Velocity-Resolved Fine Structure Lines : Results from SOFIA


RCW49 (Image: Marc Pound)

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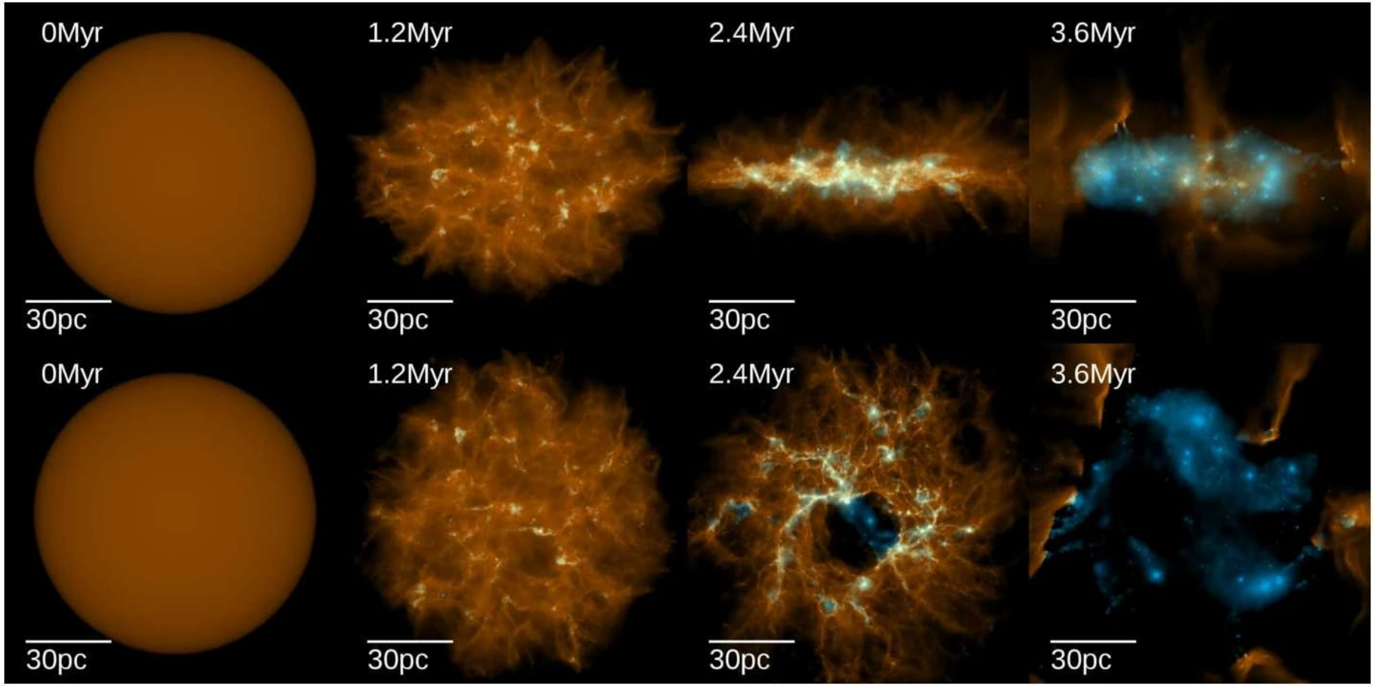
Future Role of FIR-Submm Observatories, Leiden

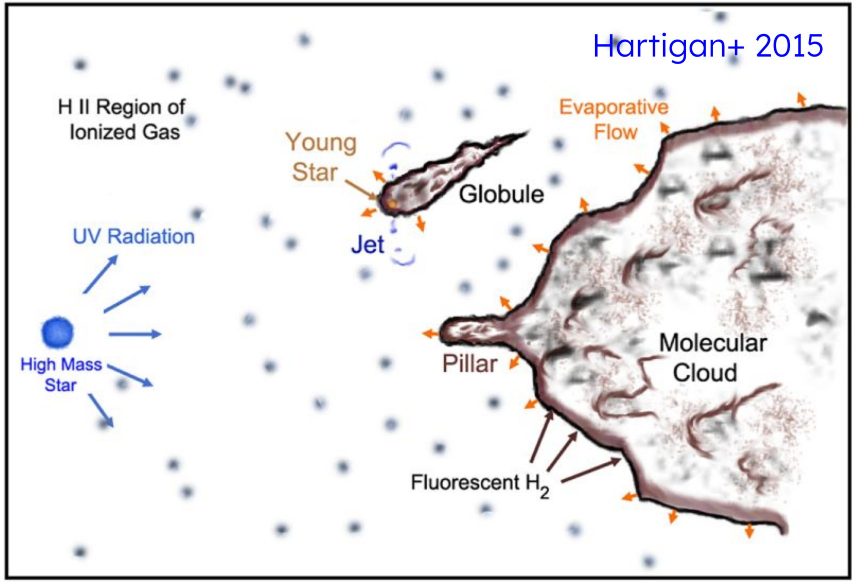
STAR FORMATION, STELLAR FEEDBACK & GALAXY EVOLUTION,

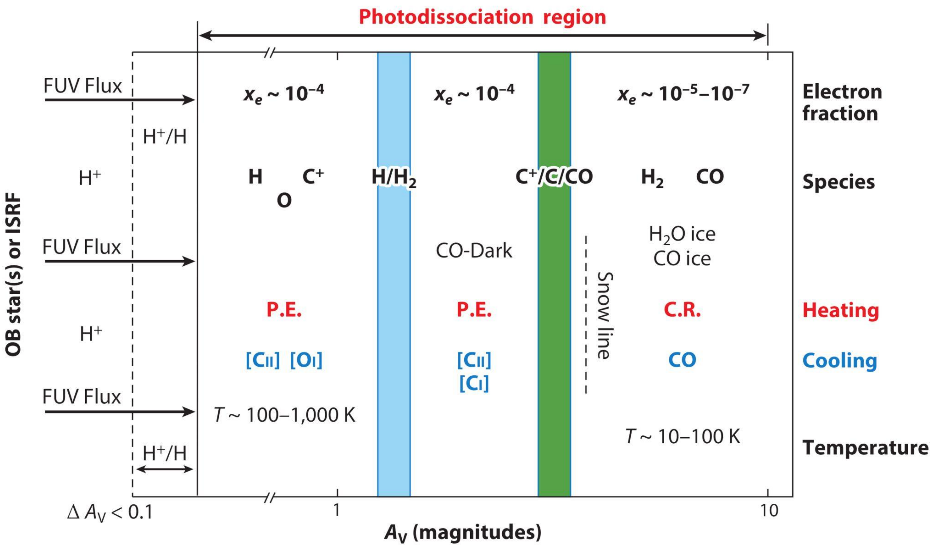


Numerical simulation of evolution of surface density of gas (orange) and stars (blue)

Grudic + 2018

FEEDBACK OF HIGH MASS STARS & PDRs





- Detailed structure of the regions with photon-dominated gas Wolfire+ ARAA 2022
- Transition from atomic to molecular gas
- Observations probe feedback from massive stars and triggered star formation

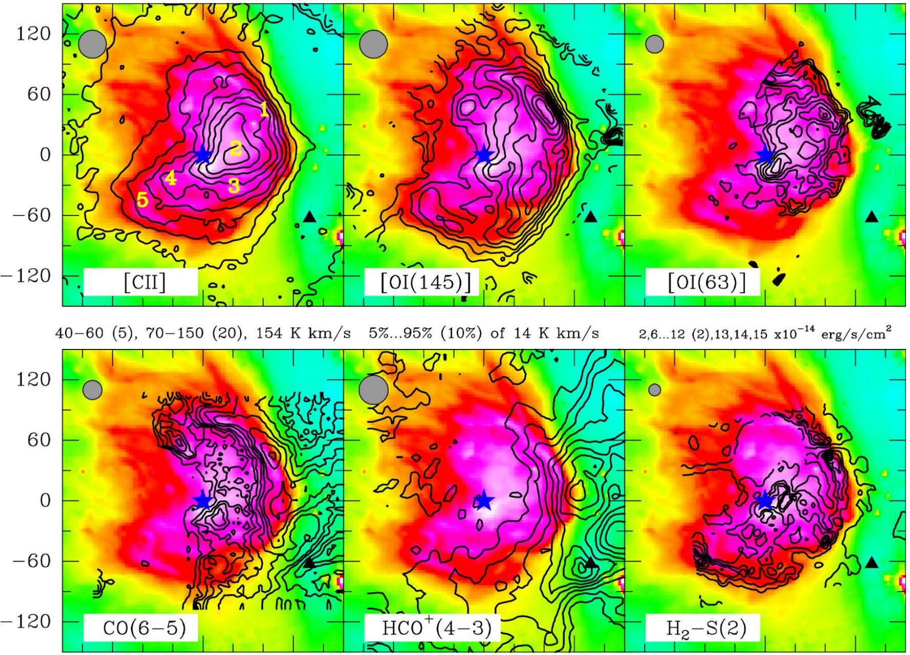
C^+ (158 μm) and O^0 (63 & 145 μm), C^0 (370 and 609 μm), Mid- & high-J CO rotational lines (>400 GHz)

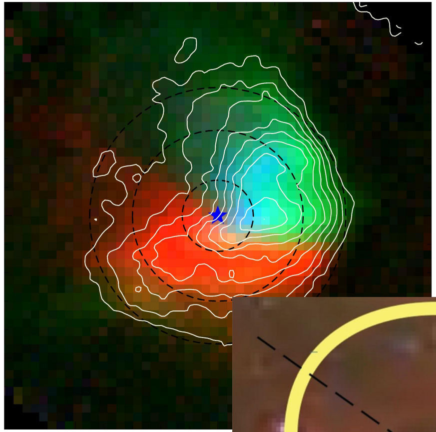
VELOCITY-RESOLVED FAR-INFRARED SPECTROSCOPY OF PDRs

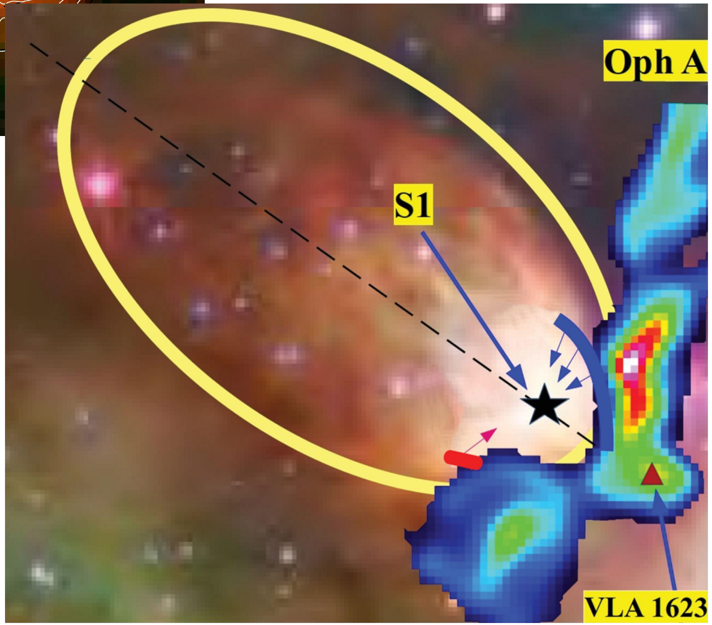
- Tomography of PDRs: 3-dimensional structure revealed through velocity information
- Properties & Energetics of PDRs: Comparison of emission from “same” gas → improved understanding of observed [C II] and [O I] intensities and contributions to cooling
- Mass, momentum & kinetic energy estimate of neutral gas – Stellar Wind or Thermal energy of ionized gas
- Discovery of neutral gas columns: [C II] emission (CO-dark gas), In absorption in [CII] & [OI] 63

Improve understanding of diagnostic powers of [C II] (multi-phase origin) & [OI 63]/[OI 145] (optically thick, absorption by cold foreground, masing of 145 line)

Structure of the S1 PDR in Rho Ophiuchus



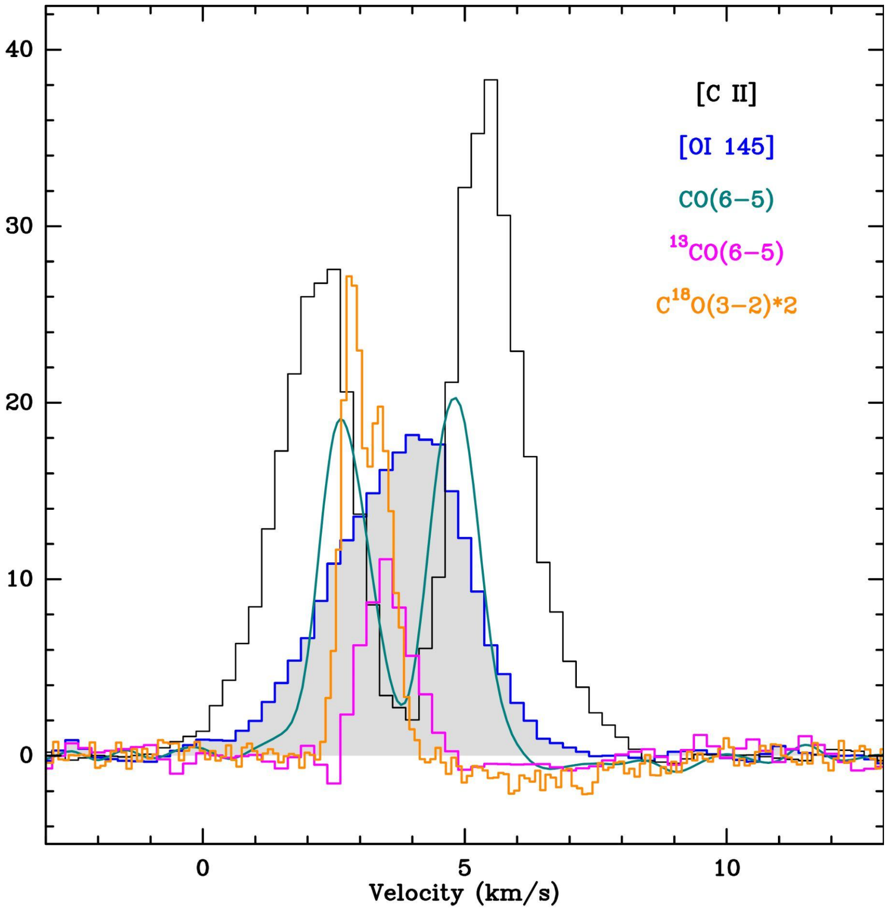


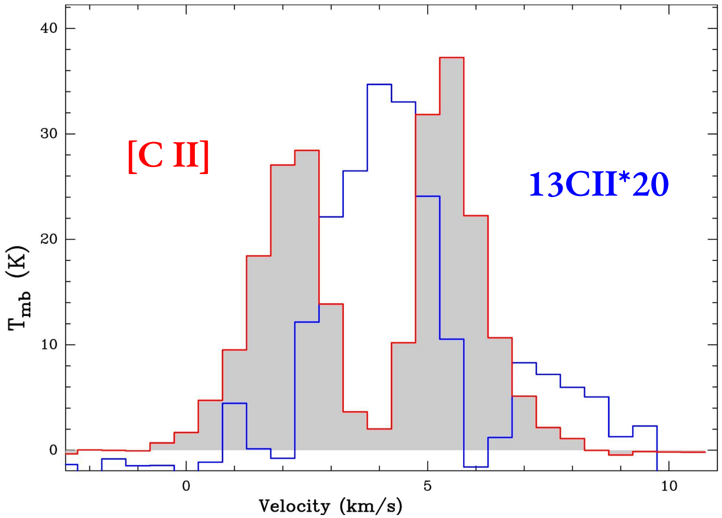


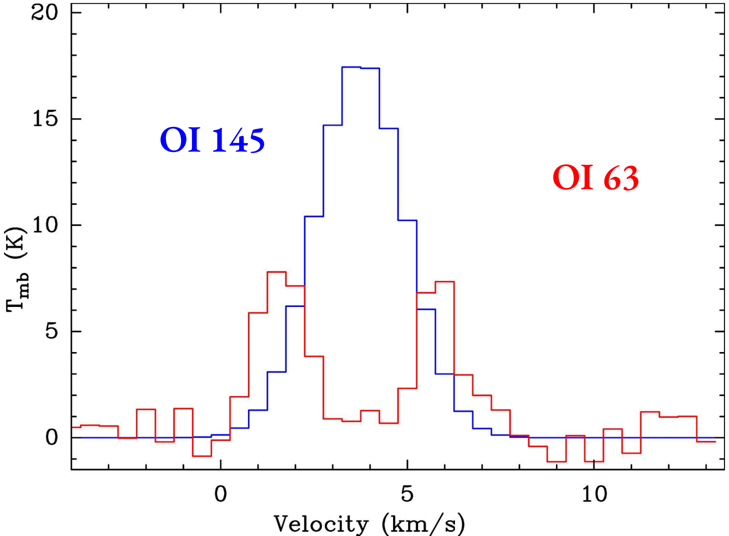
BM, Sandell, Guesten et al 2021

tifr

Emission & Absorption Dips in PDR spectra





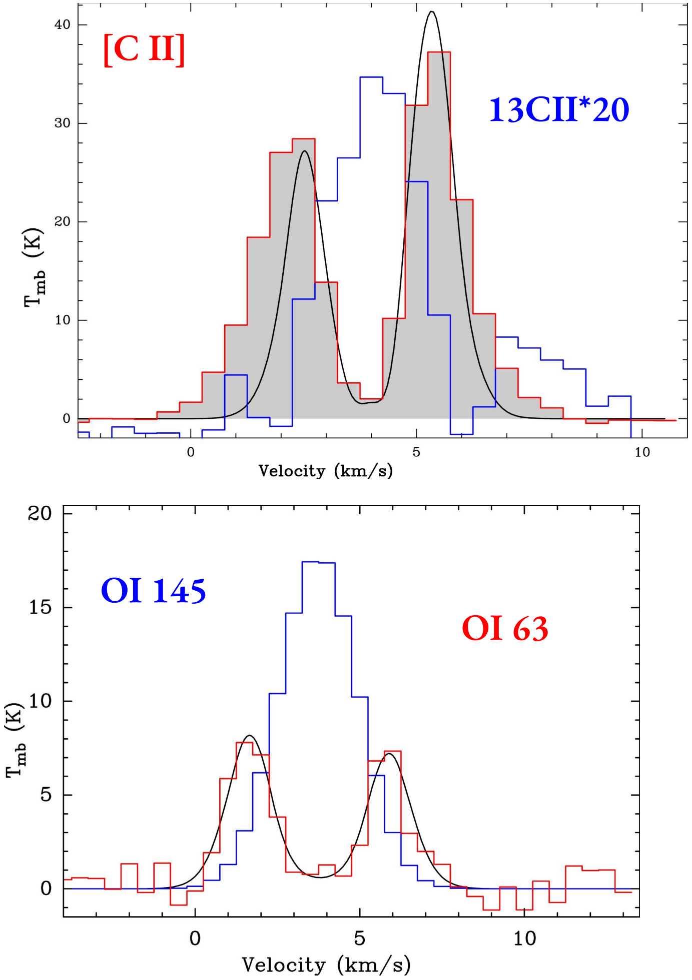


Two-Slab Model for Self-Absorbed [C II] & [O I] 63

- Optically thin [^{13}CII] & [O I] 145 are used as templates and scaled by the abundance and intensity (based on gas temperature & density) ratio
- Two layers of gas (hot PDR+Cold foreground)

$$T_{\rm obs}(v) = T_{\rm hot}(v)\exp\left(-\tau_{\mathbf{0}}\exp[-4\ln 2\,(v-v_{\mathbf{0}})^2/\mathbf{\Delta} v^{\mathbf{2}}]\right).$$

- Fitted velocity → cold foreground gas associated with the hot PDR & not just optical thickness
- Column of cold oxygen needed to fit observations N(O) ~ 0.4 – 1.3 × 10^{18} (Δv_{FWHM} /km s^{-1})
- Correction to the [O I] 63 μm line intensity due to self-absorption is typically estimated to be a factor of ~2–4



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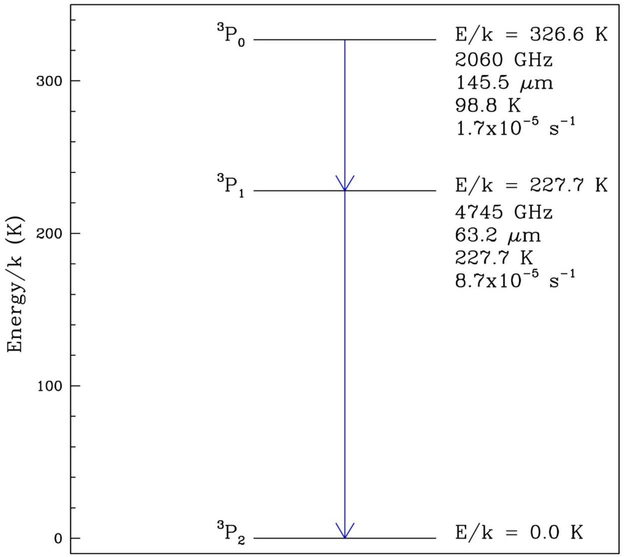
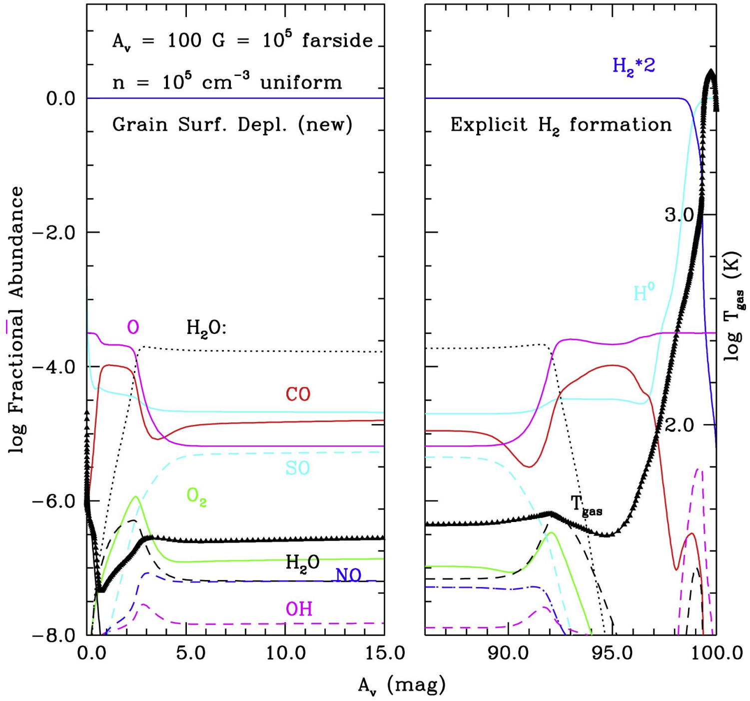
INSIGHT INTO ATOMIC OXYGEN WITH [O I] AT 63 & 145 MICRON

- [O I] 63 suspected to be optically thick based on [OI]145/[OI]63>0.1
- Velocity-resolved line observations → [OI] 63 self-absorbed but [O I] 145 is not

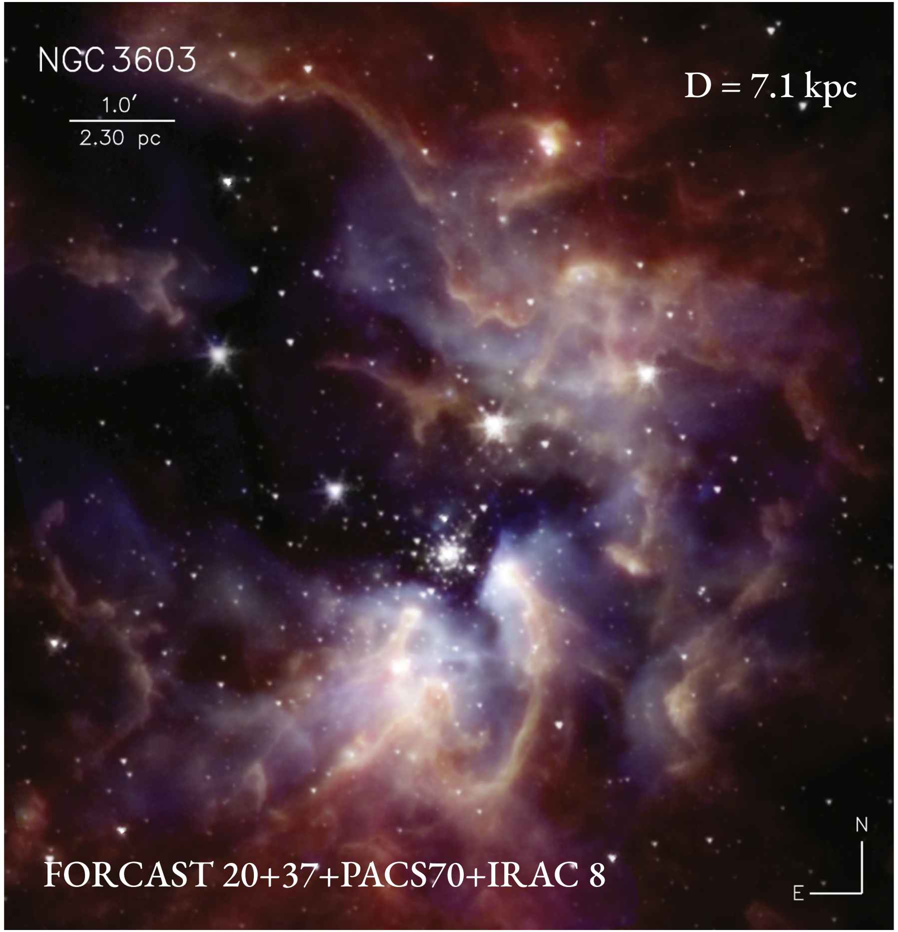


Goldsmith+ 2021



- Dramatic drop in temperature at> few magnitudes of A_V from the heating source→ low fractional population of $^3P_1$ level → absorption dip in [OI 63] & no dip in [OI 145]

NGC 3603: The Local Starburst

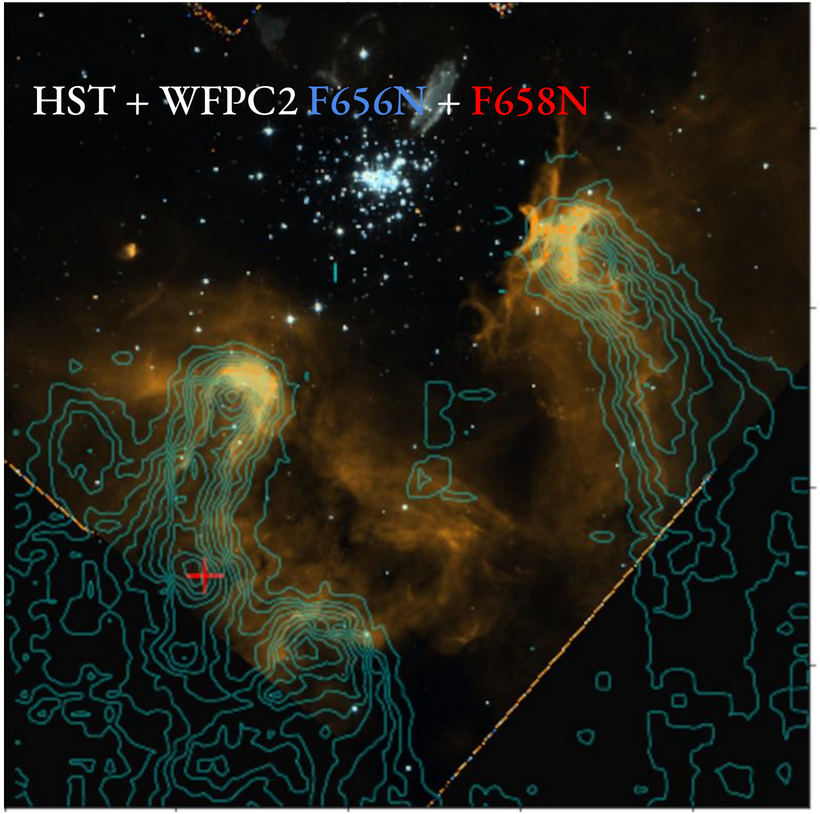


- ❑ Most powerful Giant H II region in Galaxy powered by massive OB cluster HD97950, a starburst cluster with 70 O stars (Moffat + 1994) & 3 WR stars (Melnick+ 1989)
- ❑ Lyman α photons and stellar winds carved out a bubble in NGC3603 → A_V~ 4.5 mag → pillars
- ❑ Possible triggered sequential star formation inferred based on the existence of an older population to the north (Melnick + 1989) → GAIA+SOFIA/FORCAST analysis shows the majority of evolved sources lie in projection
- ❑ Cloud-cloud collision resulted in the present state of NGC 3603 (Fukui + 2014) → Ages of YSOs, MYSOs support

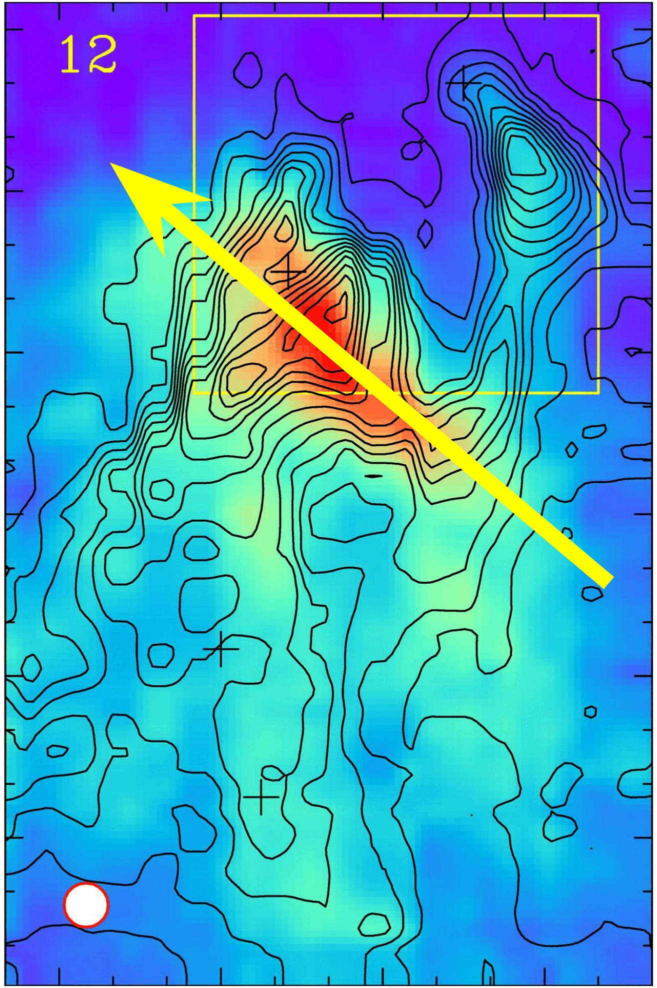
De Buizer+ 2024

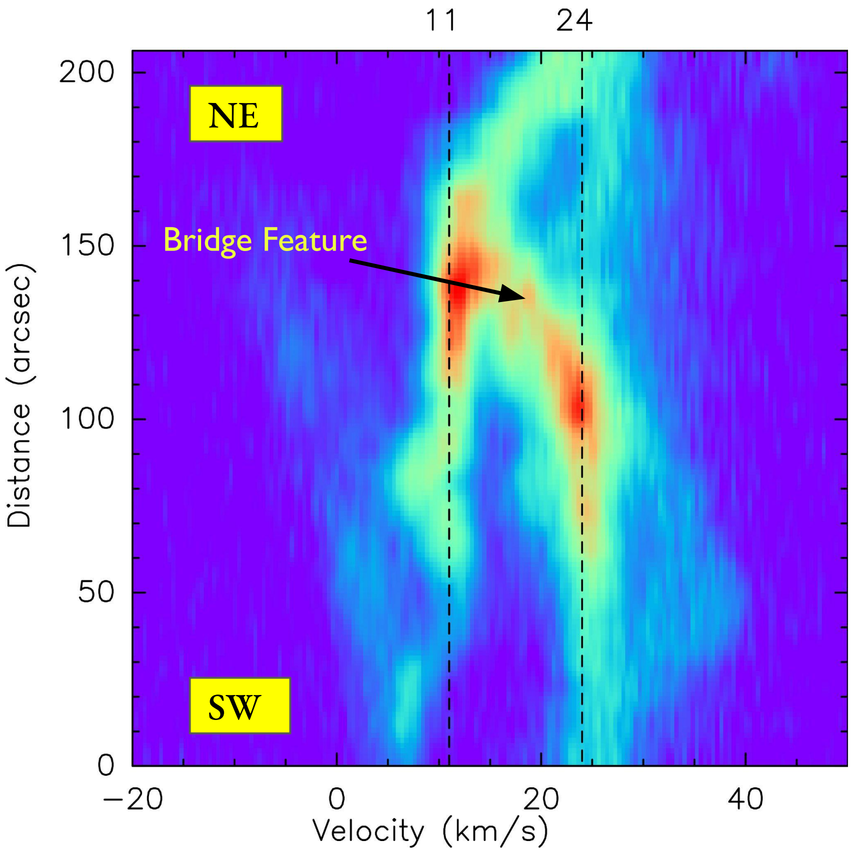
NGC 3603: SOFIA/upGREAT

[O I] 63 μm @ 6.6″

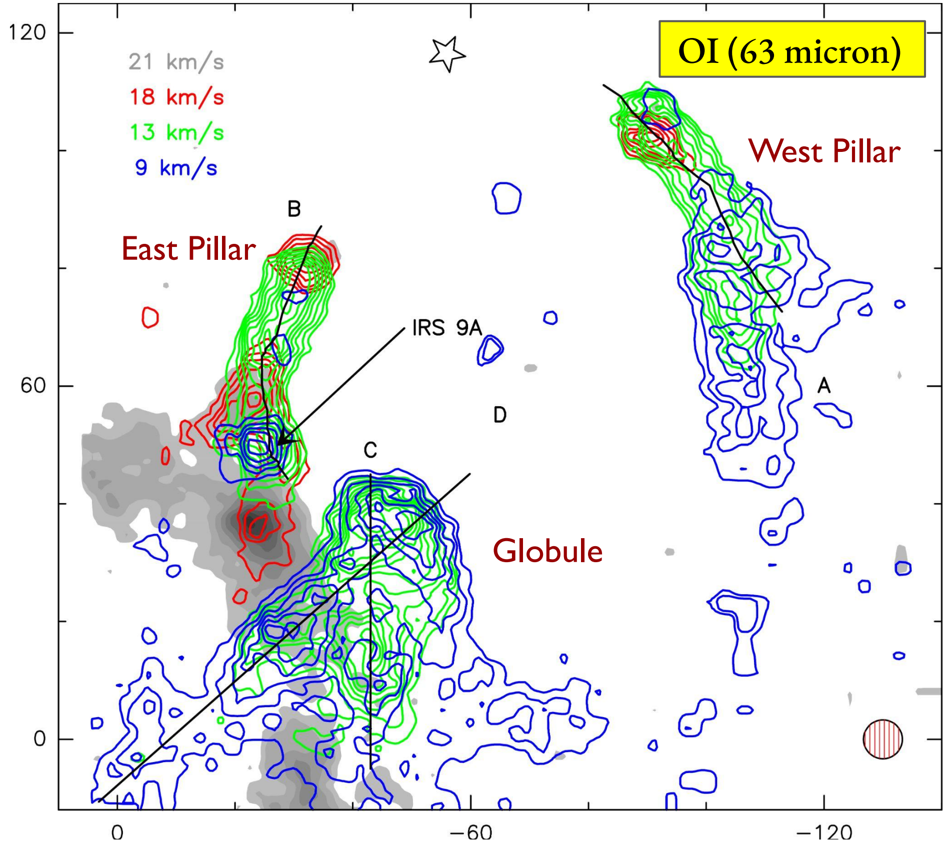


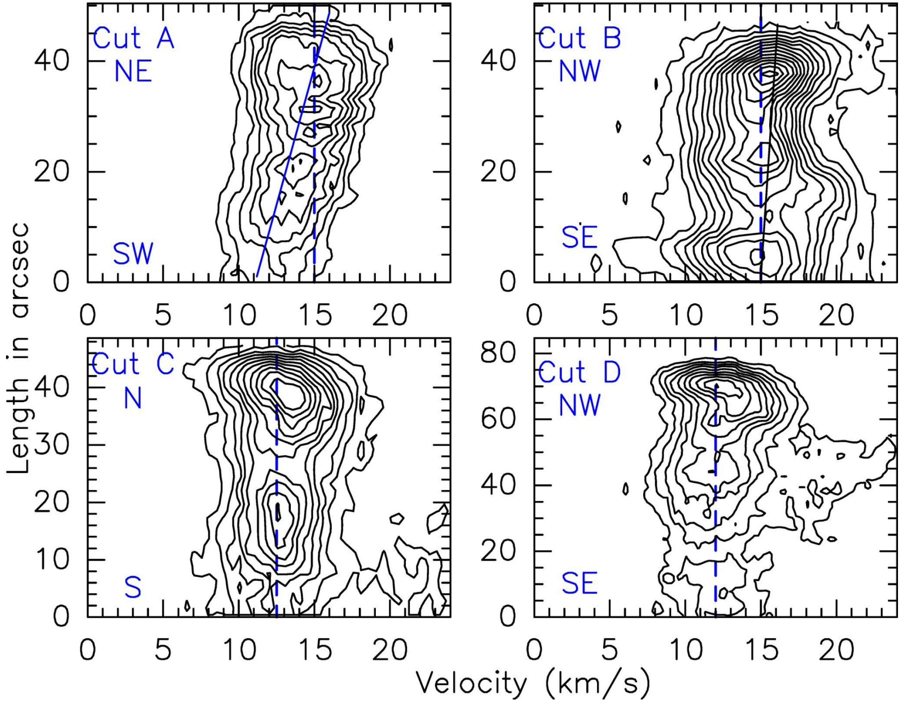
Signature of Cloud-Cloud Collisions in [C II]





3-D Distribution of Dense PDR Gas: Location of the Pillars





- ❑ Globule lies closer to the observer compared to pillars
- ❑ Blue-shifted tails of East & West pillars → lie between the HD 97950 cluster & observer

Summary of Velocity-Resolved Study of PDRs

- Complex [C II] line profiles → kinematics and energetics of gas affected by stellar feedback → driving mechanism of bubbles → thermal energy of ionized gas vs stellar winds
- Detection of [13C II] → opacity of [C II] → improved mass estimate of detected neutral gas
- [C II] profiles show foreground absorption by substantial column of cold and dense gas (A_V~13 mag) → origin of such gas not clear
- Velocity-resolved [O I] 63 μm spectra → extended low-density foreground gas produces absorption features in the [O I] → related to, but not the same as, optically thick [O I] inferred from observations that could not directly detect absorption features
- Observed [OI 145]/[O I 63] still much higher than the predictions of PDR models
- Detection of foreground absorption of both [C II] and [O I] 63 μm by cold gas has far-reaching implications on the interpretation of intensities of [C II] and [O I] for external galaxies

[O I 145] observations are few → Need far-infrared instruments with velocity-resolved capabilities including both [O I 145] & [O I 63] lines

Future of Balloon-Borne Far-Infrared Astronomy from India

- Design & Fabrication of a balloon-borne 2-3 m Far-Infrared telescope
- In-house capabilities: Complete end to end solution in scientific ballooning viz. balloon design, fabrication, launch, science data collection, balloon tracking, trajectory prediction, and payload recovery (100% payload recovery)
- 200 kbps Telemetry (via S-band) & 32 ON/OFF, 32 DATA commands each with 12-bit capacity,
- Current zero-pressure balloon capacity is up to 1000 kg
- Observation time per launch 6-8 hours
- Two seasons for launch per year
- Accesses Southern Sky
- Possibility for collaboration on payloads of mutual science interest (heterodyne/integral field spectrometer)