Submillimetre observations: forming tiny objects in-situ

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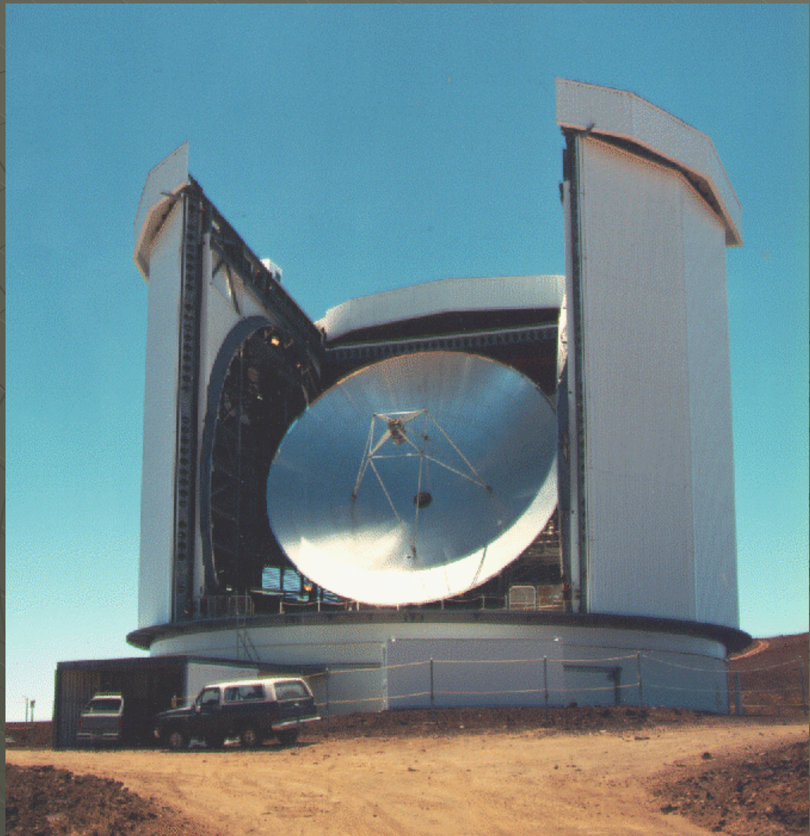
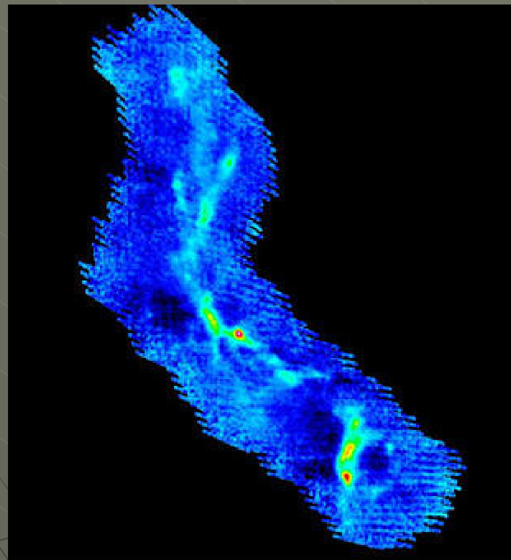
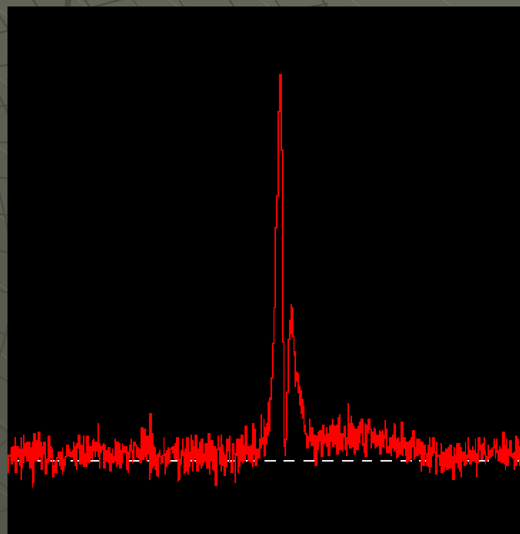
aims: detect ultra-low mass objects at the earliest stages, while still forming and embedded in clouds

important points

- thermal dust emission
  - optically thin in the submillimetre
- spectroscopy of gas molecules
  - velocities
- limitations
  - resolution

Redman et al.;
JCMT website

drivers

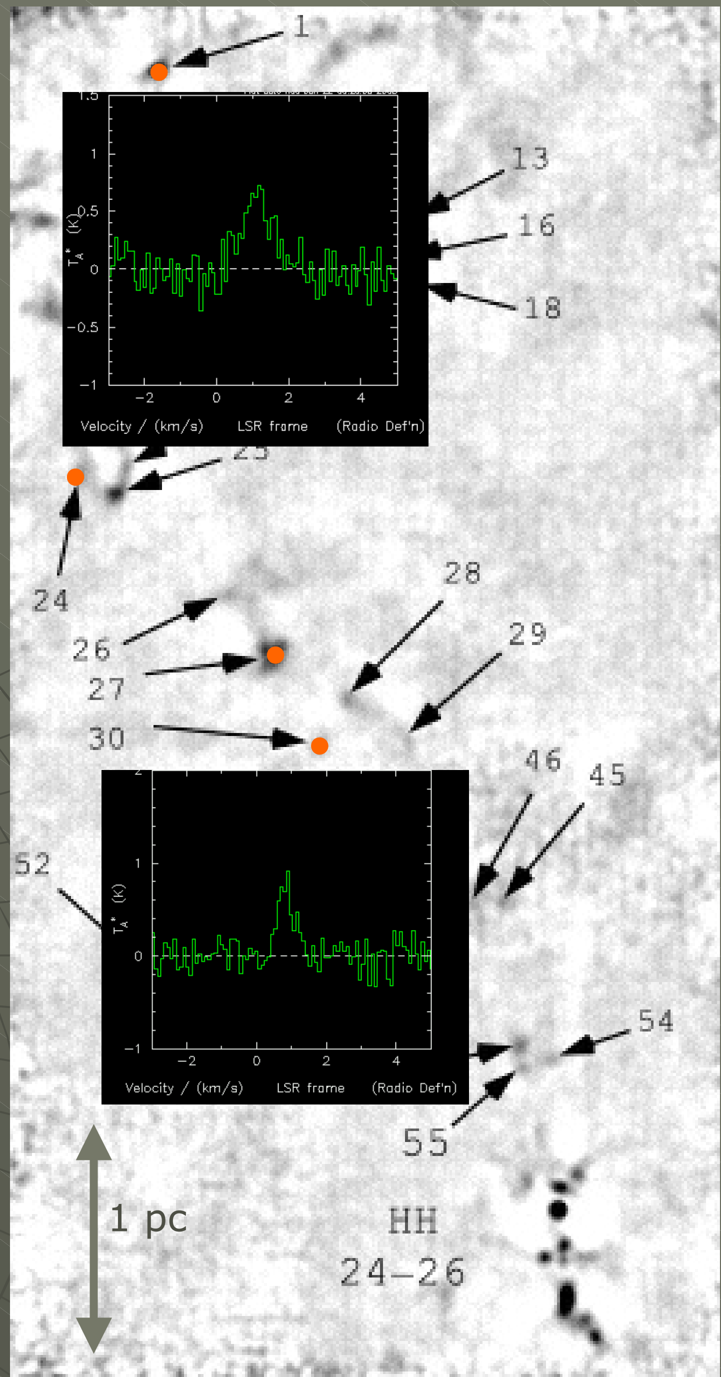
- where does star formation stop?
  (what's the lowest observed mass?)
- does the physics allow ultra-low mass objects?
  (planetary regime)
- does one core form one object?

pre-conceptions

- form mostly stellar mass objects
  - typical Jeans mass
  - declining numbers at sub-stellar masses
- lowest possible mass is ~10 $M_{Jupiter}$
  - opacity limit
- many cores are bound! (observers) ...
  many cores are transient! (theorists)

example: Orion B

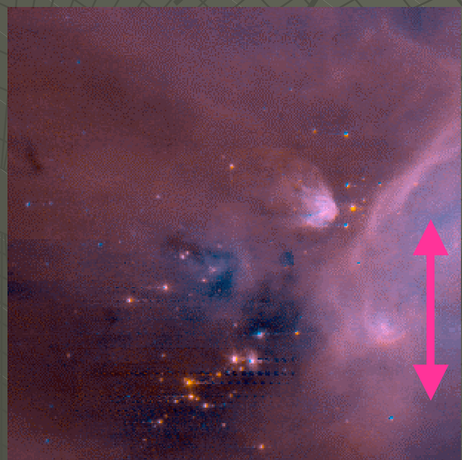
- starless clumps
  - masses of 0.2-12 M_{Sun}
- optically thin gas spectra for a few:
  - 6 bound
  - 1 ~virial
  - 1 unbound

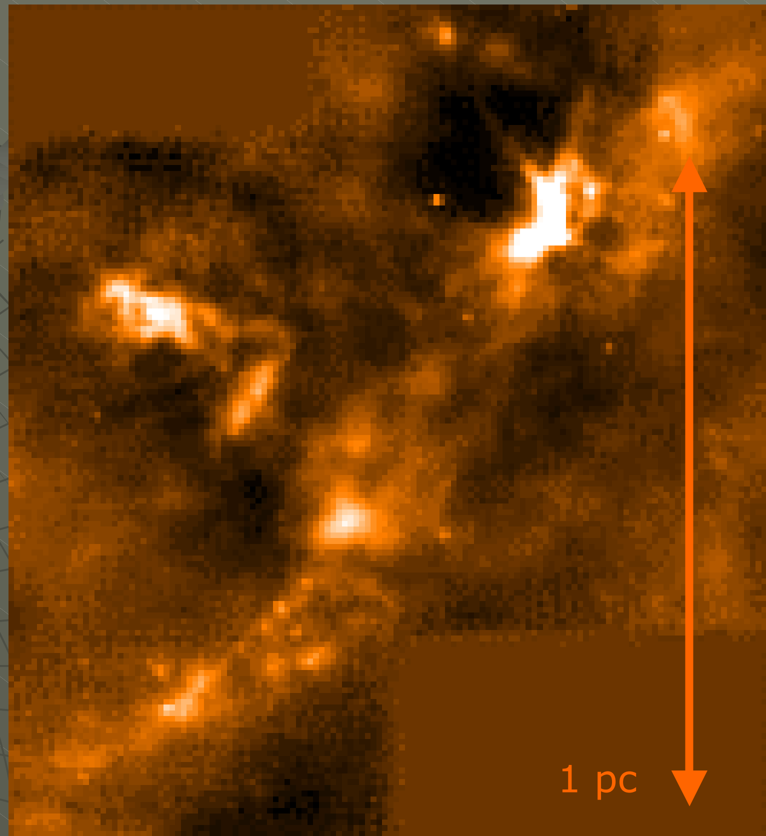


Mitchell et al. 2001; Johnstone et al. 2001; JCMT archive $H^{13}CO^+$ 3-2 spectra

forming low-mass stars: ρ Oph

- several dust studies, from stellar to planetary masses

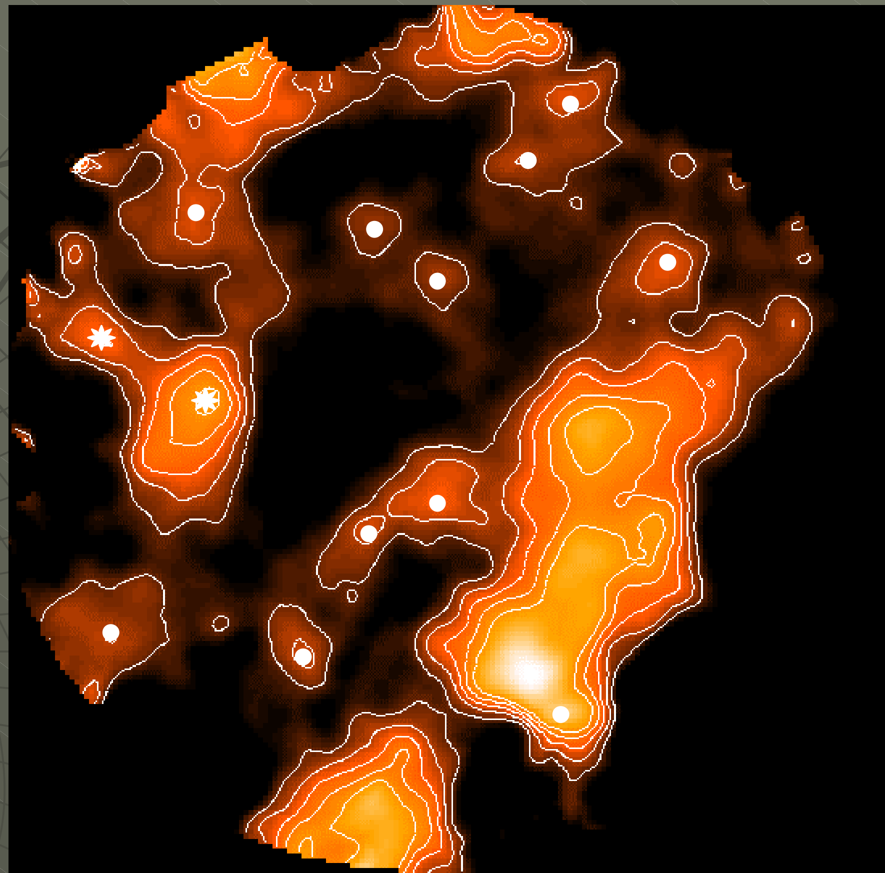


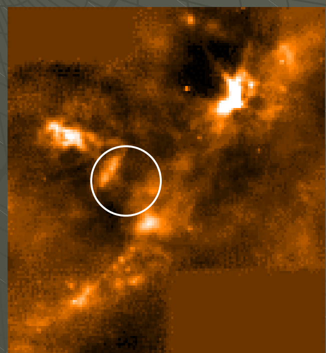


Smith et al. 2005; Johnstone et al. 2005, 2000; Greaves et al. 2003, 2005; Motte et al. 1998

Ophiuchus B

- region between the B1/B2 clouds
  - white dots mark starless clumps of $\approx$10-30 $M_{Jupiter}$
  - white stars mark young stellar objects



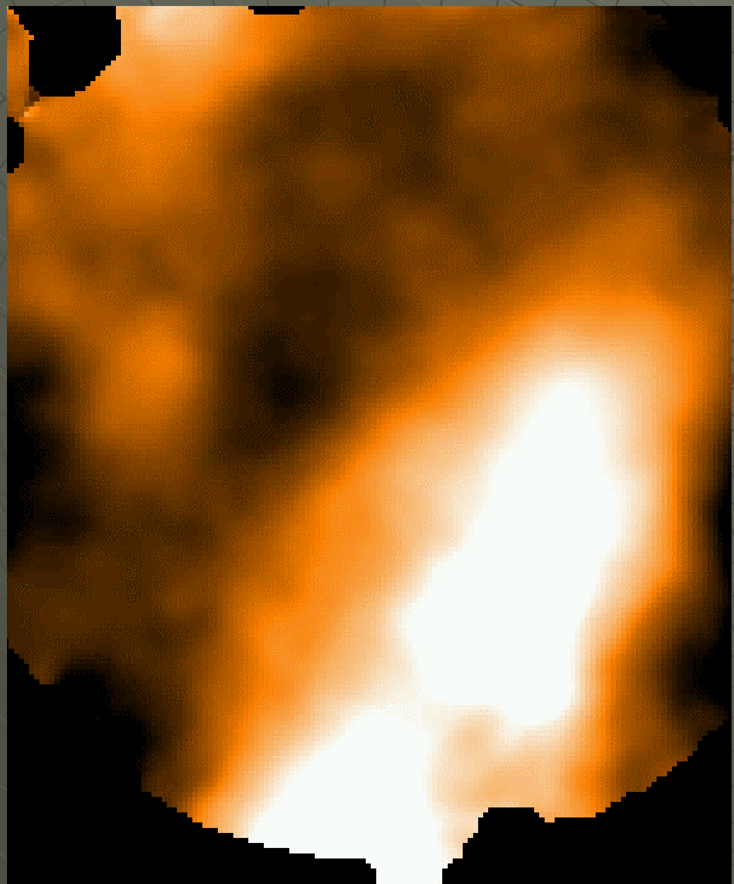


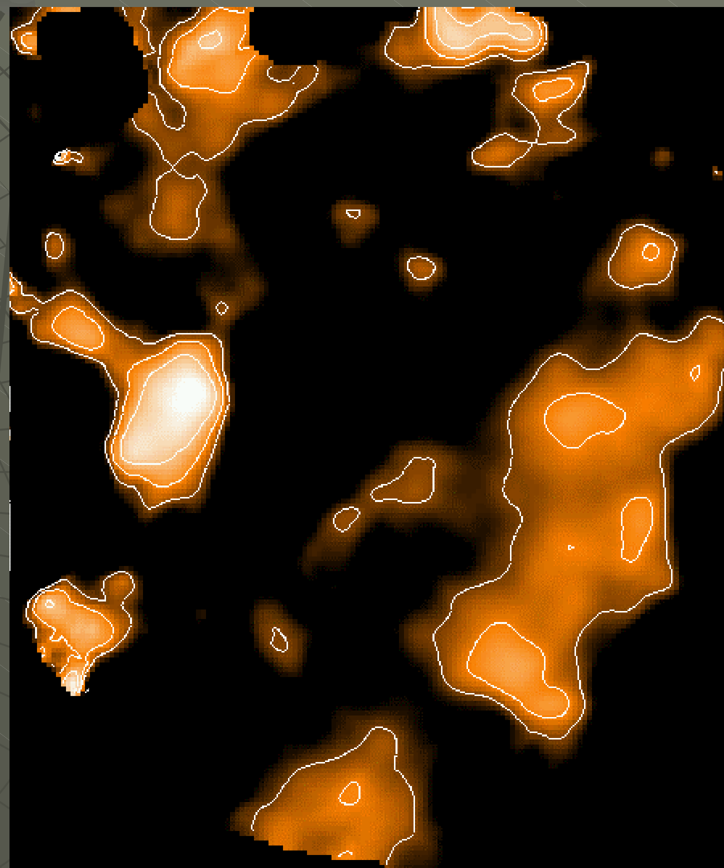
Greaves et al. 2003; Pound & Blitz 1995

masses and uncertainties

- direct conversion from flux to mass, with uncertainties in:
  - distance
    - if <160 pc, masses are smaller
  - temperature
    - gives ±25% error for T=12-20 K
  - dust emissivity
    - estimated factor ~2
- !! usually need to subtract extended emission from the surrounding cloud

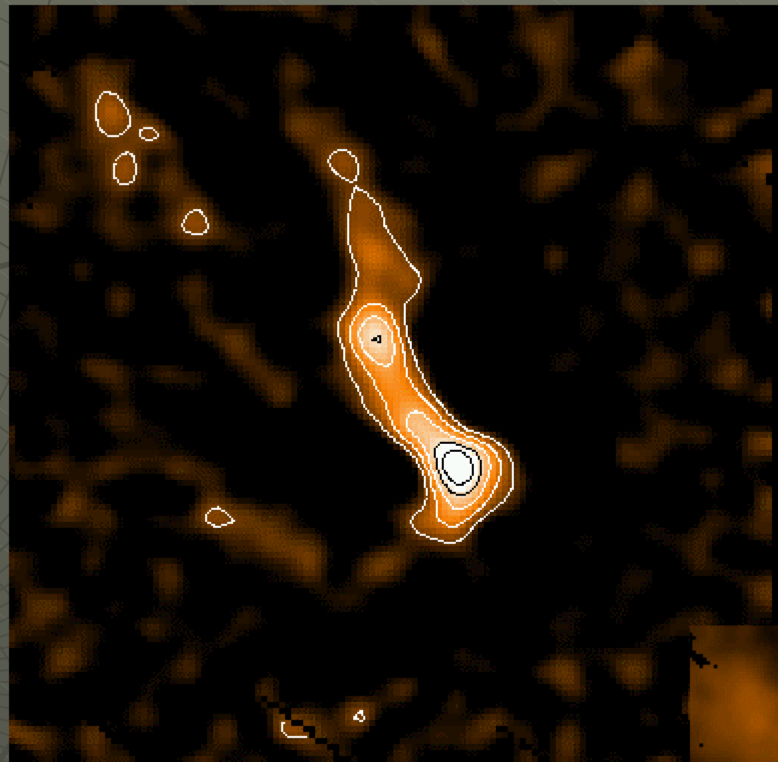
left: raw image, **right**: ratio of clump signal (10% contours) to total signal, after unsharp masking

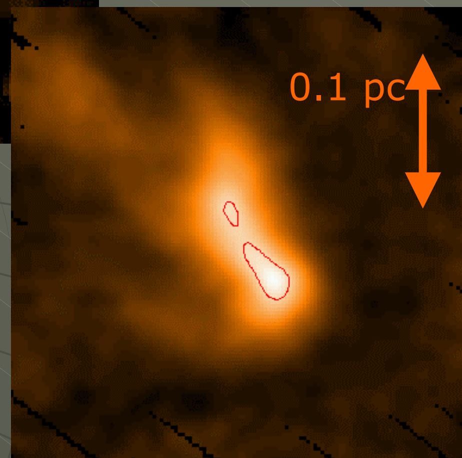




Ophiuchus D

- isolated cloud of ~3 M_{Sun}
- clumps down to 2 $M_{Jupiter}$!





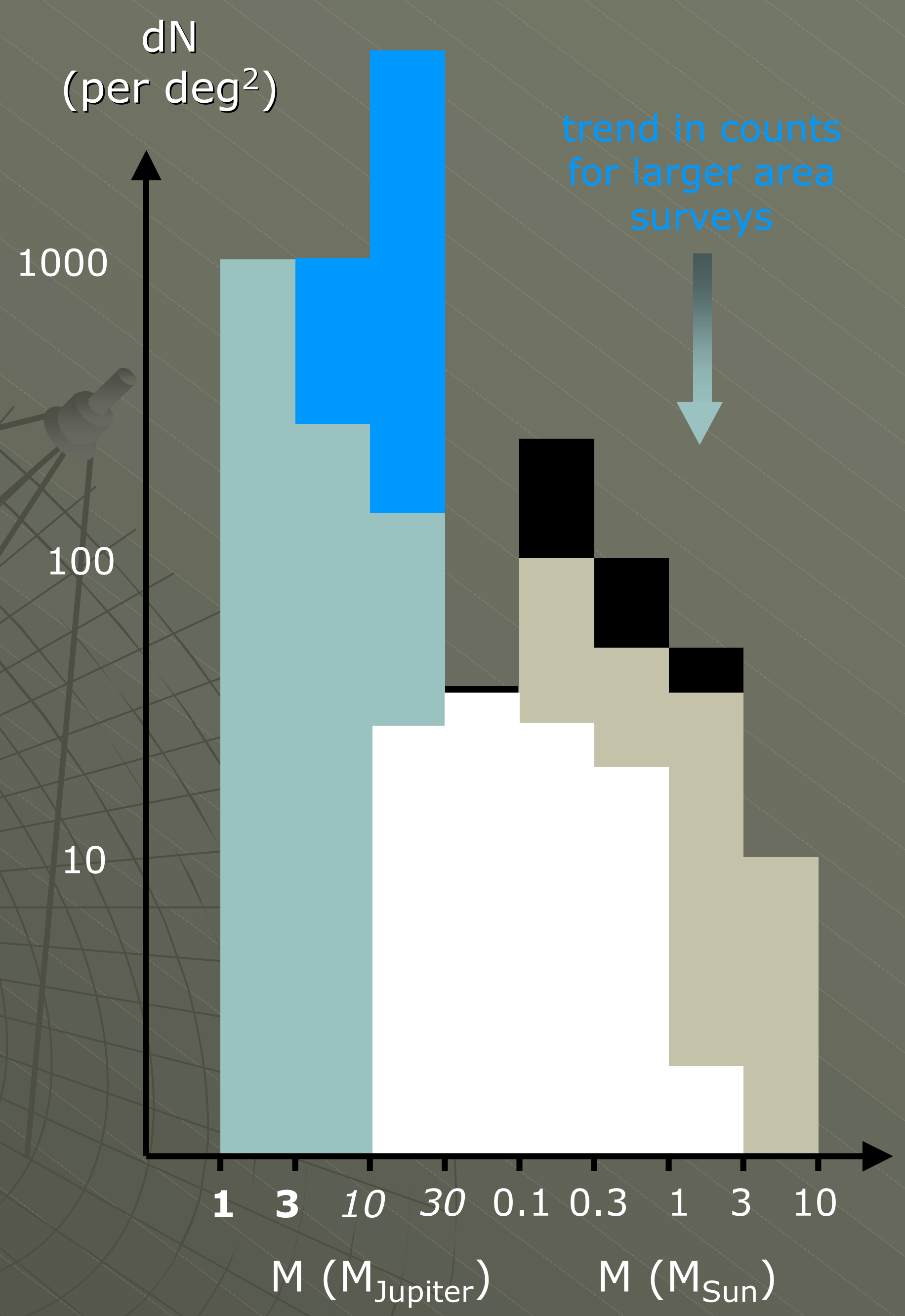
clumps, with contours at 3 $M_{Jupiter}$ intervals; **below inset**: total cloud emission, with contour at 0.075 M_{Sun} (per beam).

lowest clump masses

- in Oph D:
  - 9 planet masses, 1 brown dwarf mass
- test: mass limits for given flux
  - can not ‘hide’ a central massive object!
    - line width must increase for stability
- probable core sizes ~10-100 AU
  - limits from minimum emitting area, maximum unresolved size, and size at which thermally unbound (for given mass)

mass function

- composite clump mass function for Ophiuchus:
  - $dN/d(\log M) \sim M^{-0.6}$
- *counts still rising at lowest masses!*

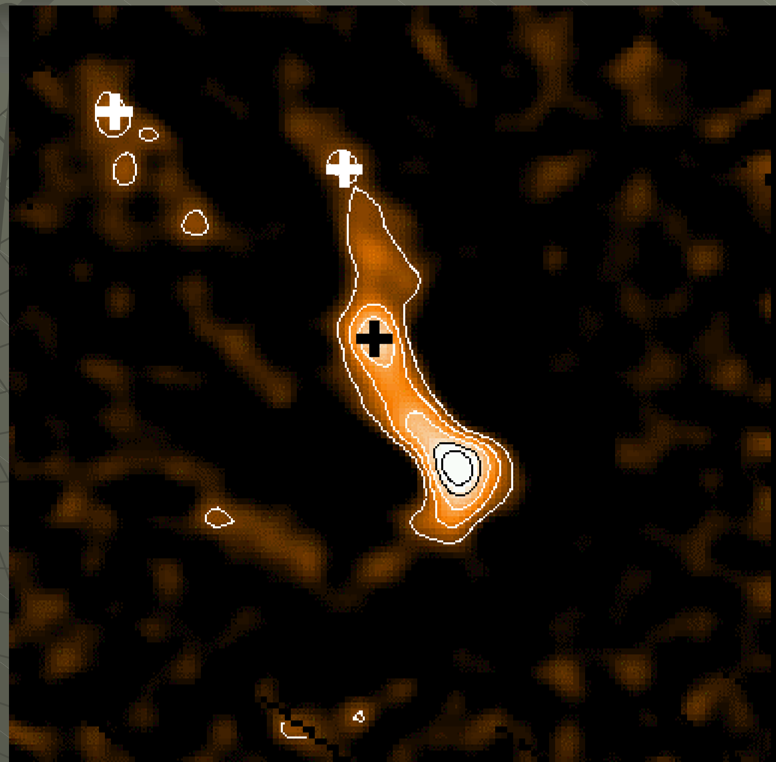


dynamics: ejection

- do low-mass objects stop accreting because thrown out?
  - Oph cores *not* outside main clouds
    - even if very young, speeds < ~1 km/s
  - spread of core-velocities is low
    - in Oph D, scatter over ~0.5 km/s
    - cf. Oph B: ~2 km/s for stellar mass clumps (Pound & Blitz 1995)

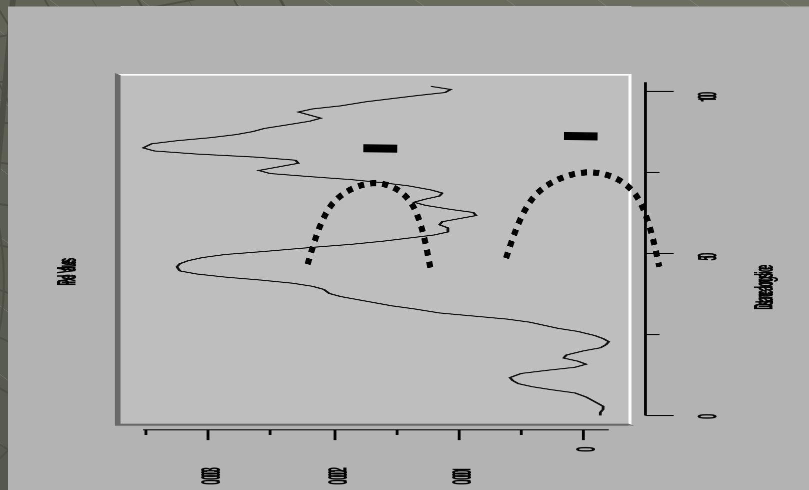
dynamics: boundedness

- detected three planetary-mass Oph D cores in DCO^+ J=3-2
  - line widths of 0.2, 0.2, 0.4 km/s
    - $v_{bound} \approx 0.2$ km/s
    - mostly thermal
  - !? 2MASS source near wide-line core



evolution

- are ultra-low mass cores ancestors of 'isolated planetary mass objects'?
  - like GY11, an ~10 $M_{Jupiter}$ infared object
- or will they accrete ~stellar mass?
  - image slice shows:
    - compact cores
    - on top of broader but faint emission

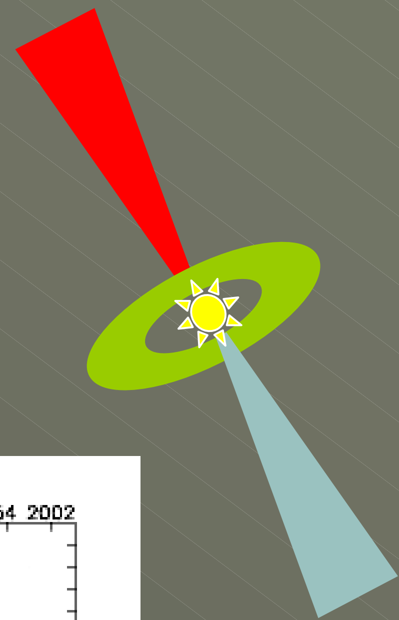


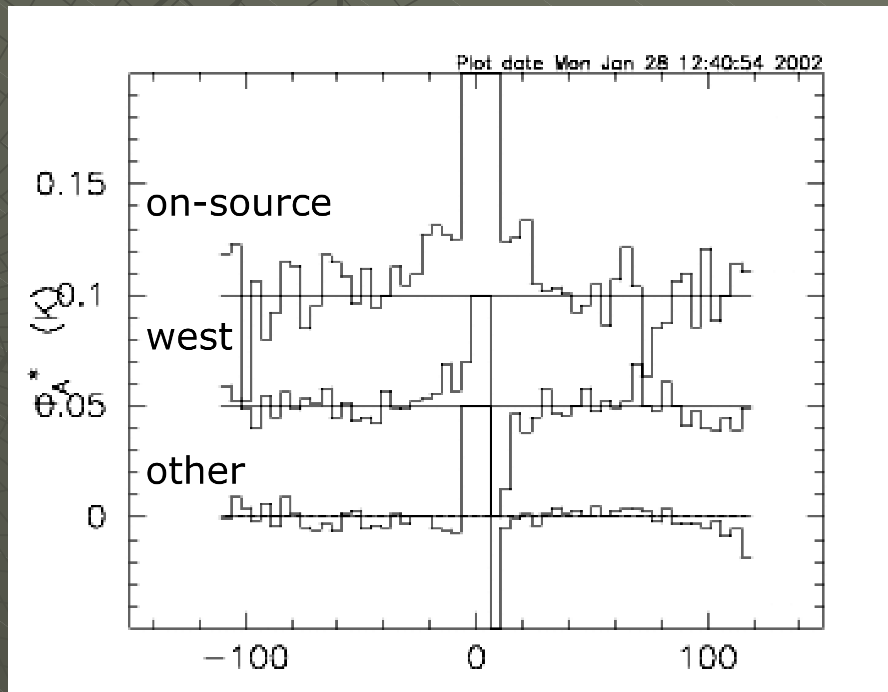
formation process

- can *one* formation process produce objects from star to planetary mass?
- test: any object forming by accretion should have a disk and outflow?
  - true for protostars
  - hypothesised for Jupiter!

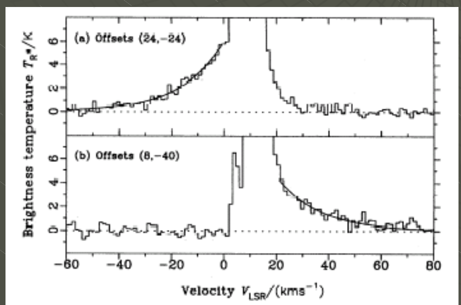
Ophiuchus B-11

- $9 \pm 4\ M_{Jupiter}$ bound core
  - line wings show outflowing gas



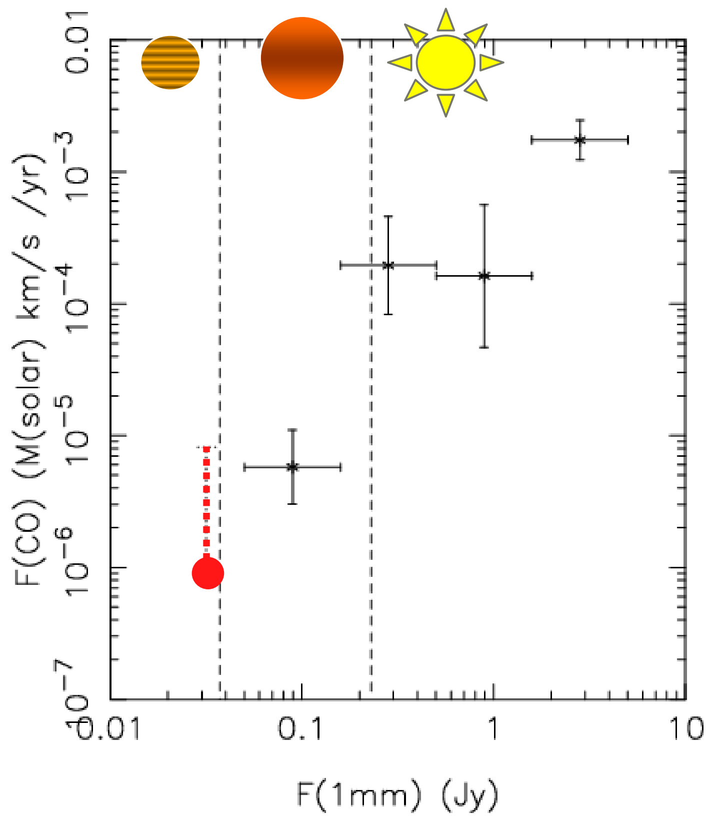


protostar example
Richer 1990; Orion



common process test

- protostellar outflows have a force vs. core-mass relation
  - Oph B-11 lies on this relation



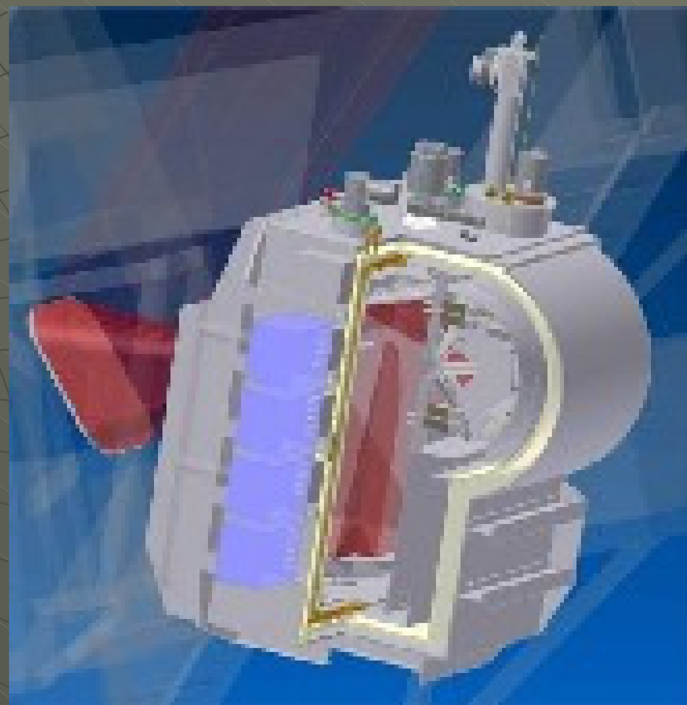
Hogerheijde et al. 1998

pre-conceptions revisited

- many low-mass cores found
  - continuous mass function!
  - subset observed in lines are ~bound
- similar processes for all core masses
  - velocities and locations
  - outflow scaling with core mass
- low mass cores may not grow more
  - outflow may even *reduce* mass

future observations

- spectral line cameras:
  - efficient outflow searches
- wide-field continuum cameras
  - many Jupiter mass cores in ~30 minutes



SCUBA-2: on JCMT in 2007

(also HARP-B for imaging spectroscopy: late 2005)

- thank you…

…any questions??