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Searching for O_2 in the SMC:

Constraints on oxygen chemistry at low metallicities[⋆]

C. D. Wilson[1], A. O. H. Olofsson[2], L. Pagani[3], R. S. Booth[2], U. Frisk[4], Å. Hjalmarson[2],
M. Olberg[2], and Aa. Sandqvist[5]

[1] Department of Physics & Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada
e-mail: `wilson@physics.mcmaster.ca`
[2] Onsala Space Observatory, 439 92 Onsala, Sweden
[3] LERMA & UMR 8112 du CNRS, Observatoire de Paris, 61 Av. de l'Observatoire, 75014 Paris, France
[4] Swedish Space Corporation, PO Box 4207, 171 04 Solna, Sweden
[5] Stockholm Observatory, SCFAB-AlbaNova, 106 91 Stockholm, Sweden

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Abstract. We present a 39 h integration with the Odin satellite on the ground-state 118.75 GHz line of O_2 towards the region of strongest molecular emission in the Small Magellanic Cloud. Our 3σ upper limit to the O_2 integrated intensity of <0.049 K km s^{-1} in a 9′ (160 pc) diameter beam corresponds to an upper limit on the O_2/H_2 abundance ratio of $<1.3 \times 10^{-6}$. Although a factor of 20 above the best limit on the O_2 abundance obtained for a Galactic source, our result has interesting implications for understanding oxygen chemistry at sub-solar metal abundances. We compare our abundance limit to a variety of astrochemical models and find that, at low metallicities, the low O_2 abundance is most likely produced by the effects of photo-dissociation on molecular cloud structure. Freeze-out of molecules onto dust grains may also be consistent with the observed abundance limit, although such models have not yet been run at sub-solar initial metallicities.

Key words. galaxies: individual: SMC – ISM: molecules – astrochemistry

1. Introduction

Oxygen chemistry in the interstellar medium is still not well understood. Despite having an abundance that is roughly twice that of carbon, oxygen-bearing species are difficult to observe in the gas phase. Molecular oxygen, originally predicted to be almost as abundant as CO under some conditions (Graedel et al. 1982), remains elusive. Although O_2 is not a significant reservoir of oxygen in the gas phase (Bergin et al. 2000), a detection of O_2 would be very helpful in distinguishing among the many different astrochemical models developed to explain its low abundance (see review in Goldsmith et al. 2000). In this Letter, we present upper limits for the O_2 abundance towards a single line of sight in the Small Magellanic Cloud (SMC) and discuss the implications of our results for astrochemical models of gas at low metallicities.

Molecular oxygen has not yet been detected convincingly in any source in the Milky Way. Goldsmith et al. (2000) report 3σ upper limits on the O_2 abundance from the SWAS satellite of $<2.6 \times 10^{-7}$ in star-forming clouds and $<3 \times 10^{-6}$ in cold dark clouds. Pagani et al. (2003) present improved O_2 upper limits from the Odin satellite, with 3σ upper limits to the O_2 abundance in 11 sources ranging from $<5.2 \times 10^{-8}$ to $<5.7 \times 10^{-7}$. Goldsmith et al. (2002) report a possible detection in the ρ Oph A outflow with $N(O_2)/N(H_2) \sim 10^{-5}$. However, the Odin upper limit over a similar region of the sky is $<9.3 \times 10^{-8}$ (Pagani et al. 2003) and so the SWAS detection must be considered tentative at best.

Extragalactic sources at moderate redshifts have their O_2 lines shifted away from high opacity regions of the Earth's atmosphere. Liszt (1985, 1992) obtained an upper limit to the O_2/CO abundance ratio of 0.1 in four Seyfert galaxies. By searching for O_2 in absorption in a system at $z \sim 0.685$ towards the radio source B0218+357, Combes et al. (1997) obtained a 3σ upper limit to the O_2/CO abundance ratio of 6×10^{-3}. If the CO abundance in this extragalactic source is similar to that in Galactic molecular clouds, the 3σ upper limit to the O_2/H_2 abundance ratio would be 6×10^{-7}. Thus, even the most sensitive extragalactic O_2 searches have now been surpassed by the Galactic results from Odin and SWAS (Goldsmith et al. 2000; Pagani et al. 2003).

There have been no previous searches for O_2 emission from objects with low intrinsic metal abundance. Frayer & Brown (1997) present a set of astrochemical evolution models aimed

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[⋆] Based on observations with Odin, a Swedish-led satellite project funded jointly by the Swedish National Space Board (SNSB), the Canadian Space Agency (CSA), the National Technology Agency of Finland (Tekes), and Centre National d'Etudes Spatiales (CNES). The Swedish Space Corporation was the industrial prime contractor and is also responsible for the satellite operation.

at predicting the abundances of key molecular species, including O_2, in high-redshift galaxies. Their results suggest that the molecular oxygen abundance is enhanced when the metallicity is reduced by even a factor of a few relative to the solar abundance. These results motivated us to search for O_2 emission towards the Small Magellanic Cloud (SMC), which has an oxygen abundance $12 + \log(\mathrm{O/H}) = 7.96$ (Vermeij & van der Hulst 2002) or 0.16 times the abundance of Orion (Peimbert et al. 1993). At a distance of 60 kpc (Harries et al. 2003) previous CO observations (Rubio et al. 1991) suggest that molecular emission should fill a substantial fraction of the large Odin beam (9′ at 119 GHz), which makes the SMC the ideal target to search for O_2 emission from low-metallicity gas.

2. Observations and analysis

We observed the position SW-1 in the SMC (Rubio et al. 1991) with Odin for 158 orbits (39.2 h on-source) between 2004 May 13 and 2004 June 2. The beam diameter of Odin's 1.1 m telescope is 9′ at the 118.750 GHz frequency of the O_2 $1_1{-}1_0$ line with a main beam efficiency of 0.9 (Frisk et al. 2003). The observations were made in position-switch mode with the off position at (+30′, 0). The pointing is estimated to be accurate to 15″. The typical single sideband system temperature of the O_2 HEMT receiver (Frisk et al. 2003) during this period was $T_{\mathrm{sys}} \sim 950$ K. The O_2 receiver was not phase-locked during these observations, so the true frequency was recovered using telluric lines observed when the Odin beam passed through the Earth's atmosphere at the beginning and end of each orbit (see Larsson et al. 2003 for a detailed description of the method applied to the NH_3 line). Satellite tests indicate a frequency stability of better than 1 MHz ($2.6\ \mathrm{km\,s^{-1}}$). The backend was an autocorrelator with a spectral resolution of 125 kHz ($0.316\ \mathrm{km\,s^{-1}}$) and 700 channels for a total bandwidth of 87 MHz ($220\ \mathrm{km\,s^{-1}}$).

The spectrum was fit with a 5th order polynomial baseline over the velocity range -35 to $155\ \mathrm{km\,s^{-1}}$. A window of $20\ \mathrm{km\,s^{-1}}$ centered on $V_{\mathrm{LSR}} = 120\ \mathrm{km\,s^{-1}}$, the observed velocity of the CO $J = 1{-}0$ line (Rubio et al. 1991), was excluded from the fit. No O_2 line is detected in the final spectrum (Fig. 1), which has an rms noise of 7.3 mK (T_A^*) per spectral channel. Using the formula from Pagani et al. (2003) with the CO line width of $15.9\ \mathrm{km\,s^{-1}}$ observed in an 8.8′ beam (Rubio et al. 1991), the 3σ upper limit to the O_2 integrated intensity is $<0.049\ \mathrm{K\,km\,s^{-1}}$.

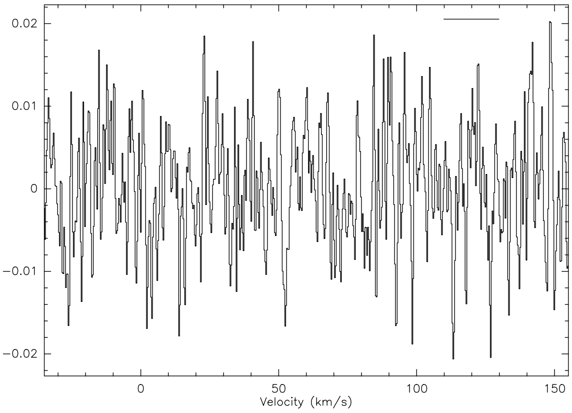

Fig. 1. O_2 spectrum towards the position SW-1 (00:46:30.08, −73:21:07.5, J2000) in the SMC. The units of the vertical axis are K (T_A^*) and the expected velocity of the undetected O_2 line is indicated by the horizontal bar in the upper right corner.

3. An upper limit to the O_2/CO abundance ratio

We need an estimate of the kinetic temperature to convert the O_2 integrated intensity into an O_2 column density, $N(O_2)$ (see Pagani et al. 2003 and references therein). The Odin O_2 beam contains a weak IRAS source (Rubio et al. 1993) and also a 170 μm source seen by the Infrared Space Observatory (Wilke et al. 2003). The 60 to 170 μm spectral energy distribution (SED) of this source (n_5#11) is more peaked towards longer wavelengths than is the average SED for the SMC, which Wilke et al. (2004) fit with three modified blackbodies of temperature 45 K, 20.5 K, and 10 K. Thus, a kinetic temperature of 10–20 K is probably most appropriate for the region observed by Odin. A kinetic temperature of $T = 20$ K gives $N(O_2) < 2.2 \times 10^{15}\ \mathrm{cm^{-2}}$, while a temperature of 10 K gives $N(O_2) < 1.9 \times 10^{15}\ \mathrm{cm^{-2}}$. We therefore adopt a value $N(O_2) < 2.0 \times 10^{15}\ \mathrm{cm^{-2}}$ as the 3σ upper limit to the O_2 column density in our further analysis.

At the position SMC-SW1, the CO $J = 1{-}0$ integrated intensity in an 8.8′ beam is $\sim 1\ \mathrm{K\,km\,s^{-1}}$ (Rubio et al. 1991). Adopting a CO-to-H_2 conversion factor of $1.5 \times 10^{21}\ \mathrm{cm^{-2}}\ (\mathrm{K\ km\,s^{-1}})^{-1}$ to account for the lower metallicity of the SMC (Wilson 1995) gives an H_2 column density $N(H_2) = 1.5 \times 10^{21}\ \mathrm{cm^{-2}}$. In the nearby region LIRS36, Chin et al. (1998) measured a CO abundance of 1×10^{-5}. Applying this CO abundance to the broader SMC-SW1 region gives a CO column density $N(\mathrm{CO}) = 1.5 \times 10^{16}\ \mathrm{cm^{-2}}$. We can also estimate $N(CO)$ directly from the CO integrated intensity. Adopting the $[^{12}\mathrm{CO}]/[^{13}\mathrm{CO}]$ abundance ratio measured in the solar neighborhood (∼60, Langer & Penzias 1993) and a $^{12}\mathrm{CO}/^{13}\mathrm{CO}$ intensity ratio of ∼12 (Rubio et al. 1996) gives a ^{12}CO optical depth of ∼5. Using the formula from White & Sandell (1995) and adopting an excitation temperature of 20 K gives a CO column density of $5.3 \times 10^{15}\ \mathrm{cm^{-2}}$, roughly a factor of three smaller than that derived via the CO-to-H_2 conversion factor. For the rest of this paper, we adopt the H_2 and CO column densities derived via the CO-to-H_2 conversion factor, which correspond to 3σ upper limits to the O_2/H_2 abundance of $<1.3 \times 10^{-6}$ and the O_2/CO abundance of <0.13, both averaged over a 150 pc diameter beam.

4. Implications for understanding oxygen chemistry

For comparison with chemical models, it is useful to know the gas-phase abundances of O and C in the SMC. Dufour et al. (1988) derive a value of $12 + \log(\mathrm{C/H}) = 7.16$ in HII regions in the SMC. Combining this with the O abundance from Vermeij & van der Hulst (2002) and in the absence of any differential depletion of oxygen relative to carbon onto dust grains, the SMC should have a ratio C/O = 0.16. This value is significantly smaller than the C/O abundance ratio of 0.4 that is commonly assumed as the initial gas-phase abundance in astrochemical models.

4.1. Comparison with pure gas-phase models

Goldsmith et al. (2000) review the key processes and issues involved in oxygen chemistry at Galactic metallicities. Steady-state, pure gas-phase models predict O_2 abundances of $5-10 \times 10^{-6}$, much higher than the current observational limits (Pagani et al. 2003). One way to decrease the gas phase abundance of O_2 is to increase the gas phase C/O ratio to near unity via some kind of preferential depletion of O onto dust grains, presumably in the form of H_2O and other ices. Bergin et al. (2000) discuss results for pure gas-phase models with C/O abundances ranging from 0.4 to 1. To fit the observed low O_2 abundances, either the gas phase C/O ratio must be close to 1, or the gas must be "chemically young", i.e., have spent at most 10^5 yr in a high A_v environment. This apparent youthfulness can be produced by processes such as turbulent mixing of shielded and unshielded regions (i.e. Chièze & Pineau des Forêts 1989), which can reduce the O_2 abundance by factors of 100−1000 compared to the steady state results.

The SMC has a C/O ratio of 0.16, much lower than the initial Galactic ratio of 0.4. For the Bergin et al. (2000) gas-phase model to be consistent with our new limit for the O_2 abundance in the SMC, either oxygen must be preferentially depleted even more strongly (by a factor of five relative to the undepleted C/O ratio), or the gas in the SMC must be *both* "chemically young" *and* suffer preferential oxygen depletion by a factor of ~2.5. Both these scenarios seem unlikely, especially since there is still not a good justification of why oxygen should be preferentially depleted from the gas phase relative to carbon (Roberts & Herbst 2002).

Viti et al. (2001) discuss steady-state solutions of gas-phase chemical models involving bi-stability solutions. In general, if the gas ends up in the high ionization phase, then the O_2 abundances are low and consistent with current upper limits. In the low ionization phase, the O_2 abundance is too high to be consistent with current upper limits. The bistability region occurs for $0.49 < C/O < 0.66$, with the high ionization phase being the sole solution for larger values of C/O. In addition, as the C/O ratio decreases, the bi-stability region occurs at lower densities. Thus, if the clouds in the SMC have relatively low densities ($n_{H_2} < 1000$ cm^{-3} or lower), the gas could be in a steady-state high ionization phase that meets our limits on the O_2 abundance.

Spaans & van Dishoeck (2001) have run chemical models of clumpy clouds where the deeper penetration of the UV field affects the chemistry and find O_2 abundances below 10^{-7} for $n_{H_2} \sim 10^3$ cm^{-3}. If the gas-phase abundance of oxygen is depleted by a factor of two, the O_2 abundance in their models drops by a further factor of 20. However, these models have been run only for solar C/O values.

4.2. Comparison with models including dust grains

Astrochemical models that include the effects of dust grains appear promising for explaining the observed low abundance of O_2. Roberts & Herbst (2002) use recent laboratory results for the mobility of H on grains to model regions with $T = 10-20$ K and $n_{H_2} = 10^4-10^5$ cm^{-3}. All their models are consistent with the SMC limits for O_2 abundance at a wide range of evolutionary times. However, it is important to note that their models have difficulty producing the low Odin limit on O_2 in L134N (Pagani et al. 2003).

Viti et al. (2001) present a grid of models that include the effects of freeze-out of molecules onto grains. These models are generally consistent with our SMC upper limits, whether general freeze-out or selective freeze-out (with CO and N_2 desorbing from the grains) is used. However, these models use an initial C/O ratio of 0.5, which, for the SMC, corresponds to preferential oxygen depletion by a factor of 3. Viti et al. (2001) claim that the selective freeze-out models give a chemistry similar to what would be obtained with a C/O abundance ratio ~1, although whether that interpretation is true regardless of the initial gas-phase C/O ratio is not addressed in the paper.

4.3. Comparison with extragalactic chemical models

Frayer & Brown (1997) combine galactic chemical evolution models with gas-phase astrochemical models to predict the abundance of O_2 relative to CO averaged over an entire galaxy as a function of time and metallicity. Their models cover a wide range of average metallicity, use pure gas-phase astrochemistry, and consider both steady-state and "early-time" solutions from a variety of models. They also consider selective depletion of oxygen in the gas phase by a factor of two, but this does not have a large impact on the O_2/CO ratio at low metallicities. Interestingly, at the O/C ratio of the SMC (6.3), there is no significant difference in the predicted abundance ratio of O_2/CO at early times compared to steady state. Both sets of models predict O_2/CO ratios of 2−3, significantly larger than our new observational limit of $O_2/CO < 0.13$. Thus, even early-time gas-phase models appear to have difficulty matching our observations of the SMC.

Frayer & Brown (1997) also consider the effects of photo-dissociation in low metallicity gas. O_2 has a higher photo-dissociation rate than CO (van Dishoeck 1988) and so will have a smaller spatial extent inside a molecular cloud. For Galactic metallicities and UV fields, Frayer & Brown (1997) estimate that CO will be self-shielding where $A_v > 1.5$ mag and O_2 only where $A_v > 5$ mag. At lower extinctions, the abundances of CO and O_2 depend on edge effects in the molecular cloud and are strongly non-linear with extinction (see Frayer & Brown 1997, for details). If the dust-to-gas ratio scales roughly linearly with metallicity (Gordon et al. 2003), a molecular cloud in a low-metallicity galaxy may not be self-shielding in O_2 even in its center and may just barely achieve strong self-shielding for CO. These effects produce a much lower abundance of CO and especially O_2 compared to H_2 in low metallicity gas. Specifically, for the metallicity of the SMC, photo-dissociation reduces the O_2/CO ratio to a value of ~0.05. Thus, gas-phase astrochemical models which include the effects of photo-dissociation at low metallicities appear to be consistent with our new observational limit.

5. Conclusions

A very deep (39 h) integration on the ground state line of O_2 with the Odin satellite has failed to detect any O_2 emission towards the region SW1 in the SMC. Our 3σ upper limit on the O_2 integrated intensity of $0.049\ \mathrm{K\,km\,s^{-1}}$ translates into an upper limit on the O_2 column density of $N(O_2) < 2.0\times10^{15}\ \mathrm{cm^{-2}}$. We have combined this measurement with published CO $J = 1-0$ data for the same region to place a limit on the molecular oxygen abundance $O_2/H_2 < 1.3\times10^{-6}$ and on the O_2/CO abundance ratio of <0.13. Although the O_2 abundance limit is substantially higher than the best limit set for a Galactic source ($<5\times10^{-8}$, Pagani et al. 2003), it is still an interesting probe of astrochemistry in low metallicity gas.

In contrast to the Galaxy, "chemically young" models appear to be ruled out for the SMC (Frayer & Brown 1997). Gas-phase models where the oxygen has been preferentially depleted from the gas phase compared to carbon do agree with our upper limit for the O_2 abundance. However, the depletion required for the SMC is a factor of two larger than that required to account for O_2 limits in the Galaxy (Bergin et al. 2000), and there is as yet no generally accepted mechanism to produce such a depletion (Roberts & Herbst 2002).

Astrochemical models which include the effects of photo-dissociation produce an O_2/CO ratio of ~0.05 (Frayer & Brown 1997) and are consistent with our 3σ upper limit. Models that include the effects of dust grains also may be consistent with our observed upper limit, although these models (Viti et al. 2001; Roberts & Herbst 2002) have not yet been run for reduced metallicity gas. If low-metallicity models that included dust grains were to fail to produce sufficiently low O_2 abundances, then the leading explanation for the low O_2 abundance in low metallicity gas would be the effect of photo-dissociation on the structure of the molecular clouds (Frayer & Brown 1997). This could stimulate renewed attention to the effect of clumpy cloud structures and photo-dissociation (i.e. Spaans & van Dishoeck 2001) in understanding the abundance of O_2 in Galactic sources.

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References

Bergin, E. A., Melnick, G. J., Stauffer, J. R., et al. 2000, ApJ, 539, L129

Chièze, J.-P., & Pineau des Forêts, G. 1989, A&A, 221, 89

Chin, Y.-N., Henkel, C., Millar, T. J., Whiteoak, J. B., & Marx-Zimmer, M. 1998, A&A, 330, 901

Combes, F., Wiklind, T., & Kanai, N. 1997, A&A, 327, L17

Dufour, R. J., Garnett, D. R., & Shields, G. A. 1988, ApJ, 332, 752

Frayer, D. T., & Brown, R. L. 1997, ApJS, 113, 221

Frisk, U., Hagström, M., Ala-Laurinaho, J., et al. 2003, A&A, 402, L27

Goldsmith, P. F., Melnick, G. J., Bergin, E. A., et al. 2000, ApJ, 539, L123

Goldsmith, P. F., Li, D., Bergin, E. A., et al. 2002, ApJ, 576, 814

Gordon, K. D., Clayton, G. C., Misselt, K. A., Landolt, A., & Wolff, M. J. 2003, ApJ, 594, 279

Graedel, T. E., Langer, W. D., & Frerking, M. A. 1982, ApJ, 48, 321

Harries, T. J., Hilditch, R. W., & Howarth, I. D. 2003, MNRAS, 339, 157

Langer, W. D., & Penzias, A. A. 1993, ApJ, 408, 539

Larsson, B., Liseau, R., Bergman, P., et al. 2003, A&A, 402, L69

Liszt, H. S. 1985, ApJ, 298, 281

Liszt, H. S. 1992, ApJ, 386, 139

Pagani, L., Olofsson, A. O. H., Bergman, P., et al. 2003, A&A, 402, L77

Peimbert, M., Storey, P. J., & Torres-Peimbert, S. 1993, ApJ, 414, 626

Roberts, H., & Herbst, E. 2002, A&A, 395, 233

Rubio, M., Garay, G., Montain, J., & Thaddeus, P. 1991, ApJ, 368, 173

Rubio, M., Lequeux, J., & Boulanger, F. 1993, A&A, 271, 9

Rubio, M., Lequeux, J., Boulanger, F., et al. 1996, A&AS, 118, 263

Spaans, M., & van Dishoeck, E. F. 2001, ApJ, 548, L217

van Dishoeck, E. F. 1988, in Rate Coefficients in Astrochemistry, ed. T. J. Millar, & D. A. Williams (Dordrecht: Kluwer), 49

Vermeij, R., & van der Hulst, J. M. 2002, A&A, 391, 1081

Viti, S., Roueff, E., Hartquist, T. W., Pineau des Forêts, G., & Williams, D. A. 2001, A&A, 370, 557

White, G. J., & Sandell, G. 1995, A&A, 299, 179

Wilke, K., Stickel, M., Haas, M., et al. 2003, A&A, 401, 873

Wilke, K., Klaas, U., Lemke, D., et al. 2004, A&A, 414, 69

Wilson, C. D. 1995, ApJ, 448, L97