

*Letter to the Editor***Detection of [O I] 63  $\mu\text{m}$  in absorption toward Sgr B2\***

J.-P. Baluteau<sup>1</sup>, P. Cox<sup>2</sup>, J. Cernicharo<sup>3</sup>, D. Péquignot<sup>4</sup>, E. Caux<sup>5</sup>, T. Lim<sup>6</sup>, B. Swinyard<sup>7</sup>, G. White<sup>8</sup>, M. Kessler<sup>9</sup>, T. Prusti<sup>9</sup>, M. Barlow<sup>10</sup>, P.E. Clegg<sup>8</sup>, R.J. Emery<sup>7</sup>, I. Furniss<sup>10</sup>, W. Glencross<sup>10</sup>, C. Gry<sup>1,6</sup>, M. Joubert<sup>1</sup>, R. Liseau<sup>11</sup>, B. Nisini<sup>11</sup>, P. Saraceno<sup>11</sup>, G. Serra<sup>5</sup>, C. Armand<sup>6</sup>, M. Burgdorf<sup>6</sup>, A. DiGiorgio<sup>6</sup>, S. Molinari<sup>6</sup>, M. Price<sup>6</sup>, D. Texier<sup>6</sup>, S. Sidher<sup>6</sup>, and N. Trams<sup>6</sup>

<sup>1</sup> Laboratoire d'Astronomie Spatiale, LP CNRS, BP 8, F-13376 Marseille Cedex 12, France

<sup>2</sup> Institut d'Astrophysique Spatiale, Bât. 120, Université Paris XI, F-91405 Orsay Cedex, France

<sup>3</sup> CSIC. IEM. Dpto. Fisica Molecular, Serrano 123, E-28006 Madrid, Spain & OAN, Ap 1143, E-28800 A. de Henares, Spain

<sup>4</sup> DAEC, Observatoire de Paris–Meudon, F-92195 Meudon Cedex, France

<sup>5</sup> Centre d'Etude Spatiale des Rayonnements, CESR/CNRS-UPS, BP 4346, F-31028 Toulouse Cedex 04, France

<sup>6</sup> The LWS Instrument Dedicated Team, ISO Science Operations Centre, PO Box 50727, E-28080 Madrid, Spain

<sup>7</sup> Rutherford Appleton Lab., Chilton, Didcot, Oxon OX11 0QX, UK

<sup>8</sup> Queen Mary and Westfield College, University of London, Mile End Road, London E1 4NS, UK

<sup>9</sup> ISO Science Operations Centre, Astrophysics Division of ESA, PO Box 50727, E-28080 Madrid, Spain

<sup>10</sup> Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK

<sup>11</sup> CNR-Instituto di Fisica dello Spazio Interplanetario, Casella Postale 27, I-00044 Frascati, Italy

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**Abstract.** A high signal-to-noise 52–90  $\mu\text{m}$  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  $\mu\text{m}$  line is detected in absorption even at the grating spectral resolution of 0.29  $\mu\text{m}$ . A lower limit for the column density of atomic oxygen of the order of  $10^{19} \text{ cm}^{-2}$  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

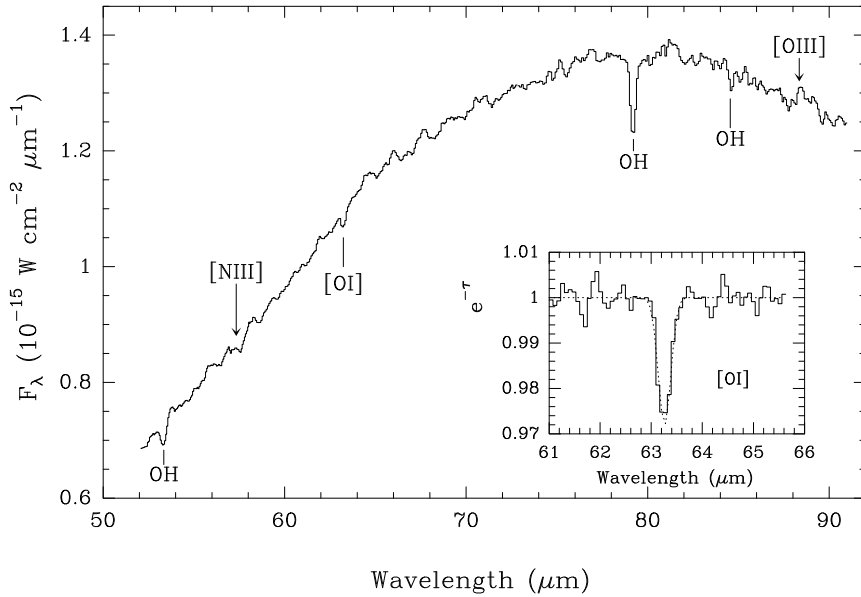
The main form in which oxygen, the third most abundant element in the Universe, is present in the cold component of the interstellar medium remains one of the major unresolved issues

*Send offprint requests to:* J.-P. Baluteau (baluteau@astrsp-mrs.fr)

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of astrochemistry. Oxygen is supposed to reside mostly in the gas phase of molecular clouds, presumably as atomic oxygen or simple molecules, such as  $\text{O}_2$ ,  $\text{CO}$ ,  $\text{H}_2\text{O}$  and  $\text{OH}$ . 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  $\text{CO}_2$  which is found to be ubiquitous in the interstellar medium (de Graauw et al. 1996) or the solid  $\text{O}_2$  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  $\text{O}_2$  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  $\text{O}_2/\text{CO}$  abundance ratio of  $1.4 \cdot 10^{-2}$ , more than an order of magnitude lower than what is predicted by chemical models. Among other O-bearing molecules, the most commonly observed is  $\text{CO}$  which only contains  $\sim 10\%$  of the total oxygen abundance (Lacy et al. 1994). Recent estimates of the gas-phase  $\text{H}_2\text{O}$  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  $\text{OH}$  fractional abundance is even smaller



**Fig. 1.** The LWS grating spectrum of Sgr B2 from 52 to 90  $\mu\text{m}$ . This spectrum was taken at  $\alpha_{1950} = 17^{\text{h}}44^{\text{m}}12.0^{\text{s}}$ ,  $\delta_{1950} = -28^{\circ}22'12''$ . The insert displays the line to continuum ratio around the [O I] 63  $\mu\text{m}$  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  $\mu\text{m}$  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  $\mu\text{m}$  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  $\mu\text{m}$  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  $\mu\text{m}$  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  $\mu\text{m}$  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  $\mu\text{m}$  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  $\mu\text{m}$ , 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  $\mu\text{m}$  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  $\mu\text{m}$  and [N III] 57  $\mu\text{m}$  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  $\mu\text{m}$  line along two cuts oriented N-S and E-W through Sgr B2. The [O I] 63  $\mu\text{m}$  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  $10^{24} \text{ cm}^{-2}$  in the 2' core diameter (Scoville et al. 1975). Sgr B2 is optically thick even at far-infrared wavelengths where the

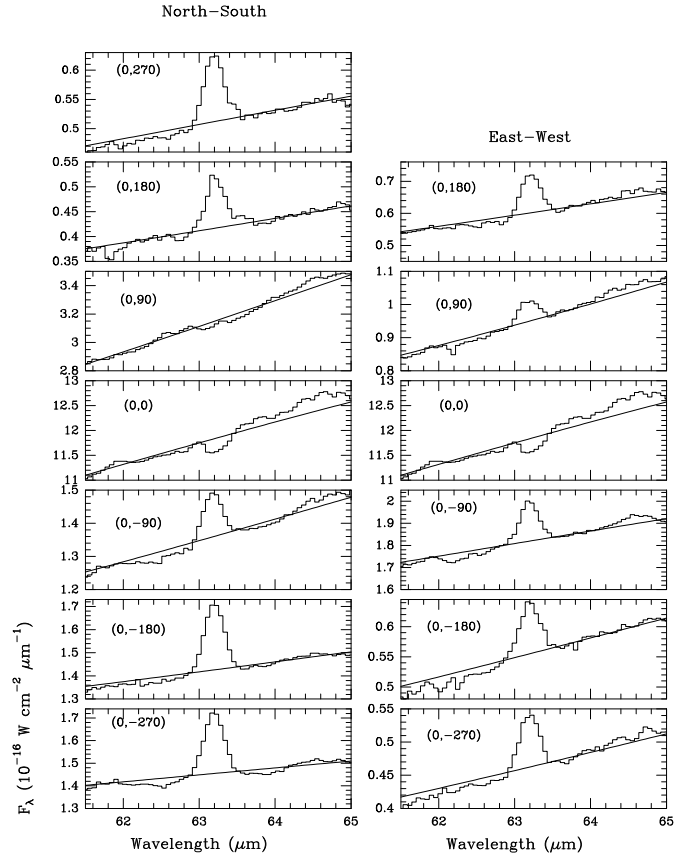
opacity at  $100 \mu\text{m}$  is estimated to be unity (Harvey et al. 1977). In Sgr B2, the warm gas seen, e.g., in the radio observations, is thus obscured completely by the associated molecular cloud. These high far-infrared opacities explain why the [O III]  $88 \mu\text{m}$  (Dain et al. 1978) and [O I]  $63 \mu\text{m}$  (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]  $63 \mu\text{m}$  line is  $\sigma = 5.093 \times 10^{-18} / (\Delta V_{\text{km s}^{-1}}) \text{ cm}^2$  where  $\Delta V$  is the line width in  $\text{km s}^{-1}$  (e.g., Allen 1973 - radiative lifetime from Baluja & Zeppen 1988). At a spectral resolution of  $0.29 \mu\text{m}$  ( $\sim 1380 \text{ km s}^{-1}$ ), the measured  $3.0 \pm 0.5 \%$  absorption-line depth of [O I] corresponds to a line equivalent width  $\Delta V_{\text{ew}} = (41.4 \pm 7) \text{ km s}^{-1}$ . Assuming uniform absorption over a velocity range  $\Delta V$  will result in a line optical depth  $\tau = -\ln(1 - \Delta V_{\text{ew}} / \Delta V)$  and a column density  $N_{\text{O}} = 1.963 \times 10^{17} \times \tau \times \Delta V \text{ cm}^{-2}$ .

In order to estimate the atomic oxygen abundance implied by the [O I]  $63 \mu\text{m}$  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  $1 \text{ cm}^{-3}$ , the hydrogen column density is  $2.5 \times 10^{22} \text{ cm}^{-2}$  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  $+80 \text{ km s}^{-1}$  (Scoville et al. 1975), we will assume that  $\Delta V$  is less than  $\Delta V_{\text{max}} = 200 \text{ km s}^{-1}$ . With  $\Delta V = \Delta V_{\text{max}}$ , we find  $\tau = 0.23$  and  $N_{\text{O}} = 9.1 \times 10^{18} \text{ cm}^{-2}$ , yielding  $N_{\text{O}}/N_{\text{H}} = 3.6 \times 10^{-4}$ . 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  $\tau$  is significantly less than unity, these conclusions do not depend critically on the exact value of  $\Delta V$ ; using  $\Delta V = 100$  instead of  $200 \text{ km s}^{-1}$  would increase  $N_{\text{O}}$  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  $+63 \text{ km s}^{-1}$  with  $N_{\text{H}_2} \sim 5 \times 10^{23} \text{ cm}^{-2}$ , (2) the expanding molecular ring at  $-105 \text{ km s}^{-1}$  with  $N_{\text{H}_2} \sim 4 \times 10^{21} \text{ cm}^{-2}$ , (3) the 3-kpc arm ( $-43 \text{ km s}^{-1}$  and  $N_{\text{H}_2} \sim 3 \times 10^{21} \text{ cm}^{-2}$ ), and (4) the local gas at  $\sim 0 \text{ km s}^{-1}$  with  $N_{\text{H}_2}$  roughly as in the two latter components. The velocity widths of these components, deter-



**Fig. 2.** The spectra around [O I]  $63 \mu\text{m}$  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) -  $\alpha_{1950} = 17^{\text{h}} 44^{\text{m}} 10.6^{\text{s}}$ ,  $\delta_{1950} = -28^{\circ} 22' 29''$ . 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

mined 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  $20 \text{ km s}^{-1}$  for the absorbing layers at  $-105$ ,  $-43$ ,  $+2$  and  $+63 \text{ km s}^{-1}$ , respectively (Scoville et al. 1975). At a  $\sim 15''$  resolution, the widths are 3, 8, and  $12 \text{ km s}^{-1}$  for the last three components (Mehring et al. 1995). The ISO/LWS beam being close to  $1.5'$ , we adopt  $\Delta V_{\text{SgrB2}} = 20 \text{ km s}^{-1}$  for the Sgr B2 cloud and  $\Delta V_{\text{fore}} = 30 \text{ km s}^{-1}$  for the sum of the three main foreground clouds. Altogether, the column density of the three latter clouds is  $N_{\text{H}_2} \sim 1.1 \times 10^{22} \text{ cm}^{-2}$ .

Assuming uniform absorption over the full velocity range  $\Delta V_{\text{molec}} = \Delta V_{\text{SgrB2}} + \Delta V_{\text{fore}}$  leads to  $\tau = 1.76$  and  $N_{\text{O}} = 1.7 \times 10^{19} \text{ cm}^{-2}$ . Considering 30/50 of this  $N_{\text{O}}$ , the atomic oxygen abundance in the foreground clouds is  $N_{\text{O}}/N_{\text{H}} = 4.6 \times 10^{-4}$ . We note, however, that  $\Delta V_{\text{molec}}$  is not very significantly larger than  $\Delta V_{\text{ew}}$ . With the quoted uncertainties,  $N_{\text{O}}/N_{\text{H}}$  is thus estimated to vary from  $3.1$  to  $9.2 \times 10^{-4}$ , to be compared to the cosmic abundance of oxygen  $[\text{O}]/[\text{H}] = 8.5 \times 10^{-4}$  (Anders & Grevesse 1989). In the relatively unlikely case of a complete absorption over  $\Delta V_{\text{SgrB2}}$ ,  $N_{\text{O}}/N_{\text{H}}$  would decrease by 30%. Conversely no solution exists if the absorp-

tion 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,  $\tau$  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  $\mu\text{m}$  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  $\mu\text{m}$  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  $10^{19} \text{ cm}^{-2}$ . 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  $\mu\text{m}$  absorption of the molecular clouds distributed along the line of sight toward SgrB2, higher spectral resolution observations are required.

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