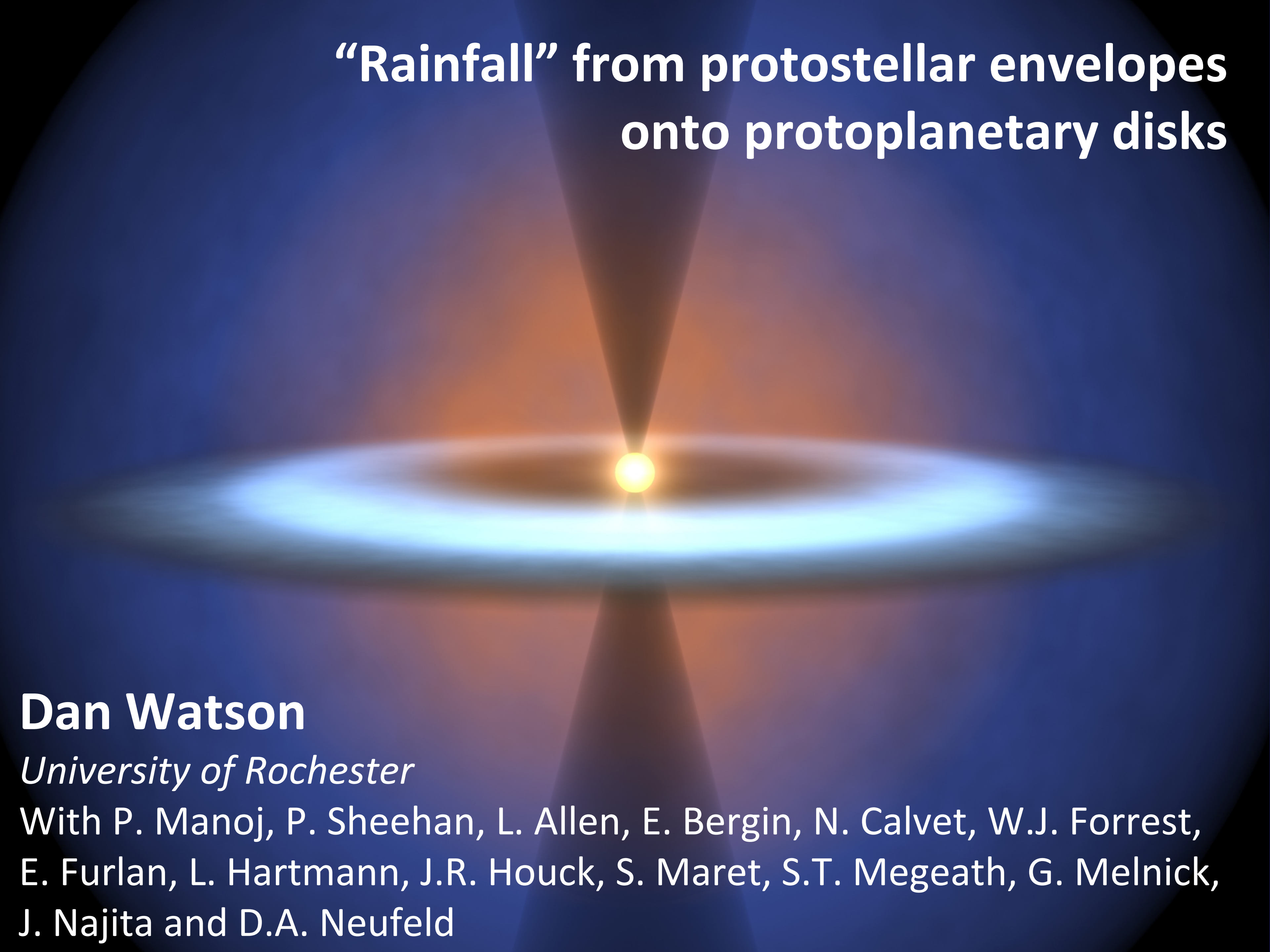

“Rainfall” from protostellar envelopes onto protoplanetary disks

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With P. Manoj, P. Sheehan, L. Allen, E. Bergin, N. Calvet, W.J. Forrest, E. Furlan, L. Hartmann, J.R. Houck, S. Maret, S.T. Megeath, G. Melnick, J. Najita and D.A. Neufeld

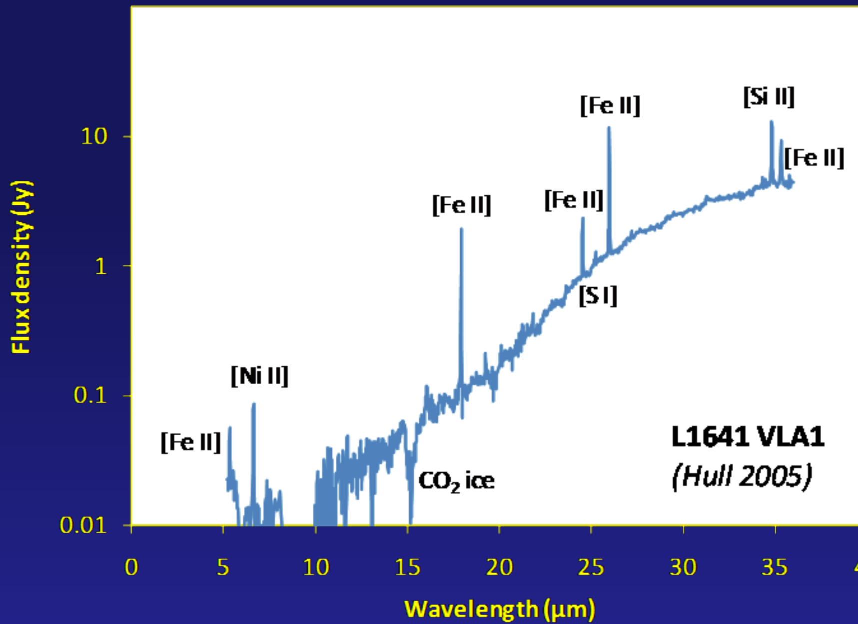
Most primitive protostars only show their outsides at mid-IR wavelengths.

In 2000, when the first GTO targets were chosen, some 50 Class 0 protostars were known. We chose the 30 brightest of them, as part of the IRS_Disks GTO project, and observed them in 2004-2005.

29 similar to each other:

- ❑ [Fe II], H_2, [S I] and [Si II] lines in outflows
- ❑ Deep CO_2, H_2O, and organic ice absorption features in the outer envelopes.

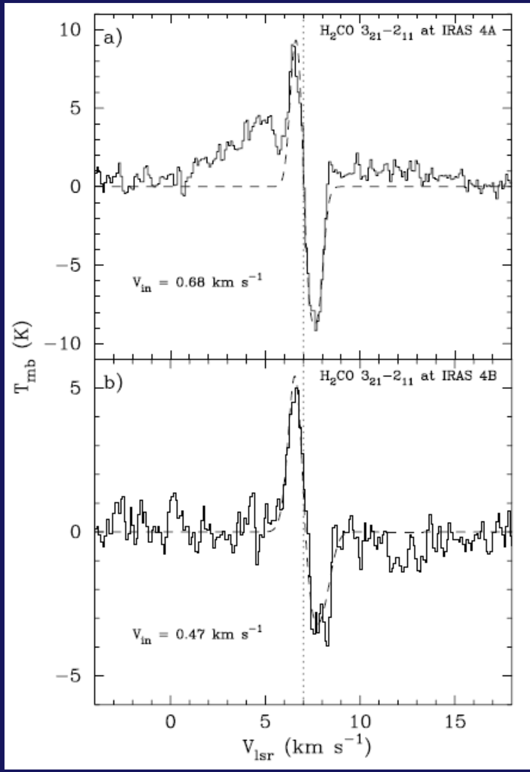
L1641 VLA1/HH1-2
(Bally et al. 2001)



But some of those seen face-on offer a view all the way to the center.

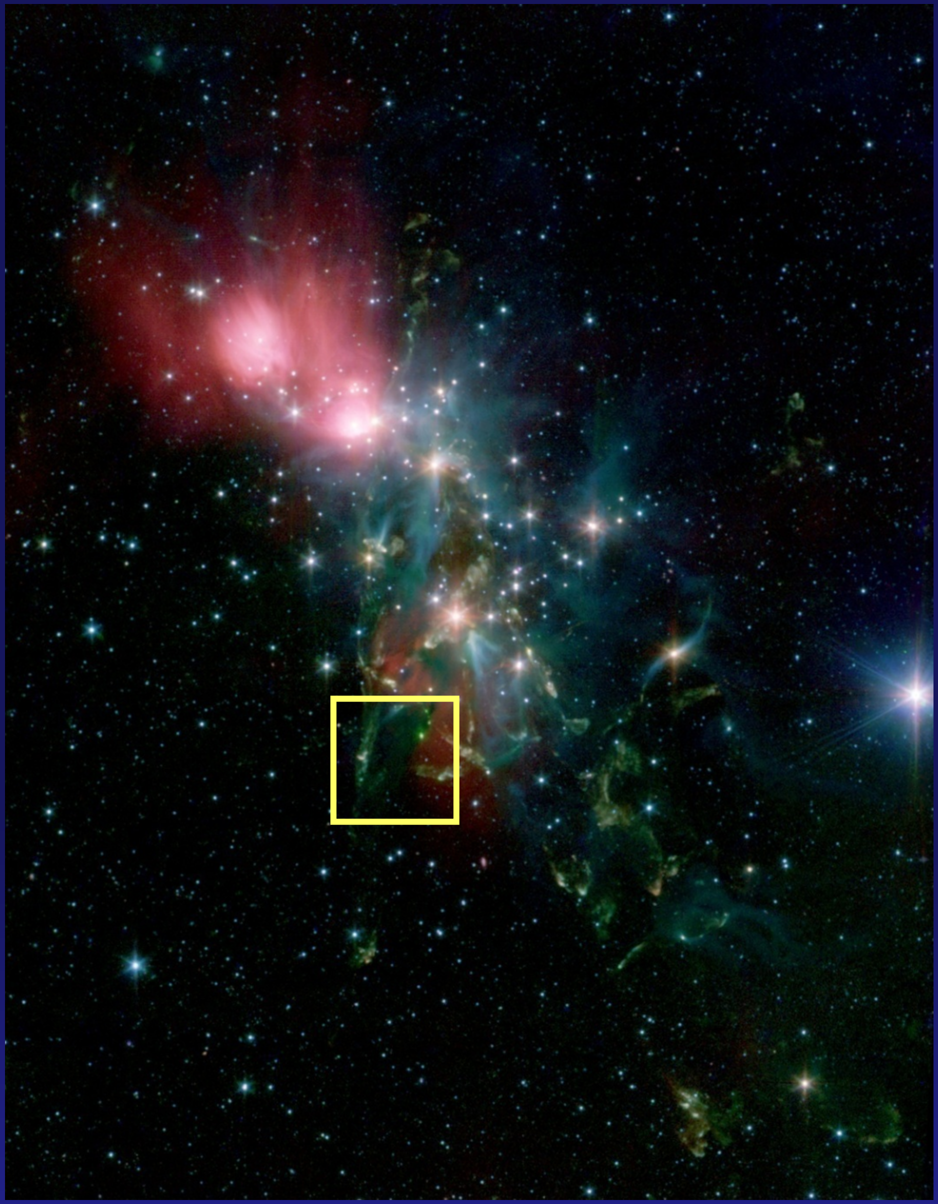
The thirtieth is NGC 1333 IRAS 4B:

- Possessor of a angularly-compact high-velocity outflow: *projected* length only about 10^4 AU.
- Near a streak of faint near-infrared emission that resembles light scattered from the inner surface of an outflow cavity.
- Thus we view it nearly face on. It is the only one of the first 30 that is viewed in this way.
- Infall observed kinematically in envelope: $\dot{M} = 10^{-4} M_{\odot}\ \mathrm{yr}^{-1}$.

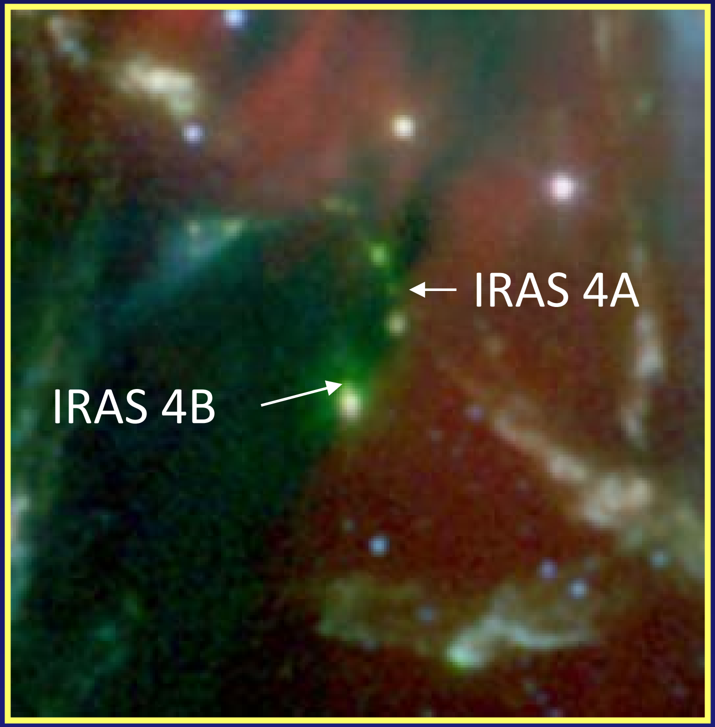


Redshifted absorption toward NGC 1333 IRAS4A and IRAS4B (di Francesco et al. 2001).

Spitzer-IRS observations of NGC 1333 IRAS 4B (Class 0)

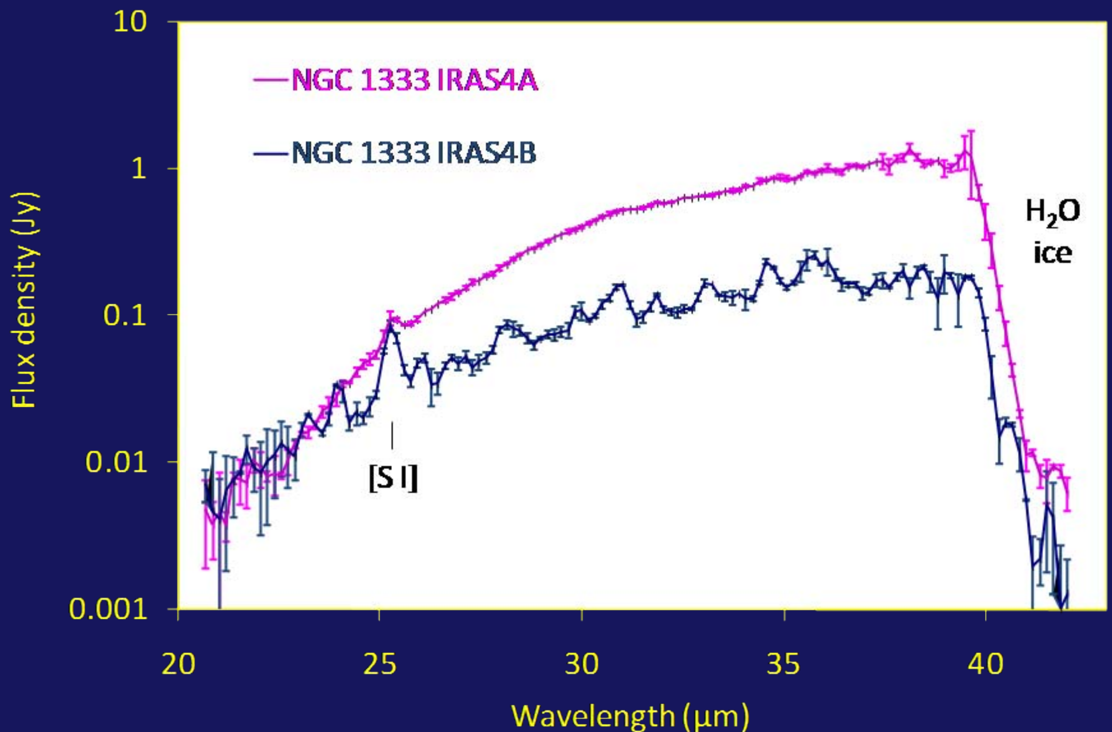


IRAC image: *BGR* = 3.5, 4.5, 8 μm

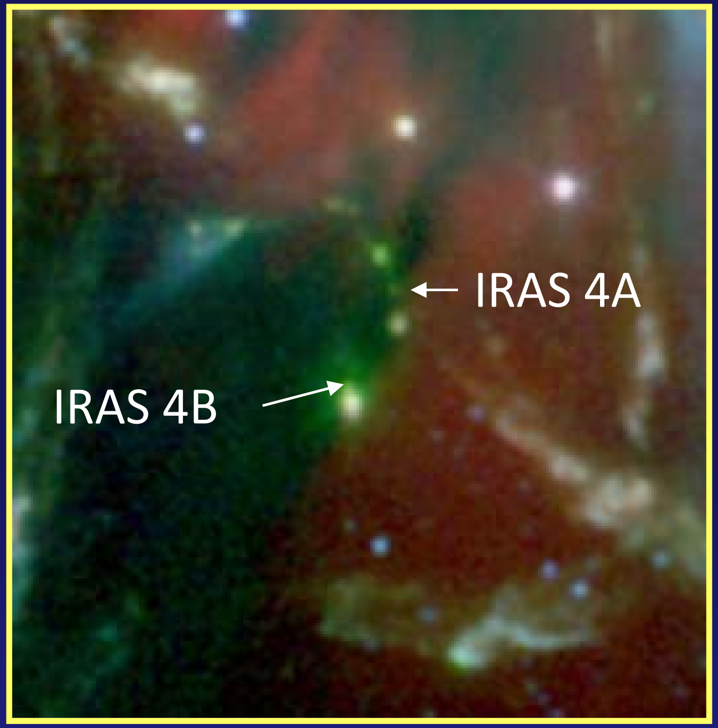


(courtesy of Rob Gutermuth)

Water and OH emission observed in NGC 1333 IRAS 4B



IRS, low spectral resolution



Both IRAS 4A and IRAS 4B have [S I] emission (from their outflows), but IRAS 4B also has broad features coincident with collections of strong transitions of **water**.

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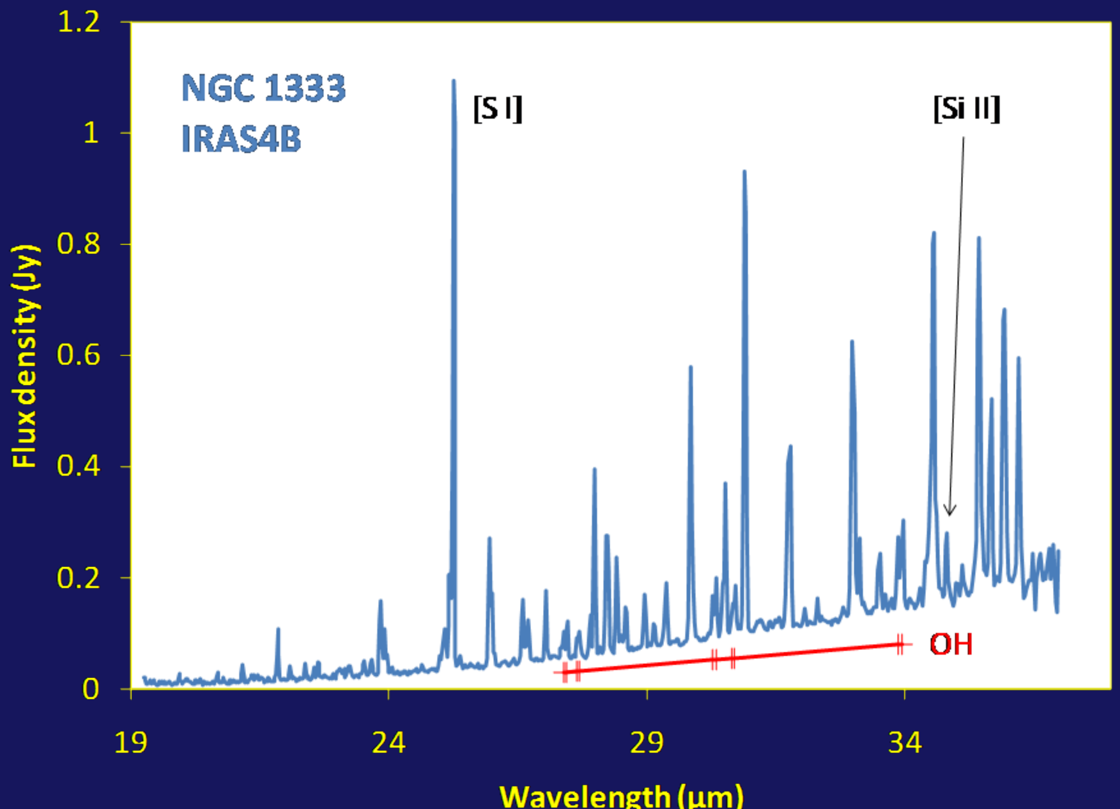
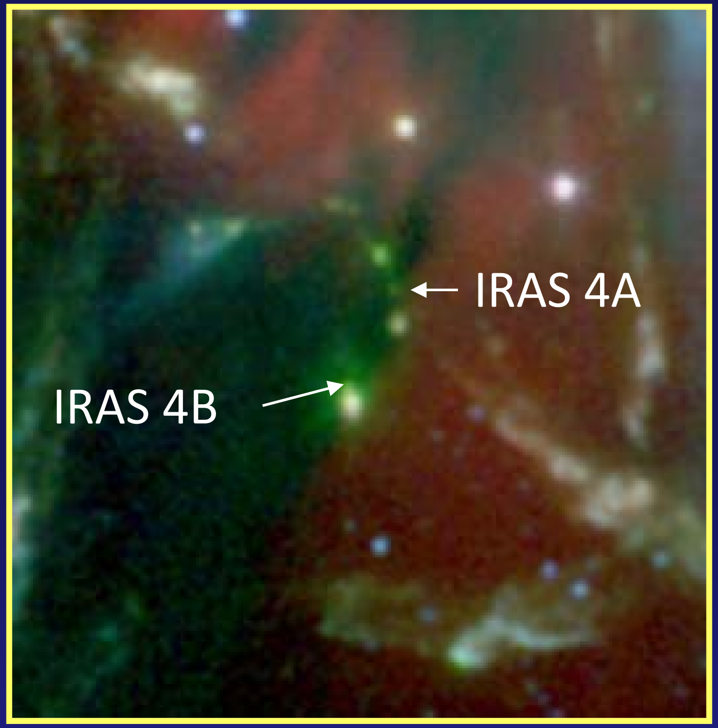
Water and OH emission observed in NGC 1333 IRAS 4B



IRS, high spectral resolution



Besides [S I] and [Si II]: >90 rotational transitions of $H_2{}^{16}O$ seen alone or in unresolved combinations, five lines of $H_2{}^{17}O$ or $H_2{}^{18}O$, and 10 rotational lines of ^{16}OH, in IRAS 4B.

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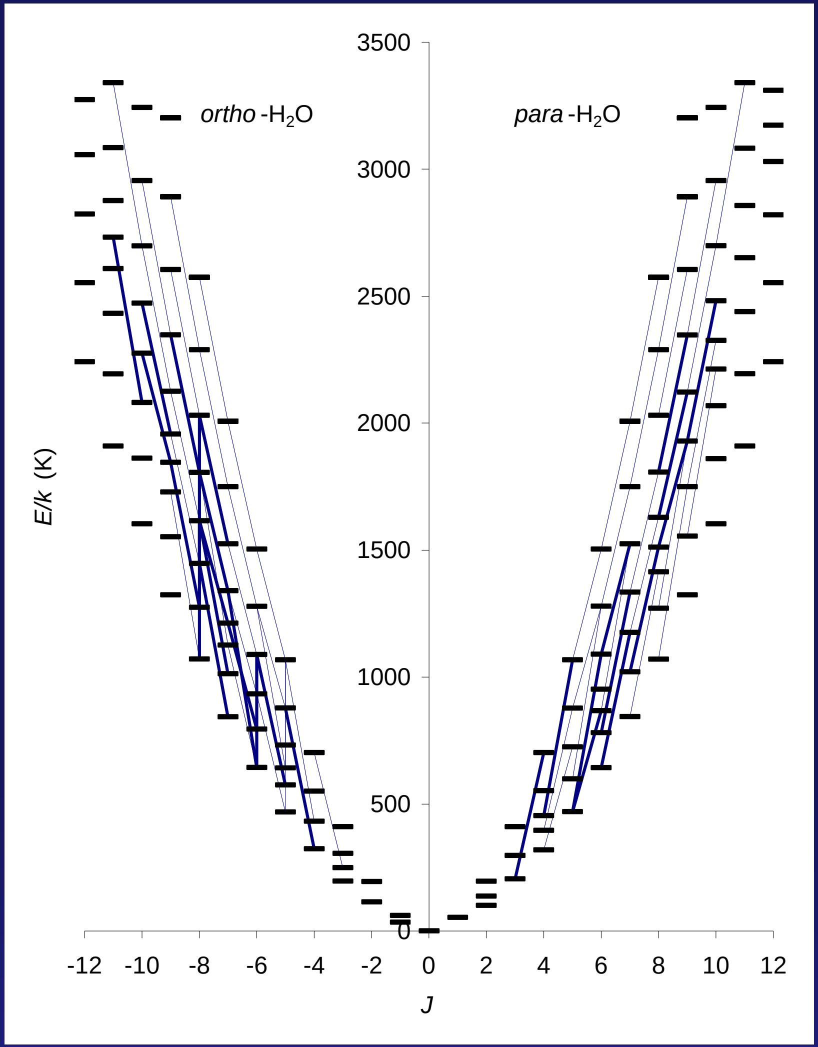
Water and OH emission observed in NGC 1333 IRAS 4B



Water transitions detected in IRAS 4B

- All lines from lowest vibrational state: the emission is not fluorescence.
- Upper states: critical densities for collisional de-excitation in the range 10^{10}-10^{13} cm^{-3}, so the gas is *very* dense.
- Collisional rate coefficients have never been computed for 40% of the detected water lines, or *any* of the detected OH lines.
- Wavelengths and excitation distributed: hotter material is not more heavily extinguished.

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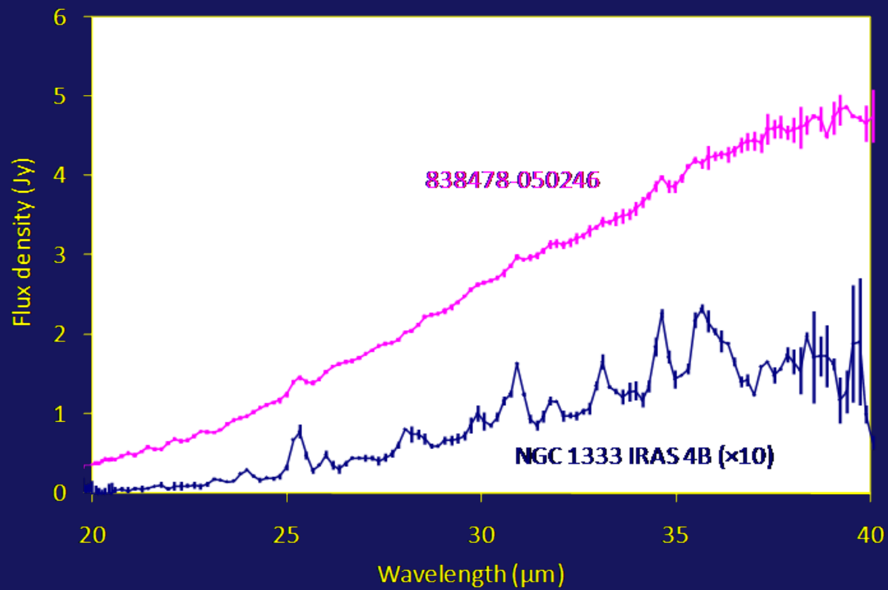
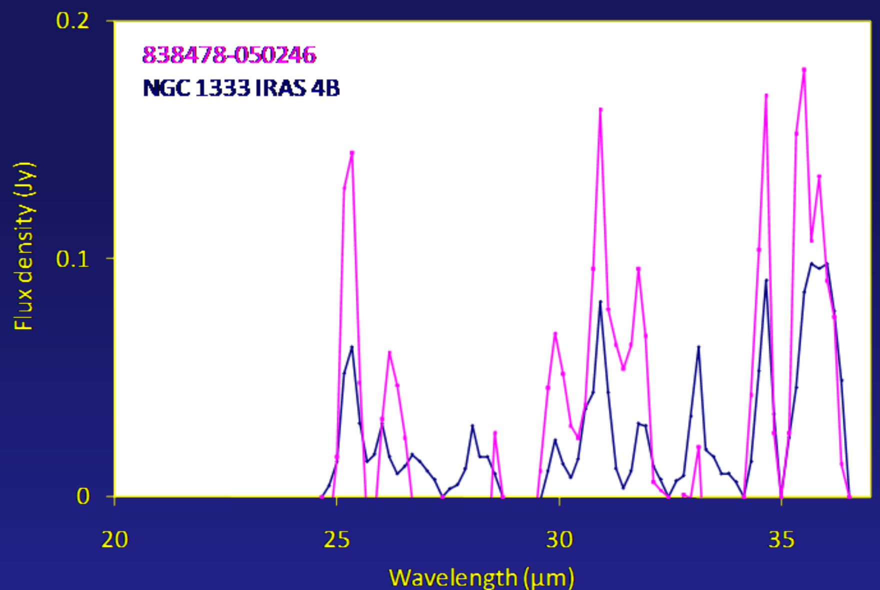
Water emission in the protostars of Orion A





30 of the 252 Class 0/I objects we have observed with IRS are viewed close to face on.

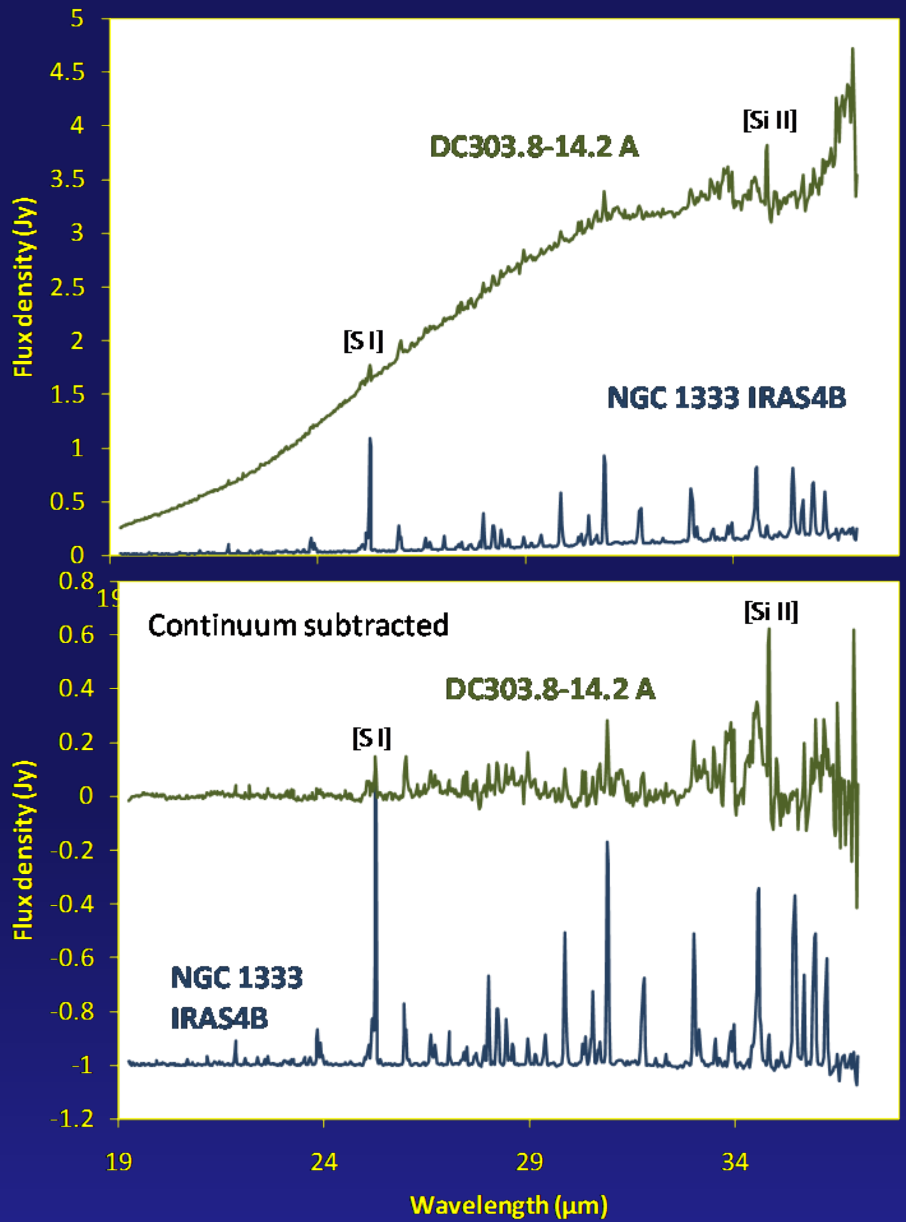
- Water emission detected in eight of them, at low spectral resolution.

Example:

8384780-5024640 is very similar in IRS spectrum (and thus temperature) and on images to NGC 1333 IRAS 4B.

- **Upper**: observed spectra of 8384780-5024640 and IRAS 4B.
- **Lower**: continuum subtracted, revealing unresolved water lines.

Water emission in a complete sample of face-on protostars within 500 pc



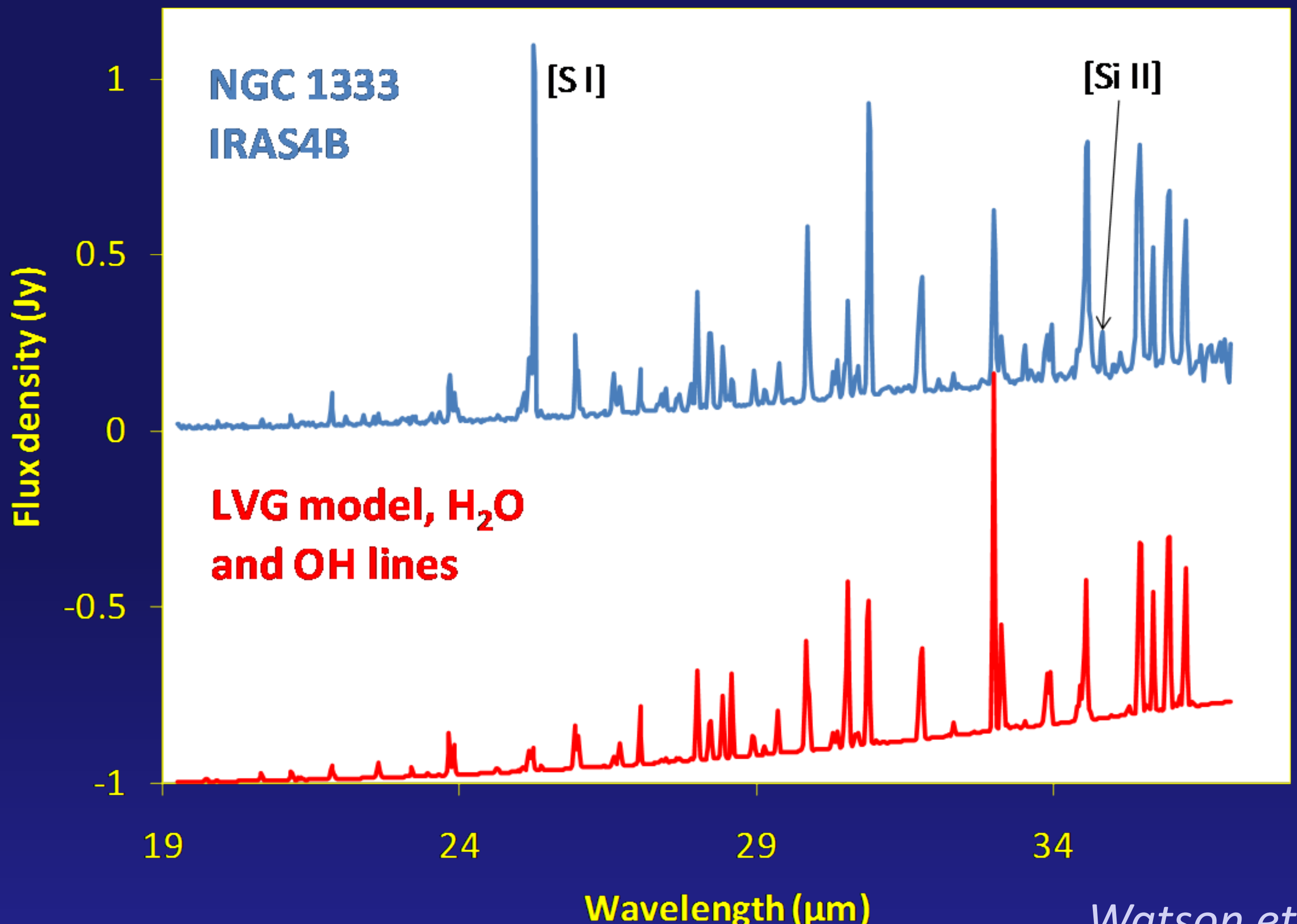
This Cycle 5 program (80 objects, LH) is not far along yet.

But the first fruits include DC303.8-14.2 A in Cha II, in which we also see many of the same water and OH lines as in NGC 1333 IRAS4B.

The physical condition of the water in NGC 1333 IRAS4B

Simple model works well for the water emission lines, OK for OH.

- Assumed: plane-parallel LVG, escape probability, LTE, screen.



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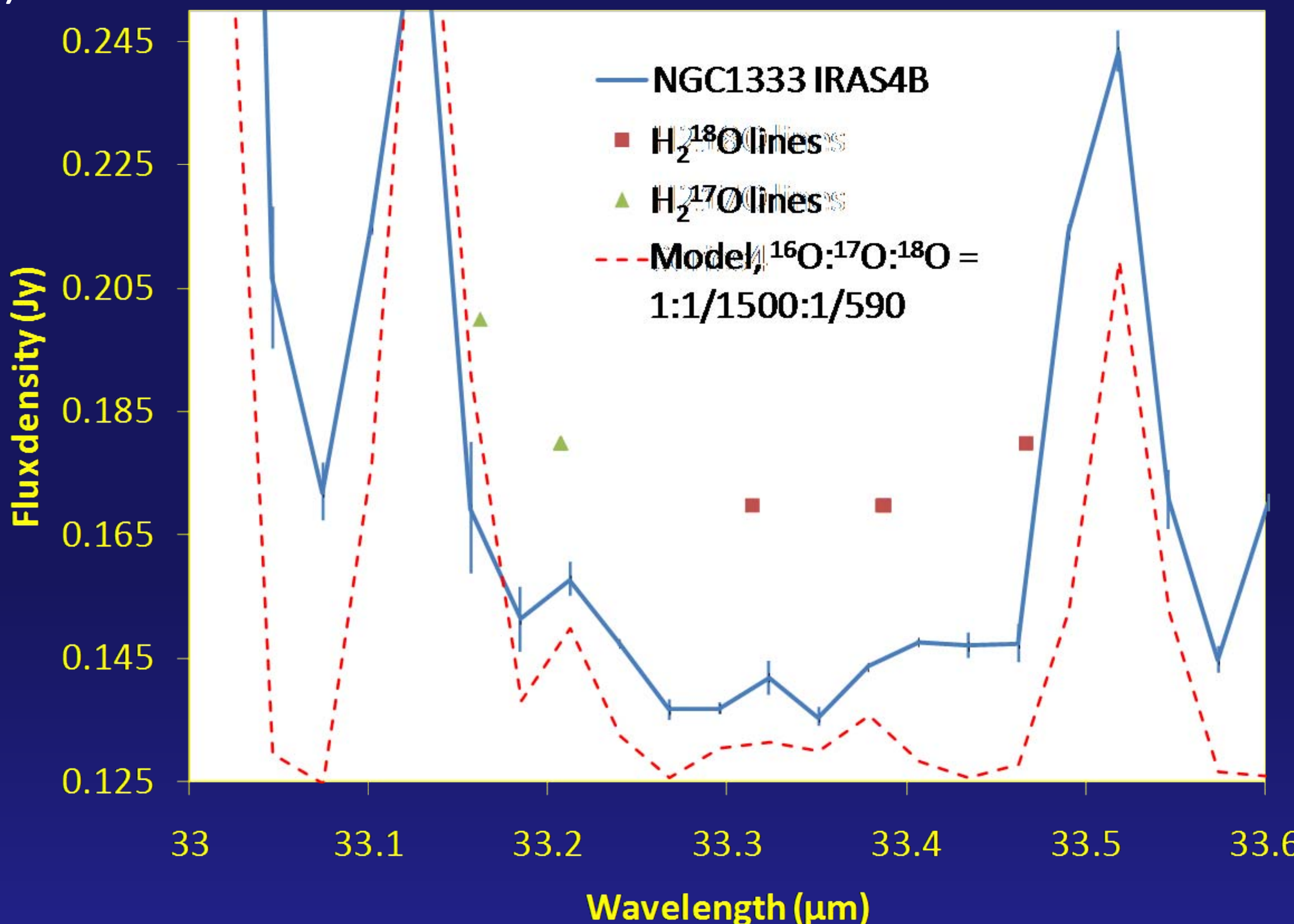
The physical condition of the water in NGC 1333 IRAS4B (continued)

Zoom in on the three clearest heavy-water detections (model offset by -0.01 Jy):



The physical condition of the water in NGC 1333 IRAS4B (continued)

According to the model:

- Brightest water lines have $\tau \sim 10$ (i.e. fairly optically thick), but most water lines and all OH lines are optically thin.
  - Thus the **column density *N*** can be determined separately from the optically-thin line fluxes, giving Δv in turn.
  - Thus the **area of the emitting region** can be determined separately from the optically-thick line fluxes and *T*.
- The total power in the water lines we detect is about a third of the total luminosity emitted by water in the object; we thus get an accurate estimate of the **total molecular cooling luminosity**.
  - Rotational water lines are very likely to be the dominant coolant of the gas (Neufeld and Kaufman 1993, Neufeld and Hollenbach 1994).
  - Nevertheless, significant cooling by dust is possible.

The physical condition of the water in NGC 1333 IRAS4B (continued)

Gas density	Thermal equilibrium, requiring $n(H_2) > 10^{10}$ cm^{-3}	**Very dense**
Gas temperature	170 K	**Not very hot**
Extinction by envelope	$A_V = 100$, interstellar-like	
H_2O column density	9.2×10^{16} cm^{-2}	
H_2O-line-emitting mass	3.8×10^{24} gm (H_2O) ~3×10^{27} gm (total)	**~3 Earth oceans**
Emitting area	6000 AU^2	**Solar-system size**
Velocity linewidth	2 km sec^{-1}	
Total H_2O-line luminosity	$0.03L_\odot$ (extinction-corrected)	
OH/H_2O	~0.01	**Very uncertain; OH states far from LTE population**
$H_2{}^{18}O/H_2{}^{16}O$	1/590	
$H_2{}^{17}O/H_2{}^{16}O$	~1/1500	
Envelope dust temperature	59 K	

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Protostellar "rain"

How is the gas heated?

- Not infall: doesn't reach these densities at these sizes (Ceccarelli et al. 1999, Maret et al. 2002).
- Not protostarlight: the luminosity of the system is only $4.2L_{\odot}$.
- However, an **accretion shock**, from envelope material raining down onto the embedded disk, works. For infall at rate $\dot{m}$ to the disk at radius *r*, shock at speed *v*: post-shock gas temperature *T* and cooling luminosity *L* are given by

$$T = \frac{2(\gamma - 1)}{(\gamma + 1)^2} \frac{\mu}{k} v^2 \quad , \quad L = \frac{1}{2} \dot{m} v^2 = \frac{GM\dot{m}}{r} \quad .$$

and we have determined *T* = 170 K and $L = 0.03L_{\odot}$ from the spectrum and the LVG model, so we get *v*, *M/r*, and $\dot{m}$.

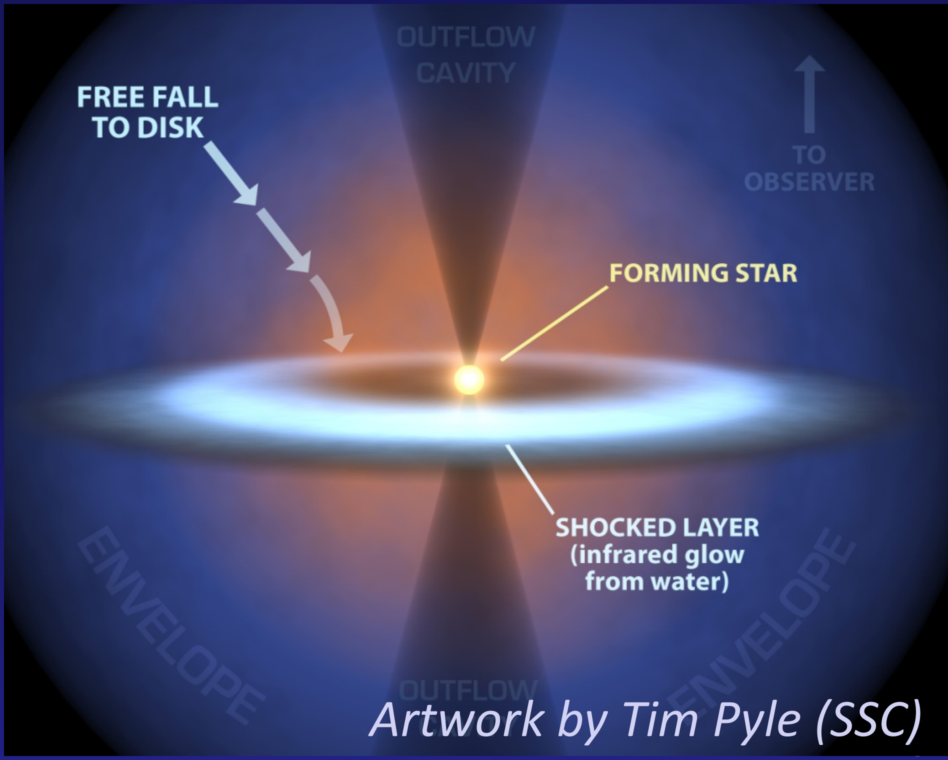
Protostellar “rain” (continued)

Disk accretion shock model summary for NGC 1333 IRAS4B:

Envelope-disk accretion rate	$0.7\times10^{-4}\ M_\odot$ year^{-1}
Shock speed	2 km sec^{-1}
H_2O-line-emitting mass, both faces of disk	7.5×10^{24} gm (H_2O) ~6×10^{24} gm (total)
Shocked area	6000 AU^2, each face
Dimensions of shock	Annulus, r = 40-60 AU
Protostar mass (if it dominates the gravity)	$0.14M_\odot$

Consistent with envelope infall rate.

Consistent with LVG model linewidth.



Artwork by Tim Pyle (SSC)

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Comparison of the protostellar "rainfall" in three Class 0 objects

	NGC 1333 IRAS4B	8384780-5024640 (OMC 3)	DC303.8-14.2 A (Cha II)
Distance (pc)	320	420	200
Envelope-disk accretion rate ($10^{-4} M_\odot$ yr^{-1})	0.7	2	0.13
Emitting area (one face of disk, AU^2)	6000	21000	810
Protostellar luminosity ($L_\odot$)	4.2	230	33

Note that if dust emission is important in the cooling of the gas, the accretion rate derived here is a lower limit.

Disk assembly and the state of water on arrival

Thus we see that in Class 0 objects, envelopes fall supersonically onto the future planet-forming region of embedded, new protoplanetary disks, at rates up to $\sim 10^{-4} M_{\odot}$ year^{-1}.

- Face-on ones; in others extinction is too large to see the disk.
- This is our first view of protostellar envelope-disk accretion shocks, and of the protoplanetary-disk assembly process.
  - Such observations yield accurate infall rates, and can give exquisite detail on physical conditions at the disk surface.
- On arrival, the material is heated well above the water-ice sublimation point, and contains both water and OH in substantial abundance.
  - Thus, although water falls as ice, and returns to ice within the disk, it *arrives* in the protoplanetary system in the form of gas, dense and warm enough to lose any isotopic anomalies rapidly.