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LOW SULFUR DEPLETION IN PHOTODISSOCIATION REGIONS

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Abstract. Sulfur is an abundant element which remains undepleted in diffuse interstellar gas but it is historically assumed to deplete (by factors of ∼1000) on grains at higher densities. Photodissociation regions (PDRs) are an interesting intermediate medium between translucent and dark clouds where the energetics and dynamics are dominated by an illuminating FUV radiation field, and thus they can provide some new insights about the sulfur depletion problem. In this work we present our latest studies on CS and HCS^+ photochemistry, excitation and radiative transfer in the Horsehead PDR, allowing us to infer the sulfur abundance.

1 Introduction

Sulfur is an abundant element (the solar photosphere abundance is S/H=1.38×10^{-5}), which remains undepleted in diffuse interstellar gas and H II regions but it is historically assumed to deplete on grains in higher density molecular clouds by factors as large as $\sim10^3$. This conclusion is *simply* reached by adding up the observed gas phase abundances of S–bearing molecules in well known dark clouds such as TMC1. As sulfur is easily ionized (ionization potential ∼10.36 eV), sulfur ions are probably the dominant gas–phase sulfur species in translucent gas. Ruffle et al. (1999) proposed that if dust grains are typically negatively charged, S^+ may freeze–out onto dust grains during cloud collapse more efficiently than neutral species such as oxygen. However, the nature of sulphur on dust grains (either in mantles or cores) is not obvious. The absence of strong IR features due to S–bearing ices in many ISO's mid–IR spectra and the presence of S II recombination lines in dark clouds such as Rho Ophiuchi all argue against a large depletion of sulfur from the gas phase. Besides, the abundance of species such as CS may indicate that something important is lacking from chemical models or that an abundant sulfur–bearing carrier has been missed. Therefore, the abundances of sulfur species remain interesting puzzles for interstellar chemistry. PDRs offer an ideal intermediate medium between diffuse and dark cloud gas to investigate the sulfur depletion problem. In particular, the Horsehead western edge is a PDR viewed nearly edge-on and illuminated by the O9.5V star σOri at a projected distance of ∼3.5 pc. The intensity of the incident FUV radiation field is $\chi \simeq 60$ relative to the interstellar radiation field (ISRF) in Draine's units.

Since 2001 we have been studying the Horsehead nebula with the IRAM telescopes as a reference, well understood source, to analyse the chemical stratification predicted in clouds illuminated by a FUV radiation field (see Pety et al. these proceedings). These studies have led e.g., to a significant increase of our knowledge of the carbon chemistry (from PAHs to small hydrocarbons) in FUV irradiated gas (see Gerin et al. 2005 and references therein). In this particular work we have tried to accurately determine and understand the CS abundance in the Horsehead PDR as a tool for estimating the sulfur gas phase abundance. Compared to other works, we now specifically treat the nonlocal, non-LTE molecular excitation and line–plus–continuum radiative transfer along the cloud edge using the output predictions of photochemical models. In this way, we can consistently link the thermal and chemical predictions of PDR models with absolute molecular line intensities observed by telescopes. This, sometimes difficult, step has a crucial importance in the accurate determination of molecular abundances and in our understanding of the prevailing chemistry by a direct comparison of chemical models with molecular line emissivities.

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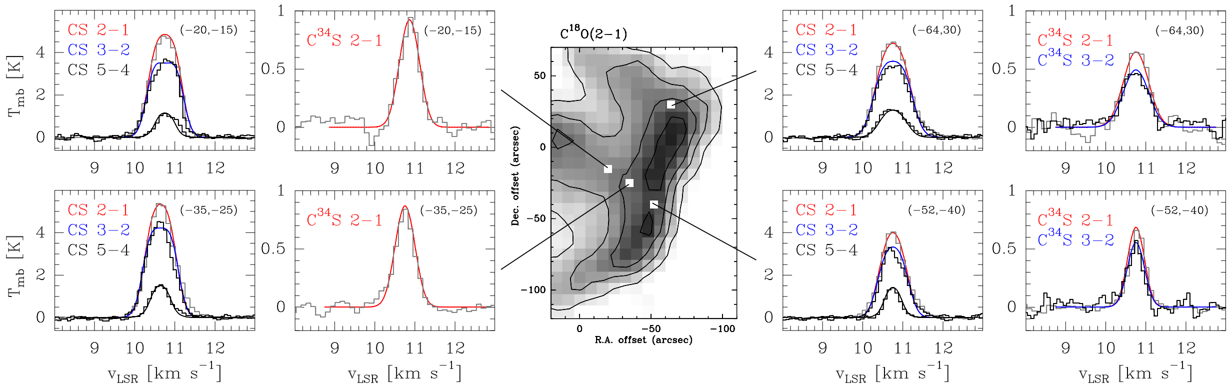

Fig. 1. Monte Carlo radiative transfer models for CS and $C^{34}S$ discussed in the text (curves) that best fits the IRAM–30m observations (histograms). Offsets in arcsec refer to the (0,0) position of the $C^{18}O(2–1)$ map (middle). Predicted line profiles have been convolved with the telescope angular resolution. Intensity scale is in main beam temperature.

2 Observations

In this work we have made use of 3.65″ × 3.34″ angular–resolution IRAM *Plateau de Bure Interferometer* (PdBI) observations of the CS J=2–1 line (Fig. 2 *left*), complemented with IRAM–30m observations of several rotational lines of CS, $C^{34}S$ and HCS^+. The frequency switching mode was used to observe the CS J=2–1, 3–2 and 5–4 lines, $C^{34}S$ J=2–1, 3–2, and HCS^+ J=2–1 lines (Fig. 1). Beam sizes of single–dish observations range from ∼10″ at 1 mm to ∼30″ at 3 mm. Data reduction was done with the GILDAS software[1].

3 Numerical methodology

To analyse the gas phase sulfur chemistry we use the *Meudon PDR code*, a photochemical model of a unidimensional stationary PDR (Le Petit et al. 2006). In few words, the PDR code solves the FUV radiative transfer in an absorbing and diffusing medium of gas and dust. This allows the explicit computation of the FUV radiation field (continuum+lines) and therefore, the explicit integration of consistent C and S photoionization rates together with H_2, CO, ^{13}CO, and $C^{18}O$ photodissociation rates. Our standard conditions for the model of the Horsehead PDR include a power–law density profile and a FUV radiation field enhanced by a factor $\chi = 60$ with respect to the Draine ISRF. Different sulfur gas phase abundances, S/H, have been investigated (see Fig. 2 *right*). To be consistent with PdBI CO multi-line observations, the thermal balance was solved until the gas temperature reached a minimum value of 30 K, then a constant temperature was assumed.

For the molecular excitation and radiative transfer in the PDR we use a nonlocal, non–LTE Monte Carlo code that allows us to directly compare our millimeter line observations. The code handles spherical and plane-parallel geometries and accounts for line trapping, collisional excitation, and radiative excitation by absorption of microwave cosmic background and dust continuum photons. Arbitrary density, temperature or abundance profiles, and complex velocity gradients can be included. A detailed description of the model is given in Goicoechea (2003) and Goicoechea et al. (2006).

The following methodology was carried out: a full PDR model with Horsehead standard conditions was run with a particular choice of the density gradient. Afterwards, the PDR output was used as input for the excitation and radiative transfer calculation. In this way, physical parameters can be tuned more accurately by iteration of different radiative transfer models. Once better parameters have been found, a new PDR computation is performed with this choice of physical parameters. Hence, the most appropriate physical and chemical description of the PDR edge and the best molecular abundances were found through the *PDR model→transfer model→check with observations→transfer model→PDR model* iterative process. We have so far analyzed CS, $C^{34}S$, $C^{18}O$ and HCS^+ line observations. Synthetic abundance profiles are consistently computed as a function of the edge distance δx (in arcsec) and directly compared with observations (see Fig. 3 for PdBI CS lines).

[1]Softwares supported at IRAM. See `http://www.iram.fr/IRAMFR/GILDAS` for more information.

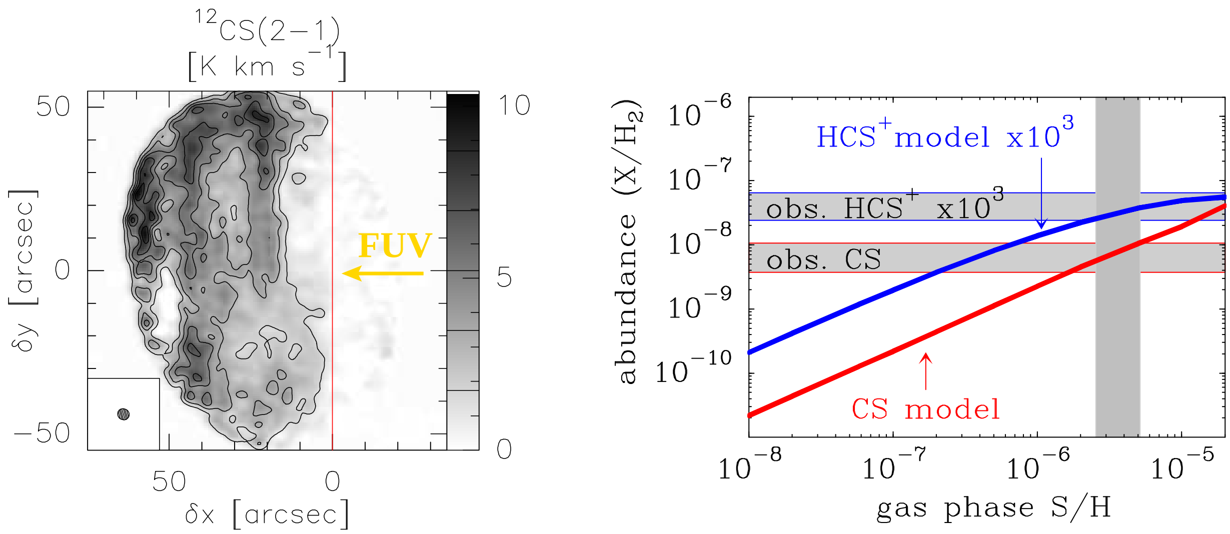

Fig. 2. *Left panel:* CS J=2–1 integrated emission map obtained with the PdBI. The map center has been set to the mosaic phase center: RA(2000) = 05h40m54.27s, Dec(2000) = -02^{o}28$'$00$''$. The map size is 110$''$ × 110$''$. The synthesized beam is plotted in the bottom left corner. The map has been rotated by 14^o counter–clockwise around the image center to bring the exciting star direction in the horizontal direction as this eases the comparison of the PDR models. *Right panel:* Photochemical model predictions for the physical and FUV illuminating conditions prevailing in the Horsehead PDR showing the CS and HCS$^+$ abundances as a function of the sulfur gas phase abundance. Horizontal shaded regions show the CS and HCS$^+$ abundances derived from the single–dish observations and radiative transfer modeling. Note that for clarity HCS$^+$ abundances have been multiplied by a factor of 1000. The shaded vertical region shows the estimated sulfur abundance in the Horsehead nebula derived from the constrained fits of CS and HCS$^+$ abundances.

4 Main Results

In this work we have analyzed interferometric CS J=2–1 line maps of the Horsehead PDR at a 3.65$''$ × 3.34$''$ resolution together with single–dish observations of several rotational lines of CS, C^{34}S and HCS$^+$. We have studied the CS photochemistry, excitation and radiative transfer using the latest HCS$^+$ and OCS$^+$ dissociative recombination rates (Montaigne et al. 2005) and CS collisional cross–sections (Lique et al. 2006). The main conclusions are as follows (the whole work can be found in Goicoechea et al. (2006)):

1. CS and C^{34}S rotational line emission reveals mean densities around $n(H_2)$=(0.5–1.0)×10^5 cm^{-3}. The CS J=5–4 lines show narrower line widths than the low–J CS lines and require higher density gas components, ∼(2–6)×10^5 cm^{-3}, not resolved by a ∼10$''$ beam. These values are larger than previous estimates based on CO single–dish observations. It is likely that clumpiness at scales below ∼0.01 pc and/or a low density envelope play a role in the CS line profile formation.

2. Nonlocal, non–LTE radiative transfer models of optically thick CS lines and optically thin C^{34}S lines provide an accurate determination of the CS abundance, χ(CS)=(7±3)×10^{-9}. We show that radiative transfer and opacity effects play a role in the resulting CS line profiles but not in C^{34}S lines. Assuming the same physical conditions for the HCS$^+$ molecular ion, we find χ(HCS$^+$)=(4±2)×10^{-11}.

3. According to photochemical models, the gas phase sulfur abundance required to reproduce these CS and HCS$^+$ abundances is S/H=(3.5±1.5)×10^{-6}, only a factor ∼4 less abundant than the solar elemental abundance. Larger sulfur abundances are possible if the gas is significantly warmer. Thus, the sulfur abundance in the PDR is very close to the undepleted value observed in the diffuse ISM. The predicted CS/HCS$^+$ abundance ratio is close to the observed value of ∼175, especially if predicted HCS$^+$ peak abundances are considered. If not, the HCS$^+$ production is underestimated unless the gas is in a higher ionization phase, e.g. if the cosmic ray ionization rate is increased by ∼5. We are currently working on a larger inventory of sulfur–bearing molecules detected by us in the Horsehead PDR to test other limitations of the sulfur chemical network.

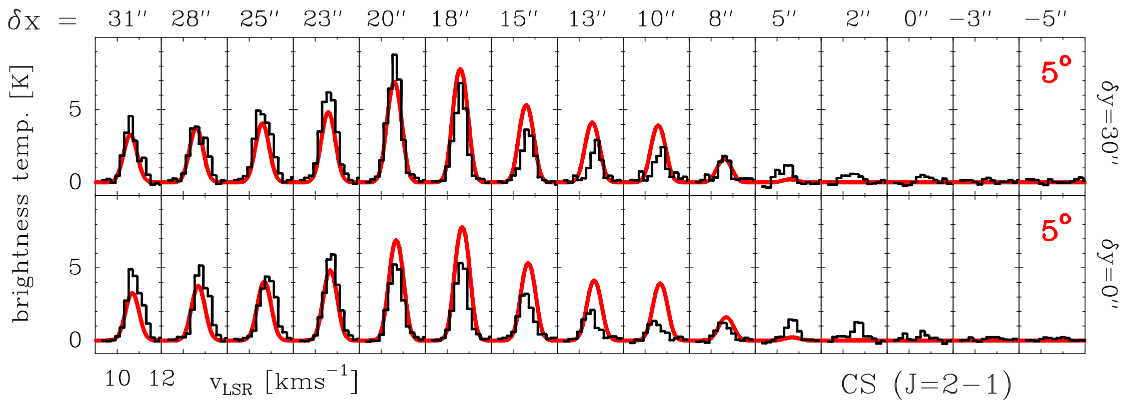

Fig. 3. PdBI CS J=2–1 spectra along the direction of the exciting star at $\delta y = 30''$ (*upper panel*) and $\delta y = 0''$ (*lower panel*). Monte Carlo radiative transfer models using the output of PDR models for CS (red curve) for the physical conditions discussed in the text (assuming that the PDR is inclined relative to the line of sight by a φ=5^o angle). Modeled line profiles have been convolved with an appropriate gaussian beam corresponding to each synthesized beam.

4. High angular resolution PdBI maps reveal that the CS emission does not follow the same morphology shown by the small hydrocarbons emission the PDR edge (Pety et al. 2005). In combination with previous PdBI $C^{18}O$ observations we have modeled the PDR edge and confirmed that a steep density gradient (see Habart et al. 2005) is needed to reproduce CS and $C^{18}O$ observations. The resulting density profile qualitatively agrees to that predicted in numerical simulations of a shock front compressing the PDR edge to high densities, $n(H_2)\simeq10^5$ cm^{-3}, and high thermal pressures, $\simeq(5\text{–}10)\times10^6$ K cm^{-3}.

5. Conventional PDR heating and cooling mechanisms fail to reproduce the temperature of the warm gas observed in the region by at least a factor $\sim$2. Additional mechanical heating mechanisms associated with the gas dynamics may be needed to account for the warm gas. The thermal structure of the PDR edge is still not fully constrained from observations. This fact adds uncertainty to the abundances predicted by photochemical models.

Observational studies of ISM clouds show that many physical and chemical variations occur at small angular scales. For PDRs, the molecular inventory as a function of the distance from the illuminating source can only be obtained from interferometric observations. High angular resolution observations contain detailed information about density, temperature, abundance and structure of the cloud, but only detailed radiative transfer and photochemical models for each given source are able to extract the information. A minimum description of the source geometry is usually needed. Future observations with ALMA will allow us to characterize in much more details many energetic surfaces such as PDRs.

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