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OBSERVATIONS OF SILICON MONOXIDE IN COOL STARS AT 4.05 MICRONS*

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ABSTRACT

Absorption due to the 3–1 vibration-rotation band head of $^{28}Si^{16}O$ at 2473 cm^{-1} has been detected in the atmospheres of a number of evolved giant and supergiant stars. The column density of $^{28}Si^{16}O$ in α Ori is determined to be $10^{21.7}$ cm^{-2}. None of the stars observed indicate measurable absorption due to the 2–0 band head of $^{30}Si^{16}O$ at 2467 cm^{-1}. A lower limit of 20 is established for the ratio $^{28}Si/^{30}Si$ in α Sco.
Subject headings: abundances, stellar — molecules — spectra, infrared

Spectra of 17 stars with high infrared luminosities have been obtained near the 3–1 vibration-rotation band head of $^{28}Si^{16}O$ at 2473 cm^{-1} (4.05 μ). Absorption due to $^{28}Si^{16}O$ is clearly present in 10 of the 17 spectra. Upper limits to the absorption are obtained for the remainder. For those sources which exhibit absorption due to $^{28}Si^{16}O$, upper limits are placed on the absorption due to the band head of the 2–0 vibration-rotation transitions of $^{30}Si^{16}O$ at 2467 cm^{-1}. The complete results are given in table 1. The spectrum of α Her is shown in figure 1.

The observations were made with a tandem scanning Fabry-Perot interferometer mounted at the coudé focus of the Lick 120-inch (305-cm) telescope. The tandem Fabry-Perot is designed to operate with a resolution of approximately 0.1 cm^{-1} at 2500 cm^{-1}. Spectra of α Ori and α Boo were obtained on 1972 April 26–29, using this resolution. The remaining observations were made on 1972 June 28–29, using a resolution of 0.6 cm^{-1} in order to optimize the detectability of SiO bandheads. In all cases, the beam diameter was 3 arc sec. A resolution of 0.6 cm^{-1} is in fact somewhat awkward to obtain with this instrument and results in a rather erratic instrumental profile. The consequent distortion of the continuum level makes an estimation of the equivalent width of the band head uncertain by perhaps 50 percent.

Silicon monoxide was first detected at 4 μ in α Ori by Cudaback, Gaustad, and Knacke (1971) using a Michelson interferometer with a resolution of 2 cm^{-1}. As was pointed out by Cudaback *et al.*, the calculations of Goon and Auman (1970) indicate that the SiO abundance in stellar atmospheres is a sensitive function of spectral type and may be useful in classifying evolved stars. However, in order to determine the column density from the spectrum, it is necessary to account for saturation. This requires a resolution which is comparable to the turbulent linewidth in the stellar atmosphere. Since the linewidth in giants and supergiants is typically of the order of 0.1 cm^{-1} at 2500 cm^{-1}, the present resolution of 0.6 cm^{-1}, while an improvement over earlier work, is inadequate for precise abundance measurements.

The spectrum of α Ori with a resolution of 0.1 cm^{-1} was analyzed in somewhat

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TABLE 1

OBSERVED SiO BAND-HEAD ABSORPTION AT 4.05 MICRONS

Source and Spectral Classification (1)	Fractional Absorption $^{28}Si^{16}O$ 3–1 Band Head (2)	Equivalent Width (cm^{-1}) $^{28}Si^{16}O$ 3–1 Band Head (3)	Fractional Absorption $^{30}Si^{16}O$ 2–0 Band Head (4)
Giants and Supergiants:			
α Boo,* K2 III	<0.10	...	...
α Ori,* M2 Iab	0.25	0.8	no data
α Sco, M2 Iab	0.24	1.2	<.04
β Peg, M2 II–IIIe	0.19	0.7	<.05
α Her, M5 Ib–II	0.17	0.8	<.02
R Lyr, M5 III	0.23	0.8	<.08
X Her, M6e	0.16	0.5	<.12
g Her, M6 III	0.21	0.8	<.04
SW Vir, M7	0.17	0.8	<.12
RX Boo, M7e–M8e	0.28	1.4	<.20
Mira Variables:			
o Cet, M5–M8	<0.04	...	...
W Hya, M8e	≤0.08	...	<.05
χ Cyg, S7,1e–S10,1e	0.20	0.8	<.07
Carbon Stars:			
Y CVn, N3($C5_4$)	<0.13	...	...
V Cyg, Npe($C7_4$e)	<0.05	...	...
Peculiar Objects:			
NML Cyg, M6	<0.06	...	...
VX Sgr, M4e Ia–M8	<0.07	...	...

NOTE:—Asterisks indicate spectra obtained with 0.1 cm^{-1} resolution. Otherwise, resolution is 0.6 cm^{-1}. Upper limits are determined on the basis of fractional absorptions required to produce easily observable spectral features and reflect both statistical and instrumental fluctuations.

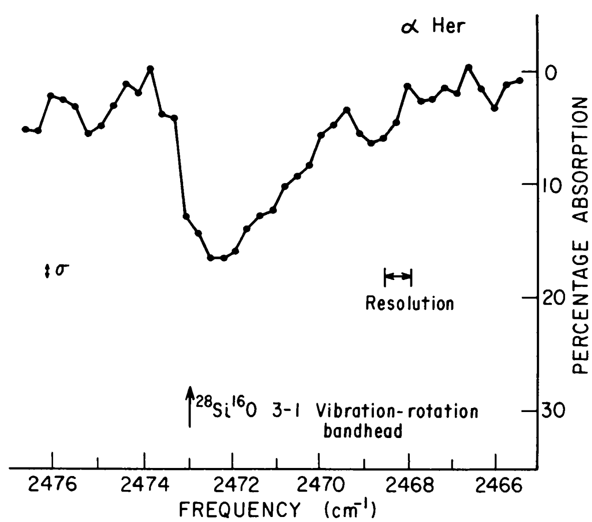

FIG. 1.—Spectrum of α Her near 2473 cm^{-1} showing absorption due to the 3–1 vibration-rotation band head of $^{28}Si^{16}O$. The σ represents the statistical fluctuations for a single data point and does not include possible fluctuations due to systematic effects.

TABLE 2

PARAMETERS FOR BEST-FITTING SIMULATION OF α ORIONIS SPECTRUM

Assumed T_{eff}	3500° K
Assumed turbulent linewidth	14 km s^{-1}
SiO temperature	2900° K
Column density $^{28}Si^{16}O$	$10^{21.7}$ cm^{-2}

greater detail than those with 0.6 cm^{-1} resolution. An isothermal shell model was used to generate a synthetic spectrum which was then fitted to the data by adjustment of the temperature and column density. The SiO molecular constants used in the calculation were those given by Beer, Barnes, and Lambert (1972), and the transition probability was taken from Hedelund and Lambert (1972). The assumed turbulent linewidth was determined from observations of CO at 4.7 μ in α Ori, which indicate a velocity width of $\sim$14 km s^{-1} (Geballe, Wollman, and Rank 1972). This value may be in error by a factor of 2 due to uncertainty in the linewidth determined from the CO observations and the possibility that SiO and CO may occupy different regions of the atmosphere. No satisfactory detailed fit to the observed spectrum of α Ori has been obtained. Nevertheless, it is possible to match the general spectral features. The parameters for the SiO used in the best-fitting synthetic spectrum are listed in table 2. The estimated accuracy is $\pm 150°$ K in the SiO temperature and a factor of 5 in the column density.

The SiO column density of $10^{21.7}$ cm^{-2} deduced from the α Ori spectrum agrees to within observational uncertainty with the column density of $10^{21.3}$ cm^{-2} predicted by the chemical equilibrium calculations of Goon and Auman (1970). On the other hand, measurements of CO column densities in evolved stars are typically two orders of magnitude less than the theoretical predictions (Geballe *et al.* 1972). These results are to be expected if CN processing of the stellar envelope has converted most of the carbon to nitrogen without significantly affecting the abundance of oxygen.

The stars in table 1 which show absorption due to $^{28}Si^{16}O$ are all oxygen-rich giants and supergiants of spectral classification M2 or later. The absence of SiO in the two carbon stars Y CVn and V Cyg is expected because of competition between Si and C for oxygen. Lack of SiO absorption in NML Cyg is additional evidence that the 4-μ continuum flux comes from a rather cool circumstellar shell. Any SiO within or outside this shell would not be hot enough to produce the high rotational excitation necessary for strong band-head formation. The same is probably true for the peculiar object VX Sgr (Wallerstein 1971). Low SiO abundance in α Boo, a K2 giant, is consistent with the calculations of Goon and Auman (1970). Differences in the SiO absorption for the three Mira variables o Cet, W Hya, and χ Cyg may reflect actual differences in atmospheric abundances or periodic variations of atmospheric structure and chemical composition.

The spectral region scanned with 0.6 cm^{-1} resolution includes the position of the 2–0 band head of $^{30}Si^{16}O$ (2467 cm^{-1}). Upper limits to the fractional absorption at this frequency are listed in table 1. A comparison of these limits to the fractional absorption due to the $^{28}Si^{16}O$ band head yields lower limits for the ratio $^{28}Si/^{30}Si$ which are not corrected for saturation. In the case of α Sco, an estimate of the level of saturation of the $^{28}Si^{16}O$ band head can be obtained from the SiO parameters determined for α Ori (table 2), since both stars are of the same spectral type and luminosity class. Using these parameters, a simulation of the spectrum at 0.6 cm^{-1} resolution produces a $^{30}Si^{16}O$ band head with fractional absorption less than the limit of 0.04 obtained for α Sco if the abundance ratio $^{28}Si/^{30}Si$ is greater than 20. The terrestrial value for this ratio is 30.

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