First Look at Orion-KL with FIFI-LS Onboard SOFIA

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Background

- The Kleinmann-Low Nebula in Orion is the closest region of high-mass star formation
  - Includes the young Trapezium cluster, which emits large amounts of UV radiation
  - This has created a blister HII region bounded by the molecular cloud
  - Has also created a photon-dominated region (PDR), including the Orion Bar
- Observations of Orion-KL provide a prototype for more distant star forming regions
- We present the first look at Orion-KL in the far-IR, using FIFI-LS onboard SOFIA
  - Observations made during flights in 2014–2017
  - High-resolution view of impact of high-mass SF on the surrounding cloud
- We observed six fine-structure lines and six high-J CO transitions
  - These are all at wavelengths inaccessible from the ground
  - Probe physical conditions in Orion-KL, and illustrate mapping ability of FIFI-LS
- We present maps here of four fine-structure lines:
  - [CII] 158 μm, [OI] 146 μm, [OIII] 52 and 88 μm
  - The ratio of the 52 and 88 μm [OIII] lines is used to map electron density
  - [CII] dominates the cooling of the neutral medium
- We also present maps of the six CO transitions:
  - J = 38-37; 22-21; 17-16; 16-15; 14-13; 13-12

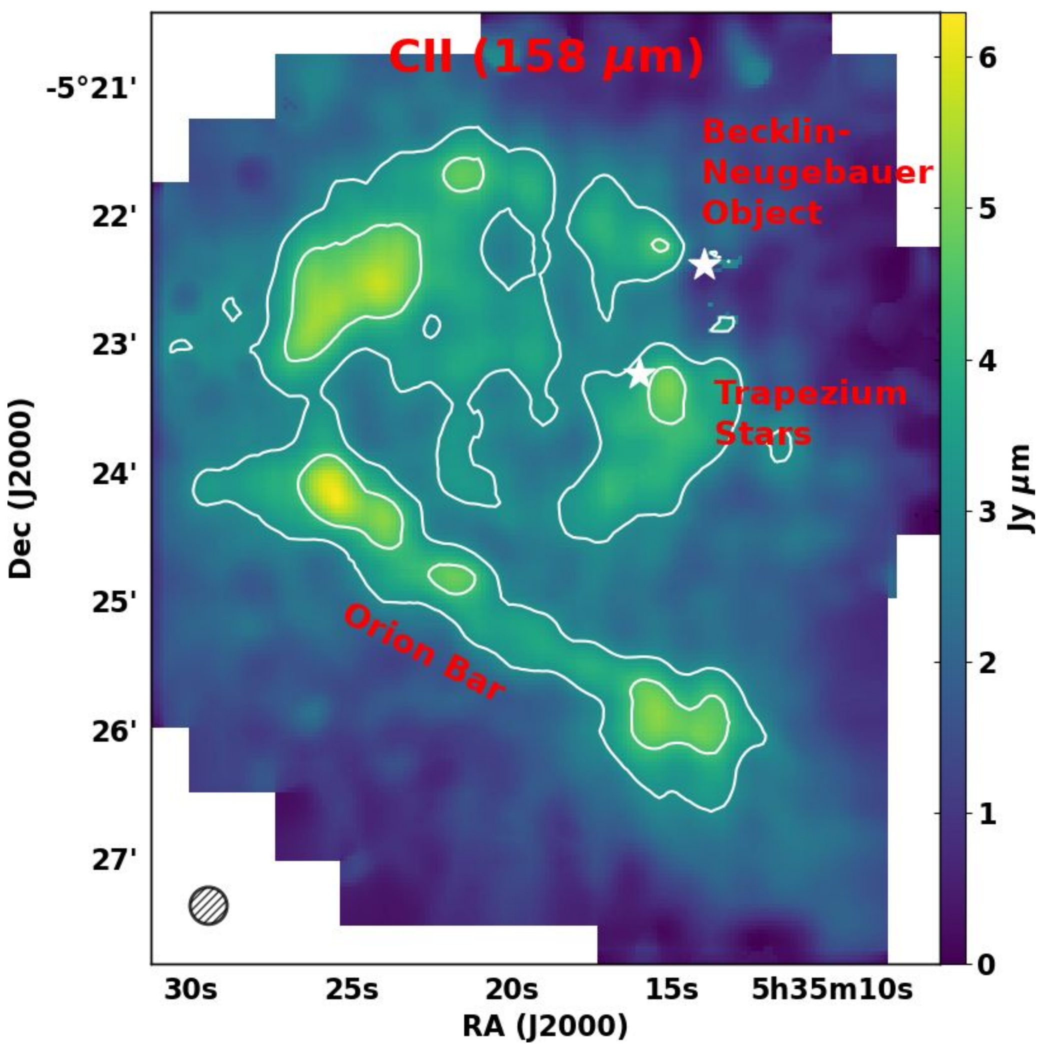


Figure 1: [CII] emission in Orion-KL (colorscale and contours)

The [CII] emission morphology and peak intensities (Fig. 1) highlight the overall shape of the blister region and specific PDRs of the Bar, near the Trapezium cluster, and complexes to the East of the BN protostar. These structures and brightnesses are consistent with previous velocity resolved Herschel observations (e.g., Goicoechea et al. 2015). The continuum emission (Fig. 2 contours) and the [CII] emission are correlated, but there is variation in the [CII] to continuum ratio as the [CII] traces the cloud blister surface while the continuum traces the dense line of sight material. The [OI] emission (Fig. 2 colorscale) shows a very similar pattern, which is likely a mixture of PDR emission as well as emission from the inner surface of the molecular cloud. Although the [CII] emission near the peaks is slightly optical thick, the [OI] is not (e.g., Goicoechea et al. 2015).

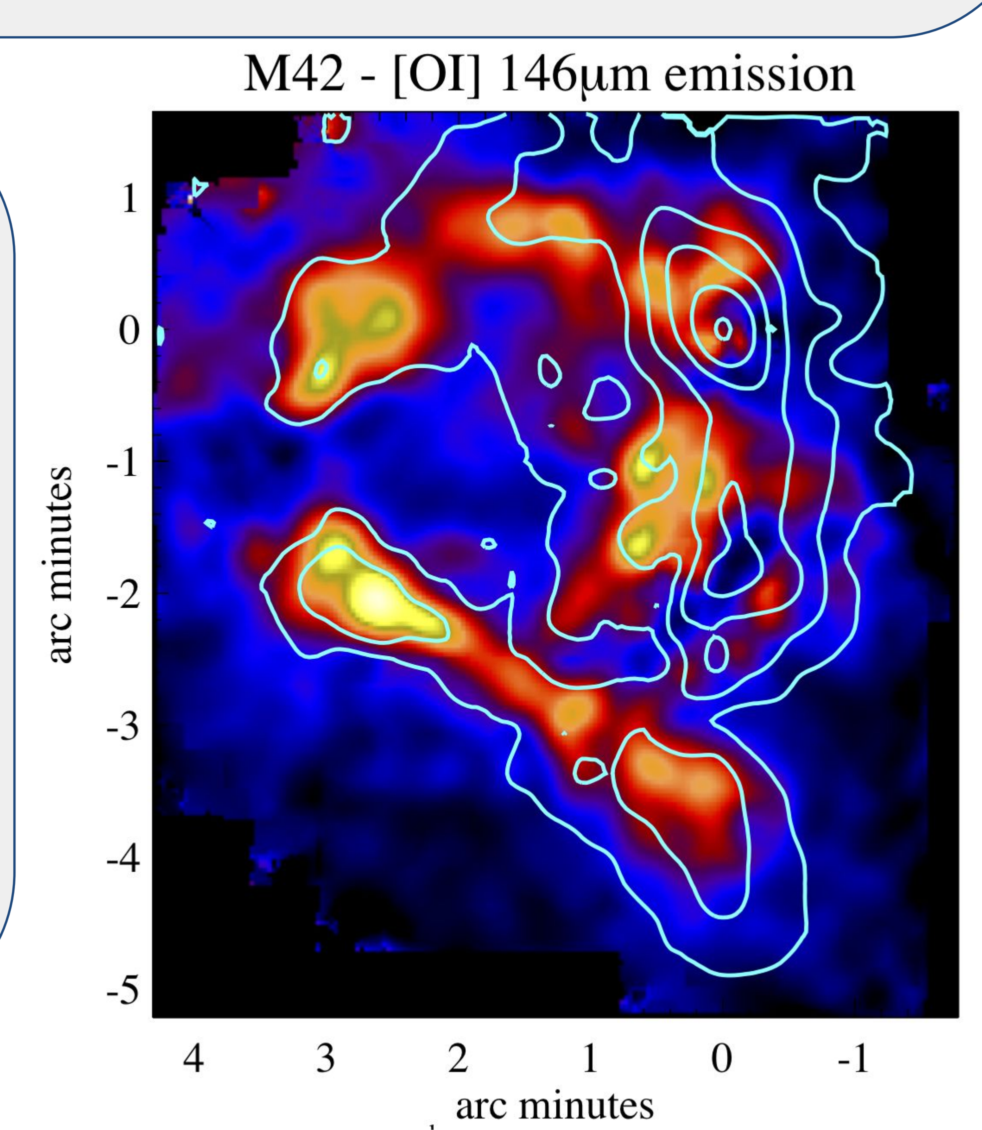


Figure 2: [OI] emission in Orion-KL (colorscale) and associated continuum emission (contours)

The [OIII] lines well trace the ionized component of the PDRs, and the 52 and 88 μm line ratio can be used to infer the electron density (e.g., Vacca et al. 1996). Fig. 3 shows the emission from the two lines with contours giving the derived electron density (log scale). The regions of highest electron density are around BN and near the Trapezium, slightly decreasing toward the Bar in the south. This is consistent with the blister morphology and the previous observations of the edge-on bar (e.g., Bernard-Salas et al. 2012).

The higher-J CO lines were only detected around BN (Fig. 4). The observations are consistent with previous observations from PACS (e.g., Goicoechea et al. 2015) with emission morphologies and intensities from multiple temperature distributions. With the possible exception of J=13-12, the CO lines are strongest in the northwest and/or southeast, which coincide with the two peaks seen in the outflow H_2 (Johnstone & Bally 1999) from an explosive event ~1,000 years ago (e.g., Bally & Zinnecker 2005). Hot shocked CO gas is unusual in star forming regions, thus the gas seen here is likely to be from this event.

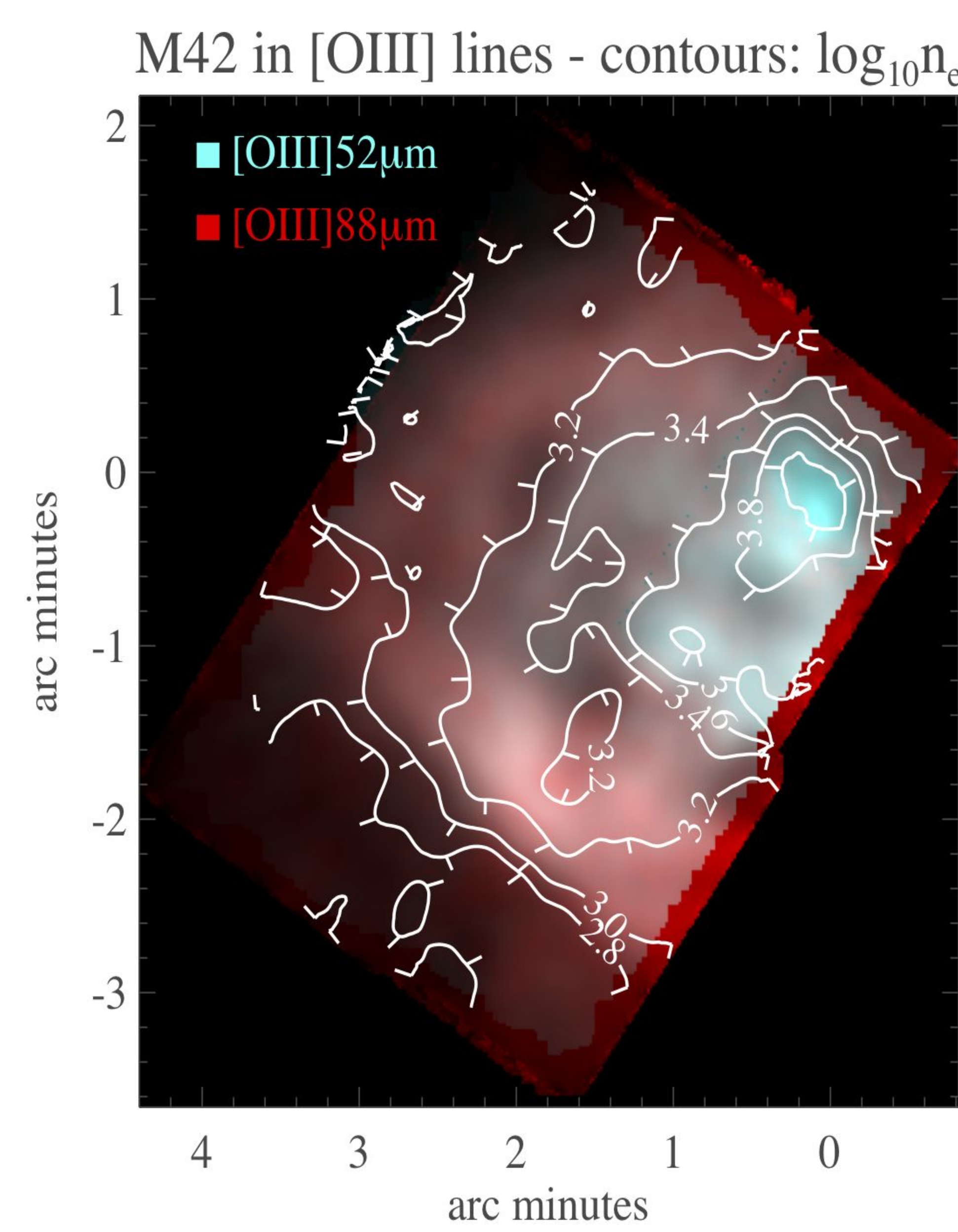
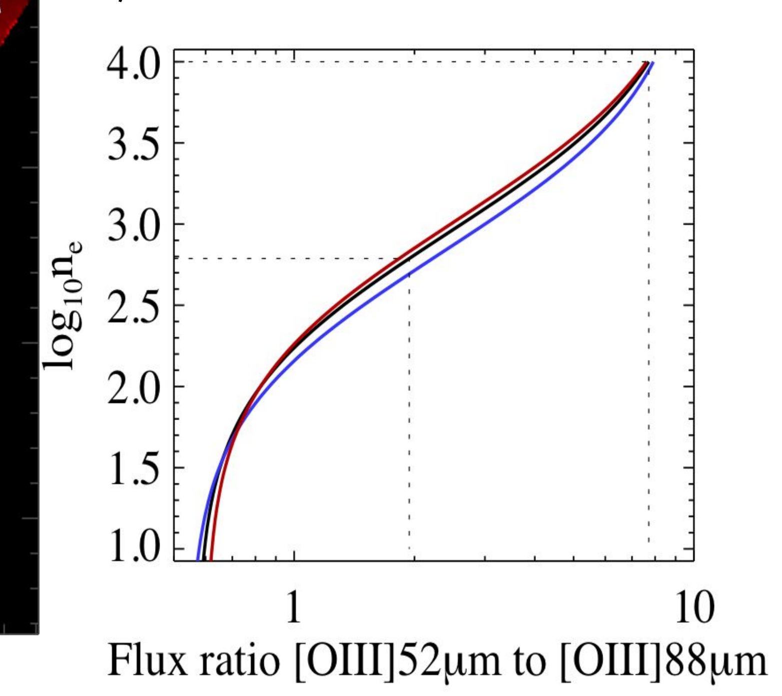


Figure 3. Left: the two [OIII] line color scale intensities in the cavity of M42 from the BN-object to the Bar. Contours show the derived electron density assuming 10,000K ($\log_{10}$ in cm^{-3}). Below: the ratio of the line intensities can be translated into an electron density mostly independent of electron temperature blue: 5,000K, black: 10,000K, red: 15,000K



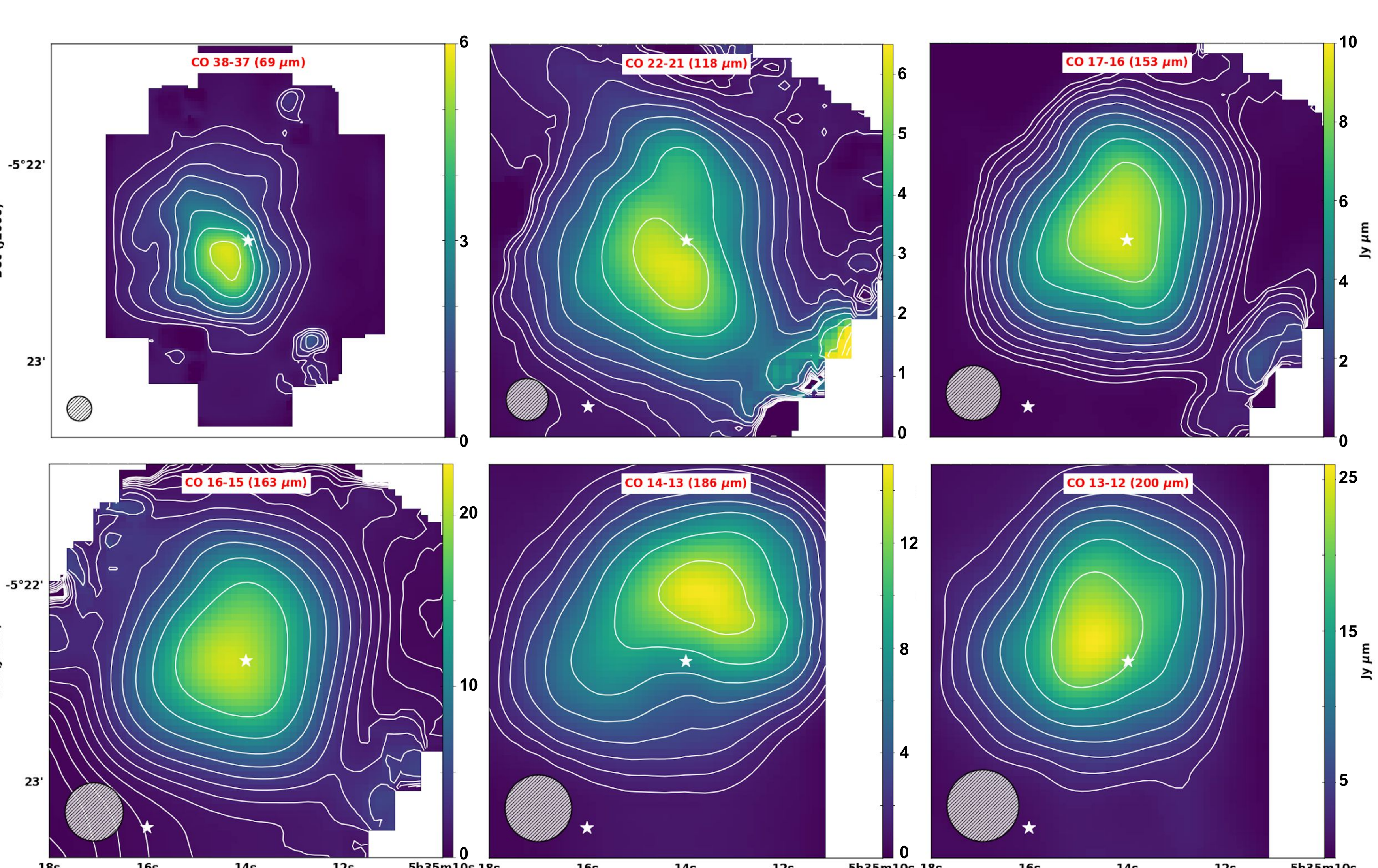


Figure 4: CO emission in color-scale and contours centered around the BN object (indicated by the central white star) with the Trapezium stars in the bottom left (also indicated by a white star).

Conclusions

- FIFI-LS observations of Orion provide insight into the Orion blister nebula using simultaneous 2-channel FIR spectral observations
- The Trapezium stellar ionization is well mapped by the [CII] and the [OI] 146 μm emission lines.
- The [OIII] 52/88 μm line ratio maps the electron densities that peak around BN and Trapezium, decreasing quickly to the East and more slowly toward the bar. This morphology correlates with the dust continuum peaks indicating material being ablated from the denser regions.
- The high-J CO emission is consistent with multiple high temperatures related to H_2 outflows associated with a violent outburst about 1,000 years ago, which may make Orion a less than ideal archetype for more distant star formation regions.

Refs: Bally & Zinnecker (2005), AJ, 129, 2281; Bernard-Salas et al. (2012), A&A 538, A37; Johnstone & Bally (1999), ApJL, 510, L49; Kim et al. (2008), PASJ, 60, 991; Goicoechea et al. (2015), ApJ, 812, 75; Goicoechea et al. (2015), ApJ, 799, 102; Vacca et al, (1996) ApJ, 460, 914