NGC7538 –our key to understanding high-mass star formation

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Overview

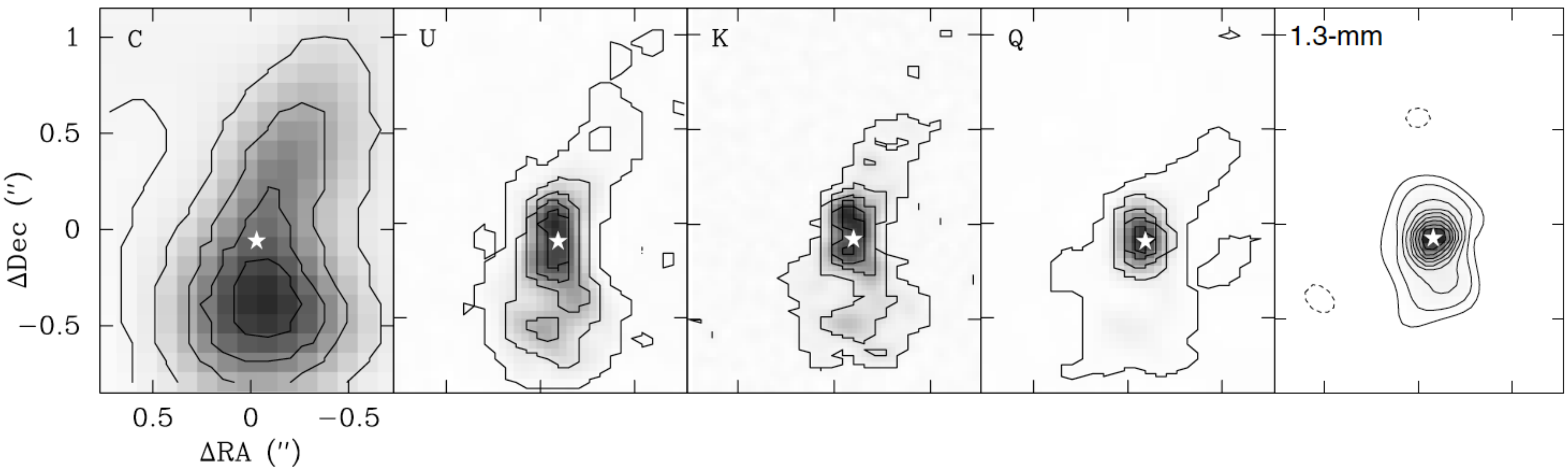
- NGC7538 at 2.65 kpc
  - Three major star forming regions in the adjacent molecular cloud: IRS1 – 3, IRS9 and South
  - All three are centers of PMS star clusters
  - Here we concentrate on IRS1 and South, both of which are still heavily accreting, driving molecular outflows and powering ionized jets
  - IRS1, O-star, HII region still quenched by accretion
  - South, early B, even higher accretion rate, no HII region yet

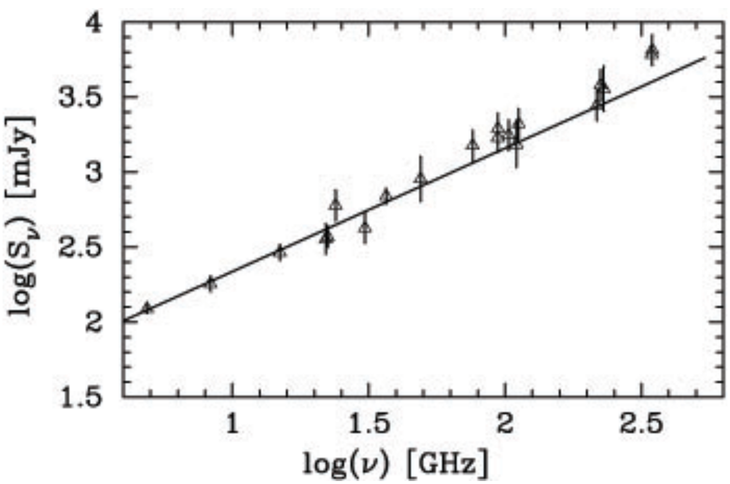
IRS 1
IRS9
S

NGC7538 IRS1

- Spectral type O5.5 – O7
- Luminosity > 1.3 10^5 L_{sun} (emission escapes in the polar regions)
- Powers a variety of masers including several clusters on methanol masers
- Drives a N-S free-free jet
- Large pc scale N-S molecular outflow
- most massive star in a cluster with 168 YSOs, core mass ~1000 M_{sun}
- Accretion rate ~ 10^{-4} M_{sun}/yr
- Keplerian disk? Probably, but not yet seen
- Will continue to grow until accretion rate drops
- Single or multiple?

IRS1 – free-free emission





IRS1 powers a N-S thermal jet (Sandell et al. 2009)

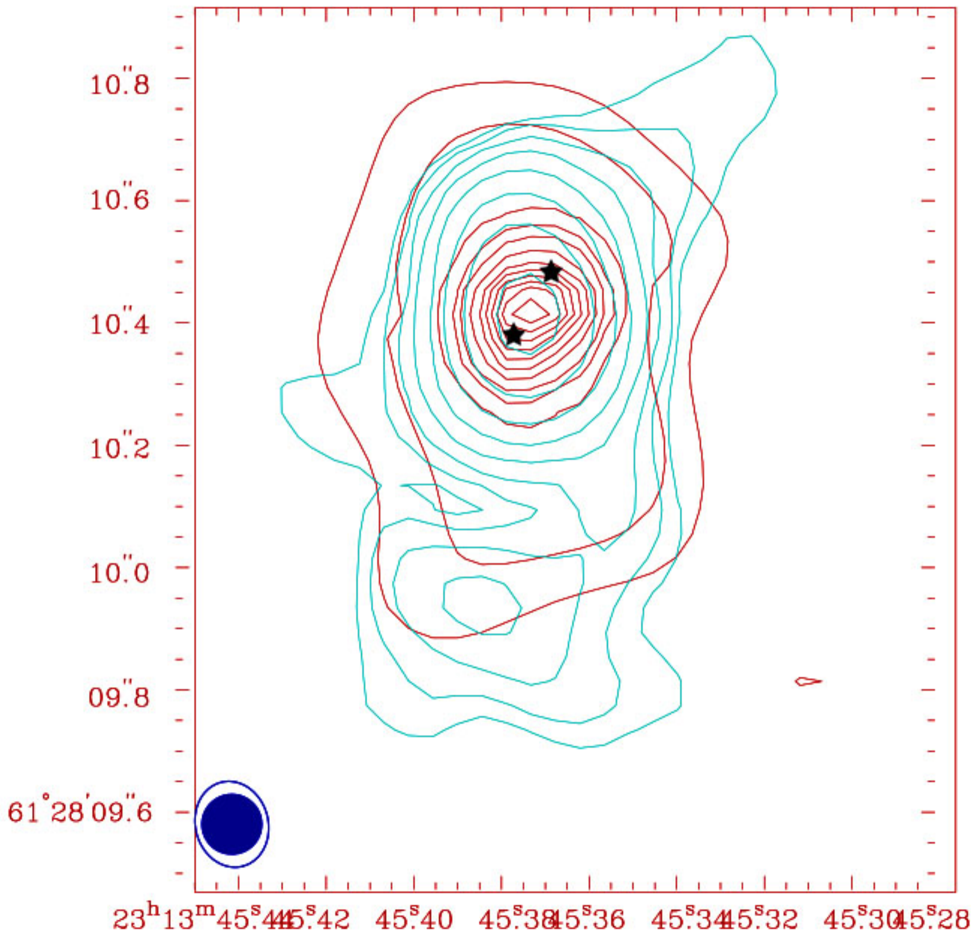
Flux density $S_\nu \propto \nu^{0.8}$

Size $\propto \nu^{-0.8}$

We start to pick up dust excess at ~ 1mm

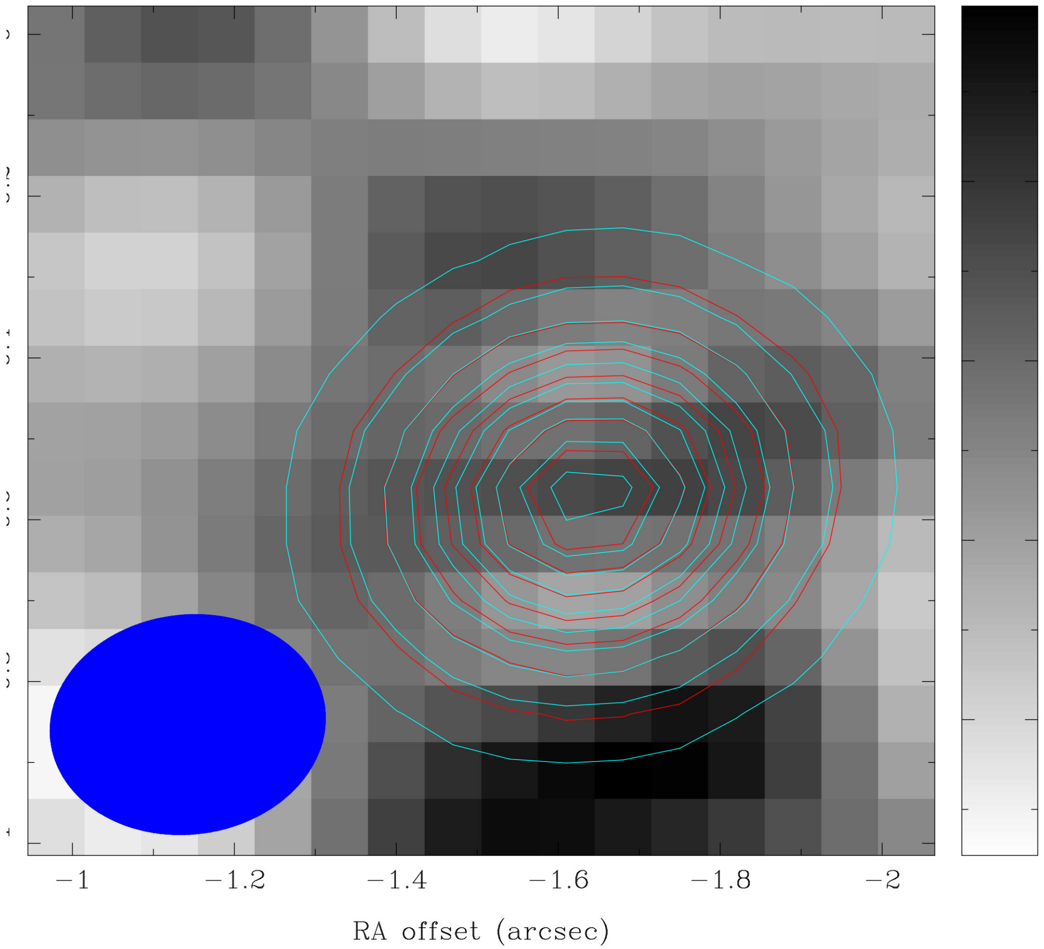
Should have an E-W disk, yet to be discovered

IRS1 VLA 43 GHz, CARMA 224 GHz



The two stars symbols mark the IRS1 cm1 and cm2, which Beuther et al. (2017) argue are individual hypercompact HII regions based on VLA high res data at 24 GHz. This is not evident in the CARMA A-array 224 GHz image (red contours), which has similar spatial resolution, nor do they stand out in the VLA 43 GHz image (cyan).

CARMA A-Array image



Synthesized beam:
0.34” x 0.27” pa -83˚

Gaussian fit:

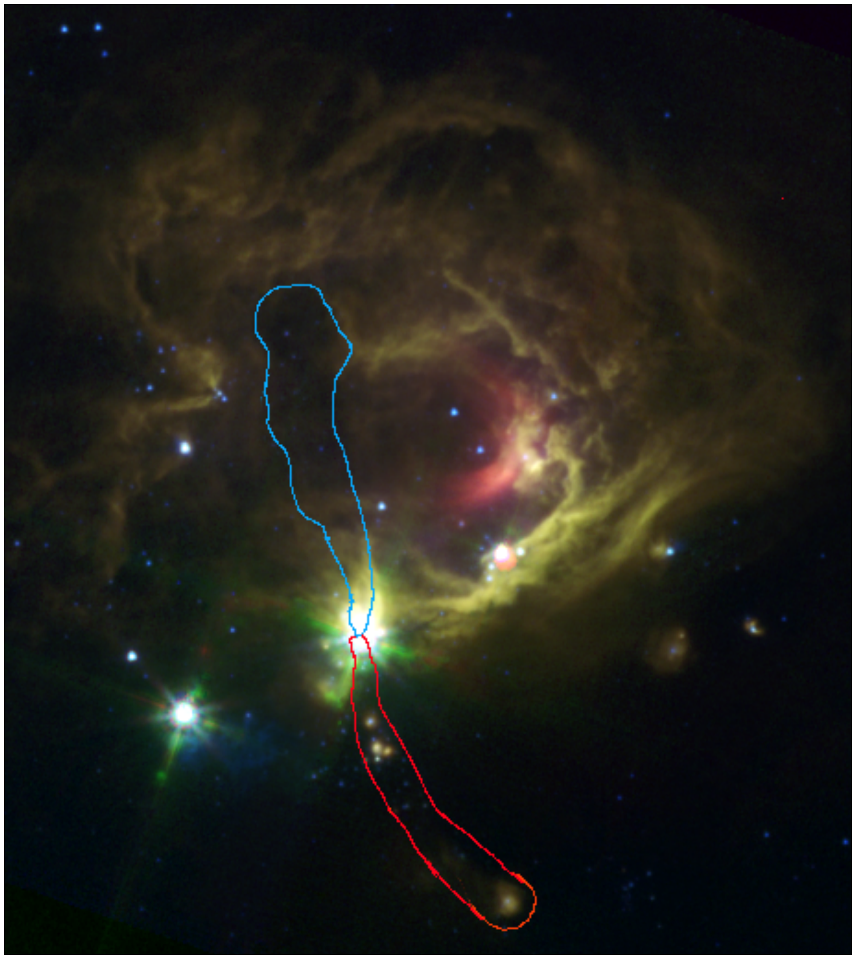
Size 0.09” x 0.06” pa -46˚
The deconvolved size does not support the two UCHII regions proposed by Beuther et al.

Clearly some extended structure, but not E-W as we would expect for a disk

IRS1 – molecular outflow

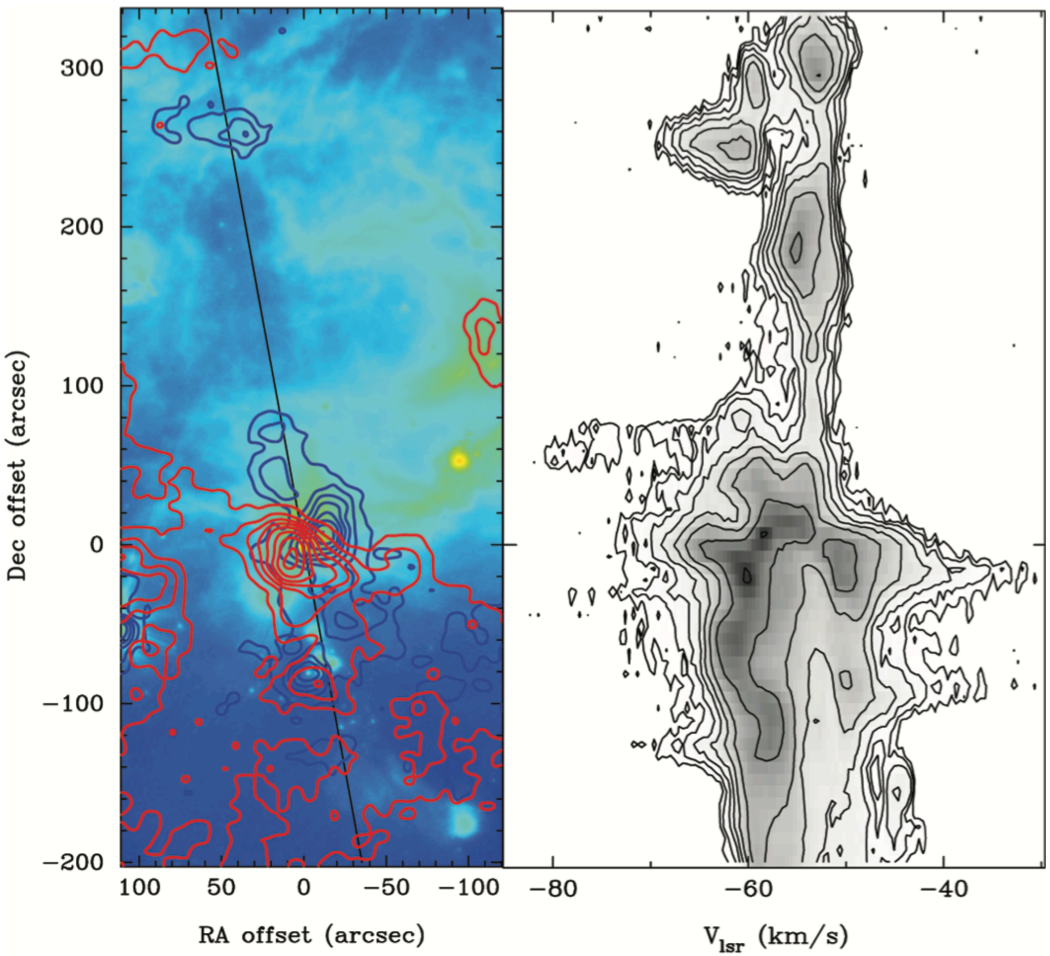
- CO(3-2) & Spitzer IRAC images show large N-S molecular outflow, especially to the north where densities are lower
  - Bowshock at ~ +80” and at 280”
- Outflow also seen in [CII] up to the bowshock at ~80” due to strong FUV radiation illuminating the gas inside the outflow cavity
- In CO(11-10) the fast moving gas is not dense enough to show the fast moving clumps in the outflow, but towards the South we see CO(11-10) all the way to NGC7538 South, i.e. 60 – 70” south of IRS1. Since the lower energy level of CO(11-10) is 304 K, and the critical density 4 10^5 cm^{-3}, the emission can only be excited by IRS1
- The strong SE-NW outflow emission seen in low J CO is absent in CO(11-10), which only traces the N-S outflow

The IRS1 outflow



- This is what I guessed in 2012 (the NRAO jets conference
  - Now largely confirmed thanks to GREAT observations and JCMT CO(3-2) HARP image covering the whole NGC7538 region
  - The morphology of the outflow to the south still uncertain, complicated by another cloud at -50 km/s largely overlapping with the denser -58 km/s cloud in which IRS1 is embedded

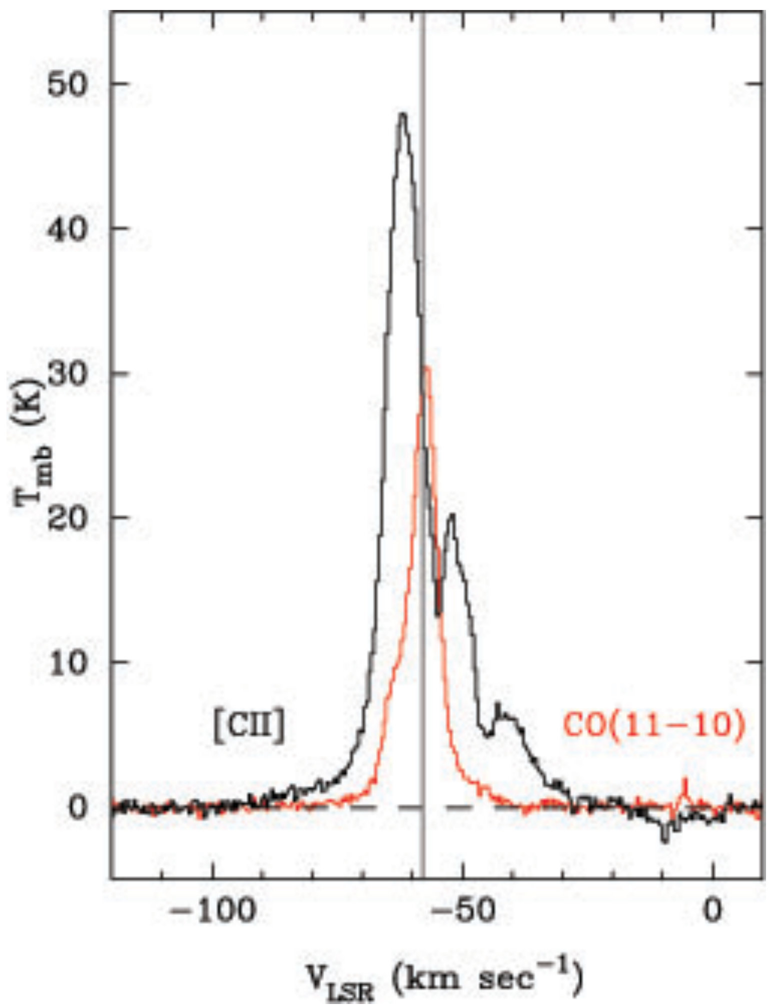
IRS1 CO(3-2)



Integrated blue and red-shifted CO(3-2) overlaid on IRAC 8μm image

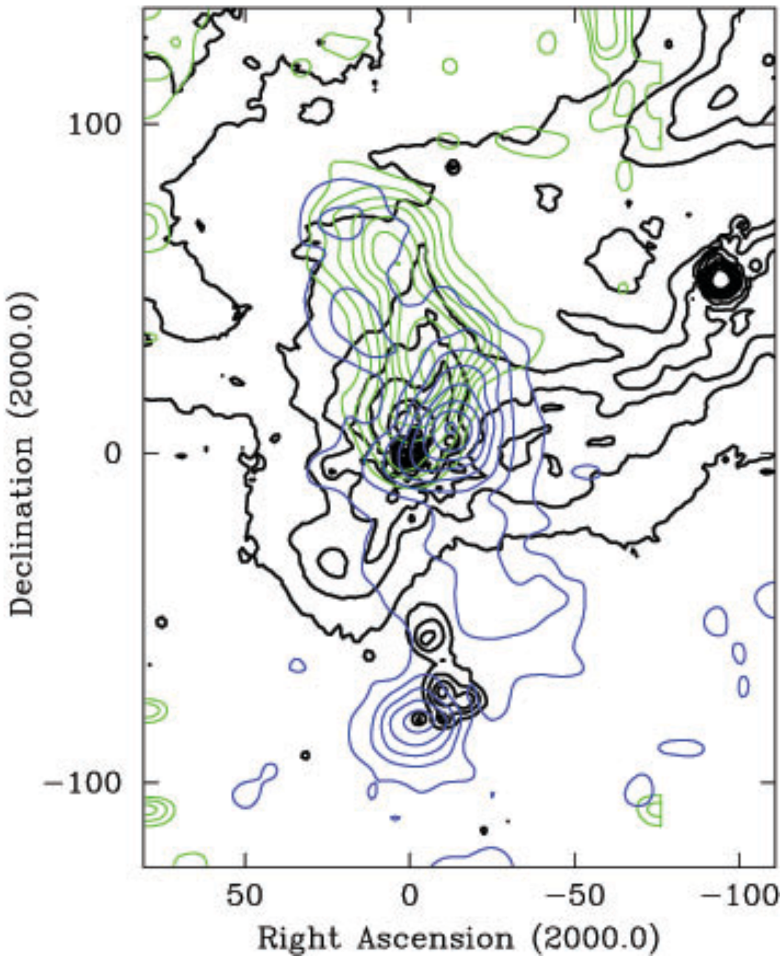
Position velocity plot at PA 10˚ shows leading shock at ~ 280" and another one at ~80" from IRS1

IRS1 [CII] and CO(11-10)



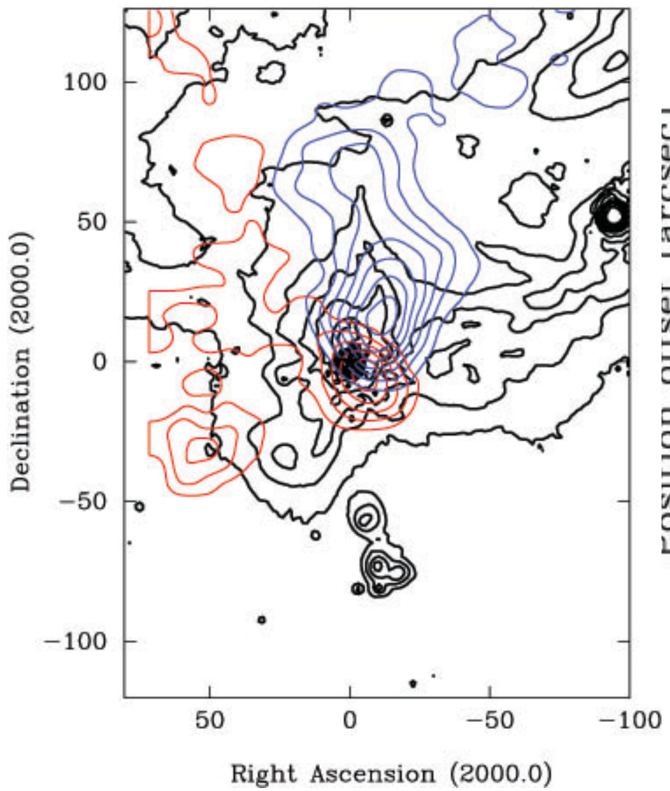
- Long integration [CII] and CO(11-10) spectra towards IRS1
  - High-velocity [CII] seen from ~ -90 km/s to -30 km/s
  - Some self-absorption due to cold foreground gas
  - The absorption at ~ -10 km/s is due the gas in the local arm
  - CO(11-10) shows more modest velocities

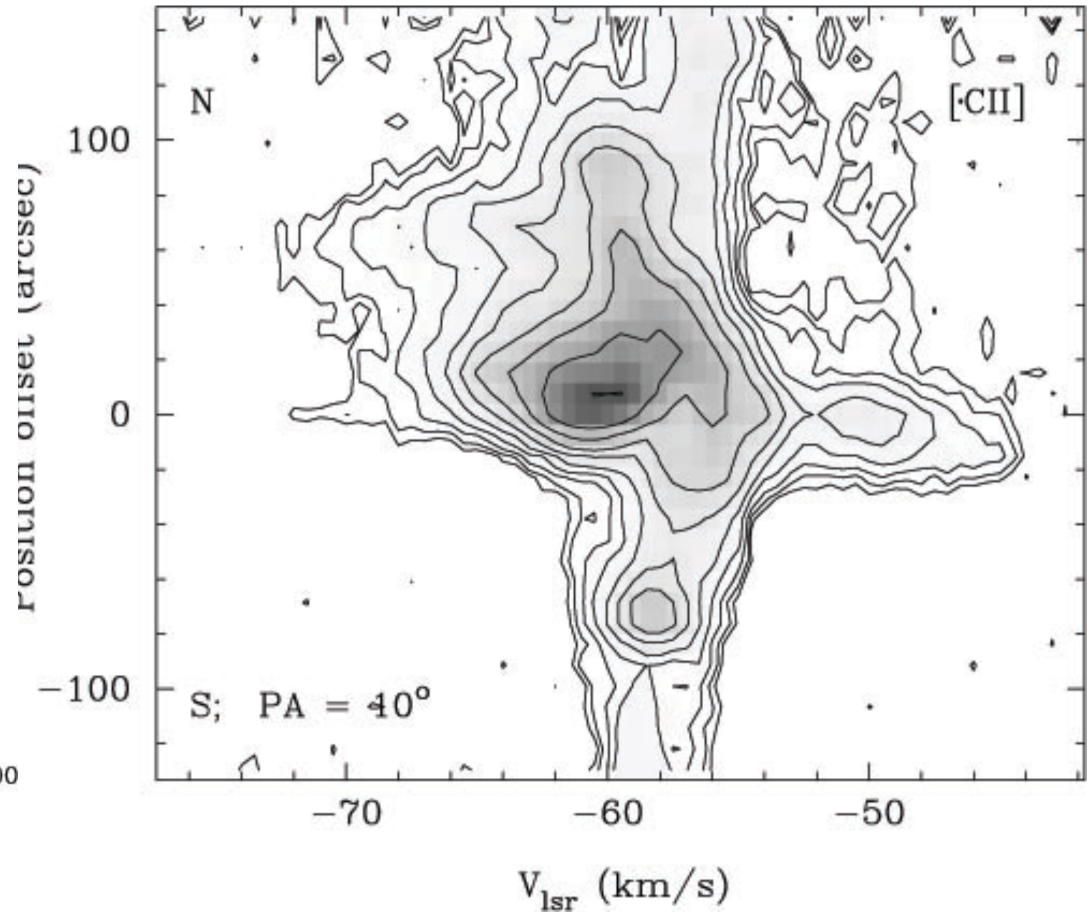
Comparison of CO(3-2) and [CII]



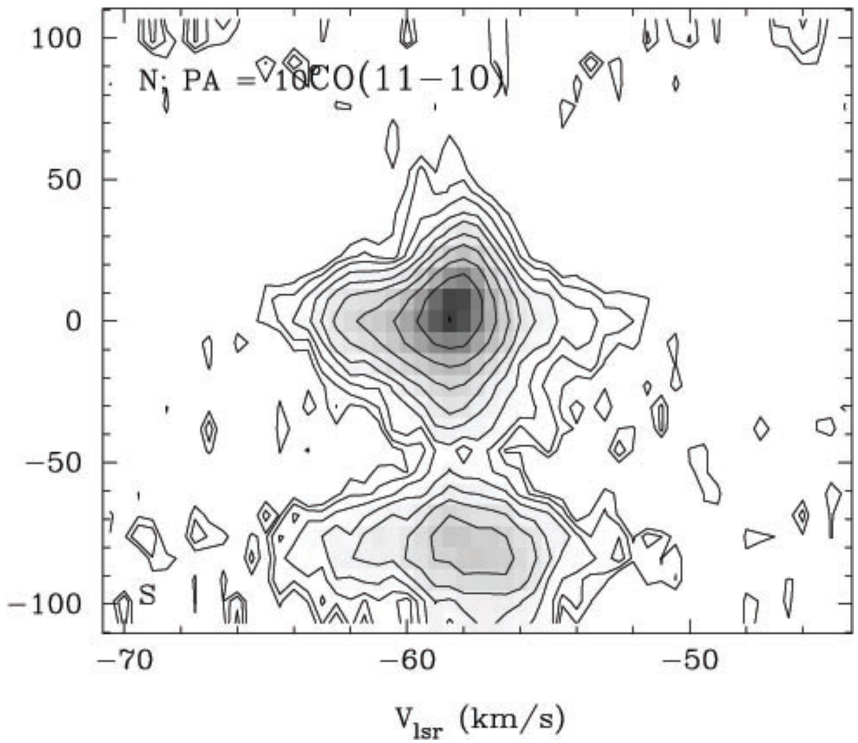
- Integrated blue-shifted CO(3-2) emission (blue contours) and [CII] emission (green contours) overlaid on IRAC 8 μm image
  - Note the good agreement between CO(3-2) and [CII] north of IRS1
  - The compact outflow from NGC7538 South also seen in CO(3-2) but weak in [CII]

IRS1 [CII] outflow





IRS1 outflow in CO(11-10)

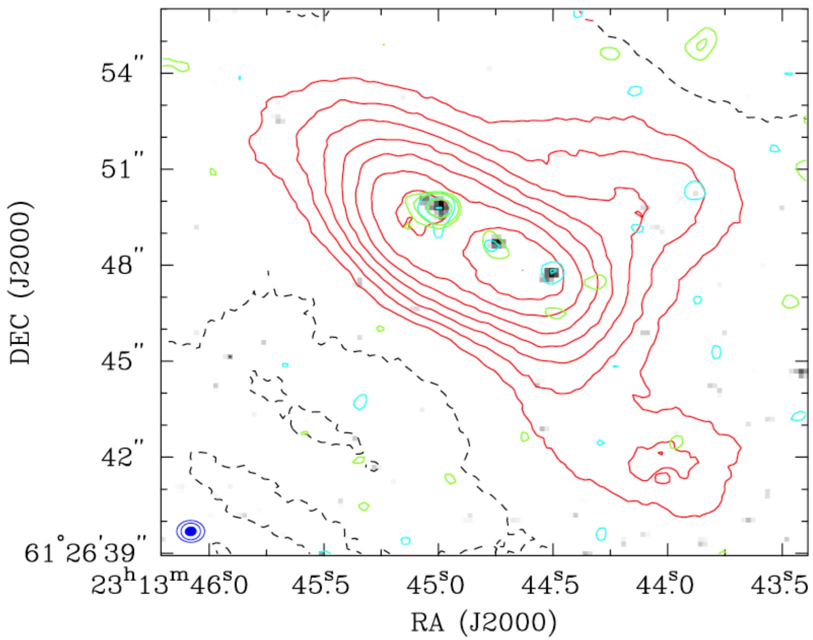


- N-S outflow also seen in CO(11-10)
  - Extends to ~50" N of IRS1
  - To the south all the way to NGC7538 South but only at near-cloud velocities
  - The strong blue-shifted emission 80" south of IRS1 is from the NGC7538 South outflow

NGC7538 South – an O star in formation

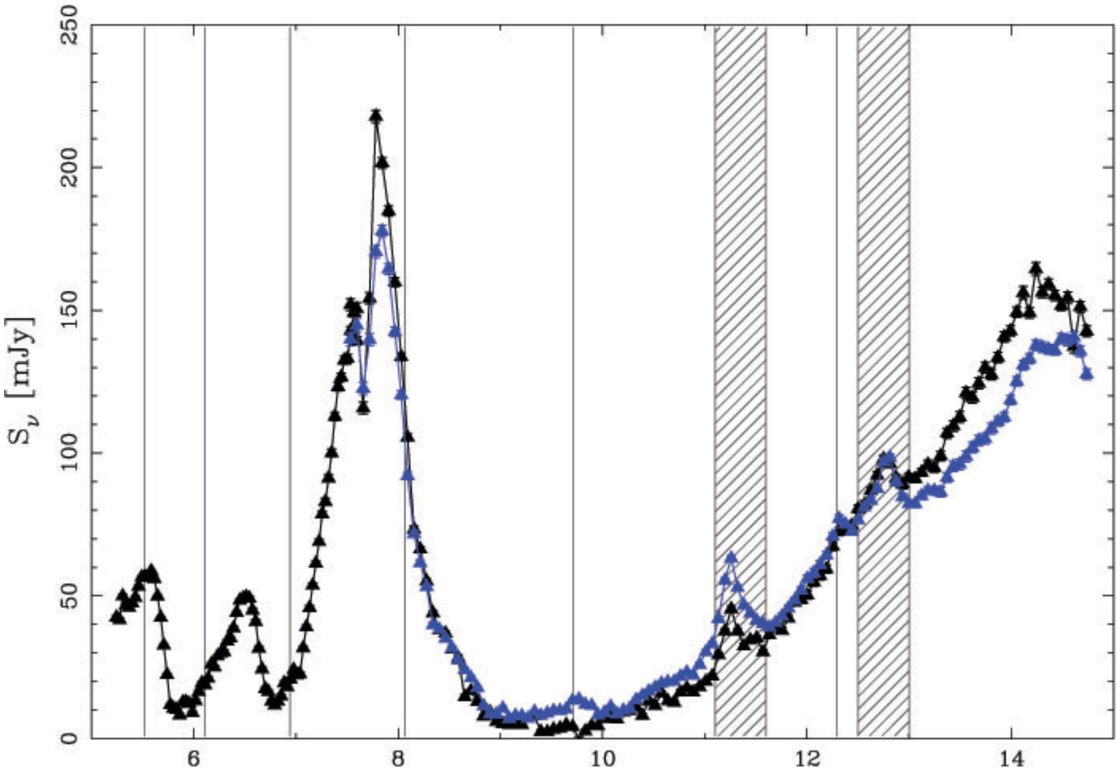
- South embedded in an elliptical core (part of a filament) with a mass of more than 1000 M_{Sun}
- Powers an ionized jet (spectral index $\alpha \sim -0.1$) and drives a compact molecular outflow
- Surrounded by rotating unstable disk
- Much higher accretion rate than IRS1, ~ 2 10^{-3} M_{Sun}
- Extremely embedded, extinction hundreds of magnitudes, still fainter than IRS11 at 30 μm, but 3 times stronger at 70 μm, where the emission from IRS11 tapers off
- Luminosity 1.3 10^4 L_{Sun} , i.e., now an early B-star (IRS11 ~ 10^3 L_{sun})

NGC7538 South imaged with CARMA



- The NGC7538 cloud core imaged with CARMA B, C, D & E array configurations at 224 GHz (Wright et al. 2012)
- At higher spatial resolution (B-array) the ridge resolves into three sources. 87 GHz (green), 111 GHz (cyan), 224 GHz (black) B-array data
- The rotating disk around S unstable
  - At the highest resolution we see a second source E of South

SPITZER IRS spectrum of NGC7538 South



- The 9 µm silicate absorption is so deep (and broad) that it essentially goes to zero.
- What looks like PAH emission bands is regions of less absorption!
- We can not determine where the continuum level is.

Conclusions

- High mass stars form as low mass stars, but in a much denser environment (deep potential well) and with much higher accretion rates
- At least some of are surrounded with accretion disks, but once they become an O star, such a disk is very hard to detect
- They power ionized jets and drive molecular outflows
- The moment the accretion rate drops the hypercompact HII region surrounding them will start to expand and disperse the surrounding molecular cloud
- Caveat: This may not be the only way high mass stars form. In thse dense environments I am sure mergers can also play a role.