PDRs with SOFIA: A motivation for the next FIR/sub-mm mission

Bhaswati Mookerjea

Tata Institute of Fundamental Research (TIFR), Mumbai, India

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Heritage of SOFIA – Scientific Highlights and Future Perspectives

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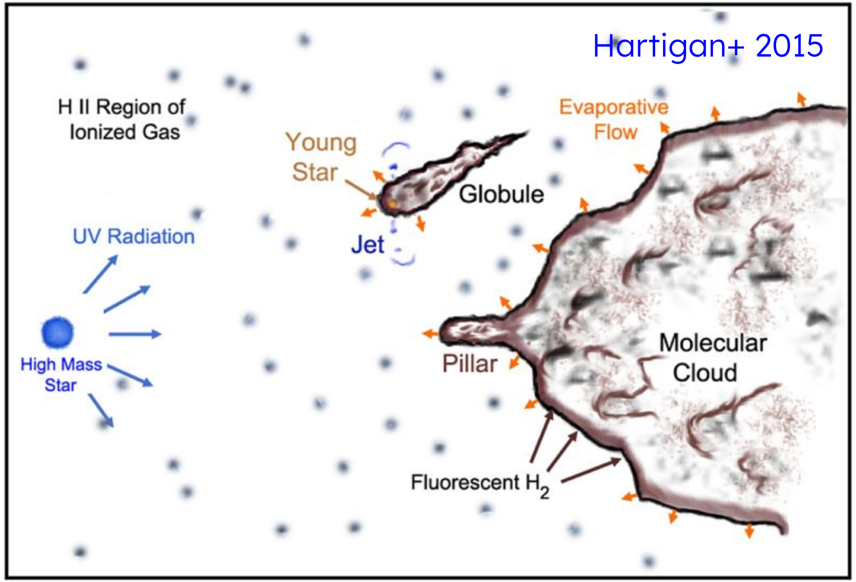
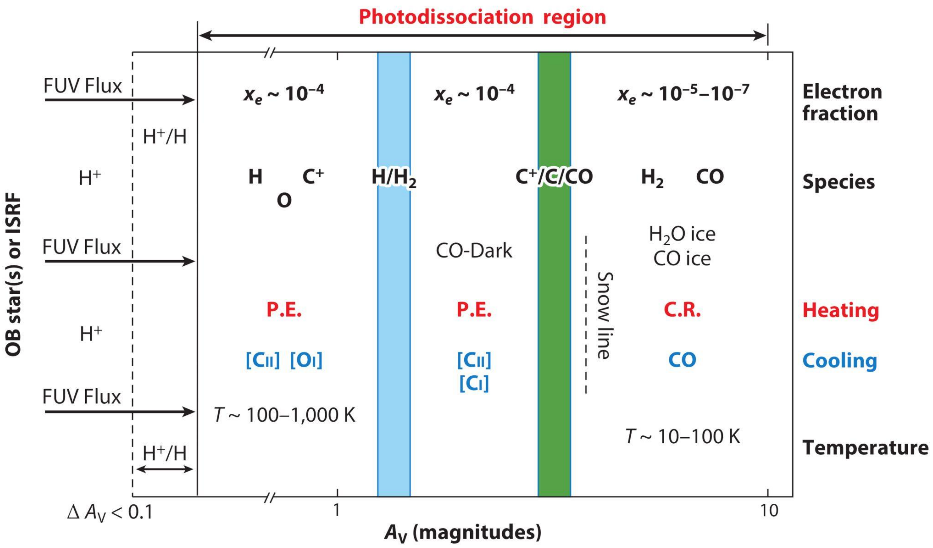
FEEDBACK OF HIGH MASS STARS & PDRs





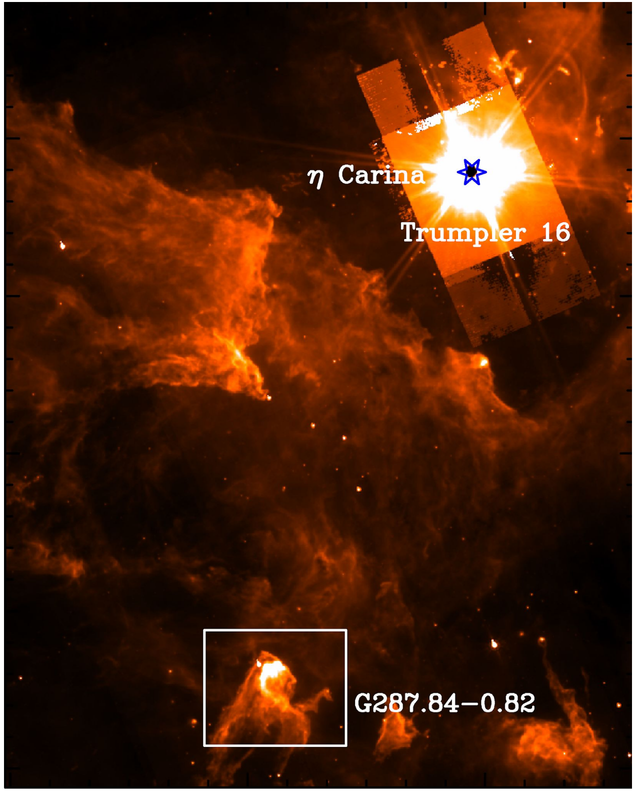
- Detailed structure of the regions with photon-dominated gas   Wolfire+ ARAA 2022
- Transition from atomic to molecular gas
- Observations probe feedback from massive stars and triggered star formation

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

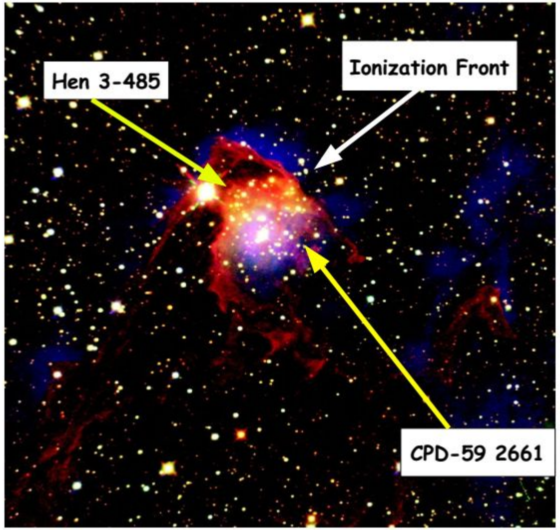
VELOCITY-RESOLVED FAR-INFRARED SPECTROSCOPY OF PDRs

- Tomography of PDRs: 3-dimensional structure revealed through velocity information (Talk: Pabst, Kabanovic, Poster: Okada)
- Energetics of PDRs: 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 (Talks: Pabst, Kabanovic, Beuther, Kavak)
- Discovery of neutral gas columns: [C II] emission (CO-dark gas), In absorption in [CII] & [OI] 63 (Talks: Ossenkopf-okada, Goldsmith)
- Accurate determination of properties of PDRs: Comparison of emission from same gas

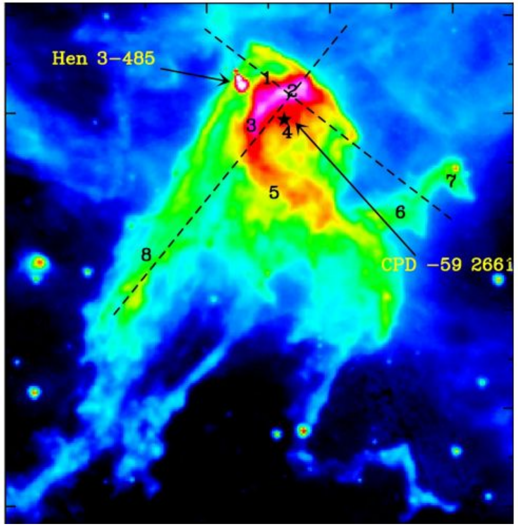
TREASURE CHEST :A PDR GLOBULE IN CARINA REGION



Carina nebula cluster (d = 2.3 kpc) has more than 65 O stars



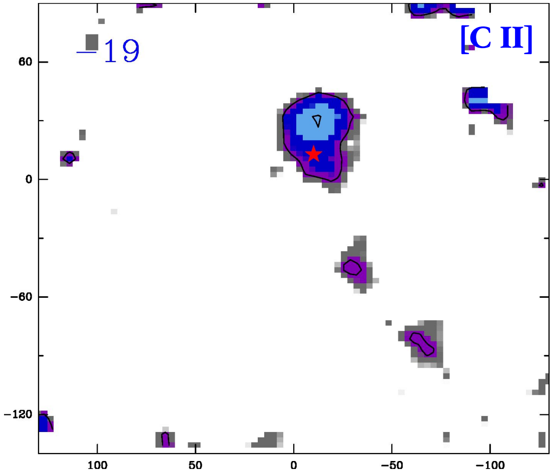
Smith et al. 2005 NIR Paβ, [Fe II], H_2 1-0 S(1)

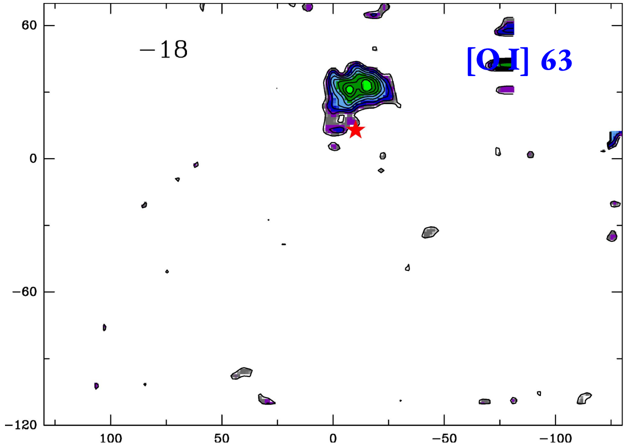


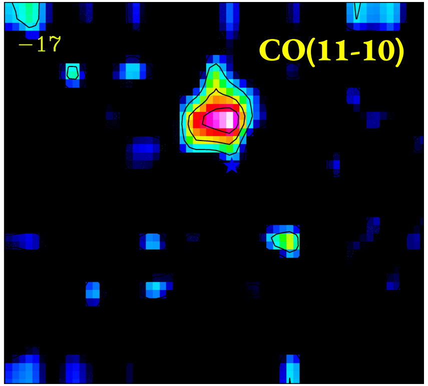
Spitzer 8μm continuum

- ❑ Pillars with bright parts of their heads pointing towards η Car and their extended tails pointing away from it ⟶ sculpted by radiation and winds from the massive stars associated with Trumpler 16 and η Car
- ❑ Treasure Chest (Smith et al. 2005), has more than 69 young stars & the cluster age is 1.3 Myr.

3D VIEW OF THE TREASURE CHEST PDR







- Diffuse PDR (10^4 cm^{-3}) traced by [C II]
- Dense PDR (2-8 × 10^5 cm^{-3}) traced by [C II], [OI] & CO(11-10)
- Treasure Chest cluster was formed before G287.84 became a cometary globule BUT erodes it faster than Trumpler 16 and η Car

BM, Sandell, Guesten et al 2019

- ❖ Bulk of the gas in the head at -14.5 km/s; Red- & Blue-shifted tails
- ❖ Stellar wind & Radiation Pressure from η Car (-20 km/s) push globule radially away along line of sight
- ❖ [OI] 63 μm clearly shows the dense PDR shell around CPD -59 2661 at v=-13 km/s
- ❖ Eastern tail shows more blue-shifted material in [C II] → lower density

TRIFID NEBULA (M20) :AN EXPANDING PUNCTURED BUBBLE

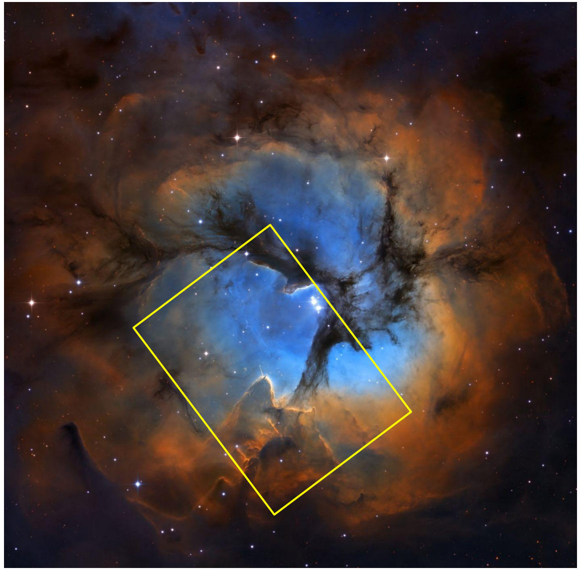
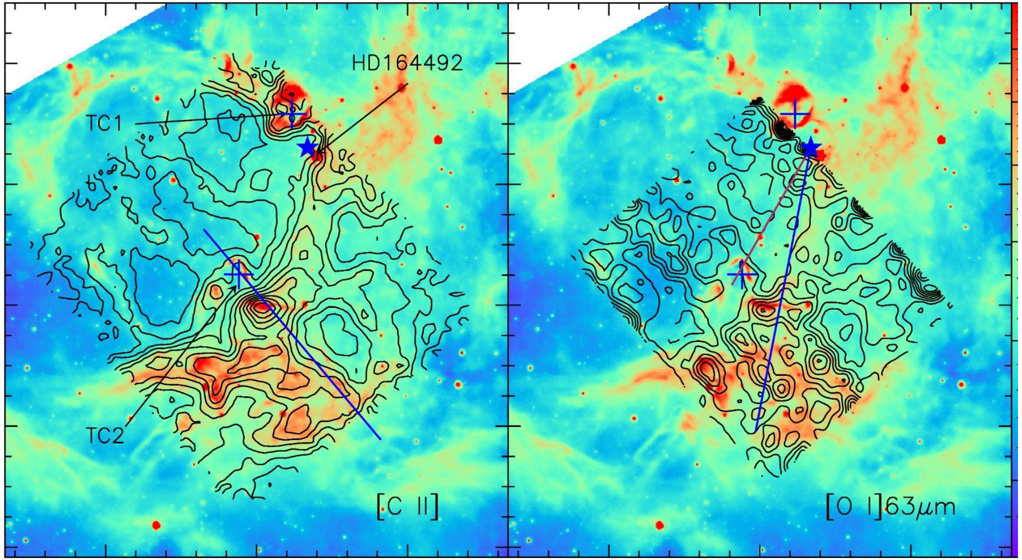


Image courtesy: Wolfgang Promper

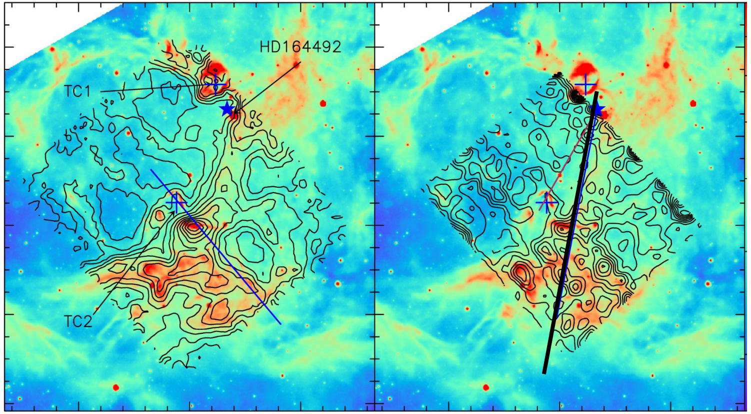


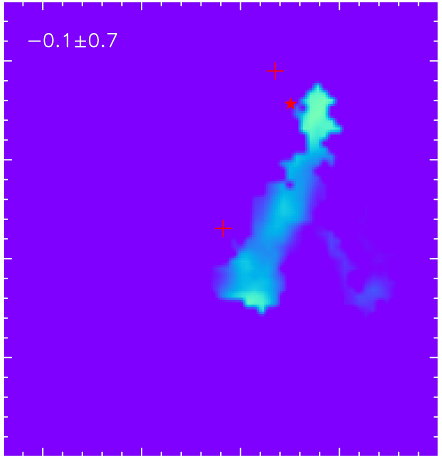
Color: 8 μm IRAC

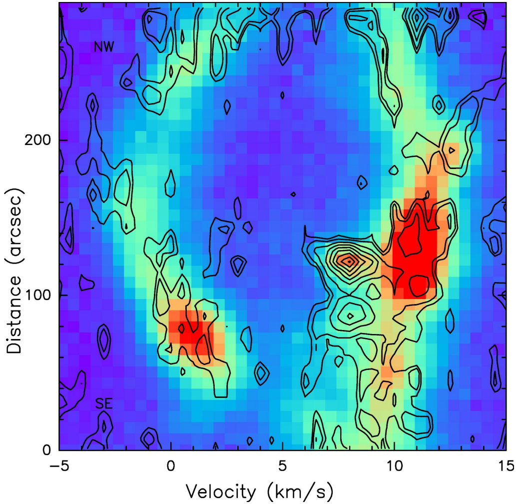
Mookerjea & Sandell (ApJ, 2024)

- 0.5 Myr old H II region ionized by the O7 V star HD164492A at a distance of ~1.2 kpc
- Expanding H II region encountering a large dense molecular cloud → triggering formation of new stars
- FUV irradiated web & dense ridges harboring the YSOs TC1 and TC2 detected in both [O I] 63 and [C II]

TRIFID NEBULA (M20) :AN EXPANDING PUNCTURED BUBBLE



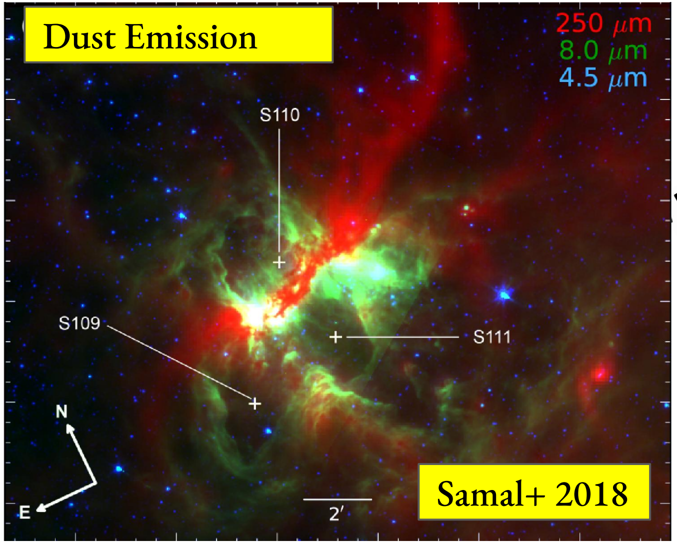


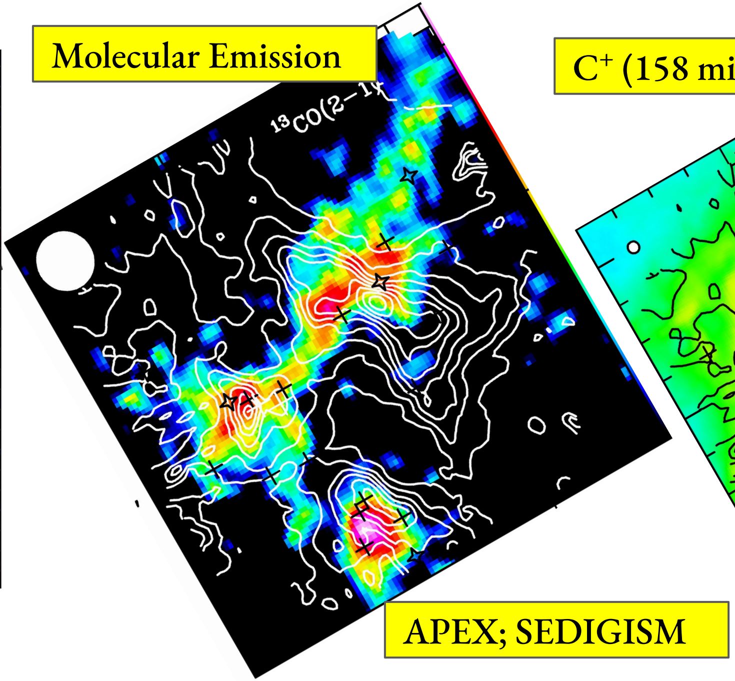


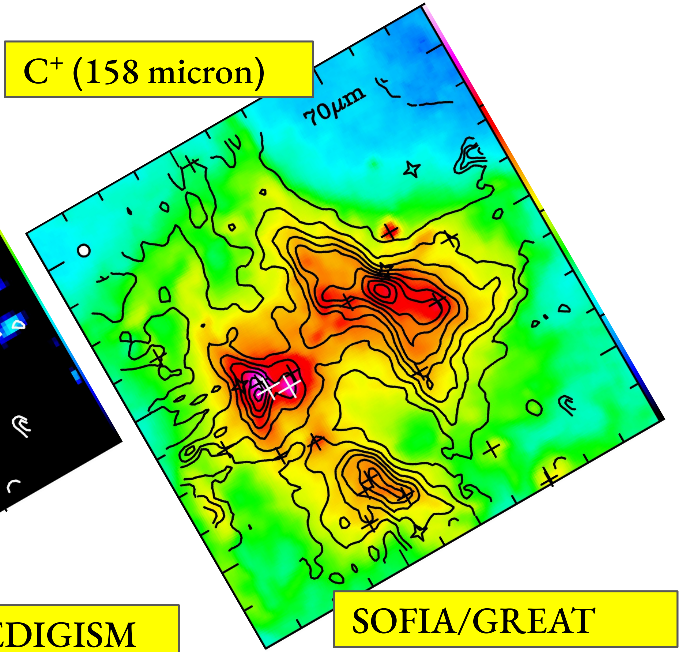
- ❖ Velocity-coherent structures & position-velocity plots → shell expanding with a velocity of 5 km/sec → red (5-15 km/s) and blue (-5 to 5 km/s) shell
- ❖ [C II]/[O I]63 intensities+PDR models → volume density (cm^{-3}) of 4000 (red) & 500 (blue)
- ❖ [C II] intensities → mass of shells → estimate kinetic energy & momentum
- ❖ Momentum << momentum imparted by expansion of H II region over 0.5 Myr → significant mass blown away → hole in the web
- ❖ Kinetic Energy >> thermal energy of the H II region → deficit matches well with the total energy pumped in by stellar wind over the lifetime of the nebula

Mookerjea & Sandell (ApJ, 2024)

THERMALLY EXPANDING INFRARED BUBBLE S111



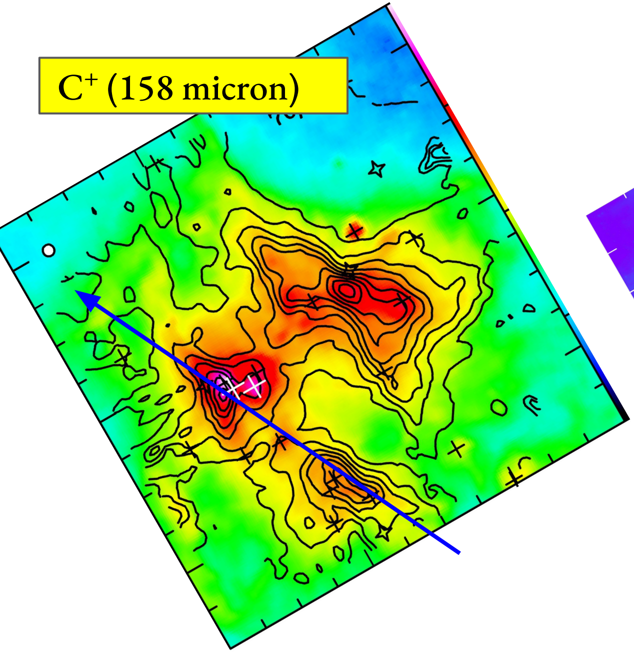


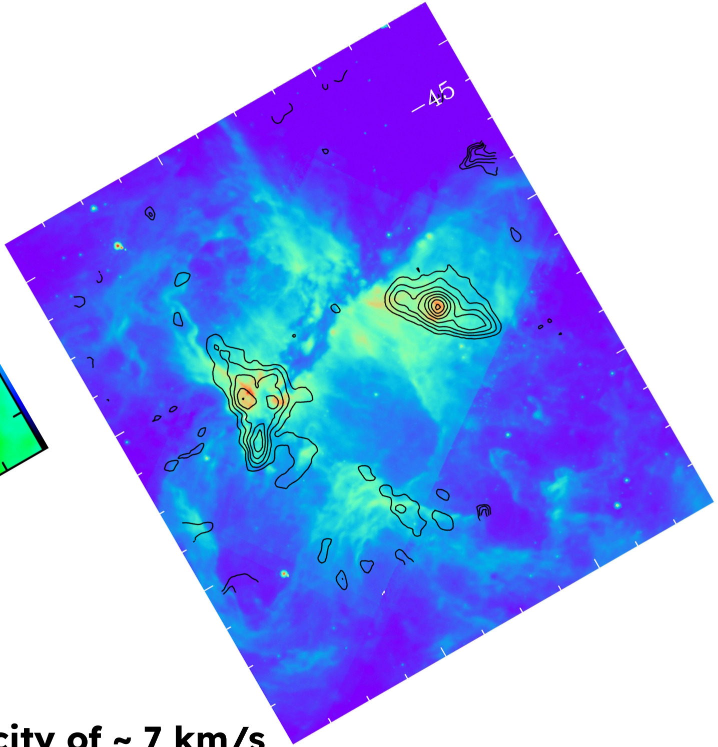


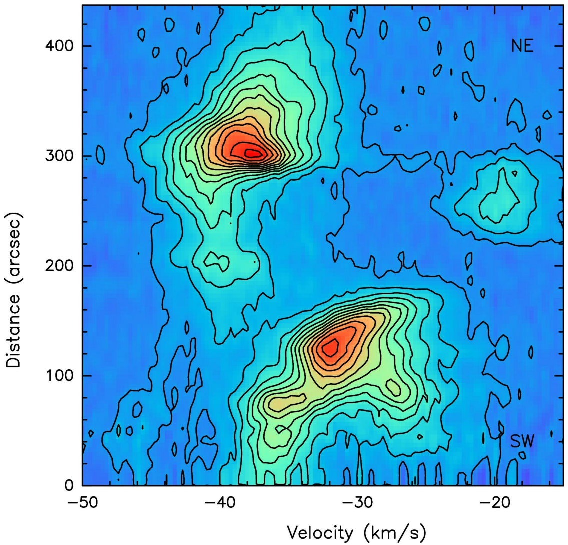
- Located at 2.7 kpc with two O-type stars
- Far-infrared emission from newly forming stars on the ridges
- Molecular emission tracing filaments
- C$^+$ emission tracing irradiated and compressed ridges (mass & density)

Mookerjea (ApJ, 2022)

THERMALLY EXPANDING INFRARED BUBBLE S111





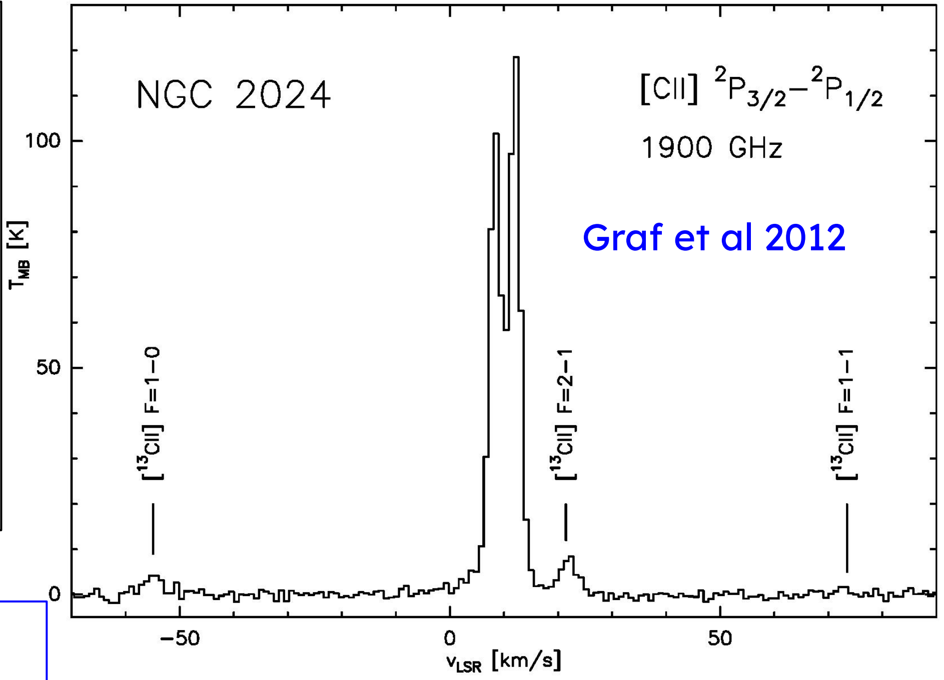


- A **shell expanding with a velocity of ~ 7 km/s**
- **Pressure** causing the expansion arises mainly from **photoionization heating of H and dust-processed radiation**
- **Kinetic energy** is comparable to the **thermal energy of H II region**
- Detected outflow from radio-quiet cores → Triggered star formation

Mookerjea (ApJ, 2022)

[CII] AS A TRACER OF NEUTRAL GAS

- ❑ Detection of [C II] emission arising out of neutral gas not emitting CO and H I (GOT C^+) → [C II] a good tracer of molecular gas column density provided it is optically thin
- ❑ Velocity-resolved spectroscopy of [C II] → detection of [^{13}C II] → [C II] optical depth of 1 to 2
- ❑ Self-absorbed [C II] profiles → significant column of neutral gas

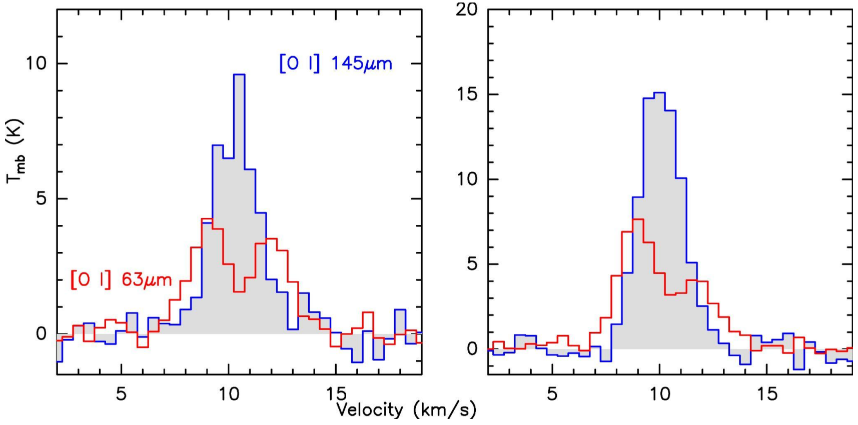


- Total gas 1.6×10^{23} cm^{-2} at a few hundred Kelvin
- Self-absorption caused by a cooler T<100 K foreground component with 10^{22} cm^{-2}

Guevara et al 2020,2023, Kabanovic 2022, Mookerjea+ 2018, 2019, 2021

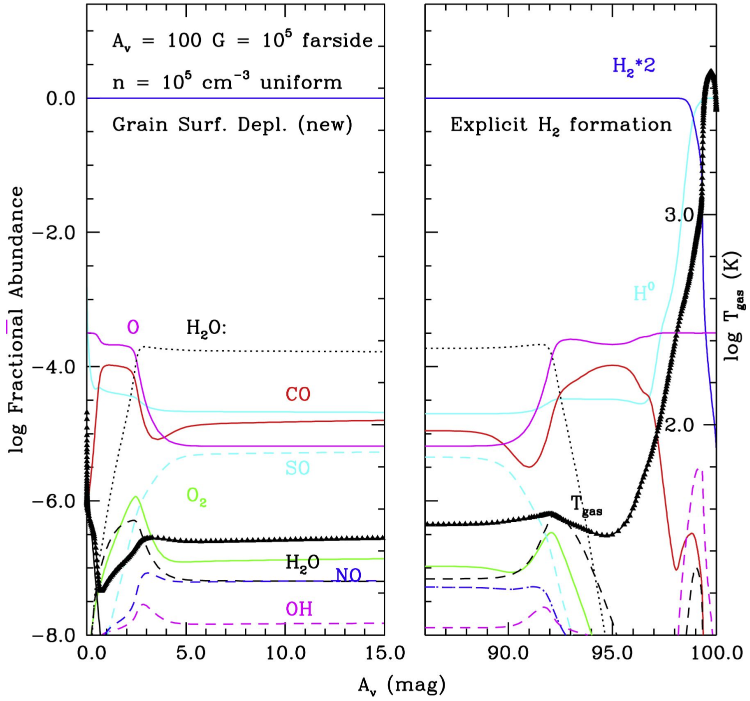
INSIGHT INTO ATOMIC OXYGEN WITH [O I] AT 63 & 145 MICRON

- [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



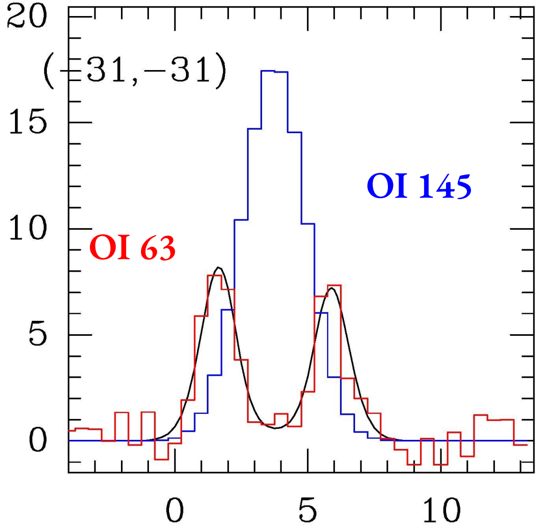
BM, Sandell, Guesten et al 2023; NGC 2023

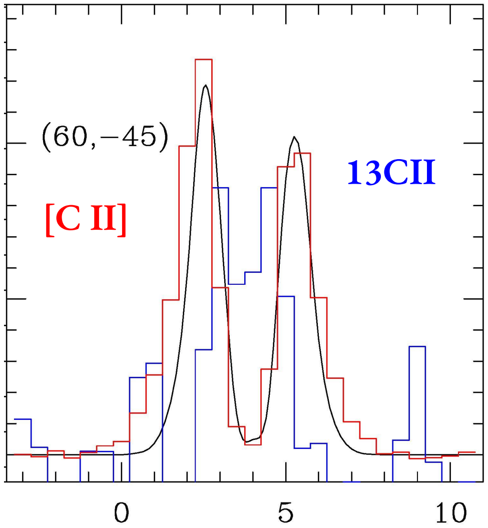
Goldsmith+ 2021



- 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]

TWO-SLAB MODEL FOR SELF-ABSORBED [C II] AND [O I] 63

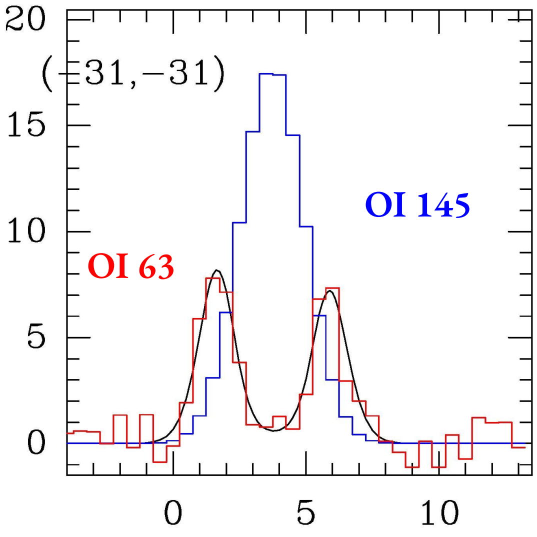




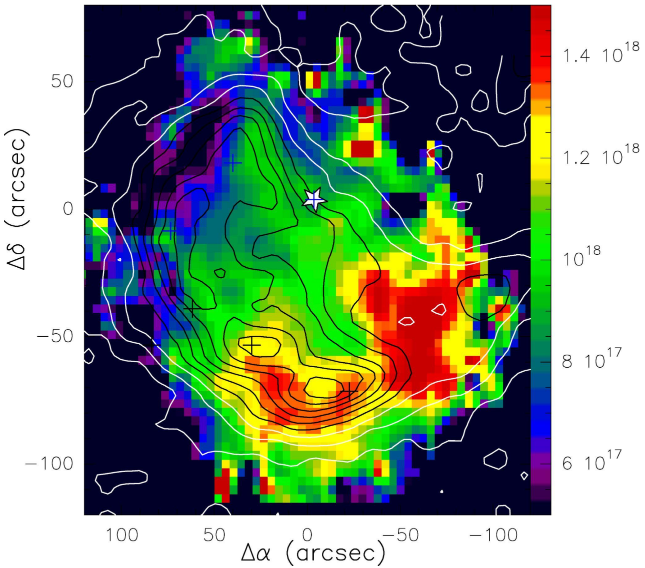
S1 PDR in Rho Oph; BM, Sandell, Guesten et al 2021

- 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

TWO-SLAB MODEL FOR SELF-ABSORBED [O I] 63 with [O I] 145



S1 PDR in Rho Oph; BM, Sandell, Guesten et al 2021



NGC 2023; Mookerjea+ 2023

- Column of cold oxygen needed to fit observations N(O) ~ 0.4 – 1.3 × 10^{18} (Δv_{FWHM} /km s^{-1})
- Velocity coherence of emission and absorption features → cold foreground gas associated with the hot PDR
- Correction to the [O I] 63 μm line intensity due to self-absorption is typically estimated to be a factor of ~2–4

VELOCITY-RESOLVED STUDY OF PDRs

- ❑ Clear identification of CO-dark neutral gas as a ubiquitous phase of the ISM & dependence of the location on the variation of its abundance
- ❑ 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
- ❑ 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

WE WERE ONLY GETTING STARTED

FUTURE INSTRUMENTATION FOR PDR STUDIES

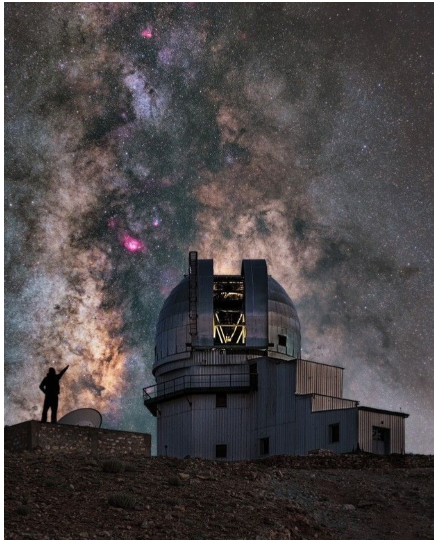
- Balloon and Satellite based far-infrared telescope + Ground-based sub-millimeter telescopes (accessing [C I], mid- & high-J CO lines)
- Large-format (≥ 100 beams) instruments with high spectral resolution (<1 km/s) between 30-600 μm to create large-area velocity-resolved spectral line maps of fine-structure transitions in GMCs: Enhanced version of upGREAT
- Broadband multi-object spectrograph with $R \sim 10^3$-10^4 and up to 1000 beams between 30-300 μm : Measuring multiple mid- & high-J CO and fine-structure lines simultaneously → easy first order characterization of PDRs in nearby galaxies: Enhanced version of FIFI-LS

Future Science and Space FIR/Sub-mm Facilities

Mission	SALTUS	FIRSST	PRIMA	GUSTO	ASTHROS
Timeline/Launch			June 2031	31 Dec 2023 (57+ days)	December 2024
Orbit	L2 Halo	L2	L2	Balloon-borne	Balloon-borne (40km)
Wavelength (micron)	34-230 (R=300) 56-660 (10^5-10^7)	35-600	24 to 235	[CII], [OI], and [NII] at 158, 63, and 205	110 to 210
Aperture (m)	Deployable 14	2	1.8	0.9	2.5
Instruments	SAFARI-Lite (34-230, R=300); HiRX (56-660, R=10^5 to 10^7)	35-260 um multi-beam (RP~100)+Virtual Imaging Phase Array (RP~10^5), 200-600 (Heterodyne)	25-80 hyperspectral imaging, 91-232 imaging polarimetry, 24-235 4 gratings R>85; High sensitivity (25-264 um) imaging	Array of 3x8 cryogenic Terahertz superconducting heterodyne receivers	4-pixel dual-band cryogenic superconducting heterodyne array camera for high-spectral resolution imaging at 1.4-2.7 THz
Mode	Pointed	Pointed	Pointed+Survey	Survey	Pointed
Key Science	Formation of stars, SMBHs in galaxies, Galaxy evolution, Water from ISM to planets, Exoplanet Habitability	Origin & evolution of planet-forming disks, water from clouds to oceans, production of gas, dust & metals in galaxies out to z~2	Formation of stars, SMBHs in galaxies, galaxy evolution, Astrochemical signatures of planet formation, Formation of heavy elements & dust over cosmic time	Array of 3x8 cryogenic Terahertz superconducting heterodyne receivers	Galaxy evolution, Star formation
Key Technology	KID Arrays SIS/HEB Arrays	Superconducting detector arrays with both low- and high-R modules	KID Array	Heterodyne SIS Array	Heterodyne SIS Array

INDIAN SUBMILLIMETER TELESCOPE: AN ISRO PROPOSAL

INDIAN ASTRONOMICAL OBSERVATORY (IAO) @4500 m



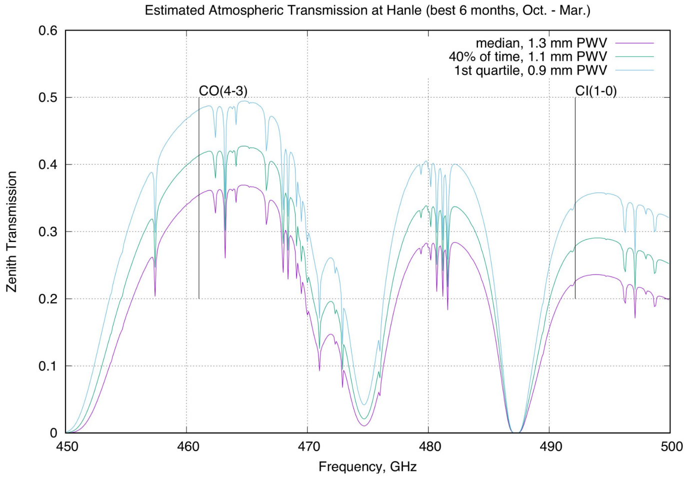
2-m HIMALAYAN CHANDRA TELESCOPE

INDIAN SUBMILLIMETER TELESCOPE: AN ISRO PROPOSAL

Designed end-to-end by Space Application Centre of Indian Space Research Organization

- At 4500m in Hanle in Ladakh
- 6-m telescope → 15-m (next step)
- Dual frequency receiver (SBD) 230/345 GHz → 500 GHz → array
- FFT-based Spectrometer BW=4 GHz (@ 1MHz)

INDIAN SUB-MILLIMETER TELESCOPE SITE



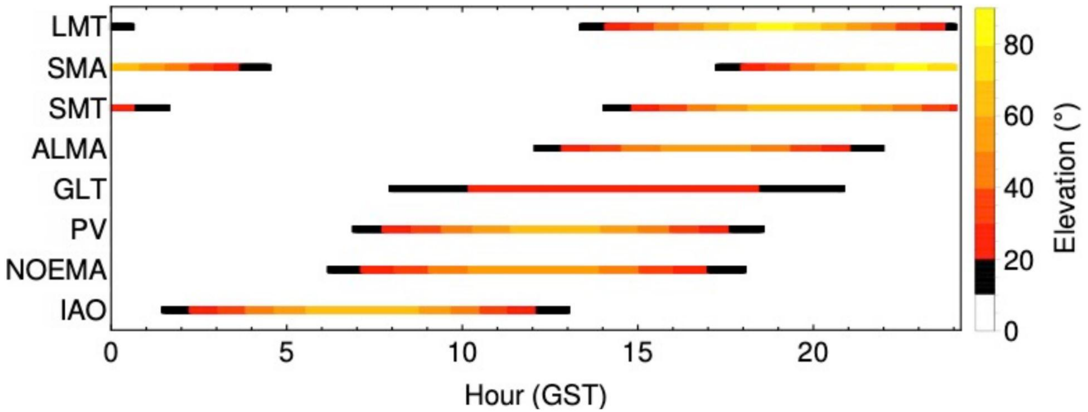
Zenith opacity quartiles at 225 GHz over best 6 months

IAO	0.05	0.07	0.1
Mauna Kea	0.05	0.08	0.14
Chajnantor	0.03	0.04	0.07

POTENTIAL SUB-MM VLBI (EHT)

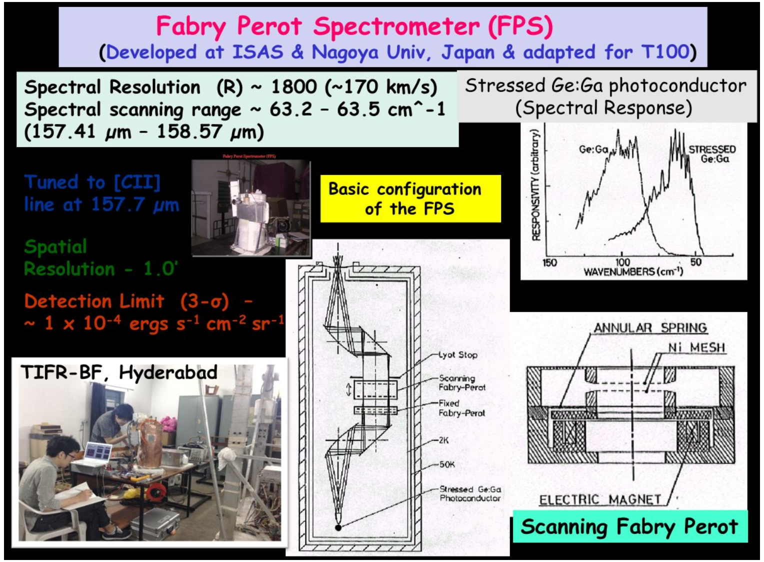
Target visibility overlap on M87 using EHT

Sridharan+ 2020



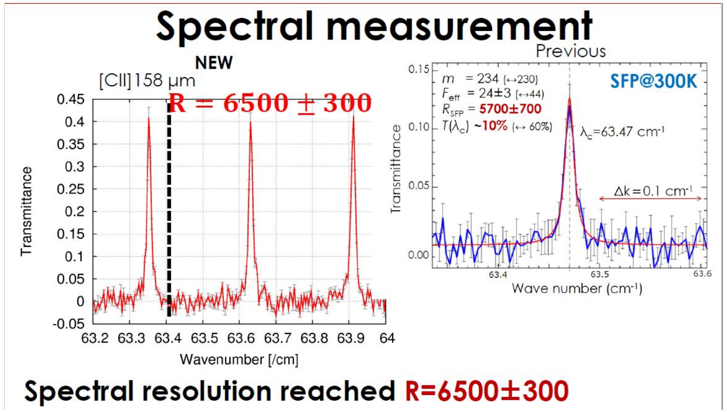
TIFR balloon-borne Far-infrared Program

Primary : 100 cm aluminium
Mass ~ 850 Kg
No. of launches : 27
(since 1983)



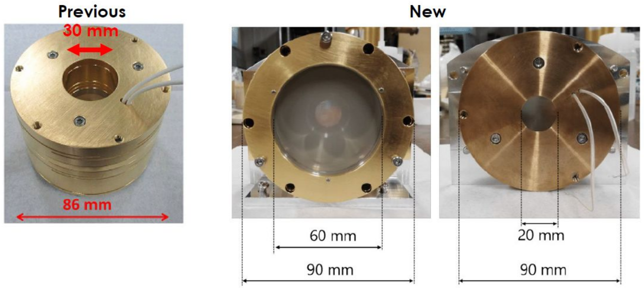
India-Japan collaboration on [C II] mapping experiment (TIFR telescope & Japanese spectrometer) since 1999

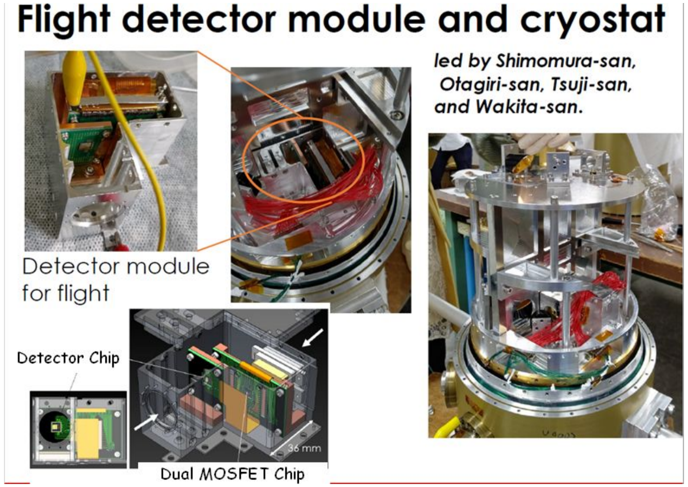
TIFR balloon-borne Far-infrared Program: Upgrade to 5x5 Array



- Ge Blocked Impurity Band (BIB) 5x5 array detector sensitive up to ~200 µm hybridized with an FD-SOI cryo-CMOS readout circuit
- Large etalons for Fabry Perot tuned to [C II] designed to reach R > 6500
- Array enables over-Nyquist sampling of PSF — super spatial resolution of 40”
- Upgrade of onboard and ground-station electronics to handle higher datarates

New structures with **larger** etalons are deigned in order to reach R=10000.





Scheduled to be flown after September 2024

TIFR BALLOON FACILITY IN INDIA

- 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)
- Low cost customized balloon design and interface electronics to user specific needs.
- Payload development and telemetry and tele-command interface support to new experimenters.
- Small balloon launches and tethered balloon hoisting throughout the year
- Special balloons supplied to Indian Space Research Organization for lunar gravity simulations

Zero pressure

Sounding

High altitude

Tethered balloon

Special balloon