The distribution of ionized, atomic and PDR gas around S 1 in ρ Ophiuchus

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ABSTRACT

The early B star S 1 in the ρ Ophiuchus cloud excites an H II region and illuminates a large egg-shaped photodissociation (PDR) cavity. The PDR is restricted to the west and south-west by the dense molecular ρ Oph A ridge, expanding more freely into the diffuse low density cloud to the north-east. We analyze new SOFIA GREAT, GMRT and APEX data together with archival data from Herschel/PACS, JCMT/HARPS to study the properties of the photo-irradiated ionized and neutral gas in this region. The tracers include [C II] at 158 μm, [O I] at 63 and 145 μm, J = 6–5 transitions of CO and 13CO, HCO+ (4–3), radio continuum at 610 and 1420 MHz and H i at 21 cm. The PDR emission is strongly red-shifted to the south-east of the nebula, and primarily blue-shifted on the north western side. The [C II] and [O I] 63 spectra are strongly self-absorbed over most of the PDR. By using the optically thin counterparts, [13C] II and [O I] 145 respectively, we conclude that the self-absorption is dominated by the warm (> 80 K) foreground PDR gas and not by the surrounding cold molecular cloud. We estimate the column densities of C II and O I of the PDR to be ∼ 3 × 10^19 and ∼ 2 × 10^18 cm⁻², respectively. Comparison of stellar far-ultraviolet flux and reprocessed infrared radiation suggest enhanced clumpiness of the gas to the north-west. Analysis of the emission from the PDR gas suggests the presence of at least three density components consisting of high density (10^19 cm⁻³) clumps, medium density (10^18 cm⁻³) and diffuse (10^17 cm⁻³) interclump medium. The medium density component primarily contributes to the thermal pressure of the PDR gas which is in pressure equilibrium with the molecular cloud to the west. Emission velocities in the region suggest that the PDR is tilted and somewhat warped with the south-eastern side of the cavity being denser on the front and the north-western side being denser on the rear.

Key words. ISM: Clouds – Submillimeter: ISM – ISM: lines and bands –(ISM :) photon-dominated region (PDR) –ISM: individual (ρ Oph)

1. Introduction

Photon-dominated Regions (PDRs) are regions where far-ultraviolet (FUV) (6 eV < hν < 13.6 eV) radiation from young massive stars dominate the physics and the chemistry of the interstellar medium (Tielens & Hollenbach 1985). The PDRs play an important role in reprocessing much of the energy from stars and re-emitting this energy in the infrared-millimeter regime. Most of the mass of the gas and dust in the Galaxy resides in PDRs (Hollenbach & Tielens 1999). In the far infrared the most important cooling lines are the fine structure lines of [C II] at 158 μm, and [O I] at 63 and 145 μm and to a lesser extent high-J CO lines, while PAH emission and H2 lines dominate in the near- and mid-IR. Of these tracers [C II] is the most abundant and easily excited is the most ubiquitous. Owing to an ionization potential of 11.26 eV for Carbon, understanding the phase of gas from which [C II] arises requires comparison with bona-fide tracers of ionized, atomic and molecular gas.

Mookerjea et al. (2018) recently published an observational study of the [C II] emission from a region around the B4V star S 1 located in the ρ Ophiuchus dark cloud (Ortiz-León et al. 2017) at a distance of 137.3±1.2 pc. The S 1 PDR is located on the eastern edge of the westernmost core ρ Oph A (Loren, Wootten & Wilking 1999). The ρ Oph A core has a filamentary structure with at least nine pre- and protostellar cores (Wilson et al. 1999; Di Francesco, André & Myers 2004), including the prototypical Class 0 source VLA 1623. Most of the cores are starless, although two of the cores may have embedded protostars (Friesen et al. 2018; Kawabe et al. 2018). Mookerjea et al. (2018) found that the [C II] emission is dominated by the strong emission from the nebula surrounding S 1 that appears to expand into the dense Oph A molecular cloud to the west and south of S 1. The [C II] emission is distributed similar to the other PDR tracers such as the 8 μm continuum tracing emission from PAHs and the velocity-integrated emission of [O I] at 145 and 63 μm measured by Larsson & Liseau (2017). A comparison of [C II] with the J = 3–2 emission of CO and 13CO shows very little similarity, although the highly compressed parts of the PDR shell traced by [C II] show up in C18O(3–2) as well as HCO+ (4–3). Mookerjea et al. (2018) also detected [C II] to be strongly self-absorbed over an extended region in the S 1 PDR and interpreted it as a cold foreground cloud being absorbed against the warm background gas. Analysing velocity-unresolved Herschel/PACS data, Larsson & Liseau (2017) deduced that this cold foreground cloud absorbs most of the 3P 1−P 2 [O I] 63 μm radiation but leaves the higher level 3P 0−P 2 [O I] 145 μm line unaffected.

In this paper we present newly observed maps of radio continuum, H i at 21 cm, [C II] at 158 μm, [O I] at 63 and 145 μm and J = 6–5 transitions of CO and 13CO and use them to study the morphology and physical properties of the PDR around the star S 1.

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2. Observations & Data Reduction

2.1. SOFIA

The S 1 PDR was observed on two occasions on June 14, 2018 and June 5, 2019 with upGREAT1 (Risacher et al. 2018) on flights leaving from Christchurch, New Zealand. All observations were done in Consortium time (Project 83_0614). The bright PDR was mapped simultaneously in both oxygen fine-structure lines: the HFA array was tuned to [O i] 63 μm (f = 4744.77749 GHz), while the LFA-H polarization sub-array was tuned to [O i] 145 μm (f = 2060.06886 GHz). The mapped field, indicated in Fig.4, was sampled at 3″ spacing, with 0.4 sec integration time per dump. In order to record the extended, lower-level PDR emission, in 2019 a wider field of 294″ × 294″ centered on S 1, was added with the LFA tuned to [C ii] 158 μm sampling every 6″ at a scan rate of 0.4 sec per resolution element. All mapping was carried out under dry atmospheric conditions at 42,000–43,000 flt altitude in total power on-the-fly mode, with the reference position at -120″, +300″ relative to S 1. The off position was clean for [O i], but there was still [C ii] emission in the off position. We therefore took a longer single pointed observation toward this off against a far off position (offset at 833″, -167″), which allowed us to correct the [C ii] map for the contamination in the (near) off position. The spectrometer setting during the [C ii] observation also covered the strongest hyperfine transition (2-1; 1900.4661 Hz) of the [13C ii].

The observations were reduced and calibrated by the GREAT team. The GREAT team also provided beam sizes (14″ for [C ii], 13″ for [O i]145 and 6″ for [O i]63) and beam efficiencies derived from planet observations. The data were corrected for atmospheric extinction and calibrated in T_A. In June 2018 the telluric 63 μm [O i] line was at V_Teff = 1.6 km s^{-1}, essentially making the 63 micron data unusable. In June 2019 the S 1 PDR was observed earlier in the month shifting the telluric 63 μm [O i] to 7.5 km s^{-1}, well away from the emission from the PDR except for some of the red-shifted [O i] spectra in the southern part of the PDR cavity. Comparison with the 2018 data which were clean at these velocities, show that very few spectra in the (near) off position (offset at 833″, -167″), which allowed us to correct the [C ii] map for the contamination in the (near) off position. The spectrometer setting during the [C ii] observation also covered the strongest hyperfine transition (2-1; 1900.4661 Hz) of the [13C ii].

The observations were part of the programme m-0102.f-9524c-16 of the German REceiver for Astronomy at Terahertz frequencies (upGREAT), funded by the MPI für Radioastronomie and the KOSMA/Universität zu Köln, in cooperation with the DLR Institut für Optische Sensorysysteme. 2

2.2. Radio observations with GMRT

We have mapped the low frequency radio continuum emission and 21 cm H i emission towards ρ Ophiuchus using the upgraded Giant Metrewave Radio Telescope (uGMRT)2. Gupta et al. (2017). India. The GMRT interferometer comprises of 30 antennae, each of diameter 45 m that are arranged in a Y-shaped configuration (Swarp et al. 1999). Of these, twelve antennae are located randomly within a central region of area 1×1 km² and the remaining eighteen antennae are placed along three arms, each of length 14 km. The shortest and longest baselines are 105 m and 25 km respectively. The configuration enables us to map large and small scale structures simultaneously. The observations were carried out during July 2018. The radio source 3C286 was used as the primary flux calibrator and bandpass calibrator whereas 1626-298 was used as phase calibrator.

The observed field was centered at ρ Ophiuchus (α_J2000: 16°26′34.0″, δ_J2000: -24°23′28.0″). The radio continuum observations were carried out at 610 and 1420 MHz. The angular sizes of the largest structure observable with GMRT are 17′ and 7′ at 610 and 1420 MHz, respectively. H i observations were carried out along with the 1420 MHz radio continuum observations. The rest frequency of H i line is 1420.4057 MHz. The H i observations were performed with a bandwidth of 12.5 MHz, which was further divided into 8192 channels. The observing frequency was estimated considering the LSR velocity of 3 km s^{-1} as well as motions of the Earth and the Sun. The settings correspond to a spectral resolution of 1.526 kHz (velocity resolution of 0.322 km/s).

The data reduction was carried out using the NRAO Astronomical Image Processing System (AIPS). The data sets were carefully checked and corrupted data due to radio frequency interference, non-working antennas, bad baselines etc. were flagged. After thorough flagging, the data was flux and phase calibrated using the calibrators 3C286 and 1626-298. The data sets were cleaned and deconvolved to create continuum maps. Several iterations of self-calibration were applied to minimize the phase errors. The final images were then primary beam corrected.

There are two sets of H i observations: one on July 12 and the other one on July 13, 2018. For the H i observations, each of the final calibrated data set was cleaned and deconvolved to produce a continuum map. Next, we subtracted the continuum (created from the line free channels). The two data sets were then combined together to increase the signal-to-noise ratio. We imaged the source with a UV tapering of 10 kλ and a spectral cube was generated. The primary beam correction was applied and the final image was obtained. The details of the images are given in Table I.

2.3. APEX

The S 1 PDR was mapped in CO(6-5) and in 13CO(6-5) using the SEPIA-660 receiver on the 12 m Atacama Pathfinder Experiment (APEX)1 telescope, located at Llano de Chajnantor in the Atacama high desert of Chile. Güsten et al. 2006. The observations were part of the programme m-0102.f-9524c-2018. SEPIA-660 is a SIS dual-polarization 2SB receiver with

Table 1. Details of the radio observations with GMRT.

| Frequency (MHz) | 610 | 1420 |
|----------------|-----|------|
| Observation date | 10 July 2018 | 12.13 July 2018 | 12.13 July 2018 |
| On source time (hrs) | 3.9 | 14.7 | 14.7 |
| Bandwidth (MHz) | 32 | 32 | 12.5 |
| Primary Beam | 45.8 | 19'7 | |
| Synthesized beam | 7'0 × 4'8 | 5'8 × 3'2 | 21'3 × 14'3 |
| Position angle (°) | -5.4 | 30.9 | 14.9 |
| Noise (mJy beam^{-1}) | 1.5 | 0.6 | 4.5 |

a Medium resolution opted to ensure detection of the emission with high fidelity in the channel maps.

1 The German Receiver for Astronomy at Terahertz frequencies (upGREAT) is a development by the MPI für Radioastronomie and the KOSMA/Universität zu Köln, in cooperation with the DLR Institut für Optische Sensorysysteme.

2 CLASS is part of the GILDAS software package, see http://www.iram.fr/IRAMFR/GILDAS

Notes:

1. [O i] map provided in Table 1.
2. [C ii] map provided in Table 1.
3. APEX, the Atacama Pathfinder Experiment is a collaboration between the Max-Planck-Institut für Radioastronomie, Onsala Space Observatory (OSO), and the European Southern Observatory (ESO).
an IF bandwidth of 4–12 GHz [Belitsky et al. 2018]. The backends used are advanced Fast Fourier Transform Spectrometers [Klein et al. 2012] with a bandwidth of 2×4 GHz and a native spectral resolution of 61 kHz. The rest frequencies for CO(6–5) and 13CO(6–5) are 691.473076 GHz and 661.0672766 GHz, respectively. The HPBWs at CO(6–5) and 13CO(6–5) are 9′′0 and 9′′4, respectively. The main beam efficiency $\eta_{mb}$ is = 0.53, as measured from observations of Jupiter (diameter 44.5″).

The 13CO(6–5) map was observed on April 19, 2019 in on-the-fly total power mode with an off position at 0″,+300″ relative to S 1 (RA 16 26′′34.17′′, Dec −24°23′28.3″). The weather conditions were good (PWV 0.66 mm) with a zenith optical depth of ~ 0.75 resulting in SSB system temperatures of ~ 1000 K. The map size was 235′′×200′′, centered at (−17°5′,0″). The field was scanned in both RA and Dec with a spacing of 4′5 (half the beam size) and oversampled to 3″ in scanning direction, resulting in a uniformly sampled map with high fidelity. Unfortunately, the off position was not clean and we did a single point long integration toward a far off at 0″,+1080″, which was used to correct the map in the post processing stage.

On April 27, 2019 we observed a smaller map in 13CO(6–5) of the SW part of the PDR, also in OTF TP mode. The map was centered at (−75°′,0″) and the map size was 60 ⋅ 120″, with the same sampling strategy as above. The weather conditions were good (PWV 0.53 mm) with a zenith optical depth of 0.67. The SSB system temperature was ~ 800 K.

The spectra were reduced in CLASS and calibrated in Tmb. We first ordered a first order baseline and resampled the spectra to 0.5 km/s velocity resolution. The final data cubes (pixel size 9″) after gridding have an rms main beam temperature noise per pixel of ~ 0.33 K and 0.24 K for CO(6–5) and 13CO(6–5), respectively.

### 2.4. Auxiliary data

For comparison with our observations, we have used maps of the J=3–2 transition of CO, 13CO and C18O [White et al. 2015] and J=4–3 transition of HCO+ [White et al. 2015] all observed with JCMT using the HARP receiver with a beamsize of 14″. The CO (and isotopologues) spectra were observed as part of the Gould Belt Survey and the HCO+ (4–3) data set, corresponding to the proposal M11AU13, was downloaded directly from the JCMT archive at the Canadian Astronomical Data Centre (CADC). Both these datasets have also been downloaded and compared with the previous [C] observations of the S 1 PDR by Mookerjea et al. [2018]. The emission maps of S(2) and S(3) pure rotational transitions of H2 observed with ISOCAM-CVF by Larsson & Liseau [2017] were also used for comparison.

### 3. Results

#### 3.1. Properties of the ionized gas around S 1

The radio continuum emission from ionized plasma at 610 and 1420 MHz are shown in Fig. [I] The emission at 610 MHz shows a bright core surrounded by low brightness diffuse emission. The emission is extended up to 25″ which corresponds to 0.02 pc at a distance of 137 pc. The emission at 1420 MHz extends up to 50″. A central bright peak is observed surrounded by low surface brightness halo emission. Both 610 and 1420 MHz images reveal an elongation in the North west-South east direction, which is more prominent in the 1420 MHz image. Such elongated structures in radio emission are often indicative of ionized jets from massive YSOs (e.g., Purser et al. 2016). The total flux densities at these frequencies are obtained using a two component Gaussian fit to the emission. The flux density of the central unresolved source is 5.6 ± 0.2 mJy and that of diffuse halo is 41.6 ± 3.0 mJy at 1420 MHz. The flux density of the central source at 610 MHz is 6.8 ± 2.0 mJy and that of diffuse emission is 47.6 ± 2.1 mJy.

Assuming that the diffuse emission at 1420 MHz is optically thin, we have estimated the Lyman continuum photon rate and the spectral type of the star responsible for ionized emission.

The Lyman continuum photon flux at 1420 MHz towards S 1 is estimated using the equation [Schmiedeke et al. 2016]

$$\frac{N_{Ly}}{s^{-1}} = 4.771 \times 10^{42} \left[ \frac{S_{5.8} \nu}{mJy \ GHz} \right]^{0.45} \left[ \frac{T_e}{K} \right]^{-0.45} \left[ \frac{d}{pc} \right]^{-2}$$  \hspace{1cm} (1)

where $S_{5.8}$ is the flux density at frequency $\nu$ which is 41.59 mJy at 1420 MHz, $T_e$ is the electron temperature which is found to be 8200 K based on electron temperature gradient across the Galactocentric distance [Quiroga et al. 2006] and $d$ is the distance to the source which is 137 pc [Mookerjea et al. 2018]. Using the above expression, the Lyman continuum photon rate is found to be $6.7 \times 10^{31}$ s$^{-1}$. The estimated uncertainty in the electron temperature derived using the formulation by Quiroga et al. [2006] is = 100 K. Thus, no additional uncertainty in the estimated $N_{Ly}$ is introduced due to this. If a single main sequence star is responsible for the ionization, then the spectral type of the ZAMS star is earlier than B3V [Thompson 1984]. For a B3V star with $T_{eff}$=18700 K and $R$ = 4.15 $R_\odot$, Kurucz model (Castelli & Kurucz 2003) gives $N_{Ly}$ = 5.3×10$^{33}$ s$^{-1}$ and for a B2V star with $T_{eff}$=22000 K and $R$ = 5.19 $R_\odot$, we get $N_{Ly}$ = 8.2×10$^{34}$ s$^{-1}$. Thus taking the uncertainties of the derived $N_{Ly}$ into account, we conclude that the star S 1 is most likely B2.5V or B3V, which is not inconsistent with the SED fitting by Mookerjea et al. [2018]. Although they concluded a B4V type for the star, they noted that a B3V would fit equally well if a slightly larger extinction of 13.3 mag was adopted instead of 12.7 mag.

From the VLA high frequency mapping of $\rho$ Oph at 5 and 15 GHz [André et al. 1988] showed that the radio emission towards this region comes from a non-thermal unresolved source surrounded by a thermal extended halo. It is now known that S 1 is a close binary [Ortiz-León et al. 2017] with the secondary being responsible for the non-thermal emission. The flux density of the central source at 1420 MHz within the uncertainties is consistent with the flux measurements of André et al. [1988] and Stine et al. [1988]. Using the flux densities of 6.8 and 5.6 mJy at 610 and 1420 MHz respectively, we derive a spectral index of $-0.2 \pm 0.3$, where the uncertainty in the derived index is contributed primarily by the uncertainty of the 610 MHz flux.

#### 3.2. The Morphology of the S 1 PDR cavity

IRAC and MIPS images [Padgett et al. 2008] Gutermuth et al. [2009] show that S 1 illuminates a large elongated spheroidal or egg shaped cavity with the major axis at a position angle of 54° and a length of ~105′ and a minor axis of ~5′. There is very strong PDR emission towards south-west (SW) where it is blocked from expanding by the surrounding dense molecular cloud. Toward the north-east (NE), where the PDR shell emerges out of the cloud, the emission is rather faint and barely visible. S 1 is ~80″ from the SW tip of the PDR shell [4]. We have used

In the following we refer to NE to SW as being the direction of the major axis of the PDR shell and north-west (NW) to south-east(SE) being perpendicular to it.

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A combination of spatial and velocity information in the form of line integrated emission, velocity-channel maps as well as position-velocity diagrams along selected directions in the maps of the observed PDR tracers to understand the basic geometry of the PDR associated with S 1 (Fig. 2). To the west the PDR borders the Rho Oph A ridge, which curves to the east south of the PDR. To the NW the molecular cloud becomes very diffuse and is not seen in CO (White et al. 2015). In the past there have been no spectral line observations of the PDR emission east of S 1 and most observations did not even fully capture the PDR emission to N of S 1, which prompted Larsson & Liseau (2017) to model the PDR shell as a gaseous sphere with a radius of 80′.

We have mapped extended regions around S 1 in several PDR tracers: [C ii], [O i] 63 and 145 μm, CO (6–5) and HCO’(4–3). Although HCO’(4–3) is not really a PDR tracer and is mainly a dense gas tracer, it does show some excess emission from the PDR (Fig. 3). These data have been compared with previous observations of the J=3–2 transitions of CO, ^13CO and C^{18}O (Mookerjea et al. 2018). The emission seen in these PDR tracers match well with the emission from neutral hydrogen (H i) and other PDR tracers such as 8 μm PAH emission and the S(2) pure rotational transition of H₂ at 12.3 μm (Fig. 5) see also Larsson & Liseau (2017). The visual extinction toward S 1 is ~ 13.3 mag and may even be higher over part of the nebula (Mookerjea et al. 2018). Additionally, the emission from all observed PDR tracers with the exception of [O i] 145 μm, which is optically thin, are heavily self absorbed. The [^{13}C ii] F=2–1 line is also optically thin, but relatively faint and only securely detected where the [C ii] emission is strong. The [O i] 63 μm line is so strongly self absorbed, that no emission is seen in the v_{LSR} range 3–4.5 km s⁻¹ (Fig. 4). It is therefore unusable as a tracer of the morphology of PDR cavity. There is a strong CO(6–5) emission from the Rho Oph A ridge. However, near the SW tip of the PDR cavity the emission from the PDR starts to dominate. The CO(6–5) and [O i] 145 μm maps also capture the dense molecular PDR to the north-east of S 1.

The channel maps of [C ii] and [O i] 145 μm (Fig. 5) show that the PDR emission is strongly red-shifted on the south-eastern side of the nebula while the emission is primarily blue-shifted on the north-western side. The H i emission is also strongly red-shifted on the south-eastern side. This implies that gas is moving away from the observer on the south-eastern side, while it is streaming toward the observer on the north-western side, although blue-shifted emission is also detected to the SE. At the SW tip of the PDR one can see both blue- and red-shifted gas. The blue-shifted emission dominates to the NW, and red-shifted emission to the SE. The same is true for the rest of the PDR nebula. This streaming gas must be due to photo evaporating gas, which is commonly seen in PDRs. On the SE side of the cavity and toward SW, the PDR emission is generally more red-shifted than the emission from the surrounding cloud. Figurc 5 shows that the CO(6–5) emission traces the NW PDR boundary extremely well at velocities from 1.5–3 km s⁻¹ and the red-shifted filament south of S 1. The CO(6–5) emission is strongly self-absorbed in the PDR in the velocity range 3–4 km s⁻¹, similar to [O i] 63 μm, though not as extreme. The emission from the filament detected in CO(6–5) is by no means smooth. It shows two clumps in emission in the velocity channels from 4.5 and 5.5 km s⁻¹. The CO(6–5) emission is quite faint to the East of S 1, where the [O i]145 and [C ii] emission is still quite strong. One can also see faint CO(6–5) emission NE of S 1, which may be unrelated to the PDR. The velocities of emission of the H i 21 cm...
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Fig. 3. Comparison of 8 µm continuum image observed with IRAC/Spitzer (color) with contours of integrated intensity images of tracers (marked) overlayed on the 8 µm continuum image observed with IRAC/Spitzer. The color scale is shown in the wedge to the right of the top row, with numbers in units of MJy/sr. For each of the tracers shown as contours, levels are shown on the top of the panel and beams are shown at the top left corner of each panel. The range of velocities over which integrations are done are as follows: [C ii] -0.5 to 7.5 km s\(^{-1}\), [O i] 145 µm 1 to 5.5 km s\(^{-1}\), [O i] 63 µm 0.5 to 6.5 km s\(^{-1}\), H\(_i\) -0.5 to 5 km s\(^{-1}\), CO(6–5) 0 to 10 km s\(^{-1}\), HCO\(^+\)(4–3) 0 to 10 km s\(^{-1}\) and \([^{13}\text{C} \text{ii}] F=2–1\) 1 to 5 km s\(^{-1}\). The positional offsets are relative to the center \(\alpha=16^\text{h}26^\text{m}34^\text{s}\ 175, \delta=-24^\circ23'28''\ (J2000).\) The asterisk and the triangle, mark the positions of S 1 and VLA 1623, respectively. The numbers in the top left panel mark selected positions which are studied in detail. The offsets for the positions are 1(-61,45), 2(-33,6), 3(-31,-31), 4(32,-23) and 5(60,-45).

In order get a more detailed view of the S 1 PDR cavity, we created position velocity diagrams (Figs 7–10) of several PDR tracers both along cuts parallel and perpendicular to the major axis of the cavity as shown in Fig 7. In the following, we refer to these position-velocity diagrams as pv-cuts. The [C ii] map is more extended than the other maps and in [C ii] one can still see faint PDR emission 120′′ to the NE of S 1 (Fig. 7). There will be [C ii] emission even further to the East, although it is likely to be faint. However, since the gas densities and FUV radiation field is low, it is possible that only the rim outlining the PDR shell can be detected. The position-velocity diagrams show that the SW tip of the cavity is somewhat red-shifted suggesting that the PDR is tilted away from us in the SW and coming toward us in the NE. The perpendicular pv-cuts across the PDR cavity show that the cavity is less extended to the SE (\(\sim 80''\)) than to the NW (\(\sim 100''\)), suggesting that the surrounding molecular cloud must be much denser on the SE side than on
Fig. 4. Channel maps of [C ii] (left), [O i] 63 µm (middle) and [O i] 145 µm (right). The color scale for each map is shown next to the map. Velocities corresponding to the channel are marked in each panel. The red star sign marks the position of S 1. The positional offsets (in arcseconds) are relative to the center $\alpha=16^\text{h}26^\text{m}34^\text{s}175$, $\delta=+24^\circ 23^\prime 28^\prime\prime$ (J2000). The area mapped in CO(6–5) is shown with dashed boundaries on the top-left panel of the [C ii] channel map.

Fig. 5. Same as in Fig. 4 but for channel maps of CO(6–5) (left), $^{13}$CO(6–5) (middle) and H i (right) emission. The area mapped in CO(6–5) is smaller than the maps in Fig. 4. The area mapped in $^{13}$CO(6–5) is marked with dashed boundaries in the top-left panel of the CO(6–5) channel map.

3.3. Analysis of Spectral Profiles

The [C ii], CO(6–5), H i spectra throughout the observed map show self-absorption, along with red- and blue-shifted line wings. The [C ii] lines are the broadest among the PDR and molecular tracers. The [O i] 145 µm spectra typically show a single peak centered on the absorption in the [C ii] spectra as well as an extended blue wing at a few positions. The [O i] 63 µm on the other hand is completely absorbed between 3 – 4.5 km s$^{-1}$. The spectra of $^{13}$CO(6–5) show absorption dips at positions close to the CO(6–5) peak but is single-peaked at positions to the southwest of the map as well as in the region immediately to the west of the S 1. This suggests that the foreground material is optically dense.

The perpendicular pv-cuts also show strong blue-shifted emission to the NW with more red-than blue-shifted emission to the SE. The flip from red-shifted to blue-shifted emission occurs roughly at the symmetry axis of the PDR cavity. The HCO$^+$ emission, which is dominated by the surrounding cloud, also shows the same velocity gradient across the PDR cavity. These pv-cuts suggest that on the SE side of the cavity the surrounding cloud must be very dense on the front side, i.e. the side facing us, while on the NW side the cloud is denser on the back side. This forces the photo evaporation flow from the PDR to be mostly red-shifted in the SE and blue-shifted in the NW. We have tried to visualize this in the cross-sectional view of the PDR SW of S 1 (Fig. 2), which is a very simplified picture, because the PDR layer is by no means smooth. There may be ridges and valleys and there can also be dense clumps of gas inside the PDR, like what appeared to be the case for NGC2023 (Sandell et al. 2015). There is a strong red-shifted filament just SE of S 1, which stands out prominently in the [O i] 63 µm channel maps at velocities from 5 – 6.5 km s$^{-1}$ (Fig. 4). This filament is also seen in the [O i] 145 µm, [C ii], H i and CO(6–5) channel maps (Fig. 4 and 5).

3.3. Analysis of Spectral Profiles

The [C ii], CO(6–5), H i spectra throughout the observed map show self-absorption, along with red- and blue-shifted line wings. The [C ii] lines are the broadest among the PDR and molecular tracers. The [O i] 145 µm spectra typically show a single peak centered on the absorption in the [C ii] spectra as well as an extended blue wing at a few positions. The [O i] 63 µm on the other hand is completely absorbed between 3 – 4.5 km s$^{-1}$. The spectra of $^{13}$CO(6–5) show absorption dips at positions close to the CO(6–5) peak but is single-peaked at positions to the southwest of the map as well as in the region immediately to the west of the S 1. This suggests that the foreground material is optically dense.
Fig. 6. Left: Three-color map of [C ii] emission in velocity interval $v_{LSR} = -0.5$–1 km s$^{-1}$, 1.5–3 km s$^{-1}$ and 4.5–7 km s$^{-1}$ shown as blue, green and red channels respectively. The contours show the [C ii] emission in the velocity interval -0.5–7 km s$^{-1}$. The orthogonal sets of lines show the cuts along which position–velocity diagrams are derived. Right: Three-color map of [O i] 145 μm emission in the velocity intervals $v_{LSR} = 1$–2.5 km s$^{-1}$, 3–4 km s$^{-1}$ and 4–5.5 km s$^{-1}$ as blue, green and red channels respectively. The contours show the [O i] 145 μm emission in the velocity interval 1–5.5 km s$^{-1}$.

thin in [O i] 145 μm throughout the entire map, while $^{13}$CO(6–5) is still moderately optically thick at a few positions. Figure 11 shows the spectra at the location of S1 and five additionally selected positions (shown in Fig 3) within the mapped region, which sample a variety of [C ii] lineshapes that are representative of the entire map.

Our observations are deep enough to detect the F = 2–1 transitions of $^{13}$C [C ii] at 90 positions in the entire region. Closer inspection of the [C ii] spectra at five out of the six selected positions also reveal clear detection of the $F = 2–1$ transition of $^{13}$C [C ii]. Unlike the [C ii] profiles which show a strong absorption dip, the $^{13}$C [C ii] spectra peak exactly at the location of the [C ii] dip (Fig 12). Similar trends are also visible when the [O i] 63 and 145 μm spectra are compared at these five positions (Fig 13).

We start with trying to understand the role of the foreground material in shaping the [C ii] and [O i] 63 μm spectrum profiles characterized by deep self absorption. We model the observed [C ii] and [O i] 63 μm spectra considering two layers, a background one (the main PDR) that emits and a foreground cloud that absorbs. We take an empirical approach and assume that the $^{13}$C [C ii] and [O i] 145 μm spectra which are optically thin, represent (except for a scaling factor) the [C ii] and the [O i] 63 μm spectra respectively, that the PDR would emit in the absence of the foreground absorbing gas. The scaling factor used for the $^{13}$C [C ii] spectrum is $^{12}$C/$^{13}$C = 70 (after correcting for the detection of only the strongest of the hyperfine structure line of $^{13}$C [C ii] which accounts for 0.625 of total $^{13}$C [C ii] intensity). The ratio of the [O i] 63/[O i] 145 intensities in the background emitting gas depends strongly on the physical conditions, here we use a scaling factor of 2 for the [O i] 145 μm spectrum which corresponds to $F_{63 μm}/F_{145 μm}$ of 24, a value that is representative for warm, medium dense PDR conditions (Goldsmith 2019, e.g. Fig. 5). Thus, we consider that at each position the [C ii] ([O i] 63 μm) spectrum is given by the scaled $^{13}$C [C ii] ([O i] 145 μm) spectrum and the foreground gas is a pure absorbing screen with a constant velocity, width and optical depth. In this approach we assume that the effect of the foreground material on the background emission is to attenuate the latter by the factor $\exp\left(-\tau_0 \exp\left(-4 \ln 2 (v - v_0)^2/\Delta \nu_0^2\right)\right)$. Here $\tau_0$, $v_0$ and $\Delta \nu_0$ denote the peak optical depth, the velocity at which the foreground cloud has a value of $\tau_0$, and the FWHM of the foreground absorption profile. In order to generate the $^{13}$C [C ii] spectra with higher fidelity we have co-added the $^{13}$C [C ii] and all other spectra over 20″ with centers at the selected offsets. Additionally, to improve the quality of the template spectra generated from $^{13}$C [C ii], and [O i] 145 μm, we do not use the observed spectra to simulate the emission, but instead we use the Gaussian profiles generated from fits to the observed spectra. Figures 12 and 13 also show the results of such two-slab modeling at five selected positions in the observed region.

Table 2 presents the results of fitting of the two-component model to the [C ii] and [O i] 63 μm spectra. The C$^+$ absorbing layer shows peak opacities ($\tau_0$) between 3.5–4.8 at velocities ($v_0$) between 3.5–4.4 km s$^{-1}$, with a width ($\Delta \nu_0$) between 1.4–3.4 km s$^{-1}$. The O$^+$ absorbing layer gives rise to peak opacities for [O i] 63 μm of 4–8, at velocities between 3.7–4.1 km s$^{-1}$ with a linewidth of 1.7–2.2 km s$^{-1}$.

We point out that in particular the blue part of the [C ii] spectrum is not fully reproduced at some of the positions, likely due to the fact that the $^{13}$C [C ii] lines being fainter do not trace the line wings where [C ii] is optically thin. Similarly, at (32–23) for the fit to the [O i] 63 μm spectrum, a broader red-shifted velocity component is completely missed out and part of the blue wing is not fully reproduced by the fit based on the [O i] 145 μm spectra. For both (-31,31) and (-61,45) the fits lack somewhat at lower velocities. The central velocity and linewidth of the foreground absorbing component derived for fits to both [C ii] and [O i] 63 μm spectra are consistent with the two-component LTE-based modeling that was performed by Mookerjea et al. (2018). However, the fit presented here is better constrained because of the availability of $^{13}$C [C ii] and [O i] 145 μm.

Table 2 presents the column densities in the lower energy level of C$^+$ and O$^+$ in the foreground absorbing gas estimated based on the $\int \tau dv$ values derived from the fits and using the relation:

$$N_I = \frac{g_I}{g_a} \frac{8 \pi}{\lambda A_{Pal}} \int \tau dv$$

(2)

where, $g_I$ and $g_a$ denote the statistical weights of the lower and upper energy levels, $A_{Pal}$ denotes the Einstein’s A-coefficient for spontaneous emission and $\lambda$ denotes the wavelength of the transition.

We obtain N(O) of the absorbing gas to be between (2.3–3.0) $10^{18}$ cm$^{-2}$. For these column densities, based on non-LTE...
3.4. Temperature of [C ii] emitting PDR gas

In our analysis of the absorption features in the [C ii] profile, we have considered the background [C ii] profile to be an optically thin scaled-up version of the \(^{13}\)C ii profile. However, based on the recent [C ii] observations of most of the Galactic PDRs it is likely that the background PDR emission is likely to have an optical depth close to 1. Guevara et al. (2020) performed an elaborate fitting procedure involving multi-component LTE components to explain optically thick background [C ii] spectra that are absorbed by a foreground layer of gas. Here we approximate the background [C ii] spectrum, by assuming it to be a scaled up version of the \(^{13}\)C ii spectrum modulated by an optical depth of 1. The Planck-corrected peak of the optically thick [C ii] spectrum so derived provides a lower limit of the temperature of the [C ii] emitting PDR gas. Table 2 also presents the temperatures of the [C ii] emitting PDR gas at the selected positions estimated using this method.

We use the integrated line intensities of the optically thin \(^{13}\)C ii spectra at these selected positions to estimate N(C\(^+\)). We estimate the total integrated intensity of \(^{13}\)C ii by considering that the observed $F=2–1$ transition accounts for 62.5% of the...
total intensity (Table 3). The column density of $^{13}$C$^+$ is estimated following Eq (26) from Goldsmith et al. (2012):

$$N(^{13}\text{C}^+) = \frac{8\pi k_B v_{ls}^2}{A_{ul} \nu c^3} \left[ 1 + 0.5 e^{v_1 - 25/T_{\text{kin}}} \left( 1 + \frac{A_{ul}}{C_{ul}} \right) \right] \int T_{\text{mb}} dv$$  \hspace{0.5cm} (3)

where, $v_{ls} = 1900.4661$ GHz, $A_{ul} = 2.3 \times 10^{-6}$ s$^{-1}$, $T_{\text{kin}}$ is the gas kinetic temperature, the collision rate is $C_{ul} = R_{ul} n$ with $R_{ul}$ being the collision rate coefficient with H$_2$ or H$^0$ which depends on $T_{\text{kin}}$ and $n$ is the volume density of H. For $n_H > 10^4$ cm$^{-3}$, $C_{ul} \gg A_{ul}$ so that the last term in Eq. 3 can be neglected.

We assume a $^{12}$C/$^{13}$C ratio of 70, based on the Galactocentric distance of the S 1 PDR (Wilson & Rood 1994), using the observed integrated $^{13}$C ii] intensities and the estimated $T_{\text{kin}}$ (Table 2), we estimate $N(^{13}\text{C}^+)$ at the selected positions to be between 1.3–3.8 $\times 10^{18}$ cm$^{-2}$ (Table 3). Comparing the total C$^+$ column density derived here with $N(^{13}\text{C}^+)$ estimated for the foreground absorbing gas (Table 2), we find that for all positions the column density of the colder foreground gas is approximately one-third of the $N(^{13}\text{C}^+)$ of the background PDR gas.

### 4. The S 1 PDR

Figure 14 shows a comparison of the observed distribution of the PDR and high density tracers with the molecular hydrogen column density, dust temperature and FUV intensity, all derived from dust continuum detected with PACS as part of the Herschel key program on Gould Belt Survey (André et al. 2010). The column density and dust temperature maps are directly taken from the Gould Belt Survey website and we have estimated the FUV intensity from the observed far-infrared (FIR) intensity as described in Mookerjea et al. (2018). The circles drawn in Fig. 14 are centered on S 1 with radii of 45 and 75$''$ to guide the eye. The column density peak in the Oph A cloud is close to the position of VLA 1623. The dust temperature peaks at a position slightly offset from S 1 and closer to the [C ii] peak and the embedded YSO LFAM 9. The peak in the FIR continuum map is located close to S 1 and also to the south-west (Fig. A.1 in Mookerjea et al. 2018). As indicated earlier, the PDR is bound by the dense ambient cloud to the south-west and is more tenuous to the north-east. Thus, the fraction of stellar FUV radiation intercepted by the cloud is likely to be larger towards the south-west than at positions towards the east and north-east which are radially equidistant from S 1. The [C ii] traces the entire PDR gas, which is also seen in the FUV map derived from the FIR continuum maps. The [O i] 145$\mu$m which has a higher critical density preferentially picks up the denser and warmer edge-on PDR rim to the west. The CO(6–5) traces only the PDR clumps within a very narrow strip and the HCO$^+$ (4–3) traces the higher density (and column density) molecular clouds in the Oph A ridge, which also harbors the YSO VLA 1623.

Table 3 presents results of fitting Gaussian profiles to the optically thin spectra of $^{13}$C ii], [O i] 145$\mu$m, C$^{18}$O(3–2) and $^{13}$CO(6–5) at the positions already analyzed in Fig. 12. We find
Fig. 9. Position-velocity diagrams of HCO$^+$ (4–3) emission along parallel (top) and perpendicular (bottom) cuts shown in Fig. 6 and plotted the same way as Figs. 7 & 8 using the same angular resolution as for [C ii]. Ten linear contours from 0.3–6.9 K are shown and their peak intensity is 7.0 K. To the NE, the HCO$^+$ is barely detectable 60′′ from S 1 confirming that the density of the surrounding cloud falls off towards the NE. The southwestern most perpendicular position velocity cut 120′′ west of S 1 does not cross the PDR, but is plotted to illustrate that the emission in the Rho Oph A ridge is more blue-shifted than the emission from the S 1 PDR.

that the $^{13}$C ii and [O i]145 lines are significantly broader than the $^{13}$CO(6–5) lines, except at the position (-61,45) which corresponds to the peak of [O i] 145 µm as well as $^{13}$CO(6–5). Additionally, the central velocities of the PDR tracers are red- and blue-shifted relative to the molecular cloud tracer depending on whether the positions are to the north or south of S 1 respectively. The C$^{18}$O(3–2) primarily traces the ambient molecular cloud and hence typically peaks around 3.1 km s$^{-1}$.

4.1. The FUV field

The distribution and emission from the PDR is primarily a function of the FUV (6 eV ≤ hν < 13.6 eV) radiation field and volume density of the PDR gas. The star S 1 is the primary source of FUV radiation for this PDR. Based on the observed radio continuum flux at 1420 MHz we estimate the S 1 to have a spectral type of B2.5–B3V. We thus used the Schmidt-Kaler relation for a B3V star ($T_{\text{eff}}=18,700$ K and a radius of 4.15 $R_\odot$) and Kurucz model atmosphere to estimate the FUV radiation field distribution considering only projected distances and geometrical dilution. The FUV field is typically expressed in units of the Habing (1968) value for the average solar neighborhood FUV flux, 1.6×10$^{-3}$ ergs cm$^{-2}$ s$^{-1}$. We find that at a radial distances of 45″ and 75″ from S 1 the unattenuated FUV field from S 1 is 2.70×10$^4$ and 8500 G$_0$, respectively. An alternative method of estimating the strength of the FUV radiation in the region involves the use of the observed total far-infrared (FIR) intensity, assuming that the entire FUV energy is intercepted and absorbed by the grains and is reradiated in the FIR. We used the far-infrared observations of Herschel/PACS to estimate the values of FUV radiation field around S 1 (Fig. 14). We find that the observed FIR distribution is neither spherically symmetric around S 1, nor does it peak at the position of S 1. The peak in FIR emission (coinciding with the peak $T_{\text{dust}}$) is primarily to the north-west, where the derived FUV radiation is around 4000 G$_0$ at a radius of 75″. To the east at similar radii from S 1 the estimated FUV emission is ∼ 1200 G$_0$. By making a pixel to pixel comparison, we find that only for the ridge-like structure to the north-west the FUV flux predicted from the S 1 FUV radiation and from the FIR continuum agree to within a factor of 2. For regions between 40″ to 75″ from S 1 and at the ridge in the west, the two estimates differ by up to a factor of 10. The discrepancy between the FUV radiation field derived theoretically considering only geometric dilution and the field derived indirectly from the observed far-infrared radiation can be due to: (a) the emission in far-infrared continuum arising from regions, which are at much larger distances than the projected distance used here (b) FUV radiation escaping the region without being intercepted by material particularly to the east and north-east, (c) presence of very high A$V$ clumps, which attenuate the FUV drastically but
are too small to be detected in single-beam continuum observations.

As discussed in Sec 3.1, the region is bound in the west and south-west by the dense Rho Oph A ridge and possibly freely expanding to the north-east. The structures visible in the far-infrared continuum images primarily trace the column density of dust (and gas) along the lines of sight, as is shown in the H$_2$ column density maps generated from the same PACS maps (Fig. 14). The lower levels of FIR continuum emission closer to S1, as well as to the east is therefore a result of lower column densities of dust (and molecular gas) in these regions, while the higher FIR continuum emission to the north-west indicate the presence of higher column density clumps, which is also substantiated by the detection of HCO$^+$(4–3) with JCMT and NH$_3$ with the Green Bank Telescope (Friesen et al. 2017).

4.2. Comparison of observed intensities with PDR models

We compare the observed intensities of optically thin tracers $^{13}$C n, [O i] 145 μm and 13CO(6–5) with the predictions of plane-parallel steady-state PDR models, which self-consistently calculate the intensities as a function of the FUV flux and gas density of H nuclei $n_{H}$. These PDR models are from an updated version of the models by Kaufman et al. (2006) (Wolfire, private communication). We perform the analysis at the five selected positions, since these lie at different radial distances from S1 to the east-west and north-south of S1, thus tracing the distribution of the spectral lines arising from PDR reasonably well. The S(2) and S(3) transitions of H$_2$ are produced by FUV pumping, and hence the intensities are proportional to the FUV radiation. At the positions where the rotational lines of H$_2$ S(2) and S(3) have been detected, we have also compared their intensities with the PDR model predictions. Figure 15 shows a comparison of the observed intensities of the tracers (shown as contours) with the values predicted by the models. The lower and upper limits of the FUV intensities (shown by dashed horizontal lines in Fig. 15) are determined by the values derived from the FIR intensities and from the stellar FUV radiation field, respectively (Sec. 4.1). At most positions the observed $^{13}$C n exceed the intensities predicted by the models for the entire parameter space explored, hence the corresponding contours are not visible in Fig. 15.

The critical densities (and $E_u$) for $^{13}$C n, [O i] 145 μm and CO(6–5) are 3000 cm$^{-3}$ (91 K), 5.8×10$^6$ cm$^{-3}$ (325 K), 2.9×10$^5$ cm$^{-3}$ (116 K), respectively. The S(2) and S(3) transitions of H$_2$ have critical densities (and $E_u$) of 2.2×10$^5$ cm$^{-3}$ (1682 K) and 9.4×10$^5$ cm$^{-3}$ (2504 K), respectively. Thus [O i]145, $^{13}$CO(6–5) and S(2) H$_2$ transitions could arise from PDR gas of similarly high densities, while $^{13}$C n traces the low-density PDR. Though the H$_2$ lines have rather high critical densities and high upper energy levels, these are produced by FUV pumping. For
values of $G_0/n < 10^{-2}$ the intensities of the S(2) and S(3) lines of H$_2$ depend on the FUV intensities while for $G_0/n > 10^{-2}$ the same intensities are indicators of the densities (Kaufman et al., 2006). At the selected positions, the FUV radiation field lies between $10^3$--$10^4$, which implies that $G_0/n = 10^{-2}$ corresponds to n=$10^2$--$10^3$ cm$^{-3}$. For most positions the [O I]145 and H$_2$ line intensities indicate $n \sim 10^4$ cm$^{-3}$ while $^{13}$CO(6–5) where detected suggest $n > 10^5$ cm$^{-3}$. For most positions, the observed $^{13}$C I intensities exceed the intensities predicted by the model corresponding to the densities indicated by the [O I]145 and the
Table 3. Results of fitting Gaussian profiles with single velocity components to observed spectra at selected positions. $N(C^+)$ is calculated assuming the lower limits of kinetic temperature, $T_{kin}$ from Table 2.

| $(\lambda\nu, \Delta\nu)$ | Transition | $T$ K km s$^{-1}$ | $v_{vel}$ km s$^{-1}$ | $\Delta v$ km s$^{-1}$ | $N(C^+)$ cm$^{-2}$ |
|--------------------------|------------|------------------|-----------------|-----------------|-----------------|
| (-61,45) | $[1^3C]\eta$ | $3.99 \pm 0.38$ | $2.97 \pm 0.1$ | $1.74 \pm 0.2$ | $2.8(18)$ |
| $[O\eta]\alpha$ | $70.77 \pm 0.33$ | $2.67 \pm 0.1$ | $1.79 \pm 0.1$ | |
| $^{13}\text{CO}(6-5)$ | $38.62 \pm 0.22$ | $2.71 \pm 0.1$ | $1.65 \pm 0.1$ | |
| $^{13}\text{C}^+$(3-2) | $19.25 \pm 0.09$ | $3.08 \pm 0.1$ | $1.09 \pm 0.1$ | |
| $H_2$ S(2) | | | | $1.5 \times 10^{-4}$ |
| $H_2$ S(3) | | | | $1.0 \times 10^{-4}$ |
| $(-33,6)$ | $[1^1C]\eta$ | $5.33 \pm 0.42$ | $2.55 \pm 0.1$ | $3.08 \pm 0.3$ | $3.8(18)$ |
| $[O\eta]\alpha$ | $50.77 \pm 0.47$ | $2.45 \pm 0.1$ | $2.55 \pm 0.1$ | |
| $^{13}\text{CO}(6-5)$ | $12.62 \pm 0.68$ | $3.4 \pm 0.1$ | $1.03 \pm 0.1$ | |
| $^{13}\text{C}^+$(3-2) | $6.73 \pm 0.11$ | $3.06 \pm 0.1$ | $0.90 \pm 0.1$ | |
| $H_2$ S(2) | | | | $1.0 \times 10^{-4}$ |
| $H_2$ S(3) | | | | $2.0 \times 10^{-5}$ |
| $(-31,31)$ | $[1^1C]\eta$ | $4.34 \pm 0.29$ | $4.02 \pm 0.1$ | $2.28 \pm 0.2$ | $3.4(18)$ |
| $[O\eta]\alpha$ | $48.21 \pm 0.47$ | $3.90 \pm 0.1$ | $3.02 \pm 0.1$ | |
| $^{13}\text{CO}(6-5)$ | $11.48 \pm 0.60$ | $3.5 \pm 0.1$ | $0.97 \pm 0.1$ | |
| $^{13}\text{C}^+$(3-2) | $10.83 \pm 0.10$ | $3.10 \pm 0.1$ | $0.90 \pm 0.1$ | |
| $H_2$ S(2) | | | | $1.2 \times 10^{-4}$ |
| $H_2$ S(3) | | | | $3.5 \times 10^{-5}$ |
| $(32,23)$ | $[1^1C]\eta$ | $3.34 \pm 0.35$ | $4.25 \pm 0.2$ | $2.74 \pm 0.3$ | $3.0(18)$ |
| $[O\eta]\alpha$ | $19.17 \pm 0.50$ | $3.45 \pm 0.1$ | $2.93 \pm 0.1$ | |
| $^{13}\text{CO}(6-5)$ | $4.77 \pm 0.09$ | $3.20 \pm 0.1$ | $1.09 \pm 0.1$ | |
| $^{13}\text{C}^+$(3-2) | | | | $3.0 \times 10^{-5}$ |
| $H_2$ S(2) | | | | $1.1 \times 10^{-5}$ |
| $H_2$ S(3) | | | | $1.1 \times 10^{-5}$ |
| $(60,45)$ | $[1^1C]\eta$ | $1.95 \pm 0.24$ | $3.91 \pm 0.2$ | $2.20 \pm 0.3$ | $1.3(18)$ |
| $[O\eta]\alpha$ | $24.27 \pm 0.67$ | $3.58 \pm 0.1$ | $2.42 \pm 0.1$ | |
| $^{13}\text{CO}(6-5)$ | $6.50 \pm 0.10$ | $3.23 \pm 0.1$ | $0.81 \pm 0.1$ | |
| $^{13}\text{C}^+$(3-2) | | | | $8.8 \times 10^{-5}$ |
| $H_2$ S(2) | | | | $1.4 \times 10^{-4}$ |
| $H_2$ S(3) | | | | $1.4 \times 10^{-4}$ |

* $H_2$ data taken from Larsson & Liseau (2013) and intensities expressed in units of erg sec$^{-1}$ cm$^{-2}$ sr$^{-1}$.

Fig. 14. Comparison of distribution of $[C\eta]$, $[O\eta] 145\mu m$, CO(6-5) and HCO$^+$(4-3) emission vis-a-vis the column density, dust temperature and FUV intensities estimated from PACS continuum data observed as part of Herschel Gould Belt Survey. The color scales are shown to the extreme right of each row of panels. The contour levels for $[C\eta]$, $[O\eta] 145\mu m$ and HCO$^+$(4-3) are at 20-100% (in steps of 10%) of the peak values of 191, 88 and 14 K km s$^{-1}$ respectively. For CO(6-5) the contours are at 40-100% of the peak of 136 km s$^{-1}$. Circles drawn correspond to radii of 45” and 75”.

Estimated range of FUV radiation fields, by factors of 1.2-3. The largest discrepancy, a factor of 3-6, is seen at the position (-33,6). Additionally, the model predictions for the $[O\eta] 145\mu m$ intensity ratios indicate unrealistically high (for $^{13}\text{C}^+$(3-2) emission) densities at all positions, that is not corroborated by the high-density tracers such as CO(6-5) and HCO$^+$(4-3).

Comparison of the observed emission from the S1 PDR with models clearly shows the contributions of gas at primarily three different density regimes, $10^5$–$10^6$ cm$^{-3}$, $10^3.5$–$10^4.5$ cm$^{-3}$ and $< 10^5$ cm$^{-3}$, although the $[C\eta]$ emission is significantly under-produced by the models as is seen both from the $^{13}\text{C}^+$(3-2) intensity and the $[O\eta] 145\mu m$ intensity ratio. The highest density regions are traced by $^{13}\text{CO}(6-5)$ and to some extent by $[O\eta] 145\mu m$. Additionally, $[O\eta] 145\mu m$ emission is excited in the medium density gas as well, which is also traced by the $H_2$ S(2) and S(3) lines. The most diffuse component is primarily traced by the $[C\eta]$, and for the positions (-33,6) and (-61,45), the observed intensities, estimated to be only from the diffuse component still far exceed the values predicted by the PDR models.

The lower $^{13}\text{C}^+$(3-2) intensities and correspondingly high $[O\eta] 145\mu m$ ratio predicted by the face-on uniform density plane-parallel PDR models can not both be explained either by stacking layers of such PDRs along the line-of-sight or by changing the viewing angle of the model. The most plausible explanation for higher observed $^{13}\text{C}^+$(3-2) intensities relative to $[O\eta] 145\mu m$ intensity is in terms of the higher filling factor of the $[O\eta]$ emission, which typically should have significant contribution from the diffuse.
gas than from the high density gas emitting mostly in [O ii]145. Such discrepancies are also expected to arise from the shadowing effects of clumps as well penetrability of non-uniform density PDRs consisting of clump and inter-clump gas (Suzuki et al. 1988). Use of three-dimensional PDR models with inhomogeneity is needed, however such models also involve additional parameters which need to be pre-determined using other observational constraints. In the case of the S 1 PDR, the self-absorption of the main PDR tracers and the complex geometry of the region does not allow us to further observationally constrain the parameters for such clumpy PDR models. Qualitatively we can conclude that the fraction of $^{13}$C/H intensity putatively arising from diffuse PDR gas being higher towards the west of S 1 is likely to be an indicator of increased clumpiness towards the west.

5. Discussion & Conclusion

Presence of multiple emission and absorption components along the line of sight towards the PDR associated with the S 1 star in the $\rho$ Ophiuchus molecular cloud, results in complicated spectra that are difficult to interpret. In this region, the emission arising from the PDR as well as the molecular cloud overlap, and spectra are self-absorbed and there are additional foreground filaments which cross-cut the region. The S 1 PDR is restricted by the dense Oph A molecular cloud to the west and south-west and appears to be expanding freely to the east. The PDR is tilted and somewhat warped with the front surface (facing the observer) of the south-eastern side of the cavity being very dense and on the NW side the cloud is denser on the back side. The gas distribution in the PDR is rather inhomogeneous with clumps and ridges arising due to the disruption of the dense ambient molecular cloud by the radiation from the star S 1 and also by the embedded YSOs. Analysis of the emission from the photon dominated gas suggests the presence of at least three density components consisting of high density ($10^5$ cm$^{-3}$) clumps and medium density ($10^3$ cm$^{-3}$) and diffuse ($10^2$ cm$^{-3}$) interclump medium.

Using the velocity information and the optically thin spectra of $^{13}$C [I] and [O ii]145 $\mu$m we have shown that the absorption features in [C II] and [O II] 63 $\mu$m arise due to the foreground layers of the same PDR. The ratio of column densities of C$^+$ and O$^+$ in the diffuse foreground PDR layers, within the limits of uncertainties introduced particularly by the assumed value of the scaling factor for the [O II] lines is between 2–3, which is comparable to the solar [O]/[C] abundance ratio of 3.5. Spectral analysis of our data allows to qualitatively constrain the temperature of the absorbing layers. The presence of heavy foreground absorption in the [O II]63 spectra, but the complete absence of self-absorption in the [O II]145 line profiles suggests a low-excitation status of the foreground gas - low compared to the energy of the $\text{OI}$ 3$P_1$ level which is 227 K above ground. On the other hand, the prominent self-absorption in the CO(6–5) line points to a somewhat elevated temperature of the absorbing gas, sufficient to populate the J=5 level (80 K above ground).

The [C II] spectra show the self-absorption dips even far to the east and the rarer isotope $^{13}$C$^+$ has been detected at a large number of positions, suggesting an N(C$^+$)~ of a few times $10^{18}$ cm$^{-2}$ over an extended region. The estimated N(C$^+$) lie within the typical range of values between $10^{18}$–$10^{19}$ cm$^{-2}$ that is found in Galactic PDRs (Ossenkopf et al. 2013; Mookerjea et al. 2019). The H$_2$ column density estimated from dust continuum emission maps range between 1–2.5$10^{19}$ cm$^{-2}$ at these positions. This suggests values of [C$^+$/H$_2$] ranging between (1.5–4.8) $10^{-4}$ which leads to C$^+$/H = (0.8–2.4) $10^{-4}$. The derived value of C$^+$/H is consistent with the value C$^+$/H = 1.5$10^{-4}$ obtained considering solar abundance with the assumption that half of the carbon is in C$^+$. The uncertainties in the value of N(C$^+$) arise due to the assumed values of T$_{\text{kin}}$ used, which were derived from the peak of the planck-corrected [C II] spectra (Sec. 3.4) and are likely a lower limit to the temperature.

Based on the comparison of the observed intensities with the PDR models (Fig. 15) we have identified the range of densities which could explain the [O II] 145 $\mu$m intensities. We find that for the [O II] 145 $\mu$m peak, densities between $10^3$–$10^4$ cm$^{-3}$ can explain the [O II]145 intensities. Using non-LTE approximations, the observed intensities for these densities can only be explained by T$_{\text{kin}}$> 100 K (consistent with our derived T$_{\text{kin}}$ of 157 K) and for N(O II) between (1.5–3)$10^{19}$ cm$^{-2}$. Similar considerations suggest that for the positions (-33,6) and (-31,-31) the observed intensities can be explained by a T$_{\text{kin}}$ of 100 K and N(O II) of (2–3)$10^{19}$ cm$^{-2}$ for n = $10^3$ cm$^{-3}$. For these two positions the lower-density-higher-G$_0$ solution require T$_{\text{kin}}$ = 120 K and N(O II) = 5$10^{19}$ cm$^{-2}$. However, we emphasize that it is likely that both the high- and low-density gas with possibly different filling factors contribute to the emission. For positions to the west of S 1, as pointed out earlier, the FUV flux derived from FIR intensities is lower than the value expected from the estimated stellar radiation since part of the radiation is not intercepted by dust. For these positions the higher FUV radiation values corresponding to the geometrically diluted stellar radiation are likely to be a closer representation of reality. The densities at these positions are thus ~ $10^2$–$10^3$ cm$^{-3}$, which correspond to N(O II)~ $10^{19}$ cm$^{-2}$ for T$_{\text{kin}}$ = 100 K.

Most of the observed [O II] 145 $\mu$m intensities can be explained by N(O II) between (1–3)$10^{19}$ cm$^{-2}$. On the other hand, the column density N(O II) of the self-absorbing gas dominating the [O II] 63 $\mu$m profile is only one-tenth of the O$^+$ column density, which shows up in emission. The total N(O II) estimated for the S 1 PDR is similar to the column densities (> $10^{19}$ cm$^{-2}$) seen in dense molecular gas in sources like OM C-1 (Herrmann et al. 1997) and L1689N (Caux et al. 1999). Typical values of N(O II) estimated from observations lie between $10^{18}$–$10^{19}$ cm$^{-2}$ (Vastel et al. 2003, 2002).

We estimate the gas pressure to be in the range of $10^6$ – $10^8$ K cm$^{-3}$ for densities between $10^3$–$10^4$ cm$^{-3}$ and temperatures, T$_{\text{kin}}$, of 60–120 K in the three gas components we identified. The ambient high density cloud that harbors the $\rho$ Oph A region to the west with typical temperature of 10–20 K and density of $10^4$ cm$^{-3}$ (Liseau et al. 2015) has a thermal pressure of around $10^5$ cm$^{-3}$. Although we have detected photoevaporation flows, no streaming motions indicative of large pressure gradient were observed in the PDR and to the west, where it interfaces with the high density molecular cloud. Interestingly, for an assumed temperature of T$_{\text{kin}}$ of 100 K, the density of the PDR gas primarily contributing to the thermal pressure and maintaining equilibrium at the interface with the molecular gas, would be $10^5$ cm$^{-3}$. This is consistent with the medium density interclump medium as identified from our analysis of the emission from the PDR gas.

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