SiO in protostellar outflows

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Abstract

We report the results of a JCMT survey for SiO(5−4) emission towards 15 molecular outflow sources. The survey produced two new detections, the strongest being associated with the Class 0 protostar HH211. The SiO(5−4) line in this object is the brightest known in any low-mass outflow source. These data confirm that SiO emission from outflows is rare, and that it is seen preferentially toward the youngest (Class 0) protostars. However, four other Class 0 sources in our sample were not detected, suggesting that these objects may be older than had previously been thought, or that SiO emission is not a universal feature of the early evolution of molecular outflows.

The survey was followed up with VLA imaging of the SiO(1–0) emission from HH211 and from Cep A at 1.8″ resolution. For HH211 the emission arises from a well-defined jet emanating from the millimetre source; the SiO is less extended than the accompanying outflow delineated by shocked H_2, indicating it is tracing a more highly excited region of the flow.

1. Background

SiO emission has been detected in several outflow sources, and appears to trace a molecular component quite different from that seen in CO. In those objects where SiO is observed, its abundance is thought to be enhanced by the passage of dust grains through a shock, with SiO forming in the gas phase from the dust destruction products. SiO can therefore potentially trace an element of the jet/cloud interaction not detectable by other methods. In a few cases the SiO emission has been imaged (e.g., Guilloteau et al. 1992; Bachiller et al. 1994), and the SiO is observed to originate both from collimated jet features and from regions identified as shocks from their molecular hydrogen emission.

2. JCMT observations of SiO(5–4) emission

2.1. Survey results

Our sample comprises 15 well-known outflows drawn from the list of Fukui et al. (1993), and includes Class 0, I and II protostars. The SiO J=5–4 line (ν=217 GHz) was observed in each object in beam-switched mode using the JCMT in 1995 October. The beam size was 22″ and the main beam efficiency was 0.7. The spectra were binned to 4.3 km s^{-1} resolution, and had linear baselines removed. In Table 1 the results of spectroscopy at the location of the driving objects are presented as line fluxes integrated over an 80 km s^{-1} range in LSR centred on the source systemic velocity. This choice of velocity range was motivated by the typical observed velocity width of SiO emission in other outflows (e.g., Bachiller et al. 1991). In those sources which were detected the peak line temperature in a 4.3 km s^{-1} channel is given; for the non-detections a 3σ upper limit to any emission features is listed.

Table 1: Summary of SiO(5–4) survey results.

Source	Class	$\int T_A^* \, dv$ /K km s^{-1}	Peak T_A^* /mK
L1448-mm	0	12.3 ± 1.0	250
GL490	I	-0.3 ± 0.3	<63
HH211-mm	0	15.6 ± 0.8	580
B5 IRS3	II	-0.8 ± 0.5	<82
DG Tau	II	0.3 ± 1.4	<110
HL Tau	II	0.1 ± 0.6	<91
RNO43-mm	0	0.9 ± 0.4	<120
HH34-mm	I	2.4 ± 1.5	<110
HH1/2-mm	I	0.2 ± 0.7	<110
NGC2024-FIR5	0	0.0 ± 2.1	<450
NGC2024-FIR6	0	3.6 ± 0.7	410
HH24MMS	0	0.5 ± 0.3	<48
NGC2071	I	2.3 ± 0.4	275
IRAS05487	I	0.0 ± 0.8	<75
HH111-VLA	I	0.6 ± 0.7	<150

Only four objects were detected at a level of 3σ or greater, these being L1448-mm, NGC 2071, HH211 and NGC2024-FIR6. The first two SiO detections have been previously reported (Bachiller et al. 1991; Chernin & Masson 1993), but the last two are new. HH211 is extremely bright in SiO (see Figure 1), showing both blue and redshifted emission about the systemic velocity of approximately 5 km s^{-1}; this is the strongest SiO(5–4) line detected so far in any low-mass outflow source. The line was mapped and the blue and redshifted SiO emission found to be relatively compact, following closely the CO lobes reported by McCaughrean et al. (1994). The SiO(5–4) emission from NGC2024-FIR6 is predominantly blueshifted, and its velocity is similar to the strong blueshifted CO(2–1) line detected by Richer (1990).

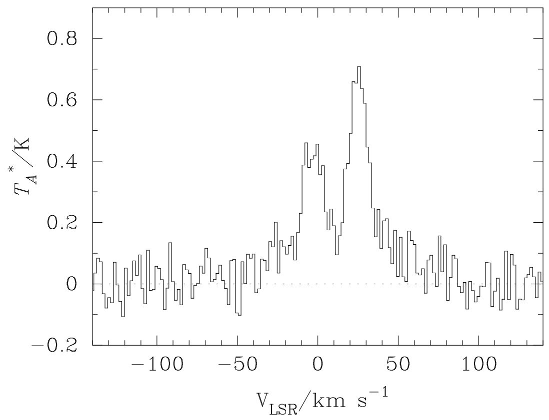

Fig. 1.— SiO(5–4) spectrum of HH211.

For most sources a small search for SiO emission away from the driving star was also carried out. Typically this involved a one-dimensional grid of points along

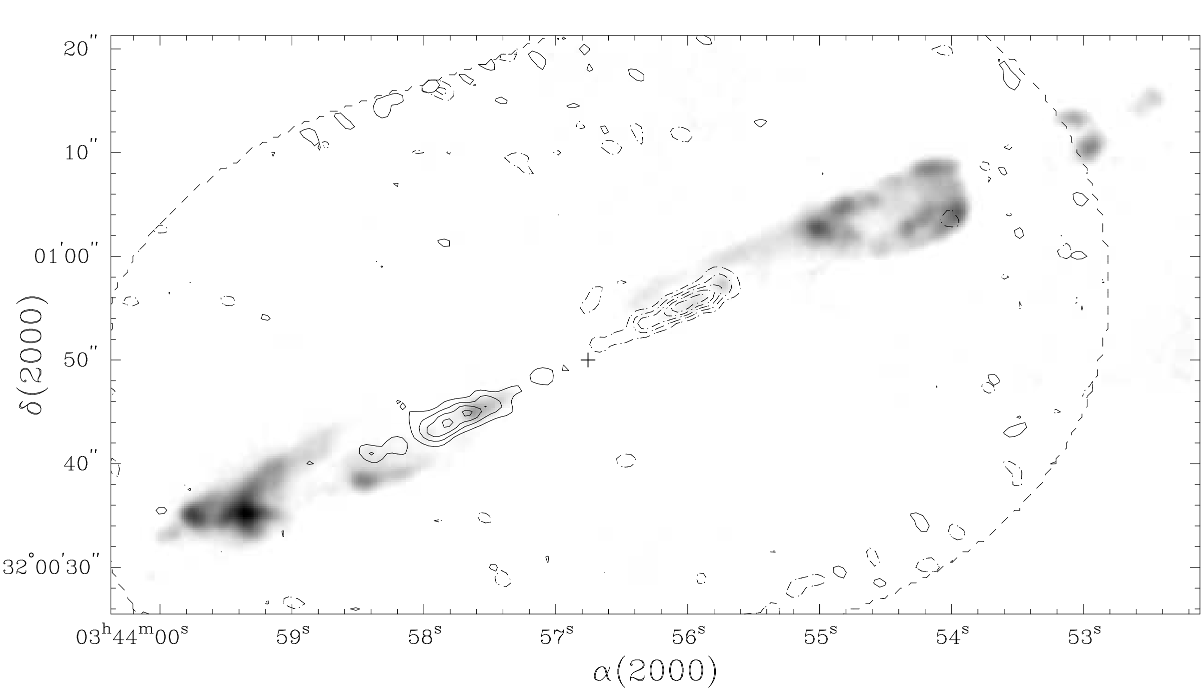

Fig. 2.— SiO(1–0) map of the redshifted (dot-dash contours) and blueshifted (solid contours) emission from HH211. The integrated H_2 v=1–0 $S(1)$ emission from McCaughrean et al. (1994) is plotted as a logarithmic greyscale, and the position of HH211-mm is marked by a cross.

the outflow axis, or pointed observations at the locations of peaks in high-velocity CO emission. Previous work has shown that SiO emission can be much brighter away from the driving source (e.g., in IRAS03282: Bachiller et al. 1994), where the jet driving the outflow encounters the molecular cloud. However, no further detections were obtained at any of these locations; the full details of the positions searched will be reported by Richer & Chandler (in preparation).

2.2. Discussion

Most of the low-mass outflow sources which display bright, jet-like SiO emission are Class 0 objects. Although the older sources Cep A-HW2 and NGC2071 were both detected, there is no evidence for fast, bright jets in these objects. It is possible that it is only in young objects that sufficient dust remains in the vicinity of the driving jet to generate SiO emission; older sources are expected to have larger cocoons around the jets, and if these cocoons are dust-free, dust entrainment and hence SiO emission will be supressed. However, this survey shows that not all Class 0 objects have high velocity SiO emission: notably, none of HH24MMS, NGC2024-FIR5, and RNO43-mm was detected. It is possible that the outflows from these objects are therefore not as young as those detected in SiO, or that SiO emission is not a universal feature of the early evolution of molecular outflows, perhaps due to environmental effects.

3. VLA imaging of SiO(1–0) emission

We used the 43 GHz receivers on 10 antennas of the VLA to image the SiO 1–0 emission in HH211 and Cep A-HW2. The high spatial resolution allows us to examine the relationship between the SiO and the emission from molecular hydrogen in both objects. The synthesized beam is approximately 1.8″ FWHM, and the spectral channel spacing is 5.4 km s^{-1}.

3.1. Cep A-HW2

Although Cep A-HW2 is the origin of an energetic molecular outflow observed in CO most recently by Narayanan & Walker (1996), and extensive H_2 emission is associated with numerous bow shocks nearby (Hartigan et al. 1996), we find SiO(1–0) emission only in an unresolved component coincident with the radio source. The emission is detected in three consecutive channels centred on the systemic LSR velocity of -10 km s^{-1}. A comparison of the integrated flux in the J=1–0 line with the flux detected in higher transitions by the single-dish measurements of Martín-Pintado et al. (1992) shows that the gas is quite warm ($T_{\rm ex} \gtrsim 45$ K) and thermalized at least up to the J=5 level, with an optical depth in SiO(1–0) of ~ 0.14.

3.2. HH211

Figure 2 presents the integrated red and blueshifted SiO(1–0) emission from HH211 overlaid on a logarithmic greyscale of the molecular hydrogen emission from McCaughrean et al. (1994). The SiO is well-collimated and appears to be associated only with the jet from the exciting star. No emission is detected at the brightest H_2 peaks, although they fall well inside the 50% response level of the observations. The SiO is mainly located inside a faint shell of H_2 emission, and in the case of the redshifted component, even terminates at an H_2 knot.

The peak beam-averaged brightness temperature in the data set is 18 K, and occurs in the redshifted component of the jet, which is unresolved laterally. This provides a firm lower limit on the excitation conditions in the gas traced by the SiO. Further constraints can be obtained by comparing the SiO(5–4) flux with the 1–0 line, giving a 1–0 optical depth of ~ 0.3, and a corresponding lower limit on the excitation temperature of $T_{ex} \gtrsim 70$ K. This is considerably higher than that expected for ambient molecular gas, and confirms that the SiO originates in a region of enhanced excitation.

In Figure 3 we plot the FWHM of a Gaussian fit to the jet, perpendicular to the outflow axis, as a function of offset from the millimetre continuum source reported by McCaughrean et al. (1994). Most of the bright emission in the jet is unresolved, but towards the end of both the blue and red components the jet appears to widen.

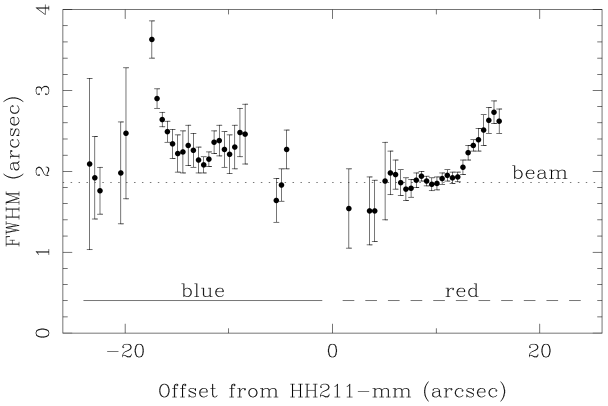

Fig. 3.— FWHM of the SiO(1–0) jet in HH211 as a function of distance from the source believed to be driving the outflow.

The ends of the oppositely-directed jets are also the locations of highest radial velocity compared to the ambient cloud. The redshifted lobe in particular shows a smooth gradient along the jet, with a maximum at 30 km s^{-1} from the systemic LSR velocity of 10 km s^{-1}. The first moment of the SiO(1–0), or intensity-weighted mean velocity, is shown as a greyscale in Figure 4, overlaid with contours of shocked H_2 emission. Only emission at greater than the 3σ level has been included in making the first moment image.

Further evidence suggesting that the SiO is associated directly with shocks can be seen in the second moment map of the SiO emission (Figure 5). This shows that the positions of highest velocity dispersion are not necessarily the brightest either in the individual channels, nor in the integrated emission shown in Figure 2, but are instead coincident with the molecular hydrogen emission.

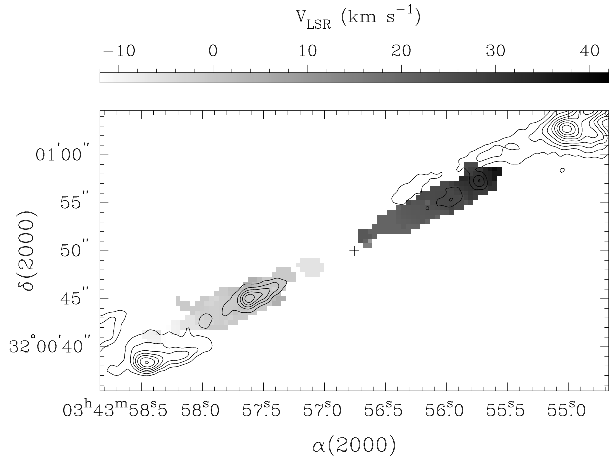

Fig. 4.— Greyscale of the first moment (intensity-weighted mean velocity) of the SiO(1–0) emission from HH211, overlaid by contours of the H_2 emission.

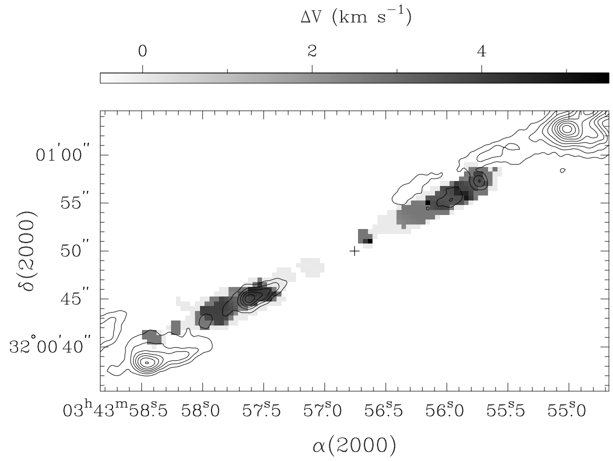

Fig. 5.— Greyscale of the second moment (a measure of the velocity dispersion) of the SiO(1–0) emission from HH211, overlaid by contours of the H_2 emission.

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