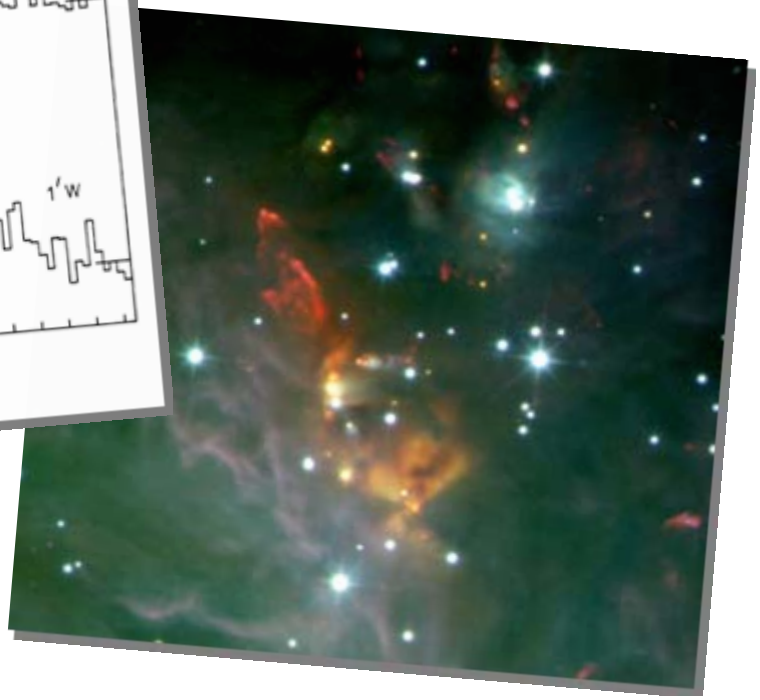
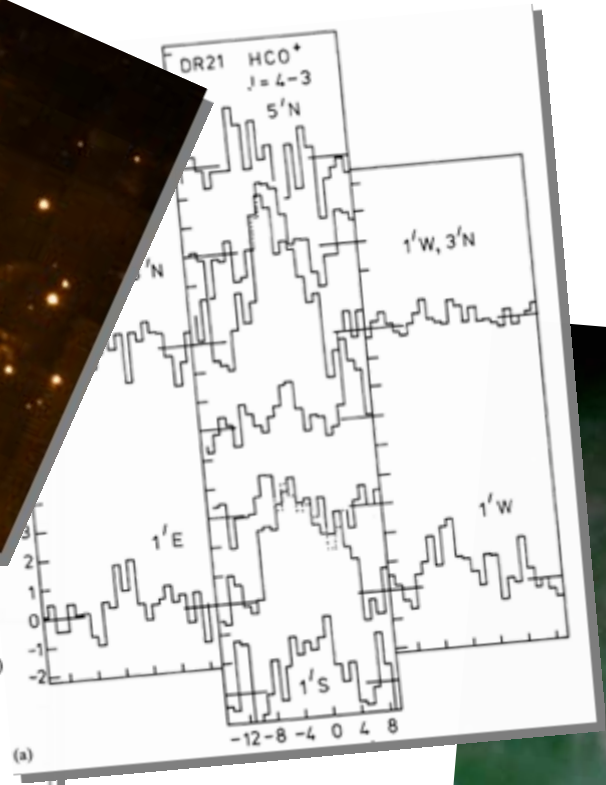
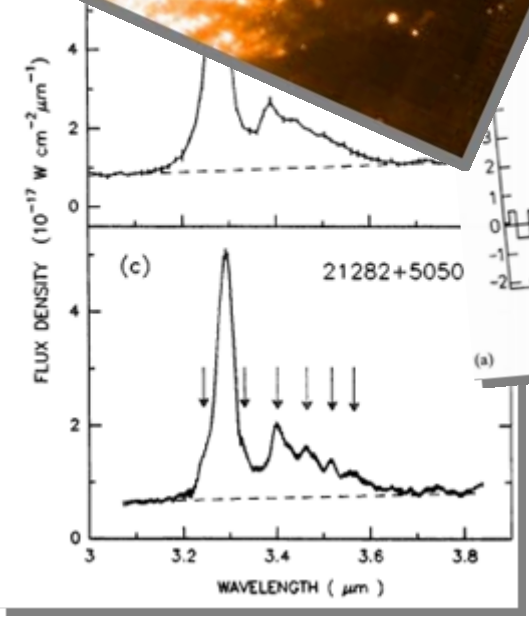
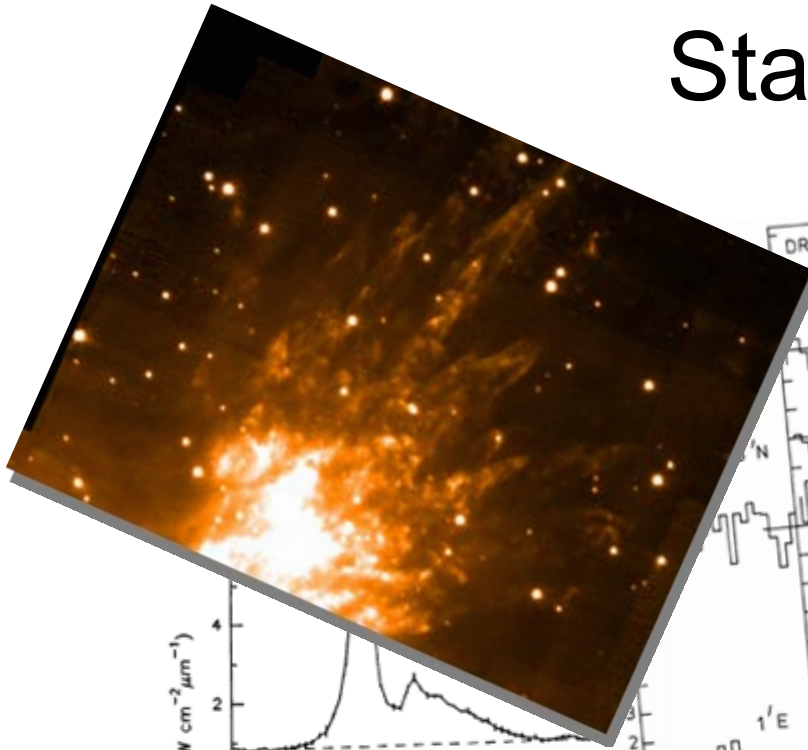


A somewhat biased view ~~30 years~~ of Star Formation at UKIRT

Chris Davis
(UKIRT/JAC)



UKIRT Schedule 89b - Staff Only

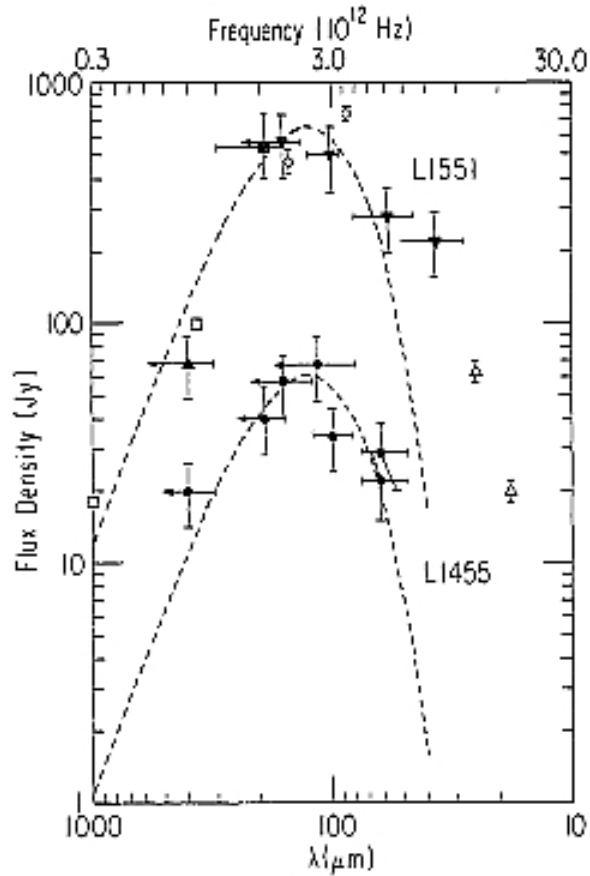
sep1989

Date	Day	Observers	Prog	Inst	SS	TSS	Comment	Moon	UT
1-Sep	Sat	Cowie,Gardner	U/H/1	IRCAM2(1,2)	Hawarden	Walther	-	-	2-Sep
2-Sep	Sun	"	"	"	"	"	-	-	3-Sep
3-Sep	Mon	"	"	"	"	"	-	-	4-Sep
4-Sep	Tue	"	"	"	"	Aycock	-	-	5-Sep
5-Sep	Wed	Geballe	AICDT	UKT16,CGS2,UKT9	Geballe	"	I2 warmup, filter chg	-	6-Sep
6-Sep	Thu	Strom	U/Q/32	UKT16,CGS2,UKT9	"	"	Morn. obs 0600-1000 (TRG)	-	7-Sep
7-Sep	Fri	"	"	"	"	"	"	-	8-Sep
8-Sep	Sat	"	"	"	"	"	"	-	9-Sep
9-Sep	Sun	Doyon,Wright	U/Q/56	IRCAM2(1.2),CGS2,UKT9	Wright	Wold	"	-	10-Sep
10-Sep	Mon	"	"	"	"	"	"	-	11-Sep
11-Sep	Tue	Hawarden	AICDT	-	Bailey	"	", move sec.	-	12-Sep
12-Sep	Wed	"	"	IRCAM1(0.6)?	"	"	-	-	13-Sep
13-Sep	Thu	Hawarden,Casali	"	IRCAM1(0.6)	"	"	Morn. obs 0600-1000 (TRG)	Full	14-Sep
14-Sep	Fri	Hough,Minchin	U/Q/16	IRCAM1(0.6)+Pol,CGS2	Aspin	Walther	"	-	15-Sep
15-Sep	Sat	"	"	"	"	"	"	-	16-Sep
16-Sep	Sun	"	"	"	"	"	"	-	17-Sep
17-Sep	Mon	"	"	"	"	"	"	-	18-Sep
18-Sep	Tue	Puxley	U/H/3	CGS2	Geballe	"	"	-	19-Sep
19-Sep	Wed	"	"	"	"	Wold	"	-	20-Sep
20-Sep	Thu	Chambers	U/Q/4	IRCAM1(0.6)	Casali	"	-	-	21-Sep
21-Sep	Fri	"	"	"	"	"	-	-	22-Sep
22-Sep	Sat	"	"	"	"	"	-	-	23-Sep
23-Sep	Sun	"	"	"	"	"	-	-	24-Sep
24-Sep	Mon	"	"	"	"	Walther	-	-	25-Sep
25-Sep	Tue	Dunlop	U/Q/14	"	Aspin	"	I2:Fell filters	-	26-Sep
26-Sep	Wed	"	"	"	"	"	-	-	27-Sep
27-Sep	Thu	"	"	"	"	"	-	-	28-Sep
28-Sep	Fri	"	"	"	"	"	-	New	29-Sep
30-Sep	Sat	Dunlop,Hughes	U/Q/29	"	"	Aycock	-	-	31-Sep
31-Sep	Sun	"	"	"	"	"	-	-	1-Sep

Key to Background Colours

PATT	UKIDSS	Japan	Korean	Engin.	Serv/DDT	CMP	UH
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Photometry of young stars

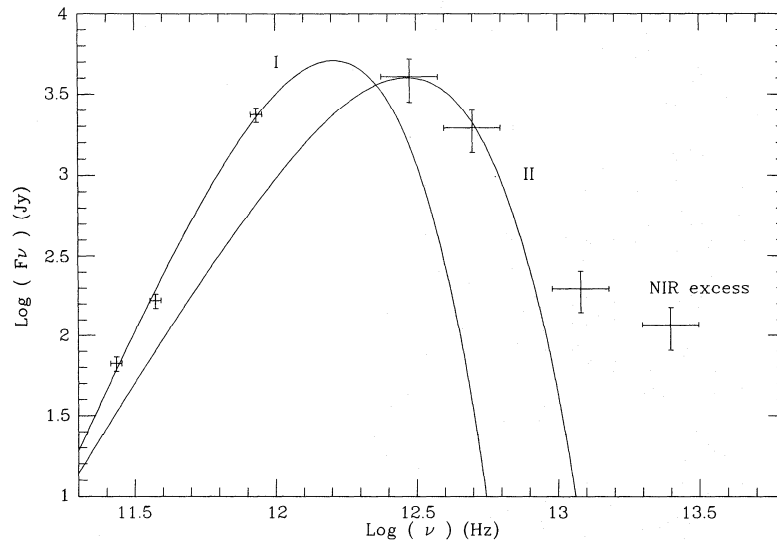


Davidson & Jaffe 1984, ApJ, 277, L13

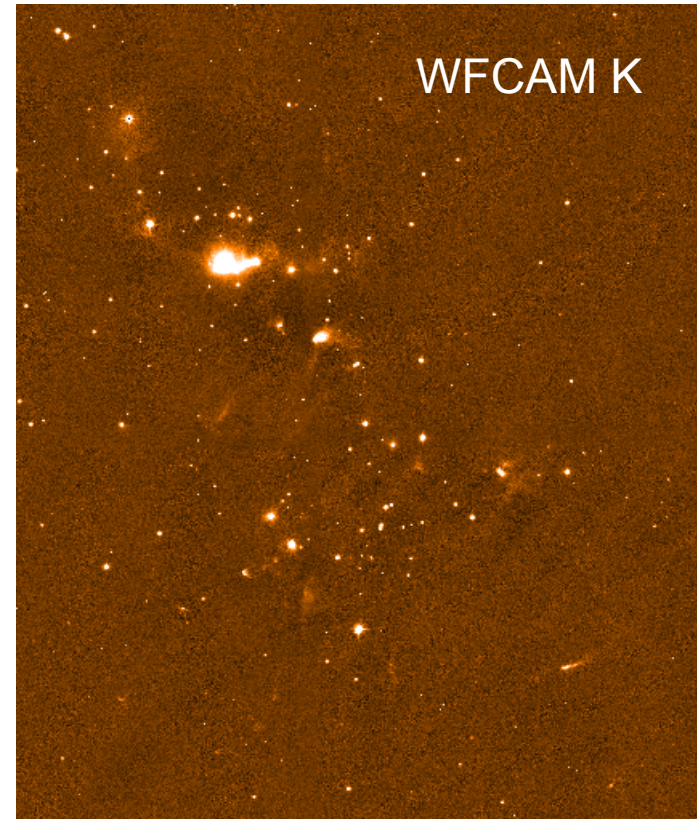
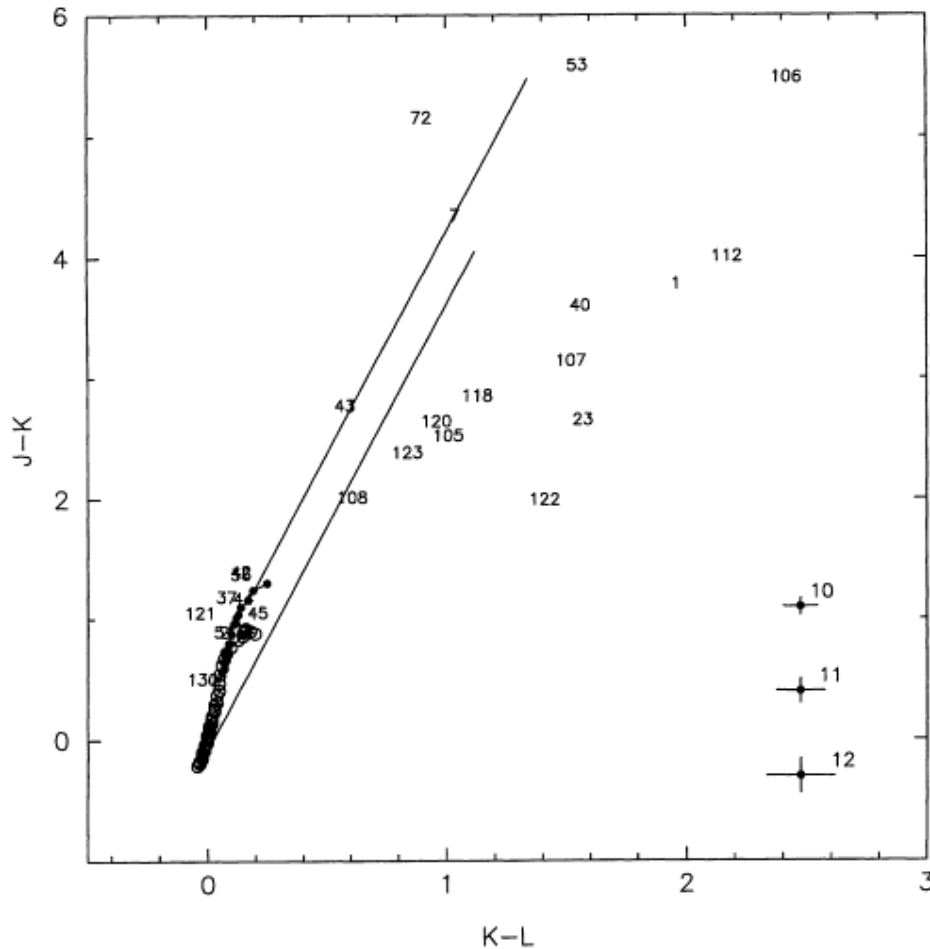
- UKIRT with the Univ of Chicago f/35 SMM photometer (+ KAO); photometry at 400 μm from November 1981.

Ward-Thompson, Robson, Whittet, Gordon, Walther, Duncan, 1989, MNRAS, 241, 119

Submm photometry (UKT14) and near-IR spectroscopy (CGS2) of ρ Oph



Photometry of young stars



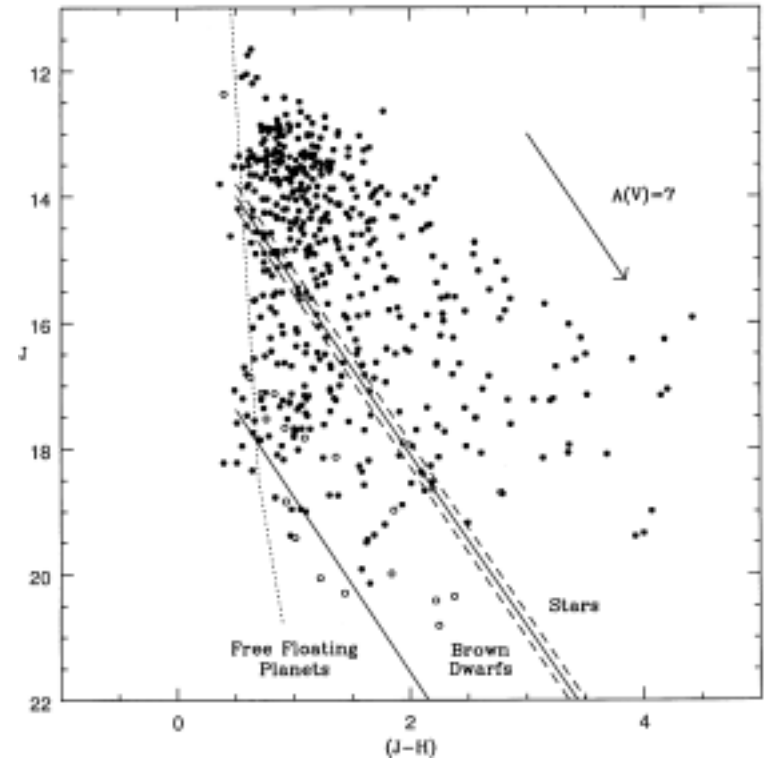
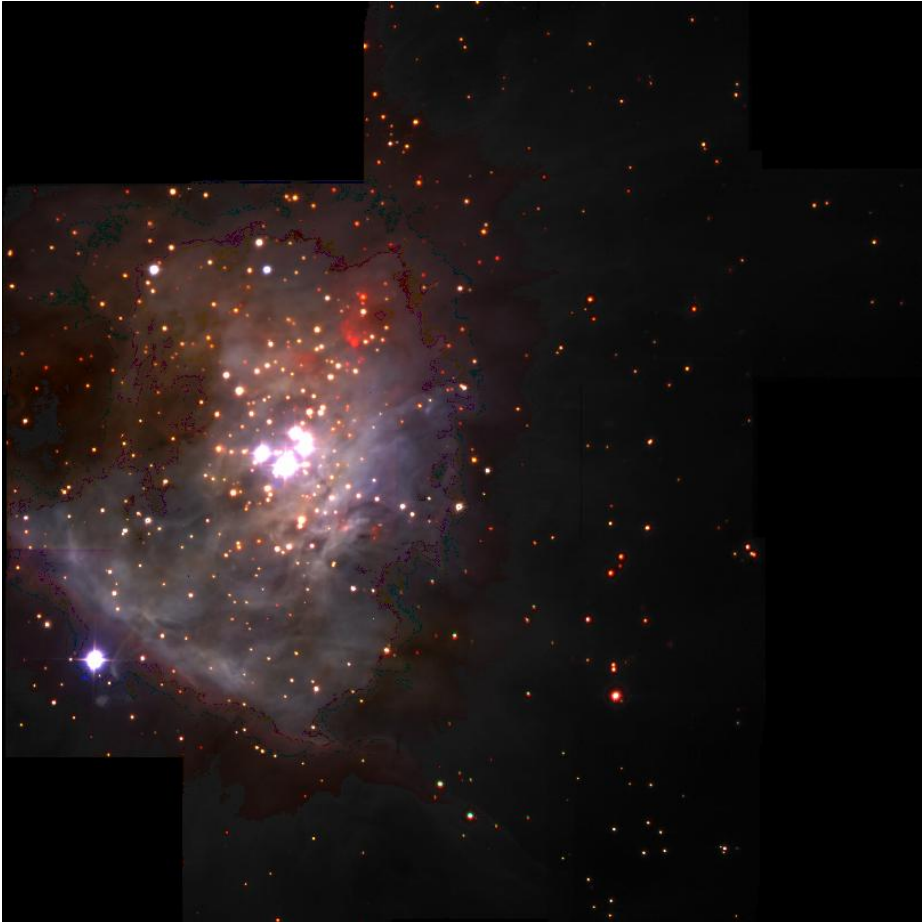
Aspin, Sandell, Russell, 1994, A&A, 106, 165;
Aspin, Sandell, 1997, MNRAS, 289,1
- UKIRT IRCAM imaging of **NGC 1333**;
- JHKL C-C diagrams; importance of mid-IR.
(CGS4 spec follow-up in **Aspin, 2003.**)

Eiroa & Casali, 1992, A&A, 262, 468 - JHKL photometry of **Serpens** cluster (IRCAM)

Aspin & Barsony, 1994, A&A, 288, 849 - JHKL photometry of red sources in **LkH α 101** (IRCAM)

Carpenter, Meyer, Dougados, et al. 1997, AJ, 114, 198 - JHKL in **Mon R2** cluster (IRCAM3/CGS4)

Photometry in Orion



Lucas & Roche, 2000, MNRAS, 314, 858

- UKIRT +UFTI IJH photometry in **Orion**
- search for young brown dwarfs and “free floating” planets in the Trapezium cluster.

Lucas et al., 2008, MNRAS, 391, 136

- UKIDSS GPS paper

Photometry with WFCAM and ...

Spitzer

Kumar et al., 2007, MNRAS, 374, 54

WFCAM+Spitzer photometry of YSO population in DR21/W75

- Extinction maps
- Surface density plots
- Distribution of young stars w.r.t. dense cores and filaments

Luhman et al. 2008, ApJ, 688, 362

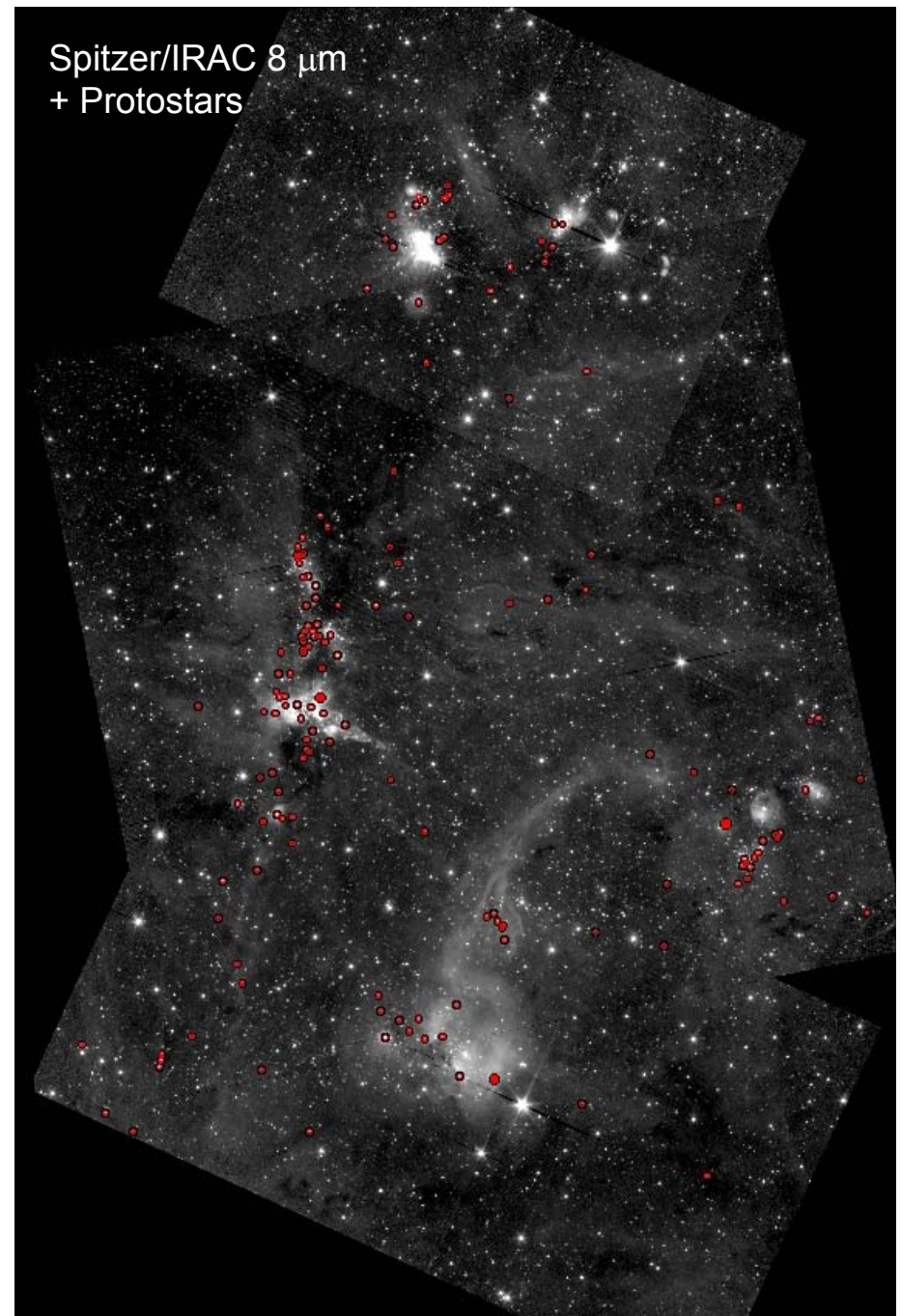
WFCAM+Spitzer to search for disks around BDs in Orion

Chandra

Wright & Drake, 2008, ApJS, 184, 84

WFCAM colours of Chandra X-ray sources in massive SF region Cyg OB2

- Near-IR counterparts to 1500 sources

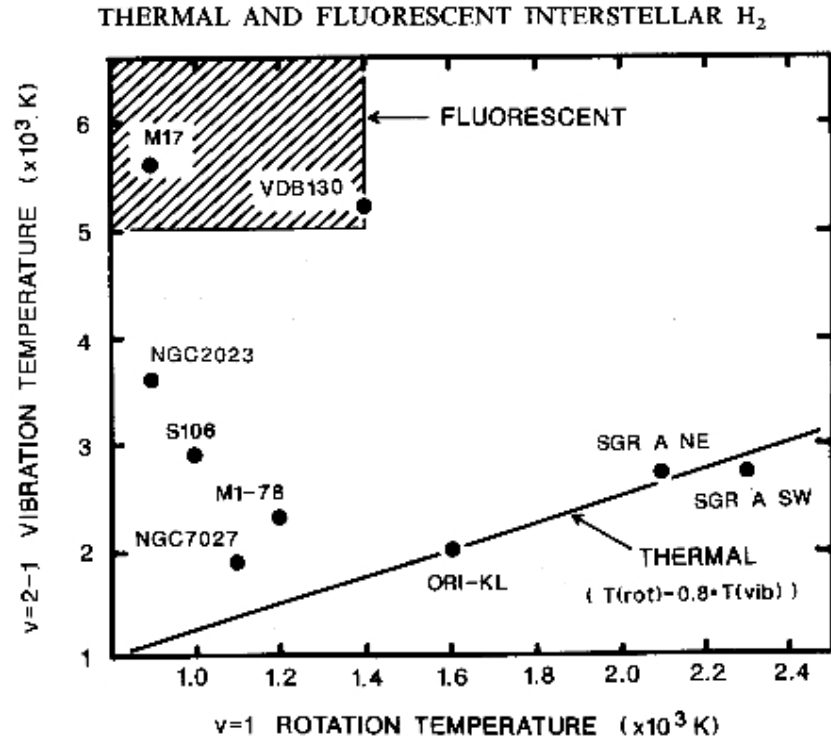
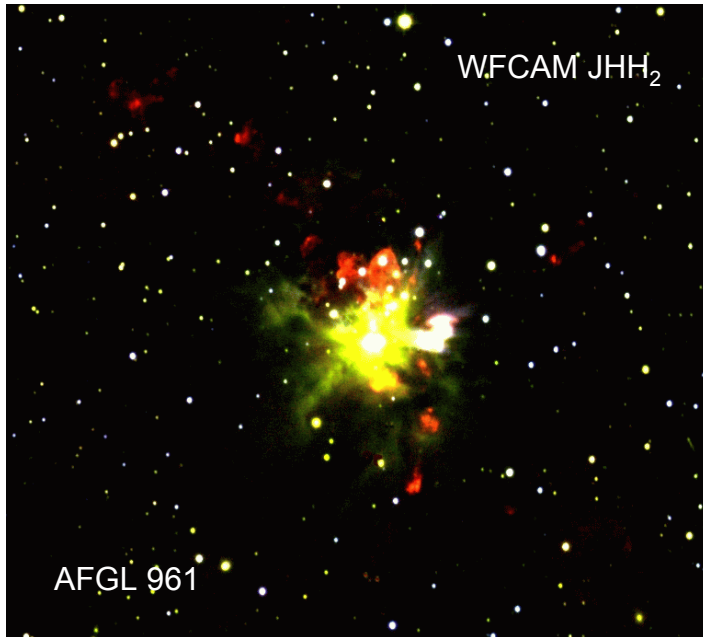


Variability Studies



Alves de Oliveira & Casali, 2008, A&A, 485, 155 (Oph - 14 epochs sampling days/months)
Ongoing: Aspin et al. (Cyg OB7), Reipurth et al. (Orion), Stauffer et al. (Orion - WFCAM/Spitzer)

Excitation and the ISM in Star Forming clouds

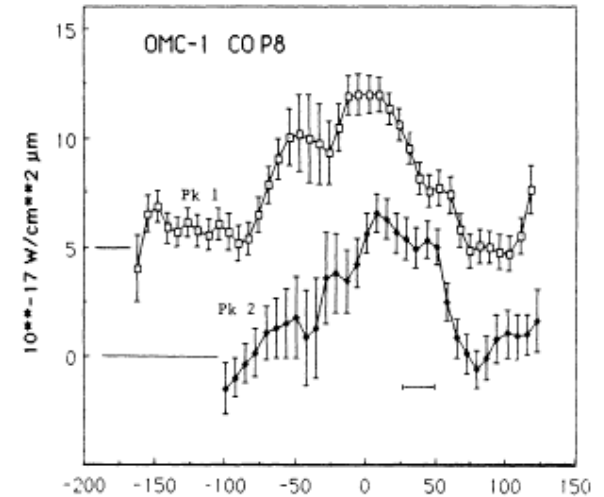
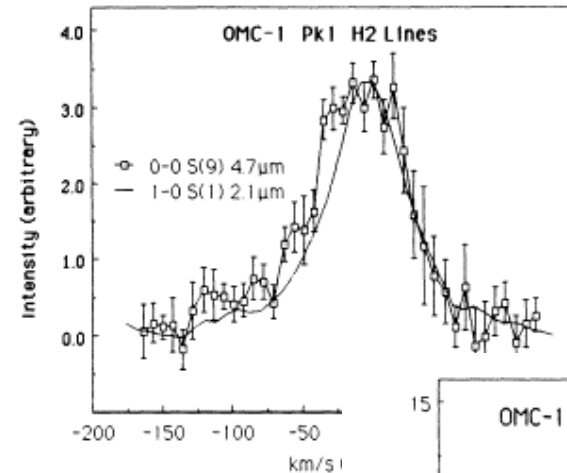
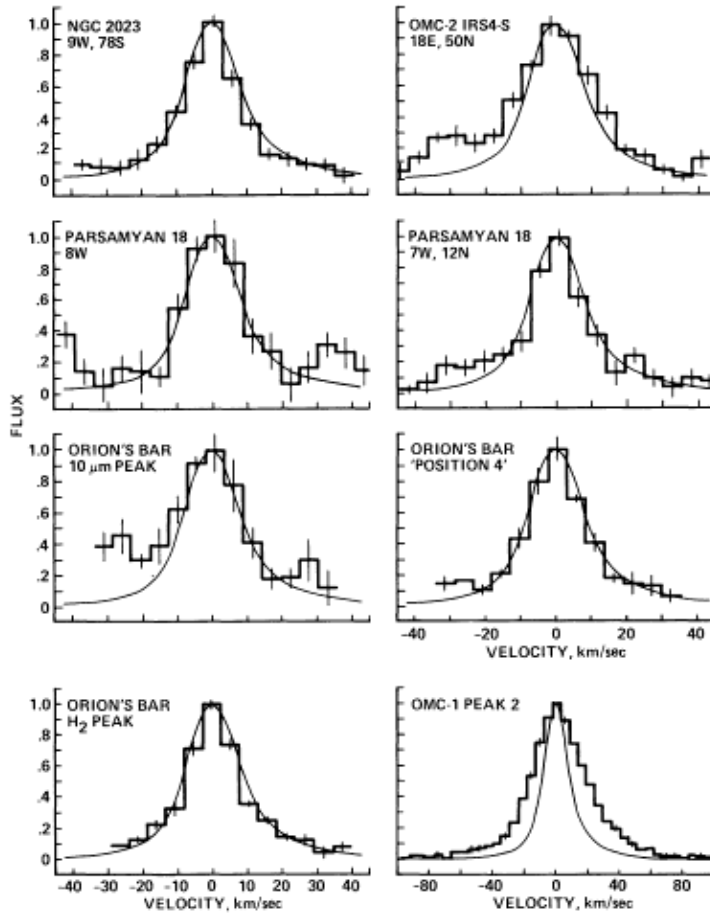


Tanaka, Hasegawa, Hayashi, Brand & Gatley 1989, ApJ, 36, 207
(Gatley et al. 1987; Hasegawa et al. 1987 - earlier UKIRT obs on H₂ excitation...)

Used UKT9 + CVF (order sorter) + FP (scan across lines at spec resoln. ~ 130 km/s).
H₂ line ratios in a variety of Galactic Sources; assess relative contribution of shock versus fluorescent excitation.

Molecular line profiles

FLUORESCENT MOLECULAR HYDROGEN



Burton, Geballe, Brand, Moorhouse,
1990, ApJ, 352, 625

H₂ 1-0S(1) with FP + CVF (1988)

Narrow lines @ 0 km/s - **fluorescence**

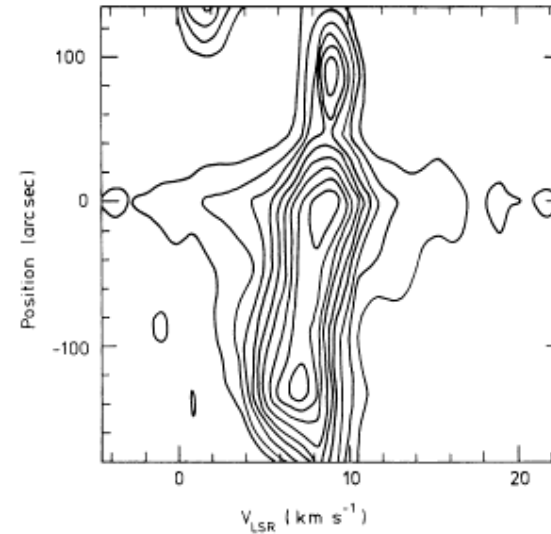
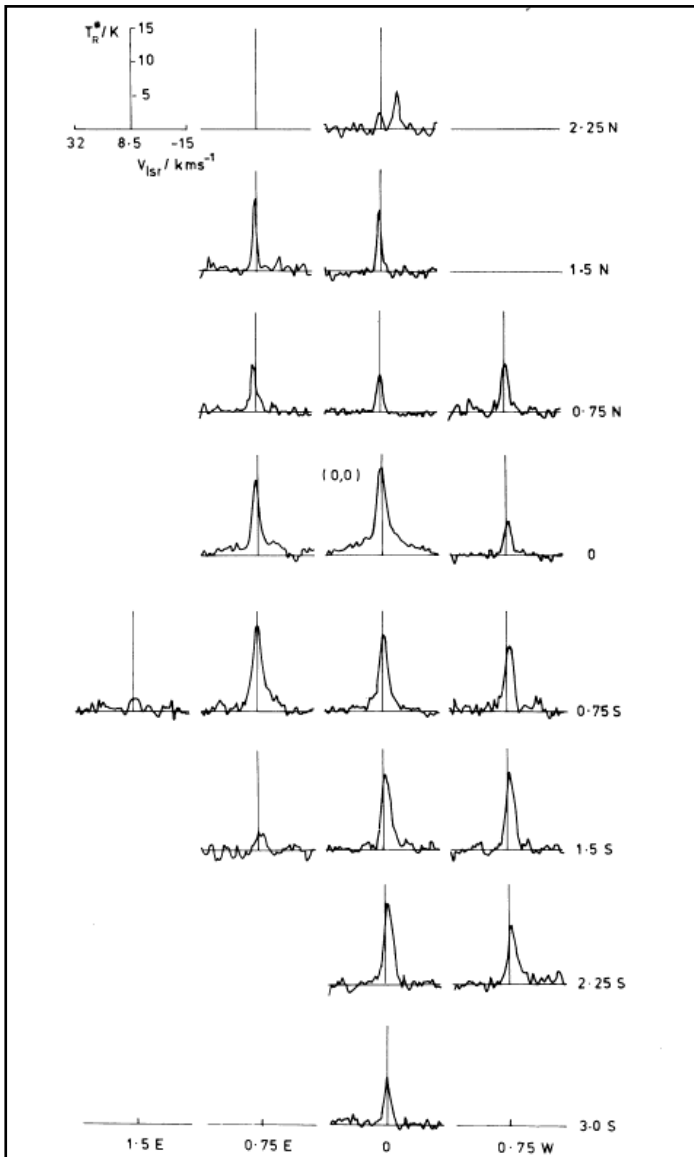
Geballe & Garden, 1990, ApJ, 365, 602

4.7mm CO 1-0P(8) and H₂ 0-0S(9)

Complement earlier near-IR spectroscopy.

Broad lines - **shocked**.

Molecular line profiles (at submm wavelengths)

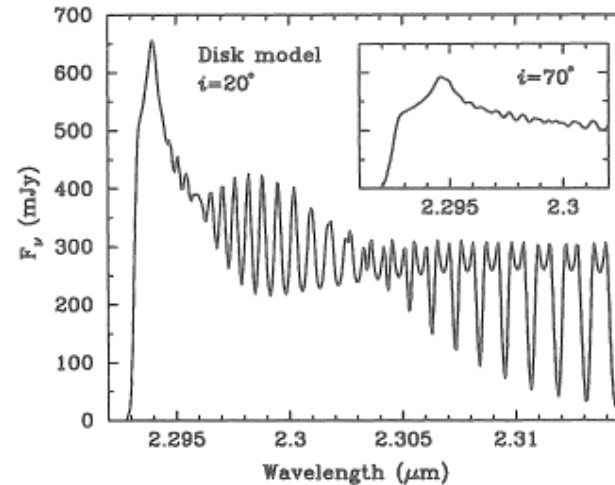
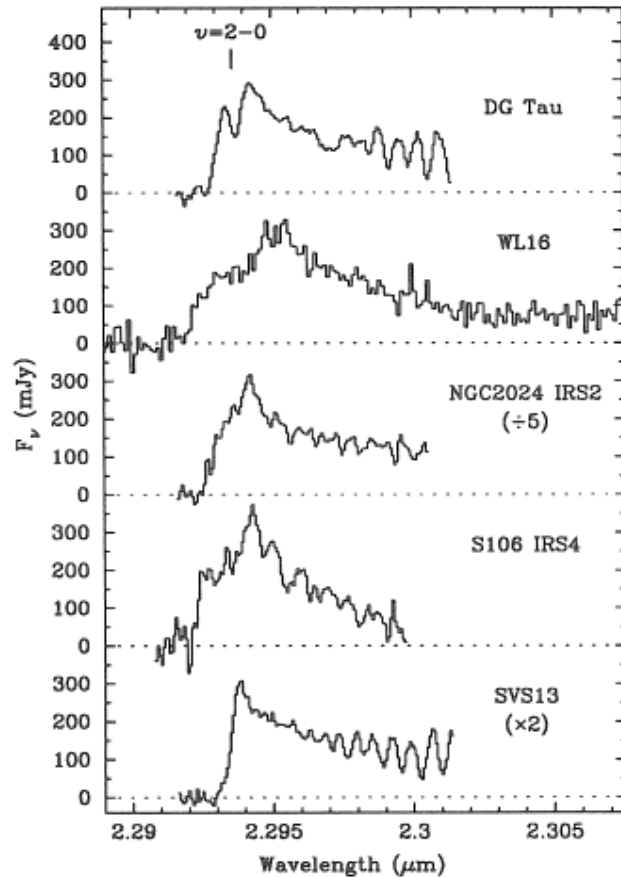


**Padman, Scott, Vizard, Webster, 1984,
MNRAS, 214, 251.**

Heterodyne receiver "A" (1983) -
CS 5-4 in OMC-1.

Cold, clumpy, high-velocity doughnut.

Accretion and Outflow



Chandler, Carlstrom, Scoville, Dent, Geballe, 1990, ApJ, 412, L71 (see also Chandler et al., 1995, ApJ, 446, 793)

- UKIRT CGS4 spectroscopy of embedded YSOs - CO as a disk tracer...

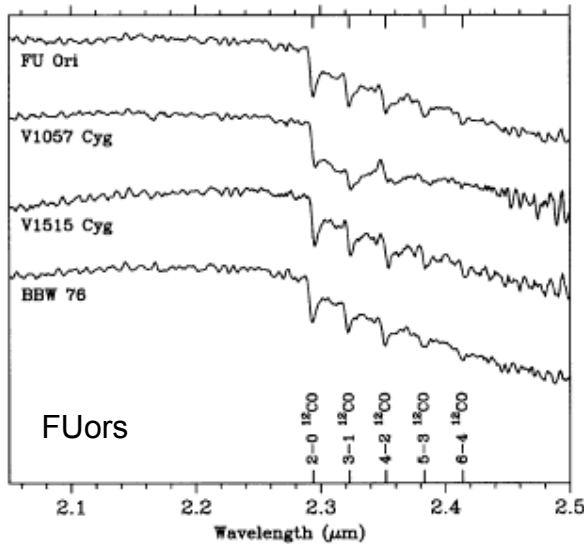
Casali & Matthews, 1992, MNRAS, 258, 399

- □ CO absorption in YSOs

Aspin 1994, A&A, 281, L29

- Scattered CO bands in **GGD-27** massive YSO

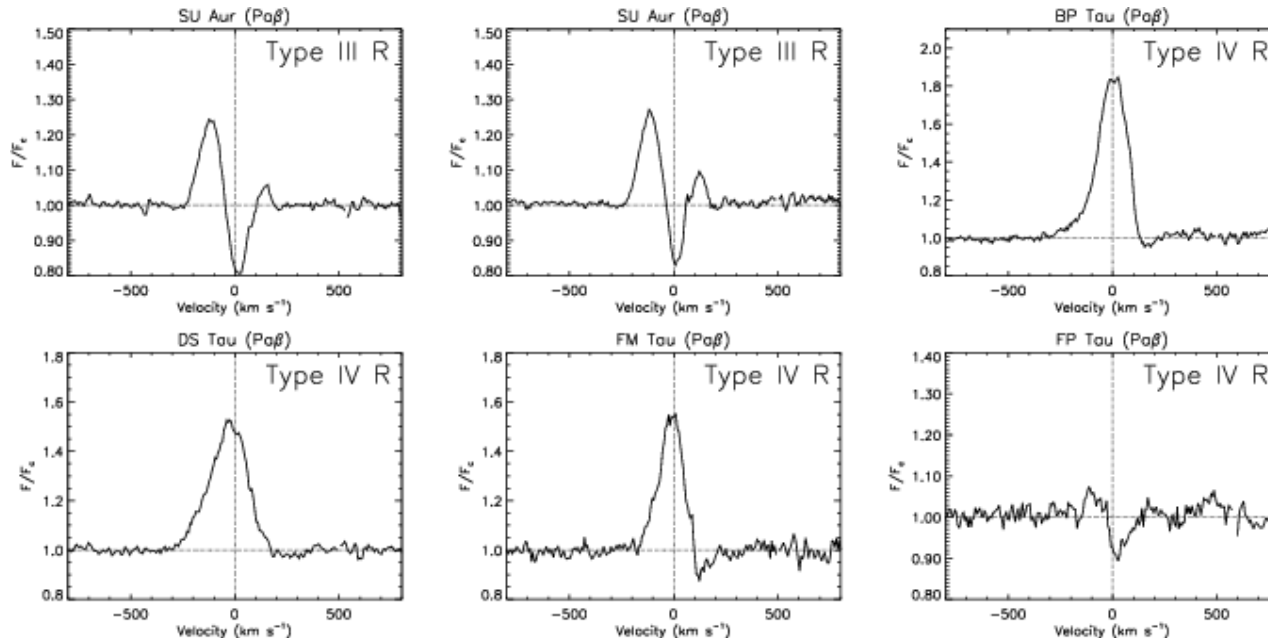
Accretion and Outflow



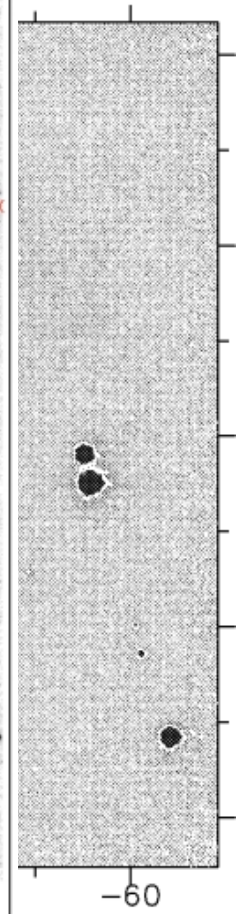
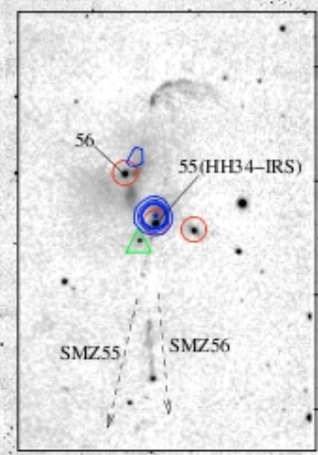
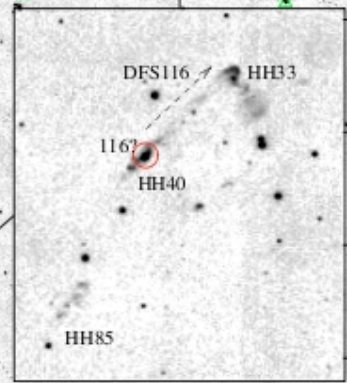
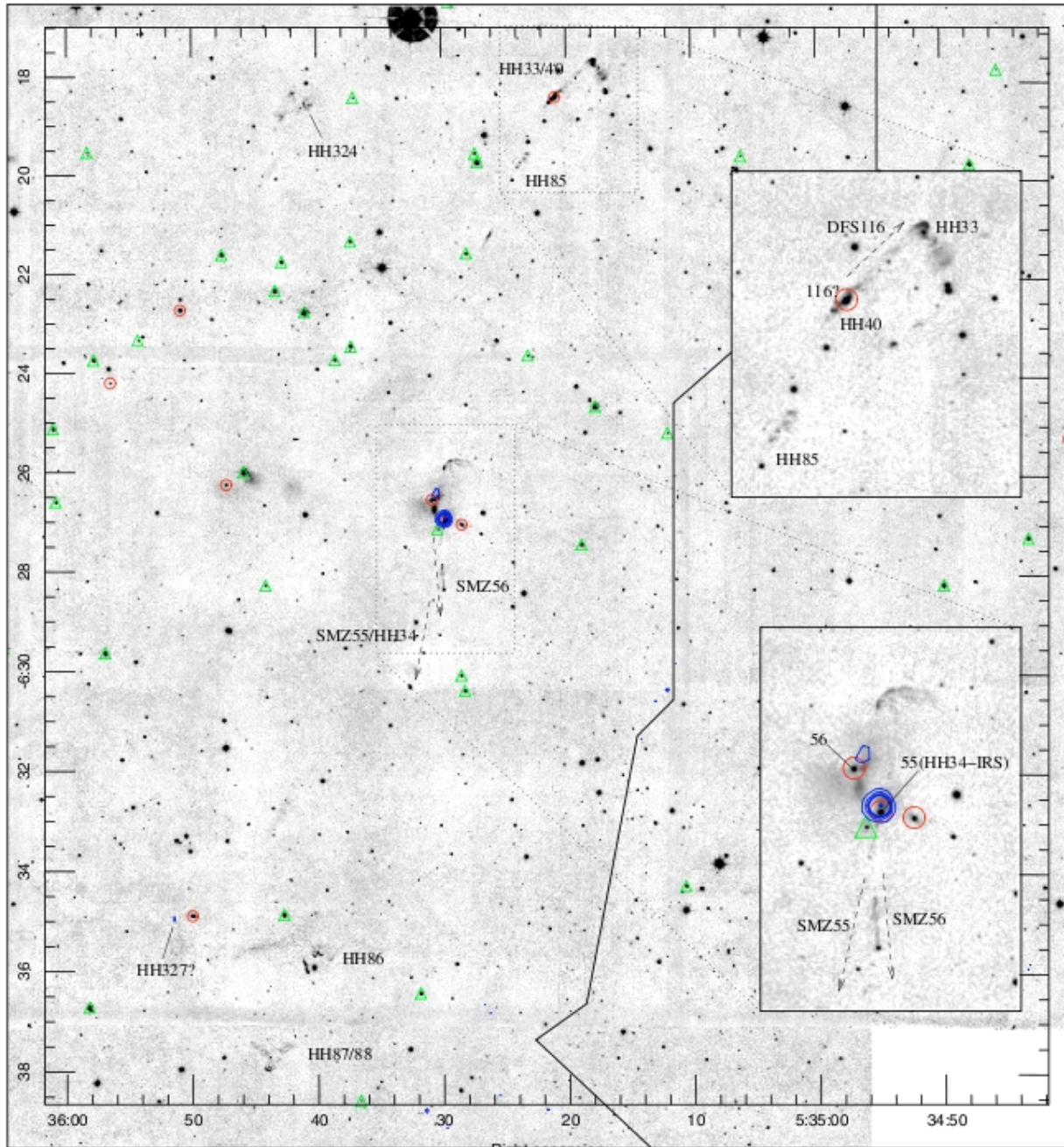
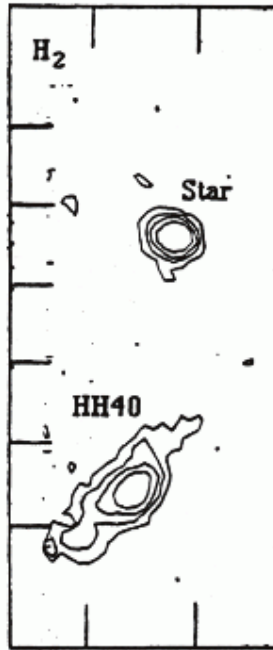
Reipurth, Aspin, 1997, AJ, 114, 6 (left)
CGS4 K-band survey of embedded outflow sources

Folha, Emerson, 2001, A&A, 365, 90 (below)
CGS4 echelle spectroscopy of 50 T Tauri stars; using Pa β and Br γ profiles to probe accretion and outflow.

Sheret, Ramsay Howat, Dent, 2003, MNRAS, 343, L65,
Search for pure-rotational H₂ in disk of two PMS stars with Michelle; found “some indication” of 4-2 emission at 12.2 μm in AB Aur; upper limits in 3-1.

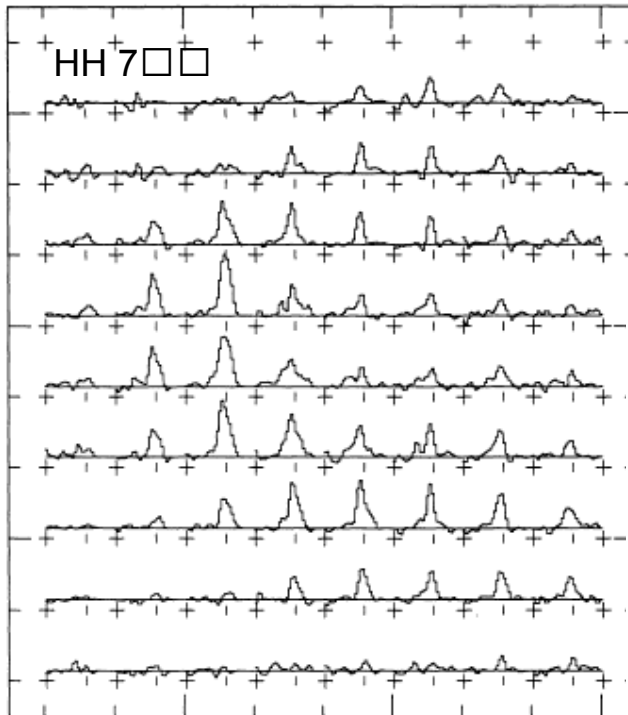


Inverse P Cygni profiles - magnetic accretion and infall at 100s of km/s.



Zealey, Williams
 1992, AA, 262, 5
 Chrysostomou,
 Berndsen, 2000,
 Davis, Froebrich
 et al., 2009, AA, 49
 UKIRT - IRCAM/I

Accretion and Outflow

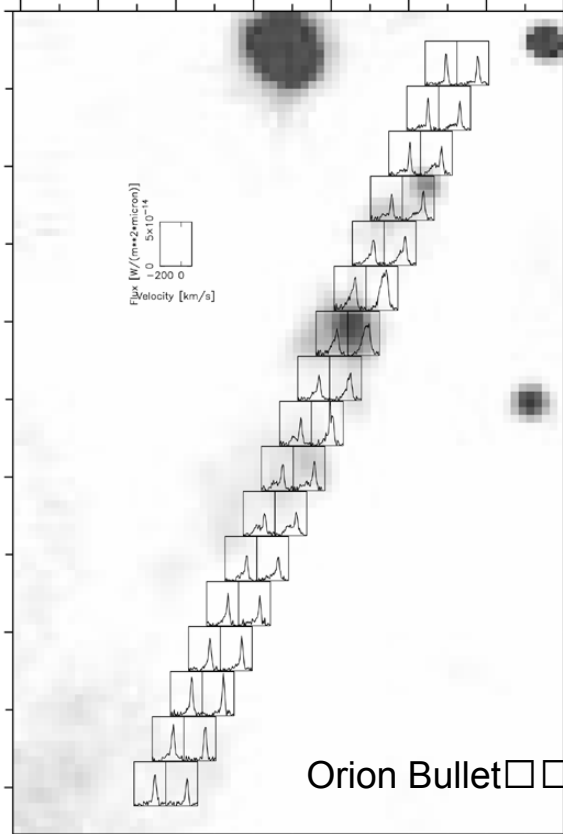
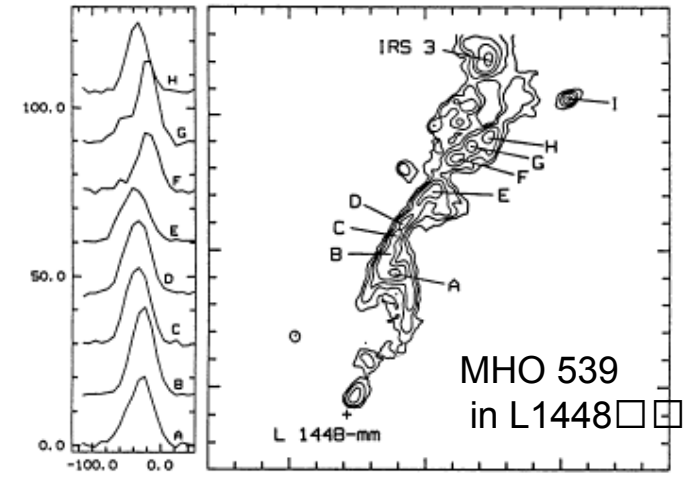


Carr, 1993, ApJ, 406, 553

- IRCAM + 1% NB filter + FP,
 $\Delta v \sim 25$ km/s - **HH 7-11 (above)**

Chrysostomou et al., 1997

- FP spectra in **OMC-1**



Orion Bullet

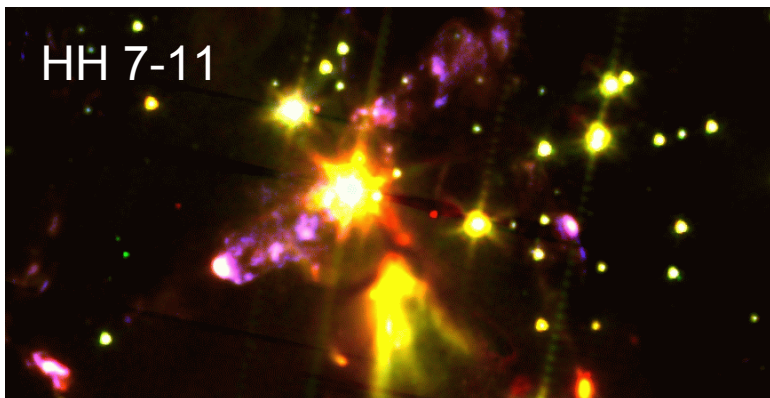
Davis & Smith 1996, A&A, 309, 929

- CGS4 + echelle H_2 profiles mapped across **MHO 539**; comparison with “Smith” bow models

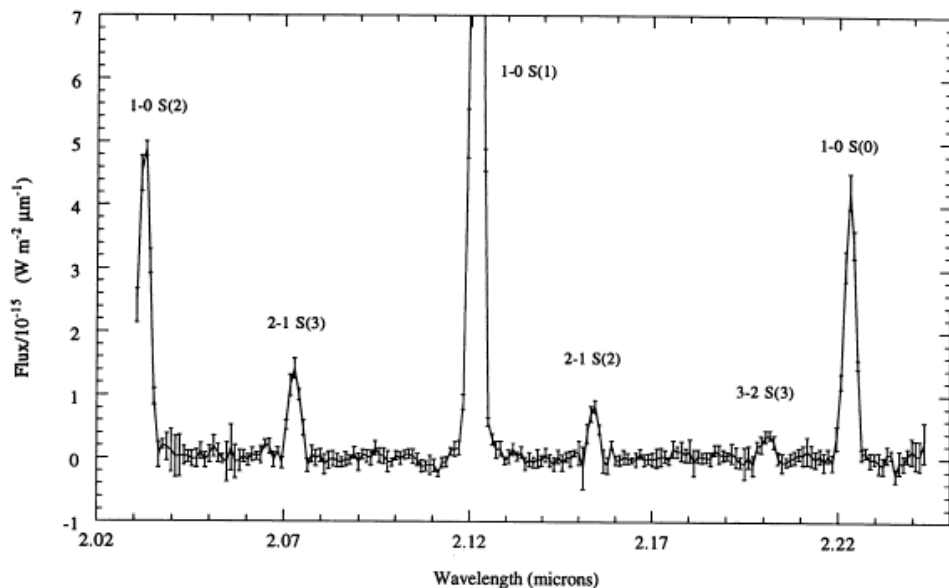
Tedds, Brand & Burton 1999, MNRAS, 307, 37

CGS4+ echelle H_2 and [FeII] profiles mapped across two **Orion Bullets**; comparison with bow models.

Accretion and Outflow



H₂ spectrum at the HH7 emission peak: first grating position



Fernandes, Brand, 1995, MNRAS, 274, 639
 CGS4 low-res spec of **HH 7**; Shocks + fluorescence!
 Fernandes, Brand, Burton, 1997 - **DR21**...

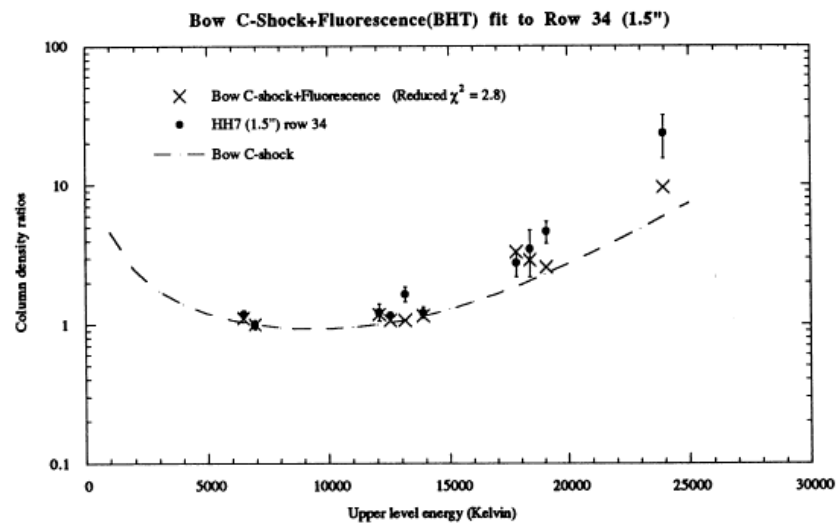
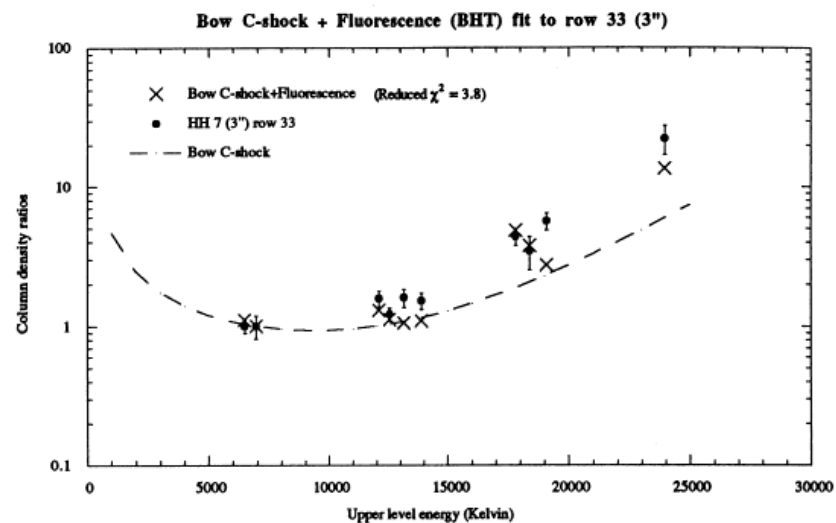
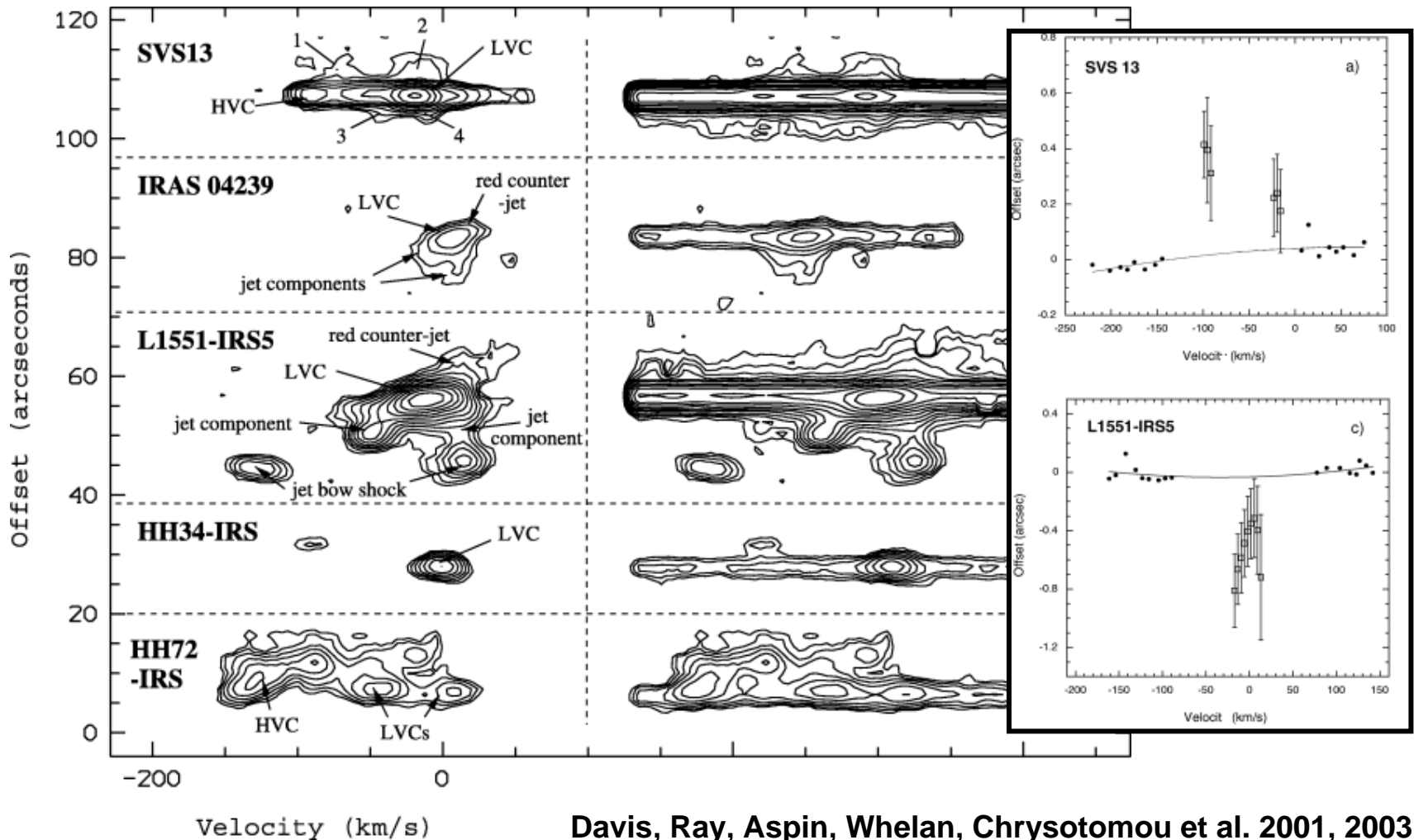


Figure 12. As Fig. 11, but for 1.5-arcsec data.



Accretion and Outflow

(Spectro-astrometry and Integral Field Spectroscopy)



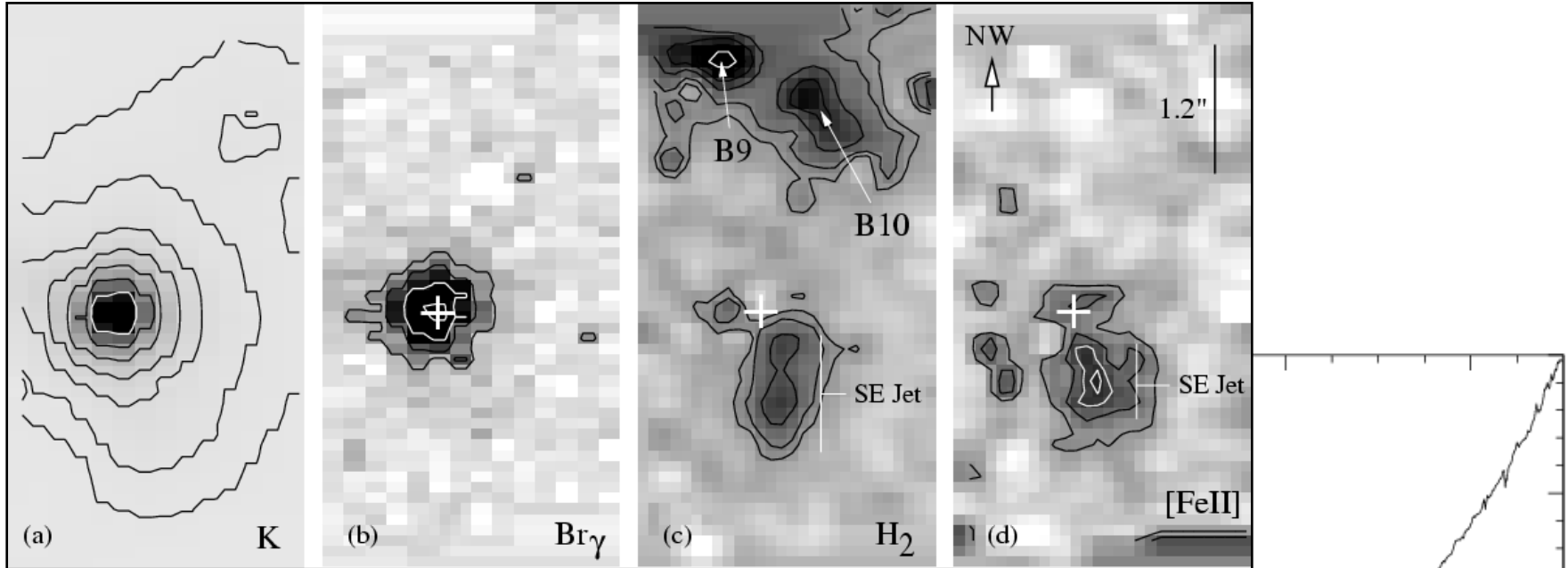
Velocity (km/s)

Davis, Ray, Aspin, Whelan, Chrysotomou et al. 2001, 2003.
 UKIRT CGS4 spectroscopy of embedded YSOs in H₂ and [FeII].

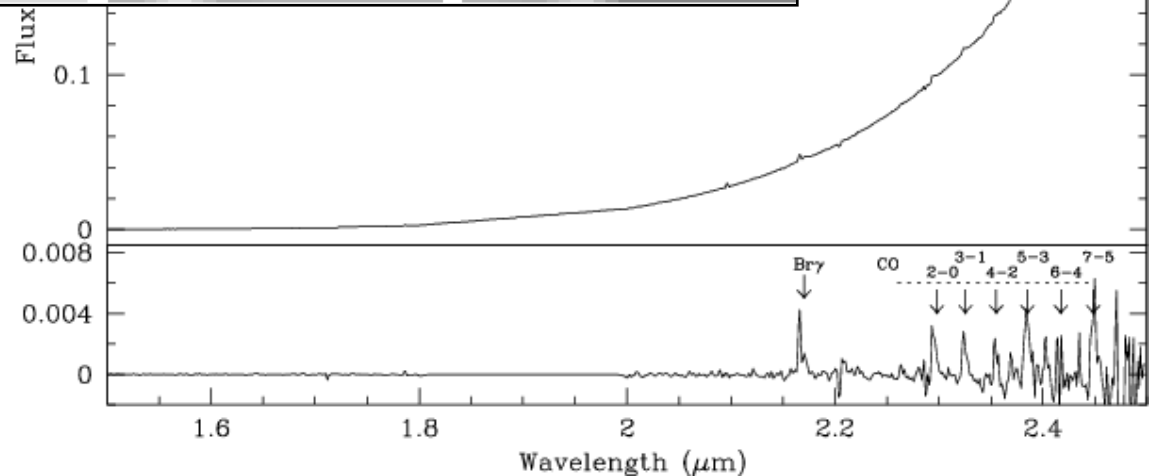
(See also spectro-astrometry in Pa β in T Tauri stars; Whelan et al. 2004, A&A, 417, 247)

Accretion and Outflow

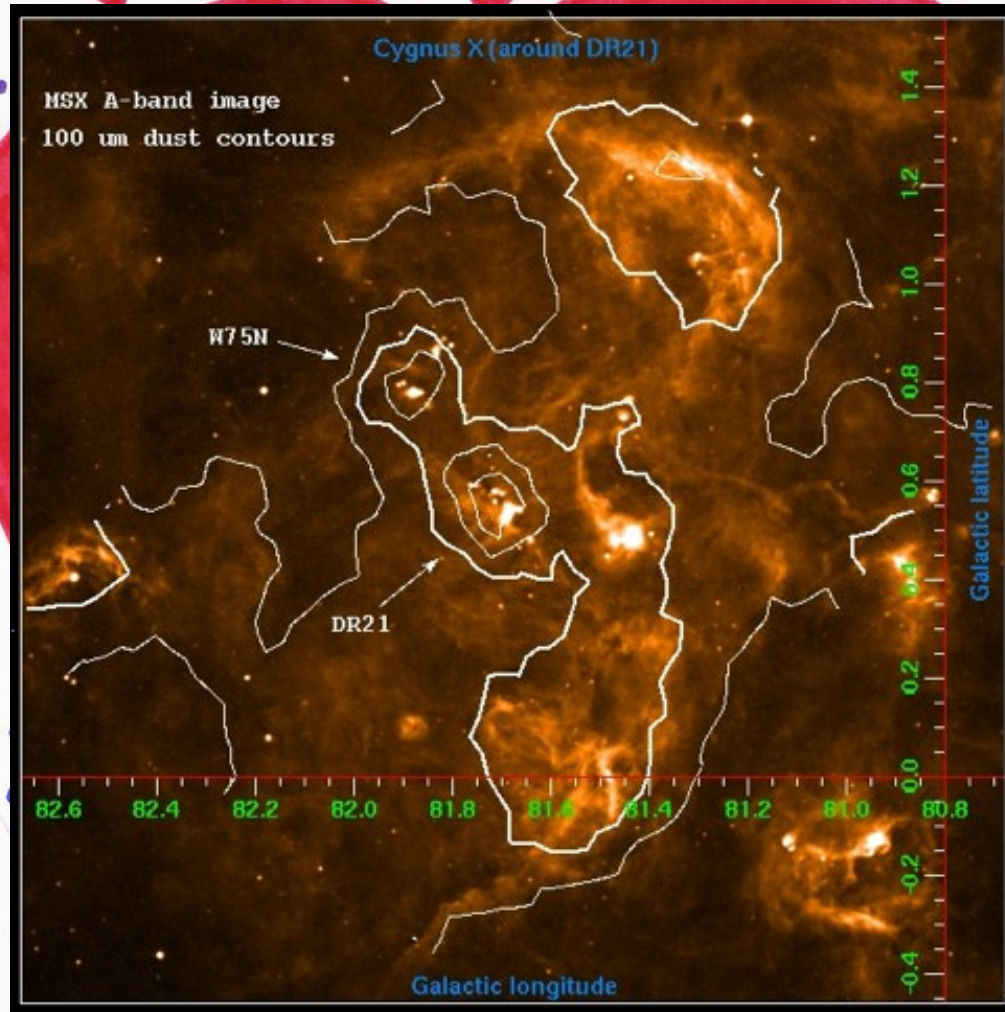
(Spectro-astrometry and Integral Field Spectroscopy)



Davis, Varricatt, Todd,
Ramsay Howat, 2004, A&A,
425, 981
UKIRT UIST HK IFU
spectroscopy (+ CGS4 echelle
spectroscopy) of **MHO 2201**
outflow source

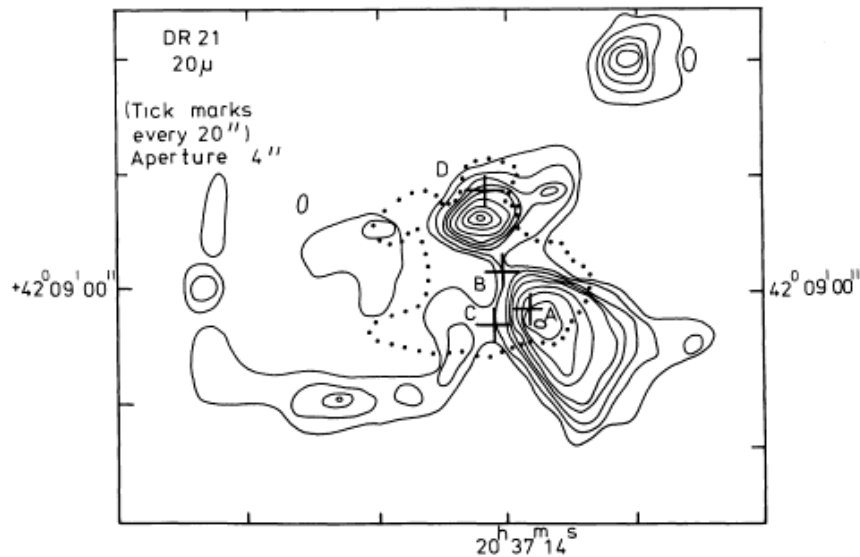


Massive Star formation; UKIRT's love affair with DR 21...



Massive Star formation - DR 21...

Far-IR spectroscopy + continuum mapping

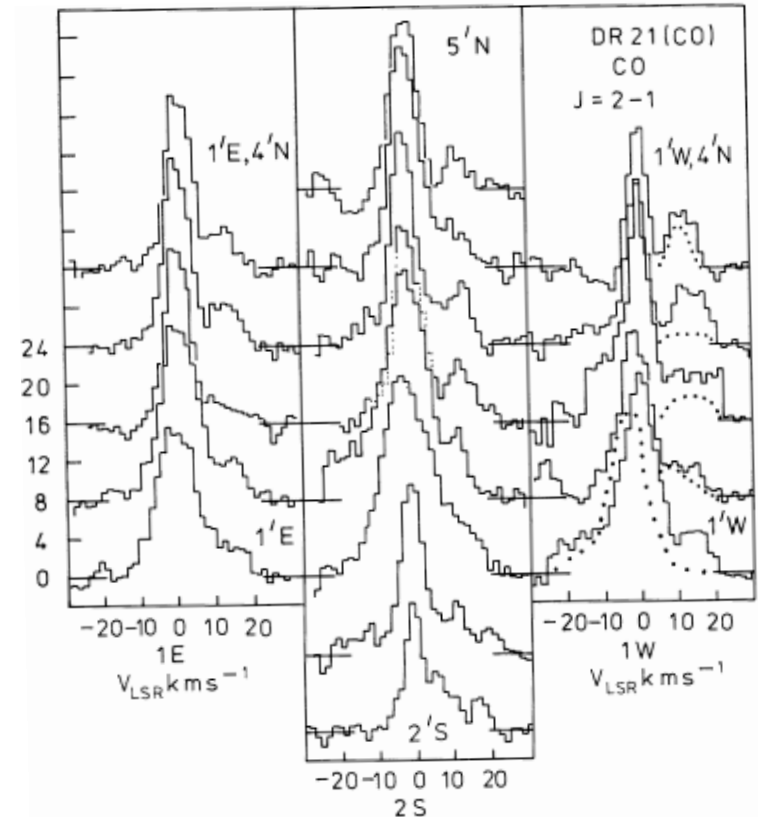


**Richardson, White, Phillips, Avery, 1986,
MNRAS, 219,167**

CO 2-1, CO 3-2, HCN 4-3, HCO⁺ 4-3, H¹³CO⁺
4-3, CS 7-6 + continuum obs at 20 μ m and 300 μ m !!!

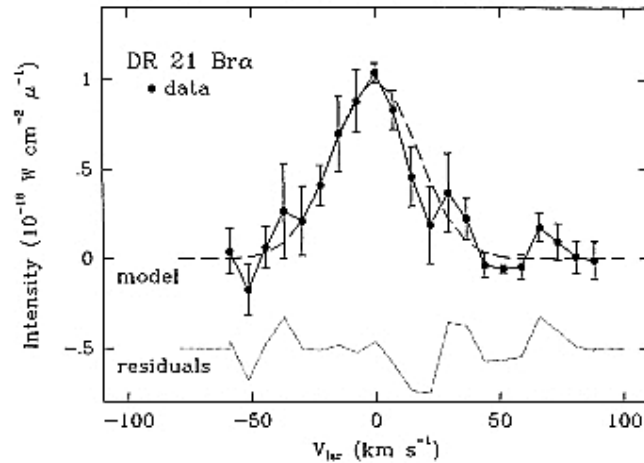
Data acquired in 1982/1983 with the UKIRT and QM
college bolometers.

Map the high velocity gas and model the distribution of ambient material...



Massive Star formation - DR 21...

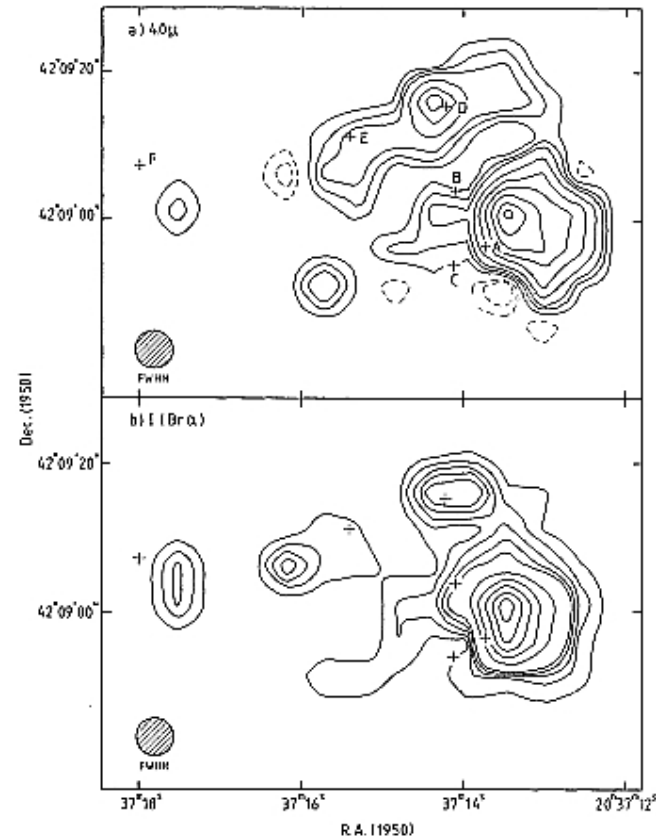
Mid-IR spectroscopy



Roelfsema, Goss & Geballe 1989, AA, 222, 247

High-res spec using CGS2+FP (1984).

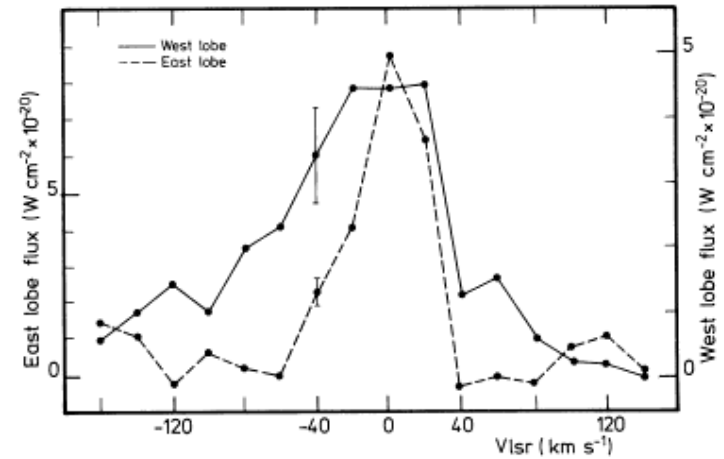
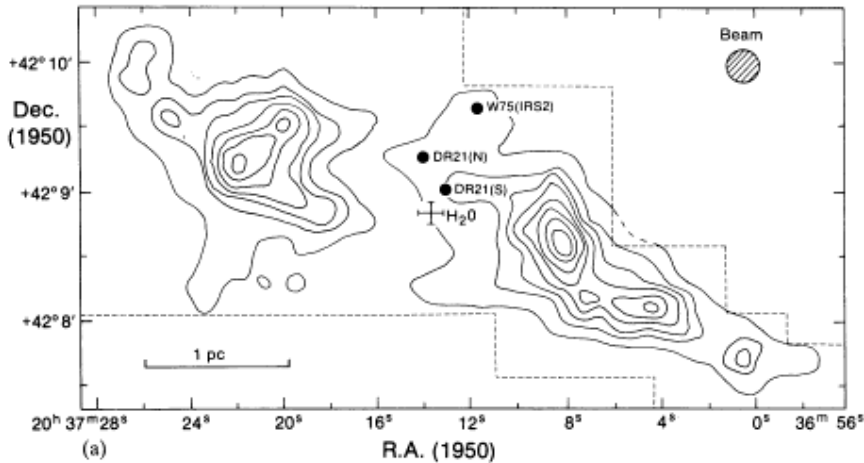
Mapped extinction across the region and provide a detailed description of physical state of ionised gas.



4 μ m continuum (top) and Br α (bottom)
Obtained with UKIRT

Massive Star formation - DR 21...

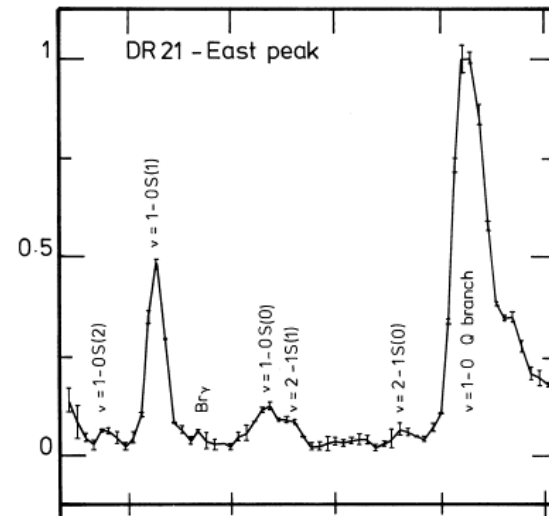
Near-IR imaging and spectroscopy



Garden, Geballe, Gatley, Nadeau, 1986,
MNRAS, 203, 221

Narrow-band imaging using a 130 km/s FP and a CVF filter; frequency switching (every 3 sec) with sky sampled every 10 points. Map built up over 400 points. (1984)

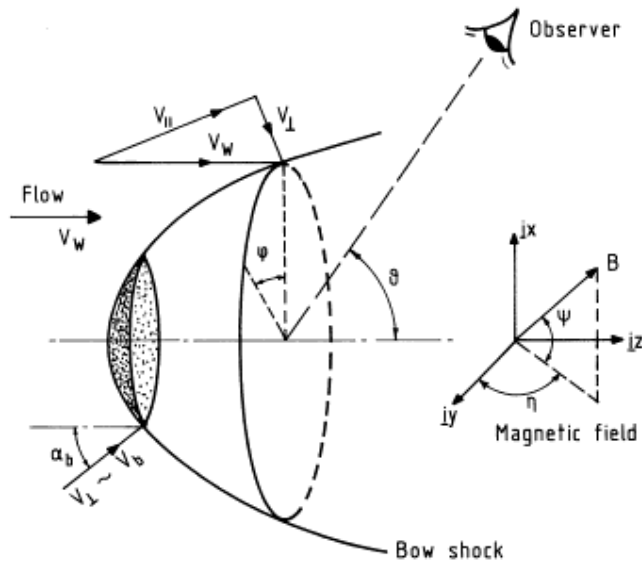
Prior to these observations, only **OMC-1** had been studied in this way...



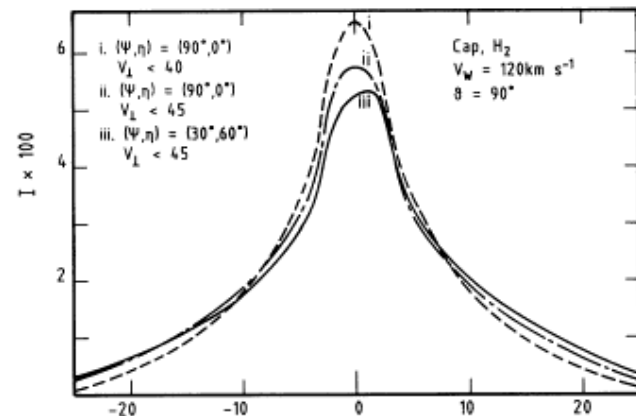
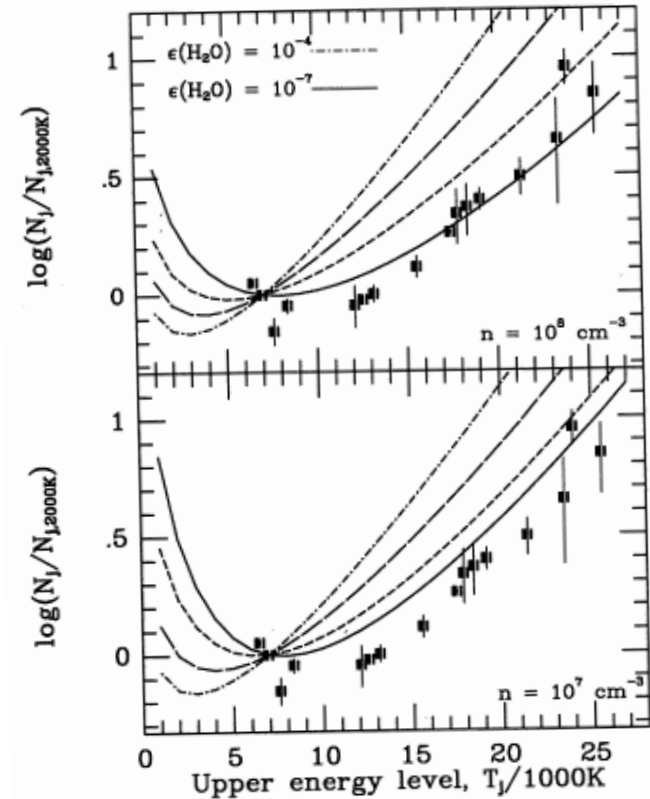
Massive Star formation

- DR 21 (and OMC-1...)

Near-IR modelling!

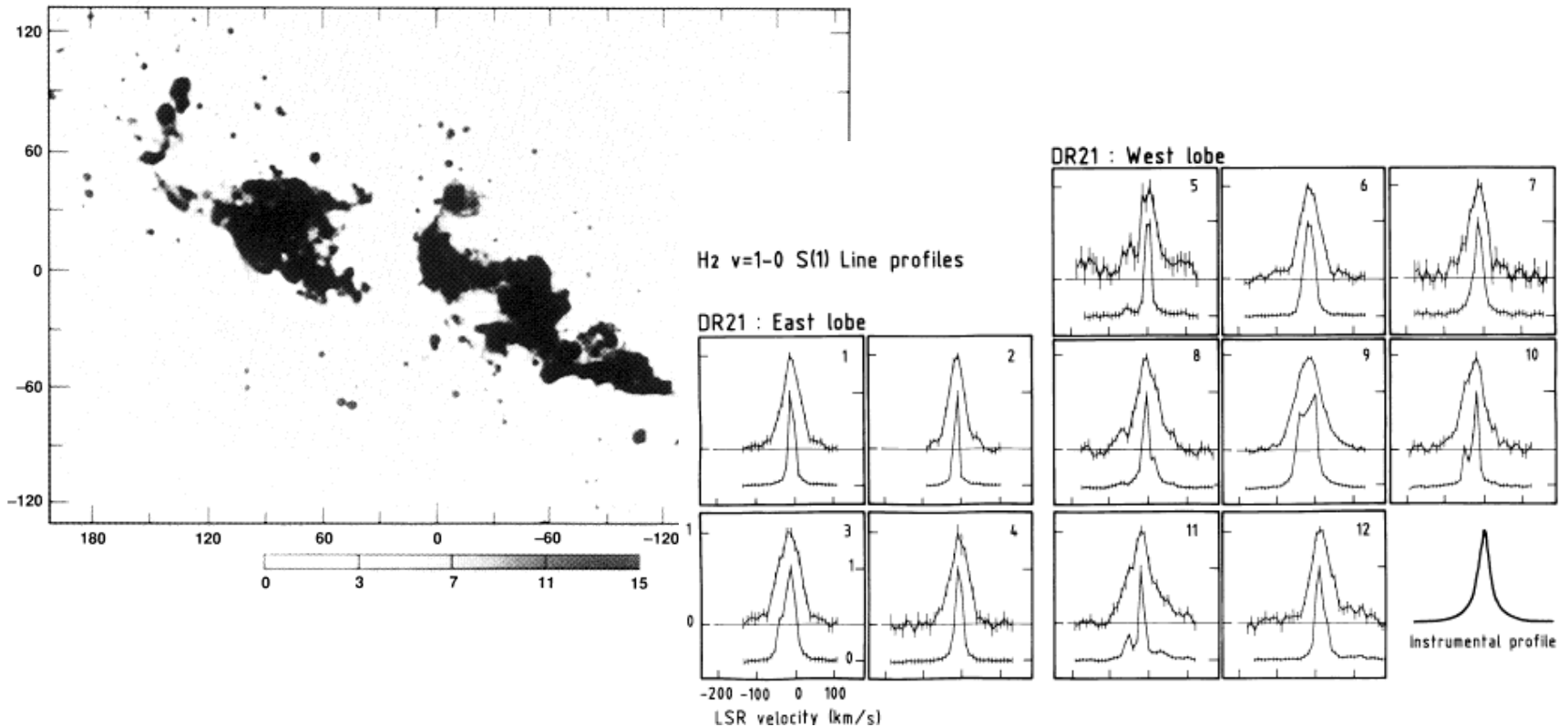


Smith & Brand 1990a, MNRAS, 203, 221
 Smith & Brand 1990a, MNRAS, 242, 495
 Smith & Brand 1990c, MNRAS, 245, 108
 Smith, Brand & Moorhouse 1991a, 248, 451
 Smith, Brand & Moorhouse 1991b, 248, 730
 Smith, 1994, MNRAS, 266, 238
 and then some!



Massive Star formation - DR 21...

Real near-IR imaging and spectroscopy

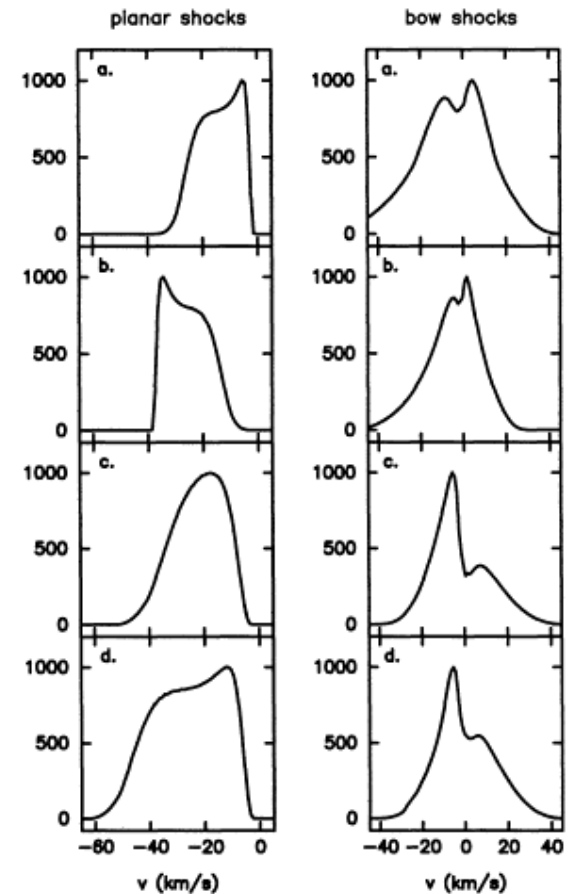
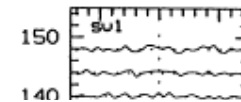
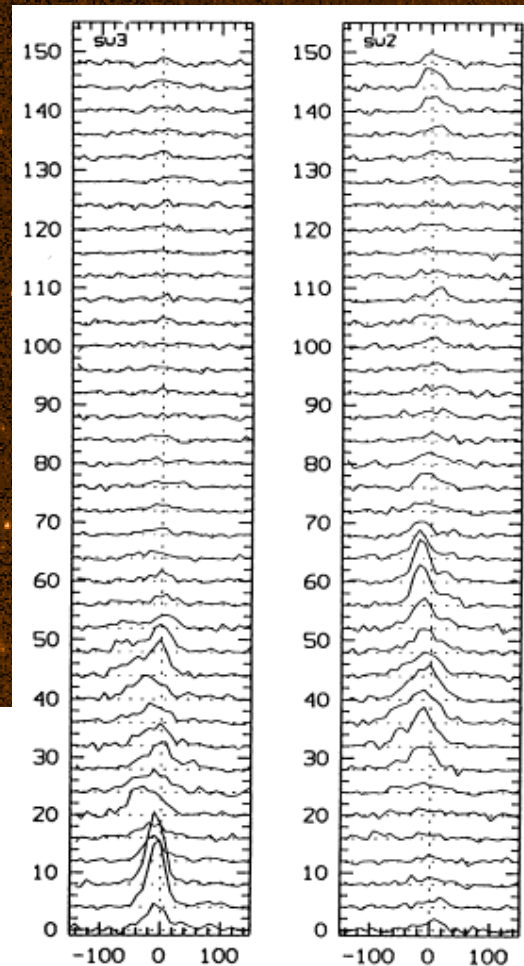
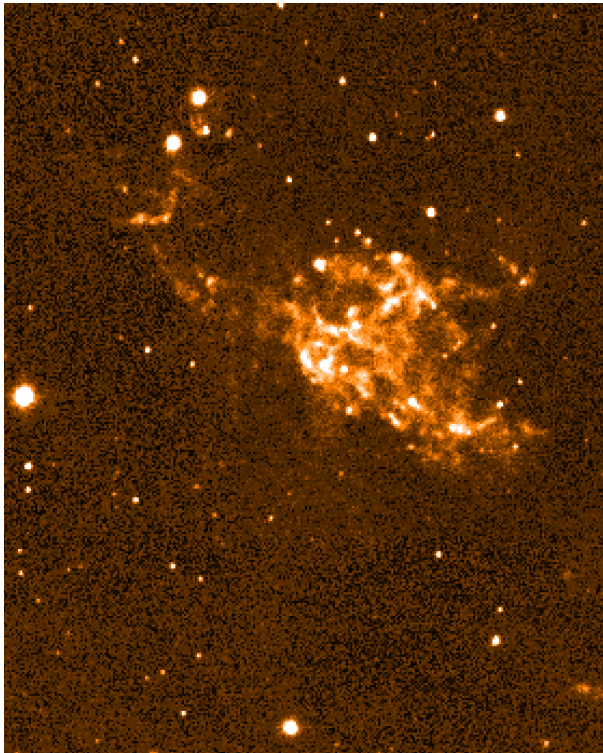


Garden, Russell & Burton, 1990, ApJ, 354, 232 - H₂ imaging (IRCAM)

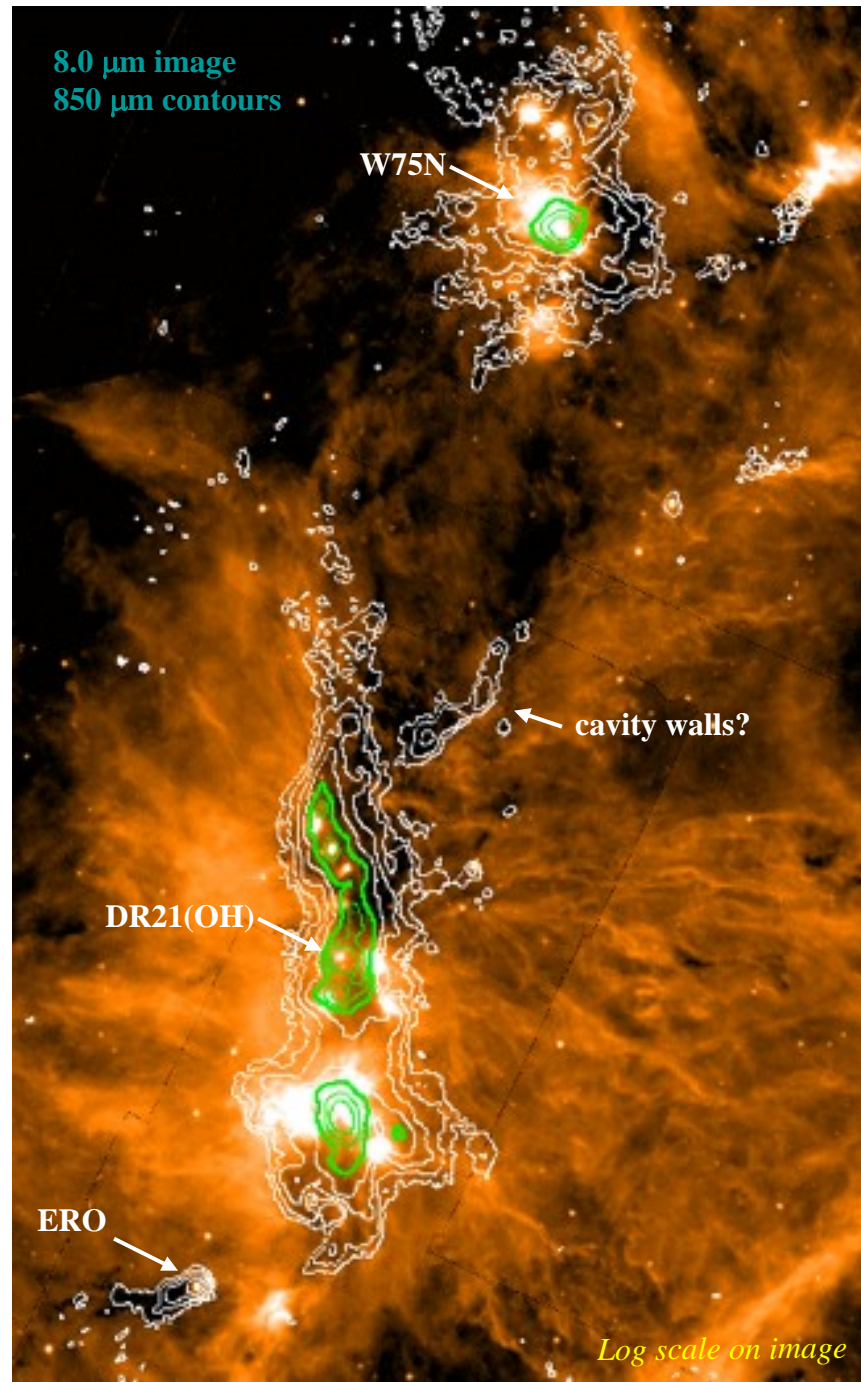
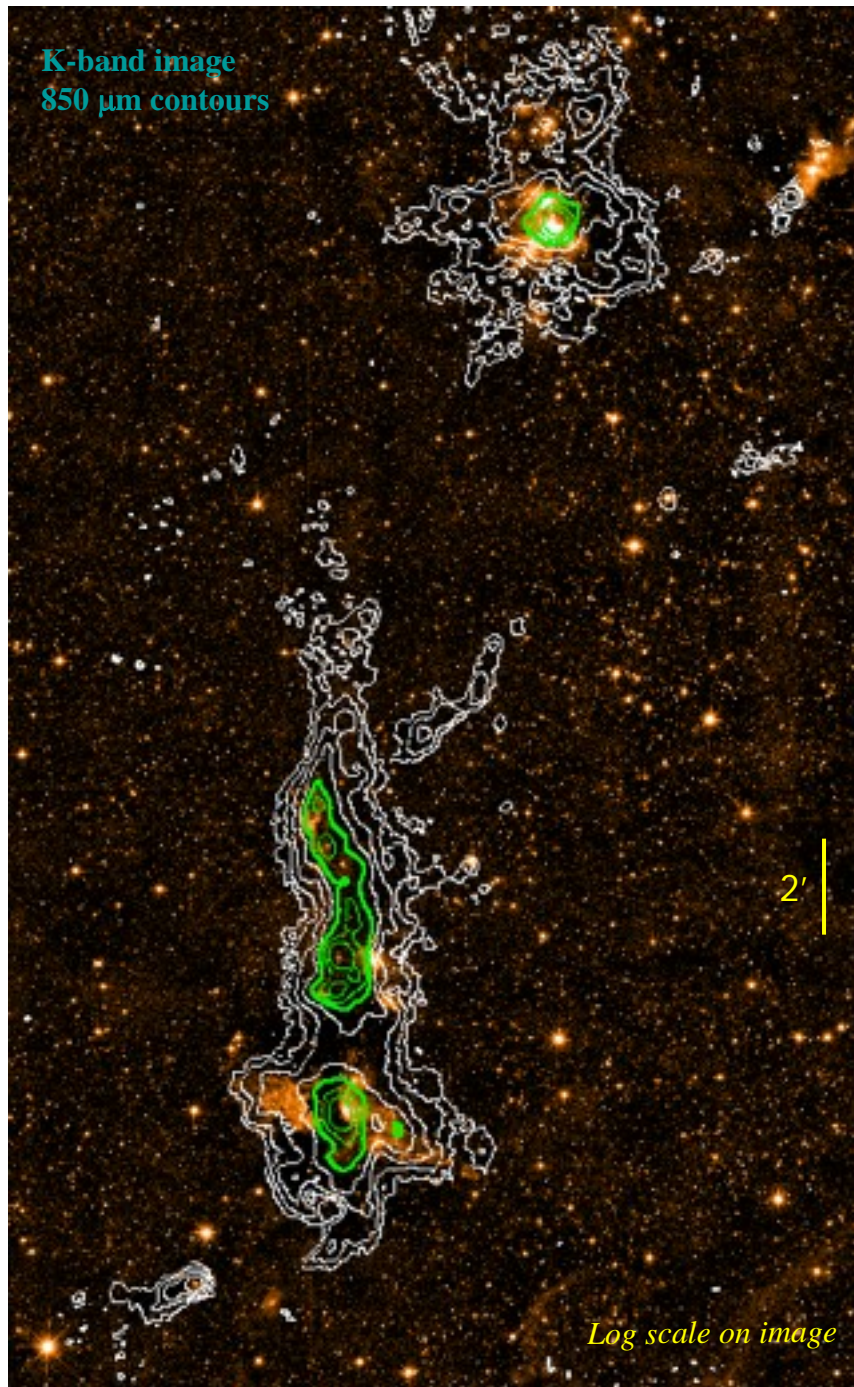
Garden, Geballe, Gatley, Nadeau, 1991, ApJ, 366, 474 - H₂ line profiles (FP, 10" beam, 35 km/s res.); complemented by CO, HCO⁺, etc. from Nobeyama, Hat Creek...

Massive Star formation - DR 21...

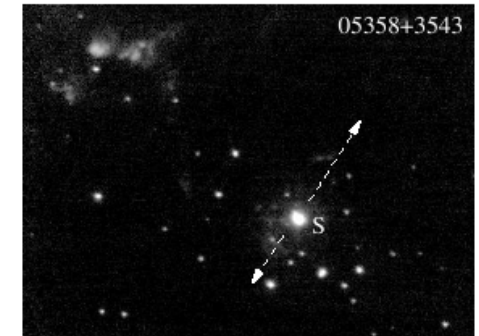
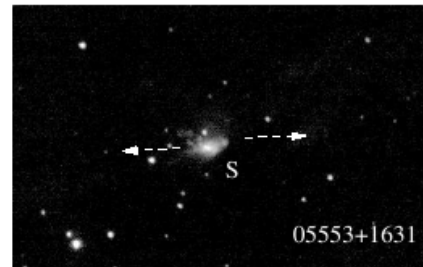
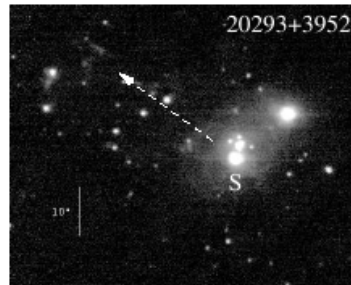
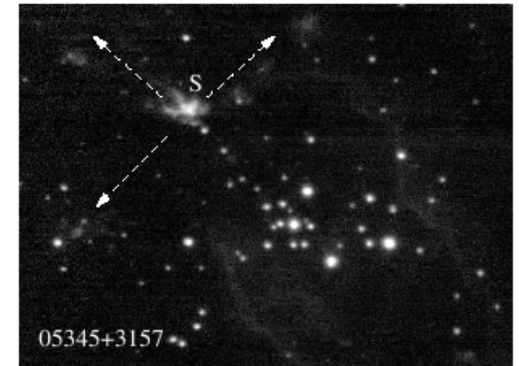
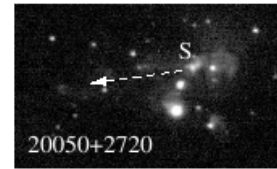
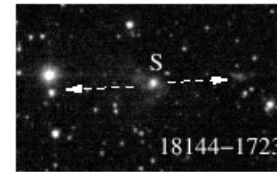
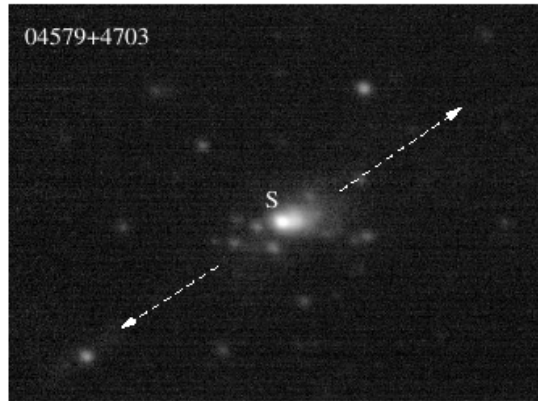
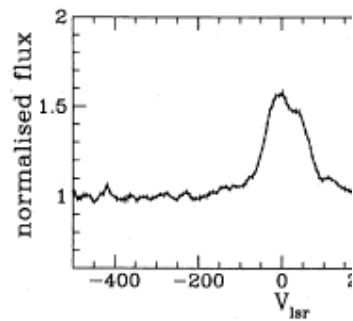
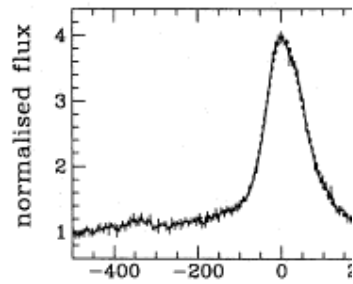
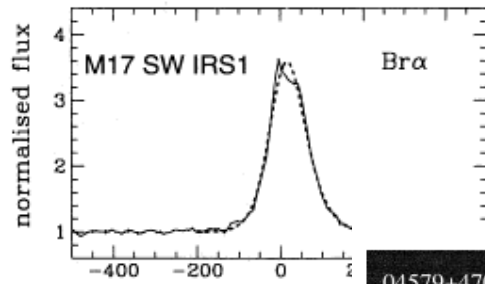
Real near-IR imaging and spectroscopy



Davis & Smith, 1996, A&A, 310, 961 - H_2 imaging, CGS4 echelle spectroscopy and bow models...



Massive star formation (cont.)



Bunn, Hoare, Drew, 1995, MNRAS, 272, 346
 CGS4 echelle spec of massive young stars
 • $\text{Br}\alpha$, $\text{Br}\gamma$, $\text{P}\gamma$ - trace high velocity winds.
 (See similar spec. studies of Drew, Bunn & Hoare, 1993; Lumsden & Hoare, 1996, 1999)

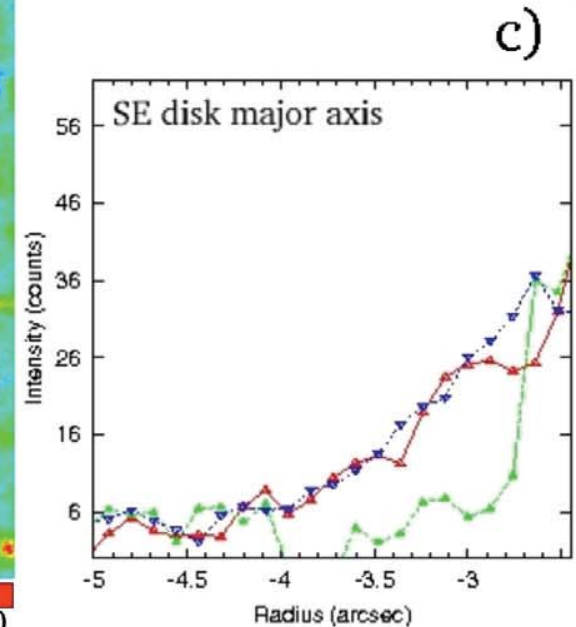
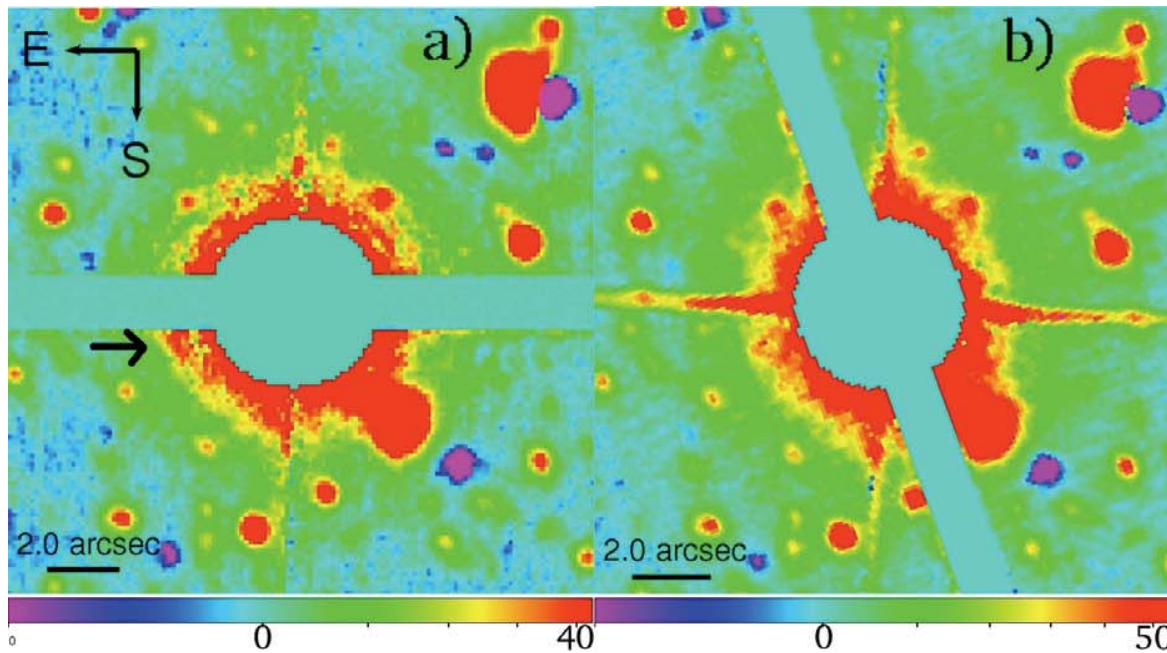
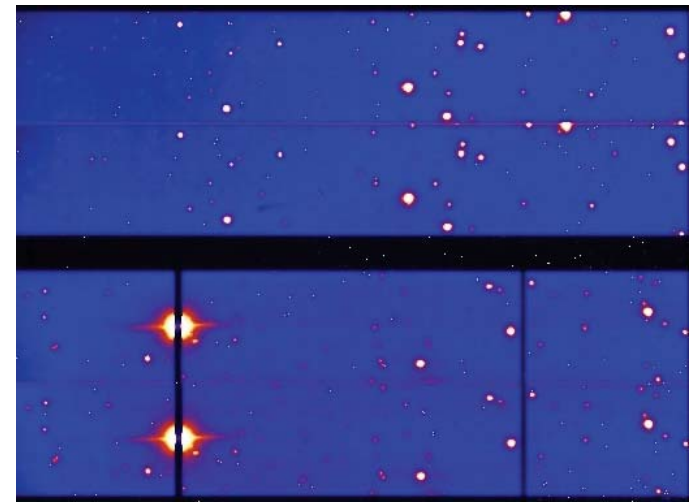
Varricatt, Davis, Howatt, Todd, 2009, submitted.
 UFTI/UIST JHKLM+H2 imaging **survey of 50 Massive YSOs** and their outflows; follow-up echelle and UIST IFU spectroscopy. (see also Kumar et al. 2002, UFTI imaging of H2 around MYSOs.)

Polarimetry

- Grain alignment via spectro-polarimetry of the 4.7 μm CO Ice feature (UIST)
(Hough, Aitken, Whitet, Adamson, Chrysotomou et al., 2008, 387, 797).
- IR imaging polarimetry of dusty young stars (UIST)
(Hales, Gledhill, Barlow, Lowe, 2006, MNRAS, 365, 1348)
- Search for circularly polarised IR radiation in OMC-1 (UFTI)
(Buschermohle et al., 2005, ApJ, 624, 821)
- Spectro-polarimetry of hot, massive young stars (UIST)
(Oudmeijer, Drew, Vink, 2005, MNRAS, 364, 725)
- Imaging-Pol of T-Tauri stars (IRCAM)
(Lucas, et al. 2004, MNRAS, 352, 1347)
- Spectro-polarimetry of the 3 μm water-ice feature towards YSOs (CGS4)
(Holloway, Chrysostomou, Aitken, Hough, McCall, 2002, MNRAS, 36, 425)
- Imaging-polarimetry of a new circumstellar disk system (IRCAM3)
(Kuhn, Potter, Parise, 2001, ApJ, 553, 189)
- Polarimetry of Young Stellar Objects III - Circular Pol of OMC-1 (IRCAM3)
(Chrysostomou, Gledhill, Menard, Hough, Tamura, Bailey, 2000, MNRAS, 312, 103)

Coronagraphic Imaging Polarimetry

(Wisniewski, Kowalski, Bjorkman et al., in prep. - see UKIRT Newsletter #22, Spring 2008)



UIST coronagraphic imaging polarimetry of T Tauri disk.

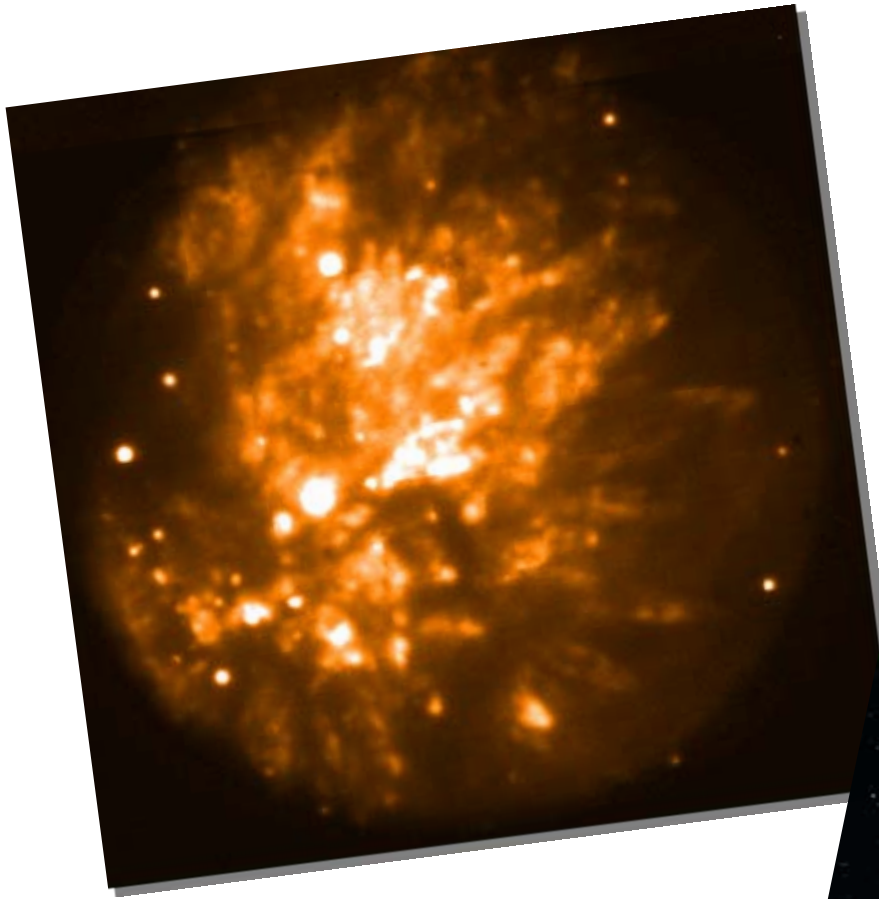
Disk of star clearly detected following subtraction of properly scaled and registered PSF star.
Examine disk in polarised light...

The Future...

WFCAM obviously is and will play a major role... but so can UPF!

- **yYSO population** with Spitzer+WFCAM = JHK[3.6],[4.5]...[24] - mapping star formation across the galactic plane; star formation in IRDCs; triggered star formation...
- **Extinction mapping**; 2MASS (Lada, Alves, Froebrich); applying the “NICER” method to WFCAM data - dense SCUBA-2 cores [$A_v > 5$] versus diffuse cloud [$A_v \sim 1-10$].
- **Variability** - YSOs vary on time-scales of days and even hours...
- **Stellar spectroscopy** at high-R; spectral classification of young stars and MYSOs requires $R > 20,000$ (Greene et al.).
- **Spectro-astrometry** of low and high-mass YSOs

Thank You!



UFTI+FP of Orion Bullets (above)
WFCAM + Spitzer imaging of OMC 1/2/3 (right)

Orion @ UKIRT

Robberto et al., 2005, “**The Orion Nebula at UKIRT**” □, AJ, 129, 1534 [MAX]

Oliveira, Jeffries, van Loon, Rushton, 2006, “**Circumstellar disks in the young sigma Orionis cluster**”, MNRAS, 369, 272 [*UIST KL imaging photom.*]