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LETTER

Letter to the Editor

Low interstellar abundance of O_2 confirmed by the PIROG 8 balloon experiment

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Abstract. Using a balloon-borne 60 cm telescope equipped with an SIS receiver we have searched for the 425 GHz molecular oxygen line in the NGC7538 and the W51 regions. The experiment was technically successful (confirmed by the detection of the ^{13}CO (4–3) line at 440 GHz), but we failed to detect emission from molecular oxygen. The inferred upper limits of the O_2/CO ratio are 0.04 and 0.05 ($3\,\sigma$) for the two regions, which are the lowest upper limits so far determined for Galactic clouds.

Key words: interstellar medium: abundances – interstellar medium: clouds – interstellar medium: molecules – interstellar medium: individual objects: NGC7538, W51 – radio lines: interstellar medium

1. Introduction

Our understanding of the chemistry prevailing in molecular clouds is closely connected to the distribution of a few oxygen-bearing constituents: CO, CO_2, OH, H_2O, O and O_2. The observational progress has, however, been slow because of obvious reasons: the large amount of O_2, CO_2 and H_2O in the telluric atmosphere effectively blocks the line emission from cosmic sources. In addition, the fine-structure lines of atomic oxygen and the (non-masing) transitions of OH appear in the far infrared region which is inaccessible from the ground. As regards O_2, two ways have been used to get around this problem. The first method can be applied to Galactic clouds with moderate radial velocities, namely to observe the rare isotopomer $^{18}O^{16}O$. Thus, Maréchal et al. (1997a) have put an enormous effort (in total 1200 effective observing hours) to search for the (2,1–0,1) transition at 234 GHz. They derived an upper limit for the O_2/CO abundance ratio of 0.1 ($3\,\sigma$) for three dense regions – which should be compared to the expected value 0.2–0.4 (for regions well protected to UV radiation, see Maréchal et al. 1997b). The second method takes advantage of the rare case of a molecular cloud in a high redshift galaxy along the line of sight to a background quasar. A surprisingly low upper limit, $O_2/CO > 0.006$ ($3\,\sigma$), was derived by Combes et al. (1997) for a cloud at z = 0.685. This result is quite remarkable, but it should be noted that nothing is known about the structure of the cloud or the external UV field. In any case, the evidence so far points towards much lower abundance of molecular oxygen than the chemical schemes predict. In this letter we describe the first in a series of attempts (see Maréchal et al. 1997b) to measure O_2 from the upper atmosphere and from space: the PIROG 8 experiment focused on the (3,2–1,2) transition of O_2 at 425 GHz.

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2. Observations

The PIROG (Pointed Infra-Red Observation Gondola) project started 15 years ago and the present gondola represents a third generation in this development. The system is designed for day-time operation and the azimuth stability is based on a sun sensor and gas-jet system. PIROG 1–6 carried a 30 cm telescope equipped with a helium cooled Fabry-Perot spectrometer tuned for the C^+ line at 158 μm (Nordh & Olofsson 1990) and PIROG 7 carried a 60 cm telescope with a heterodyne receiver for the 557 GHz H_2O line (Tauber et al. 1996).

For the PIROG 8 experiment the 60 cm telescope was kept and a new SIS receiver was developed for observations of the 425 GHz O_2 line (Febvre et al., 1996). The receiver was combined with a 400 channel auto-correlator with selectable resolution in the range 0.05–0.8 MHz.. The receiver noise as measured before the flight was 270 K (double side-band). PIROG 8 was launched from the CNES balloon-base in southern France on Sept. 25, 1997. The duration of the flight at float altitude (39.5 km) was 8 hours. The main target was the giant molecular cloud associated with NGC7538 (hereafter we refer to the cloud as NGC7538). This source was selected because of its high column density and favorable geocentric radial velocity ($\approx -80\,\mathrm{km\,s^{-1}}$ in September), which means that the atmospheric O_2 line opacity is just a few per cent. After stabilisation at altitude and the initial alignment tests our strategy was to peak up on NGC7538 with the receiver tuned on the ^{13}CO (4–3) 440 GHz line (in the image sideband to that of the 425 GHz O_2 line). To gain time we used frequency switching but unfortunately a telluric ozone line resulted in poor base-line cancellation and in order to improve this we turned to position switching. This mode was inefficient and we could only confirm that the source was brighter at the nominal position than at two adjacent positions (half-beam, i.e. 2.′5 away). Thus a slight uncertainty remains on the exact pointing, but – as discussed below – a possible pointing error will be included in the source coupling efficiency factor. The O_2 425 GHz line was then observed for about two hours in the position switching mode and altogether useful data were collected for 15 min on the source and the same time on the reference position.

The receiver noise at altitude, as determined by inserting loads into the beam, was found to be T_{rec} = 240 K (DSB). The sideband gain ratio was estimated to be unity by observing an ozone line in each sideband and comparing to atmospheric modeling (for further details of the atmospheric observations, see Pardo et al. 1998). In order to interpret the O_2 observation we must estimate the beam efficiency. By scanning across the moon and comparing the observed total power to that of a model for the phase of 24 days (based on measurements by Low & Davidson 1965), we could confirm the beam size, the alignment of the telescope and calculate the beam efficiency. It was lower than expected, 0.42, and as the angular size of the moon is much larger than the PIROG beam, this number essentially represents just the forward scattering and spill-over efficiency. This means that the main beam efficiency is still lower, which remains unexplained. Jupiter, the only planet which is bright enough for a calibration given our small telescope, was not observable and we could not measure the small source beam efficiency. Instead we used observations of a $5' \times 5'$ region in the centre of NGC7538 from the ground with the Caltech Submillimeter Observatory, CSO (kindly provided by J. Keene), in the ^{13}CO (4–3) line and convolved that map with the PIROG beam. The CSO map was not quite large enough to fully cover the PIROG beam, but by comparing with a larger map in ^{13}CO (3–2) by Röhrig (1996) we estimate that the region outside the CSO map would contribute ≈20% to the PIROG ^{13}CO (4–3) line. We apply this correction and find that the expected brightness temperature of the ^{13}CO (4–3) line, measured with the PIROG beam should be 3.6 K and as we measured an antenna temperature of just 0.54 K, this means that the beam efficiency of PIROG on this source is as low as 0.15. Consequently the source coupling efficiency is 0.15/0.42 = 0.36 which is lower than expected and as discussed above, a pointing error may contribute to this low value. We note that, regardless of the reason for this low efficiency, the O_2 line observation suffers from the same low efficiency and no additional uncertainty is introduced. In Fig. 1 the CSO map of the ^{13}CO (4–3) line convolved with the PIROG beam is compared to the PIROG observations assuming a system temperature of $2\times240/0.15$ = 3200 K. We note that the line profiles agree quite well, which gives confidence to the experiment.

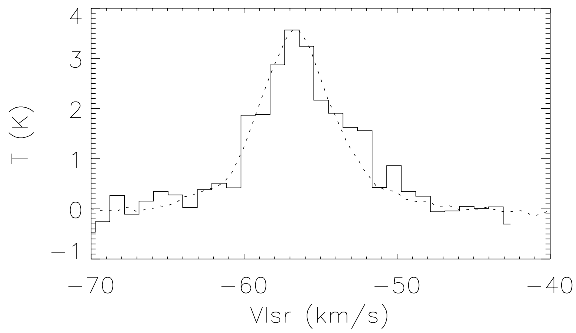

Fig. 1. The brightness temperature of the ^{13}CO (4–3) line of NGC7538 as observed with PIROG 8 scaled to agree with the expected line constructed from CSO observations (dotted line). The same scaling factor (6.7, equivalent to a beam efficiency of 0.15) between brightness temperature and antenna temperature was used for the O_2 observation.

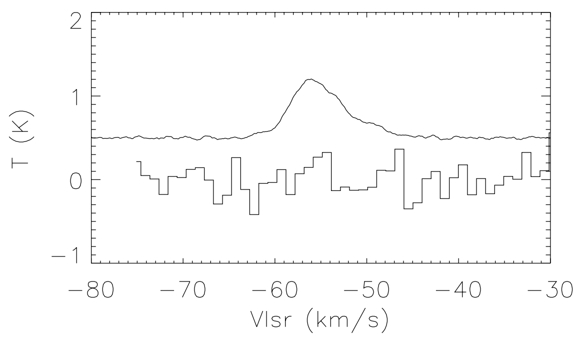

Fig. 2. The PIROG 8 observation of NGC7538 in the region of the O_2 425 GHz line (lower curve) compared to the $C^{18}O$ (1–0) line (shifted by 0.5 K) as it would be if observed with the PIROG beam (constructed from the Onsala map). No O_2 line is detected.

In order to connect our O_2 observations to the CO abundance, we used observations of the $C^{18}O$ (1–0) line with the Onsala 20 m telescope (kindly provided by A. Nilsson) and from a $8' \times 9'$ map we derived the PIROG beam weighted spectrum. The result is shown in Fig. 2 together with the PIROG spectrum of the region of the O_2 425 GHz line, for which we have assumed a system temperature of 3200K. We find that the integrated brightness of the C^{18} O line is $4.6\,\mathrm{K\,km\,s^{-1}}$ and if we assume the same line profile for the non-detected O_2 line we can estimate a $3\,\sigma$ upper limit of $1.5\,\mathrm{K\,km\,s^{-1}}$.

By the end of the flight we turned to the W51 region, but due to telemetry drop-outs, we could only secure a limited data set. In this case we were, however, able to observe in the frequency switching mode which almost compensated for the short (5 min)

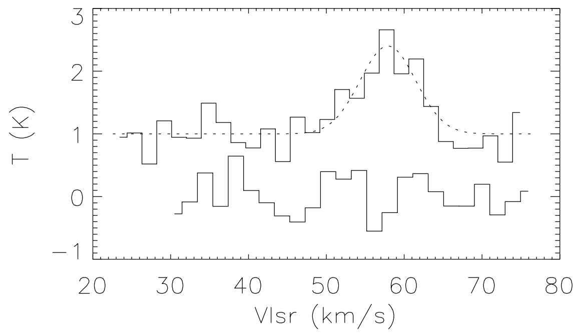

Fig. 3. The brightness temperature of the ^{13}CO (4–3) line of W51 as observed with PIROG 8 (upper curve – for display reasons it has been divided by 5 and shifted 1 K). The dotted curve represents a Gaussian fit to the line and the peak position (58 km s^{-1}) corresponds to the main cloud component. The lower curve represents the region of the O_2 425 GHz line, which is not detected. The resolution has been degraded to 2 km s^{-1}.

useful integration time spent on O_2. In Fig. 3 we show the region of the O_2 425 GHz line and the detected ^{13}CO (4–3) line. We have assumed the same (low) beam efficiency as that derived for NGC 7538 and compensated for the attenuation of the telluric atmosphere (the wing of the O_2 425 GHz line).

3. Discussion and conclusions

We first consider the NGC 7538 case for which we have more data. If we assume that both the C^{18}O (1–0) and the O_2 (3,2–1,2) lines are optically thin and formed in LTE, we get the following relation

$$\frac{X(O_2)}{X(CO)} = \frac{X_u(C^{18}O)}{X_u(O_2)} \frac{X(C^{18}O)}{X(CO)} \frac{A(1-0)}{A(3,2-1,2)} \left(\frac{\nu_{O_2}}{\nu_{C^{18}O}}\right)^2 \frac{\int T(O_2)dv}{\int T(C^{18}O)dv} \quad (1)$$

where X denotes the relative abundance, X_u the relative abundance for the upper level of the transition, A the Einstein coefficient, and the other symbols have their usual meanings.

In order to calculate the relative numbers of molecules in the upper states we need a representative excitation temperature for the bulk of the cloud. Mitchell et al. (1990) find that the ^{13}CO absorption lines of the fundamental vibrational band observed towards two infrared sources in NGC7538 could be explained in terms of a hot and a cold component, where the cold component for each the sources is well represented by a single temperature of about 25 K. The angular distance between the two sources is 2$'\!$.1 and the column densities of the cold gas are (within the uncertainties) the same and thus it seems that this cold component well represents the 'bulk' of the cloud.

The C^{18}O/CO abundance ratio can be influenced by the different self-shielding to UV dissociation, but in this case most of the cold gas is efficiently shielded by dust, and we only need to consider the ^{18}O/^{16}O ratio. This ratio has a clear dependence on the distance to the galactic centre (Wilson & Rood 1994) decreasing from 1/250 at the Galactic centre to 1/600 at R$_{GC}$ = 9 kpc. There are indications that the corresponding trends for ^{12}C/^{13}C (Wouterloot & Brand 1996) and e.g. N/O (Rudolph et al. 1997) continues far beyond the solar circle. For NGC7538 the distance is uncertain; using the radial velocity from our C^{18}O observations (v$_{lsr}$ $= -56$ km s^{-1}) and the rotation curve derived by Brand & Blitz (1993) the kinematic distance becomes 5.6 kpc. The photometric distance to the brightest exciting star of the adjacent H II region was estimated to 2.8 kpc by Crapton et al. (1978). There are uncertainties involved in both methods, but if we adopt the photometric distance we must accept that this giant molecular cloud has a very large deviation from circular motion. In a recent investigation based on Cepheids (which should well represent the young disk population), Pont et al. (1997) show that these tracers follow circular motions quite well. We here adopt the kinematic distance, 5.6 kpc, which means that the GC distance is 11.8 kpc. If the $\frac{^{18}O}{^{16}O}(R_{GC})$ trend is extrapolated to this GC distance we get 1/730.

Numerically we now get

$$\frac{X(O_2)}{X(CO)} < \frac{0.25}{0.11} \frac{6.22 * 10^{-8}}{2.4 * 10^{-8}} \frac{1}{730} \left(\frac{424.8}{109.8}\right)^2 \frac{1.5}{4.6} = 0.039$$

as a 3 σ upper limit. We realise that there may in addition be systematic errors due to the simplified analysis. It may, for instance, not be true that the C^{18}O (1–0) line is optically thin in the densest parts. To check this we can compare the column density derived by Mitchell et al. (1990), using NIR ^{13}CO absorption lines towards IRS 1 to the column density derived for that position from the Onsala C^{18}O observation. Assuming an abundance ratio ^{13}CO/C^{18}O=7.6 which should be appropriate for R$_{GC}$ = 11.8 kpc (Wilson & Rood 1994) we predict a column density towards IRS 1 of N(^{13}CO)=1.4 10^{17} cm^{-2}, which is in perfect agreement with the 1.5 10^{17} cm^{-2} found by Mitchell et al. (1990) – if IRS 1 resides on the rear side of the cloud. It thus seems as if the C^{18}O line is essentially optically thin (and if not quite true, the limit derived above would be still lower). It can also be questioned if the LTE assumption is valid for the level population of O_2, but assuming that the cloud has about the same extent in the line of sight as the projected size, the average number density is n(H_2) $\approx$1 10^4 cm^{-3} which means that the lower O_2 energy levels have a thermal distribution (Maréchal et al. 1997b). One may also question the adopted ^{18}O/^{16}O ratio of 730 – if we instead use the terrestial value of 500, this would result in a correspondingly higher upper limit for the O_2/CO ratio. In addition to these systematic uncertainties we should also add the usual uncertainties involved in the ground-based observations, in particular the beam coupling efficiencies (we assumed 0.65 for the CSO and 0.55 for the Onsala observations). There are consequently many possible systematic errors and even if each of those probably is modest, a 'worst case' combination could amount to as much as a factor two increase of the derived limit.

For the W51 region we lack ground-based ^{13}CO (4–3) data, which means that we cannot independently check the source coupling efficiency. In addition, we have only access to a 4$'\times$4$'$ C^{18}O (1–0) Onsala map (A. Nilsson, private communication), and it is consequently hard to estimate the signal in a 5$'$ beam.

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Ohishi (1984), who extensively mapped the region in a 6′ beam, noticed that two massive clouds overlap and that the 59 $\mathrm{km\,s^{-1}}$ component dominates. He estimated the total column density of ^{13}CO to $3\,10^{17}$ $\mathrm{cm^{-2}}$. He had to compensate for a relatively high optical depth which of course gives an unreliable result, in particular as the spatial variations within his wide beam are large (which our Onsala map clearly shows). However, it turns out that the average column density of $C^{18}O$ over the Onsala map, $3.6\,10^{16}$ $\mathrm{cm^{-2}}$ (assuming T_{kin} = 30K, TE and optically thin emission), is in good agreement with Ohishi's estimate; if we use a $^{12}CO/^{13}CO$ ratio of 45 (Langer & Penzias 1990) and a $C^{16}O/C^{18}O$ ratio of 480 (Wilson & Rood 1994) we get a ^{13}CO column density of $3.8\,10^{17}$ $\mathrm{cm^{-2}}$. We only detect the dominant 58 $\mathrm{km\,s^{-1}}$ velocity component in the ^{13}CO (4–3) transition (see Fig. 3) and if we assume that the O_2 line would have the same profile we estimate a $3\,\sigma$ upper limit of 3.5 $\mathrm{K\,km\,s^{-1}}$. Combined with the column density for this component, N(^{13}CO) = $2.5\,10^{17}$ $\mathrm{cm^{-2}}$ (Ohishi 1984), we arrive at an upper limit ($3\,\sigma$) of 0.045 for the O_2/CO abundance ratio.

The reason for this low abundance of O_2 remains unclear; Maréchal et al. (1997b) showed that a gas phase C/O $>$ 0.7 could be one explanation and other models involving a high ionization degree (Le Bourlot et al. 1995) or a higher C^+ abundance in the dense parts of the clouds (Pineau des Forêts et al.1992) yield equally low O_2 abundances which can explain our upper limits. But before any real theoretical progress can be made, more sensitive experiments are required. The ODIN experiment (Nordh 1997) has the potential for a break-through in this respect; in fact, with the presently expected sensitivity for that experiment the detection limit (for realistic integration times) should be a factor 30 better.

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