Unveiling the remarkable photodissociation region of M8

Maitraiyee Tiwari (PhD student)
Prof. Dr. Karl Menten & Dr. Friedrich Wyrowski

Max Planck Institute for Radioastronomy

mtiwari@mpifr-bonn.mpg.de

June 13, 2018

IMPRS astronomy & astrophysics Bonn and Cologne

bcgs Bonn-Cologne Graduate

Overview

Photodissociation regions

Source: M8

Goals

- To characterize the PDR of M8: Morphology, molecular abundances, temperatures

Observations

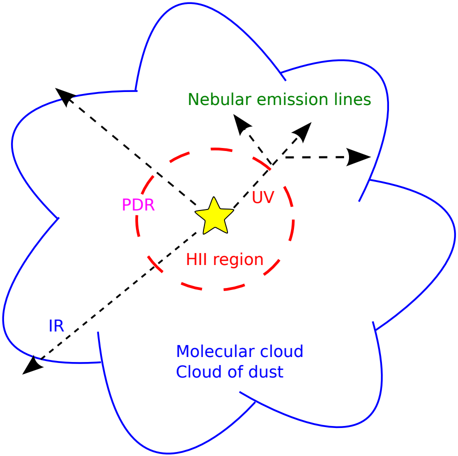
Analysis and determination of physical parameters

- Comparison with the ancillary data
- Determination of physical parameters
- Morphology

Conclusions

Introduction

- **Photodissociation regions** (PDRs): neutral regions of ISM.
- They are at the interface between the HII region and the molecular cloud.
- Heating and chemistry are regulated by far UV photons (6 eV $\leq h\nu \leq$ 13.6 eV).



M8, the Lagoon nebula

- Emission nebula lying in Sagittarius-Carina Arm, 1.25 Kpc away.
- The prominent HII region (NGC 6523/33) of M8 is excited by several O stars in the open cluster NGC 6530.
- Main source of ionization is the star **Herschel 36** (O7 V) similar to the θ^1 Orionis C star in the Orion nebula cluster.

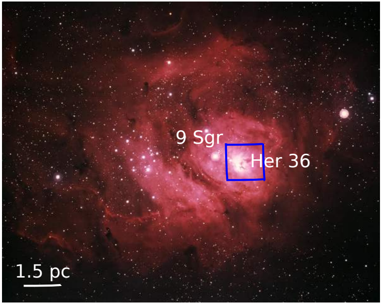


Image taken from National Optical Astronomy Observatory gallery

Motivation

Understanding the interstellar medium

Study of PDRs is the study of the effects of FUV photons on the structure, chemistry, thermal balance and evolution of the neutral interstellar medium.

One of the brightest PDRs

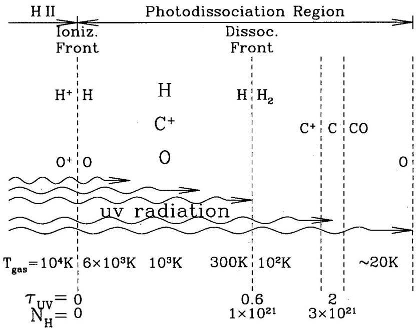
- White et al., 1997 reported the 2nd brightest CO(3-2) emission has been observed along Her 36.
- One of the brightest PDRs in our galaxy with a number of star forming regions, HII region and star cluster, yet little explored!

New template

It can act as a new template to study PDRs and HII regions.

Goal: A comprehensive survey

- To characterize the PDR of M8.
- **Qualitative analysis:** To know the **morphology** of the PDR and the HII region around Her 36.
- **Quantitative analysis:** To determine the physical parameters like **excitation temperatures, optical depths and column densities** of molecules.



Structure of a PDR (Sternberg et al., 1995)

Observations: SOFIA, IRAM 30m and APEX

Atacama Pathfinder EXperiment (APEX)

Institut de Radioastronomie Millimétrique (IRAM)

Stratospheric Observatory for Infrared Astronomy (SOFIA)

- CII and high J CO OTF maps were obtained with SOFIA.
- Mid J CO OTF maps were observed with APEX.
- Low J CO OTF maps were observed with IRAM 30 m.

Astronomy & Astrophysics manuscript no. main
December 8, 2017

Unveiling the remarkable photo dissociation region of M8

M. Tiwari[1,⋆], K. M. Menten[1], F. Wyrowski[1], J.P. Pérez-Beaupuits[1,2], H. Wiesemeyer[1], R. Güsten[1], B. Klein[1], C. Henkel[1,3]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel, 53121 Bonn, Germany
e-mail: mtiwari@mpifr-bonn.mpg.de
[2] European Southern Observatory, Alonso de Córdova 3107,Vitacura Casilla 7630355, Santiago, Chile
[3] Astron. Dept., King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia

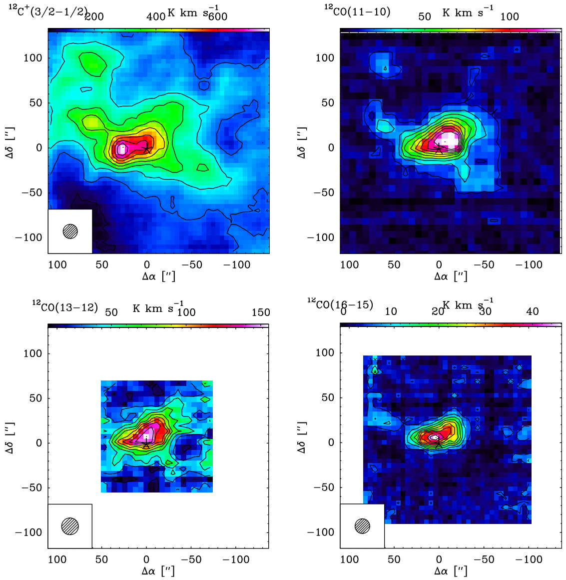
Received September ....; accepted ...

ABSTRACT

Aims. Messier 8, the Lagoon Nebula, is one of the brightest HII regions in the sky. We collected an extensive dataset comprising multiple submillimeter spectral lines from neutral and ionized carbon and from CO. Based on it, we aim to understand M8's morphology and that of its associated photo dissociation region and to carry out a quantitative analysis of the regions' physical conditions such as kinetic temperatures and volume densities.
Methods. Using the Stratospheric Observatory For Infrared Astronomy (SOFIA), the Atacama Pathfinder Experiment (APEX) 12 m and the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescopes, we have performed a comprehensive imaging survey of the emission from the fine structure lines of [C II] and [C I] and multiple rotational transitions of carbon monoxide (CO) isotopologues within 1.3×1.3 pc around the dominant Herschel 36 (Her 36) system composed of at least three massive stars. To further explore the morphology of the region we compare archival infrared, optical and radio images of the nebula with our newly obtained fine structure line and CO data, in particular with the velocity information they provide. We perform a quantitative analysis, using both LTE and non-LTE methods to determine the abundances of some of the observed species as well as kinetic temperatures and volume densities.
Results. Bright CO, [C II] and [C I] emission has been found towards the HII region and the photodissociation region (PDR) in M8. Our analysis places the bulk of the molecular material in the background of the nebulosity illuminated by the bright stars Her 36 and 9 Sagitarii. Since the emission from all observed atomic and molecular tracers peaks at or close to the position of Her 36, we conclude that the star is still physically close to its natal dense cloud core and heats it. A veil of warm gas moves away from Her 36 toward the Sun and its associated dust contributes to the foreground extinction in the region. One of the most prominent star forming regions in M8, the Hourglass Nebula, is particularly bright due to cracks in this veil close to Her 36. By using radiative transfer modeling of different transitions of CO isotopologues, we obtain H_2 densities ranging from $\sim 10^4$ to 10^6 cm^{-3} and kinetic temperatures of 100 - 150 K in the bright PDR caused by Her 36.

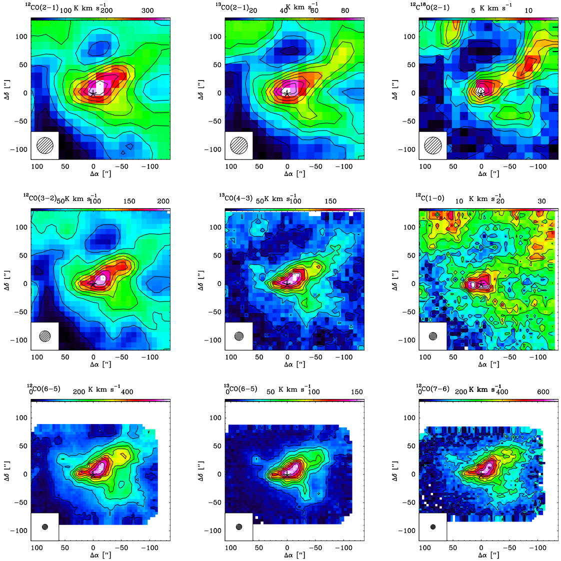
Key words. galactic: ISM — galactic: individual: M8 — submillimeter: ISM — ISM: HII region — ISM: clouds

SOFIA Observations



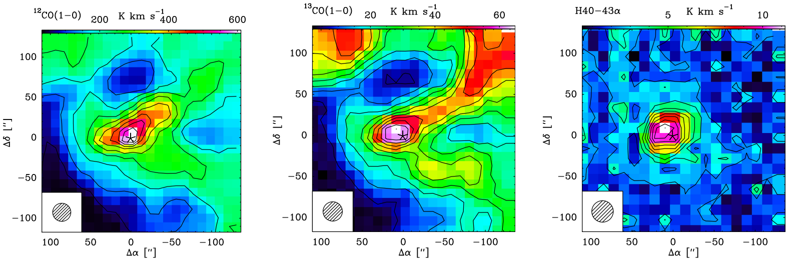
- Asterisk represents Her 36 at (0'' , 0'').
- CII emission is maximum at an offset of (30'' , -2'').
- High-*J* CO transitions' emissions peak almost at Her 36 (0'',0'').

APEX Observations



- Asterisk represents Her 36 at (0'', 0'').
- The mid *J* CO transitions peak towards north-west of Her 36.

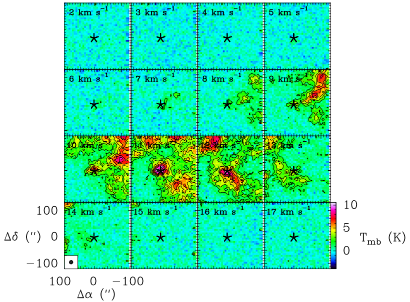
IRAM 30 m Observations

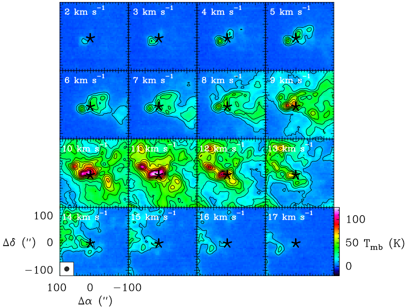


- Asterisk represents Her 36 at (0”, 0”).
- Low J CO transitions peak at Her 36 and the emission is towards north-west of it.

Velocity channel maps

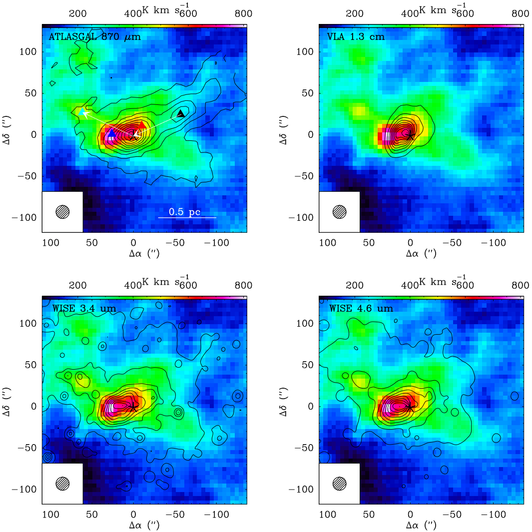
Similar to M17 SW (Perez et al., 2015)





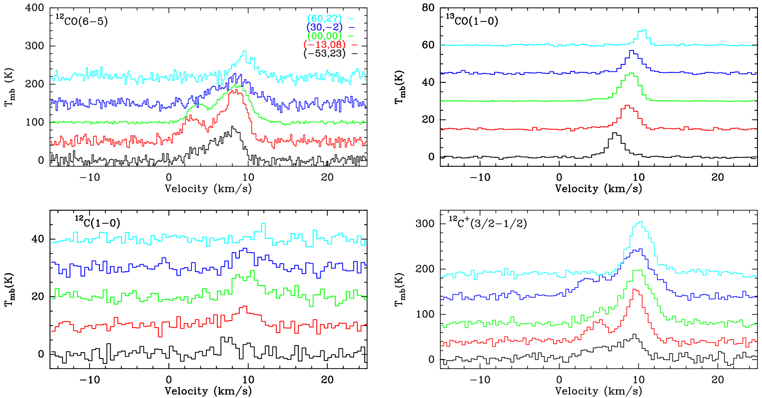
- CI (similar to ^{12}CO) doesn't show any significant emission at (60", 27").
- **HII region towards north-east of Her 36?** It is close to 9 Sgr responsible for an HII region around it (Tothil., et al 2008).

Comparison with ancillary data



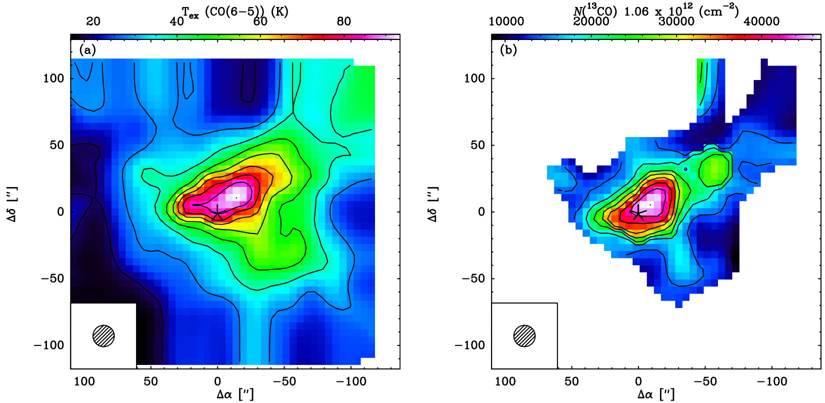
- CII+ATLASGAL 870 μm contours. Probes dust and it's column density.
- CII+VLA 1.3 cm contours. Probe hot gas like CII.
- CII+WISE 3.4 μm contours. Probe hot gas like CII.
- CII+WISE 4.6 μm contours. Probe hot gas like CII.

Spectra of ^{12}CO, ^{13}CO, [CI] and [CII] emission lines at different offsets



- A lower velocity: 2 km s^{-1} - 6 km s^{-1}.
- The higher velocity component emission lines have blue-shifted wings in the molecular cloud in the west while the emission is red-shifted towards the CII peak toward the east compared to their emission peaking at 9 km s^{-1} Her 36.

Physical parameters



- H_2 column density $N(\mathrm{H_2})$ of $\sim 3.7 \times 10^{22}$ cm^{-2}.
- Mass of CO warm gas $\sim$ 470 $M_\odot$ in a region of 3.1 arcmin^2.
- Mass of cold gas $\sim 10^3$ $M_\odot$ in a region of 5.1 arcmin^2.

Rotational diagrams of ^{13}CO

To investigate about the excitation conditions prevalent in M8

$$\ln \frac{N_u^{\mathrm{thin}}}{g_u} + \ln C_\tau = \ln N - \ln Q_{\mathrm{rot}} - \frac{E_u}{KT} \qquad (1)$$

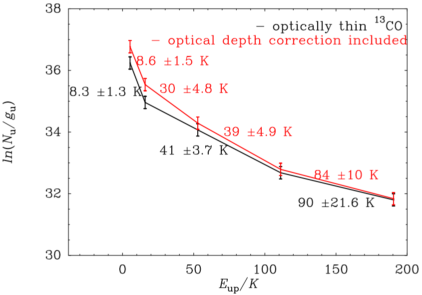


Table : Physical parameters calculated from rotational diagrams.

Optically thin ^{13}CO		Correction factor included	
T_{rot}[a] (K)	$N(^{13}$CO) (cm^{-2})	T_{rot}[a] (K)	$N(^{13}$CO) (cm^{-2})
8.3	3.6×10^{16}	8.6	6.2×10^{16}
40.6	3.6×10^{16}	29.6	5.4×10^{16}
90.1	1.9×10^{16}	38.8	4.6×10^{16}
		83.5	2.1×10^{16}

[a] Calculated for different gradients in the plot as indicated in the figure.

Temperature gradients in the gas, as expected in a PDR.

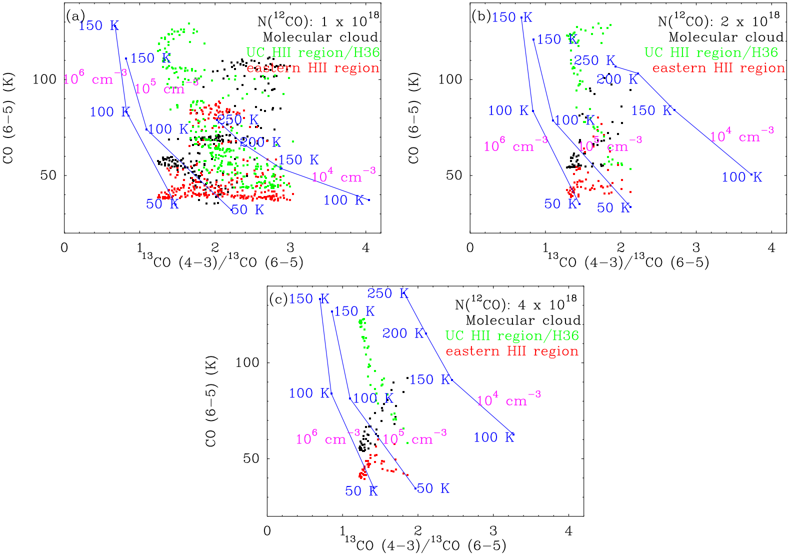
Non-LTE calculation

RADEX: A non-LTE radiative transfer program (Van der Tak et al., 2007).

- Leiden Molecular and Atomic Database (LAMDA) provides rates coefficients for collisions of CO and H_2.
- Grids in $T_{\rm kin} \sim 50 - 250$ and $n(\rm H_2) \sim 10^4 - 10^8$ are computed.
- Input: $N(\rm CO)$ from LTE analysis, Δv from observed spectra, $T_{\rm bg}$ of 2.73 K
- Compared the temperatures obtained from the modeling with the observed temperatures.
- Constrains on $T_{\rm kin}$ and $n(\rm H_2)$

Non-LTE calculation

RADEX results in blue → T_{kin} and $n(\mathrm{H_2})$

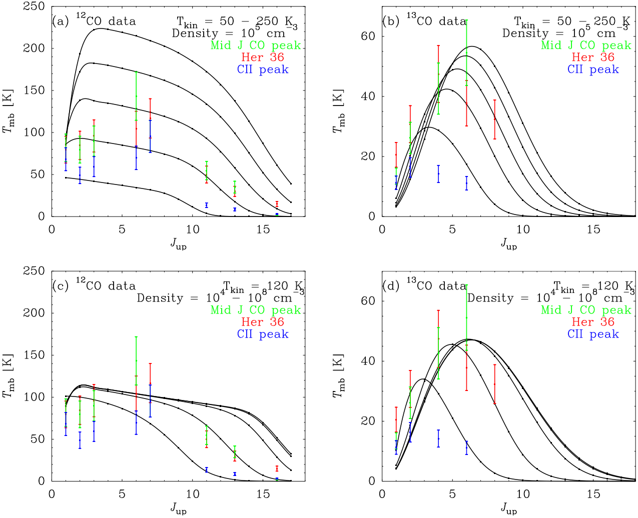


Non-LTE calculation

All observed CO transitions

Transition	Frequency(GHz)	η_{mb}	$\theta_{mb}('')$	Peak line flux (K km s^{-1})	rms (K km s^{-1})	Telescope
			^{12}CO			
$J = 1 \rightarrow 0$	115.271	0.73	22.5	610.2	0.6	IRAM 30m/EMIR
$J = 2 \rightarrow 1$	230.538	0.65	28.7	355.5	0.2	APEX/PI230
$J = 3 \rightarrow 2$	345.796	0.73	19.2	210.2	0.4	APEX/FLASH$^+$
$J = 6 \rightarrow 5$	691.473	0.43	9.6	580.1	2.0	APEX/CHAMP$^+$
$J = 7 \rightarrow 6$	806.652	0.34	8.2	673.4	10.0	APEX/CHAMP$^+$
$J = 11 \rightarrow 10$	1267.014	0.68	22.9	130.9	1.8	SOFIA/GREAT
$J = 13 \rightarrow 12$	1496.923	0.68	19.1	155.3	1.2	SOFIA/GREAT
$J = 16 \rightarrow 15$	1841.346	0.70	14.8	46.2	1.0	SOFIA/GREAT
			^{13}CO			
$J = 1 \rightarrow 0$	110.201	0.73	23.5	64.9	0.2	IRAM 30m/EMIR
$J = 2 \rightarrow 1$	220.399	0.65	30.1	92.6	0.3	APEX/PI230
$J = 4 \rightarrow 3$	440.765	0.59	15.0	198.1	1.3	APEX/FLASH$^+$
$J = 6 \rightarrow 5$	661.067	0.45	10.0	158.8	1.6	APEX/CHAMP$^+$

Non-LTE calculation

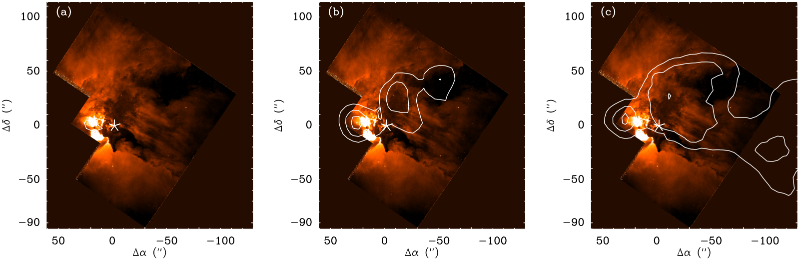


No single kinetic temperature or density!

- T_{kin} = 100 - 150 K, n = 10^4 - 10^6 cm^{-3}

Understanding the geometry

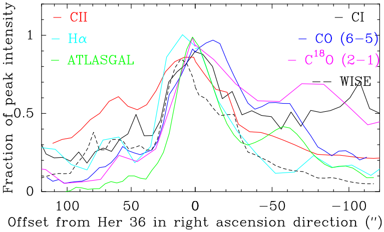
HST F487N (4865 Å) image of Her 36 + CII channel map contours: (a) 2 $km\ s^{-1}$; (b) 5 $km\ s^{-1}$ and (c) 7 $km\ s^{-1}$

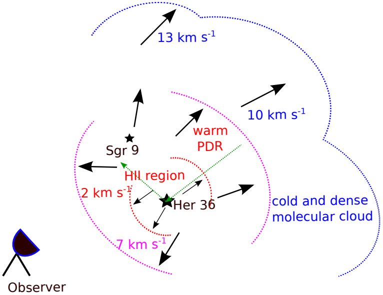


In the warm veil, N**(CII)** $\sim$ $\mathbf{1 \times 10^{18}\ cm^{-2}}$
Maximum extinction $A_\text{v} \sim$ **4.2**

Geometry: Our hypothesis

M8 has a face-on geometry in contrast to Orion bar and M17 SW!





- All emissions peak close to Her 36.
- Dense molecular cloud in the background, HII region close to Her 36, warm PDR veil in the foreground!

Luminosities and comparison to the Orion Bar

Similar to Orion Bar!

$$L = 1.04 \times 10^{-9} S \Delta V \nu D_{\mathrm{L}}^2 , \quad (2)$$

Total CO luminosity of L_{CO} = 9.5 $L_\odot$
CI 609 μm line luminosity of L_{CI} = 0.11 $L_\odot$ (lower limit to total CI luminosity).
CII luminosity of L_{CII} = 95.8 $L_\odot$
FIR luminosity of $L_{\mathrm{FIR}} \sim 10^4$ $L_\odot$ (White et al., 1998)

Luminosity Ratio	M8	Orion bar
$L_{\mathrm{CII}}/L_{\mathrm{FIR}}$	10^{-3}	1.1×10^{-3}
$L_{\mathrm{CII}}/L_{\mathrm{CO2-1}}$	7.5×10^{2}	1.6×10^{3}
$L_{\mathrm{CO2-1}}/L_{\mathrm{FIR}}$	1.3×10^{-6}	6.6×10^{-7}

Comparison with the Orion Bar

- G_0 and n values obtained for M8 are similar to that of Orion bar → Direct comparison with the PDR model results of Orion bar.
- At A_v = 2: H → H_2
- At A_v = 4: C^+ → C → CO
- At A_v = 8: All O will be in atomic form except in CO until very deep into the molecular cloud
- Gas surface layer at 500 K while dust will be at 30 – 75 K
- M8 has a face on geometry unlike Orion bar

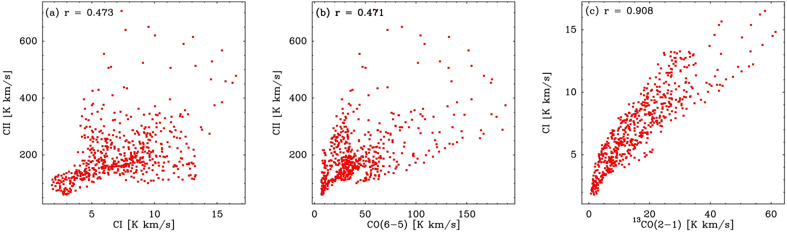
Conclusions

- We presented for the first time the maps of [CII], [CI] and various CO transitions.
- **Geometry**: M8 has a face-on geometry where the cold dense molecular cloud lies in the background with Her 36 being very close to the dense core and is powering the HII region towards the east of it along with 9 Sgr while the foreground veil of a warm PDR is receding away from Her 36 towards the observer.
- **Quantitative analysis**: LTE and non-LTE methods were used to calculate the temperatures and H_2 number density in the PDR around Her 36. Kinetic temperatures T_k: 100 - 150 K and densities n: 10^4 - 10^6 cm^{-3} were obtained.

Extra slide: Comparison with M17 SW

- M17 has an edge-on geometry compared to the face-on geometry of M8.
- CII, CI and CO show only a weak correlation both in M8 and M17 $\rightarrow$ they don't originate from the same spatial region.
- the CO SEDs follow similar trend for all positions in M8 while in M17 the SEDs have variations for different positions.

Extra slide: Correlation plots



- CII is least correlated with ^{12}CO(6-5). Two branches: upper left → north-east of Her 36, lower right → west of Her 36.
- CII and CI: upper left → north-east of Her 36, lower right → west of Her 36.