High spectral and spatial resolution observations of the PDR emission in the NGC2023 reflection nebula with SOFIA and Apex

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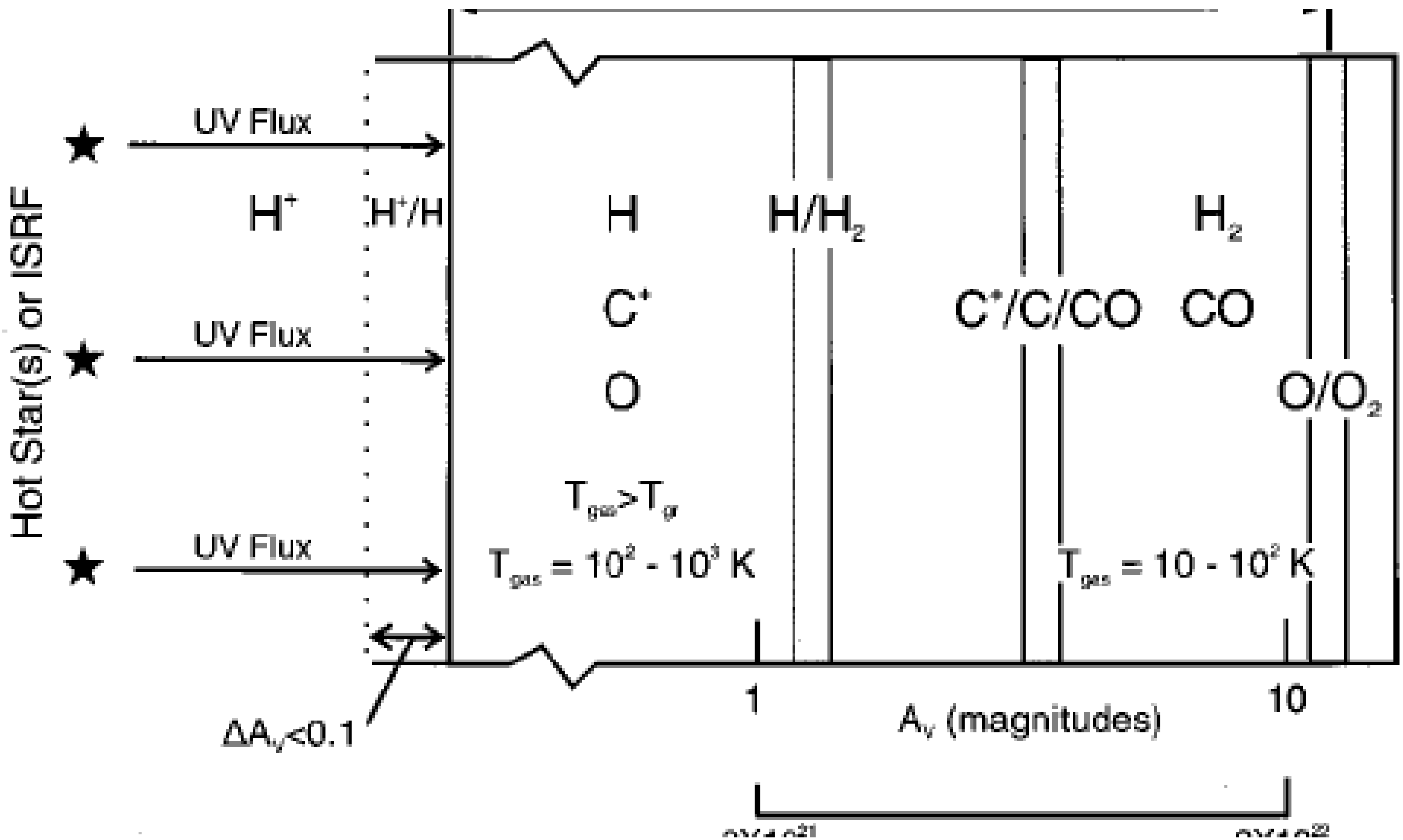
Outline

- Introduction to PDRs
- Brief summary of NGC2023 (and pretty pictures)
- Data sets
- [CII] dominated by PDR emission
- [13CII] emission
- The hot molecular shell, also PDR dominated
- Modeling
- Summary & Conclusions

Introduction to PDRs

- PDR, a region where FUV radiation, 6 – 13.6 eV (912 – 2066 Å) dominates the physics and chemistry of the interstellar medium
- All of the atomic gas and most of the molecular gas in the Galaxy is in PDRs
- Intense emission of [CII], [OI],[CI], ro-vibrational H_2, CO, and PAH emission bands and dust continuum dominate the infrared emission from PDRs

Schematic diagram of a PDR



NGC2023

- One of the best studied reflection nebulae in the whole sky
- Distance 350 pc, embedded in the L1630 dark cloud (Orion)
- Illuminated by the B2 V star HD37903
- This is where Kris Sellgren first confirmed the existence of PAHs
- Used as a test bed for most PDR models (going back to Black & van Dishoeck 1987)

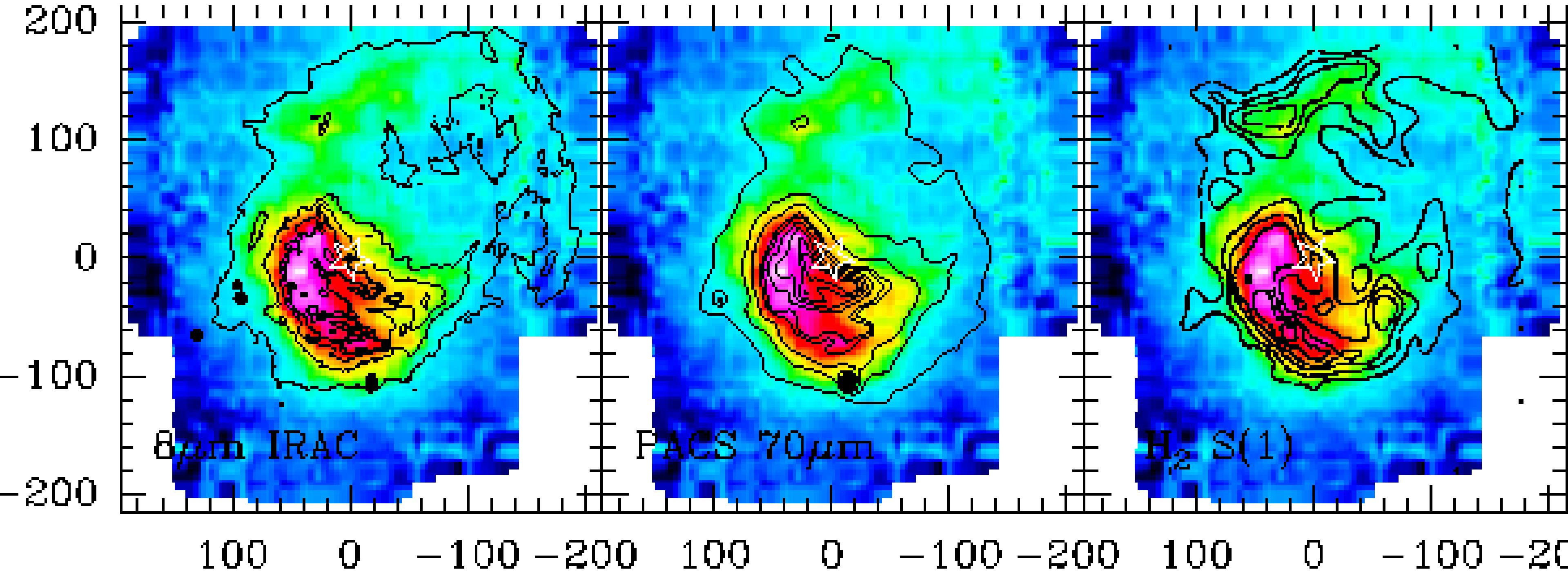
NGC 2023 and the Horsehead as seen by VISTA

Close up view of NGC2023

Observational data

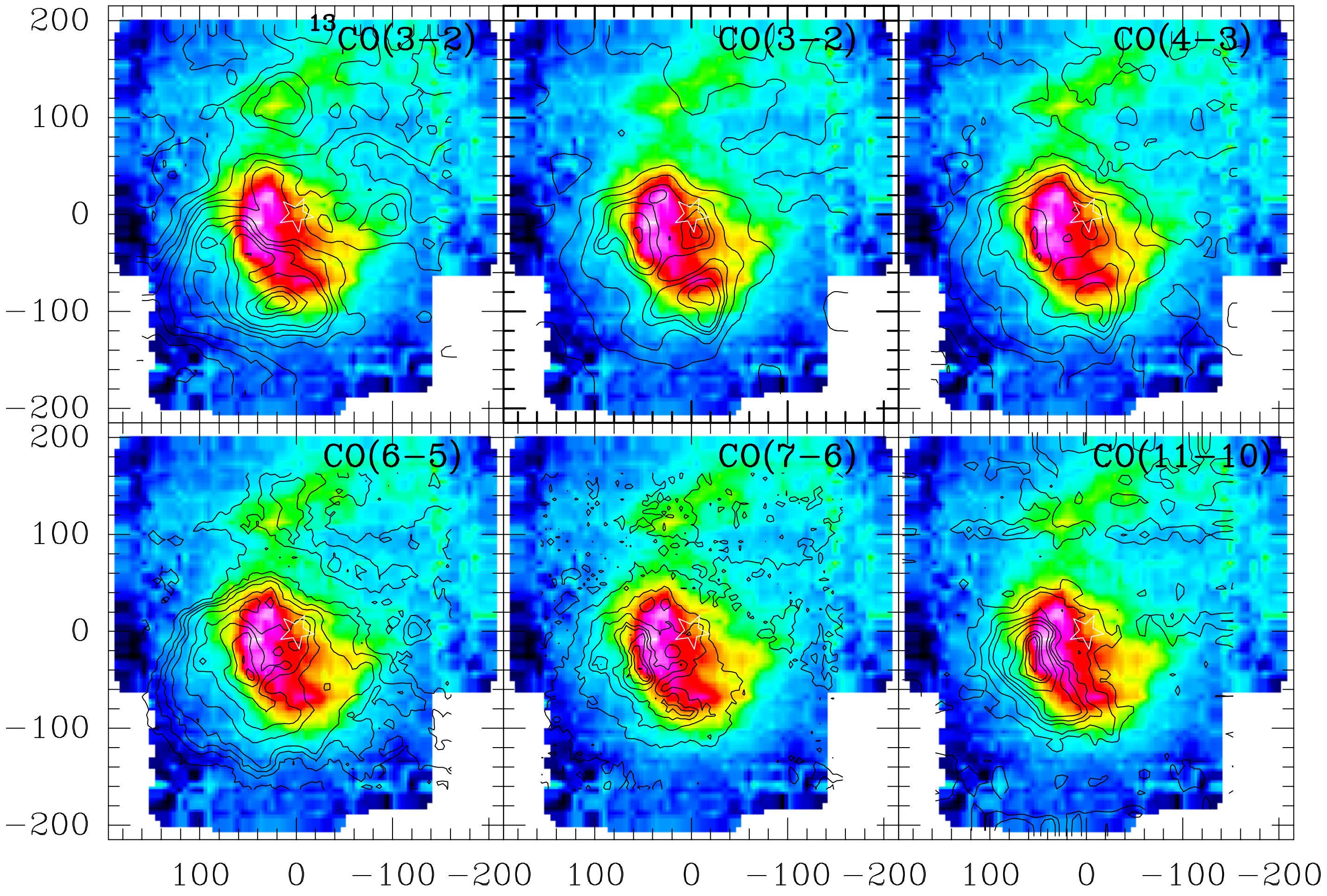
- SOFIA/GREAT:
  - Maps of [CII] (and [^{13}CII]) and CO(11-10) covering almost the whole reflection nebula
- APEX
  - Sligthly smaller maps in CO(3-2),^{13}CO(3-2), CO(4-3), CO(6-5) & CO(7-6)
- Herschel/HIFI
  - Deep [CII] integration towards HD37903, the B2e star illuminating the nebula, showing two of the [^{13}CII] hyperfine lines
- Herschel/PACS
  - 70/160 µm images of the whole reflection nebula

[CII] emission is PDR (i.e. FUV) dominated



Integrated [CII] emission (color image). Contours : 8μm PAH emission (left), 70 μm dust emission (middle), 2.1 μm H_2 (right) – all three trace PDR emission. Therefore [CII] also PDR dominated

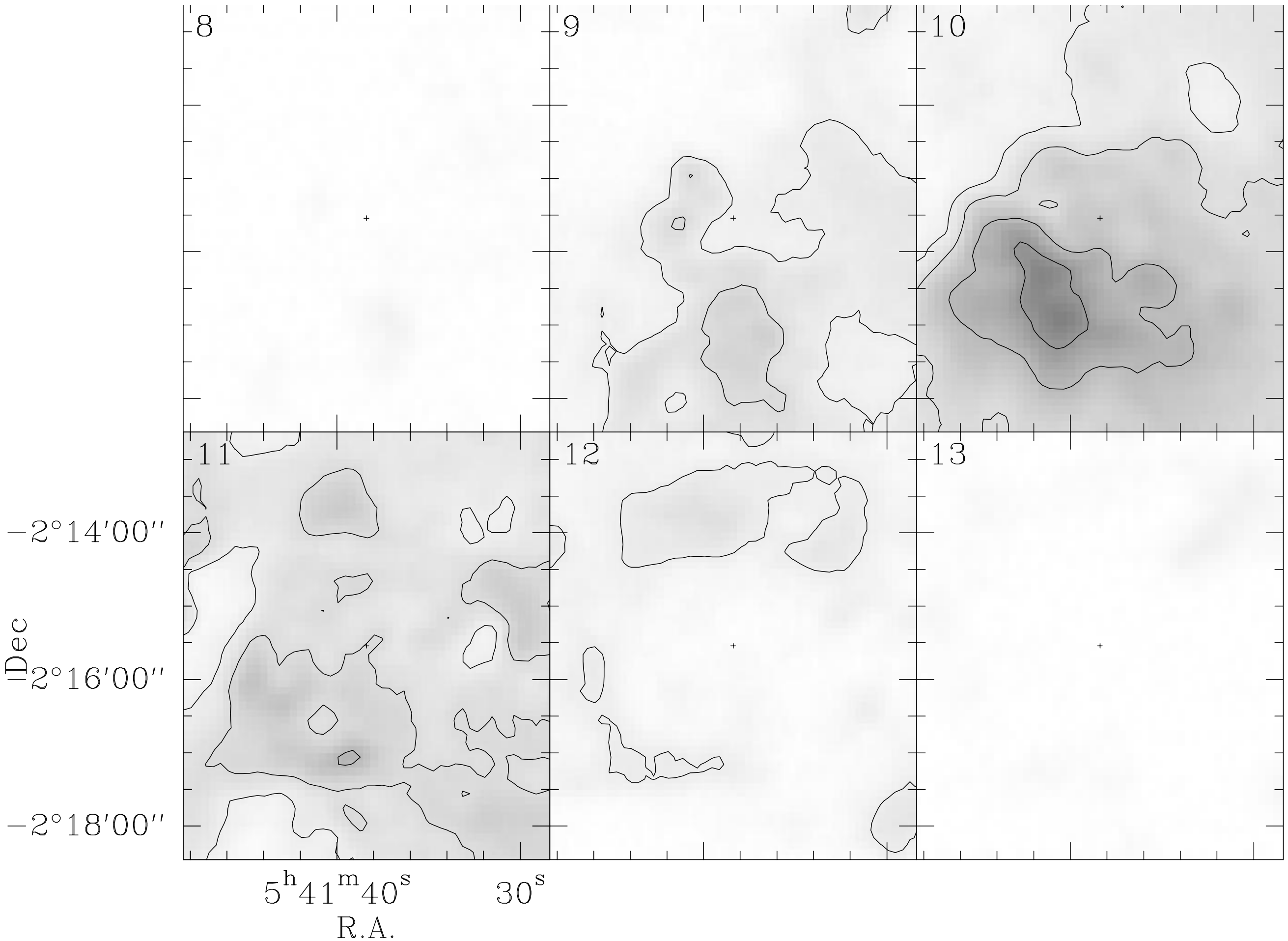
CO maps overlaid on [CII]



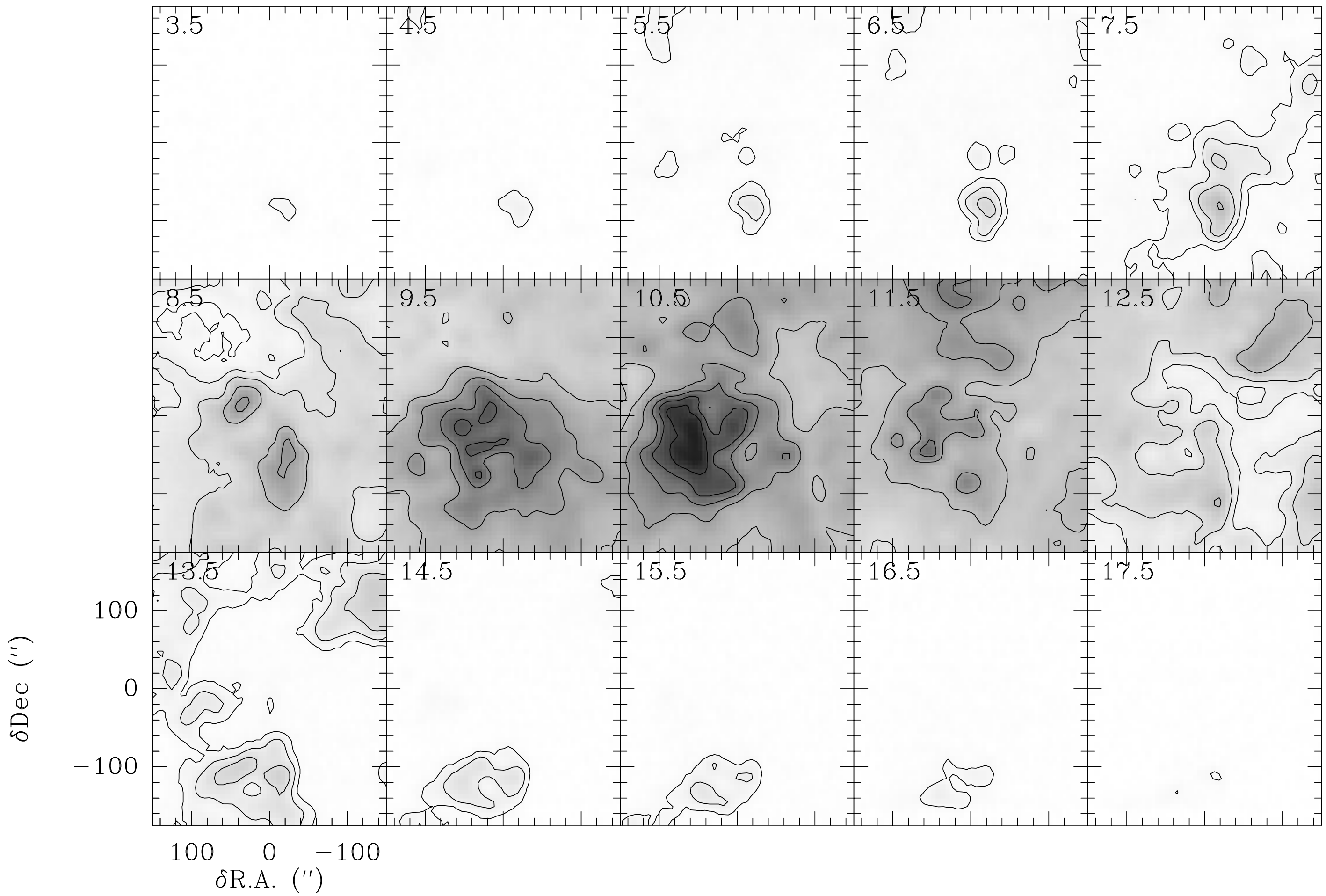
The surrounding cloud

- The surrounding cloud dominates the CO emission at low J CO transitions (^{13}CO traces the column density, ^{12}CO temperature)
- The cloud contributes to the CO emission even at CO 7-6, higher J transitions only see the hot PDR emission
- Dense cloud ridge in the SE, cloud more diffuse to the NW; cloud emission more red-shifted in the N & NW.
- Radex modeling of low J CO (3-2, 4-3) and ^{13}CO suggest that the cloud has a kinetic temperature of 35 - 40 K, and densities of 10^5 to a few times 10^6 $cm^{-3.}$

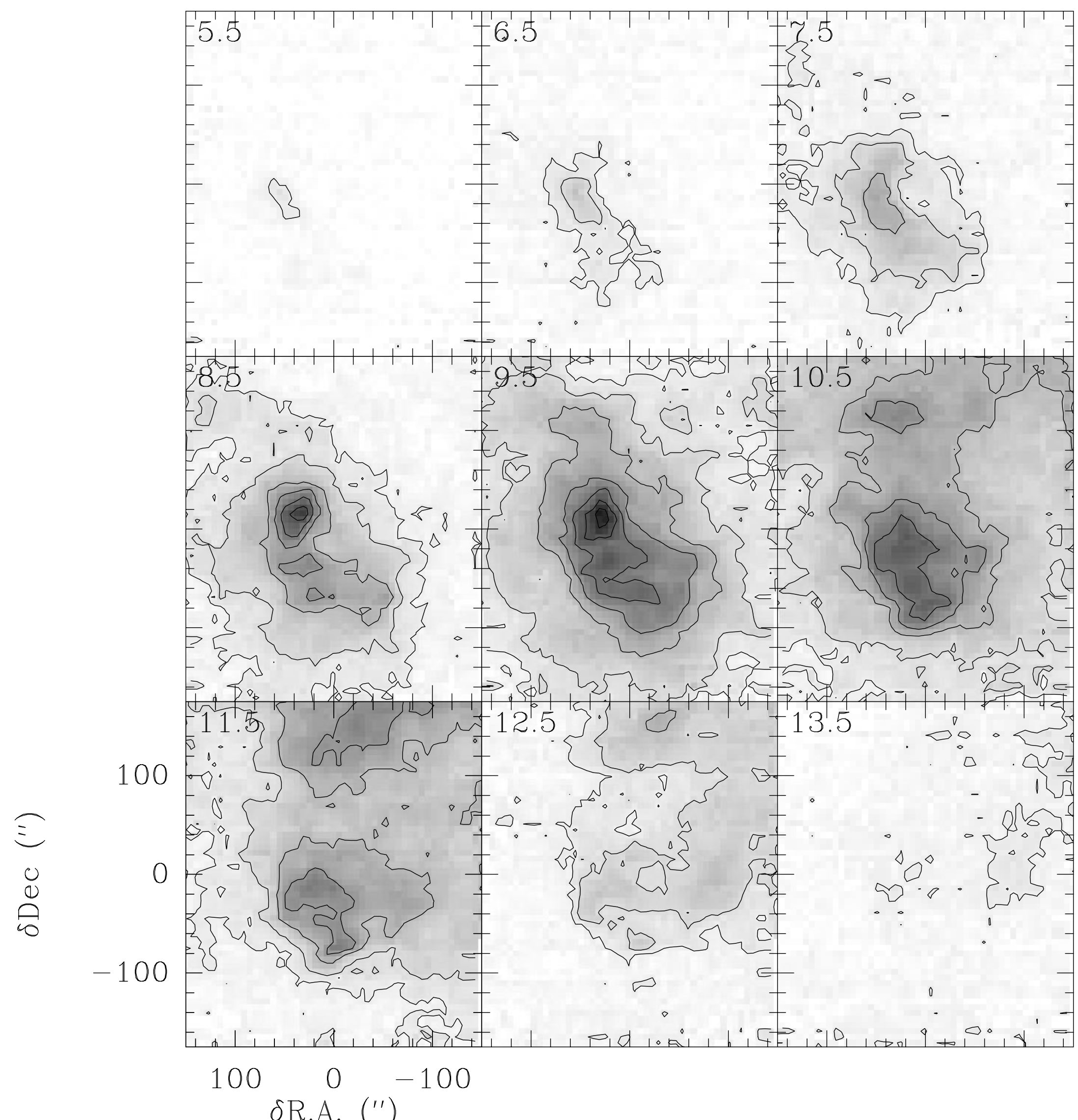
^{13}CO 3-2 channel maps



^{12}CO 3-2 channel maps



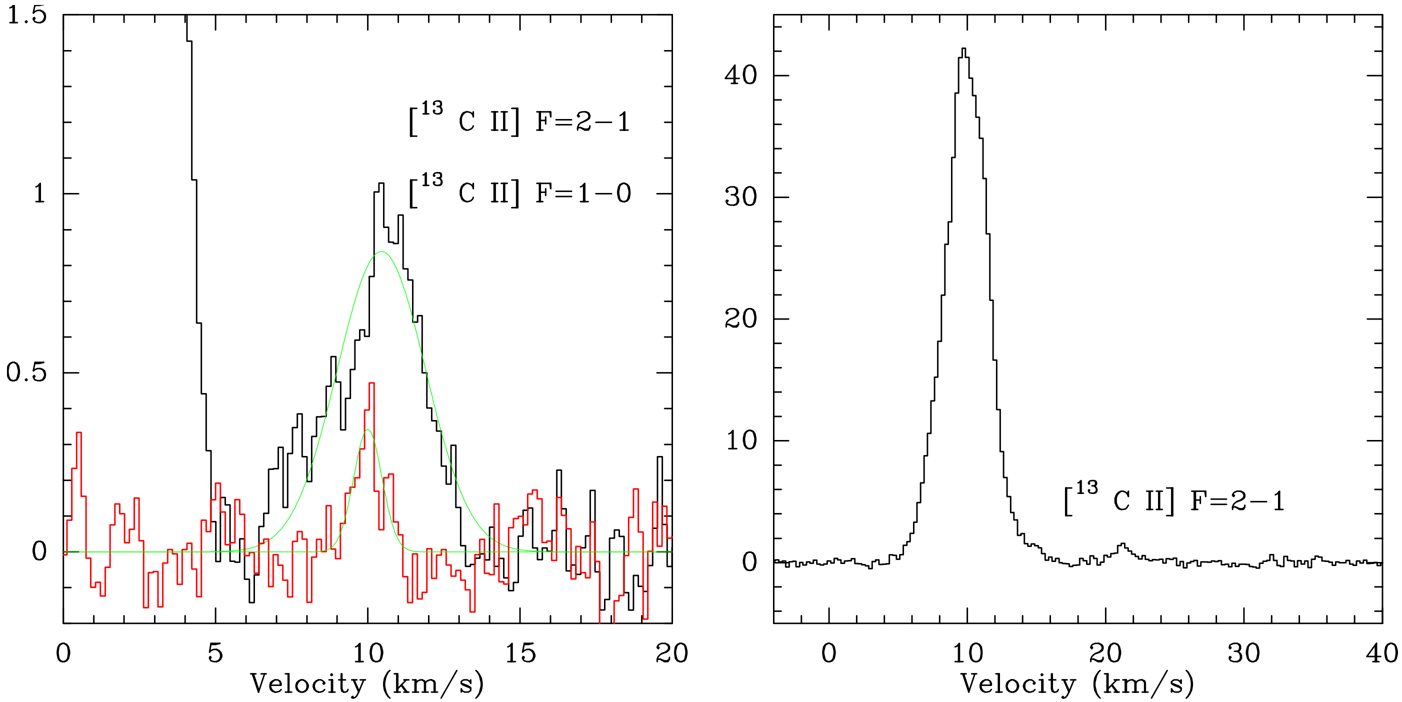
[CII] channel maps



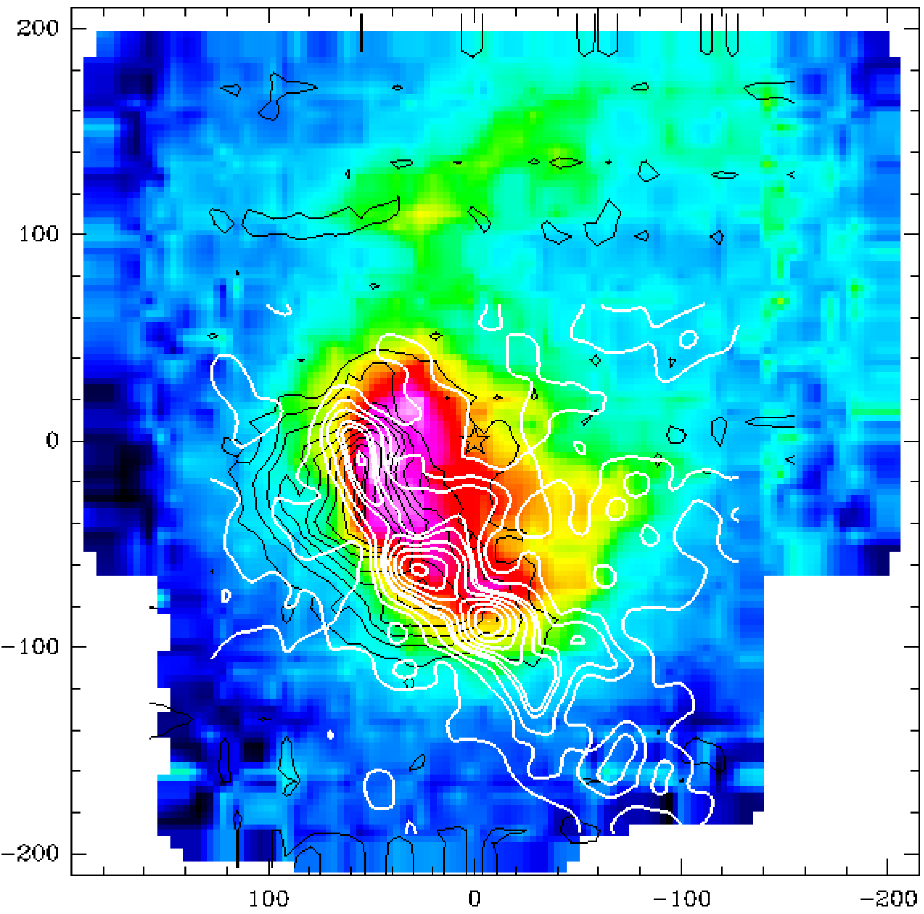
[^{13}CII]

[CII] somewhat optically thick, τ ~ 1 -2. [13CII] F=2-1 not seen in individual spectra, but visible in the average of all spectra in the cube.

Below is an average of all spectra in the SE quadrant with [CII] brighter than 35 K. To the left is the HIFI spectrum

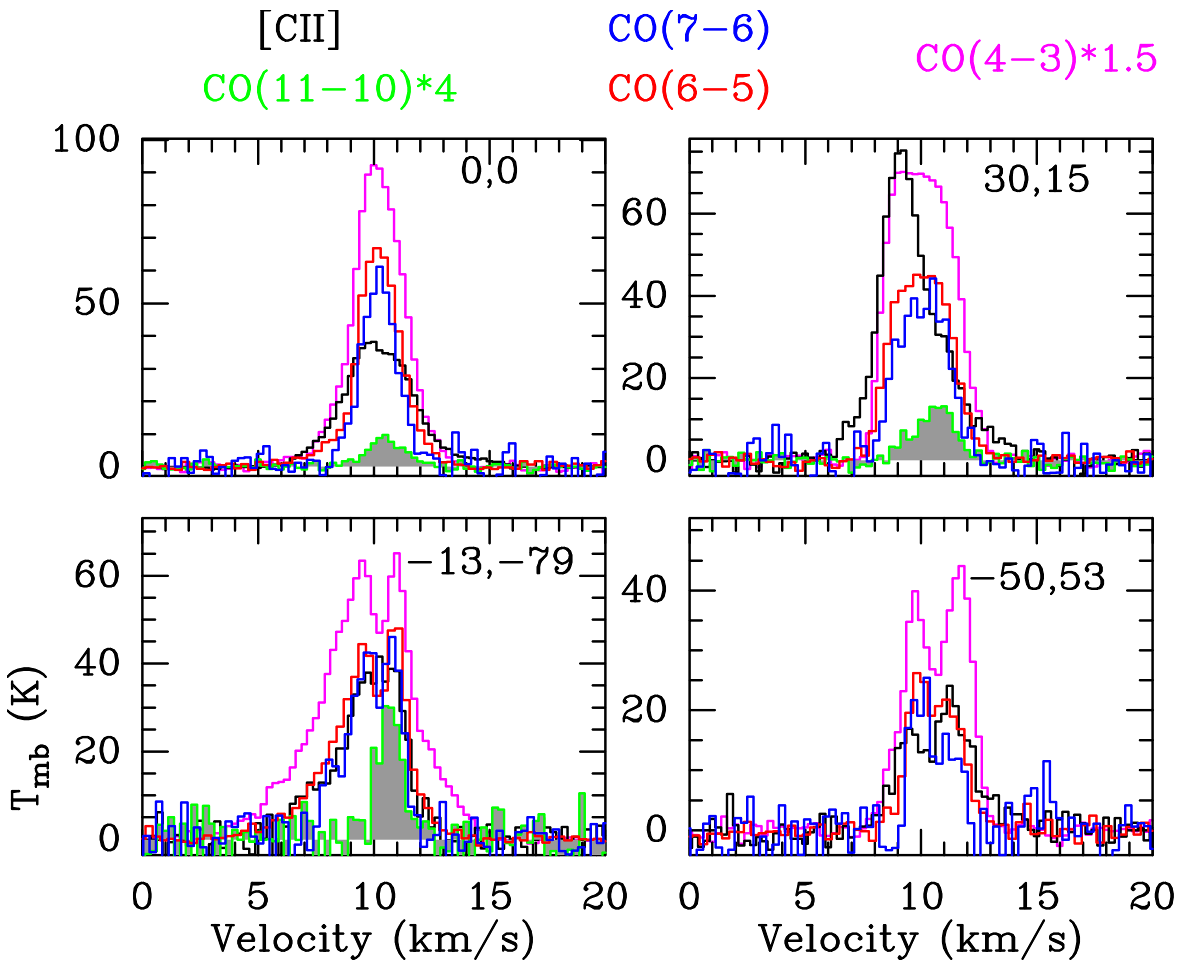


CO(11-10) overlaid on [CII]



The ellipsoidal (egg-shaped) CII region is surrounded by a thin hot molecular shell, seen clearly in CO(11-10) (black contours) in the SW quadrant of the map, where the CII region expands into the dense molecular cloud ridge. The CO lines are very narrow (0.5 km/s), where we see the shell tangentially. The temperature of the gas is ~ 100 K; density >~ 10^6 cm^{-3}

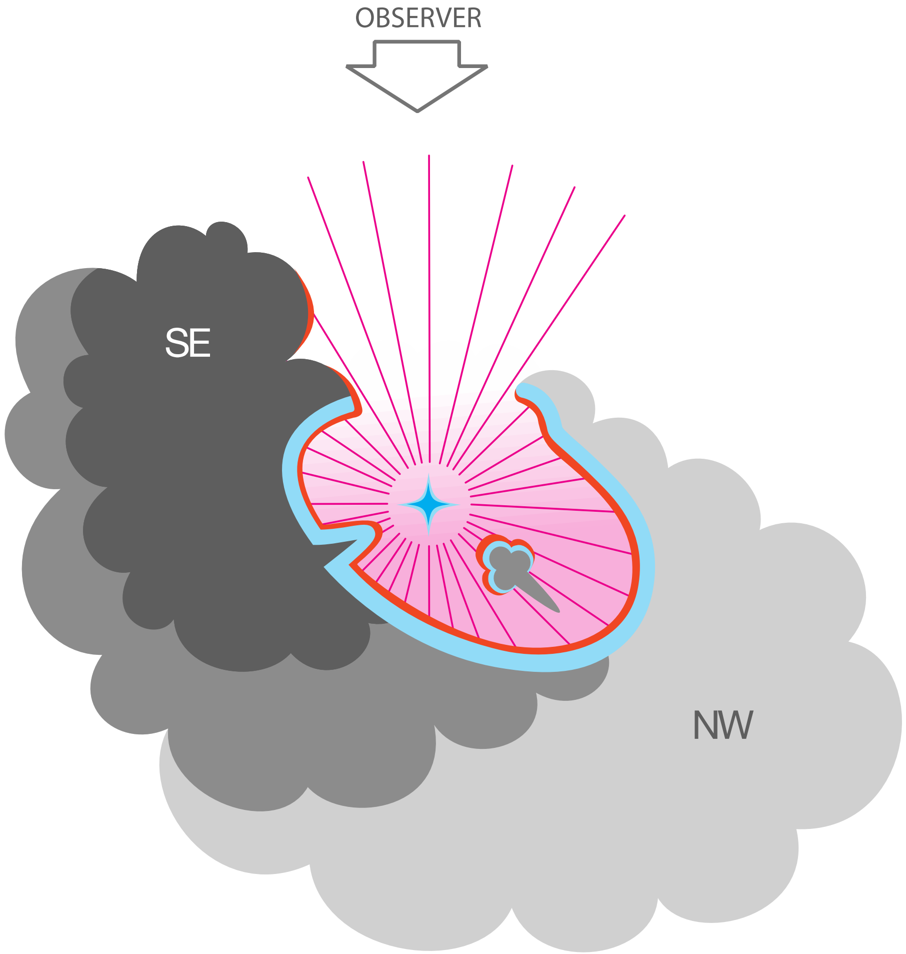
A few spectra



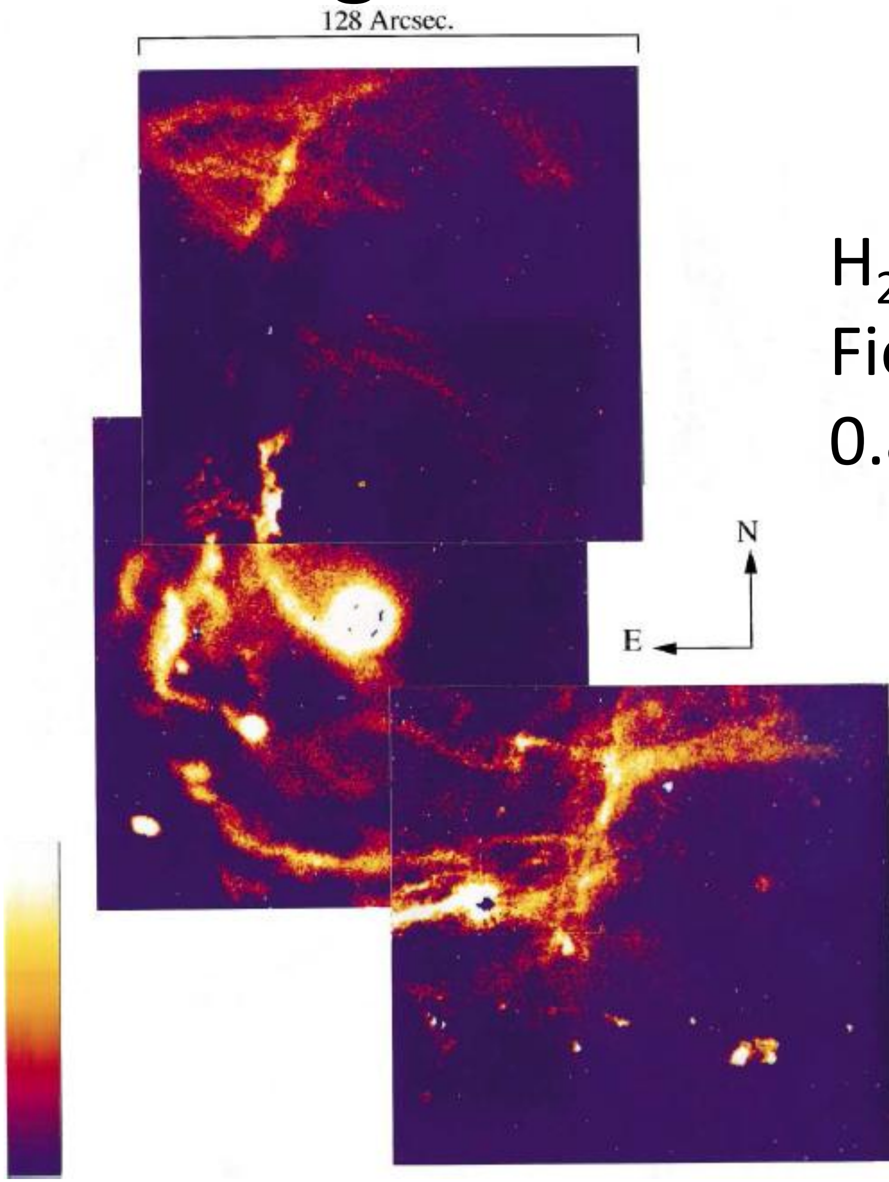
Line profiles

- [CII] and CO lines often double peaked. This is not due to self-absorption, but because we see the front and the back side of the shell. The centroid of [CII] emission is offset by a few tenth of km/s to blue or red depending on whether the emission comes from the front or the backside of the shell
- The expansion velocity in the SW quadrant is ~ 0.5 km/s, in the NE ~ 1 km/s, consistent with the CII region extending twice as far in the SW (lower density) than NE.
- [CII] shows strong blue and sometimes red-shifted wings. This is due to photo-evaporation flows from the PDR and most of the PDR emission comes from the backside.

Simple cartoon of the NGC2023 PDRs and the L1630 cloud



Reality more complicated ridges and 'filaments'



H_2 S(1) map from Fields et al (1998), 0.8" resolution

Triangle
Seahorse
IR cross
SR Southern ridge

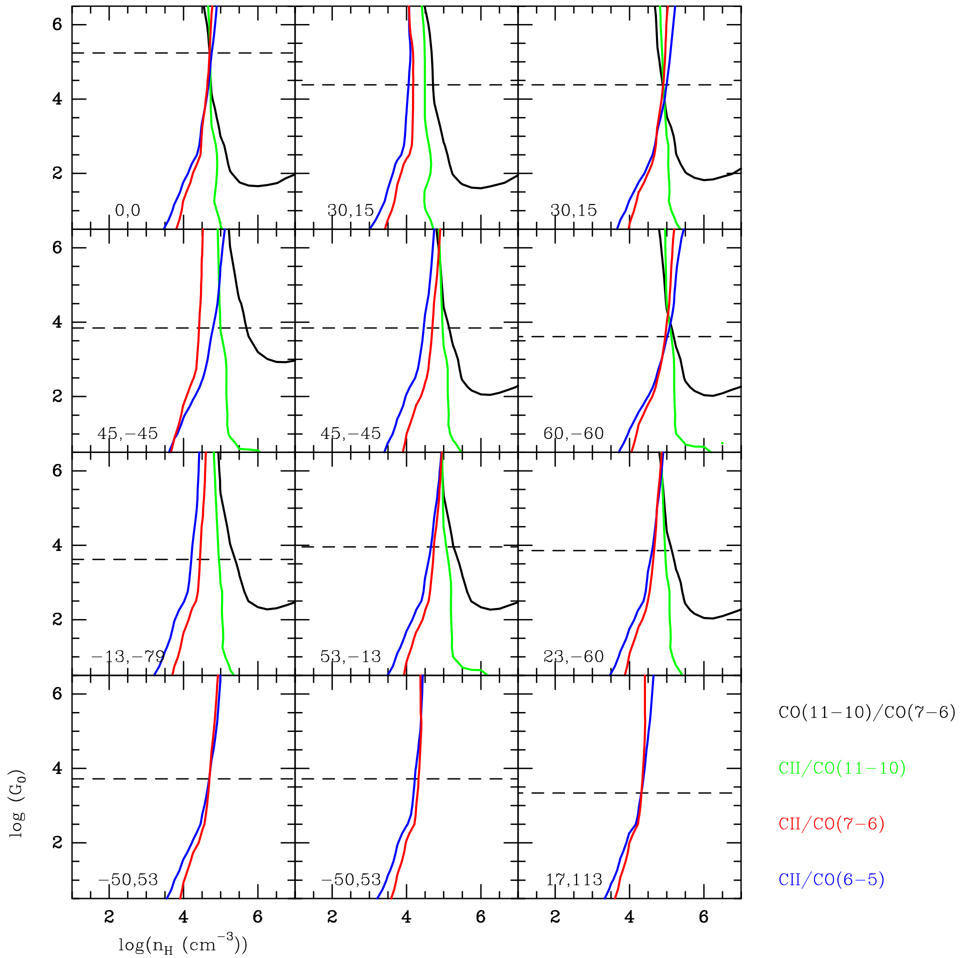
Modeling

- We use RADEX (non-LTE code, van der Tak et al. 2007) to explore the physical conditions of the hot molecular shell using ratio maps of different CO transitions
- We model the PDR using the model by Kaufman et al. (1999) (see also Tielens & Hollenbach 1985) in selected position, where we smoothed the spectra to the beam width of [CII]

PDR modeling

- Modeling [CII] trickier than for ex. Fluorescent H_2 (many lines – all originate in the PDR)
- Low J CO lines dominated by the cold surrounding cloud and may originate in regions which have no knowledge about the PDR. Where they overlap with the PDR we have strong self-absorption
- Only three CO lines are PDR dominated 6-5, 7-6 and 11-10.

PDR Modeling results



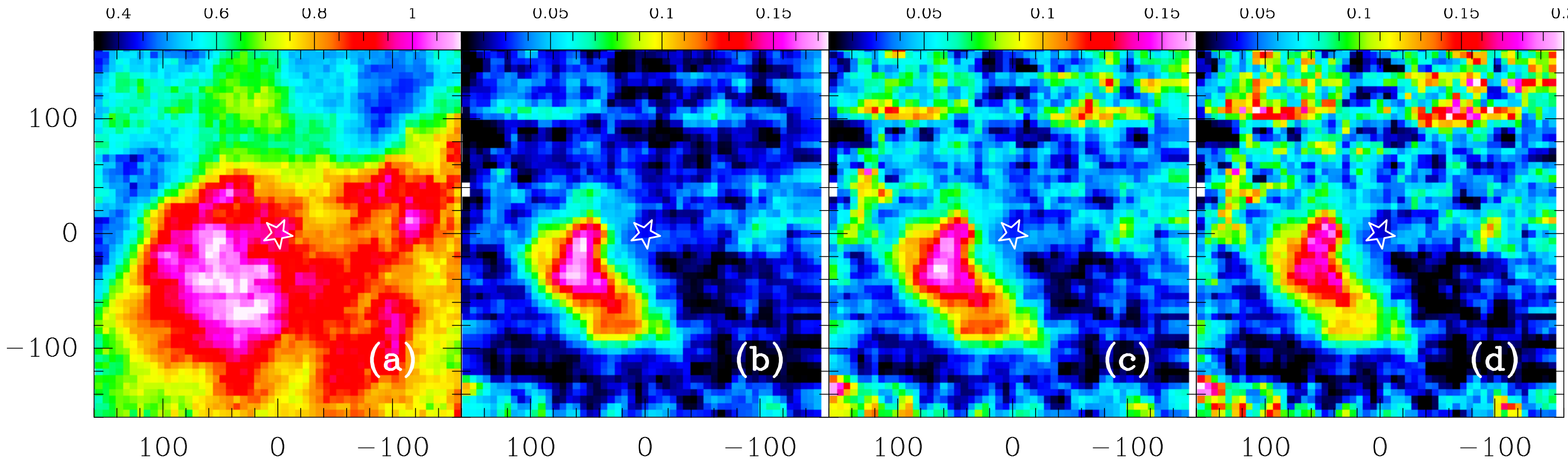
Not often that well constrained due contamination of CO emission from the surrounding cloud,

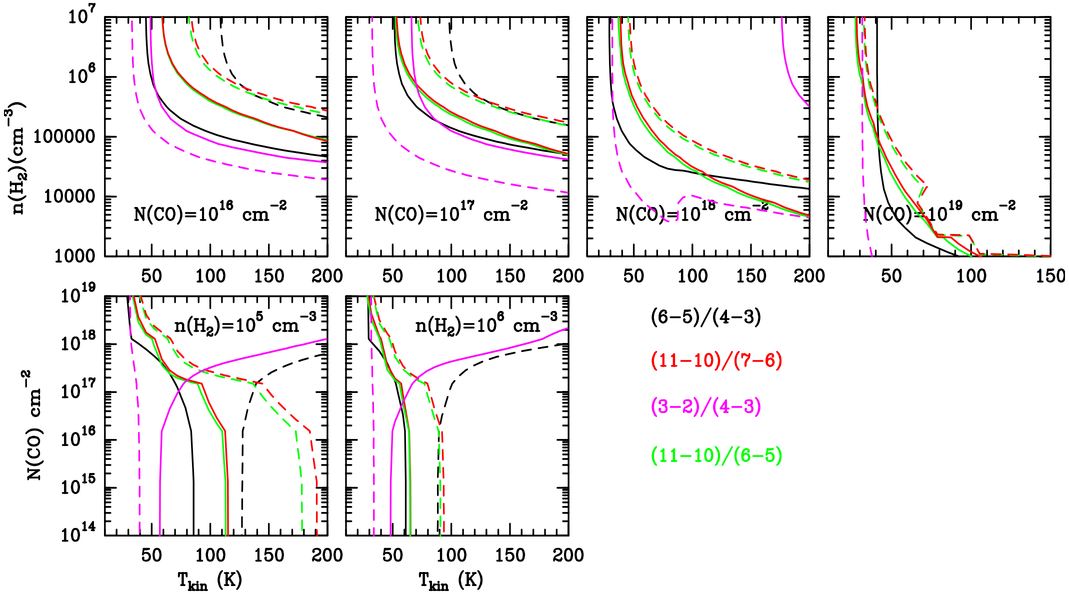
Our results for the SR lie between what Draine & Bertoldi (2000) (G = 5000, n = 5 10^4 cm^{-3}), and Sheffer et al (2011) (G = 10^4, n = 2 10^5 cm^{-3}), i.e. not too bad.

Summary & Conclusions

- High spatial and spectral images of [CII] ([^{13}CII]) and CO (both low and high J) gives us a unique insight to the morphology, kinematics and physical conditions of the CII region surrounding NGC 2023
  - RADEX modeling shows that the CO(3-2) and (4-3) emission primarily comes from the surrounding molecular cloud, which has a temperature of 35 - 40 K and densities of 10^5 - 10^6 cm^{-3}. The higher J CO lines come from the hot, thin molecular shell surrounding the [CII] region with temperatures of 90 – 120 K for densities of 10^5 - 10^6 cm^{-}
  - PDR modeling of selected positions predicts somewhat lower densities, 10^4 – 10^5 cm^{-3} with the FUV flux varying between 2.2 10^3 – 1.7 x 10^5 G_0 (Habing units), depending on location in the nebula
  - The [CII} luminosity is 1.6% of the total FIR luminosity. In the dense SE quadrant the fractional [CII] luminosity is somewhat lower, 1.1%, while the CO luminosity may be as high as 0.3%.

Radex analysis of the hot molecular shell





Ratios insensitive to column density. Density ≥ 10^6 cm^{-3}, T_{kin} 90 - 120 K