GRAIN EVOLUTION ACROSS THE SHOCKS IN THE L1448-mm OUTFLOW

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Received 2005 April 7; accepted 2005 June 2; published 2005 June 21

ABSTRACT

The recent detection of shock precursors toward the very young L1448-mm outflow offers us the possibility to study the grain chemistry during the first stages of the shock evolution, constraining the molecules ejected from grains and the species formed in gas phase. Observations of key molecules in the grain chemistry such as SiO, CH$_3$OH, SO, CS, H$_2$S, OCS, and SO$_2$ toward this outflow are presented. The line profiles and the derived abundances show three distinct velocity regimes that trace the shock evolution: the preshock, the shock precursor, and the postshock gas. The SiO, CH$_3$OH, SO, and CS abundances are enhanced with respect to the quiescent gas by 1 order of magnitude in the shock-precursor component, and by 3 orders of magnitude in the postshock gas. The derived SiO and CH$_3$OH abundances are consistent with the recent ejection of these molecules from grains. Since H$_2$S is only enhanced in the shock-precursor component and OCS and SO$_2$ are undetected, SO and CS are the most abundant sulfur-bearing species in the grain mantles of L1448-mm. The ejection of mainly SO and CS rather than H$_2$S or OCS from grains suggests that the sulfur chemistry will depend on the chemical “history” of the grain mantles in outflows and hot cores.

Subject headings: ISM: individual (L1448) — ISM: jets and outflows — stars: formation

1. INTRODUCTION

Observational studies of the abundances of shock tracers like SiO, CH$_3$OH, and the sulfur-bearing molecules H$_2$S, SO, CS, OCS, or SO$_2$ toward relatively evolved ($t \geq 10^4$ yr) outflows and hot cores (Blake et al. 1987; Bachiller & Pérez-Gutiérrez 1997; van der Tak et al. 2003) have established that these molecules are largely enhanced ($\sim 10^{-7}$) due to the release of material from grains. Since silicon is heavily depleted onto grains (Ziurys et al. 1989; Martín-Pintado et al. 1992) and since CH$_3$OH has been firmly detected on icy mantles (Tielens & Allamandola 1987), SiO and CH$_3$OH are accepted as being ejected from grains. For the sulfur chemistry, since H$_2$S is only enhanced in the shock-precursor component and OCS and SO$_2$ are undetected, SO and CS are the most abundant sulfur-bearing species in the grain mantles of L1448-mm. This enhancement, the lack of SO$_2$ and OCS, and the fact that H$_2$S is only enhanced in the shock-precursor component indicate that the sulfur chemistry in L1448-mm strongly depends on the chemical composition of grains.

2. OBSERVATIONS AND RESULTS

We mapped the L1448-mm outflow, observing toward the five-point map previously measured in SiO, H$^{13}$CO$^+$, and HN$^{15}$C by Jiménez-Serra et al. (2004). The observations were carried out with the IRAM 30 m telescope at Pico Veleta, Spain. The beam size was $\sim 27''$, $16''$, and $10''$ at $\sim 90$, 150, and 240 GHz. The SIS receivers were tuned to single sideband with image rejections $\geq 210$ dB. We observed lines of SO$_2$, H$_2$S, SO, OCS, CH$_3$OH, and CS. Observations were done in frequency-switching and wobblor-switching modes with frequency and position throws of 7.2 MHz and 240$''$, respectively. A spectral resolution of $\sim 40$ kHz was achieved with the autocorrelators, which corresponds to velocity resolutions of $\sim 0.14$, $0.08$, and 0.05 km s$^{-1}$ at the observed frequencies. The system temperatures were typically $\sim 150$–400 K. Toward L1448-mm (0, $-20$), we also observed the CO $J = 1 \rightarrow 0$ transition in position-switching mode.
with the 1 MHz filter bank, which provided a velocity resolution of \(~2.6 \text{ km s}^{-1}\). The system temperature was \(~1000 \text{ K}\). All the line intensities were calibrated in antenna temperature (\(T_A^*\)).

Figure 1 shows the emission of H\(^{13}\)CO\(^+\), HN\(^{13}\)C, and shock tracers like SiO, CH\(_3\)OH, SO, CS, H\(_2\)S, SO\(_2\), and OCS, measured toward the five-point map of L1448-mm. The line profiles, except those of SiO, have line widths of \(~1 \text{ km s}^{-1}\) and are double-peaked, showing the preshock component at 4.7 km s\(^{-1}\) and the shock-precursor component at 5.2 km s\(^{-1}\) (vertical dotted lines; Jiménez-Serra et al. 2004). Toward L1448-mm (0, \(-20\)), SiO, CH\(_3\)OH, CS, and SO also show broader redshifted emission, with terminal velocities that vary from \(~7.5 \text{ km s}^{-1}\) in the case of CS to \(~14 \text{ km s}^{-1}\) for CH\(_3\)OH (dashed horizontal line). SiO and SO have similar terminal velocities of \(~10 \text{ km s}^{-1}\) (third dotted line from the left).

Neutral species like HN\(^{13}\)C and HCO trace the quiescent gas of the preshock component at 4.7 km s\(^{-1}\) (Jiménez-Serra et al. 2004). We do not detect SiO, OCS, and SO\(_2\) at this component, which supports this idea. The molecular emission observed toward L1448-mm (0, \(-20\)) peaks at 4.7 km s\(^{-1}\), indicating that these regions are unaffected by the precursors (Jiménez-Serra et al. 2004). The upper limits of \(\leq 10^{-13}\) to the SiO abundance and \(\leq 10^{-10}\) to the OCS and SO\(_2\) abundances are respectively the same and 1 order of magnitude smaller than those found in L134N or TMC-1 (Ziurys et al. 1989; Martín-Pintado et al. 1992; Matthews et al. 1987; Ohishi et al. 1992). The CH\(_3\)OH, SO, CS, and H\(_2\)S abundances are similar

2.1. Preshock Gas

Neutral species like HN\(^{13}\)C and HCO trace the quiescent gas of the preshock component at 4.7 km s\(^{-1}\) (Jiménez-Serra et al. 2004). We do not detect SiO, OCS, and SO\(_2\) at this component, which supports this idea. The molecular emission observed toward L1448-mm (0, 20) and (20, 0) peaks at 4.7 km s\(^{-1}\), indicating that these regions are unaffected by the precursors (Jiménez-Serra et al. 2004). The upper limits of \(\leq 8 \times 10^{-13}\) to the SiO abundance and \(\leq 10^{-10}\) to the OCS and SO\(_2\) abundances are respectively the same and 1 order of magnitude smaller than those found in L134N or TMC-1 (Ziurys et al. 1989; Martín-Pintado et al. 1992; Matthews et al. 1987; Ohishi et al. 1992). The CH\(_3\)OH, SO, CS, and H\(_2\)S abundances are similar
to those derived from dark clouds (\(10^{-10}\) to \(10^{-8}\); Ohishi et al. 1992; Martín-Pintado et al. 1992).

### 2.2. Shock-Precursor Component

The very narrow (\(\sim 0.6\) km s\(^{-1}\)) SiO emission detected at \(5.2\) km s\(^{-1}\) with an abundance of \(\sim 10^{-11}\), in addition to the enhancement of the molecular ions like \(^{13}\)CO\(^{+}\) and \(\text{N}_2\text{H}^+\), have been proposed as signatures of the interaction of the C-type shock precursor (Jiménez-Serra et al. 2004). Our data show that like the ions, \(\text{CH}_3\text{OH}, \text{H}_2\text{S}, \text{SO}, \text{CS}\), peak at the shock-precursor component in the regions where we detect narrow SiO (see Fig. 1). This is even more clear toward L1448-mm (0, \(-20\)), where the velocity peaks of these molecules are slightly redshifted (\(5.4-5.6\) km s\(^{-1}\)) in just the same direction as the broader postshock gas, suggesting that the material is already accelerated by the precursor. Like SiO, the abundances of \(\text{CH}_3\text{OH}, \text{H}_2\text{S}, \text{SO}, \text{CS}\) are enhanced by up to a factor of 10 in the shock-precursor component with respect to the quiescent gas (see Fig. 2). Assuming that grain mantles are completely removed in the postshock regime (see § 2.3), this enhancement implies the ejection of 0.1% of the total mantle material in the shock precursor. SO is only detected toward L1448-mm (0, \(-20\)) and (0, \(-20\)), showing a similar behavior to SiO (Fig. 1). The upper limits to the SO abundance toward L1448-mm (0, 20), (20, 0), and (\(-20, 0\)) are \(\leq 10^{-10}\). All these facts suggest that the production of these molecules is closely related to the precursor interaction. OCS and \(\text{SO}_2\) are also undetected at this component (see Fig. 2).

### 2.3. Postshock Gas

L1448-mm (0, \(-20\)) is the only position where SiO shows broad emission, suggesting that the gas has already entered the shock (\(v_v \sim 10\) km s\(^{-1}\); Jiménez-Serra et al. 2004). As expected for \(\text{CH}_3\text{OH}, \text{SO}, \text{CS}\), these molecules also present broad line profiles toward this position. The SiO and the \(\text{CH}_3\text{OH}\) abundances, enhanced by a factor of 10000 in the postshock gas (\(10^{-8}\) and \(10^{-6}\), respectively; Fig. 2), are similar to those observed in other outflows (Bachiller & Pérez-Gutiérrez 1997; Blake et al. 1987), suggesting the idea that icy mantles have been completely removed from grains (nearly 90% of the mant-
produces the ejection of material from grains (Flower et al. 1996; Markwick et al. 2000), enhancing the SiO, CH3OH, SO, CS, and H2S abundances by up to a factor of 10 in the shock-precursor component (Fig. 2). The detection of slightly redshifted emission for these shock tracers toward the L1448-mm (0, −20) position (Fig. 1) is also consistent with the kinematical effects expected for this precursor (Draine 1980).

As the gas enters the shock and reaches the shock velocity, the rate of molecules ejected from grain mantles is largely increased, leading to the broadening of the line profiles of SiO, CH3OH, SO, and CS toward the L1448-mm (0, −20) position (see Fig. 1). These shock tracers are “instantaneously” enhanced by a factor of ~1000 in the postshock gas. For SiO and CH3OH, this enhancement is consistent with the abundances observed in other outflows (Bachiller & Pérez-Gutiérrez 1997; Blake et al. 1987) and predicted by chemistry models with injection of material from grains (Flower et al. 1996; Charnley 1997). However, in the case of the sulfur chemistry, the lack of broad H2S emission and the fact that the timescales for the injection of material from grains (Flower et al. 1996; Charnley et al. 1997) and predicted by chemistry models with injection of material from grains (Flower et al. 1996; Charnley 1997) are much larger (≥10^4 yr; Charnley 1997) than the dynamical age of the outflow contrast with the general assumption that this molecule is also released from grains (Charnley 1997). The H2S abundances derived from the shock precursor (~2 × 10^{-6}) and the postshock (~2 × 10^{-4}; Fig. 2) components cannot be responsible for the large SO and CS abundances (~10^{-3}) observed in the postshock gas.

OCS has been detected on grains (Palumbo et al. 1997), and van der Tak et al. (2003) and Martín et al. (2005) have reported large OCS abundances in massive star-forming regions and in the nucleus of NGC 253. One may consider that OCS could play an important role in the sulfur chemistry of L1448-mm. However, the upper limits of the OCS abundance (~3 × 10^{-8}) observed toward L1448-mm cannot explain the large SO and CS abundances either. The fact that SO is also undetected toward this young outflow suggests that OCS and SO, are late-time products of the sulfur chemistry (Charnley 1997).

Finally, Wakelam et al. (2004) have recently proposed that the sulfur of grain mantles could be directly released into gas phase in atomic form or in molecules that would be rapidly converted into it. Recent Spitzer observations have shown that S is very abundant toward the young Cepheus E outflow (Noriega-Crespo et al. 2004). As noted by Wakelam et al. (2004), S or S2 may produce large abundances of SO by reacting with O2 or O for t ~ 100–1000 yr. However, the predicted SO/CS abundance ratio is 4 orders of magnitude larger than the SO/CS ratio observed in the postshock gas, and O2 is undetected toward young outflows like NGC 2071 or IRAS 16293 (Pagani et al. 2003). It is then unlikely that SO and CS have been formed by gas-phase chemistry from atomic sulfur in the postshock gas of L1448-mm.

The most likely explanation is that the amount of SO and CS within the grain mantles of L1448-mm must be larger than initially thought, suggesting the idea that these molecules could have been generated by gas-phase chemistry in the past and afterwards depleted onto grains (Bergin et al. 1998). This would be consistent with the fact that SO or CS are more abundant than H2S or OCS in the grain mantles of the L1448-mm outflow. In general, the chemistry of sulfur-bearing molecules in shocks and hot cores will strongly depend on the “history” of the formation of the grain mantles.

In summary, the line profiles and the abundances of the shock tracers measured at the different velocity components in the L1448-mm outflow indicate that we have observed the “fingerprints” of the three stages of the shock evolution: the preshock, the shock precursor, and the postshock gas. The observed enhancement in the abundance of SiO, CH3OH, SO, and CS by 1 order of magnitude in the shock-precursor component, and by 3 orders of magnitude in the postshock gas, indicate the recent ejection of these molecules from grains. The abundances of the proposed sulfur-bearing parents such as H2S and OCS, cannot explain the large enhancement of SO and CS in the postshock gas. This suggests a strong dependence of the sulfur chemistry on the chemical evolution of the grain mantle composition. The lack of OCS and SO, in L1448-mm indicates that these molecules are late-time products of the sulfur chemistry.

This work has been supported by the Spanish MEC under projects AYA2002-10113-E, AYA2003-02785-E, and ESP2004-00665. We are grateful to the IRAM 30 m telescope staff for the help provided during the observations. We also thank an anonymous referee for useful comments and suggestions.

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