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Letter to the Editor

Detection of [O I] 63 μm in absorption toward Sgr B2*

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Abstract. A high signal-to-noise 52–90 μm spectrum is presented for the central part of the Sagittarius B2 complex. The data were obtained with the Long Wavelength Spectrometer on board the Infrared Space Observatory (ISO). The [O I] 63 μm line is detected in absorption even at the grating spectral resolution of 0.29 μm. A lower limit for the column density of atomic oxygen of the order of 10^{19} cm^{-2} is derived. This implies that more than 40% of the interstellar oxygen must be in atomic form along the line of sight toward the Sgr B2 molecular cloud.

Key words: ISM: abundances – (ISM:) dust, extinction – (ISM:) H II regions – ISM: individual objects: Sgr B2 – Infrared: ISM: continuum – Infrared: ISM: lines and bands

1. Introduction

The main form in which oxygen, the third most abundant element in the Universe, is present in the cold component of the interstellar medium remains one of the major unresolved issues of astrochemistry. Oxygen is supposed to reside mostly in the gas phase of molecular clouds, presumably as atomic oxygen or simple molecules, such as O_2, CO, H_2O and OH. Depletion of oxygen onto dust grains is not expected to exceed $\sim$ 25% (van Dishoeck et al. 1993) most of the oxygen being incorporated into silicate grains. This estimate does not include the solid CO_2 which is found to be ubiquitous in the interstellar medium (de Graauw et al. 1996) or the solid O_2 which may be an important grain mantle constituent (Ehrenfreund et al. 1992).

From chemical models the atomic oxygen is expected to account for 10–30% of the gas-phase oxygen within molecular clouds (e.g. Bergin et al. 1995 and references therein). Although the abundance of O_2 in dark clouds is predicted to be similar to that of atomic oxygen (Black & Smith 1984), the search for this molecule has so far been unsuccessful. The best limit has been obtained toward extragalactic dense molecular clouds by Combes & Wiklind (1995) who report an upper limit on the O_2/CO abundance ratio of 1.4 10^{-2}, more than an order of magnitude lower than what is predicted by chemical models. Among other O-bearing molecules, the most commonly observed is CO which only contains $\sim$ 10% of the total oxygen abundance (Lacy et al. 1994). Recent estimates of the gas-phase H_2O abundance which are based on ISO results indicate that water vapour can account for only a few percent of the total oxygen abundance (van Dishoeck & Helmich 1996, Cernicharo et al. 1997). Finally, the OH fractional abundance is even smaller

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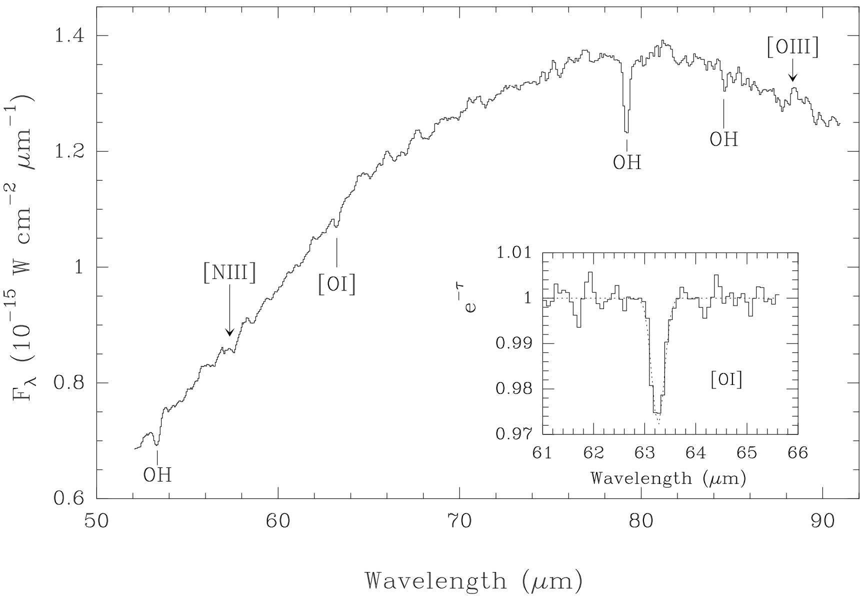

Fig. 1. The LWS grating spectrum of Sgr B2 from 52 to 90 μm. This spectrum was taken at $\alpha_{1950} = 17^h44^m12.0^s$, $\delta_{1950} = -28^o22'12''$. The insert displays the line to continuum ratio around the [O I] 63 μm line which is seen in absorption

with OH/O less than 0.7% (Viscuso et al. 1985). In conclusion, none of the above molecules can account for the bulk of the gas-phase oxygen.

Recent observations have suggested that in the interstellar medium most of the gas-phase oxygen might be in atomic form. A first suggestion was made by Schulz et al. (1991) in order to interpret their HDO observations. From HST ultraviolet spectroscopy, Sofia et al. (1994) derived in two molecular clouds [O]/[H] values as high as 1/3 of the cosmic abundance of oxygen. Poglitsch et al. (1996) reported a possible detection of the [O I] 63 μm fine structure line in absorption toward DR 21. They derived a relative abundance of atomic oxygen [O]/[H] $\sim 6 \times 10^{-4}$, implying that, in the foreground absorbing cloud, most of the oxygen is in atomic form.

In this Letter, we report the detection of [O I] 63 μm in absorption toward the main core of Sgr B2, a highly obscured H II region complex close to the galactic center. The data are based on grating spectra obtained with the Long Wavelength Spectrometer (LWS) on board of ISO. They provide a first estimate of the atomic oxygen content along the line of sight to Sgr B2. Higher spectral resolution data of the [O I] 63 μm taken with the LWS Fabry-Perot will be published as part of a general ISO study of [O I] absorption in molecular clouds by Phillips et al. (1997).

2. Observations and results

Full LWS grating scans from 43 to 196 μm were obtained toward Sgr B2 during Revolution 287 (30 August 1996) using AOT L01 as part of the ISO guaranteed time program ISM_V. The LWS capabilities and the calibration procedure are described by Clegg et al. (1996) and Swinyard et al. (1996), respectively. Sixteen full grating scans were taken with 0.5 sec integration time per grating step. The spectra were sampled at 1/4 of the spectral resolution element, being 0.29 μm for the short-wavelength detectors. The total on-target time was 3047 sec. The data have been processed through the LWS Pipeline Version 6.0.

Fig. 1 displays the spectrum between 52 and 90 μm obtained toward Sgr B2 after combining the results of detectors SW2 to SW5. Small scaling factors (a few %) have been applied to the individual spectra so that they join smoothly. The spectrum consists of a strong dust continuum (at 80 μm, the flux density is 34,000 Jy) with a series of lines all seen in absorption. The signal-to-noise ratio being very high ($\sim$ 200) most of the features seen in Fig. 1 are probably real. The OH absorption lines which are labelled in Fig. 1 will be discussed in a forthcoming paper. A major aspect of the Sgr B2 spectrum is the presence of the [O I] 63 μm line which is seen *in absorption* - see insert in Fig. 1. The absorption-line depth is 3.0 $\pm$ 0.5 % at the LWS grating resolution. A further important point is the absence of emission in the [O III] 88 μm and [N III] 57 μm atomic fine structure lines normally detected toward compact H II regions.

A LWS grating raster map of Sgr B2 was also obtained during Revolution 287 as part of an open time program (see Cernicharo et al. 1997 for details). Fig. 2 displays the data around the [O I] 63 μm line along two cuts oriented N-S and E-W through Sgr B2. The [O I] 63 μm line intensity varies drastically over the cut. The [O I] is seen in emission in most of the positions, with a maximum 180$''$ south of Sgr B2. Around the position of Sgr B2, the [O I] line gradually changes from an emission line into a line in absorption.

3. Discussion

Sgr B2, one of the most luminous star-forming regions in the Galaxy, consists of several compact H II regions (Gaume et al. 1995) which are embedded in a massive molecular cloud. The hydrogen column densities have been estimated to be a few 10^{24} cm^{-2} in the 2$'$ core diameter (Scoville et al. 1975). Sgr B2 is optically thick even at far-infrared wavelengths where the opacity at 100 μm is estimated to be unity (Harvey et al. 1977). In Sgr B2, the warm gas seen, e.g., in the radio observations, is thus obscured completely by the associated molecular cloud. These high far-infrared opacities explain why the [O III] 88 μm (Dain et al. 1978) and [O I] 63 μm (Lester et al. 1981) lines were not detected in the spectrum of SgrB2. The present ISO/LWS data confirm these early measurements (Fig. 1) and the quality of the data allows to detect the [O I] line in absorption.

Although the spectral resolution of the grating is limited, useful conclusions can be derived from the present data concerning the abundance of atomic oxygen. Clearly, higher spectral resolution measurements such as obtained by Phillips et al. (1997) will permit a more detailed analysis including the study of the velocity structure in the [O I] absorption line.

The mean photoabsorption cross section of the [O I] 63 μm line is $\sigma = 5.093 \times 10^{-18}/(\Delta\ \mathrm{V_{kms^{-1}}})$ cm^2 where Δ V is the line width in km s^{-1} (e.g., Allen 1973 - radiative lifetime from Baluja & Zeippen 1988). At a spectral resolution of 0.29 μm ($\sim$ 1380 km s^{-1}), the measured 3.0 $\pm$ 0.5 % absorption-line depth of [O I] corresponds to a line equivalent width $\Delta\ \mathrm{V_{ew}}$ = (41.4$\pm$7) km s^{-1}. Assuming *uniform* absorption over a velocity range $\Delta\ V$ will result in a line optical depth $\tau = -\ln(1 - \Delta\ \mathrm{V_{ew}}/\Delta\ \mathrm{V})$ and a column density $\mathrm{N_O} = 1.963 \times 10^{17} \times \tau \times \Delta$ V cm^{-2}.

In order to estimate the atomic oxygen abundance implied by the [O I] 63 μm absorption, we consider two simple cases. First, we assume that the [O I] absorption is dominated by a low density medium distributed uniformly in velocity along the line of sight toward SgrB2. Adopting a typical density of 1 cm^{-3}, the hydrogen column density is 2.5×10^{22} cm^{-2} for a distance of 8.5 kpc to Sgr B2. Since there is no gas in the direction of Sgr B2 at velocities smaller than -110 or larger than +80 km s^{-1} (Scoville et al. 1975), we will assume that $\Delta\ V$ is less than $\Delta\ \mathrm{V_{max}}$ = 200 km s^{-1}. With Δ V = $\Delta\ \mathrm{V_{max}}$, we find τ = 0.23 and $\mathrm{N_O} = 9.1 \times 10^{18}$ cm^{-2}, yielding $\mathrm{N_O/N_H} = 3.6 \times 10^{-4}$. In this simple approximation, the derived atomic oxygen abundance is half cosmic, suggesting that (1) atomic oxygen is the dominant form of gaseous oxygen and (2) the mean depletion of oxygen onto dust grains is, as expected, moderate. Since τ is significantly less than unity, these conclusions do not depend critically on the exact value of Δ V; using Δ V = 100 instead of 200 km s^{-1} would increase $\mathrm{N_O}$ by 15% only. Similarly, they do not depend much on the presence of clumping along the line of sight provided that the [O I] optical depth does not exceed unity at any velocity.

In the second case, we suppose that the [O I] absorption is restricted to the most prominent molecular clouds. The velocity structure toward Sgr B2, as revealed by molecular line absorption, is complex (e.g., Stacey et al. 1987). Four main layers contribute to the absorption, namely: (1) A very massive molecular cloud associated with the Sgr B2 complex itself at +63 km s^{-1} with $N_{H_2} \sim 5 \times 10^{23}$ cm^{-2}, (2) the expanding molecular ring at –105 km s^{-1} with $N_{H_2} \sim 4 \times 10^{21}$ cm^{-2}, (3) the 3-kpc arm (–43 km s^{-1} and $N_{H_2} \sim 3 \times 10^{21}$ cm^{-2}), and (4) the local gas at $\sim$ 0 km s^{-1} with N_{H_2} roughly as in the two latter components. The velocity widths of these components, determined from radio absorption line studies, depend on the angular resolution of the observations. With a 2$'$ beam, the line widths are 8, 11, 15 and 20 km s^{-1} for the absorbing layers at –105, –43, +2 and +63 km s^{-1}, respectively (Scoville et al. 1975). At a $\sim$ 15” resolution, the widths are 3, 8, and 12 km s^{-1} for the last three components (Mehringer et al. 1995). The ISO/LWS beam being close to 1.5$'$, we adopt $\Delta\ V_{SgrB2}$ = 20 km s^{-1} for the Sgr B2 cloud and $\Delta\ V_{fore}$ = 30 km s^{-1} for the sum of the three main foreground clouds. Altogether, the column density of the three latter clouds is $N_{H_2} \sim 1.1 \times 10^{22}$ cm^{-2}.

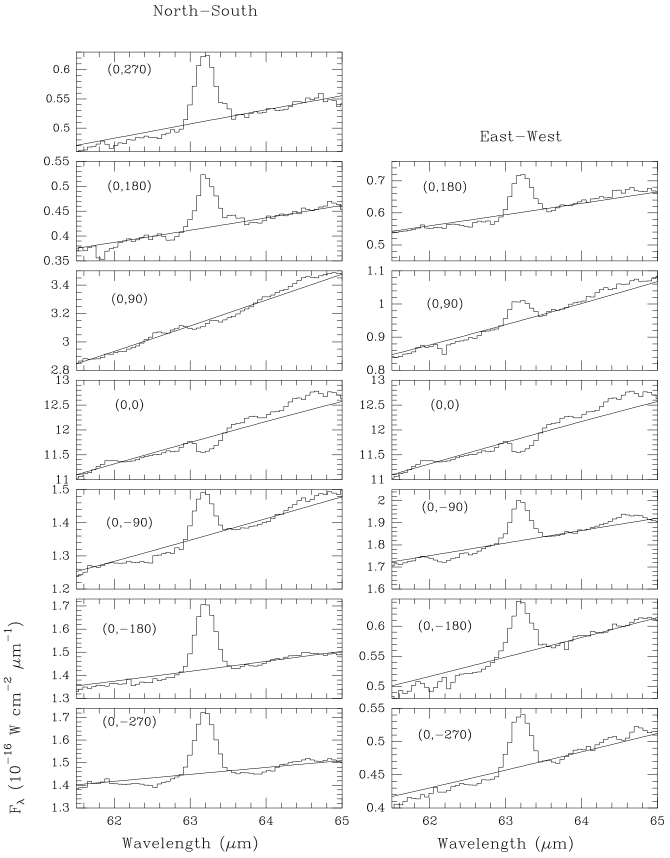

Fig. 2. The spectra around [O I] 63 μm toward several directions along N-S and E-W cuts in Sgr B2. The separation between successive positions is 90$''$. The central position (0,0) corresponds to SgrB2 (Main) - $\alpha_{1950} = 17^h44^m10.6^s$, $\delta_{1950} = -28^o22'29''$. Offset positions are given in arcsec in the upper left corner of each panel. The source Sgr B2 (North) is located at offset (0,90) in the North-South cut

Assuming uniform absorption over the full velocity range $\Delta\ V_{molec} = \Delta\ V_{SgrB2} + \Delta\ V_{fore}$ leads to τ = 1.76 and N_O = 1.7×10^{19} cm^{-2}. Considering 30/50 of this N_O, the atomic oxygen abundance in the foreground clouds is N_O/N_H = 4.6×10^{-4}. We note, however, that $\Delta\ V_{molec}$ is not very significantly larger than $\Delta\ V_{ew}$. With the quoted uncertainties, N_O/N_H is thus estimated to vary from 3.1 to 9.2 $\times 10^{-4}$, to be compared to the cosmic abundance of oxygen [O]/[H] = 8.5×10^{-4} (Anders & Grevesse 1989). In the relatively unlikely case of a complete absorption over $\Delta\ V_{SgrB2}$, N_O/N_H would decrease by 30%. Conversely no solution exists if the absorption is restricted to the range $\Delta\ V_{fore}$: absorption by the Sgr B2 cloud (over $\Delta\ V_{SgrB2}$) should be at least 50%, unless other sources of absorption are considered. Finally, τ may be much larger than the average value over restricted velocity ranges, also increasing N_O/N_H. The column density of atomic oxygen obtained in the foreground molecular clouds is thus consistent with 40 to 100% of oxygen being in atomic form.

We note that the gigantic column density of the molecular cloud associated with Sgr B2 is not directly relevant in the absorption budget since only the envelope of the cloud (its "photosphere") is seen at far-infrared wavelengths due to the obscuration. Both the absorption and emission in the continuum should be taken into account. Depending on whether a temperature gradient is present and whether the population of the upper level of [O I] 63 μm differs from the Boltzmann population, the line may or may not appear in absorption. It is quite probable that line scattering in the outskirts of the cloud will finally lead to absorption, although this absorption may not be particularly deep given that the scattering layer is nearly spatially coincident with the source of radiation and the LWS beam encompasses a large fraction of the whole cloud.

4. Conclusion

This Letter reports the detection in the ISO/LWS grating spectrum of the [O I] 63 μm line in absorption toward Sgr B2. At the grating resolution of 300, the depth of the line is $\sim 3\%$ of the continuum. This measurement implies a minimum column density of atomic oxygen along the line of sight toward SgrB2 of 10^{19} cm^{-2}. Although the Sgr B2 molecular cloud must contribute to the absorption, no conclusions can be drawn concerning its atomic oxygen content.

The abundance of atomic oxygen is thus at least 40% of the cosmic abundance, implying that atomic oxygen is the dominant form of oxygen in the interstellar medium in the direction of Sgr B2. This conclusion agrees with the results of Poglitsch et al. (1996) who studied the line of sight toward DR 21. In order to analyse in more detail the contributions to the [O I] 63 μm absorption of the molecular clouds distributed along the line of sight toward SgrB2, higher spectral resolution observations are required.

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