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# VIBRATIONALLY EXCITED SILICON MONOXIDE IN THE ORION NEBULA

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## ABSTRACT

A 1° K line has been detected in the center of the molecular cloud in the Orion Nebula which is probably the 129,363.1-MHz, $J = 3 \rightarrow 2$ rotational transition of SiO in its first excited ($v = 1$) vibrational state. The LSR radial velocity based on this assignment is 15.3 km $s^{-1}$, which is exactly that of the second strongest of the seven lines at 86.2 GHz recently found by Snyder and Buhl, and attributed by them to maser emission by the $v = 1, J = 2 \rightarrow 1$ transition of SiO. We have been unable to detect vibrationally excited SiO in any other source at 129 GHz, and a search for the $v = 1, J = 1 \rightarrow 0$ line of CO has also proved unsuccessful.

*Subject headings:* Orion Nebula — radio lines

Snyder and Buhl (1974) have recently detected an unusual group of strong millimeter-wave emission lines in the center of the molecular cloud in the Orion Nebula—the direction of the Kleinmann-Low infrared nebula, Becklin's infrared star, and the well known Orion point sources of OH and $H_2O$ maser emission. As shown by the reproduction of their spectrum in figure 1, they observe near 86,245 MHz at least seven lines blended into two broad features split by about 6 MHz in frequency or 22 km $s^{-1}$ in radial velocity; the source is compact ($\lesssim 1'$ in diameter), and the individual lines seem to be only about 2 km $s^{-1}$ wide.

Most of the 20-odd molecules observed in this direction have a single velocity component at 8.5 km $s^{-1}$ in the local standard of rest which is typically only 4–6 km $s^{-1}$ wide, but several—notably $H_2S$, SiO, and SO (Thaddeus *et al.* 1972; Dickinson 1972; Gottlieb and Ball 1973)—may also possess a broad underlying skirt of emission extending at least from −10 to +25 km $s^{-1}$; the OH and $H_2O$ emission lines also have a number of velocity components covering roughly the same range

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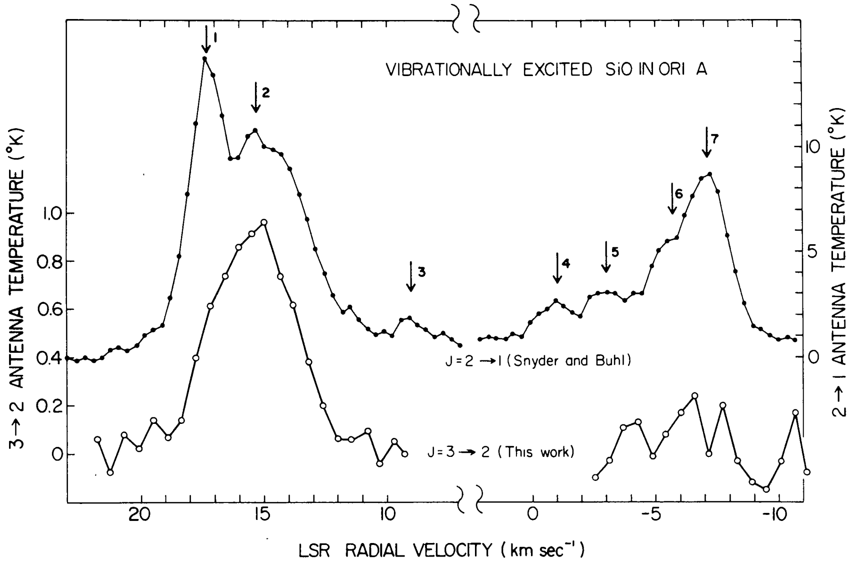


FIG. 1.—Lines attributed to the rotational spectrum of vibrationally excited SiO in the direction of Becklin's infrared star (Ori A position in table 2). The antenna temperature scales are corrected for atmospheric absorption. Arrows denote the seven velocity components which Snyder and Buhl distinguish in the $J = 2 \rightarrow 1$ transition. The $J = 3 \rightarrow 2$ line was clearly observed at different times in both sidebands of the superheterodyne receiver used at 129 GHz, the spectrum shown here on the left representing a total of about 4 hours of observation in the upper, and $1\frac{1}{2}$ hours in the lower sideband. (The spectrum on the right represents a considerably shorter integration, and the noise may be all statistical.)

(Weaver *et al.* 1968; Knowles *et al.* 1969). It seems likely, therefore, that Snyder and Buhl's lines represent velocity structure of a single transition, not many separate transitions; and a remarkable assignment has been made on the basis of this idea. By associating their lines with two of the most prominent and time-independent groups of $H_2O$ lines, Snyder and Buhl deduce a rest frequency which differs by less than 0.2 MHz from that of the $J = 2 \rightarrow 1$ rotational transition of SiO in its first-excited vibrational state 1788° K above the molecular ground state. Because of the compact nature of their source, the abnormal sharpness of their lines, and the marked difference between their complex velocity structure and that observed for the normal $v = 0$, $J = 2 \rightarrow 1$ SiO line (Dickinson 1972), Snyder and Buhl suggest that, as with $H_2O$, maser emission is being observed from a source or sources much smaller than the antenna beam.

To check this assignment, we have observed Becklin's star with the Millimeter Wave Observatory's[1] 16-foot (5-m) antenna at another rotational transition of vibrationally excited SiO—the $v = 1, J = 3 \rightarrow 2$ transition lying at a frequency 50 percent higher than Snyder and Buhl's. The rest frequency of this transition has not been measured directly, but it can be calculated accurately enough for our purpose from the spectroscopic constants which Törring (1968) derives from laboratory measurement of the $J = 1 \rightarrow 0$ transition in the four lowest vibrational states; the resulting rest frequency is $129{,}363.1 \pm 0.4$ MHz, yielding an uncertainty in radial velocity of less than 1 km $s^{-1}$.

Figure 1 shows our results. Although no spectral feature exceeding ~0.2° K in antenna temperature is found to correspond to Snyder and Buhl's strong negative-velocity feature, we do find a 1° K line that agrees very closely both in velocity and width with their broad positive-velocity one—with the notable difference that the sharp spur which they observe at +17.3 km $s^{-1}$ is absent from our spectrum. Since our observations were made 6 weeks later than theirs (1974 January 30–February 3, versus 1973 December 19), this difference might result from time variation in the source, but it could instead be another indication that we are dealing with maser lines, since the intensity of such lines can be highly sensitive to small gain variations when the gain is large. Further observations are obviously needed to choose between these alternatives, but the excellent agreement in both velocity and width between our line and Snyder and Buhl's component 2 is probably far too good to be explained by chance. We therefore conclude that both we and they are almost certainly observing vibrationally excited SiO.

If it is assumed that the 129-GHz and 86-GHz sources have the same angular size, and are both small with respect to the antenna beam, it is an easy matter to convert our data into brightness temperatures. If we let primed quantities denote the 86-GHz line and the 36-foot telescope used by Snyder and Buhl, and unprimed ones the 129-GHz line and our 16-foot telescope, the ratio of the brightness temperatures is given by

$$T_B/T_B' = 0.68\,(T_A/T_A')(\epsilon'/\epsilon)(D'\nu'/D\nu)^2$$
$$= 1.13\,T_A/T_A'\,, \qquad (1)$$

where $T_A$ is the measured antenna temperature, $\epsilon = 0.54$ and $\epsilon' = 0.40$ are the aperture efficiencies of, respectively, our telescope at 129 GHz and the 36-foot telescope at 86 GHz, and $D$ is the telescope aperture. The factor 0.68 is a correction necessary to reconcile the antenna temperature calibration scales of the two instruments (Ulich 1974). Applied to the data in figure 1, equation (1) yields $T_B$ (129 GHz) $= 0.11 T_B$ (86 GHz) for velocity component 2, and $T_B$ (129 GHz) $\lesssim 0.03 T_B$ (86 GHz) for component 7. Apparently then in terms of temperature the $v = 1, J = 3 \rightarrow 2$ line is at least an order of magnitude weaker than the $2 \rightarrow 1$ line, which may imply that the populations of the higher-frequency transition are significantly less inverted than those of the lower. This in turn makes one wonder whether the so-far unobserved $J = 1 \rightarrow 0$ line of vibrationally excited SiO at 43 GHz may turn out to be the most intense of all.

In sources other than Orion we have been unable to detect the $v = 1, J = 3 \rightarrow 2$ line, although in at least one (the stellar OH source W Hya) the $v = 1, J = 2 \rightarrow 1$ emission apparently rivals that in Orion (Snyder 1974). Our negative results are summarized in table 1.

The detection of strong rotational lines from a vibrationally excited molecule not thought on the basis of previous observations to be particularly abundant in molecular sources (Wilson *et al.* 1971; Dickinson 1972) prompts a search for similar lines from those molecules known to be plentiful; carbon monoxide is

TABLE 1

NEGATIVE RESULTS FOR THE $v = 1$, $J = 3 \rightarrow 2$ LINE OF SiO

| Source | α (1950) | δ (1950) | Peak-to-Peak Noise (° K)* | LSR Velocity Range (km $s^{-1}$)† |
|---|---|---|---|---|
| IRC+10216 | $9^h45^m15^s$ | 13°30′40″ | 0.8 | −39 to +9*h* |
| W Hya | 13 46 12 | −28 07 06 | 1.3 | +16 +46*h* |
| R CrB | 15 17 19 | 31 43 36 | 0.5 | −46 +112 |
| Sgr A | 17 42 28 | −29 01 30 | 0.6 | −83 +5 |
| | 17 42 43 | −28 58 30 | 0.5 | −83 +5 |
| | | | 0.8 | +10 +98 |
| | 17 42 47 | −28 58 30 | 0.8 | +10 +98 |
| VX Sgr | 18 02 02 | −22 14 06 | 0.6 | −46 +112 |
| NGC 6589 | 18 15 58 | −19 48 00 | 0.8 | +6 +38*h* |
| | | | 0.5 | −79 +79 |
| M17 | 18 17 26 | −16 14 54 | 0.5 | −46 +112 |
| DR 21 | 20 37 14 | 44 42 12 | 0.5 | −48 +40 |
| DR 21 (OH) | 20 37 14 | 42 12 00 | 0.3 | −67 +91 |
| NML Cyg | 20 44 34 | 39 55 54 | 0.5 | −67 +91 |
| TW Peg | 22 01 41 | 28 06 30 | 0.5 | −95 +63 |

* Channel-to-channel fluctuation in antenna temperature.

† Velocity resolution 0.6 km $s^{-1}$ when noted by *h;* otherwise 4.8 km $s^{-1}$.

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the obvious candidate. Following our SiO observations, we attempted to find the $v = 1, J = 1 \rightarrow 0$ line of CO in seven sources, including Orion, but failed entirely; table 2 presents a summary of the observations. In IRC+10216 a brief previous search for this line was also apparently unsuccessful (Penzias 1974).

One obvious difference between CO and SiO which might account for this curious result is the higher CO vibrational frequency: the $v = 1$ state of CO lies at an energy of 3100° K versus only 1800° K for that of SiO, so excitation by infrared radiation at a color temperature less than ~300° K will vibrationally excite SiO much more rapidly than CO. The highly different volatility of the two molecules might also be an important factor: one can readily imagine a situation in the vicinity of a star where SiO is being continually produced by grain evaporation long after CO and other volatile molecules have been destroyed or removed.

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TABLE 2

NEGATIVE RESULTS FOR THE $v = 1, J = 1 \rightarrow 0$ LINE OF CO

| Source | α (1950) | δ (1950) | Peak-to-Peak Noise (° K)* | LSR Velocity Range (km s$^{-1}$)† |
|---|---|---|---|---|
| S 187...... | $1^h20^m00^s$ | 61°36′24″ | 0.5 | −103 to +75 |
| W3 (OH)... | 2 23 17 | 61 39 00 | 1.0 | −106 +73 |
| Ori A...... | 5 32 47 | − 5 24 25 | 0.6 | −69 +120 |
| | | | 0.8 | +10 +22*h* |
| IC 2162.... | 6 10 09 | 18 00 00 | 0.3 | −147 +32 |
| VY CMa... | 7 20 55 | −25 40 24 | 0.8 | −73 +95 |
| IRC+10216 | 9 45 15 | 13 30 40 | 0.6 | −100 +65 |
| TW Peg.... | 22 01 41 | 28 06 30 | 0.7 | −90 +89 |

* Channel-to-channel fluctuation in antenna temperature.

† Velocity resolution 0.6 km s$^{-1}$ when noted by *h*, otherwise 4.8 km s$^{-1}$. The rest frequency of the transition is 114,221.70 ± 0.30 MHz (Lovas 1974).

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