 transitions by themselves are better fitted by $T_{\text{rot}} = 210 \text{ K}$.

In 1983 April, Ridgway and Keady acquired a wide-band FTS spectrum of IRC +10216 in the $10 \mu\text{m}$ region (Ridgway 1983). These independent observations show many lines of silane in the interval between 875 and 935 cm^{-1} . Although the FTS data are not considered in our analysis, the relative intensities appear to be consistent with the 173 K rotational temperature derived here.

b) Column Density

We have observed silane in only a small number of the rotational levels in the ground vibrational state. In order to estimate a column density, some assumption must be made about the populations in the unobserved levels. From the analysis above, we can assume that the levels are thermalized at least up to $J = 10$. What about the silane in states with $J > 10$? At $T_{\text{rot}} = 173 \text{ K}$, the fraction of the silane in such states is only 18%. For T_{rot} even as high as 250 K , the upper limits given in Table 1 restrict the fraction to be no larger than 25%. We shall assume that all the silane is in local thermodynamic equilibrium (LTE) at 173 K and by doing so will incur an error in the estimated column density that is probably less than about 25% by fraction. With this assumption, together with the partition function calculated by Fox (1970) and the integrated absorption coefficient of $32.42 \pm 0.81 \text{ cm}^2 \text{ millimole}^{-1}$ measured by Levin and King (1962), we estimate a radial column density of $2 \times 10^{15} \text{ cm}^{-2}$. This is best regarded as a lower limit. The estimate will require revision upward if future observations reveal significant amounts of high- J silane or if careful modeling reveals that our absorption lines are partially filled in by radiation from dust.

TABLE 1

A. SILANE LINES DETECTED

SiH ₄ Line	SiH ₄ Rest Frequency (MHz)	Local Oscillator	Equivalent Width, W_σ (cm ⁻¹)
$R^-(2)F_1 \leftarrow F_2$	27,544,435	¹³ C ¹⁶ O ₂ -R(6)I	1.12×10^{-3}
$P^+(4)E \leftarrow E$	26,927,774	¹³ C ¹⁸ O ₂ -P(38)I	3.53×10^{-4}
$P^+(4)F_2 \leftarrow F_1$	26,939,885	¹³ C ¹⁶ O ₂ -P(18)I	4.75×10^{-4}
$Q^0(4)F_2 \leftarrow F_1$	27,242,724	¹³ C ¹⁶ O ₂ -P(6)I	6.10×10^{-4}
$R^-(5)E \leftarrow E$	27,759,353	¹³ C ¹⁶ O ₂ -R(16)I }	1.55×10^{-3}
$R^-(5)F_2^{(2)} \leftarrow F_1^{(2)}$	27,756,819	¹³ C ¹⁶ O ₂ -R(16)I }	
$Q^0(7)F_1^{(2)} \leftarrow F_2^{(2)}$	27,239,509	¹³ C ¹⁶ O ₂ -P(6)I }	4.51×10^{-4}
$Q^0(10)E^{(2)} \leftarrow E^{(2)}$	27,242,257	¹³ C ¹⁶ O ₂ -P(6)I }	
$P^+(8)E^{(1)} \leftarrow E^{(1)}$	26,560,720	¹³ C ¹⁶ O ₂ -P(32)I	2.18×10^{-4}
$Q^0(8)E^{(1)} \leftarrow E^{(1)}$	27,045,097	¹³ C ¹⁶ O ₂ -P(14)I	3.13×10^{-4}
$Q^0(8)F_1^{(1)} \leftarrow F_2^{(1)}$	27,190,463	¹³ C ¹⁶ O ₂ -P(8)I	4.48×10^{-4}
$Q^0(8)F_2^{(1)} \leftarrow F_1^{(1)}$	27,043,262	¹³ C ¹⁶ O ₂ -P(14)I	3.05×10^{-4}
$Q^0(10)A_2 \leftarrow A_1$	27,193,096	¹³ C ¹⁶ O ₂ -P(8)I	3.69×10^{-4}

B. SILANE LINES NOT DETECTED

$Q^0(11)F_1^{(1)} \leftarrow F_2^{(1)}$..	26,833,362	¹³ C ¹⁶ O ₂ -P(22)I	$< 9 \times 10^{-5}$
$Q^0(12)F_1^{(1)} \leftarrow F_2^{(1)}$..	26,990,433	¹³ C ¹⁶ O ₂ -P(16)I	$< 7 \times 10^{-5}$
$Q^0(13)E^{(1)} \leftarrow E^{(1)}$..	26,927,141	¹³ C ¹⁸ O ₂ -P(38)I	$< 8 \times 10^{-5}$
$Q^0(13)F_2^{(2)} \leftarrow F_1^{(2)}$..	26,928,457	¹³ C ¹⁸ O ₂ -P(38)I	$< 9 \times 10^{-5}$

NOTE.—The SiH₄ line frequencies given by Gray, Robiette, and Johns 1977 are accurate only to approximately ± 200 MHz and hence have been remeasured by us. Our frequencies are all accurate to ± 3 MHz except that for $Q^0(8)F_2^{(1)} \leftarrow F_1^{(1)}$ which is accurate to ± 10 MHz. A 1 MHz uncertainty in frequency corresponds to a 0.01 km s⁻¹ uncertainty in velocity. The absolute line frequencies for the CO₂ lines are taken from Freed, Bradley, and O'Donnell 1980. For the lines not detected, the upper limits to W_σ are quoted at the 2 σ level, where we assume line widths equal to those of the lines we did detect.

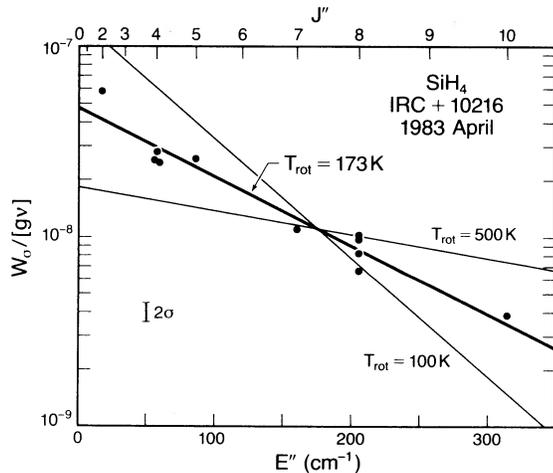


FIG. 2.—We plot (W_0/gv) vs. the energy of the initial state. An unweighted least squares fit gives an average rotational temperature $T_{\text{rot}} = 173 \text{ K} \pm 27 \text{ K}$. The error quoted is the formal $\pm 2 \sigma$ error derived from the fit. Traces for $T_{\text{rot}} = 100 \text{ K}$ and for $T_{\text{rot}} = 500 \text{ K}$ are shown for comparison.

Taking the column density of CO to be 10^{20} cm^{-2} as measured by Hall and Ridgway (1978), we find that the $[\text{SiH}_4]/[\text{CO}]$ ratio is $\geq 2 \times 10^{-5}$. This lower limit is close to the abundance predicted by Tsuji (1964) for chemical equilibrium in the photosphere of a carbon star with a temperature

$T \approx 1250 \text{ K}$ and a pressure $P \approx 1000 \text{ dynes cm}^{-2}$. More recently, McCabe, Smith, and Clegg (1979) have matched the abundances of a number of observed molecules to a “photospheric freeze-out” model with $T \approx 1250 \text{ K}$ and $P \approx 100 \text{ dynes cm}^{-2}$. We infer that, at this lower pressure, the equilibrium abundance of silane would be predicted to be lower than our observed lower limit. However, the abundances predicted by McCabe, Smith, and Clegg (1979) for the silicon-containing molecules which they considered—SiS and SiO—are higher than observed. They suggested that silicon is locked up in grains of SiC or silicates and is thus not available for gaseous species. This is not inconsistent with the high abundance of silane if an additional process, such as catalysis on grain surfaces, contributes to the formation of silane. Other saturated-bond species, such as ammonia (Betz, McLaren, and Spears 1979) and methane (Clegg, Hinkle, and Lambert 1982), are also observed to be abundant and concentrated at the terminal velocity. Whether the high silane abundance is a result of grain catalysis, a higher “photospheric” pressure, or perhaps nonequilibrium chemistry, remains to be determined.

c) Excitation

Quite modest H₂ densities are sufficient to maintain thermal populations up to $J = 10$ as we have observed. This is because radiative relaxation is available only via the “forbidden” pure rotational transitions that arise from the small dipole moment induced by centrifugal distortion (Oka 1976). If we assume a cross section of 10^{-15} cm^2 for H₂ collisions on

SiH_4 , and if we use the line strengths for the $\Delta J = 1$ forbidden transitions given by Watson (1971) with the distortion dipole moment of $\mu_D = 8.3 \times 10^{-6}$ debyes measured by Rosenberg and Ozier (1974), then we find that the collisional transition rates are comparable to the $J = 10 \rightarrow 9$ radiative transition rate when the H_2 density is approximately 10^4 cm^{-3} . In the region where we observe silane, the density is almost certainly much greater than this.

In the model of Kwan and Linke (1982), the mass loss rate of IRC +10216 is $4 \times 10^{-5} M_\odot \text{ yr}^{-1}$ and gas with a kinetic temperature greater than 100 K is confined to the region where the H_2 density is greater than 10^6 cm^{-3} . At these densities, significant deviations from thermal populations are expected to appear only for $J \geq 15$. Other authors have suggested mass loss rates at least as high as $10^{-4} M_\odot \text{ yr}^{-1}$ (Betz, McLaren, and Spears 1979; Knapp *et al.* 1982). If these estimates are correct, the densities involved are still higher and thermalization of the observed levels is assured.

d) Dynamics

Absorption lines of ammonia in IRC +10216 published by Betz (1981) show a significant shift in the line centroid between lines of low excitation and lines of high excitation.

Since high-excitation lines sample gas a bit closer to the star, this was taken to be evidence of a radial velocity gradient (i.e., acceleration). The data presented here show lines only at the terminal velocity and do not show significant gas acceleration. This suggests that the silane lines are formed over a less extended region than the ammonia lines.

Finally, we note that the line profiles all have similar features approximately 0.5 km s^{-1} redward and approximately 1.0 km s^{-1} blueward from the peak of absorption. This may be evidence of a complex velocity structure of an unknown origin, perhaps associated with some discreteness in the mass loss process.

We thank Jonas Zmuidzinas for his assistance with the observations and David Griep for his vigilant control of telescope operations. We appreciate the friendly assistance of Ron Koehler and the IRTF day crew in optimizing the telescope functions to our needs. We also thank Steve Ridgway for communicating his FTS data on IRC +10216 in advance of publication and Dan Jaffe for his comments on the manuscript. These observations were supported in part by NASA and NSF under grants NGR 05-003-452 and AST 82-12055 respectively.

REFERENCES

- Betz, A. L. 1981, in *Laser Spectroscopy V*, ed. A. R. W. McKellar, T. Oka, and B. P. Stoicheff (Berlin: Springer-Verlag), p. 81.
- Betz, A. L., McLaren, R. A., and Spears, D. L. 1979, *Ap. J. (Letters)*, **229**, L97.
- Clegg, R. E. S., Hinkle, K. H., and Lambert, D. L. 1982, *M.N.R.A.S.*, **201**, 95.
- Fox, K. 1970, *J. Quant. Spectrosc. Rad. Transf.*, **10**, 1335.
- Freed, C., Bradley, L. C., and O'Donnell, R. G. 1980, *IEEE J. Quantum Electron.*, **QE-16**, 1195.
- Gray, D. L., Robiette, A. G., and Johns, J. W. C. 1977, *Molec. Phys.*, **34**, 1437.
- Hall, D. N. B., and Ridgway, S. T. 1978, *Nature*, **273**, 281.
- Herranz, J. 1961, *J. Molec. Spectrosc.*, **6**, 343.
- Herzberg, G. 1945, *Infrared and Raman Spectra of Polyatomic Molecules* (Princeton: Van Nostrand), p. 41.
- Jennings, D. E. 1980, *Appl. Opt.*, **19**, 2695.
- Knapp, G. R., Phillips, T. G., Leighton, R. B., Lo, K. Y., Wannier, P. G., Wooten, H. A., and Huggins, P. J. 1982, *Ap. J.*, **252**, 616.
- Kwan, J., and Linke, R. A. 1982, *Ap. J.*, **254**, 587.
- Levin, I. W., and King, W. T. 1962, *J. Chem. Phys.*, **37**, 1375.
- McCabe, E. M., Smith, R. C., and Clegg, R. E. S. 1979, *Nature*, **281**, 263.
- Oka, T. 1976, in *Molecular Spectroscopy: Modern Research II*, ed. K. N. Rao (New York: Academic), p. 229.
- Olofsson, H., Johansson, L. E. B., Hjalmarson, Å., and Nguyen-Quang-Rieu 1982, *Astr. Ap.*, **107**, 128.
- Ridgway, S. T. 1983, private communication.
- Rosenberg, A., and Ozier, I. 1974, *Canadian J. Phys.*, **52**, 575.
- Tsuji, T. 1964, *Ann. Tokyo Astr. Obs.*, Ser. 2, **9**, 1.
- Watson, J. K. G. 1971, *J. Molec. Spectrosc.*, **40**, 536.
- Zuckerman, B. 1980, *Ann. Rev. Astr. Ap.*, **18**, 263.

A. L. BETZ and D. M. GOLDHABER: University of California, Space Sciences Laboratory, Berkeley, CA 94720