

## GRAIN EVOLUTION ACROSS THE SHOCKS IN THE L1448-mm OUTFLOW

I. JIMÉNEZ-SERRA, J. MARTÍN-PINTADO, AND A. RODRÍGUEZ-FRANCO<sup>1</sup>

Departamento de Astrofísica Molecular e Infrarroja, Instituto de Estructura de la Materia, CSIC, C/Serrano 121, E-28006 Madrid, Spain;  
 izaskun@damir.iem.csic.es, martin@damir.iem.csic.es, arturo@damir.iem.csic.es

AND

S. MARTÍN

Instituto de Radioastronomía Milimétrica, Avenida Divina Pastora, Local 20, E-18012 Granada, Spain; martin@iram.es

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### 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<sub>3</sub>OH, SO, CS, H<sub>2</sub>S, OCS, and SO<sub>2</sub> 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<sub>3</sub>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<sub>3</sub>OH abundances are consistent with the recent ejection of these molecules from grains. Since H<sub>2</sub>S is only enhanced in the shock-precursor component and OCS and SO<sub>2</sub> 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<sub>2</sub>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<sub>3</sub>OH, and the sulfur-bearing molecules H<sub>2</sub>S, SO, CS, OCS, or SO<sub>2</sub> 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<sub>3</sub>OH has been firmly detected on icy mantles (Tielens & Allamandola 1987), SiO and CH<sub>3</sub>OH are accepted as being ejected from grains. For the sulfur chemistry, since H<sub>2</sub>S is predicted to be efficiently formed on grain surfaces (Duley et al. 1980), this molecule is assumed to initiate this chemistry (Charnley 1997). However, H<sub>2</sub>S has not been detected so far in solid state (Smith 1991). Although other species like OCS have been proposed as playing an important role in the sulfur chemistry (van der Tak et al. 2003; Martín et al. 2005), the question of which sulfur-bearing molecule is ejected from grains still remains uncertain.

Shock chemistry models that include injection of molecules from grains show that the abundances of key species like SiO, CH<sub>3</sub>OH, or H<sub>2</sub>S evolve in timescales of a few  $10^3$  yr (Charnley et al. 1992; Flower et al. 1996; Markwick et al. 2000), much shorter than the typical ages of evolved outflows. The study of the chemistry of very young outflows like L1448-mm with dynamical timescales ( $t \sim 3500$  yr) similar to the chemical timescales offers the possibility of establishing which molecules are formed or depleted onto grains and which are generated in gas phase. In particular, since magnetohydrodynamic C-type shocks are initiated by the magnetic precursor, one can

directly measure the material released from grains by observing the gas recently affected by the precursor. The detection of extremely narrow SiO emission toward L1448-mm, in addition to the increase of the molecular ion abundances, have been interpreted as signatures of the interaction of the precursor (Jiménez-Serra et al. 2004). Measurements of the abundances of shock tracers in the shock-precursor stage can therefore help to establish the molecules that are present on grain mantles. This is particularly important in the case of the sulfur chemistry.

In this Letter, we present observations of key shock tracers such as SiO, CH<sub>3</sub>OH, SO, CS, H<sub>2</sub>S, OCS, and SO<sub>2</sub> toward the L1448-mm outflow. The enhanced abundances of SiO, CH<sub>3</sub>OH, SO, and CS in the shock precursor and the postshock components indicate the recent ejection of these molecules from grains. This enhancement, the lack of SO<sub>2</sub> and OCS, and the fact that H<sub>2</sub>S is only enhanced in the shock-precursor component indicate that the sulfur chemistry in L1448-mm strongly depends on the evolution of 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<sup>13</sup>CO<sup>+</sup>, and HN<sup>13</sup>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  $\geq 10$  dB. We observed lines of SO<sub>2</sub>, H<sub>2</sub>S, SO, OCS, CH<sub>3</sub>OH, and CS. Observations were done in frequency-switching and wobbler-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<sup>-1</sup> 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

<sup>1</sup> Escuela Universitaria de Óptica, Departamento de Matemática Aplicada (Biomatemática), Universidad Complutense de Madrid, Avenida Arcos de Jaelón s/n, E-28037 Madrid, Spain.

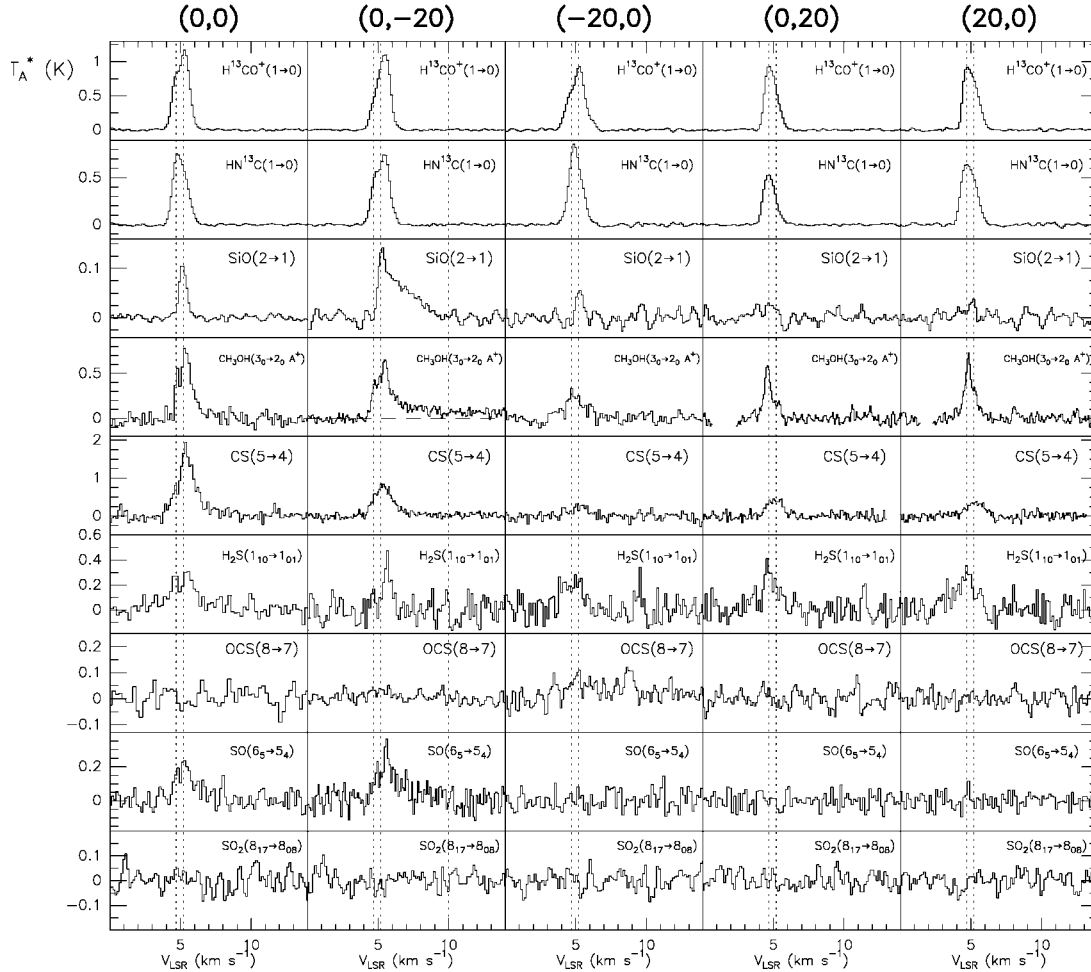


FIG. 1.—Sample of molecular profiles of  $\text{H}^{13}\text{CO}^+$ ,  $\text{HN}^{13}\text{C}$ ,  $\text{SiO}$ ,  $\text{CH}_3\text{OH}$ ,  $\text{CS}$ ,  $\text{H}_2\text{S}$ ,  $\text{OCS}$ ,  $\text{SO}$ , and  $\text{SO}_2$  observed toward the five-point map of L1448-mm. Offsets in arcseconds relative to L1448-mm ( $\alpha[\text{J2000.0}] = 03^{\text{h}}25^{\text{m}}38^{\text{s}}.0$ ,  $\delta[\text{J2000.0}] = 30^{\circ}44'05''$ ) are shown in the upper part of the columns. The dotted vertical lines show the preshock component at  $4.7 \text{ km s}^{-1}$  and the shock-precursor component at  $5.2 \text{ km s}^{-1}$ . Toward L1448-mm (0, -20),  $\text{SiO}$ ,  $\text{CH}_3\text{OH}$ ,  $\text{CS}$ , and  $\text{SO}$  show broader profiles, with terminal velocities that vary from  $7.5 \text{ km s}^{-1}$  for  $\text{CS}$  to  $14 \text{ km s}^{-1}$  for  $\text{CH}_3\text{OH}$  (dashed horizontal line).  $\text{SiO}$  and  $\text{SO}$  have similar terminal velocities of  $\sim 10 \text{ km s}^{-1}$  (third dotted line from the left).

with the 1 MHz filter bank, which provided a velocity resolution of  $\sim 2.6 \text{ km s}^{-1}$ . The system temperature was  $\sim 1000 \text{ K}$ . All the line intensities were calibrated in antenna temperature ( $T_A^*$ ).

Figure 1 shows the emission of  $\text{H}^{13}\text{CO}^+$ ,  $\text{HN}^{13}\text{C}$ , and shock tracers like  $\text{SiO}$ ,  $\text{CH}_3\text{OH}$ ,  $\text{SO}$ ,  $\text{CS}$ ,  $\text{H}_2\text{S}$ ,  $\text{SO}_2$ , and  $\text{OCS}$ , measured toward the five-point map of L1448-mm. The line profiles, except those of  $\text{SiO}$ , have line widths of  $\sim 1 \text{ km s}^{-1}$  and are double-peaked, showing the preshock component at  $4.7 \text{ km s}^{-1}$  and the shock-precursor component at  $5.2 \text{ km s}^{-1}$  (vertical dotted lines; Jiménez-Serra et al. 2004). Toward L1448-mm (0, -20),  $\text{SiO}$ ,  $\text{CH}_3\text{OH}$ ,  $\text{CS}$ , and  $\text{SO}$  also show broader redshifted emission, with terminal velocities that vary from  $\sim 7.5 \text{ km s}^{-1}$  in the case of  $\text{CS}$  to  $\sim 14 \text{ km s}^{-1}$  for  $\text{CH}_3\text{OH}$  (dashed horizontal line, Fig. 1). Since the  $\text{SiO}$  emission was observed in frequency-switching mode, we cannot rule out the possibility that the terminal velocity of the broad  $\text{SiO}$  line profile is slightly larger than that presented here. To estimate the molecular column densities, we have assumed optically thin emission. For the preshock and shock-precursor components, we used excitation temperatures (derived from the methanol emission) of  $\sim 7\text{--}14 \text{ K}$  for all positions except toward L1448-mm (0, -20), where the derived excitation temperature was of  $\sim 22 \text{ K}$ . For the postshock gas, we obtained excitation temperatures of  $\sim 20\text{--}45 \text{ K}$ . To derive the fractional abundances, the  $\text{H}_2$  column density for the preshock

and shock-precursor components was estimated from the  $\text{H}^{13}\text{CO}^+$  column densities, while for the postshock gas, we used the broad  $\text{CO } J = 1 \rightarrow 0$  emission. We considered  $\text{CO}$  and  $\text{HCO}^+$  fractional abundances of  $\sim 10^{-4}$  and  $\sim 10^{-8}$ , respectively (Irvine et al. 1987), and a  $^{12}\text{C}/^{13}\text{C}$  ratio of 90. In Figure 2, we show the comparison of the abundances of the shock tracers derived for the preshock, shock precursor, and postshock components toward the L1448-mm (0, -20) position. In the following, we discuss the abundances of these molecules for each component.

## 2.1. Preshock Gas

Neutral species like  $\text{HN}^{13}\text{C}$  and  $\text{HCO}$  trace the quiescent gas of the preshock component at  $4.7 \text{ km s}^{-1}$  (Jiménez-Serra et al. 2004). We do not detect  $\text{SiO}$ ,  $\text{OCS}$ , and  $\text{SO}_2$  at this component, which supports this idea. The molecular emission observed toward L1448-mm (0, 20) and (20, 0) peaks at  $4.7 \text{ km s}^{-1}$ , 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  $\text{SiO}$  abundance and  $\leq 10^{-10}$  to the  $\text{OCS}$  and  $\text{SO}_2$  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  $\text{CH}_3\text{OH}$ ,  $\text{SO}$ ,  $\text{CS}$ , and  $\text{H}_2\text{S}$  abundances are similar

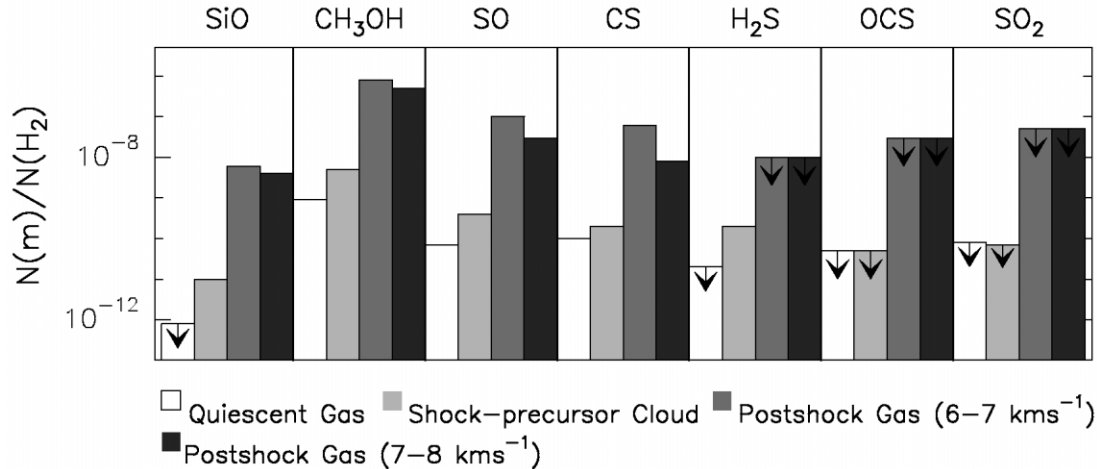


FIG. 2.—Derived abundances of SiO, CH<sub>3</sub>OH, SO, CS, H<sub>2</sub>S, OCS, and SO<sub>2</sub> for the preshock (white), the shock precursor (light gray), and the postshock components (gray and dark gray) toward L1448-mm (0, -20). The black arrows indicate the upper limits to the molecular abundances estimated from the  $3\sigma$  level noise in the spectra. SiO, CH<sub>3</sub>OH, SO, and CS are enhanced by up to a factor of 10 in the shock-precursor component and by a factor of  $\sim 1000$  in the postshock gas. As H<sub>2</sub>S is only enhanced in the shock-precursor component, and since OCS and SO<sub>2</sub> are undetected, SO and CS are the most abundant sulfur-bearing molecules in the shocked gas.

to those derived from dark clouds ( $\sim 10^{-10}$  to  $10^{-9}$ ; Ohishi et al. 1992; Martín-Pintado et al. 1992).

### 2.2. Shock-Precursor Component

The very narrow ( $\sim 0.6$  km s<sup>-1</sup>) SiO emission detected at 5.2 km s<sup>-1</sup> with an abundance of  $\sim 10^{-11}$ , in addition to the enhancement of the molecular ions like H<sup>13</sup>CO<sup>+</sup> and N<sub>2</sub>H<sup>+</sup>, 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, CH<sub>3</sub>OH, H<sub>2</sub>S, SO, and 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 ( $\sim 5.4$ – $5.6$  km s<sup>-1</sup>) 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 CH<sub>3</sub>OH, H<sub>2</sub>S, SO, and 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, 0) 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 SO<sub>2</sub> 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 ( $v_s \sim 10$  km s<sup>-1</sup>; Jiménez-Serra et al. 2004). As expected for CH<sub>3</sub>OH, SO, and CS, these molecules also present broad line profiles toward this position. The SiO and the CH<sub>3</sub>OH abundances, enhanced by a factor of  $\sim 1000$  in the postshock gas ( $\sim 10^{-8}$  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 man-

tle material is injected into gas phase for  $v_s \leq 15$  km s<sup>-1</sup>; Caselli et al. 1997). The enhancement by also three orders of magnitude of SO and CS in the postshock regime (Fig. 2) clearly contrasts with the lack of broad H<sub>2</sub>S emission toward L1448-mm (0, -20; Fig. 1). The upper limits of  $\leq 10^{-8}$  to the H<sub>2</sub>S abundance are a factor of 10 smaller than those observed in evolved outflows ( $\sim 10^{-7}$ ; Blake et al. 1987; Bachiller & Pérez-Gutiérrez 1997) and predicted by sulfur chemistry models with injection of H<sub>2</sub>S from grains (Charnley 1997). Since we detect neither OCS nor SO<sub>2</sub> arising from the postshock gas (Fig. 2), SO and CS are the most abundant sulfur-bearing molecules at the first stages of the shock evolution toward L1448-mm. The molecular abundances are not significantly altered by the ejection of CO from grains, since its fractional abundance remains unchanged after mantle desorption (Markwick et al. 2000).

## 3. DISCUSSION

The observed trend in the shock tracers to be enhanced in the shock precursor and the postshock components (Fig. 2) supports an evolutionary effect produced by the propagation of the shock into the ambient gas. The material affected by the young shocks in L1448-mm has not reached the postshock chemical equilibrium (Flower & Pineau des Forêts 1999). One then expects to distinguish between the molecules ejected from grains and the species generated in gas phase. This will help us to understand the peculiar grain chemistry observed toward L1448-mm, especially in the case of the sulfur chemistry, which seems to be strongly dependent on the chemical “history” of the grain mantles in this region.

The abundances of shock tracers like SiO, CH<sub>3</sub>OH, SO, CS, or H<sub>2</sub>S in the preshock gas are similar to those found in quiescent dark clouds. As the shock approaches the unperturbed gas, the first interaction will be driven by the precursor, modifying the physical conditions and the chemistry of the ambient cloud (Draine & McKee 1993). Jiménez-Serra et al. (2004) proposed that the enhancement of the ions in the shock-precursor component toward L1448-mm is explained by the interaction of the magnetic precursor that forces the ions to slip (Draine 1980) from the neutral quiescent gas at 4.7 km s<sup>-1</sup> to the shock-precursor component at 5.2 km s<sup>-1</sup>. This ion-neutral velocity drift

produces the ejection of material from grains (Flower et al. 1996; Markwick et al. 2000), enhancing the SiO, CH<sub>3</sub>OH, SO, CS, and H<sub>2</sub>S 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, CH<sub>3</sub>OH, SO, and CS toward the L1448-mm (0, -20) position (see Fig. 1). These shock tracers are “instantaneously” enhanced by a factor of  $\sim 1000$  in the postshock gas. For SiO and CH<sub>3</sub>OH, 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 et al. 1992). However, in the case of the sulfur chemistry, the lack of broad H<sub>2</sub>S emission and the fact that the timescales for H<sub>2</sub>S to decrease its abundance to  $\leq 10^{-8}$  are much larger ( $t \geq 10^4$  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 H<sub>2</sub>S abundances derived from the shock precursor ( $\sim 2 \times 10^{-10}$ ) and the postshock ( $\leq 10^{-8}$ ; Fig. 2) components cannot be responsible for the large SO and CS abundances ( $\sim 10^{-7}$ ) 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 ( $\leq 3 \times 10^{-8}$ ) observed toward L1448-mm cannot explain the large SO and CS abundances either. The fact that SO<sub>2</sub> is also undetected toward this young outflow suggests that OCS and SO<sub>2</sub> 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 S<sub>2</sub> may produce large abundances of SO by reacting with O<sub>2</sub> or O for  $t \sim 100$ –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 O<sub>2</sub> 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 H<sub>2</sub>S 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, CH<sub>3</sub>OH, 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 H<sub>2</sub>S 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<sub>2</sub> in L1448-mm indicates that these molecules are late-time products of the sulfur chemistry.

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