# An upGREAT view of the S1 PDR in Rho Ophiuchus

**Bhaswati Mookerjea**
Tata Institute of Fundamental Research, Mumbai, India

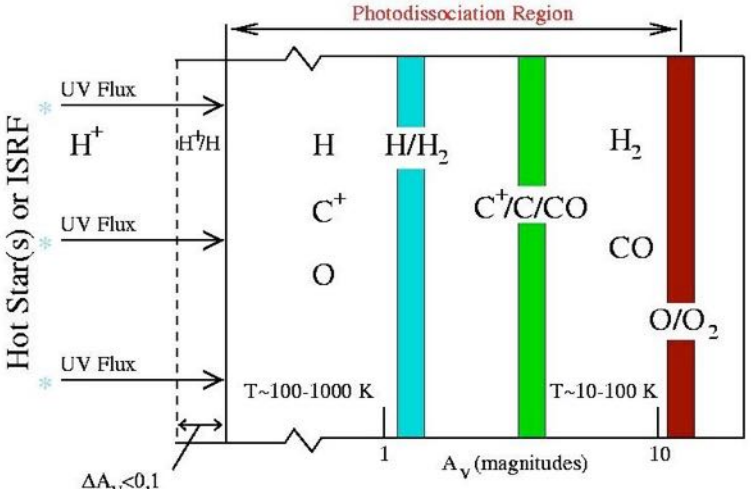
Co-authors: G. Sandell, V. S. Veena, R. Guesten,
D. Riquelme, H. Wiesemeyer, F. Wyrowski & M. Mertens

12 May 2021

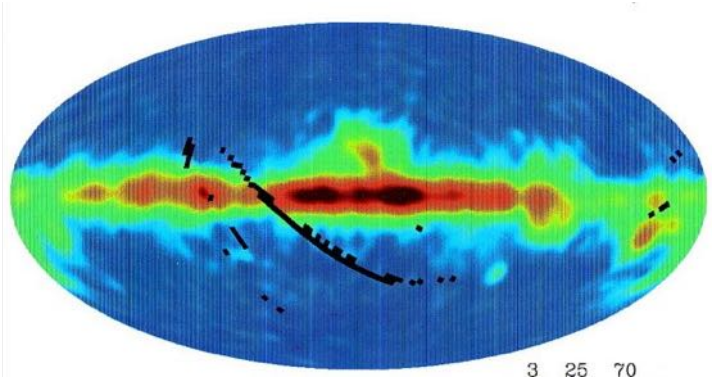
SOFIA Teletalk

# Photon Dominated or Photodissociation Regions (PDRs)

- Extremities of molecular clouds illuminated by radiation from massive stars ⟶ transition regions ionized-atomic-molecular ⟶ associated primarily with neutral (atomic/molecular) hydrogen
- Mapping observations of limited regions in fine structure transition of $C^+$ at 158 μm revealed association with molecular cloud & extended nature of the emission
- Tracers: Far-IR fine structure lines of $C^+$ (158 μm) and $O^0$ (63 & 145 μm)




**COBE 158 μm [C II] Map**

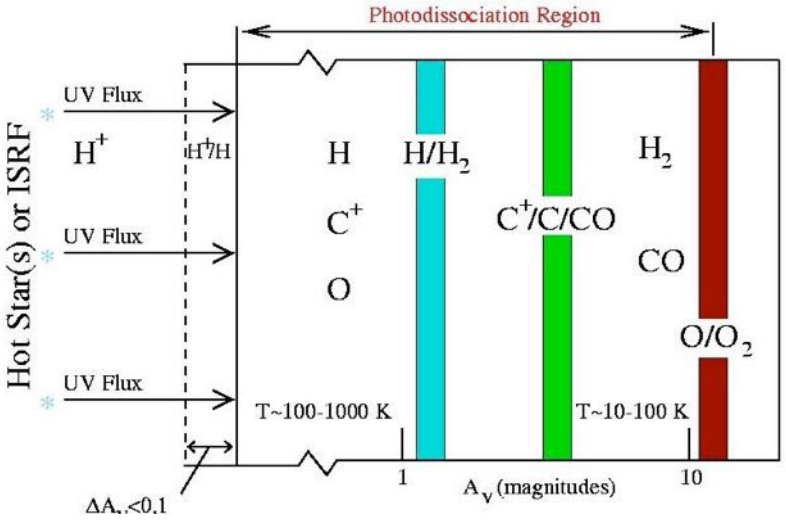


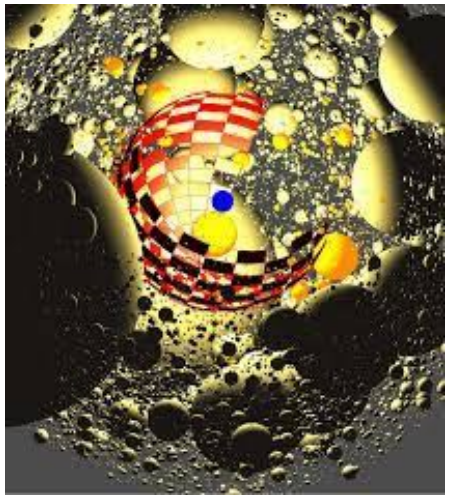

Established [C II] as an additional probe for neutral photo-irradiated gas (atomic/molecular)

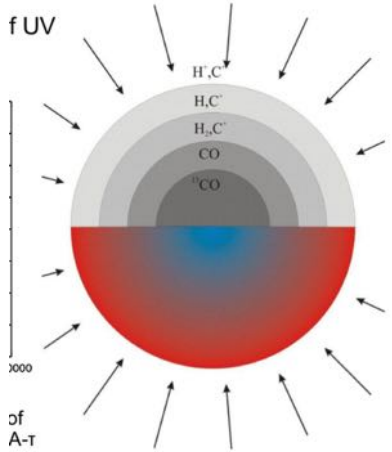
- PDRs account for most of the neutral mass of ISM
- Emit strongest cooling lines ⟶ structure formation
- Trace the impact of massive stars on the ISM
- Indicators of star formation and galaxy evolution

# Far-infrared Spectroscopy of PDRs

Detailed structure depends on far-UV flux and density (distribution/clumpiness)

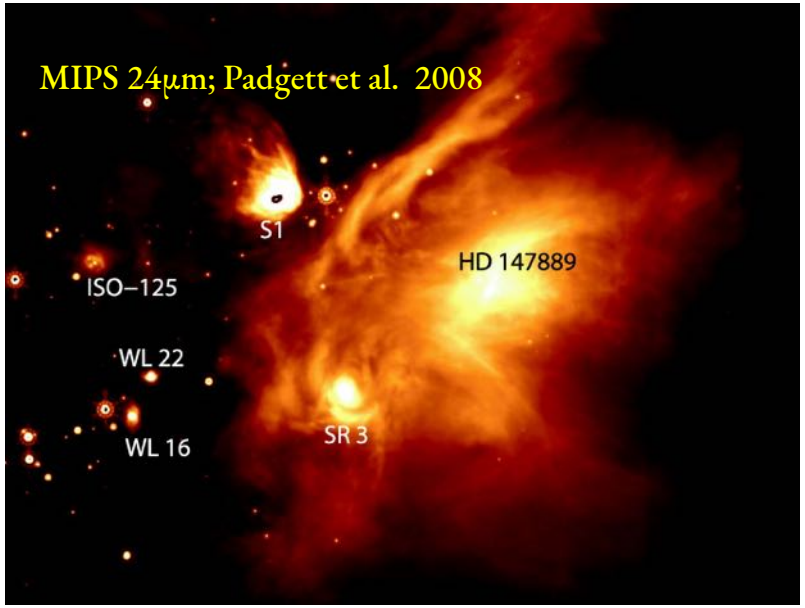


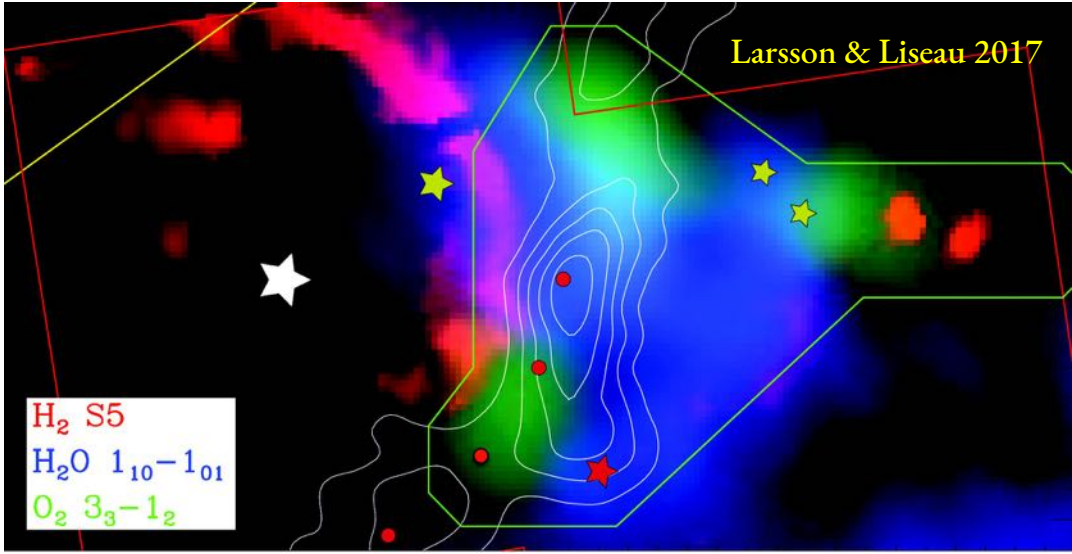






- Inhomogeneity ⟶ radiative transfer can not be simply described by an average Av
- Deeper penetration of FUV radiation & Larger number of PDR surfaces ⟶ Observed [C II] intensities often not reproduced by homogeneous slab models

# S1 PDR in Rho Ophiuchus

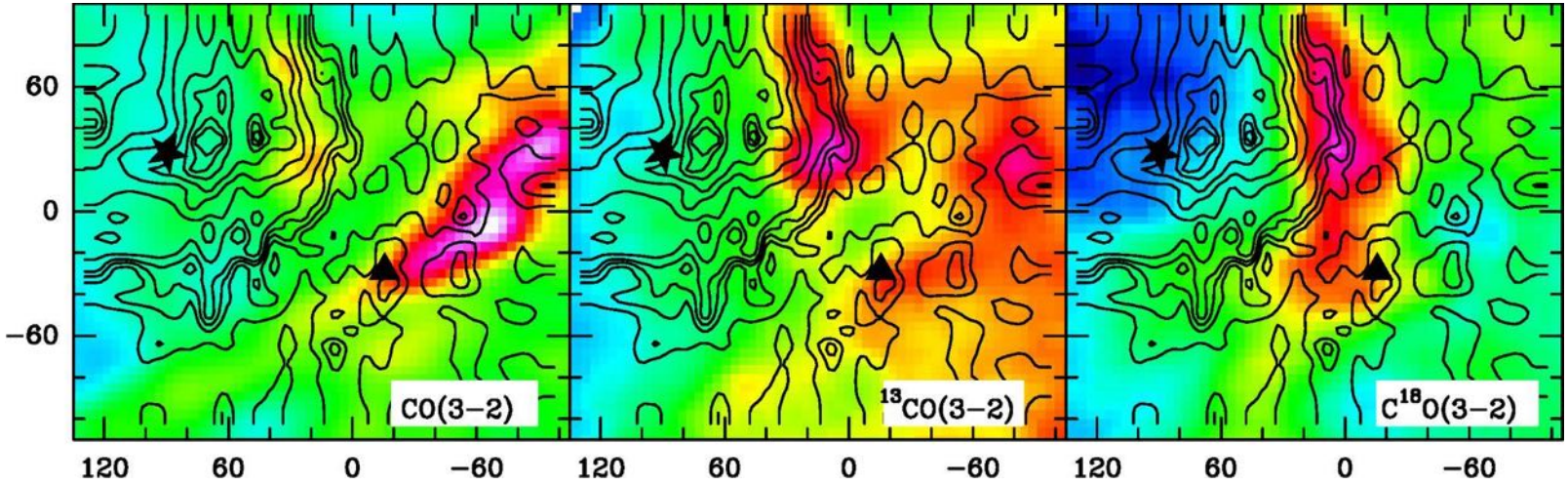



- Located in the nearby (137pc) star forming cloud Rho Oph, illuminated by the B3 V star S1 ($A_v$=13 mag)
- PDR is restricted to the west and southwest by the dense molecular ρ Oph A ridge, expanding more freely into the diffuse low-density cloud to the northeast
- Larsson & Liseau (2017) used ISO-LWS data to observe the PDR shell and concluded that [O I]63 is absorbed by a foreground layer that was optically thin in [O I] 145

# S1 PDR in Rho Ophiuchus

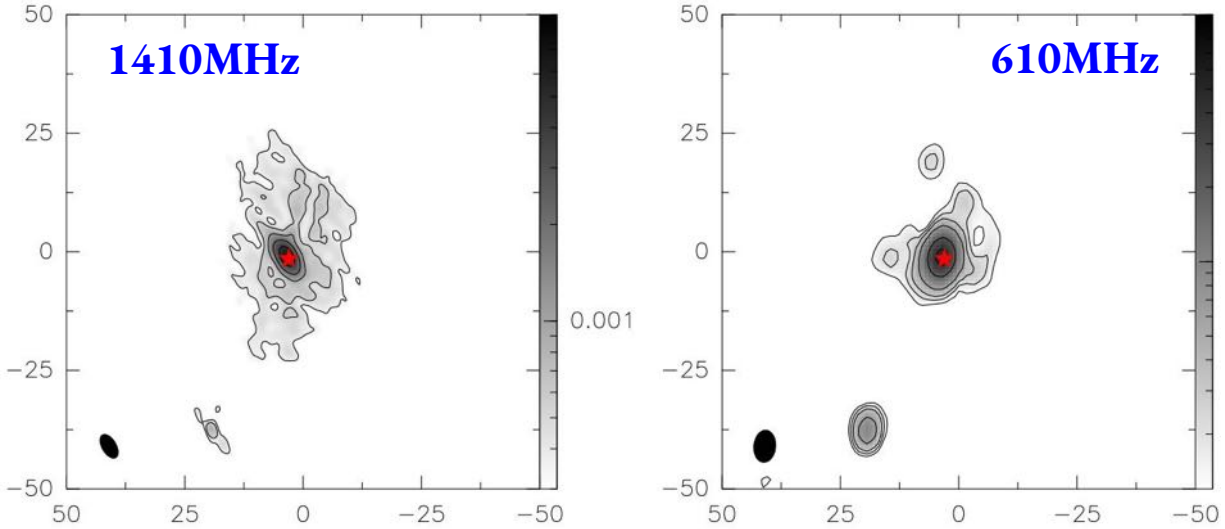
MOOKERJEA ET AL (2018)




- PDR confined in the large egg-shaped cavity and [CII] is blue-shifted relative to the ambient cloud (Mookerjea et al 2018)
- Followed up with maps of radio continuum, H I at 21 cm, [C II], [O I] 63 and 145 μm, CO(6-5), and $HCO^+$(4-3) to study morphology & kinematics of the PDR

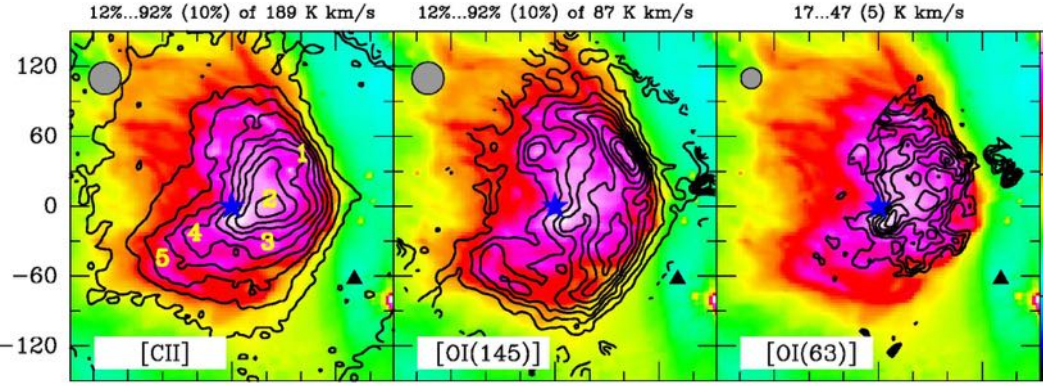
# Ionized Gas Distribution : GMRT Observations

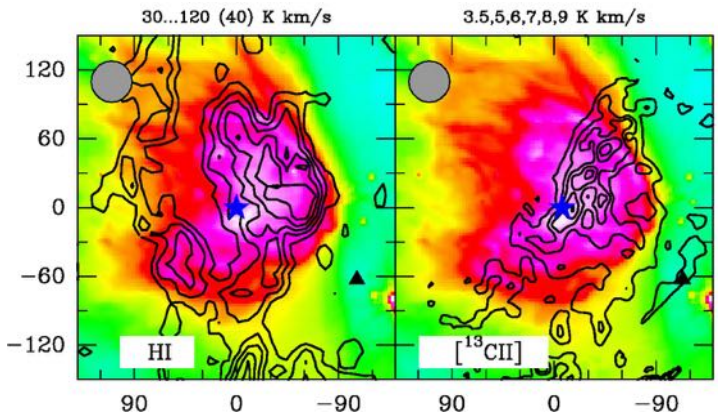
MOOKERJEA ET AL (2021)

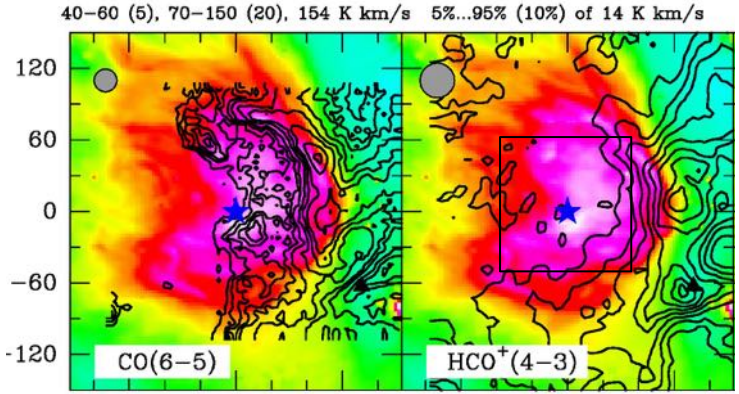



- Assuming diffuse emission at 1420 MHz to be optically thin, → $N_{Lyc} = 6.7 \times 10^{43}$ $s^{-1}$ for $T_e = 8200$ K and D = 137pc
- S 1 is most likely B2.5V or B3V, consistent with the SED fit suggesting B3V for Av=13.3mag (Mookerjea et al 2018)

# Atomic, PDR & Molecular Gas around S1



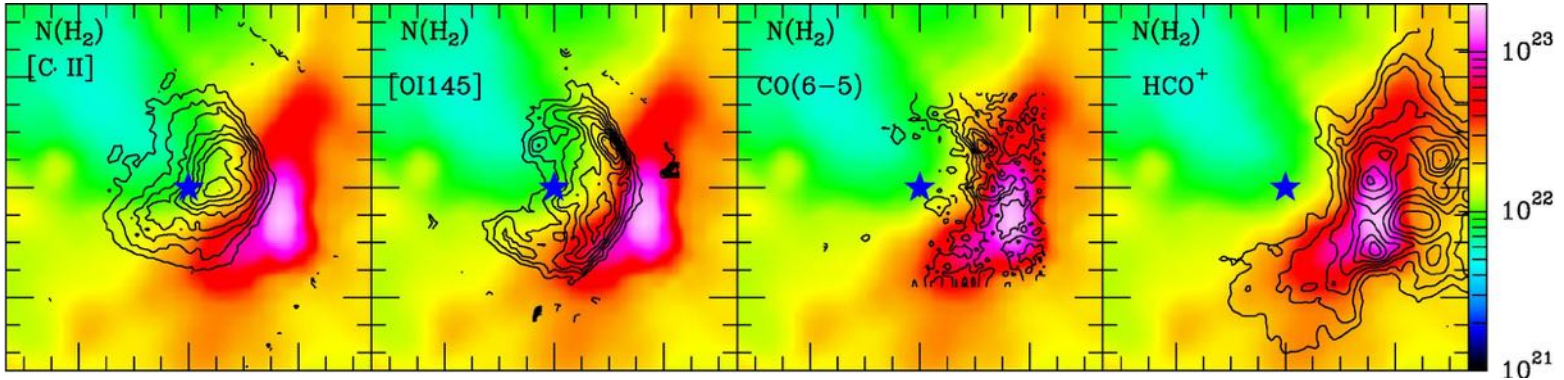



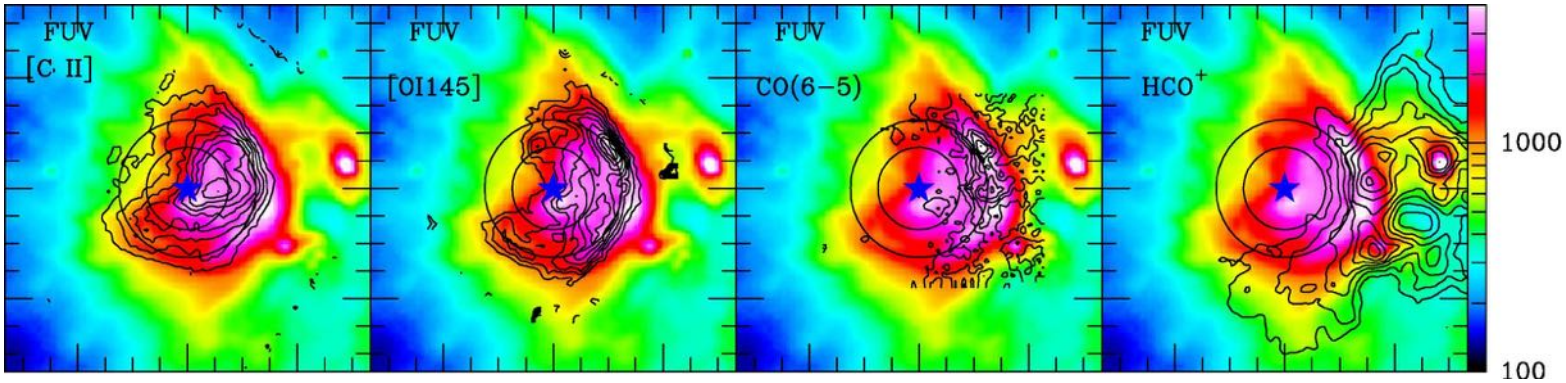

- IRAC 8 micron (Color plot)
- [C II] at 158 & [O I] at 63 & 145 mic (upGREAT/SOFIA)
- CO(6-5) map (APEX)
- $HCO^+$(4-3) (JCMT)
- H I 21 cm (GMRT)
- [$^{13}$C II] also detected over an extended region

MOOKERJEA ET AL (2021)

# Atomic, PDR & Molecular Gas around S1

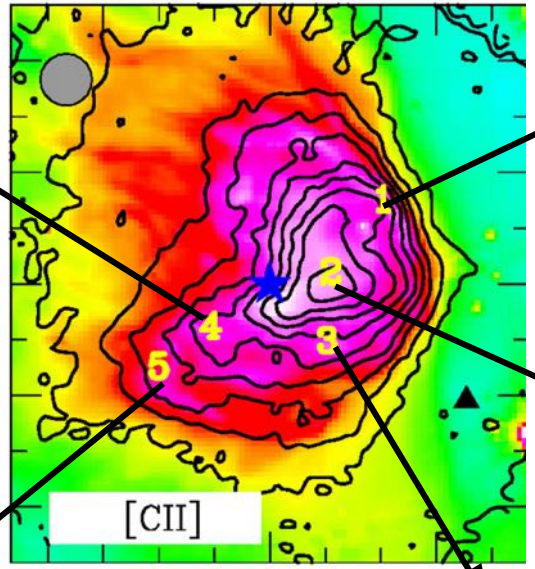


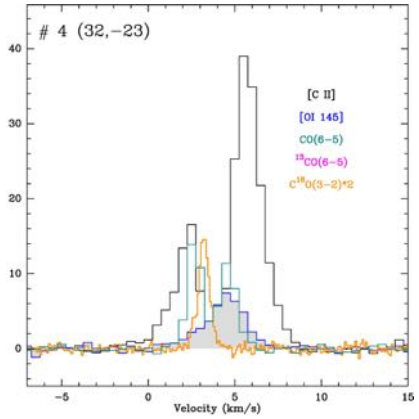

❑ Spatially [C II] and [O I] emission only from the PDR & not from ambient molecular cloud

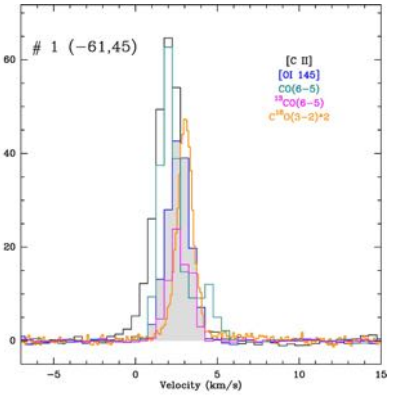


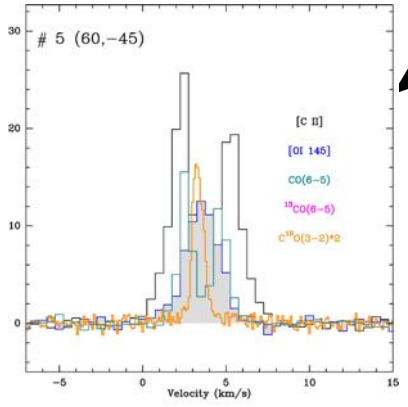

❑ FUV radiation from stellar content does not match the radiation field derived from far-infrared continuum emission ⟶ distribution of matter enhanced clumpiness to the north-west

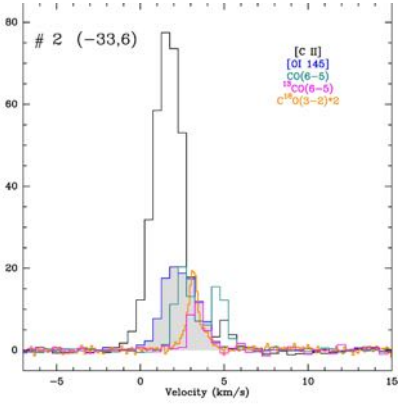
# Complex Emission Profiles

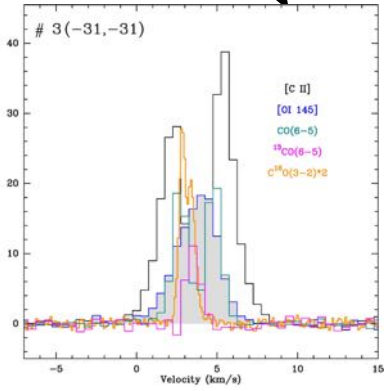


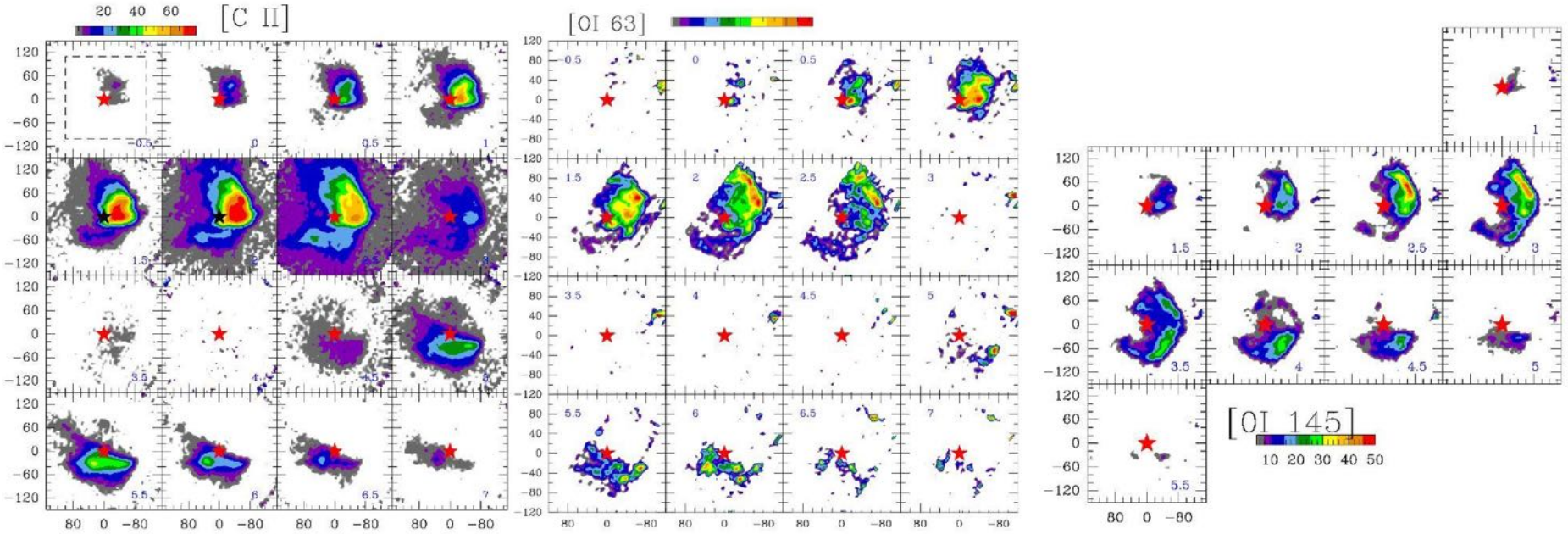



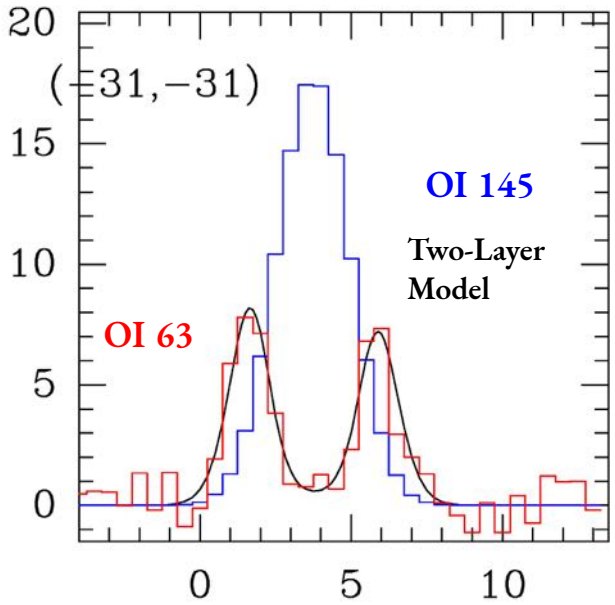
# Velocity-Channel Maps

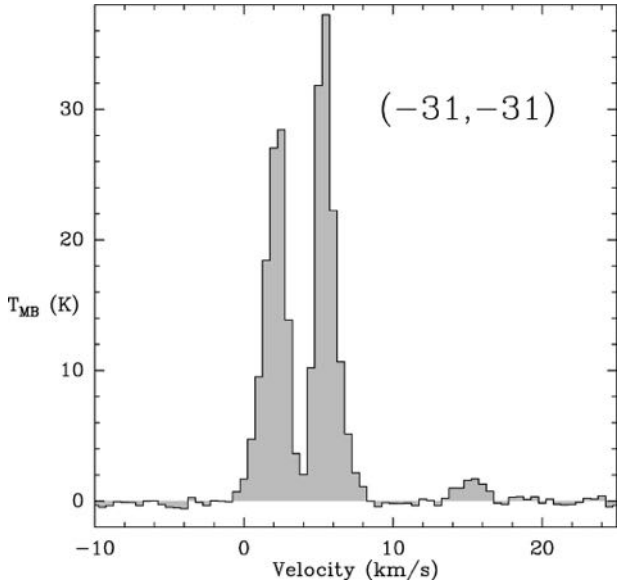


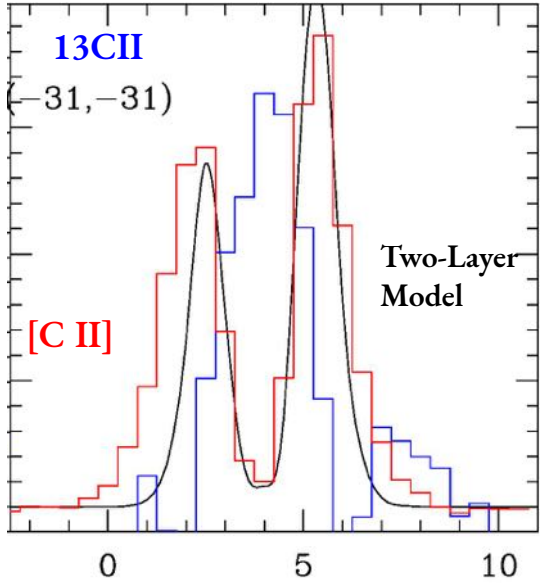

- Strongly self-absorbed spectra of [C II], [O I] 63 and H I at 21 cm over the entire face of the PDR
- [O I] 145 shows no self-absorption in the region
- PDR emission is strongly redshifted on the southeastern side & blue-shifted on the northwestern side of the nebula
- Strongly red-shifted east-west extended stream seen in [C II], [O I] 63 & H I

# Two-Layer Model for Emission from S1 PDR



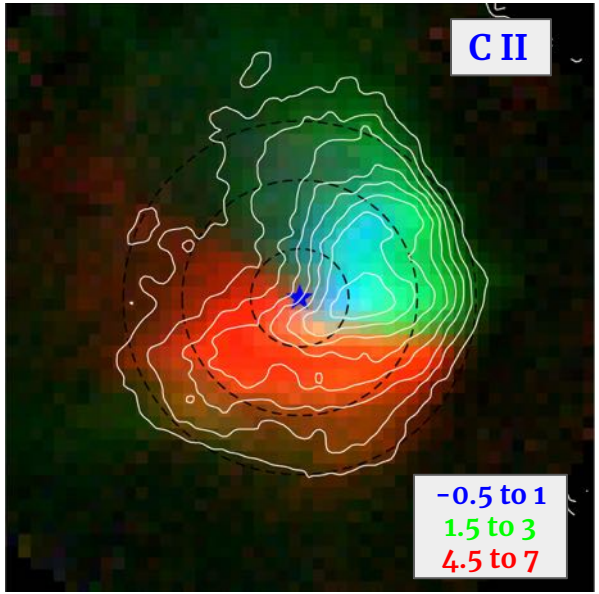


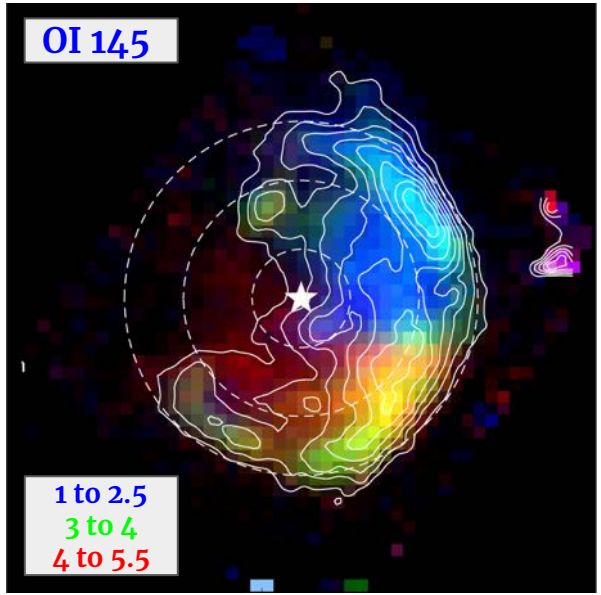



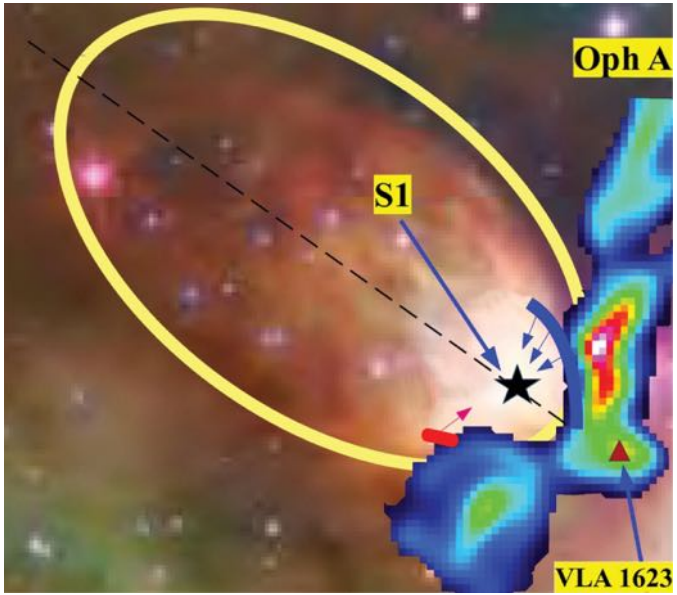




- Modeled in combination with optically thin [$^{13}$CII] & [O I] 145 →self-absorption arises due to colder foreground layer of the same PDR & not from ambient molecular gas
- From peak of optically thick [C II] lines → minimum $T_{kin}$ between 80-130 K
- Absence of [OI] 145 in absorption → $T_{kin}$ < 227K and presence of absorption in CO(6-5) → $T_{kin}$>80 K
- No large-scale streaming motion detected → red- and blue-shifted photo-evaporative flows constrain location of star relative the PDR & the observer

# Velocity & Morphology of S1 PDR



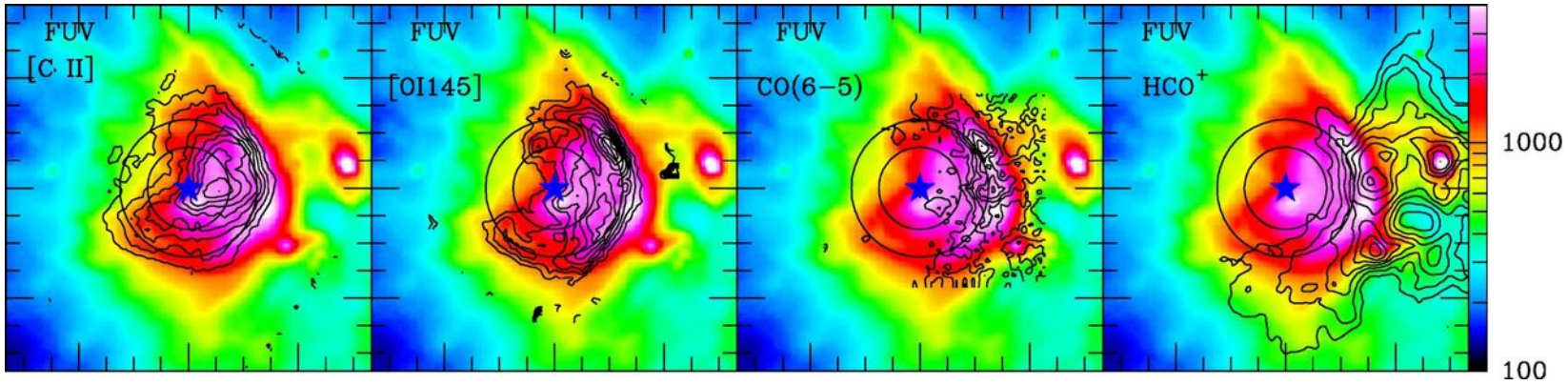




PDR is tilted and somewhat warped, with the front surface (facing the observer) of the southeastern side of the cavity being very dense, and on the NW side, the cloud is denser at the far side.

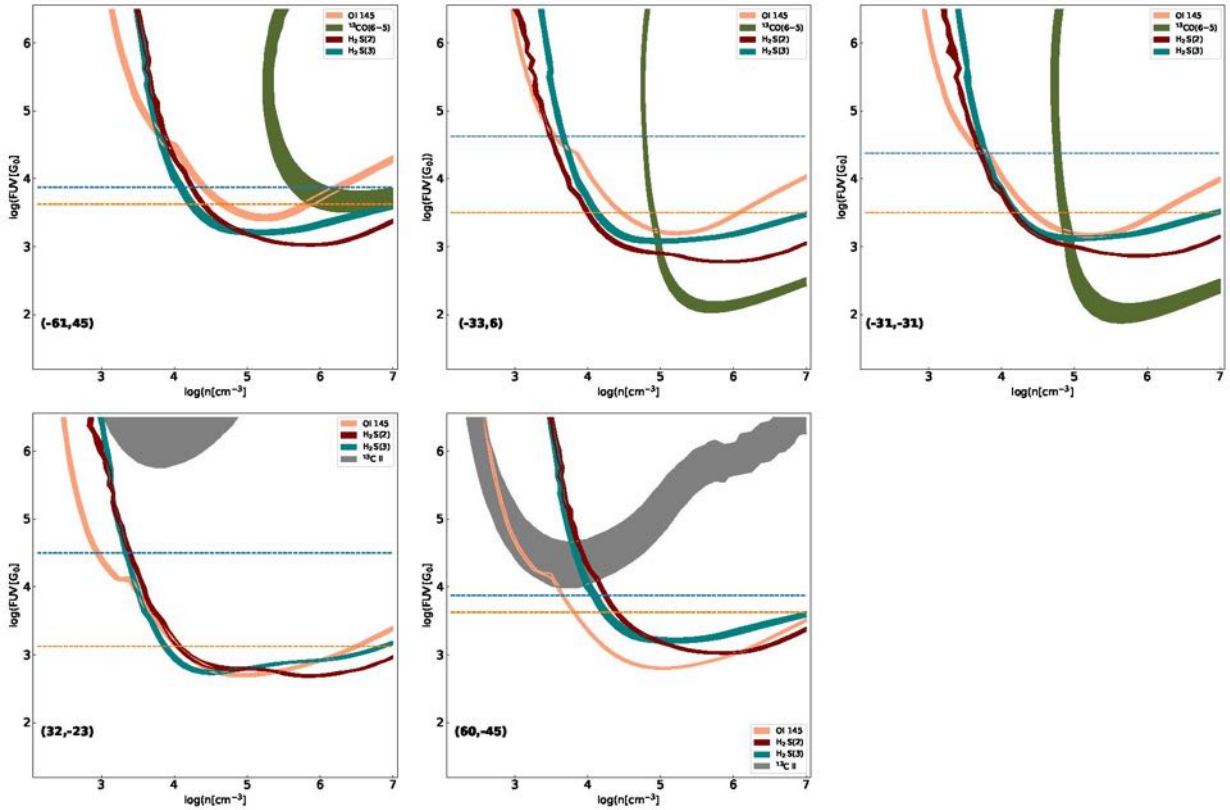
# Properties of the PDR






- Observed FIR distribution NOT symmetric about S1 ; lower than the value estimated for a B3 V star assuming only geometrical dilution ; discrepancy is more to the east than to the west :
  - FIR continuum arises from regions that are at much larger distances than the projected distance
  - FUV radiation escapes the region without being intercepted by material, particularly to the east and northeast
  - Presence of very high AV clumps, which attenuate the FUV drastically but are too small to be detected in single-beam continuum observations

# Properties of the PDR




- Compared observed intensities and ratios homogeneous plane-parallel PDR model (Kaufman et al 2006; Wolfire pvt comm)
- Models underpredict [$^{13}$C II] intensities (no other tracer used here is expected to have similar filling factors)
- High-density ($10^6$ cm$^{-3}$) clumps, medium-density ($10^4$ -$10^5$ cm$^{-3}$) and diffuse ($10^3$ cm$^{-3}$) inter-clump medium
- At the interface between the PDR and molecular region (10-20 K, $10^6$ cm$^{-3}$) pressure equilibrium maintained by the warm (200 K) medium density inter-clump gas

$H_2$ S(2) & S(3) : ISOCAM-CVF (Larsson & Lisseau 2017)

# Summary & Discussion



- Velocity-resolved spectra of both [O I] lines & optically thin [$^{13}$C II] line → characterization of the properties (temperature, density, morphology) of the PDR gas
- Comparison with PDR models & non-LTE radiative transfer models suggest N($C^+$) & N(O) between $10^{18}$-$10^{19}$ $cm^{-2}$
- Evidence for at least three density components of PDR gas uniquely traced by dedicated tracers
- Edge-on PDR shell is in pressure equilibrium with ambient molecular cloud hosting Rho Oph A
- Large-scale detection of [$^{13}$C II] and high opacity of [C II] emission over the entire PDR with line intensities far exceeding the predictions of homogeneous PDR models & hugely discrepant FUV estimates from different methods → complex clumpy distribution of material in S1 PDR
- PDR models with clumpiness are certainly better suited, however such models also have larger number of parameters for which constraints on initial guesses from observations are difficult