Outflows in regions of massive star formation

Suzanne Ramsay (ESO), Watson Varricatt (UKIRT), Chris Davis (NSF)
Do high mass stars (>8\(\text{Msolar}\)) form in the same way as low mass stars?

Formation mechanisms for massive stars

- Via gravitational collapse and disk accretion as for low mass stars?
- Via competitive accretion? (e.g. Bonell et al. 2005, Bate et al. 2005)

Problems with disk accretion mechanism

- For \(M>\sim 10\text{Msolar}\), Kelvin Helmholtz timescale exceeds the free fall timescale (\(t_{KH}\sim 10^4\) years for an O star)
- Contraction proceeds faster than accretion and hydrogen burning begins while the protostar is still embedded in the cloud
- Radiation pressure prevents further accretion of mass (but see e.g. Krumholz et al. 2009, Kuiper et al. 2010, 2011, Zinnecker & Yorke 2007 review)
Sample of 50 HMYSOs selected

- NH$_3$ (1,1) and (2,2) emission (Molinari et al. 1996), H$_2$O and CH$_3$OH maser emission (Sridharan et al. 2002), High velocity CO (Shepherd & Churchwell 1996, Beuther 2002)

Imaging survey searching for outflows around HMYSO candidates with the UKIRT-UFTI

- Filters: K, 1-0 S(1) H2 at 2.122µm, also HI Br $\gamma$
- 2.2’x2.2’ images, 5$\sigma$ limit: K=19, 1.3x10$^{-18}$wm$^{-2}$arcsec$^{-2}$

SiO jet (Chandler & Richter 2001) on greyscale image of H2 (McCaughrean et al 1994)
Results

- New detections of embedded young stellar clusters
- 76% of sources have $\text{H}_2$ emission
- $\text{Br} \gamma$ not detected in any of the sources

IRAS 20062+3550
  $d=4.9\,\text{kpc}$, $L=3.2\times10^3\,L_\odot$

IRAS 20162+4104
  $d=1.7\,\text{kpc}$, $L=10.0\times10^3\,L_\odot$

IRAS 05137+3919
  $d=11.5\,\text{kpc}$, $L=225.0\times10^3\,L_\odot$
Results

- 2MASS and IRAS colours used to identify YSOs that may be the driving sources of the outflows.

* = Beuther et al. 1.2mm sources
▲ = IRAS position
+ = MSX position

IRAS 22570+5912

Varricatt et al 2010
Results on outflows

- 76% of sources have H$_2$ emission; 50% aligned
  - collimation factor: max=19; min=2; typically 4-8
  - factors typical of low mass YSOs
- Where CO data exist, outflow origin and direction agree
- Aligned knots of H$_2$ due to shock excitation in jets
- Objects from early B to late O spectral type form collimated outflows. Accretion happens in the pre-UCHII phase
- Survey supports disk accretion as the main mechanism for formation

3D spectroscopy of IRAS 18264-1152/JAC Nov 2016
Open questions/next steps

- Improve association of NIR sources with the outflows and sources at other wavelengths
- Determine outflow characteristics
  - Mass flow rates; Opening angles; Kinematics; Excitation conditions
- K band spectroscopy offers the possibility to determine these at high spatial and spectral resolution (Caratti o Garatti et al. 2008, Davis et al. 2004, Caratti o Garatti et al. 2015)
- ‘Wide’ field IFU spectroscopy with KMOS has the potential to survey and characterize simultaneously
KMOS observations

- Near infrared 0.8-2.5um
- 24 fields of 2.8 x 2.8 arcsecs, 0.2 arcsec per spaxel
- Our observations: mosaic mode, K band grating with R~4000 (75km/s), 70,000 spectra over ~1’sq
Introducing IRAS 18264-1152

$d=3.5\text{kpc}, L=10^4\ L_{\text{solar}}, \text{outflow length}\sim 45\text{arcsecs}/0.75\text{parsec}$

IRAS position=open triangle; $1.3\text{cm sources}=\text{’x’}, 7\text{mm source}=\text{‘#’}; 1.2\text{mm-source} = \text{’*’}

Varricatt et al. (2010)
IRAS 18264-1152

d=3.5kpc, $L=10^4 \, L_{\text{solar}}$

KMOS v=1-0 S(1) of $H_2$

300s per pixels; 2.6h inc overheads for the map

65 arcsecs/1.1pc
Properties of the outflowing gas

H$_2$ rotational-vibrational emission line spectrum.

$H_2$ v=3-2 $S(3)$
$E_j=19089$ K
H$_2$ Excitation Mechanism

Boltzmann diagram of log (H$_2$ column density) vs energy level. Fully thermalized, shock excited gas has a single characteristic temperature. Deviations indicate non-LTE distribution e.g. UV excited, fluorescent emission. Detected emission is characterized by temperatures in the range 2000-2500K.
Counterpart of the HMYSO?

SPITZER (red) plus KMOS H$_2$ v=1-0 S(1) (green) plus K continuum (blue)
Counter part of the HMYSO?

KMOS H2 1-0 S(1)
WFCAM K – blue
UIST L – green
MICHELLE 12.5um - red
WFCAM K band/UIST L band
Accretion luminosity calculated from Brγ luminosity (Muzerolle et al. 1998)

$\text{L}_{\text{acc}} \approx 100 L_{\odot}$ for these sources
spectrally resolved \( \text{Br}\gamma \) (65km/s)

Estimated \( \text{Lacc} \) ~14\( \text{L}_\odot \)
IRAS 18264-1152

$d=3.5\text{kpc}, \, L=10^4 \, \text{L}_\odot$

KMOS $v=1-0 \, S(1)$ of $H_2$

300s per pixels; 2.6h inc overheads for the map

65 arcsecs/1.1pc
Velocity map in 1-0 $S(1) \ H_2$

Black: $-60 \text{ km/s} \ < v \ < -30 \text{ km/s}$
Blue: $-30 \text{ km/s} \ < v \ < 0 \text{ km/s}$
Green: $0 \ < v \ < 30 \text{ km/s}$
Red: $30 \ < v \ < 60 \text{ km/s}$

Radial velocity of IRAS18264-1152: 43.6 km/s (Bronfman, Nyman & May 1996)

3D spectroscopy of IRAS 18264-1152/JAC Nov 2016
Counter part of the HMYSO?
CGS4/WFCAM H$_2$
## Measured velocities of the outflow

<table>
<thead>
<tr>
<th></th>
<th>Vmax blue, Vmax red kms⁻¹</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>1-0 S(1) H₂</td>
<td>75.3, 58.4</td>
<td></td>
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<tr>
<td>SiO (2-1)</td>
<td>13.4, 64.2</td>
<td>Sánchez-Monge et al. (2013)</td>
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<tr>
<td>SiO (5-4)</td>
<td>13.4, 62.6</td>
<td></td>
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<tr>
<td>HCO⁺ (1-0)</td>
<td>33.4, 61.8</td>
<td></td>
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<tr>
<td>SiO (8-7)</td>
<td>?, 63</td>
<td>Leurini et al. (2014)</td>
</tr>
<tr>
<td>CO (4-3)</td>
<td>?, 73</td>
<td></td>
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<tr>
<td>$^{12}$CO (2-1)</td>
<td>28, 52</td>
<td>Beuther et al. 2002</td>
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</table>
The brightest knots have $L_{H_2} \sim 3L_{\text{solar}}$, typical of other HMYSO outflows

- In total $\sim 17L_{\text{solar}}$

Mechanical luminosity in CO

- $\sim 20L_{\text{solar}}$ (Beuther et al. 2002)

Typical outflow rate (warm gas),

- $\sim 10^{-7.5} \, M_{\text{solar}} \, \text{yr}^{-1}$

Dynamical timescale $\sim 2.4 \times 10^4$ years

Outflow rate:

$$\dot{M}(H_2) = 2 \, \mu m H N H_2 A v_t / l t$$

(Caratti o Garatti et al. 2008, Nisini et al. 2005)
H$_2$ luminosity versus source bolometric luminosity

Sequence for low mass >> high mass YSOs from Caratti o Garatti et al. (2015)

IRAS 18264-1152

$L(H_2) \propto L_{bol}^{0.57}$

$L(H_2) \propto L_{bol}^{0.68}$
Conclusions on the outflows

- Spectral imaging with KMOS permits a complete survey of such a region with simultaneous determination of the excitation in the region, outflow rates and accretion luminosity of YSOs in the region.

- Velocity information is crucial in interpreting these regions.

- Identification of the driving source the outflow remains a challenge.

- The properties of the outflow from IRAS 18264 may be consistent with other HMYSOs.
The ambient medium
Emission from the gas surrounding the outflow and at the rest velocity of the cloud shows evidence of fluorescent excitation and with an ortho-para ratio of 1.75
Emission from [Fe II] detected at a single location in the vicinity of source ‘B’ and the bow shock.

Narrow 1-0 S(0)
Broad [Fe II] $^2H_{11/2} - ^2G_{9/2}$

Blue – Source ‘B’
Red – $H_2$
Green - [Fe II]
Next steps

- From the existing data set
  - SED modelling of the central source
  - Confirmation of the nature and origins of the [Fe II] emission

- Follow-up with higher angular resolution at longer wavelengths of both the outflow and the central source