



Sub-arcsecond Infrared Imaging of Molecular and Ionized Gas in Three Prototypical High-Mass Star-Formation Regions

John H. Lacy, Daniel T. Jaffe & Shadrian B. Strong
University of Texas, Austin, TX



Observations

The observations were made with TEXES (Lacy et al. 2002), a cross-dispersed mid-infrared spectrograph with 3-4 km s⁻¹ spectral resolution. NGC 7538 and W3 were observed on Gemini North with 0.4'' spatial resolution. Orion was observed on the NASA IRTF with 1.2'' resolution. Maps (data cubes) were made by stepping the spectrograph slit across the source, with a step size of 1/3-1/2 the spatial resolution.

Orion Kleinmann-Low Nebula

KL was observed in spectral settings near 13 μm, 8 μm, and 5 μm including numerous lines of C₂H₂, HCN, SiO, H₂, OCS, and CO. Spectra showing lines of C₂H₂, ¹³CCH₂, and HCN, extracted from the data cube, are shown with a map made from one spectrograph order in Figure 2. Lines are marked at their rest frequencies (v_{LSR} = 0). The line profiles vary considerably from place to place in KL, going into emission toward IRc3. The varying Doppler shifts are shown in Fig. 3 as a fan diagram, where the fans represent the Doppler shifts, widths, and depths of absorbing ‘clouds’, fitted to the C₂H₂ spectra, with v_{LSR} = 0 at 12:00, -10 at 9:00, and +10 at 3:00.

The observations of SiO and H₂ emission near 8 μm are shown as contour maps in Figure 4. The SiO distribution is consistent with that of thermal SiO rotational line emission. The H₂ J=6-4 emission is consistent with the location and Doppler shift of the hot core. If it is actually from the hot core, this is the first observation of hot core gas in the infrared.

The observations generally support the Wynn-Williams et al. (1984) model of KL, in which the IR sources are either holes through which we can see into a hot cavity (IRc2, 7, and probably 4) or clouds illuminated by hidden luminosity sources (IRc3). The molecular absorption is caused by ‘plateau’ gas flowing out through the holes in the hot core that hides source I. The apparent C₂H₂ emission is actually resonant scattering by molecules of photons originally emitted by dust, which is consistent with the fact that near infrared radiation from these regions is polarized by scattering from dust. The SiO lines probably are formed by resonant scattering of photons from source I by SiO in a wind from I. Our sketch of the region is shown in Fig. 5.

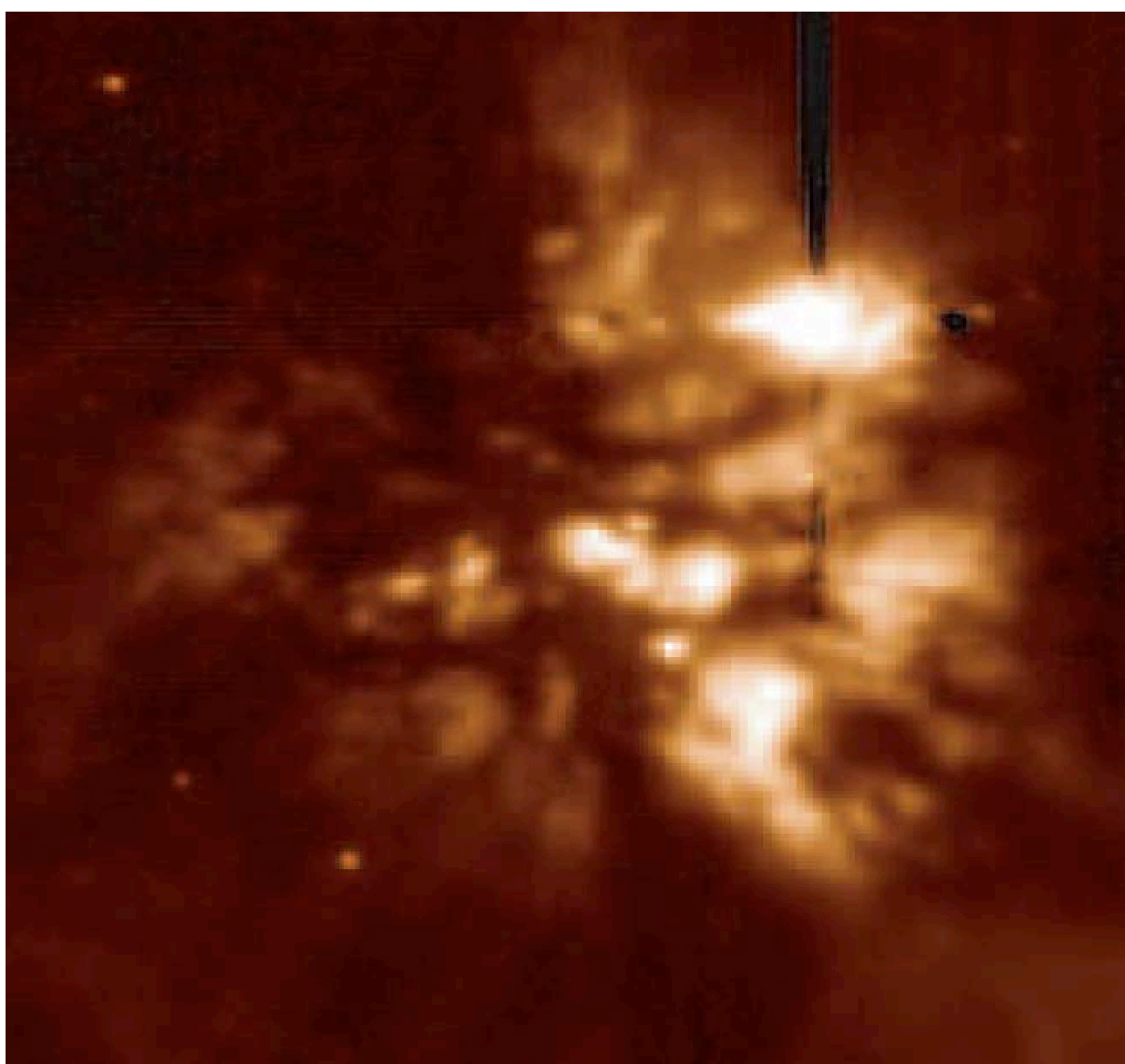


Fig. 1. 11.7 μm continuum image of KL taken from Smith et al. (2005).

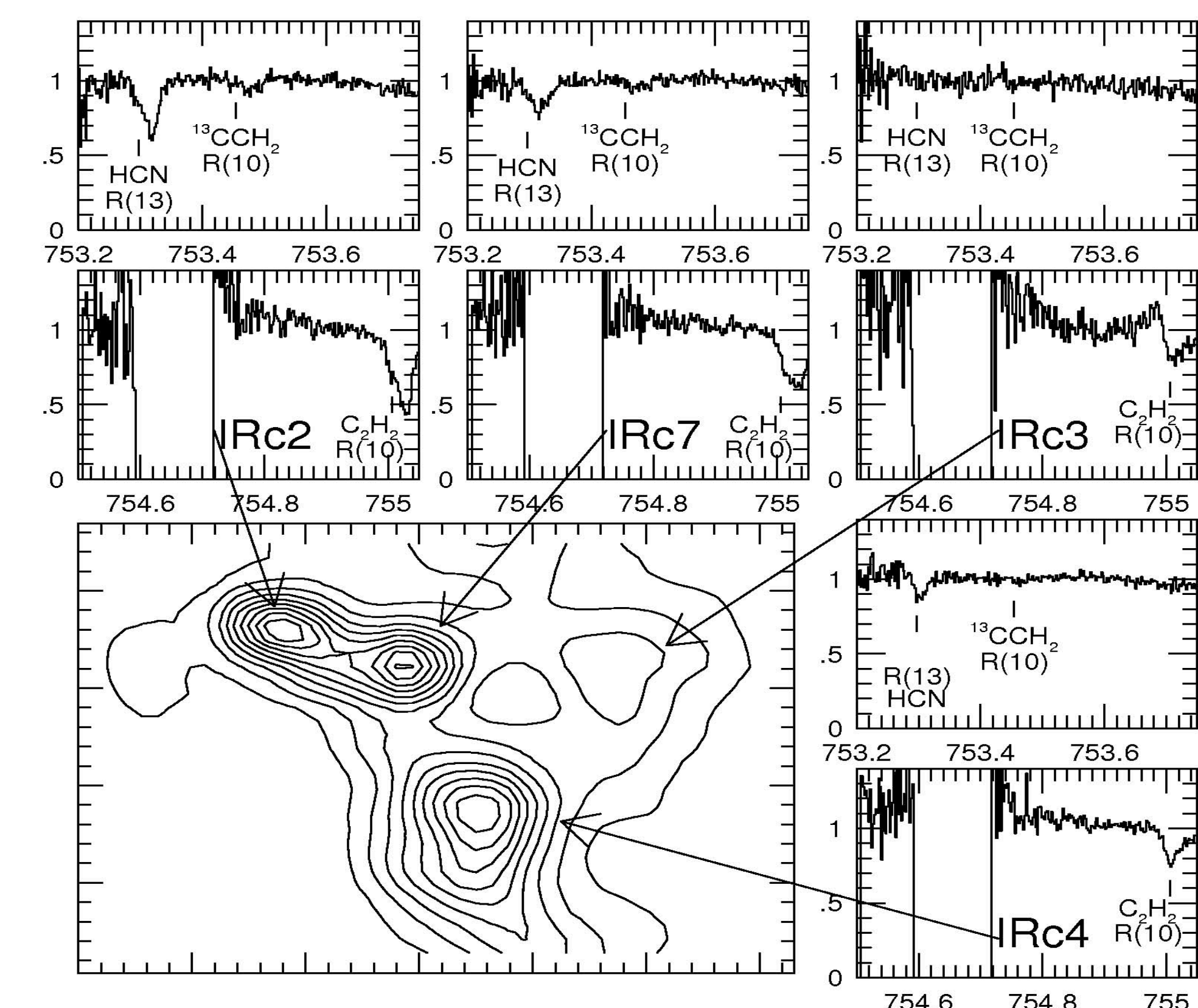


Fig. 2. Spectra showing lines of C₂H₂ and HCN and a contour map of the 13 μm continuum from KL taken from a scan map data cube.

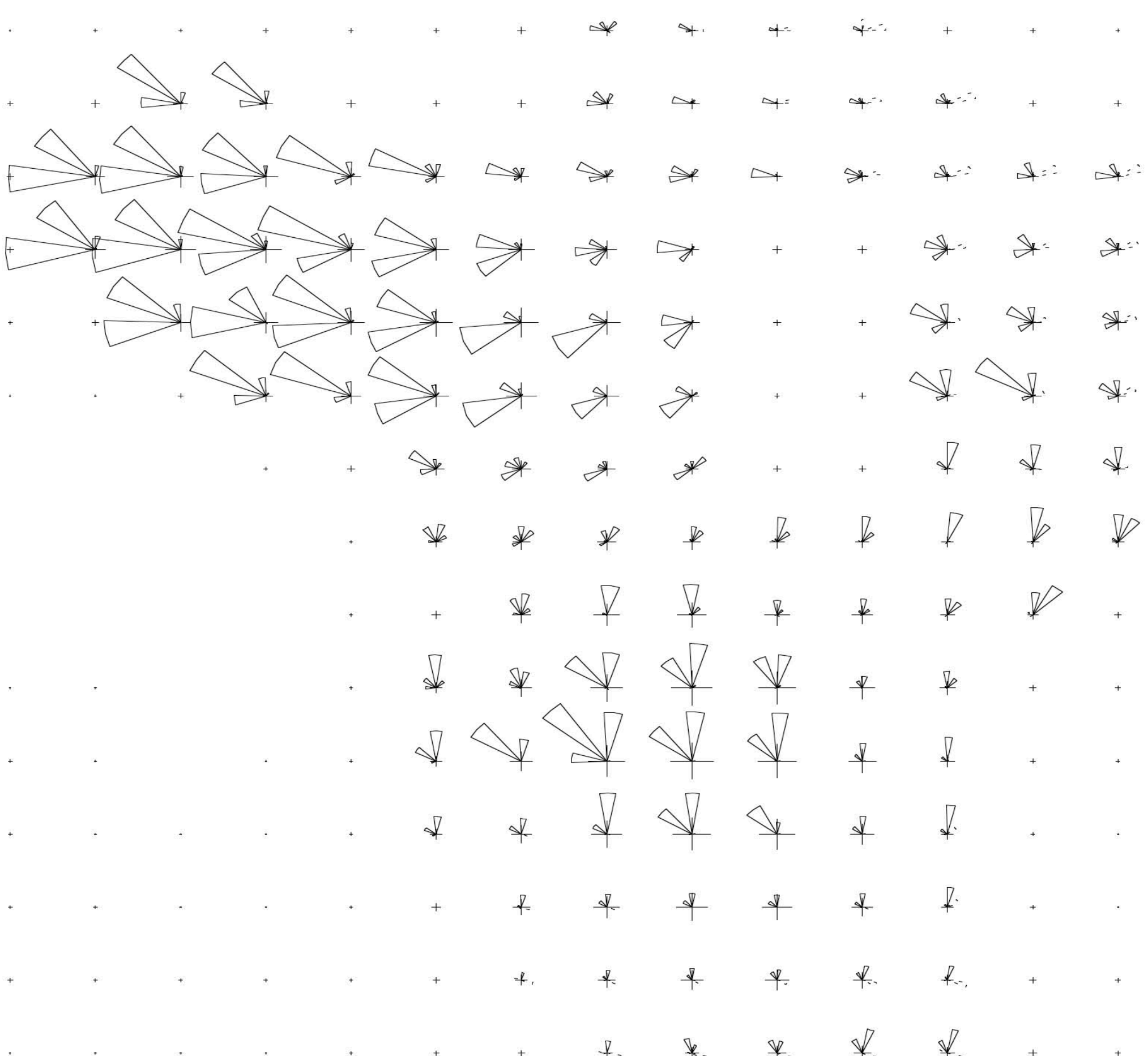


Fig. 3. Fan diagram showing the absorbing and emitting (dotted fans) clouds toward KL.

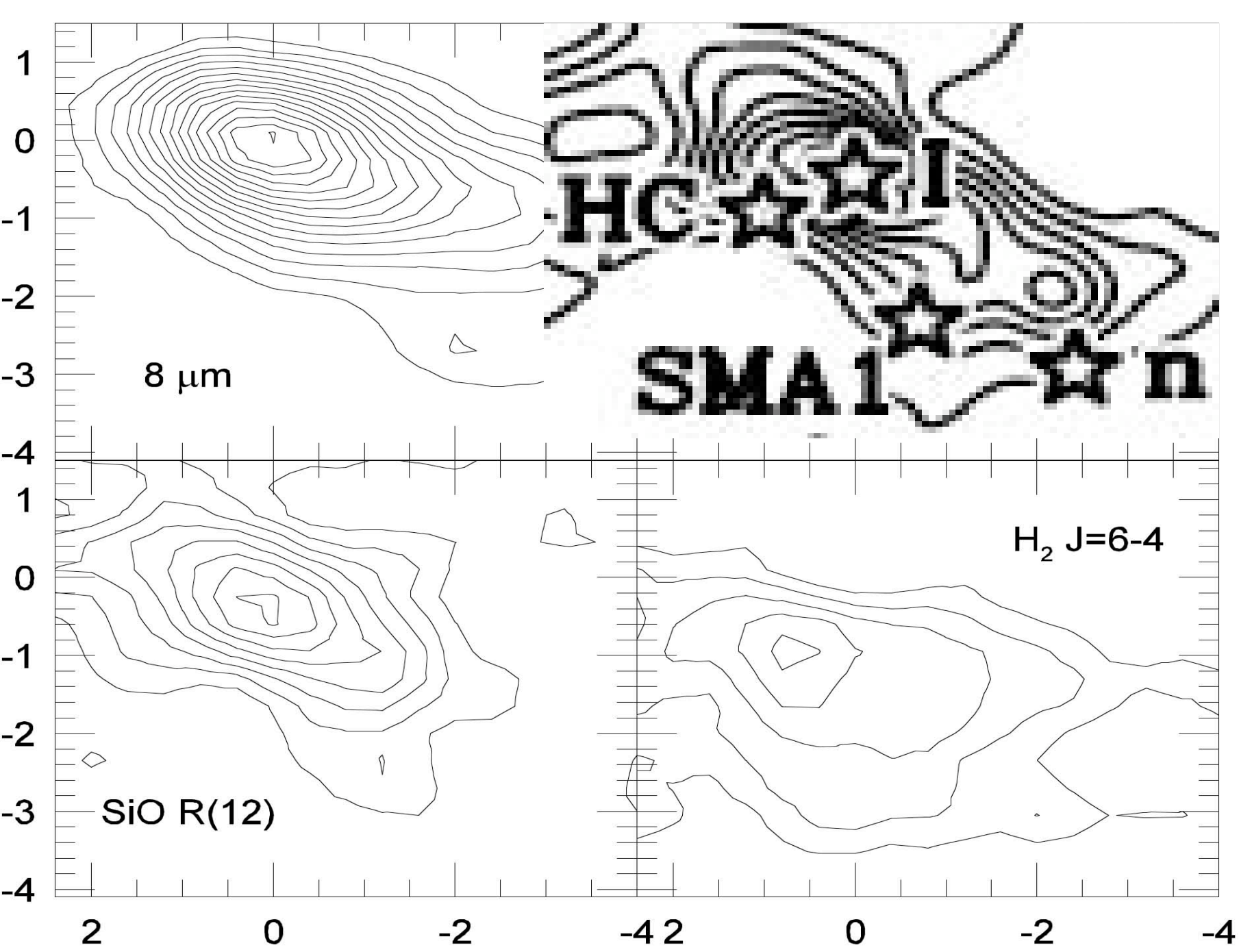
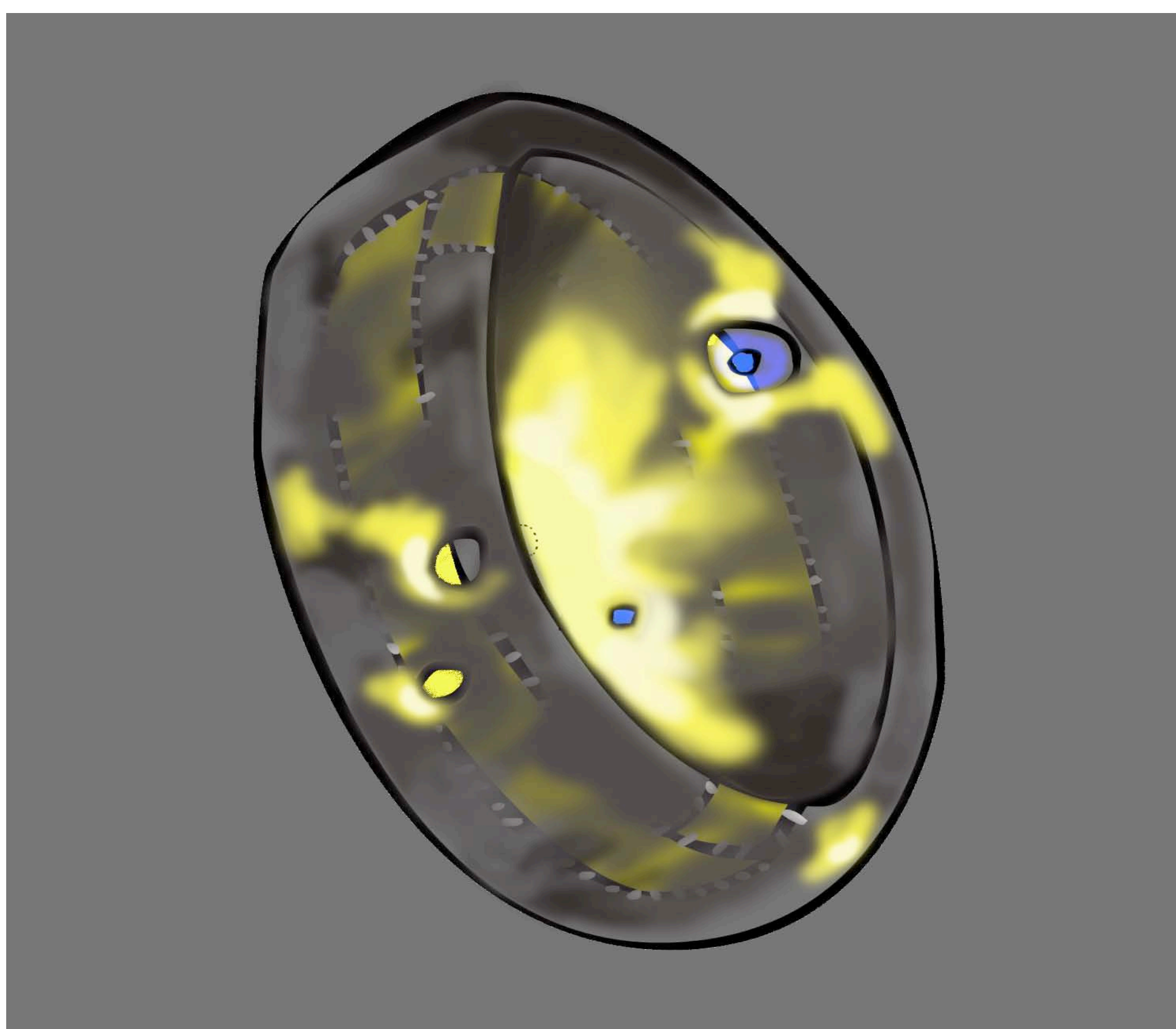


Fig. 4. Maps of 8 μm continuum, SiO J=8-7 (Beuther et al. 2005), SiO v=1-0, and H₂ emission from IRc2 and the hot core.



NGC 7538 IRS 1

IRS 1 was observed in two spectral settings: 780 cm⁻¹ (12.8 μm), including the [Ne II] emission line and several absorption lines of NH₃ and HNCO, and 767 cm⁻¹ (13.0 μm), including absorption lines of C₂H₂ and HCN. Spectra of the [Ne II] line, with NH₃ and HNCO lines in its wings, and the C₂H₂ v₃ R(15) line, extracted from several locations in the data cubes are shown in Fig. 6. Also shown is a map made from one spectral order at 13 μm. The map has been deconvolved with a maximum entropy routine. A map of the 1.3 cm f-f continuum and NH₃ masers, from Gaume et al. (1991) is shown for comparison.

The spectra indicate that the elongated infrared source is a blend of two sources. The southern source shows broad ionic emission and deep molecular absorption. The northern source, as well as more extended emission, shows narrower ionic emission and little molecular absorption. Assuming the f-f and 13 μm continuum coincide, which is supported by the similarity of the [Ne II] and 13 μm emission, the southern IR source coincides with the maser cluster C of Minier et al. (2000). This maser cluster also agrees in Doppler shift with the molecular absorption. The northern IR source coincides with their maser cluster A, which they suggest is in a rotating disk.

De Buizer & Minier (2005) have suggested that the sub-arcsecond scale elongated IR emission is the disk which collimates molecular outflow. We conclude that the elongation is caused by two unresolved sources. The collimating disk may be on a yet smaller scale. It may be the disk traced by maser group A, or it may surround the southern source, which apparently is the source of an ionized outflow (see Fig. 7.).

W3 IRS 5

IRS 5 was mapped in the 767 cm⁻¹ R(15) line of C₂H₂ and R(18) line of HCN. The 13 μm continuum map and extracted C₂H₂ spectra are shown in Fig. 8. With MEM deconvolution, IRS 5 is seen to consist of three sources, the well-known 1.2'' separation binary and a fainter source between them. C₂H₂ and HCN absorption is seen toward the brighter sources. It is weaker or absent toward the central source.

The absorbing gas could either surround the entire cluster or the individual sources, as the small velocity difference between the sources could be due to their motions or to a velocity gradient in the surrounding cloud.

Acknowledgements

These observations were made on the Infrared Telescope Facility, which is operated by the University of Hawaii under Cooperative Agreement no. NCC 5-538 with the National Aeronautics and Space Administration, and the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy under a cooperative agreement with the NSF on behalf of the Gemini partnership. This work was supported by NSF grant AST-0607312.

Fig. 5. A sketch of a model of the KL region. The hot core forms an obscuring ring around source I. IRc2, 4, and 7 are seen through holes in the ring. IRc3 may lie on the surface of the ring, illuminated by I. Compare to Fig. 1, in which the hot core can be seen as the dark lane through KL.

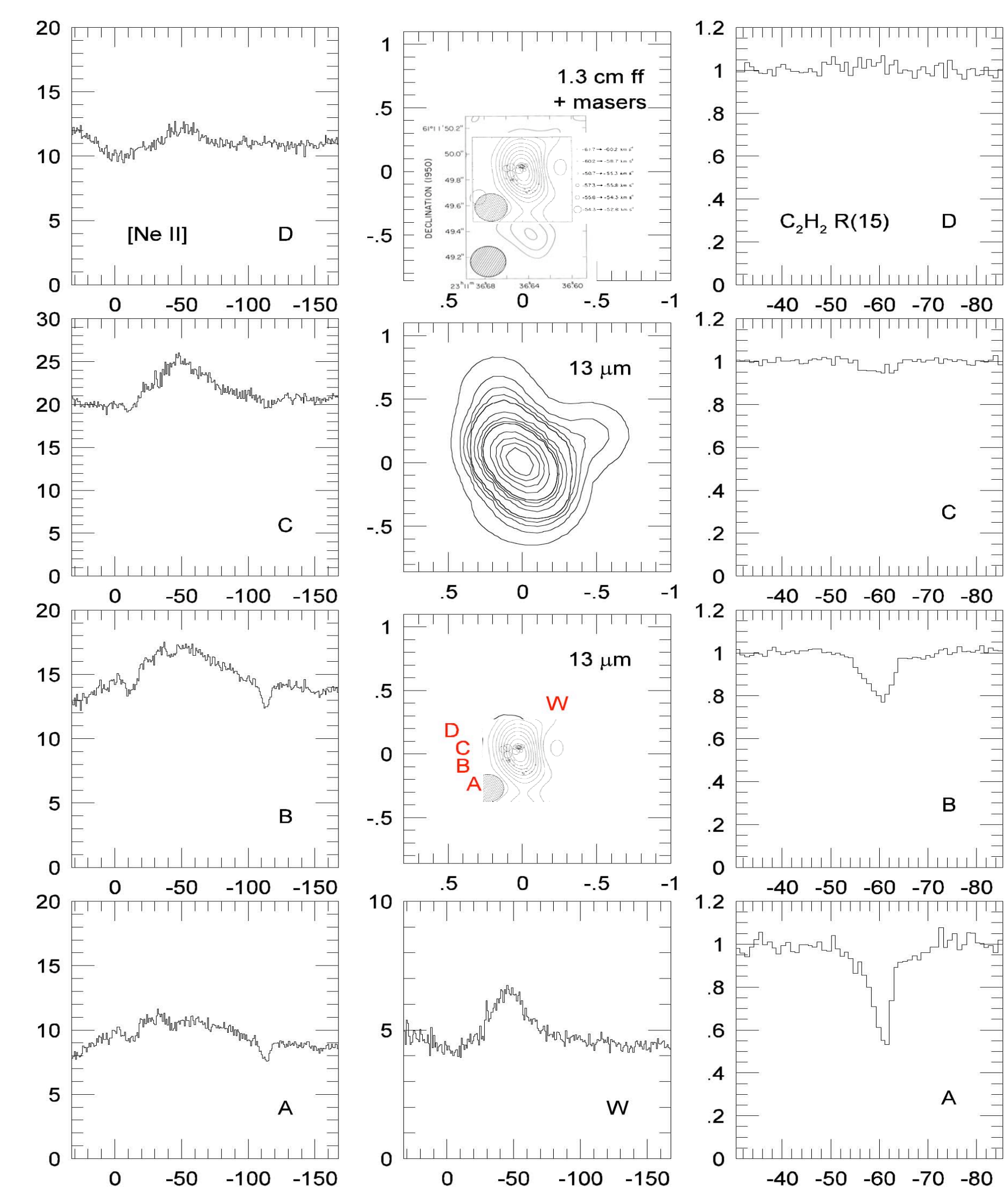


Fig. 6. Continuum map and spectra extracted from a data cube of NGC 7538 IRS 1. The image was deconvolved with MEM before extracting the spectra. The upper center box shows the 1.3cm continuum for comparison.

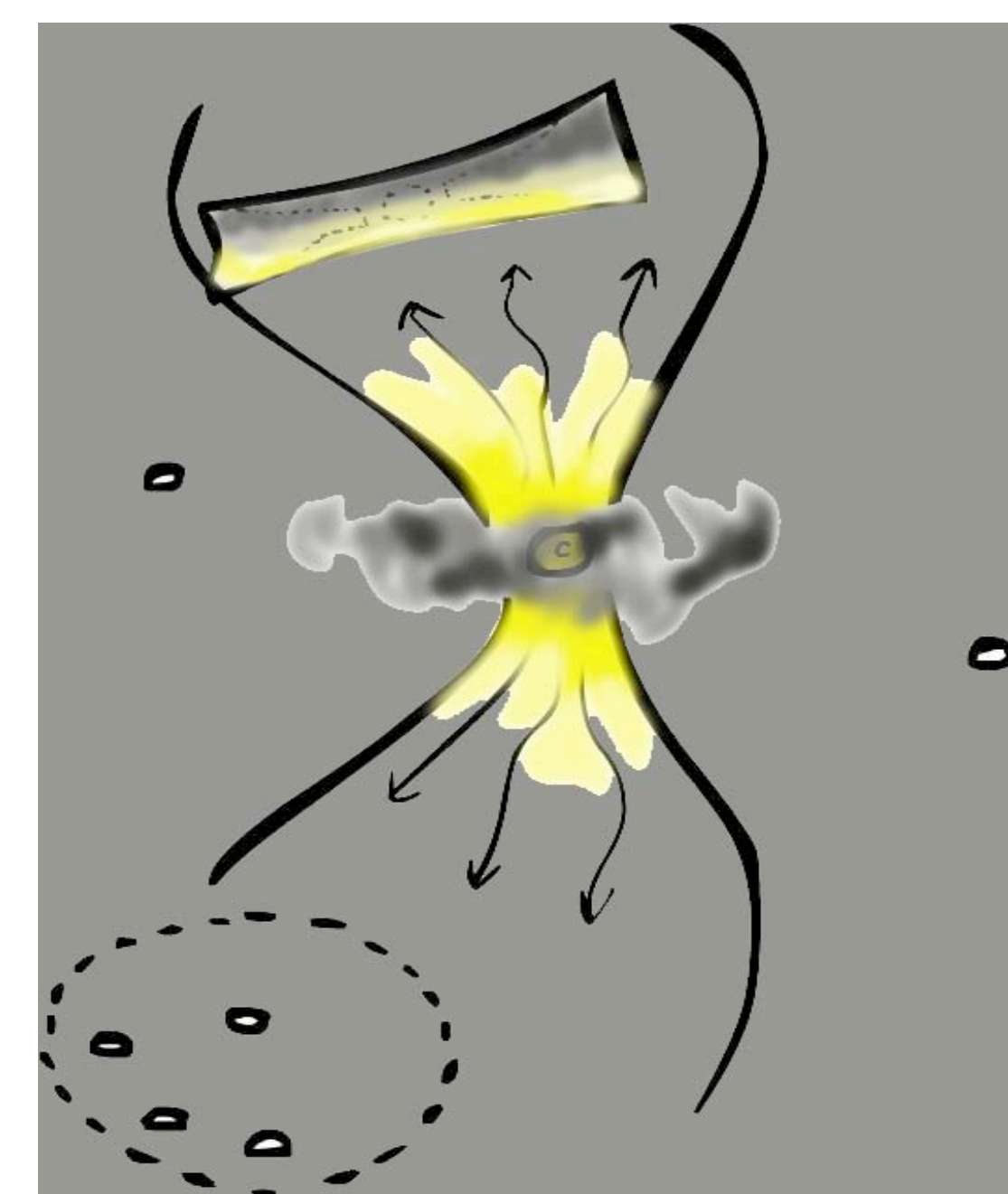


Fig. 7. A sketch of the NGC 7538 IRS 1 region showing two possible locations of the disk which collimates the molecular outflow.

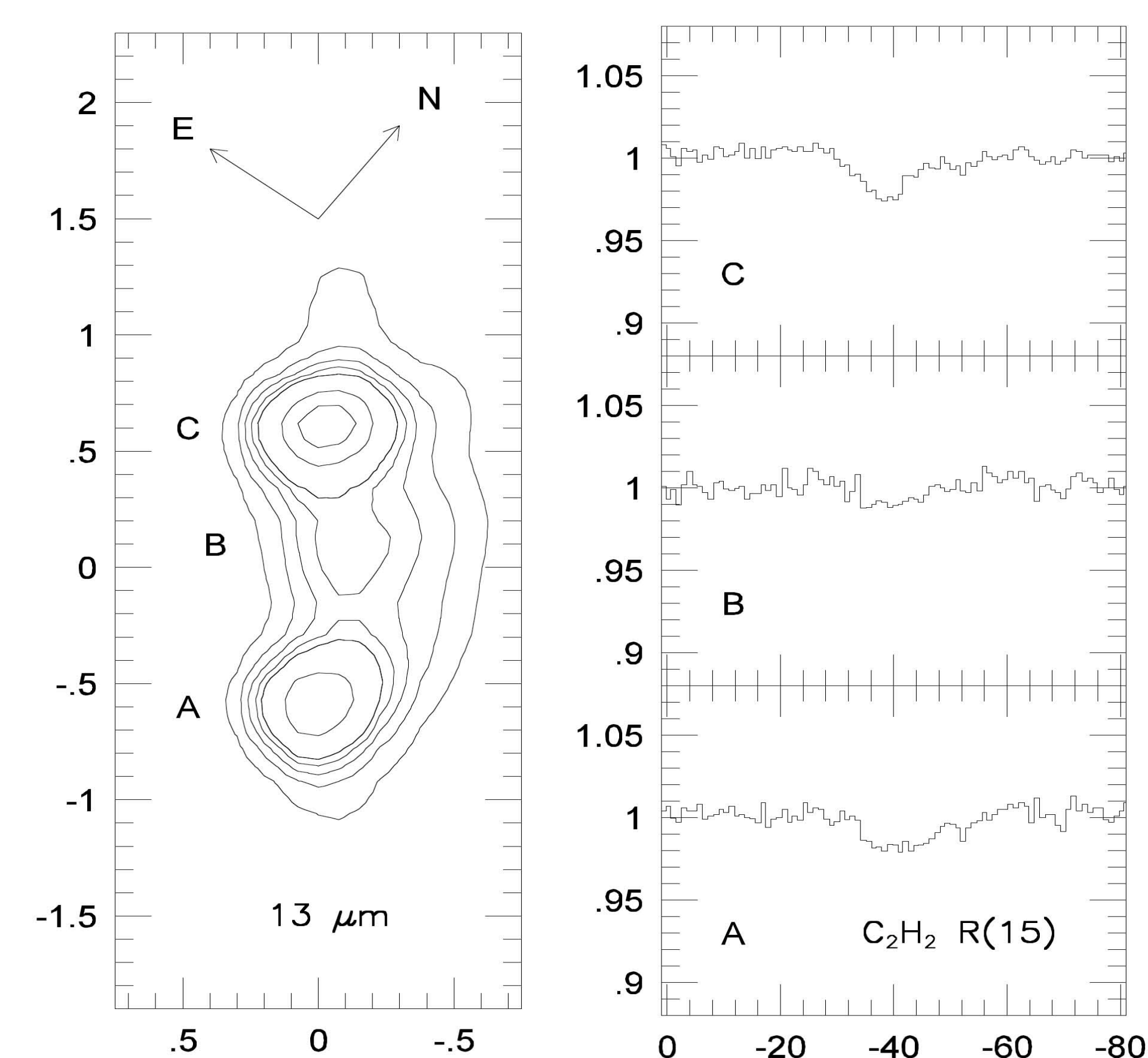


Fig. 8. Continuum map and spectra extracted from a W3 IRS 5 data cube. The map was deconvolved with MEM.

