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Letter to the Editor

Observations of high-J SiO emission along the HH211 outflow

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Abstract. Spectra of the pure rotational SiO J = 11–10 and J = 8–7 lines, at 477.5 GHz and 347.3 GHz respectively, have been obtained along the HH211 protostellar jet. Bright emission has been observed localized inside about 15″ of projected distance from the central source, where a compact and collimated SiO jet was previously discovered by means of SiO J = 1–0 interferometric observations (Chandler & Richer 2001). The detection of the high-J lines testifies for the extreme conditions of density and temperature of the SiO emission. Values of $T > 250$ K and $n_{\rm H2} \sim 2{-}5\times10^6$ cm^{-3} are inferred from the observed line ratios, while a SiO abundance in the range $\sim10^{-7}{-}10^{-6}$ has been estimated through a comparison with the CO rotational lines at $J > 14$ observed by the ISO Long Wavelength Spectrometer. Both the estimated physical conditions and abundance are in agreement with a picture in which the observed SiO emission directly arises at the front of a C-type shock with $\upsilon_{\rm s} < 35$ km s^{-1}, where all the silicon released from the grains by sputtering and/or grain-grain collisions is converted into gas-phase SiO.

Key words. circumstellar matter – radio lines: stars – Herbig-Haro objects – ISM: individual objects: HH211

1. Introduction

High velocity shocks along molecular outflows induce strong modifications in the chemical composition of the ambient medium. As a consequence, molecules commonly present in the interstellar matter may disappear while different species may increase their abundances by order of magnitudes with respect to pre-shock conditions (Richer et al. 2000; Bachiller & Tafalla 1999). One of the most typical example comes from SiO, whose abundance has been estimated to be more than 10^4 times larger than in quiescent clouds (e.g. Codella et al. 1999; Gueth et al. 1998). The production of silicon monoxide along outflows is mainly due to the shock reprocessing of dust, which releases silicon in the gas phase allowing a quick formation of SiO through reactions involving the OH molecule (e.g. Schilke et al. 1997). So far, SiO has been mainly observed through its low lying transitions with $J \leq 5$, which have excitation temperatures of less than ~20 K. A number of evidences do however suggest that SiO is actually produced in a much hotter gas, with kinetic temperature exceeding 100 K: 1) to remove silicon from the grain core, shocks with velocities larger than about 20 km s^{-1} are needed; such shocks can easily rise the gas temperature up to more than 1000 K (Schilke et al. 1997), 2) SiO is often observed in very localized spots of extremely high velocity (EHV) gas (the so called molecular bullets), suggesting that it directly traces the shocked gas and it is not simply cold material entrained along the flow, 3) an high 5–4/2–1 ratio is often observed (e.g. ≳1.5 in L1448, Bachiller et al. 1991) testifying for the presence of dense (>10^5 cm^{-3}) and warm (>100 K) gas.

Here we report the observations of SiO J = 11−10 and J = 8−7 transitions, which are tracers of high density and warm gas, along the flow of the HH211 protostellar outflow. HH211 (at a distance of about 350 pc) is among the nicest examples of high collimated molecular outflows from young protostars (Gueth & Guilloteau 1999). Strong SiO J = 1−0 emission along this outflow has been detected in localized spots of high velocity gas at about 15″ from the driving source (Chandler & Richer 2001). This outflow has been also observed in the far infrared by the ISO satellite, which evidenced the presence of gas at temperatures in excess of 300 K in both its collimated lobes (Giannini et al. 2001). HH211 represents therefore a suited candidate to search for high excitation shocked SiO emission.

2. Observations and results

Observations of the SiO J = 11−10 and J = 8−7 lines at 477.503 GHz and 347.330 GHz, respectively, have been obtained at the James Clerk Maxwell Telescope ($JCMT$) on November 24th, 2001. The used instruments were the heterodyne receivers RxW in the C band ($HPBW$ = 12″) and RxB3 ($HPBW$ = 14″) for the 480 GHz and the 350 GHz lines

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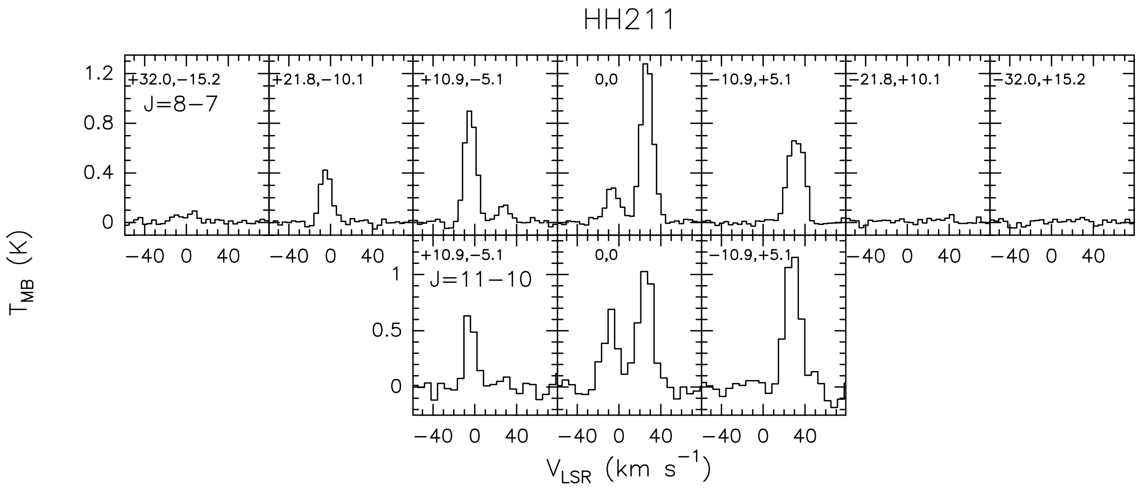

Fig. 1. Spectra of the SiO J = 8−7 and J = 11−10 line emission taken along the HH211 molecular jet. Offsets (in arcsec) indicated in the upper left corner of each panel are with respect to the HH211-mm position (α(2000) = 03^{h}43^{m}56.8^s, δ(2000) = +32°00′50″).

Table 1. Observed SiO intensities along the HH211 flow.

Offset[a]	Lobe	J = 8−7 $\int T_{MB}\,dV$ K km s^{-1}	ΔV (*FWHM*) km s^{-1}	V_{LSR} km s^{-1}	J = 11−10 $\int T_{MB}\,dV$ K km s^{-1}	ΔV (*FWHM*) km s^{-1}	V_{LSR} km s^{-1}
(−10.9, +5.1)	red	13.2 ± 0.2	17.7(0.4)	+31.5(0.1)	23.8 ± 1.3	15.7(0.9)	+28.0(0.4)
(0, 0)	red	19.5 ± 0.2	13.2(0.2)	+26.7(0.1)	14.3 ± 1.6	14.5(1.3)	+25.9(0.5)
	blue	4.9 ± 0.2	15.1(1.1)	−5.8(0.4)	13.9 ± 1.6	12.2(2.5)	−7.6(0.8)
(+10.9, −5.1)	red	2.0 ± 0.23	13.6(2.0)	+27.8(0.7)	<4.8	...	...
	blue	12.7 ± 0.24	12.7	−4.2(0.1)	9.6 ± 1.7	11.6(1.9)	−4.6(0.8)
(+21.8, −10.1)	blue	5.8 ± 0.19	12.4(0.45)	−4.4(0.2)	...	...	...
(+32.6, −15.2)	blue	1.7 ± 0.2	...	...	...	...	...

[a] Offset in arcsec with respect to HH211-mm.

respectively. The J = 8−7 (J = 11−10) measurements were performed making a grid map of 7 (3) positions along the major axis of the HH211 outflow (PA = 115°), with a 12″ spacing. The (0, 0) position correspond to the exciting source of the outflow, HH211-mm, having coordinates α(2000) = 03^{h}43^{m}56.8^s and δ(2000) = +32°00′50″. Beam-switching was employed to subtract sky emission, using a throw of 180″ oriented in a direction perpendicular to the outflow axis. The system temperature during the observations was T_{sys} ~ 800 K for the B3 receiver and T_{sys} ~ 2500 K for the W receiver. To convert the antenna temperature (T_A) into brightness temperature, a main beam efficiency η_{MB} equal to 0.63 and 0.52 were adopted for receivers B3 and W respectively.

In Fig. 1 we show the spectra obtained along the flow while in Table 1 the main parameters derived from these spectra have been reported. A comparison of the obtained spectra with the interferometric map of SiO J = 1−0 by Chandler & Richer (2001) indicates that the bulk of the high-J SiO emission is probably localized towards the two peaks of emission at about 10″ from the central source in each side of the outflow. Weak J = 8−7 emission is also observed to extend in the blue lobe up to ~30″ of distance from the mm source, where an $H_2$2.12 μm peak is localized (McCaughrean et al. 1994). Given however the large difference in critical densities of the high-J SiO and $H_2$2.12 μm lines (n_{cr} ~ 10^6 and 10^4 cm^{-3} respectively), it is not surprising to find no strict spatial correlation between these two tracers of shocked gas. Looking at Fig. 1 and Table 1, we notice that the red-shifted J = 8−7 emission peaks towards the (0, 0) position, and its velocity increases going outwards, from V_{LSR} = 26.7 to 31.5 km s^{-1}; the same trend of increasing velocity is observed in the red-shifted J = 11−10 emission and it closely matches the velocity gradient exhibited by the SiO J = 1−0 and CO J = 2−1 emission (Gueth & Guilloteau 1999). In the blue-shifted lobe, however, such a positive velocity gradient is not observed. Indeed, the SiO J = 1−0 velocity channel map reported by Chandler & Richer (2001) shows a much less pronounced velocity gradient in the blue-shifted jet.

3. Analysis and discussion

To constrain the physical conditions of the observed high-J SiO emission, we compare the measured intensities of the 8–7 and 11–10 lines with the intensity of the SiO J = 5–4 line,

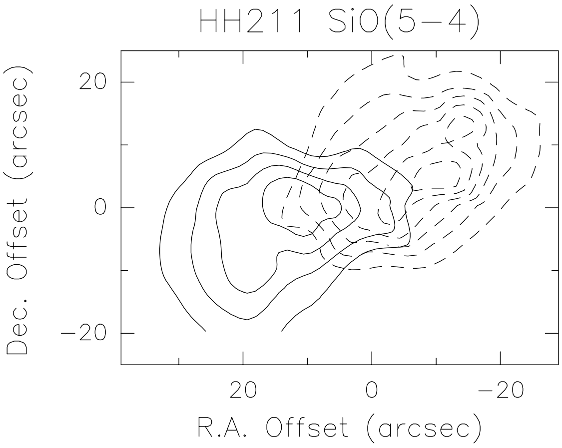

Fig. 2. Map of the SiO $J = 5{-}4$ line intensity integrated in the velocity intervals from −20 to 11.6 and from −11.6 to +47.0 km s^{-1} for the blueshifted (solid contours) and redshifted (dashed contours) emission, respectively. The first contour is at 2 K km s^{-1} (about 5σ from the rms noise) which is also the value of the contour intervals.

Table 2. Ratios of the beam-filling corrected line intensities in the SiO bullets.

knot	I(11–10)/I(5−4)	I(5−4)/I(8–7)
blue	0.57(0.21)	1.55(0.09)
red	0.58(0.12)	1.39(0.09)

obtained at the JCMT with a 22″ beam (Chandler & Richer 1997). A map of the HH211 flow in the $J = 5{-}4$ line is given in Fig. 2, and in spite of the poor angular resolution, it shows again that the emission is peaked at about 10″ from the central source, and thus that the bulk of the SiO gas is confined in the two high velocity knots (bullets) partially resolved in the $J = 1{-}0$ interferometric observations and having an extention of about 15″×2″. This emission size has been assumed to compare the 5–4 line with the higher-J lines observed with a different beamsize. Since the bullets are covered by both the (0, 0) and the (±10, ±5) offset positions in the 8–7 and 11–10 observations, we summed-up these contributions, each corrected for a proper beam-filling to derive the intensity of the blue- and red-shifted gas, integrated over the assumed emission region. In Table 2 we list the derived ratios of line intensities. We notice that these ratios do not significatively differ in the blue and red bullets, indicating similar physical conditions. We compare these ratios with the result of a Large Velocity Gradient (LVG) code which considers the first 20 SiO levels and the rate coefficients for collisions with H_2 given by Turner et al. (1992). These rates, which are given only for a maximum temperature of 300 K, have been extrapolated up to $T = 1000$ K by linearly fitting the data at $T \geq 200$ K. We have also checked that in the high temperature and high density regimes the inclusion of more levels does not change significantly the results for the lines considered here.

In such a model, the opacity of the considered lines is maintained below ~0.2 in a wide range of densities and temperatures (i.e. $n < 10^7$ cm^{-3} and $T > 100$ K) and for SiO column densities smaller than about 10^{13} cm^{-3}. We therefore consider a good approximation to assume optically thin emission, providing an a posteriori check will be done about the validity of this assumption on the final derived physical conditions. Figure 3 plots the expected line intensity ratios as a function of both the gas kinetic temperature and the particle density, compared with the observed values. The $J = 8{-}7$ and 11–10 lines have upper level energies of ~75 and 140 K, respectively. If the gas temperature is much larger than these values ($T > 400$ K), their intensity becomes insensitive to the temperature. On the other hand, since these lines are usually sub-populated, no appreciable emission is expected from the 11–10 line for temperatures below ~100 K. The SiO (5–4)/(8–7) ratio, which is less sensitive to the gas temperature, has been used to constrain a range of densities of about 1–5 × 10^6 cm^{-3} in a temperature range between 100 and 1000 K (Fig. 3a). On the other hand, the SiO(11–10)/SiO(5–4) observed ratio (Fig. 3b), narrows the range of possible densities in between ~2.5–5 × 10^6 cm^{-3}, furthermore constraining a temperature larger than ~250 K.

This set of values is in agreement with models of C-type shocks in which SiO is produced through sputtering of Si-bearing material in grains (Schilke et al. 1997). In this model, a density between 10^6 and 10^7 cm^{-3} is required to reproduce the observed ratios, and in particular to significantly collisionally populate the $J = 11{-}10$ transition. Moreover a shock velocity larger than 20 km s^{-1} is required to produce a SiO column density enough to have appreciable emission; at such a velocity, the shocked gas temperature is expected to be larger than 300 K. The density and temperature inferred from the SiO line ratios analysis are also consistent with the range of values found from the analysis of the high-J ($J > 14$) CO lines detected by the ISO Long Wavelength Spectrometer in the HH211 flow, i.e. $n_{H2} = 0.1{-}4 \times 10^6$ cm^{-3}, $T = 250{-}950$ K (Giannini et al. 2001).

Assuming $n_{H2} = 2.5 \times 10^6$ cm^{-3} and $T \gtrsim 300$ K, we derive a N_{SiO} of the order of 1.5 × 10^{13} cm^{-2} for the red lobe and of ~8 × 10^{12} cm^{-2} for the blue lobe. We remark that in such conditions the opacity of the considered lines is ≲0.2, and thus their intensity effectively trace the column density.

Assuming moreover that the high-J SiO and high-J CO lines observed by ISO originates from the same localized shocked gas, the derived X(SiO) abundance is ~0.5–1×10^{-7}, for a standard [$^{12}CO/H_2$] value of 10^{-4}. It is however more likely that the high-J CO emission is not so localized as the SiO emission, as testified by the fact that ISO-LWS (which has a beam of about 70″) has detected warm CO gas also in different positions along the HH211 flow and not just close to the central source. An upper limit on the X(SiO) abundance can be otained by assuming that the CO emission is still localized along the collimated jet but comes from all the jet length covered by the ISO-LWS beam (i.e. assuming an emitting area of the order of 70″ × 4″), in which case a value of X(SiO) = 0.6–1 × 10^{-6} is derived. We note how the derived range of abundances are smaller than the value X(SiO)>10^{-6} derived by Chandler & Richer (2001) which compared the SiO $J = 1{-}0$ line with ground based CO 2–1 observations.

Values of the gas-phase SiO abundance in the range ~10^{-7}–10^{-6} are expected to be produced in C-type shocks with

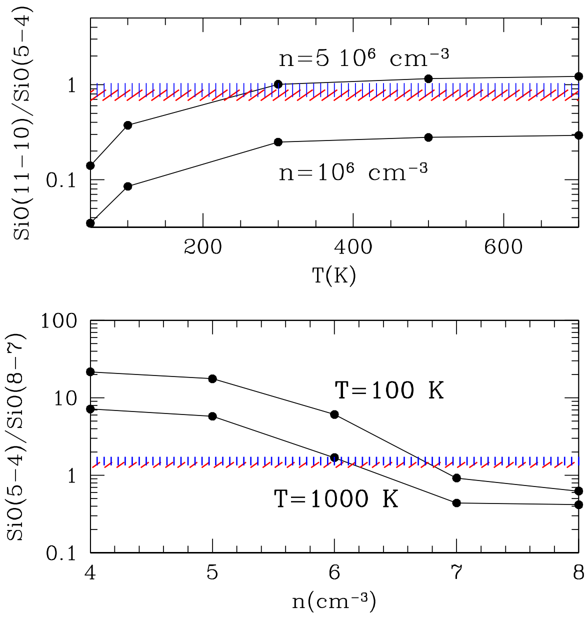

Fig. 3. Lower panel: expected SiO(5–4)/SiO(8–7) line ratio as a function of the particle density in the temperature range 100–1000 K. The hatched areas indicate the range of values allowed by the ratio observed in the blue (vertical lines) and red (diagonal lines) lobes. Upper panel: expected SiO(11–10)/SiO(5–4) line ratio as a function of temperature for the density range constrained by the SiO(5–4)/SiO(8–7) ratio. In both the panels, optically thin emission is assumed.

velocities between ∼30–35 km s^{-1}, if sputtering of Si-bearing species is assumed to be the main channel for releasing silicon from either the core and the mantle of dust grains (Schilke et al. 1997). At such velocities, the temperature of the post-shocked gas is predicted to reach more than 1000 K, thus consistent with the 250 K lower limit derived here. Grain-grain collisions can be however also effective in injecting silicon into the gas-phase (Caselli et al. 1997), and they are indeed expected to dominate over the sputtering at low velocity (v_s < 30 km s^{-1}) and high pre-shock densities (>5 × 10^5 cm^{-3}).

4. Conclusions

We have detected SiO emission from the pure rotational lines J = 11−10 and J = 8−7 in selected positions along the molecular outflow HH211. The mere detection of these lines, having critical densities larger than ∼10^6 cm^{-3} and upper level energies larger than 100 K, testifies for the extreme conditions pertaining to this highly collimated molecular jet. The main results obtained from these observations can be summarized as follows:

– The bulk of the high-J SiO emission is localized inside ∼15″ from the driving source, and it is probably confined in two blue- and red-shifted emission bullets which where previously identified by means of interferometric observations of the J = 1−0 line.
– The measured intensities of the 8–7 and 11–10 lines have been combined with the intensity of the SiO J = 5−4 line (Chandler & Richer 1997) to constrain the physical conditions of the SiO emitting gas. A comparison with the results of an LVG model indicate that densities of the order of 2.5−5 × 10^6 cm^{-3} and a gas temperature ≳250 K are needed to take into account the observed ratios. Such conditions agree with the values derived from the analysis of ^{12}CO lines with J > 14 observed by ISO along the HH211 flow.
– Assuming that the high-J CO lines originates from the same gas component giving rise to the SiO emission, a [SiO/H_2] abundance ratio of the order of 10^{-6}–10^{-7} can be derived. Such a range of values, and the derived physical conditions, are in agreement with a picture in which the observed SiO emission directly arises at the front of a C-type shock with v_s < 35 km s^{-1}, where all the silicon released from the grains by sputtering and/or grain-grain collisions is converted into gas-phase SiO.

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