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A near-infrared imaging survey of intermediate and high-mass young stellar object outflow candidates

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Abstract: We present a new near-infrared imaging survey of 50 luminous young stellar outflow candidates. Using high spatial resolution observations in the v=1-0 S(1) line of H_2 we detect the outflows with a high success rate: 76% of the objects exhibit H_2 emission and 50% or more of the objects exhibit aligned H_2 emission features suggesting collimated outflows. Many of these are new detections. The young stellar objects responsible for the outflows are positively identified in many of our images based on their locations with respect to the outflow lobes, 2MASS colours and association with MSX, IRAS, millimetre and radio sources. The main results of our survey are as follows. The observations suggest that disk accretion is probably the leading mechanism in the formation of stars, at least up to late O spectral types. The close association of molecular outflows detected in CO with the H_2 emission features produced by shock excitation by jets from the young stellar objects suggests that the outflows from these objects are jet-driven. Towards strong radio emitting sources, H_2 jets were either not detected or were weak when detected, implying that most of the accretion happens in the pre-UCHII phase; accretion and outflows are probably weak when the YSO has advanced to its UCHII stage.

1 Why observe outflows from young high-mass stars?

The debate as to whether accretion or merger is the main mechanism for the formation of high ($>8M_\odot$) mass stars has been carried on for a number of years. Observational progress in understanding high mass star formation has been inhibited by a few well known factors. Massive stars are far fewer and have much shorter time scales for formation compared to low-mass stars. Hence, high-mass YSO candidates are rarer than their lower mass counterparts. Most regions of high-mass star formation are at distances of a few kpc or greater and since high-mass stars form in clusters, high spatial resolution is required to resolve the HMYSOs from other young stars in the region. Finally, observations at longer wavelengths are required to reduce the effect of extinction. Nevertheless, growing evidence for the accretion scenario as a method of forming high-mass stars has come from observations of small samples or individual objects. Evidence for disks has recently been reported by e.g. Wheelwright et al. (2010), Zapata et al. (2009) and Patel et al. (2005). Outflows have been observed by Zhang et al. (2005), Beuther et al. (2002a) and Wu et al. (2004) etc.

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Further proof requires work on statistically significant samples and a crucial contribution to the debate has come from the numerous observational programmes dedicated to identifying samples of high-mass YSO candidates and to searching for signposts of starformation by accretion associated with the HMYSOs (e.g. Molinari et al. 1996, 1998, 2000; Brand et al. 2001; Sridharan et al. 2002). This work has resulted in the identification of substantial numbers of well-characterised HMYSO candidates.

The survey presented here (Varricatt et al. 2010) is a search for the outflows associated with HMYSO outflow candidates in the v=1-0 S(1) line of H_2. This line is readily observed in the outflows associated with low-mass YSOs where it is excited by shocks from the outflows. Most previous studies of outflows from HMYSOs have been in CO at mm wavelengths using single dish telescopes with large beam sizes. One diagnostic of the formation scenario is the degree of collimation of the outflow: accretion generates highly collimated outflows, a merger would not. Observed high-mass outflows are often apparently poorly collimated, an effect which may be due to the low spatial resolution of the observations and the presence of multiple outflows in the beam. Using shock-excited H_2 as a tracer and exploiting the high spatial resolution and large field of infrared array cameras, sensitive observations of a substantial sample of sources could be carried out (see also Carratti o Garatti et al. 2008).

2 Target Selection and Observations

We selected candidates that are young, high-mass objects with evidence for outflows. Sources were selected that showed ammonia emission (Molinari et al. 1996) and also H_2O and CH_3OH maser emission (Sridharan et al. 2002), indicators of youth and high-mass. Those with high velocity CO, indicating outflows, from Shepherd & Churchwell (1996) and Beuther et al. (2002a) were included in the final list which totals 50 sources. The sources range in distance from $\sim 0.5 - 8$kpc and in measured bolometric luminosity from log($L/L_\odot$)$\sim 2.2 - 5.4$. The observations were carried out with the UKIRT Fast Track Imager (UFTI) on the UK Infrared Telescope (UKIRT). A 2.2×2.2arcmin^2 field was observed in the H_2 v=1-0 S(1) , Brackett-gamma and K band filters. In total, each source was observed for 15min.; the sensitivity reached was a 5σ limit of $K = 19$ for continuum sources and a per pixel sensitivity of 5σ at 1.3× $10^{-18}\mathrm{Wm}^{-2}\mathrm{arcsec}^{-2}$ for the narrow band filters. The angular resolution obtained was limited by the seeing conditions to be from 0.5 to 1.0 arcsec. The data were reduced using standard infrared techniques to combine jittered images and remove instrumental effects. A continuum-subtracted H_2 image was produced following the method in Varricatt, Davis & Adamson (2005). Fits files of all of the images are available to download from http://cdsarc.u-strasbg.fr/ftp/cats/J/MNRAS/404/661/.

3 Results and Analysis

The immediate results from our survey were that many new embedded clusters were revealed in the K band images. Emission from H_2 was observed in 76% of our sources, many of these being new detections. An example of one source, IRAS22570+5912 is shown in Figure 1. Detailed comparison of each of the images with the published locations of the HMYSO candidates at other wavelengths was carried out, to identify the NIR counterpart of HMYSOs.

In the K band image (Figure 1) the location of the IRAS source is shown by a triangle and the MSX source by a cross. Our images reveal a cluster associated with IRAS 22570+5912, embedded in nebulosity. Five of the prominent sources in the cluster are labelled A–E. The 2MASS colours of these five sources show that D and E are the most deeply embedded. The asterisk shows the location of

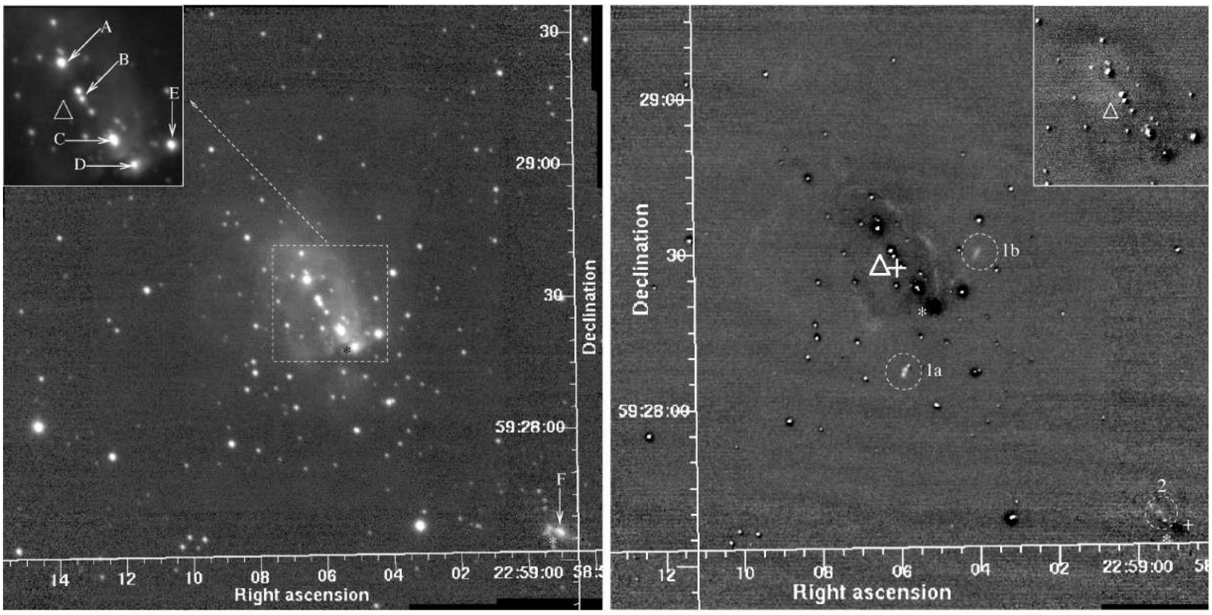

Figure 1: The K-band image of IRAS 22570+5912 (left) shows the central region at higher contrast in the inset. The H_2 line emission image of IRAS 22570+5912 (right) shows the Brackett-gamma image of the central region in the inset.

the 1.2mm peak observed by Beuther et al. (2002b) which coincides most closely with the embedded source, D. The location of a second 1.2mm peak can be seen just at the south-west edge of the field; this is associated with a source, or barely resolved cluster of sources, in the K band image. In the centre of the H_2 image, two prominent H_2 emission features (1a, 1b) are seen. We interpret these as part of the same outflow, centred on the sources D and E and on the 1.2mm peak. In the vicinity of source F and the second 1.2mm peak, further emission features from H_2 (labelled 2) are seen also with a linear geometry. The presence of two outflows in this region supports speculation that the CO velocity structure may be due to more than one outflow in this region (Shepherd & Churchwell 1996, Beuther et al. 2002a). The FIR luminosity estimated for this from the IRAS fluxes by Molinari et al. (1996) is $2.01\times10^4 L_\odot$. The ZAMS spectral type for a single source of this L_{bol} is O9 (from Panagia et al. 1973). The spatial resolution of the IRAS and MSX sources does not allow us unambiguously identify which of the sources A–E are contributing to this bolometric luminosity, and therefore this mass estimate is an upper limit. Deeper photometric studies of these regions would confirm absolutely the multiplicity of the sources and allow a more accurate determination of the mass of the driving YSOs. For this, as for all 50 sources in the sample, the 2MASS, MSX and IRAS colours were calculated and compared with the expected colours of HMYSOs. For IRAS 22570+5912, the MIR colours from IRAS place this source in the locus of UCHII regions, as given by Wood & Churchwell (1989).

Taking the sample as a whole, we find the following. H_2 emission features were detected in 38 (76%) of the 50 targets fields and in 25 (50%) of cases, aligned features were observed. The outflow collimation factors are typically in the range 4–8, with a maximum of 19 and minimum of 2, so are similar to those observed in low-mass YSOs. For sources with both H_2 and CO data, the direction and origin of the outflows are in good agreement. Based on the geometry of the sources, the strong similarity in appearance to low-mass YSO jets and the results from a few sources already followed up (Caratti o Garatti et el. 2008, Davis et al. 2004, Todd & Ramsay Howat 2006) we conclude that the H_2 emission is due to shock excitation and that the outflows are jet driven. Figure 2 shows the 2MASS colours for all the sources. Our outflow sources lie to the right of the reddening vectors for main

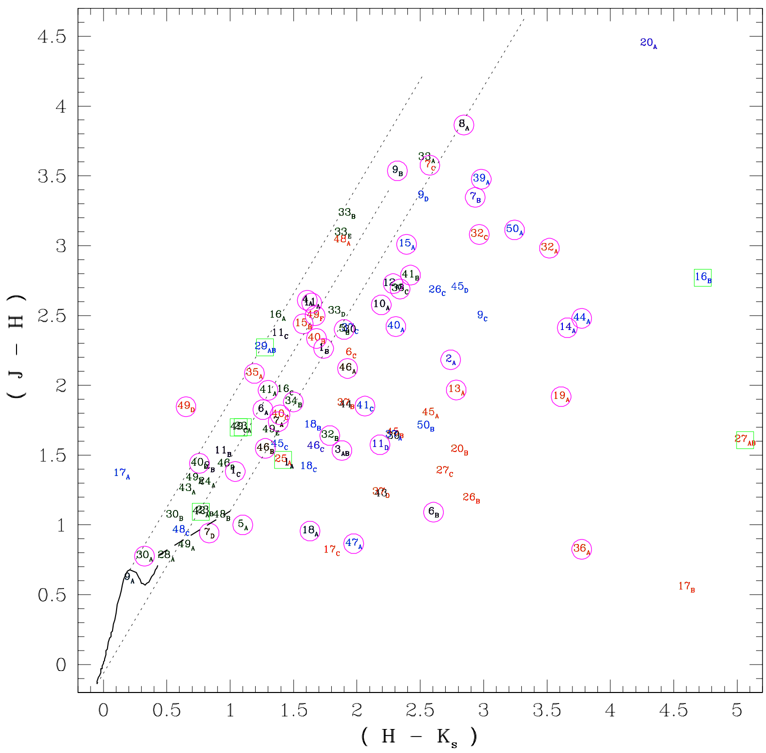

Figure 2: 2MASS colours for all the sources with source numbers from Varricatt et al. (2010). The sources of the outflows are circled, those which are confirmed as UCHII regions are enclosed in squares. The solid line shows the colours of MS stars, the dashed line shows the locus of CTTs and the dotted lines show the reddening vectors to A_v=30.

sequence stars, consistent with them being YSOs. The IRAS and MSX colours are treated similarly and the plots are shown in Figure 3. The confirmed UCHII sources are indicated with squares; they are seen to be well mixed with the other sources which are in a pre-UCHII phase. We therefore confirm the suggestion by Bik (2004) that the Wood & Churchwell (1989) colours for UCHII regions select both UCHII and pre-UCHII sources. Our sources are again consistent with the colours of HMYSOs and we believe that we have identified the NIR counterparts of the candidate HMYSOs. Following the method outlined in the case of IRAS 22570+5912, the observed bolometric luminosity for the YSOs from sub-mm or MIR data was used to estimate the single star ZAMS spectral type using the calculations of Panagia (1973) and Morton & Adams (1968). As already stated, this gives an upper limit to the mass of the YSO driving the outflow; if the source is multiple then the mass determined from the luminosity will be reduced. The single star ZAMS spectral types for the outflow sources are in the range from O7 to B3. Therefore we conclude that sources as massive as late O drive collimated outflows and disk accretion would be the main mechanism for their formation. Detailed discussion on each of the sources is presented in Varricatt et al. (2010). Strong radio emission is associated with 13 of the 50 sources: a notable result from the survey is that none of these is associated with an H_2 jet. Radio emission from the remaining 25 sources with jet-like H_2 emission is faint (in 12 cases) or not detected (in 9 cases) and, in 4 fields, clearly from a different source. It therefore appears that most of the accretion happens in the pre-UCHII phase.

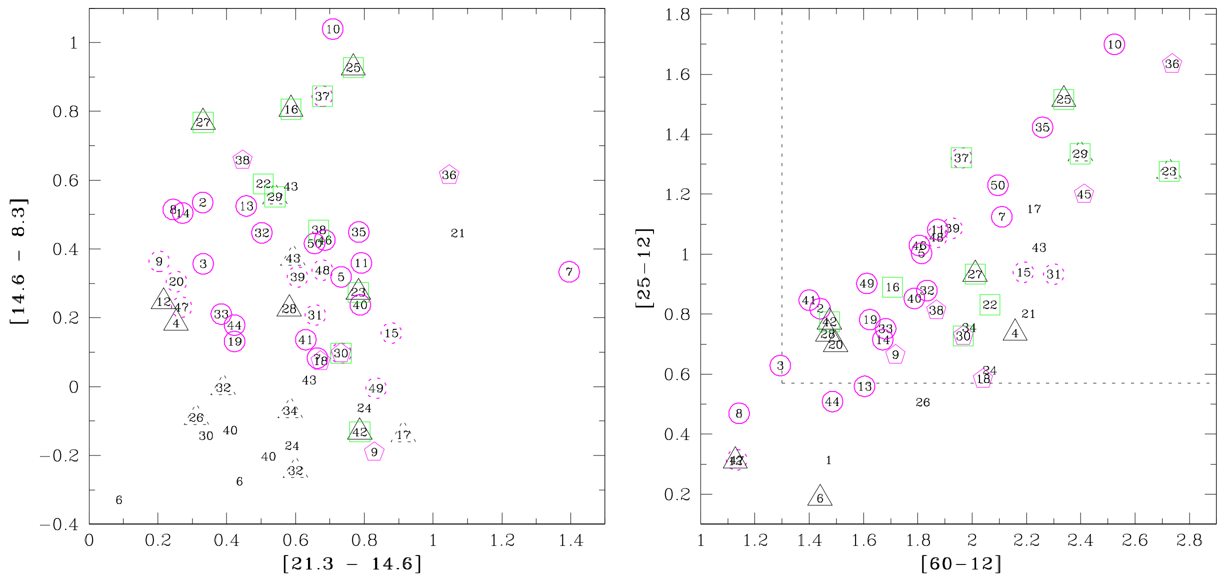

Figure 3: The MSX (left) and IRAS colours of the sources detected in our images are plotted. The dashed lines in the IRAS figure show the colour criteria for selecting UCHIIs from Wood & Churchwell (1989). Confirmed UCHII regions are shown as green squares and are seen to be well mixed with the other sources. Our candidate outflow sources have the colours of HMYSOs.

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Discussion

L. Oskinova: Can you please comment : wouldn't H_2 emission be expected from the PDRs around UCH II regions?

S. Ramsay: Yes, certainly. My comments about the lack of H_2 emission around the UCH II regions were for the case of aligned H_2. Fluorescent H_2 emission could be expected and indeed may have been seen associated with the H II YSOs near IRAS20444+4629 and IRAS18174-1612. In other sources, H_2 from PDRs may fall below our detection limit.