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Are Molecular Clouds Clumpy?

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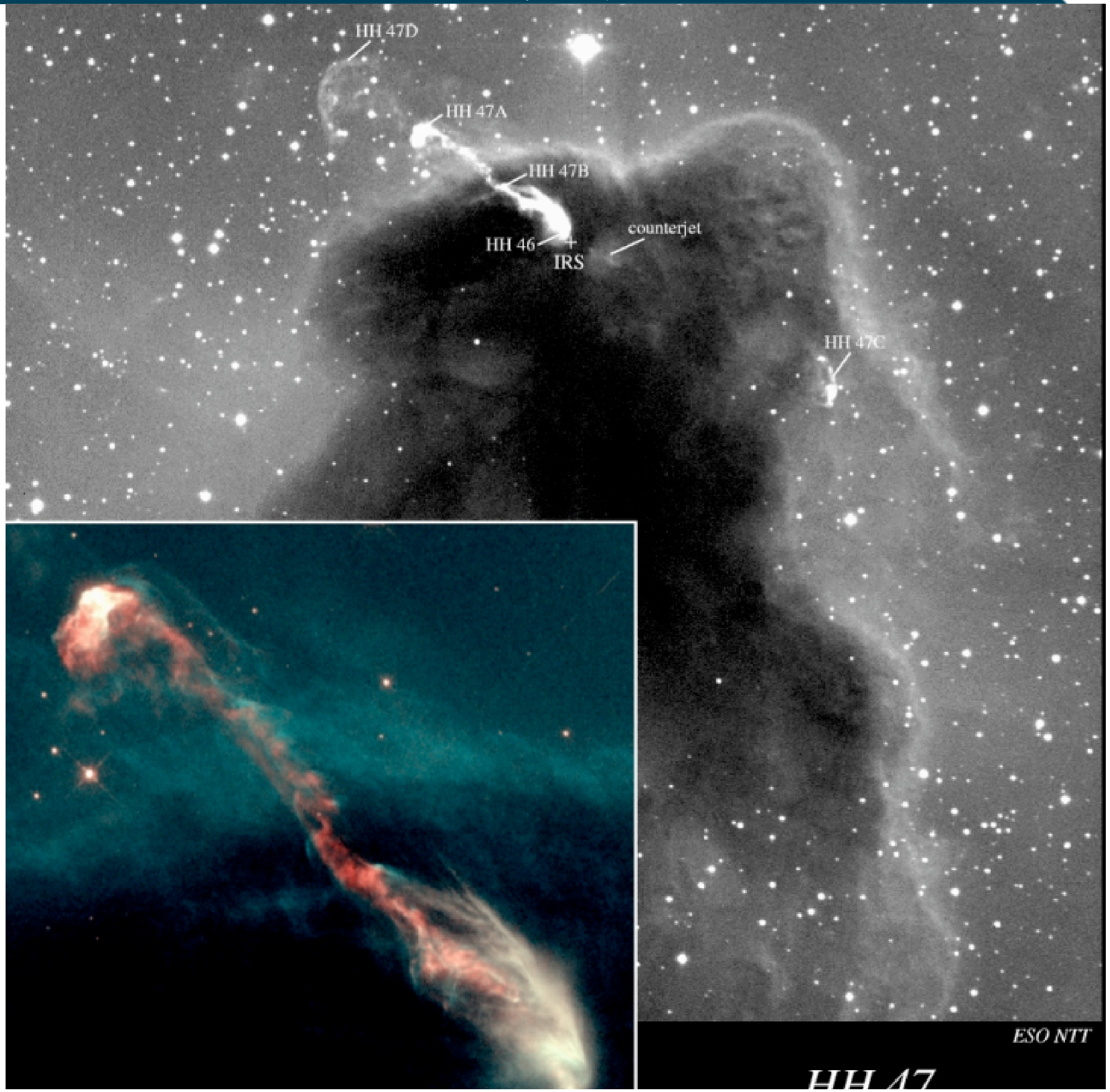

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Molecules and Molecular Clouds

- Molecules play a pivotal role in understanding the physical and chemical evolution of star-forming molecular cloud cores and primitive solar systems.

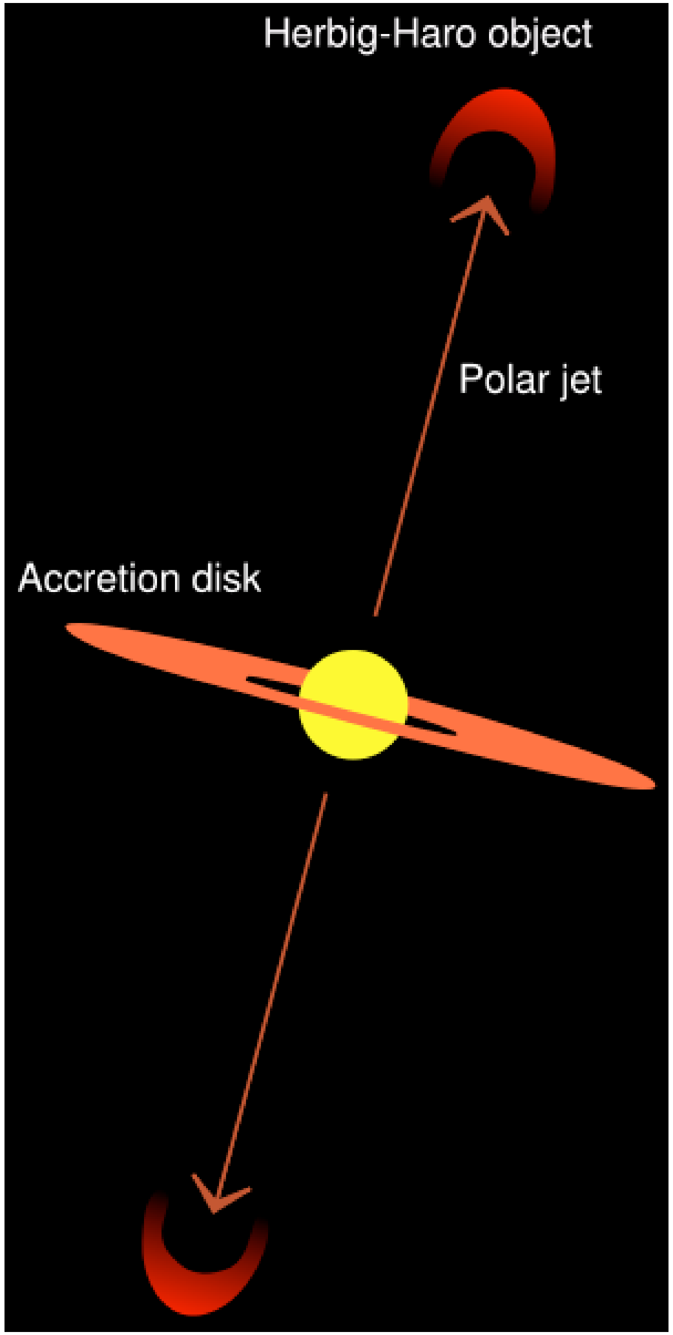
- Over 110 known interstellar molecules.

- Molecules also provide direct access to the velocity fields present in cloud cores with hundreds to thousands of magnitudes of extinction.

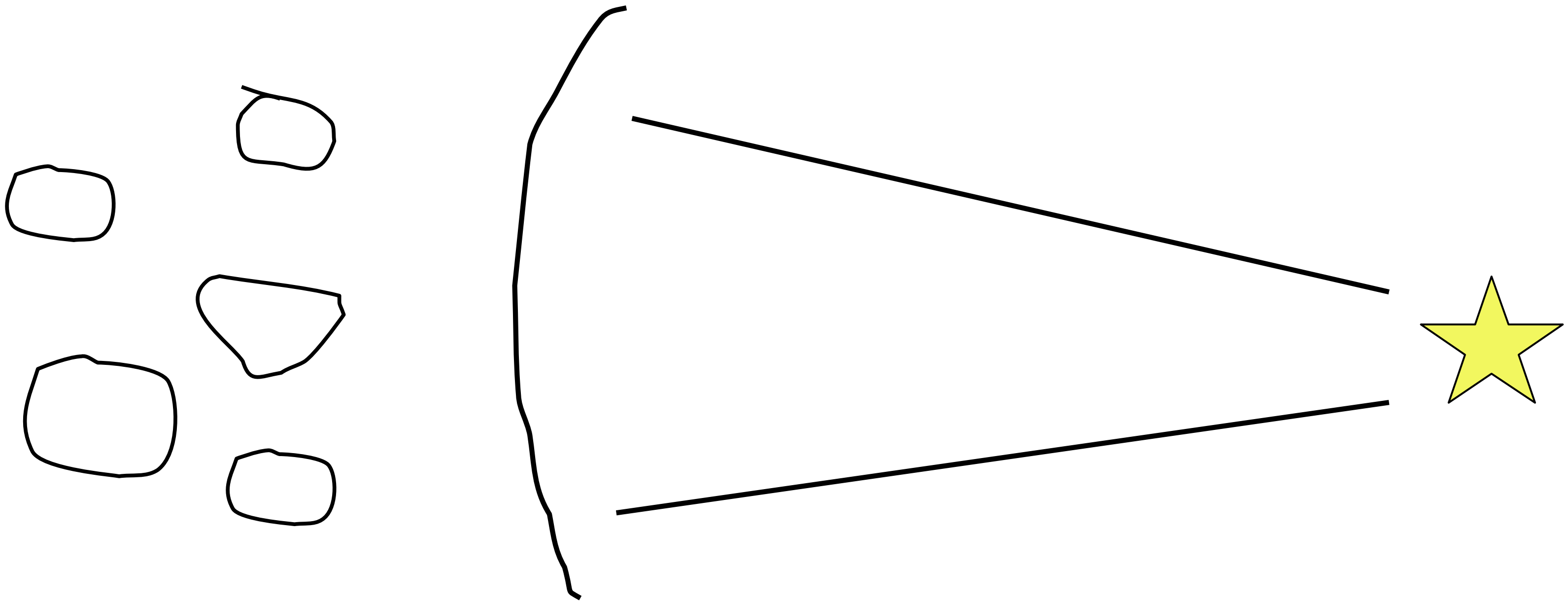
- Molecular abundances give constraints on the internal and external radiation fields, temperature, densities, filling factors and more…

Herbig Haro Objects

- During the process of star formation bi-polar outflow's are seen
- Fast - Travel through surrounding medium at 100 to 1000 km/s.
- Interact with the less dense surrounding producing bow shocks.
- Bow shocks emit intense UV and even X-ray emission.
- Very short events lasting ~ 10^3 years.

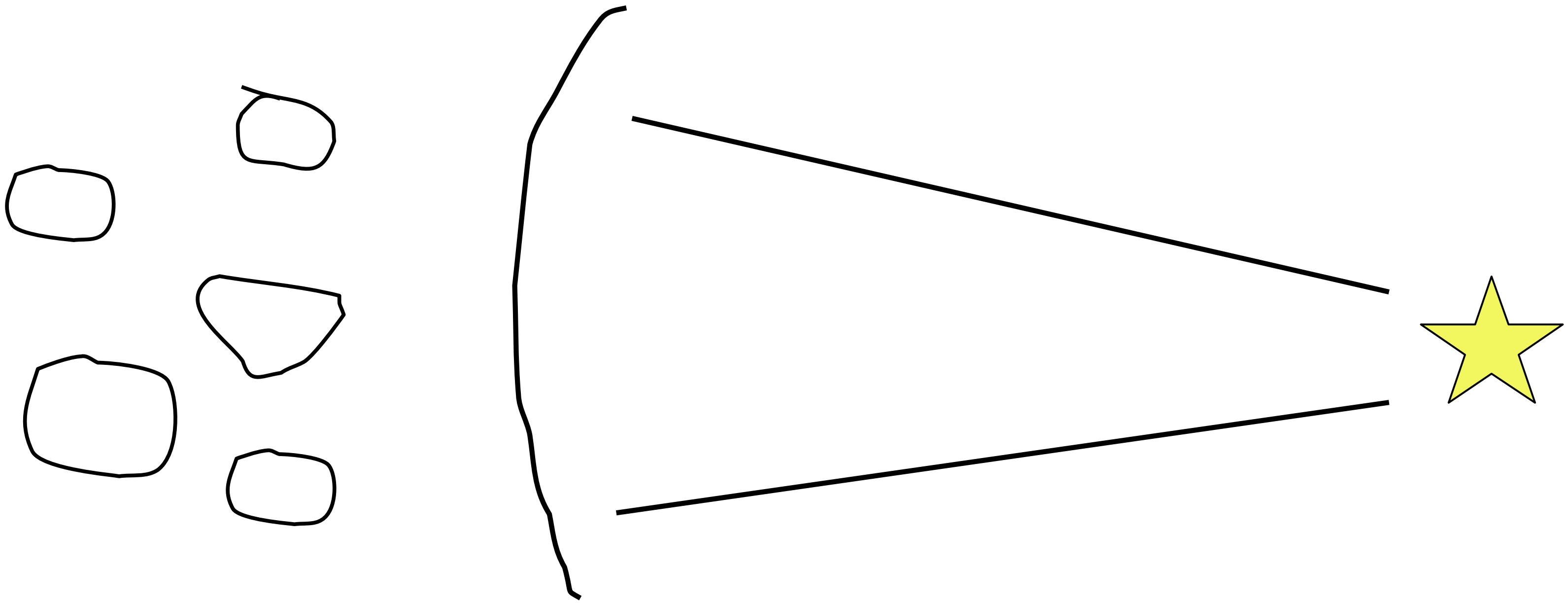


The clumps ahead of HH objects



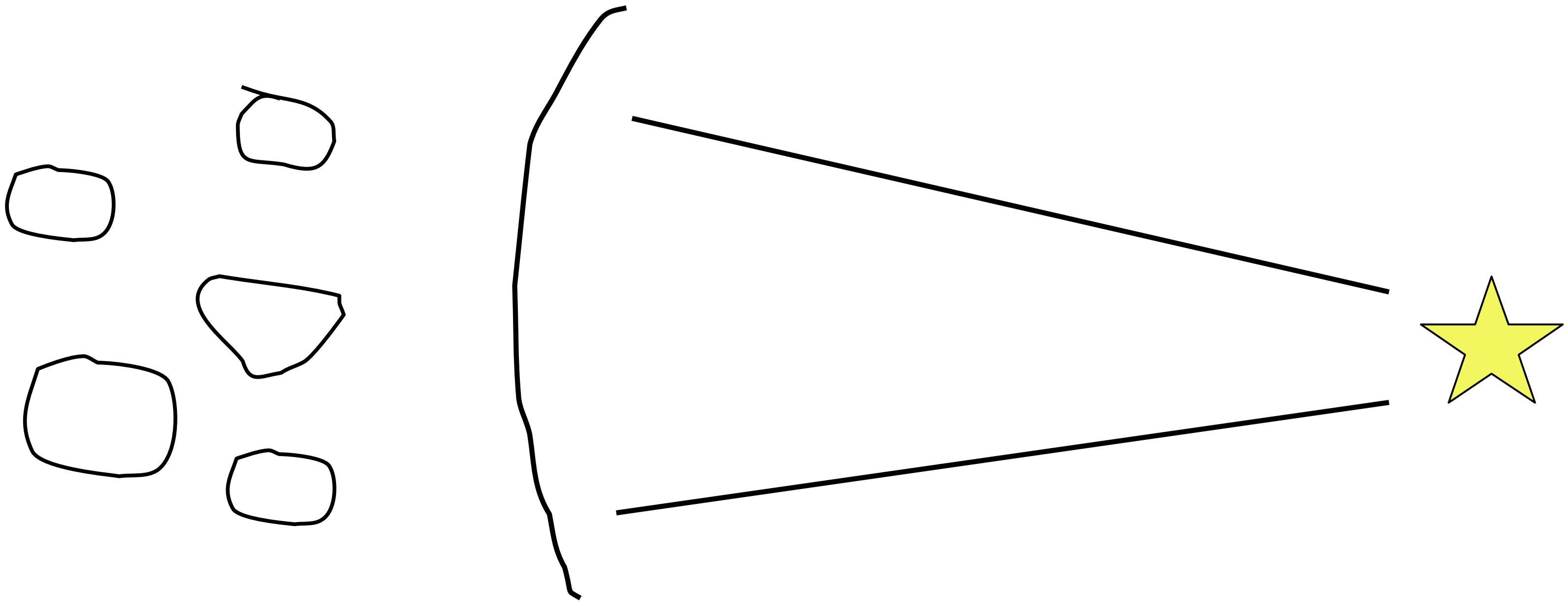
- Molecular condensations have been found ahead of HH objects by several groups over the course of the last 20 yrs (e.g. Rudolph & Welch 1988; Torrelles at al. 1992).

The clumps ahead of HH objects



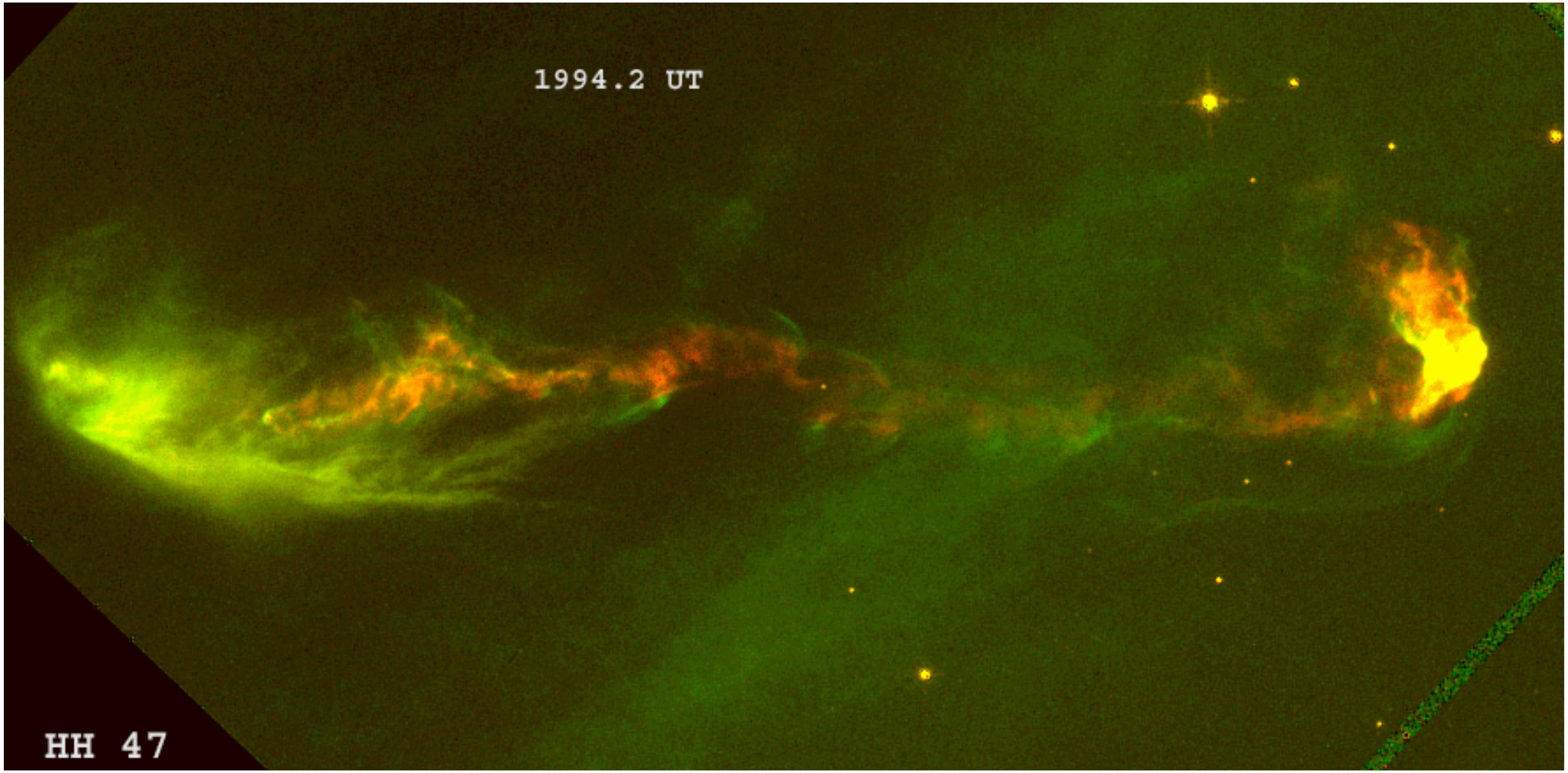
- The clumps are seen in enhanced emission from certain molecular species, particularly HCO^+ and NH_3. They are cool (10K) and quiescent and so not dynamically connected to the stellar jet.

The clumps ahead of HH objects



- As the jet is traveling at 100 - 1000 km/s these condensations must be transient as they will be destroyed when the jet reaches them, which can be in as little as 1000 years.

The clumps ahead of HH objects



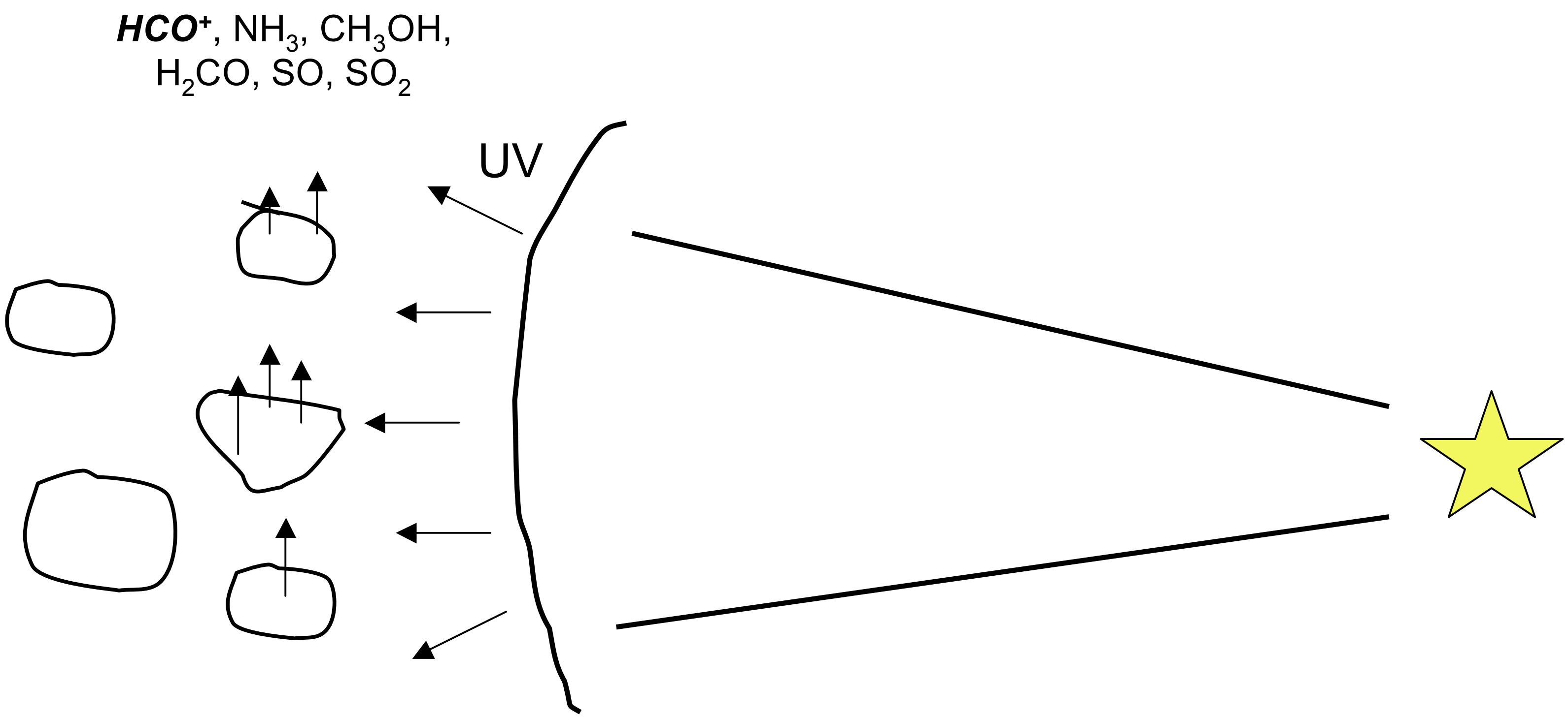
- As the jet is traveling at 100 - 1000 km/s these condensations must be transient as they will be destroyed when the jet reaches them, which can be in as little as 1000 years.

How do we explain this clumpiness?

- If the parent molecular cloud is composed of transient clumps which pre-date the HH object they would not be resolved by single dish observations - unless "illuminated" by a UV source such as the HH object.
- Theoretical predictions (Taylor & Williams 1996; Viti & Williams 1999) predicted that this UV radiation from the HH shock would enhance the abundances of many species including H_2S, CH_3OH, SO_2 and SO.
- UV radiation would lift the icy mantles from the dust grains of the clump and drive an active and fast photochemistry - which would enhance the abundances of hydrogenated species (like NH_3 & HCO^+).

- ***This results in HH objects acting like torches revealing the clumps ahead of them - and releasing the icy mantles into the gas phase.***

How do we explain this clumpiness?



- ***Therefore HH objects act like torches revealing the clumps ahead of them - and releasing the icy mantles into the gas phase.***

HH 2

- To confirm this picture detail observations of HH 2 were undertaken (Girart et al 2002, 2005; Viti et al 2003).
- Observations of 14 species

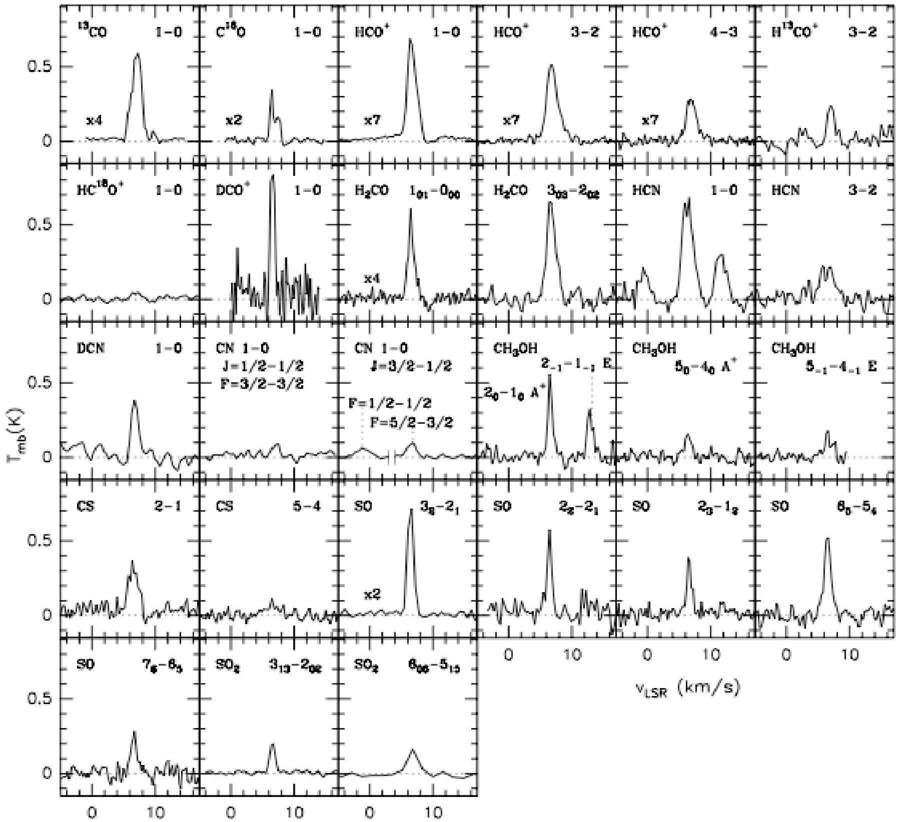


Fig. 1. Spectra of the detected lines with the BIMA and CSO telescopes. Lines from BIMA were convolved with a Gaussi order to obtain a resulting beam of 30″, approximately the beam of the CSO data at 250 GHz.

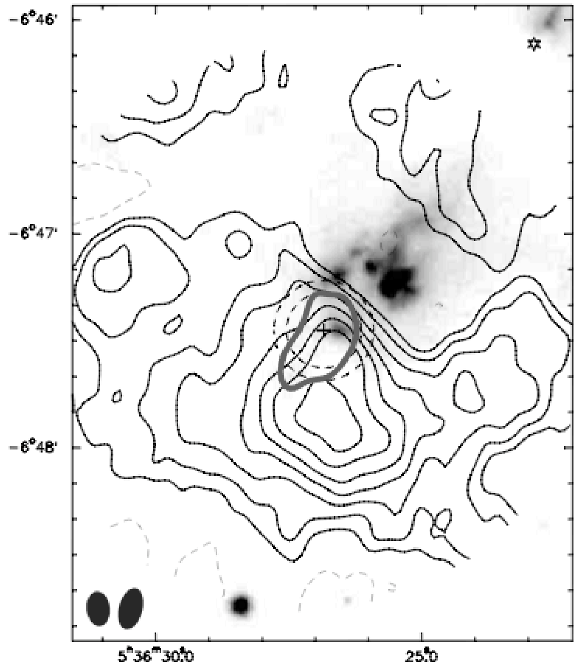


Fig. 2. Superposition of the gray scale of the [SII] image (from Curiel, private communication), the integrated emission of the ^{13}CO 1–0 line (thin contours) over the 5.1–8.1 km s^{-1} $v_{\rm LSR}$ interval, and the integrated emission of the SO 3_2–2_1 line (thick contour) over the aforementioned $v_{\rm LSR}$ range. Contours levels are 4, 13, 25, 37, 49, ... times the rms noise of the map, 47 mJy beam^{-1} for the ^{13}CO, and 50% of the peak intensity for the SO. The synthesized beam of the ^{13}CO (left) and the SO (right) are shown in the lower left corner. The star marks the position of HH 2 VLA 1, the powering source of the HH 1/2 outflow. The cross marks the center coordinates of the single–dish spectra. The two concentric dashed circles show the 21″ and 28″ beam sizes of the CSO spectra at 265 and 360 GHz, respectively.

Confirming chemical predictions

- These observations confirmed the theory. With species abundances in line with theoretical models.

- A survey of HH objects with known clumps was undertaken by Viti, Girart & Hatchell (2006) with the IRAM 30m telescope showed that in all cases where these clumps are seen there is strong HCO^+emission.

- ***Therefore HCO^+ emission can be used as a tracer to identify the clumps ahead of HH objects.***

- ***But are these clumps typical?***

- To test whether this clumpiness is seem ahead of the majority of HH objects we observed 21 HH objects and for the first time determine the fraction of HH objects that possess these molecular condensations.

The Sample

- First "large" scale search for clumps ahead of HH objects
- Avoiding dynamically effected material - so observed at end of jet
- Only 1 HH object per region/outflow where possible
- Limited to HH objects embedded in dark molecular clouds and outside SF regions
- Where possible CCD observations available
- HH 2 suggests clumps are seen 0.1 pc downstream of jet

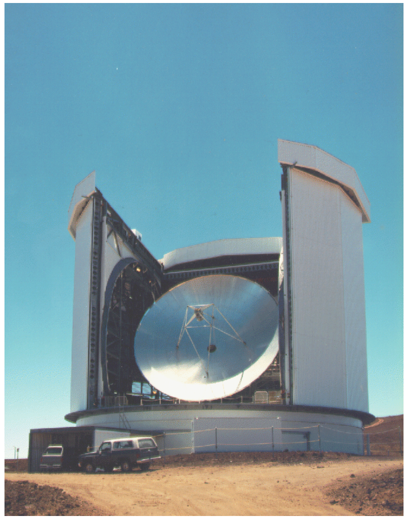
Observations

JCMT

- Northern Hemisphere
- Hawaii
- 11 sources
- 60 position observed
- HCO^+ 3-2
- 267.56 GHz
- 19.7” offsets

SEST

- Southern Hemisphere
- La Silla, Chile
- 10 sources
- 100 positions observed
- HCO^+ 3-2
- 267.56 GHz
- $H^{13}CO^+$ 1-0
- 86.75 GHz
- 23” offsets



Source List

Northern

- **HH 29**
- **HH 211**
- **HH 267**
- **HH 276**
- **HH 278**
- **HH 337**
- **HH 362A**
- **HH 366**
- **HH 427**
- **HH 462**
- **HH 464**

Southern

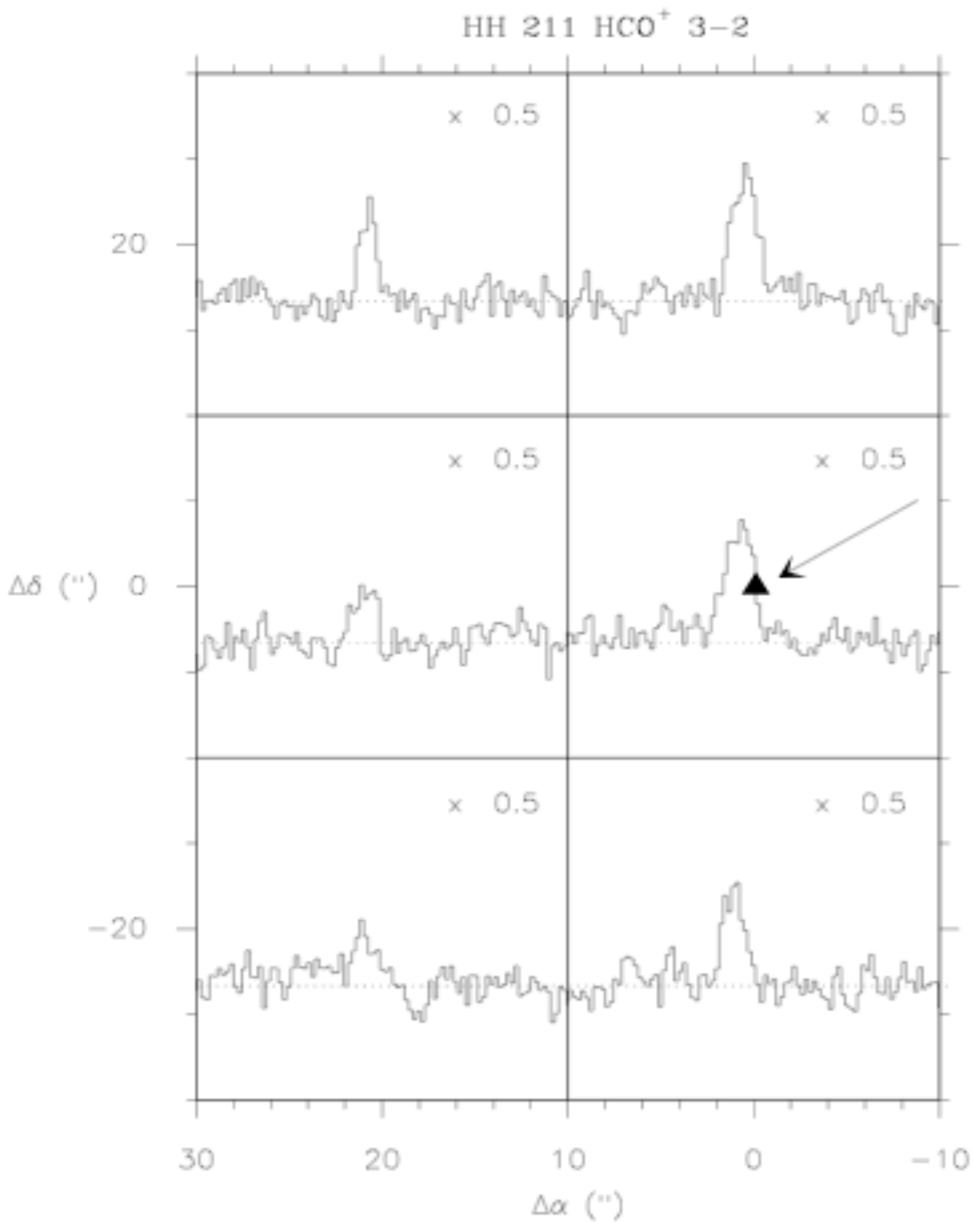
- **HH 38**
- **HH 43**
- **HH 47C**
- **HH 49**
- **HH 52-53**
- **HH 54**
- **HH 75**
- **HH 77**
- **HH 240**
- **HH 272**

Observations

Object	RA J2000	Dec J2000	Lit: V_{LSR} kms^{-1}	Location	Distance pc	Suspected Exciting Source
HH 29	04 31 27.6	+18 06 24	6.6	L1551	140	L1551 IRS 5
HH 211	03 43 56.8	+32 00 50	9.2	IC 348	300	HH 211-mm
HH 240	05 19 40.7	−05 51 44	…	L1634	460	IRAS 05173-0555
HH 267	03 24 03.0	+31 00 29	4.5	L1448	300	L1448C
HH 268	03 24 22.1	+30 48 11	4.5	L1448	300	(poss) L1448 IRAS1
HH 276	04 22 07.3	+26 57 26	6.5	L1455/L1448	140	IRAS 04189+2650*
HH 278	03 26 59.4	+30 25 58	7.0	L1448	300	L1448NB
HH 337	03 25	+31 15	4	NGC 1333	220–350	IRAS 23011+6126
HH 362A	04 04 24.1	+20 20 41	7.2	L1489	140	IRAS04106+2610*
HH 366	03 29 39.77	+31 17 44.0	5.0	B5	350	B5 IRS1
HH 427	03 30 37.71	+30 21 56.6	6	Barnard 1	220	Not known
HH 462	03 54 05.0	+38 10 35	-3.5	Perseus	350	IRAS03507+3801
HH 464	04 10 42.4	+38 07 39	-3.5	L1473	350	PP13N
HH 38	05 38 21.8	−07 11 38	8.5	L1641	470	IRAS 05357-0710(* and elsewhere)
HH 43	05 38 10.4	−07 09 25	8.5	L1641	470	IRAS 05357-0710
HH 47C	08 25 32.96	−51 01 37.4	6.0	Gum Nebula	450	HH 46/47 IRS
HH 49	11 06 00.05	−77 33 36.0	5.3	Cha I	160	Cha-MMS1
HH 52-53	12 55 06.4	−76 57 46	4	Cha II	165	IRAS12496-7650
HH 54	12 55 49.5	−76 56 08	4	Cha II	165	IRAS12496-7650
HH 75	09 11 38.5	−45 42 28	-0.9	Gum Nebula	450	-
HH 77	15 00 49.0	−63 07 46	-5	Circinus	1000	IRAS 14564-6254*
HH 240	05 19 40.7	−05 51 44	8.2	Orion	470	IRAS 05173-0555
HH 272	06 12 48.4	−06 11 21	11	L1646	830	IRAS 06103-0612*

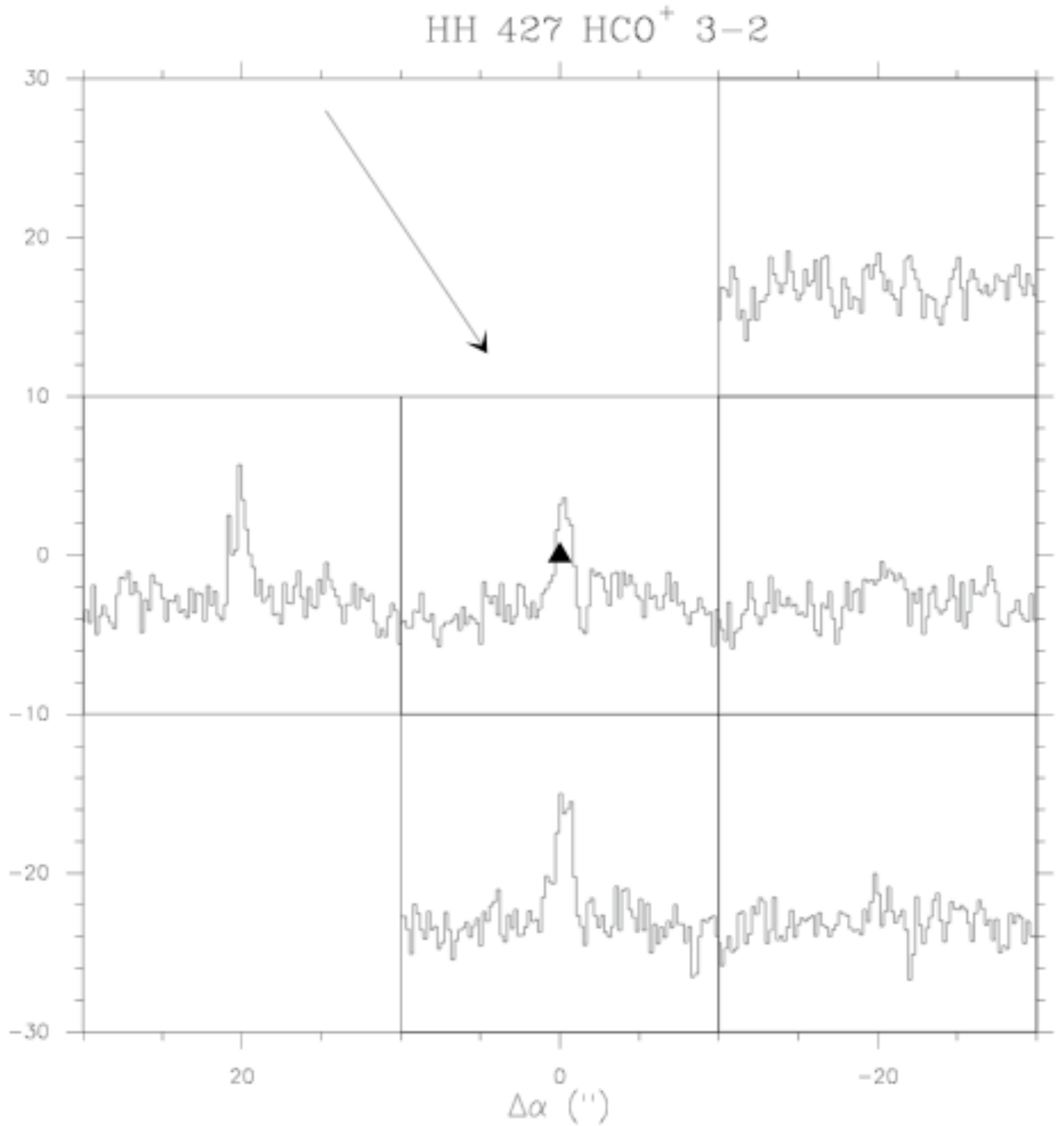
HH 211

- HH 211 is located at a distance off 300pc in the IC 348 Region/Perseus dark cloud.
- less than 2000yr old, and features a relatively small but highly collimated, bipolar jet (0.16 pc long) seen in molecular hydrogen (IR), and a molecular outflow, both powered by a cold sub-mm source.



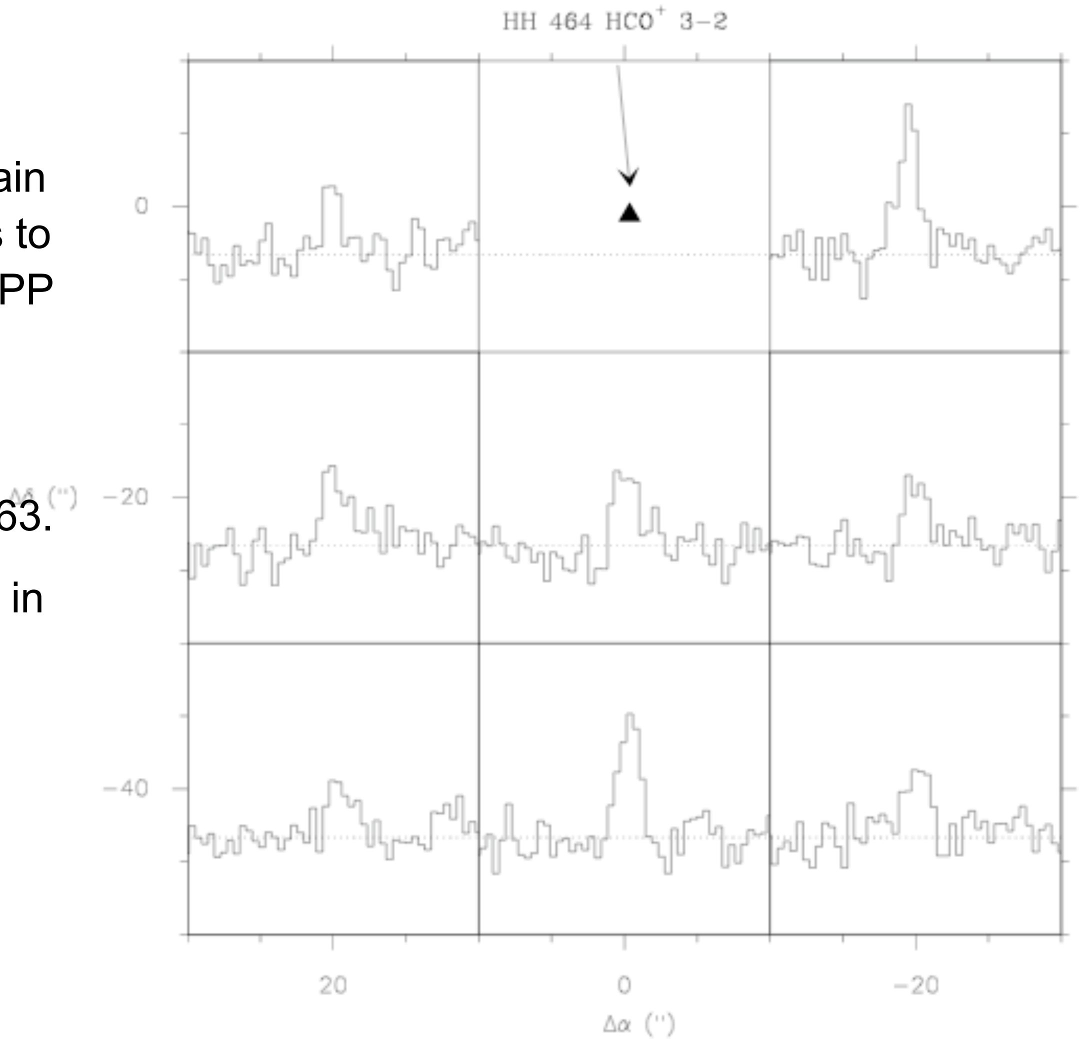
HH 427

- Located in the Barnard 1 Dark Cloud with a linear size of 0.2pc.
- The bi-polar outflow of the close source, IRAS 03271 +3013, extends in a northeast-southwest direction whilst HH 427 is located 53 south-east of the YSO.
- Hence the exciting source is unknown.



HH 464

- HH 464 is made up a curved chain of 5 HH knots; A to E. It appears to be powered by the T Tauri star PP 13N, as the chain is roughly perpendicular to the expected outflow from PP 13S, which is responsible for the nearby HH 463.
- Located in the L1473 dark cloud in the constellation of Perseus at a distance of 350 pc.



Results

- 11 sources show emission
- Volume filling factor = 0.05 - 0.65

Object	N^o of detections (total N^o)	% of standard region observed	N(HCO^+)	T_{mb}(HCO^+ 3–2) K	ΔV (HCO^+ 3–2) kms^{-1}
HH 211	6(6)	50%	4.8×10^{12}	0.84	1.29
HH 240	3(11)	.....			
HH 267	0(6)	50%	$<1.5\times10^{12}$	$<$ 0.38	-
HH 268	0(3)	25%	$<2.2\times10^{12}$	$<$ 0.56	-
HH 276	0(6)	55%	$<2.1\times10^{12}$	$<$ 0.53	-
HH 278	(0)6	50%	$<1.7\times10^{12}$	$<$ 0.43	-
HH 337	1(6)	22% - 69%	2.2×10^{12}	0.56	1.29
HH 362A	0(6)	11%	$<1.8\times10^{12}$	$<$ 0.46	-
HH 366	1(1)	2%	2.1×10^{12}	0.53	0.54
HH 427	3(6)*	22%	3.5×10^{12}	0.89	0.34
HH 462	4(5)	57%	7.9×10^{12}	2.01	1.01
HH 464	8(8)	92%	4.3×10^{12}	1.09	1.23
HH 38	1(11)*	228%	4.1×10^{12}	1.02	0.86
HH 43	1(4)*	83%	2.1×10^{12}	0.53	0.68
HH 47C	0(11)	209%	$<5.5\times10^{12}$	$<$ 1.39	-
HH 49	0(22)	47%	$<2.4\times10^{12}$	$<$ 0.62	-
HH 52-53	0(9)	23%	$<9.5\times10^{12}$	$<$ 2.4	-
HH 54	0(12)	30%	$<2.6\times10^{12}$	$<$ 0.66	-
HH 77	0(0)**	825%	$<2.5\times10^{12}$	$<$ 0.631	-
HH 240	1-3(11)	228%	4.6×10^{12}	1.15	0.64
HH 272	3(9)*	712%	3.3×10^{12}	0.83	1.37

Conclusion

- > 50 % of sources show emission
- All, quiescent - narrow lines - not dynamically effected by HH object and predate the HH object.
- The clumps are transient, in that they will be destroyed by the approaching jet on a time scale of 100 years.
- ***Therefore clumps must be a ubiquitous feature of molecular clouds.***
- ***HH objects provide a novel mechanism of probing the composition of the icy mantles around grains in molecular clouds.***

Future Work

- Observational - Extending the Maps
  - Larger maps to deduce the scale of the emission.
  - More lines to confirm clump photochemistry
  - JCMT and IRAM observations
- Modelling - Based on previous work with the UCL_PDR code to model these clumps. Working with Rob Garrod (Ohio).
  - To reproduce the observations
  - To model the effect the UV will have on clumps at different ages, densities, and fluxes

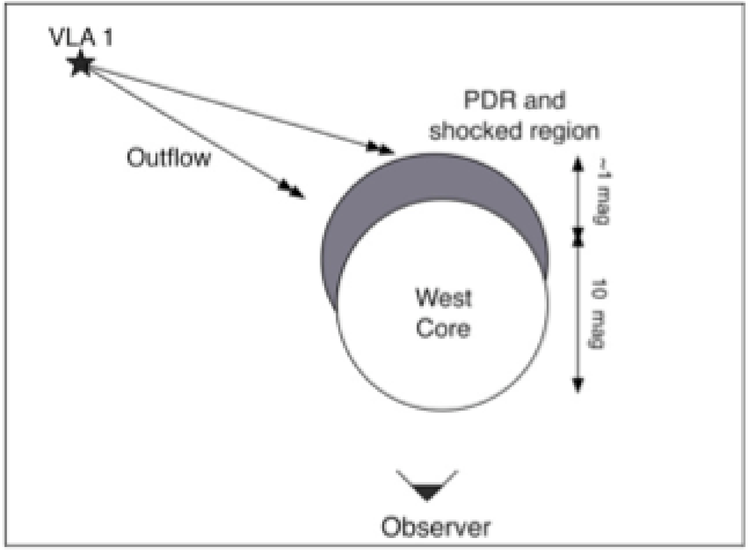


Fig. 13. Sketch of the West Core, the PDR-like structure, and shocked regions that lie behind the West Core with respect to the observer point of view.