Molecular gas in Carina - Keyhole

Group Project Presentation

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Table of Contents

Introduction and purposes

Theoretical backgrounds

Scientific method and data

Results and Discussions

Conclusion and further progress

1. Introduction and purposes
2. Theoretical backgrounds
3. Scientific method and data
4. Results and Discussions
5. Conclusion and further progress

Table of Contents

Introduction and purposes

Theoretical backgrounds

Scientific method and data

Results and Discussions

Conclusion and further progress

1 Introduction and purposes

2 Theoretical backgrounds

3 Scientific method and data

4 Results and Discussions

5 Conclusion and further progress

Introduction

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Introduction and purposes

Theoretical backgrounds

Scientific method and data

Results and Discussions

Conclusion and further progress

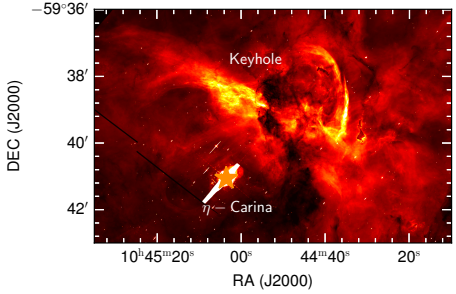

Figure 1: Keyhole region seem in H_α by the Hubble Space Telescope [a].

[a] https://archive.stsci.edu/prepds/carina/datalist.html

Introduction

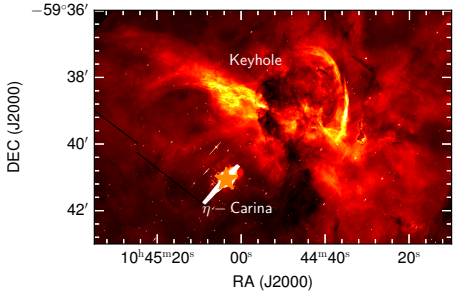

Figure 1: Keyhole region seem in H_α by the Hubble Space Telescope [a].

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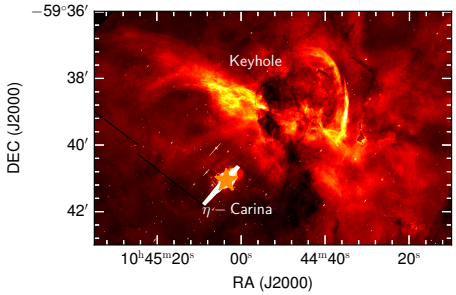
Introduction



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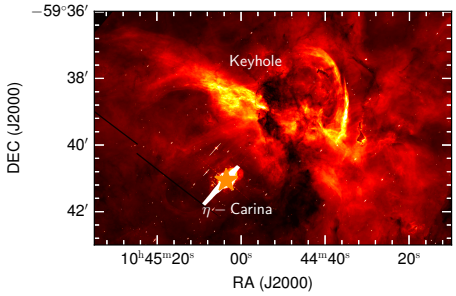

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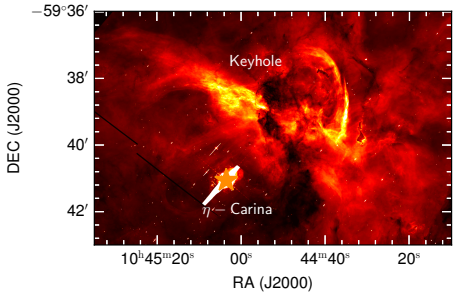

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$\longrightarrow$ How the molecular gas can survive in the photon-dominated region ?

$\longrightarrow$ We revisit this region using the new observations from APEX telescope.

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Table of Contents

Introduction and purposes

Theoretical backgrounds

Scientific method and data

Results and Discussions

Conclusion and further progress

1 Introduction and purposes

2 Theoretical backgrounds

3 Scientific method and data

4 Results and Discussions

5 Conclusion and further progress

Molecular Cloud

A molecular cloud

An interstellar gas condensation in which the atoms are bonded together as molecules rather than as free atoms or charged particles.

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- The coldest, densest phase of the interstellar medium.
- Molecules in the interstellar medium are identified by characteristic emission (or absorption) lines in their spectra.
- Molecular clouds are the sites of stars formation.

Photodissociation Regions

Photodissociation regions

Photodissociation regions (PDRs) are created by the penetration of far UV (FUV) radiation into molecular clouds.

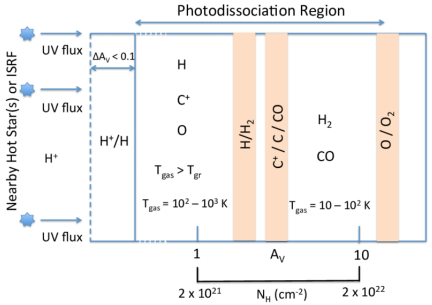


Figure 2: Schematic of a photodissociation regions.

Radiative Transfer

Radative transfer equation:

$$\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu \tag{1}$$

where j_ν is the emission coefficent, α_ν is the absorption coefficient.
Define optical depth as $d\tau_\nu \equiv \alpha_\nu ds$, the expression becomes:

$$\frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu \tag{2}$$

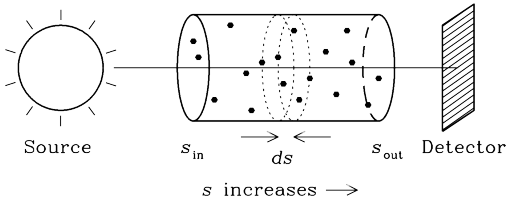


Table of Contents

Introduction and purposes

Theoretical backgrounds

Scientific method and data

Results and Discussions

Conclusion and further progress

1 Introduction and purposes

2 Theoretical backgrounds

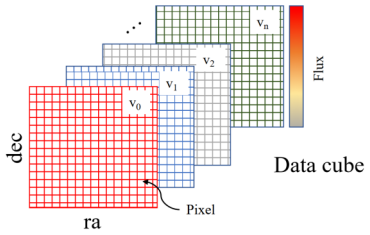
3 Scientific method and data

4 Results and Discussions

5 Conclusion and further progress

Observational Data

- Datacube of [^{12}CO(2-1)], [^{12}CO(3-2)], [^{13}CO(2-1)], [^{13}CO(3-2)], [C^{18}O] and [CI] observed in 2014 by the FLASH and SHeFI receivers on the Atacama Pathfinder EXperiment (APEX) telescope.
- Datacube of [^{12}CO(8-7)], [O I] and [N II] measured by the GREAT instrument onboard the Stratospheric Observatory for Infrared Astronomy (SOFIA).



- We combine the archival data of Herschel/PACs at 70 and 160 μm, and Herschel/SPIRE at 250, 350, and 500 μm to build the spectral energy distribution (e.g., flux vs. wavelengths).

LTE and non-LTE

The main goal is constraining some of physical properties of Carinae Keyhole such as kinetic temperature and column density by solving radiative transfer equation.

Local thermodynamic equilibrium (LTE)

LTE (Local Thermodynamic Equilibrium) is an assumption that the radiation field is in thermal equilibrium with the matter in a particular region.

Physical constraint in LTE condition

- In the LTE conditions, the radiation field of the gas is determined by Planck function and the distribution of the particle population is given by Boltzmann law.

Radiation temperature T_R

$$T_R = f(J_\nu(T_{ex}) - J_\nu(T_{bg}))(1 - e^{-\tau_\nu}) \tag{3}$$

Rayleigh-Jeans Equivalent Temperature: $J_\nu(T) = \dfrac{\frac{h\nu}{k}}{e^{\frac{h\nu}{kT}} - 1}$

Excitation temperature: T_{ex}

Beam-filling factor: f

Optical depth: τ_ν

Cosmic microwave background: $T_{bg} = 2.73K$.

Physical constraint in LTE condition

To constrain the total gas column density N(H_2), we suggest some assumptions:

- $^{12}CO(2-1)$ is an optically thick line with the value of $\tau_\nu^{12} \to \infty$.
- Excitation temperatures of ^{12}CO and ^{13}CO are the same.
- The abundance ratio of $\frac{^{12}CO}{^{13}CO} = 65$ and $\frac{H_2}{^{12}CO} = 10^4$.

Using the column density, we can derive the gas density, gas mass and visual extinction.

Dust continuum

Constraining gas column density N_{H_2} and dust temperature T_{dust} based on Spectral Energy Distribution (SED) fitting using dust data of different wavelengths.

Modified black-body radiation

$$S_\nu = B_\nu(T_d)(1 - e^{-\tau_\nu}) \tag{4}$$

where

Dust optical depth: $\tau_\nu = \mu_{H_2} m_H \kappa N(H_2)$

Absorption coefficient: $\kappa = \kappa_0 (\frac{\nu}{\nu_0})^\beta$.

RADEX: Physical constraint in non-LTE condition

RADEX

RADEX code [1] is a numerical method for solving non-LTE radiative transfer process in an isothermal and homogeneous medium based on escape probability.

- The program made use of the input format for spectroscopic and collisional data provided by the LAMDA database [2].
- Using the expanding spherical shell geometry with the escape probability expressed by the following equation:

$$\beta_{LVG} = \frac{1 - e^{-\tau}}{\tau} \tag{5}$$

- We run RADEX model and compare with observed data to constraint kinetic temperature, gas density and column density of emission lines.

[1] Van der Tak et al. 2007

[2] https://home.strw.leidenuniv.nl/ moldata/

PDR Toolbox

PDR Toolbox

An open-source, science-enabling tool for the community, designed to help astronomers determine the physical parameters of photodissociation regions from observations, developed by M. Wolfire and M. Pound from University of Maryland.

- Model: Wolfire/Kaufman 2006, a plane-parallel model, which is described by a constant H nucleus number density and solves for the chemical balance, thermal equilibrium, and radiation transfer through a PDR layer.
- Input: integrated intensity (K km s^{-1}) of $^{12}CO(3-2)$, [C I] 609 μm and [C II] 158 μm (Oberst et al. 2011) lines for the region 1.
- Output: Radiation strength and hydrogen nucleus density

Photo-Dissociation Rate

Shielding Effect

Along the line of sight looking from a star, when some molecules are in front of others, the radiation will interact with the front molecules before interacting with the molecules behind. The latter molecules are said to be shielded.

The shielded photo-dissociation rate [3]:

$$k_i = \chi k_{0,i} \Theta_i \exp(-\gamma A_V) \tag{6}$$

where:

Unshielded rate: $k_{0,CO} = 2.6 \times 10^{-10} s^{-1}$

Extinction coefficient: $\gamma = 3.53$

Scaling factor for UV intensity: χ

Visual extinction: A_V

Shielding function by molecules: Θ

[3] van Dishoeck et al. 2009

Photo-Dissociation Rate

Depth-dependent lifetime

The time needed to fully dissociate a CO cloud or lifetime depends on how many molecules a single line of radiation interacts with. This lifetime is said to be depth-dependent.

Lifetime of CO cloud:

$$t_{PD} = \frac{N(CO) \times d_{reg} \times d_{CO}}{k_{CO}} \tag{7}$$

Column density: $N(CO)$
Region diameter: d_{reg}
CO diameter: $d_{CO} = 164pm$
Shielded photo-dissociation rate: k_{CO}

Main Progression

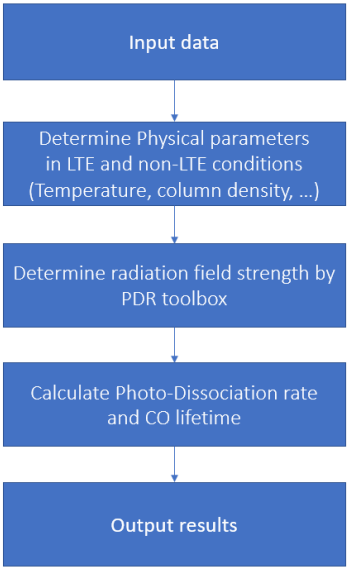


Table of Contents

Introduction and purposes

Theoretical backgrounds

Scientific method and data

Results and Discussions

Conclusion and further progress

1 Introduction and purposes

2 Theoretical backgrounds

3 Scientific method and data

4 Results and Discussions

5 Conclusion and further progress

Integrated Intensity Maps

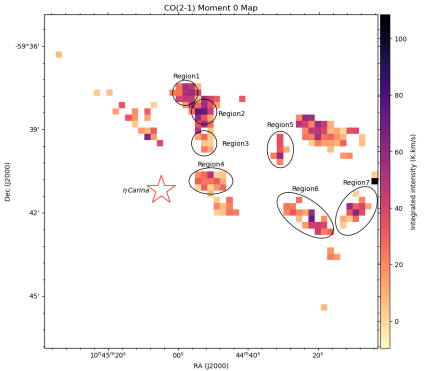


Figure 3: Integrated intensity maps of $^{12}CO(2-1)$ observed by APEX and our classification of 7 regions. The location of η Carina is symbolised by a star.

- Integrated intensity: $M_0 = \int I_v \, dv$
- All pixels with the peak value of $T_{mb} < 3\sigma$ (error) are removed from the map.

Spectral Lines

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Introduction and purposes

Theoretical backgrounds

Scientific method and data

Results and Discussions

Conclusion and further progress

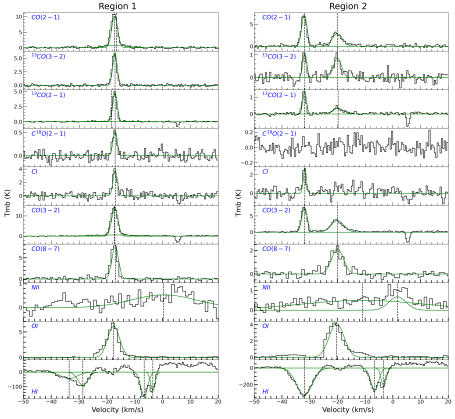

Figure 4: Average spectra toward regions 1&2 (black lines). A multi-Gaussian fitting has been deployed (green lines).

Table 1: Observational values of CO(2-1) from spectral data.

region	$T_{\rm mb}^{\rm max}$ (K)	$\bar{v}_{\rm LSR}$ (km s^{-1})	σ_v (km s^{-1})
#1	10.41	−17.2	1.04
#2	7.25	−31.93	0.93
	2.86	-19.99	1.90
#3	5.68	−31.92	0.77
#4	2.35	−7.81	1.81
	2.16	9.21	0.90
#5	3.63	−24.84	1.13
#6	2.29	−6.37	0.98
	1.26	-0.73	0.79
#7	3.44	−30.98	0.88

The similarity in peak position and profile of all tracers for position.

Physical Properties: LTE constraints

Table 2: Physical properites constrained by LTE and dust continuum SED fitting.

region	T_{ex} (K)	$N(H_2)^{CO}$ (10^{21} cm^{-2})	$N(H_2)^{dust}$ (10^{21} cm^{-2})	A_V	M_{gas}^{CO} ($M_\odot$)	M_{gas}^{dust} ($M_\odot$)	$n(H_2)^{CO}$ (10^3cm^{-3})	$n(H_2)^{dust}$ (10^3cm^{-3})	T_{dust} (K)
#1	17.45	4.42	5.36	4.70	45.3	54.99	5.60	6.80	36.78
#2	13.99	0.87	4.08	0.93	9.10	42.58	1.10	5.13	38.42
	8.71	1.57	-	1.67	16.38	-	1.97	-	-
#3	12.19	0.41	2.76	0.44	4.69	32.21	0.50	3.34	39.59
#4	8.01	1.02	2.70	1.09	51.98	134.77	0.59	1.56	38.49
	7.74	0.67	-	0.72	33.54	-	0.39	-	-
#5	9.71	1.25	2.81	1.33	62.51	140.09	0.54	1.20	37.71
#6	7.79	0.95	2.90	1.01	57.56	176.06	0.46	1.39	36.11
	6.33	0.40	-	0.42	24.12	-	0.19	-	-
#7	9.46	0.44	2.43	0.47	28.42	155.52	0.33	1.80	34.87

Notes. For regions with two peaks (2,4,6), the density of gas derived from dust can be understood that are contributed from both.

Physical Properties: Non-LTE constraints

Table 3: Physical properties constrained by non-LTE constraints.

region	$T_{\rm kin}$ (K)	$n_{\rm gas}$ ($\rm cm^{-3}$)	N(CO) ($\rm cm^{-2}$)	N(H_2) ($\rm cm^{-2}$)
#1	80 - 110	$\sim 10^5$	2.5×10^{17}	2.5×10^{21}
#2	≥ 20	$\geq 10^3$	$\sim 10^{16} - 10^{18}$	$10^{20} - 10^{22}$
	80 - 100	$\sim 10^5 - 5 \times 10^5$	3×10^{17}	3×10^{21}
#3	≥ 40	$\geq 10^4$	$\geq 10^{18}$	$> 10^{22}$
#4	90	$\sim 10^5$	2.5×10^{17}	2.5×10^{21}
	-	-	-	-
#5	80 - 120	$\sim 5 \times 10^4 - 10^5$	9×10^{17}	9×10^{21}
#6	≥ 40	$\geq 10^4$	$\sim 10^{16} - 10^{18}$	$\sim 10^{20} - 10^{22}$
	≥ 10	$\geq 10^3$	$\sim 10^{16} - 10^{18}$	$\sim 10^{20} - 10^{22}$
#7	≥ 20	$\geq 10^3$	$\sim 10^{16} - 10^{18}$	$\sim 10^{20} - 10^{22}$

Notes. There are no constraints for the second component of region 4 because of missing the CO(3-2) and CO(8-7) lines.

Radiation strength

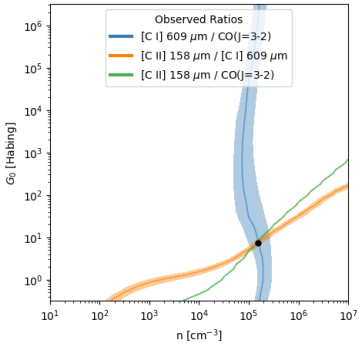

Figure 5: Overlay plots show the observed intensity ratios in the G_0 and n_H grids of the PDR Toolbox. The shaded area represents the observational error.

- n_H is well constrained by the ratio 609 μm [C I] / $^{12}CO(3-2)$.
- The ratio 158 μm [C II]/609μm [C I] and 158μm [C II]/$^{12}CO(3-2)$ are helpful for determining the field G_0.
- The radiation field is just about 7.3 Habing [a] (consistent with Oberst et al. 2011).

[a] $1 Habing = 1.63 \times 10^{-3}$erg $cm^{-2}s^{-1}$

Photo-Dissociation Rate and Dissociated Time

Table 4: Photo-Dissociation information of each region.

region	A_V	k (Molecule$\times s^{-1}$)	$A_{current}^{CO}$ (Molecules)	$\Delta n_{etacar}^{CO}(*)$ (Molecules)	t_{PD} (*Million* years)
#1	4.70	9.022786×10^{-20}	5.894959×10^{27}	0	2.071731×10^{33}
#2	0.93	5.021941×10^{-13}	1.171256×10^{27}	47	7.395604×10^{25}
#2	1.67	2.194837×10^{-13}	2.111219×10^{27}	20	3.050173×10^{26}
#3	0.44	1.027869×10^{-14}	5.808129×10^{26}	9	1.791809×10^{26}
#4	1.09	3.244180×10^{-14}	3.283634×10^{27}	307	3.209543×10^{25}
#4	0.72	5.195587×10^{-14}	2.166555×10^{27}	491	1.322295×10^{25}
#5	1.33	3.270516×10^{-13}	3.673553×10^{27}	31	3.561750×10^{26}
#6	1.01	1.207392×10^{-13}	4.107930×10^{27}	114	1.078867×10^{26}
#6	0.42	2.939979×10^{-13}	1.718491×10^{27}	278	1.853516×10^{25}
#7	0.47	3.413327×10^{-13}	1.803640×10^{27}	32	1.675580×10^{26}

Notes.$(*)$ These values were rounded to the closest integer numbers.

The age of $\eta - Carina$ is about 3 mil years $\ll t_{PD}$
$\Rightarrow$ CO clouds survived

Discussions

Motion of clouds

Some clouds in considered regions are moving at different velocities indicating these clouds are not in the proximity of $\eta - Carina$.

Number of CO molecules

CO abundance can be inferred by using 3D column density in which the shape of the region hence can be assumed to be spherical.

Table of Contents

Introduction and purposes

Theoretical backgrounds

Scientific method and data

Results and Discussions

Conclusion and further progress

1 Introduction and purposes

2 Theoretical backgrounds

3 Scientific method and data

4 Results and Discussions

5 Conclusion and further progress

Scientific Conclusions and Upcoming works

Conclusions

- Since CO lifetime of each cloud is larger than $\eta - Carina$ lifetime, these observed CO clouds can survive in the proximity of this star.
- Self-shielding and mutual-shielding effects have a strong contribution to reducing the photo-dissociation rate of CO in 7 given regions, hence increasing the lifetime of these clouds.

Future works

- Indicate the impact of interstellar feedback on our clumps.
- Complete a manuscript to publish.

Questioning time

Thank you for listening!

Time for questions and defense

Acknowledgement

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Introduction and purposes

Theoretical backgrounds

Scientific method and data

Results and Discussions

Conclusion and further progress

Acknowledgment

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