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THERMAL SiO AS A PROBE OF HIGH VELOCITY MOTIONS IN REGIONS OF STAR FORMATION

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ABSTRACT

New observations of the $v = 0$, $J = 2 \rightarrow 1$ line of SiO at 86.8 GHz show a close association of the thermal SiO emission and infrared and maser sources in regions of star formation. In addition to SiO emission with low velocity dispersion ($\Delta v \leq 7$ km s^{-1}), we report the first detection of *high velocity* ("plateau") emission toward W49 and W51. The low velocity SiO component may come from the core of the molecular cloud which contains the infrared and maser sources. The "plateau" may indicate mass outflow from stars within the infrared clusters. In Orion-KL, the positional centroid of the high velocity SiO emission ($|\Delta v| \geq 20$ km s^{-1}) is near that of the component we identify as the "18 km s^{-1} flow." However, the centroids of the blue- and redshifted wings are displaced from each other by a few arcseconds, to the NW and NE of the position of the 18 km s^{-1} component. The mass-loss rates of the high velocity flow and the 18 km s^{-1} flow are similar.

Subject headings: interstellar: molecules — masers — nebulae: individual — nebulae: Orion Nebula — stars: mass loss

I. INTRODUCTION AND OBSERVATIONS

The proper motions of H_2O masers show that the radial velocity dispersions of ± 20 to ± 250 km s^{-1} in many maser sources are caused by systematic motions, possibly mass loss from newly formed stars (Genzel *et al.* 1981). The high velocity thermal gas associated with these motions has been detected only in Orion and a few lower luminosity regions toward the galactic anticenter. Detection of this gas toward galactic longitudes $l < |\pm 60°|$ is hindered by the small size of the high velocity regions and by the emission from other, quiescent, clouds along the line of sight. A good tracer for the high velocity gas may be the ground vibrational state "thermal" emission of SiO, which is weak in extended molecular clouds, but possibly associated with compact infrared and maser sources (Gottlieb, Reid, and Dickinson 1978).

To study this possibility, we observed thermal SiO in 1981 March with the Onsala 20 m telescope and a cooled mixer receiver. The system temperature, including radome and atmosphere, was 300–400 K (single sideband, depending on elevation and weather). Total power spectra were taken in 512 and 256 channel filter banks of resolution 1 MHz (3.45 km s^{-1}) and 250 kHz (0.86 km s^{-1}), respectively. The extinction was estimated from sky noise, with a standard atmospheric model. Antenna temperatures were divided by 0.46 (which corrects for main beam efficiency and harmonic losses in the mixer) to obtain main beam brightness temperature ($T_{mb} = T_A^*$). At 86.8 GHz, the half-power beam width (HPBW) was 43″, and the aperture and beam efficiencies were 0.4 and 0.55. The telescope tracking accuracy was $\pm 3''$(rms), and the pointing repeated to $\pm 10''$ from day to day.

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II. RESULTS

a) *Narrow-line $v = 0$* SiO *Emission in Regions of Star Formation*

Table 1 and Figure 1 show our observations of the $v = 0$, $J = 2 \rightarrow 1$ line toward H_2O masers and compact IR sources. We mapped W49N, W51M, and W51N, and found the SiO emission to have sizes $\leq 30''$ and to coincide with the maser positions to $\pm 10''$. In six other sources the ratios of brightness temperatures measured with beams of 43″ (this paper) and 2′ (Wolff 1980) also indicate that the SiO emission is confined to $< 30''$. The thermal SiO emission may come from dense molecular gas in the immediate vicinity of the IR and maser sources. If the excitation is collisional, the observed intensities and the high dipole moment of SiO (3.098 debye) imply hydrogen densities $> 10^5$ cm^{-3}. In Orion, such densities would be found within ~ 0.1 pc of the IR/maser sources, or within 3″ to 10″ in sources at distances of a few kpc. Alternatively, if the SiO lines are radiatively excited through the vibrational levels at 8.1 μm (Morris and Alcock 1977), then the SiO emission would also originate close ($< 5''$) to the near-IR sources. In either case, moderate to high optical depths are likely

TABLE 1

SiO AND $H^{13}CO^+$ OBSERVATIONS[a]

Source	R.A. (1950)	Decl. (1950)	SiO $v = 0, J = 2 \rightarrow 1$ v_{LSR} (km s^{-1})	Δv_{HP}[b] (km s^{-1})	Δv_{ZP}[b] (km s^{-1})	T_{mb} (K)	$H^{13}CO^+$ $J = 1 \rightarrow 0$ v_{LSR} (km s^{-1})	Δv_{HP}[b] (km s^{-1})	Δv_{ZP}[b] (km s^{-1})	T_{mb} (K)
W3 IRS 5	$02^h21^m53^s.2$	+61°52′21″	−40	5	16	0.3	−40	5	14	0.25
W3 OH	02 23 17.3	+61 38 58	−48	7	17	0.35	−48	5	16	0.55
GL 490	03 23 41.4	+58 36 52	...	...	...	< 0.1	...	...	...	≤ 0.15
HH 7 → 11	03 25 58.0	+31 05 45	...	...	...	0.15	+6	8	18	0.4
L1551 IR	04 28 40.0	+18 01 52	...	...	...	0.13	...	...	...	...
ORION IRc2	05 32 47.0	−05 24 23	+7	22	115	7.5	+8	7	33	0.8
ORION 3 N	05 32 47.0	−05 21 20	...	...	...	< 0.12	...	...	...	...
ORION 1 NE	05 32 49.8	−05 23 38	+12	20	26	0.3	+8	5	26	0.5
12.2−0.1	18 09 43.7	−18 25 09	...	...	...	< 0.25	...	...	...	...
30.8−0.1	18 45 11.0	−01 57 57	+97	10	26	0.7	+97	8	20	0.65
W49N	19 07 49.8	+09 01 17	+6	13	60	1.4	+7	15	40	0.8
W51N	19 21 22.4	+14 25 13	+61	7	30	0.55	+61	10	15	0.65
W51M	19 21 26.2	+14 24 43	+57	9	30	1.5	+56	9	21	1.35
ON1	20 08 09.9	+31 22 42	+11	4	12	0.6	+11	6	15	0.8
ON2	20 19 51.8	+27 17 01	−1	20	41	0.5	0	9	15	0.5
W75N	20 36 50.4	+42 27 01	+9	9	29	0.45	+8	8	20	0.9
W75S	20 37 13.8	+42 12 13	−4	7	20	1.1	−3	6	17	1.5
S140	22 17 41.2	+63 03 43	...	...	...	< 0.15	−7	5	10	1.0
Cep A	22 54 23.4	+61 45 54	...	...	...	< 0.1	...	...	...	...
NGC 7538S	23 11 36.1	+61 10 30	−56	7	30	0.8	−57	5	16	0.9
NGC 7538 IRS 1	23 11 36.7	+61 10 49	−56	7	...	0.6	−57	5	16	0.9

[a]Assumed rest frequencies: $v = 0, J = 2 \rightarrow 1$ SiO: 86.846 891 GHz; $J = 1 \rightarrow 0$ $H^{13}CO^+$: 86.754 330 GHz (Lovas, Snyder, and Johnson 1979). T_{mb} is the main beam brightness temperature. Typical uncertainties (1 σ) are 1–2 km s^{-1} in velocities and line widths, 25% in T_{mb}. Upper limits for T_{mb} are 2 σ.

[b]Δv_{HP}, Δv_{ZP} = full widths to half and zero power, including broadening by the 3.5 km s^{-1} filter widths.

at 86.8 GHz (see also the SiO isotope measurements by Penzias 1982).

b) *High Velocity Emission in* SiO

In addition to the "narrow" SiO component (full width to half-power $\Delta v_{HP} = 7 \pm 2$ km s^{-1}), we found weaker emission over a larger velocity range in several sources (Fig. 1). The best example is W51N (= W51 IRS 2, Genzel *et al.* 1982). The high velocity components are unlikely to come from other clouds along the line of sight, as may be seen by comparing the SiO and $H^{13}CO^+$ profiles. The narrow components of SiO and $H^{13}CO^+$ are similar, but there is no plateau emission in the $H^{13}CO^+$ line. This is consistent with the low level of the $H^{13}CO^+$ plateau in Orion (Fig. 1, top left). The SiO is correlated, however, with H_2O in both strength and range of the high velocity emission. H_2O masers with no or weak high velocity features (W3, ON1, W75) have narrow SiO profiles, while strong high velocity H_2O masers (Orion, W49, W51) show wide SiO emission. W49N, in particular, has the widest H_2O emission known (± 250 km s^{-1}) and the broadest SiO line (± 30 km s^{-1}).

c) *Do the Mass-Loss Rates Scale with Luminosity*?

If the high velocity SiO emission is optically thin and is interpreted as spherical outflow at expansion velocity v_e from a source at distance D, then the mass-loss rate (g s^{-1}) of SiO molecules scales as $T_{mb} v_e^2 D^2$ (see Genzel *et al.* 1980; Morris 1975), provided the kinetic temperatures and source radii are about the same (note that the H_2O maser features are distributed over $\sim 10^{17}$ cm in all these sources). The brightness temperatures T_{mb} of most of the SiO high velocity components are $\sim$ 0.1–0.3 K, or $\sim$ 0.1 times those in Orion. Since the velocity ranges are comparable and the distances 10–30 times larger, the mass-loss rates in W51 and W49 may be $\sim$ 10 times those of Orion-KL. The IR and maser luminosities of these sources are also at least 10 times Orion. Conversely, we did not detect SiO emission from GL 490, L1551, HH 7 → 11, S140, or Cep A, which have lower IR luminosities ($\leq 10^4\ L_\odot$) than the sources where SiO was found. Although nearly all these sources have high velocity CO emission, H_2O masers are weak or absent, except for Cep A. Hence, the SiO data and the H_2O masers are both consistent with the energy in the high velocity gas increasing with luminosity or mass of the regions.

d) *Mapping of the $v = 0$ Emission in Orion-KL*

The $v = 0, J = 2 \rightarrow 1$ SiO profile toward Orion-KL has two components (Fig. 1 [top] and Fig. 2). The central part ($-12 < v_{LSR} < 24$ km s^{-1}) has a velocity

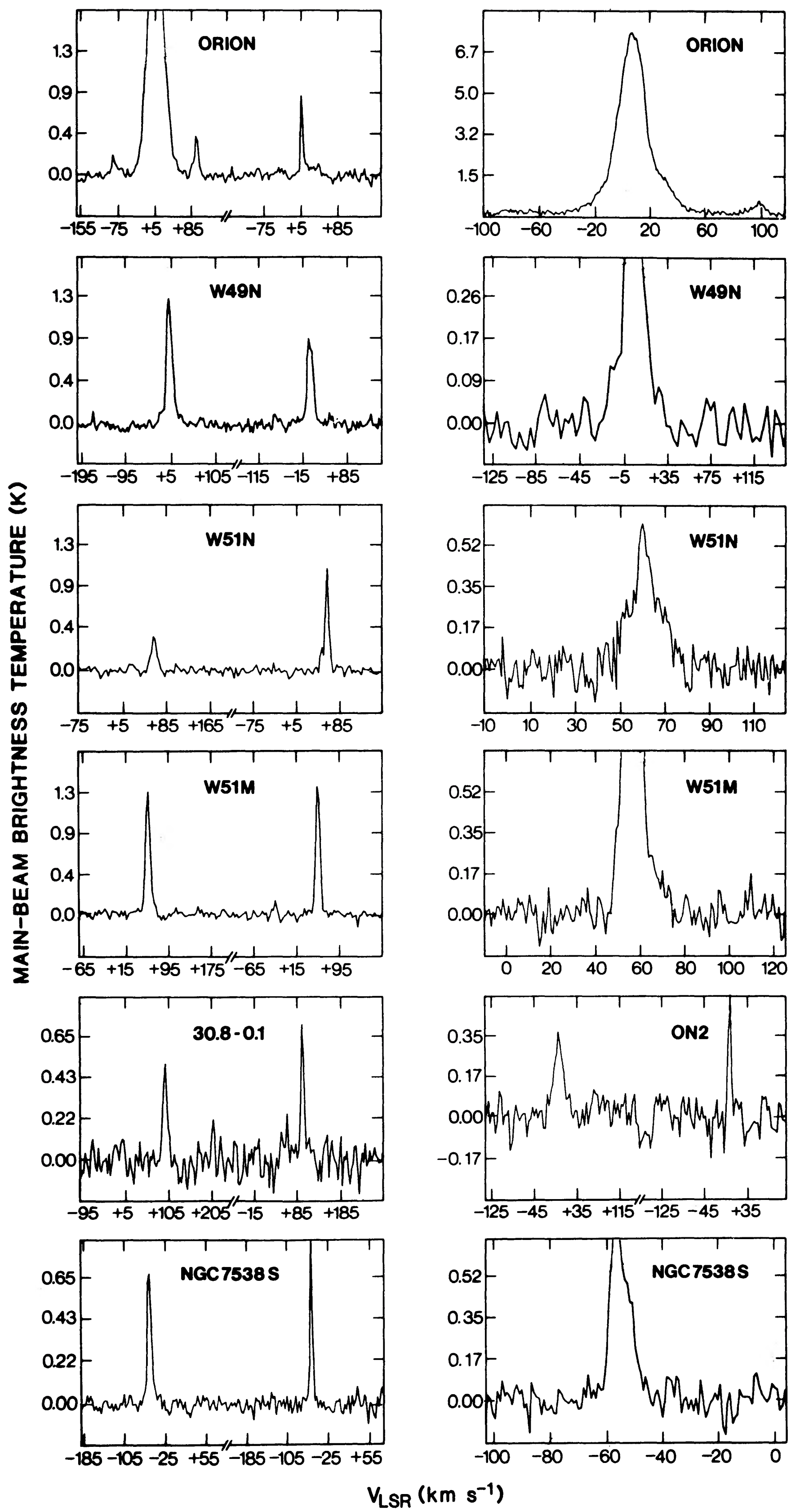

FIG. 1.—*Left column*: Spectra with 3.54 km s^{-1} resolution of the $v = 0$, $J = 2 \rightarrow 1$ line of SiO (*left*) and the $J = 1 \rightarrow 0$ line of $H^{13}CO^+$ (*right*). The Orion spectrum (*top*) also has an unidentified line and CH_3CH_2CN to the left and right, respectively, of SiO. *Right column*: higher resolution spectra (0.86 km s^{-1}) of the SiO line (except for 3.54 km s^{-1} resolution in the second and fifth spectra from the top).

centroid ~ 6 km s^{-1} and full width to zero power $\Delta v_{ZP} = 36 \pm 2$ km s^{-1}; we identify it with the "18 km s^{-1} flow" which appears in the SiO, H_2O, and OH masers in Orion and in the $v = 0, J = 1 \rightarrow 0$ "thermal" line of SiO at 43 GHz. As discussed by Baud *et al.* (1980), Genzel *et al.* (1980, 1981), and Hansen and Johnston (1980), this component is centered within $\pm 1''$ of IRc2. The Hat Creek interferometer measurements have shown that the size of the 18 km s^{-1} component in the $v = 0$ SiO line is $\sim 12''$.

In addition to the 18 km s^{-1} component, there is high velocity SiO extending over 115 km s^{-1}, (Fig. 1, top left). Its velocity centroid of ~ 10 km s^{-1} is shifted from that of the 18 km s^{-1} flow. We identify this second component with the high velocity "plateau" seen in various molecular lines. The size and centroid of the plateau are more uncertain than those of the 18 km s^{-1} flow. To determine the location of the high velocity emission relative to the 18 km s^{-1} flow, we mapped the SiO line in a joint project with Olofsson, Hjalmarson, and Rydbeck (1982).

Angular Size.—The map (Fig. 2) was made from scans (positive offset/peak-negative offset) in NS, EW, and diagonal directions during 1 week. Most scans were repeated, and pointing was optimized on the SiO line peak before each run. Comparison of the SiO thermal emission with a map of the Orion $v = 1, J = 2 \rightarrow 1$ SiO maser point source shows that both the 18 km s^{-1} component and the high velocity wings are unresolved. The size limit of $\lesssim 20''$ for the 18 km s^{-1} component agrees with the result from Hat Creek. The emission at $7 < V_{LSR} < 11$ km s^{-1}, however, broadens the beam in declination and was possibly detected (~ 0.3 K) at 1′ NE of the peak. This may be a narrow-line ("spike") component from the extended molecular cloud, as in other sources in Table 1 (see Penzias 1982). Because Orion is nearby, its SiO "spike" appears weak relative to the "flow" components in a small beam.

Displacement of Blueshifted and Redshifted Wings.—Relative displacements within a profile can be determined more accurately than our absolute positional accuracy ($\sim 10''$), particularly for the $v = 0$ SiO emission in Orion, where the high velocity wings can be measured relative to the unresolved 18 km s^{-1} flow. This relative measurement compensates for small pointing offsets and short-term changes in atmospheric transmission. We integrated numerically the emission in bins of 10 km s^{-1} and calculated positions relative to the 18

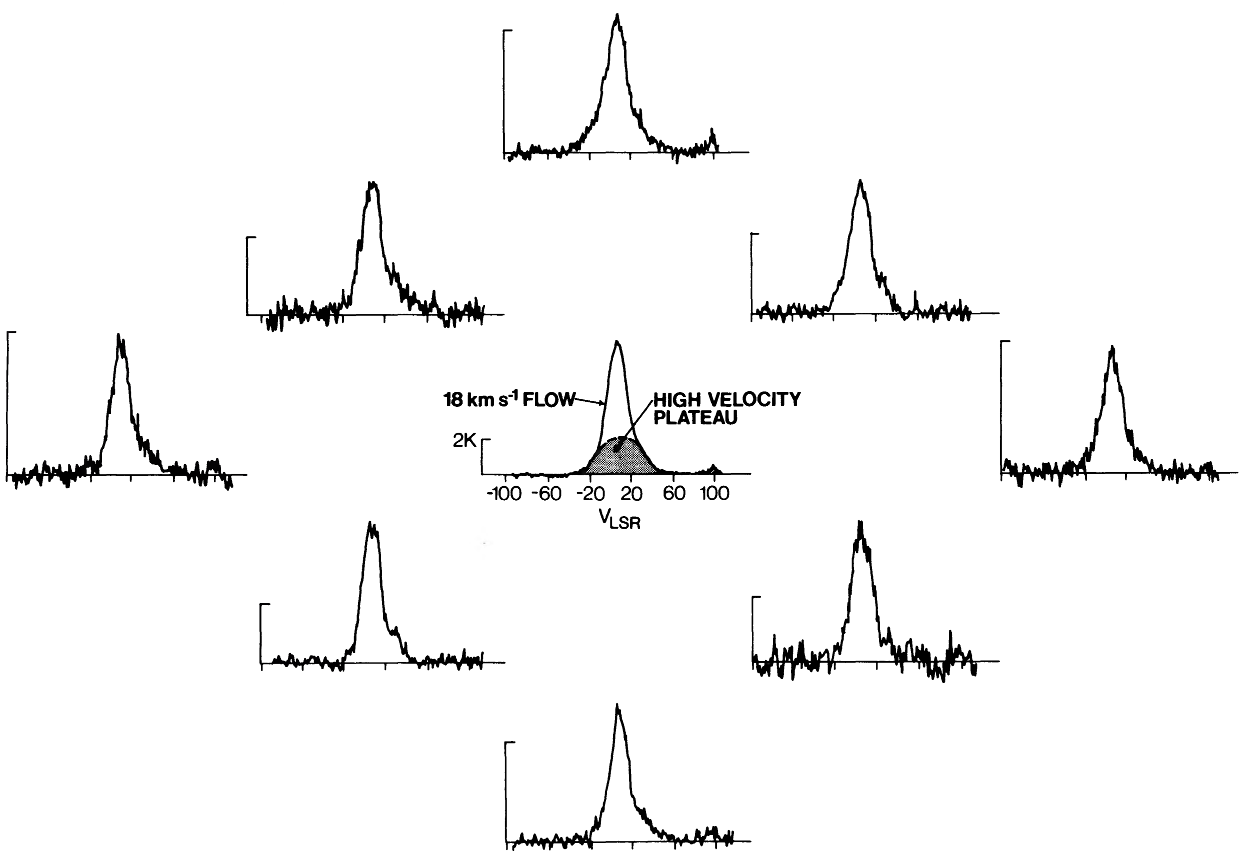

FIG. 2.—Map of the $v = 0, J = 2 \rightarrow 1$ SiO line in Orion-KL. The resolution was 0.86 km s^{-1} and linear baselines were subtracted from the data. North is to the top and east to the left. The positional offsets are 33″ NS, WE and 22″ diagonally. The central position coincides with IRc2. The beam size is 43″. The spectra are scaled to the same height for easier comparison, with the vertical bar corresponding to 2 K.

km s^{-1} component from the intensity ratios at each offset. The resulting relative positions are accurate to $\pm 3''$. The centroid of the integrated high velocity SiO emission is very near ($\sim 2''$ NW) to that of the 18 km s^{-1} flow component. The brightness centroid of the blueshifted wings ($V_{LSR} = -20$–0 km s^{-1}) is 5″ NW of the peak of the 18 km s^{-1} component (note the intensity above the -20 km s^{-1} tick mark in the spectra in Fig. 2). The redshifted wings ($20 < V_{LSR} < 40$ km s^{-1}) are 3″ NE of the centroid of the 18 km s^{-1} component (note the difference in the redshifted wings in the NE and SW spectra, Fig. 2).

e) *Implications for the Interpretation of Orion-KL*

It is clear from the SiO mapping and observations of NH_3, HCN, and SO (Bastien *et al.* 1981; Rydbeck *et al.* 1981; Welch *et al.* 1981) that the high velocity "plateau" component can be found within a few arcseconds of IRc2 and the center of the infrared cluster. The dynamical time scale, R/v_e, of this gas is only $\sim 10^2$ years, so the high velocity material seen farther out (in CO and H_2O to radii of 40″) cannot have been ejected in an explosion. The high velocity motion, like the 18 km s^{-1} flow, is probably continuous outflow from one or more stars in the IR cluster (see Downes *et al.* 1981). Although it is unclear whether the high velocity flow comes from the same object as the 18 km s^{-1} flow, the data show that both flows nearly coincide at the center of Orion-KL. The displacement of the blue- and red-shifted SiO wings may indicate nonisotropic ejection, as in the CO flows in L1551, Cep A and GL 490 (Snell, Loren, and Plambeck 1980; Rodriguez, Ho, and Moran 1980; Lada and Harvey 1981).

f) *Ratio of Mass-Loss Rates*

Estimates of the mass-loss rate and the mass contained in the 18 km s^{-1} or the high velocity flows are uncertain (3×10^{-4} to 3×10^{-2} $M_\odot$ yr^{-1} and 0.3–30 $M_\odot$; e.g., Genzel *et al.* 1981). However, a relatively accurate *ratio* of the mass loss in the 18 km s^{-1} and high velocity flows can be derived from the SiO lines. Direct comparison of the two flows in the $J = 2 \to 1$ line is not useful since the parabolic line shape suggests that the 18 km s^{-1} component is optically thick. Hence, we compare the $J = 2 \to 1$ high velocity component with the $J = 1 \to 0$ 18 km s^{-1} flow. The $J = 1 \to 0$ profile is flat-topped, indicating a low optical depth (Genzel *et al.* 1980). The optical depth of the $J = 2 \to 1$ high velocity component is probably also low; the intensity ratio of the two flows is 2.4 for $J = 2 \to 1$, but > 5 for $J = 1 \to 0$. The ratio of mass-loss rates can then be estimated (e.g., Genzel *et al.* 1980) to be:

$$\dot{M}_{hv}/\dot{M}_{18} = (0.7 \pm 0.3) R_{18} T_k(\text{hv}) / R_{hv} T_k(18). \quad (1)$$

We have assumed that the high velocity component has an expansion velocity of 50 km s^{-1} and that both flows are spherically symmetric (but see the preceding section). H_2O maser observations imply that the high velocity flow has larger radius, R, than the low velocity one, while NH_3 observations suggest a lower kinetic temperature T_k for the high velocity flow than for the 18 km s^{-1} component (Bastien *et al.* 1981).

An independent estimate of the mass-loss ratio can be made from ^{29}SiO (Olofsson, Hjalmarson, and Rydbeck 1982). In this isotope, the $v = 0$, $J = 2 \to 1$ line is optically thin, and the ratio is $\dot{M}_{hv}/\dot{M}_{18} = 1.0 \pm 0.5$. Hence, both estimates agree and show that the mass-loss rates, the mass of ejected material, and the transported momenta are similar for the two flows.

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