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THE BEHAVIOUR OF THE [O I] 63 μm and [O I] 145 μm LINES IN THE ρ OPHIUCHI CLOUD

R. Liseau[1], **G.J. White**[2] **& B. Larsson**[1]

[1]Stockholm Observatory, Saltsjöbaden, Sweden
[2]Queen Mary & Westfield College, Dept. of Physics, London, UK

ABSTRACT

The dense cores B 1, B 2 and C North in the active star forming ρ Oph cloud have been observed with the ISO LWS (λ = 43–197 μm, $R = 140 - 330$). Detailed modelling of the FIR spectra shows that the emission originates in a PDR on the rear side of the cloud. However, the behaviour of the O I ground state lines ([O I] 63 μm, [O I] 145 μm) appears anomalous in the sense that observed flux ratios are too small compared to those predicted by theoretical models of O I excitation and line transfer. Based on the LWS data, we argue that self absorption in the [O I] 63 μm line by cool foreground material is not a viable explanation in the case of ρ Ophiuchi: the expected reduction in [O I] 63 μm flux towards the dense cores is not reflected by the data. In contrast, the [C II] 158 μm and [O I] 63 μm lines behave in accordance with model predictions. It seems likely, therefore, that it is not the [O I] 63 μm line being too weak, but that the [O I] 145 μm line is relatively too strong and we propose that slight masing in the [O I] 145 μm line is responsible for the observed line ratio anomaly.

Key words: ISM; Molecular Clouds; ρ Ophiuchi Cloud; PDRs; Star Formation.

1. INTRODUCTION

The relative strengths of the fine structure lines of atomic oxygen, viz. $O^0\ {}^3P_1$–${}^3P_2$ (63 μm) and $O^0\ {}^3P_0$–${}^3P_1$ (145 μm), are known to be difficult to predict theoretically for a number of astronomical sources (e.g., Tielens & Hollenbach 1985a & b; Saraceno et al. 1998). The ground state of O^0 is inverted, with the 145 μm line connecting the middle level with the upper level, more than 300 K above ground. The 63 μm transition, on the other hand, occurs between the middle level ($\Delta E/k \gtrsim 200$ K) and the lowest level at zero energy.

In several observed cases, 63 μm absorption (and/or scattering) by cool material along the line of sight towards the emitting source was directly suggested by the data (e.g., Baluteau et al. 1997). Such absorption could be expected to apply also to selected regions in the nearby (150 pc) ρ Oph cloud, harbouring a number of well studied dark and dense cores. In fact, the ρ Oph cloud could serve as a case study, since (1) the geometry of the emitting and of the putative absorbing regions is known, (2) the distribution of the volume and the column density is known, and (3) the spatial distribution and local strength of the UV-field (expressed in units of G_0, the integrated flux of the local interstellar field) is known from observation and theoretical modelling (Liseau et al. 1998, hereafter Paper I).

The regions ρ Oph B and ρ Oph C (Loren et al. 1990) appear as dark patches at wavelengths at least as long as 15 μm (see the ISOCAM image by Abergel at al. 1996). It is therefore most likely that the illuminating source (HD 147889, see: Paper I) is situated behind the bulk of the cloud and, consequently, that most of the PDR (Photon Dominated Region) emission originates at the rear side of the cloud. This scenario is in agreement with our detailed model presented in Paper I. In the present contribution, we examine the [O I] 63 μm and [O I] 145 μm observations with the LWS towards the dense cores ρ Oph B 1, B 2 and C 1 (C North).

2. OBSERVATIONS AND DATA QUALITY

In Fig. 1, the pointings of the ISO LWS (Kessler et al. 1996, Clegg et al. 1996) towards ρ Oph B are shown superposed onto a map in the emission of CS (J=5–4) (unpublished 15m SEST data of R. Liseau). The integrated CS line intensity traces the density distribution of the cloud. The high density clumps ρ Oph B 1 (south-west) and ρ Oph B 2 (north-east) are clearly revealed in this figure. The LWS data are spatially oversampled in the scan direction (Δ=40″, LWS-beam about 80″) and displayed in Fig. 2, where the positions of ρ Oph B 1 (b 4) and ρ Oph B 2 (b 11) are identified. The IRAS source IRS 37 (Wilking et al. 1989) is at b 6.

In Figs. 2 and 3, the positions of b 3 and c 6 are especially marked. The latter refers to a different scan (Paper I), which was obtained at a *different date*. The pointing towards c 6 was originally intended to coincide with b 3 for cross calibration checks. The actual angular distance between the two positions is only 25″, implying that these observations should

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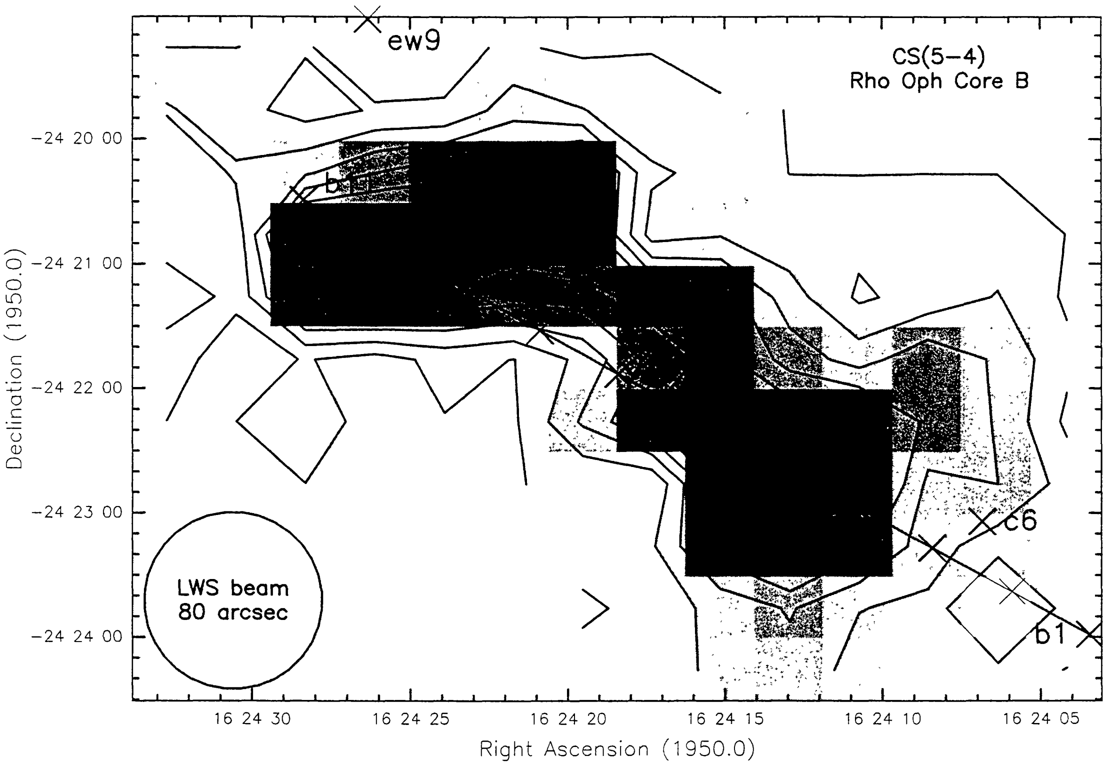

Figure 1. The positions of the LWS scan through the dense cores in ρ Oph B are shown and the first position, b 1, is identified. Offsets are 40″ and the shown beam of the LWS has a half power width of 80″. Also shown are two positions from different scans (c 6 and ew 9), the observations of which are separated in time. The LWS pointings have been overlayed onto a map in CS (5–4), obtained with the 15m SEST (R. Liseau, unpublished data). The CS data clearly reveal the cold and dense cores ρ Oph B 1 (south-west) and ρ Oph B 2 (north-east).

give nearly identical results (within the 30% accuracy of the absolute flux calibration; Swinyard et al. 1996). From Table 2 of Paper I one infers that the agreement is, in fact, excellent. Similar is true also for other cross-checks (e.g. b 11 and ew 9), although there the angular separations are larger. The good internal agreement of the LWS data, obtained at different dates, lends credence to their reliability.

Further, in Paper I, comparisons were made with *independent* observations, particularly with the KAO, which resulted in satisfactory agreement between the different data sets. Taken together, we regard it highly unlikely that the line line ratio anomaly discussed below is entirely of instrumental origin.

3. DISCUSSION AND CONCLUSION

In a scenario, where a small [O I] 63 μm/[O I] 145 μm line ratio (< 10) is caused by decreased 63 μm line flux due to self absorption in cool foreground material, one would expect the [O I] 63 μm flux to anticorrelate with the column density of the cold gas. Such behaviour is not observed anywhere in ρ Oph, however (see also Figs. 2 and 3). Surprisingly, rather the opposite seems to occur, viz. that the line strength appears to grow with the column density of cold gas (near their centres, the temperature of the cores is as low as below 10 K). Since G_0 is approximately constant over the core regions and the [O I] 63 μm emission is not optically very thick ($\tau_0 \sim 1 -$ a few, Paper I), the increase in line flux could reflect an increase in density in the emitting regions, i.e. in the PDR. Such increase could refer to either (1) an enhanced hydrogen density, for a constant (depleted) oxygen abundance or (2) an augmented abundance of atomic oxygen relative to hydrogen. The latter could be due to gas-grain chemical activity. However, on the basis of the available observational evidence we are not able to distinguish one possibility from the other. Alternatively, the IRAS source IRS 37 could contribute significantly to the [O I] 63 μm flux.

We recall the fact that the [C II] 158 μm and [O I] 63 μm lines behave in accordance with model predictions. It thus seems that the encountered difficulties are due to [O I] 145 μm alone and that the observed [O I] 63 μm/[O I] 145 μm line ratios in ρ Oph are not easily explained. In particular, self absorption of [O I] 63 μm seems to be ruled out. Should our comprehension of the source geometry be incorrect,

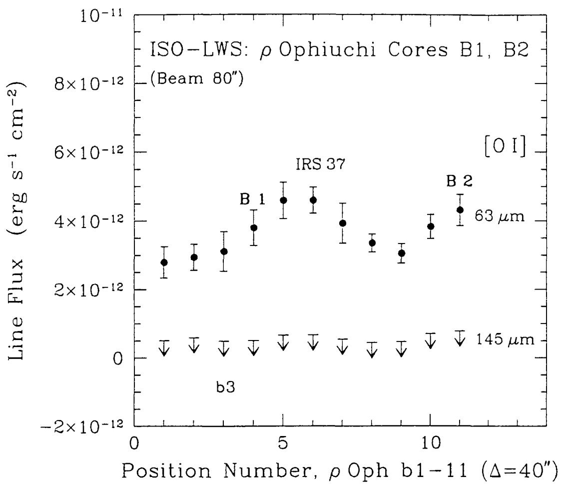

Figure 2. [O I] 63 μm and [O I] 145 μm data from the LWS-scan through the ρ Oph cores B 1 and B 2. Along the abscissa, the number of the individual pointings (b 1 to b 11) is given and along the ordinate the observed flux in the lines, corrected for continuum emission. The points are separated by 40″. The positions of the dense cores are indicated and the pointing b 3 is marked (cf. Fig. 3). No significant decrease in [O I] 63 μm flux towards the dense cores is discernible.

the self absorption picture would suffer even further, since the PDR would then be on the side of the cloud facing the Earth and little, if any, foreground material to absorb or scatter 63 μm photons would be available. It seems more likely, therefore, that the causes of small line ratios are not external, but internal to the physics of O^0 excitation and/or line transfer. In Paper I, we have examined a large number of possible explanations and reached the conclusion that the hypothesis of slight masing in the [O I] 145 μm line seems most promising. A physical mechanism, accomplishing the maser action, should be investigated in more detail.

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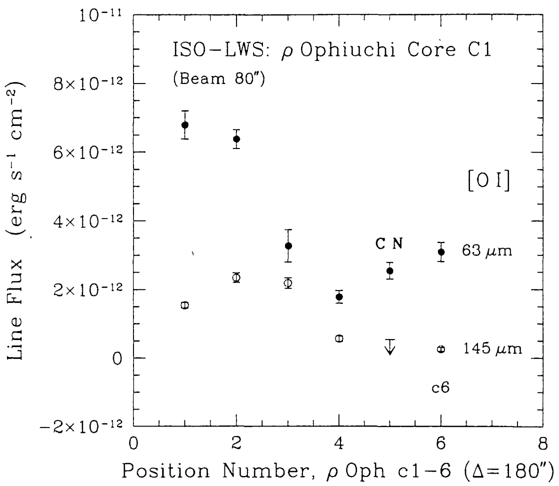

Figure 3. Same as Fig. 2, but for the LWS-scan through the ρ Oph core C 1, designated by CN (North), and with offsets of 180″. The [O I] 63 μm flux is not markedly reduced towards the dense core CN. The position c 6 is close to b 3 in Fig. 2, both showing identical flux. At positions, where both lines are clearly detected, the [O I] 63 μm/[O I] 145 μm flux ratio is smaller than ten.

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