

# A General Catalogue of Molecular Hydrogen Emission-Line Objects (MHOs) in Outflows from Young Stars <sup>★</sup>

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**Abstract.** We present a catalogue of Molecular Hydrogen emission-line Objects (MHOs) in outflows from young stars, most of which are deeply embedded. All objects are identified in the near-infrared lines of molecular hydrogen, all reside in the Milky Way, and all are associated with jets or molecular outflows. Objects in both low and high-mass star forming regions are included. This catalogue complements the existing database of Herbig-Haro objects; indeed, for completeness, HH objects that are detected in H<sub>2</sub> emission are included in the MHO catalogue.

**Key words.** ISM: jets and outflows – Herbig-Haro objects – ISM: molecules – Stars: mass-loss

## 1. Introduction

For over 30 years, astronomers have been observing Herbig-Haro (HH) objects, jets and outflows in star forming regions in the near-infrared. The molecular hydrogen  $v=1-0$  S(1) line at  $2.122\ \mu\text{m}$  is a particularly powerful tracer of shock-excited features in molecular outflows (e.g. Wilking et al. 1990; Garden, Russell & Burton 1990; Zealey et al. 1992; Gredel 1994; Davis & Eislöffel 1995; Zinnecker, McCaughrean & Rayner 1998; Reipurth et al. 1999; Eislöffel 2000; Stanke, McCaughrean & Zinnecker 2002; Caratti o Garatti et al. 2006; Walawender, Reipurth & Bally 2009; Davis et al. 2009). Although excited in a similar way to HH objects, these molecular hydrogen emission-line features are often too deeply embedded to be seen at optical wavelengths. They are thus not classified as HH objects, which are strictly defined by optical criteria, and are instead labelled in a rather hap-hazard way, often with the authors' initials. In large on-line databases this can lead to some ambiguity.

Our goal with this catalogue was therefore to develop a self-consistent list of H<sub>2</sub> emission-line objects, in a manner similar to that used so successfully for HH objects. With guidance from the International Astronomical Union (IAU) Working Group on Designations, we have adopted a scheme that simply lists objects sequentially, although objects are grouped by region (see below). The simple acronym “MHO”, for Molecular Hydrogen emission-line Object, is used to refer to these objects. This acronym has been approved by the IAU registry, and has been

entered into the on-line Reference Dictionary of Nomenclature of Celestial Objects<sup>1</sup>.

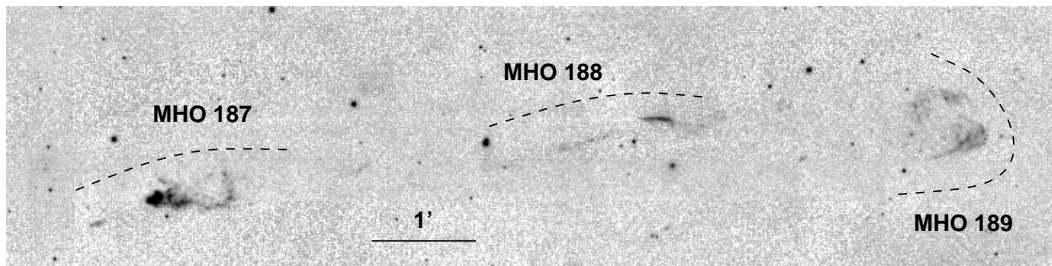
## 2. What constitutes an MHO

Only objects associated with outflows from Young Stellar Objects (YSOs) and protostars are included in this catalogue. We do not list outflows from evolved stars (AGB stars or Proto-Planetary Nebulae) or extra-galactic sources. Also, objects should be spatially resolved; unresolved emission-line regions associated with an accretion disk or the base of an outflow (that were observed spectroscopically) are not listed.

Since large-scale imaging surveys are now revealing tens or even hundreds of objects in some regions (e.g. Stanke et al. 2002; Khazadryan et al. 2004b; Walawender et al. 2009; Davis et al. 2009), spectroscopic confirmation of every feature is not usually practical (although multi-object spectrographs that operate in the infrared will certainly help in this regard). Therefore, to properly identify an MHO, narrow-band molecular hydrogen images should be accompanied with either adjacent narrow-band continuum images or (flux-scaled) broad-band K images. It is obviously important that these shock-excited features be distinguished from wisps and knots of continuum emission. Morphology alone should not be used to identify MHOs, although the shape of an object may help distinguish features in outflows from fluorescently excited emission regions, especially in high-mass star-forming regions. If

<sup>★</sup> <http://www.jach.hawaii.edu/UKIRT/MHCat/>

<sup>1</sup> <http://cdsweb.u-strasbg.fr/cgi-bin/Dic?MHO>



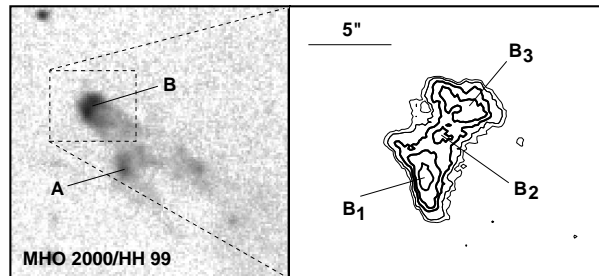
**Fig. 1.** H<sub>2</sub> (+ continuum) image of the MHO 187-189 outflow in Orion A. Data from Davis et al. (2009).

available, MHOs should have a near-infrared spectrum consistent with thermal (shock) excitation, rather than non-thermal (fluorescent) excitation (e.g. Gredel 1994; Lorenzetti et al. 2002; Caratti o Garatti et al. 2006; Gianninni et al. 2008). Kinematic studies - either proper motion studies (Hodapp 1999; Davis et al. 2009) or high spectral-resolution line studies (Carr 1993; Schwartz & Greene 2003; Davis et al. 2004; Li et al. 2008) - are also useful for distinguishing MHOs from what are essentially stationary emission-line features in Photon-Dominated Regions (PDRs). The association of an MHO with a bipolar molecular outflow, traced in (sub)millimeter molecular lines such as CO, likewise confirms the dynamical nature and shock-excitation of the object, and its association with a protostar (e.g. Yu et al 1999, 2000; Shepherd, Testi & Stark 2003; Beuther, Schilke & Stanke 2003; Reipurth et al. 2004).

The MHOs listed in this catalogue have all been identified in the near-infrared (1-2.5  $\mu$ m) lines of molecular hydrogen. Objects detected only in other near-IR lines (e.g. [FeII]) are not included. We also exclude objects observed only in the UV or mid-infrared (e.g. with the *Spitzer Space Telescope*). If an object is subsequently detected in molecular hydrogen line emission in the near-IR, it will be included in the MHO catalogue.

Examples of MHOs are shown in Figures 1, 2 and 3. In most cases we have labelled “groups of knots” rather than individual features or whole outflows. Assigning an MHO number to every resolved feature would of course lead to a vast catalogue that was impossible to maintain. On the other hand, associating widely-spaced knots with a single outflow is often difficult, given the variability of these line emission features and the large sizes of some outflows. MHO 187-189 (shown in Figure 1) is a good example, where three complex groups of features that may well form part of the same outflow are nonetheless catalogued separately, although individual knots within each region are not. As with HH objects, if necessary, individual knots should be identified with letters; sub-knots should then be labelled with letters and numbers. HH 99 (MHO 2000) is shown as an example in Figure 2 (see also the labelling of the knots and sub-features in the detailed, proper-motion study of HH 47/46 in Eislöffel & Mundt 1994).

In some regions multiple knots and bow shocks radiate in many directions from a tight cluster of young stars. Since the relationship between these objects is often unclear – each bow shock may for example be driven by a different outflow that is powered by a different protostar in the central region – we also label these features separately. An example of such a region, the spectacular AFGL 961 massive star forming cluster in the



**Fig. 2.** A simple example of how knots and sub-knots within a single MHO should be labelled, using letters and, for the sub-knots, numbers.

Rosette nebula (described in detail by Aspin 1998 and Li et al. 2008), is shown in Figure 3.

Finally, for completeness we have also given a catalogue number to many well-known HH objects (e.g. HH 1/2 = MHO 120/125, HH 212 = MHO 499), though only if these are detected in the near-IR lines of molecular hydrogen. Whenever possible, we group features together in a manner consistent with the HH object catalogue.

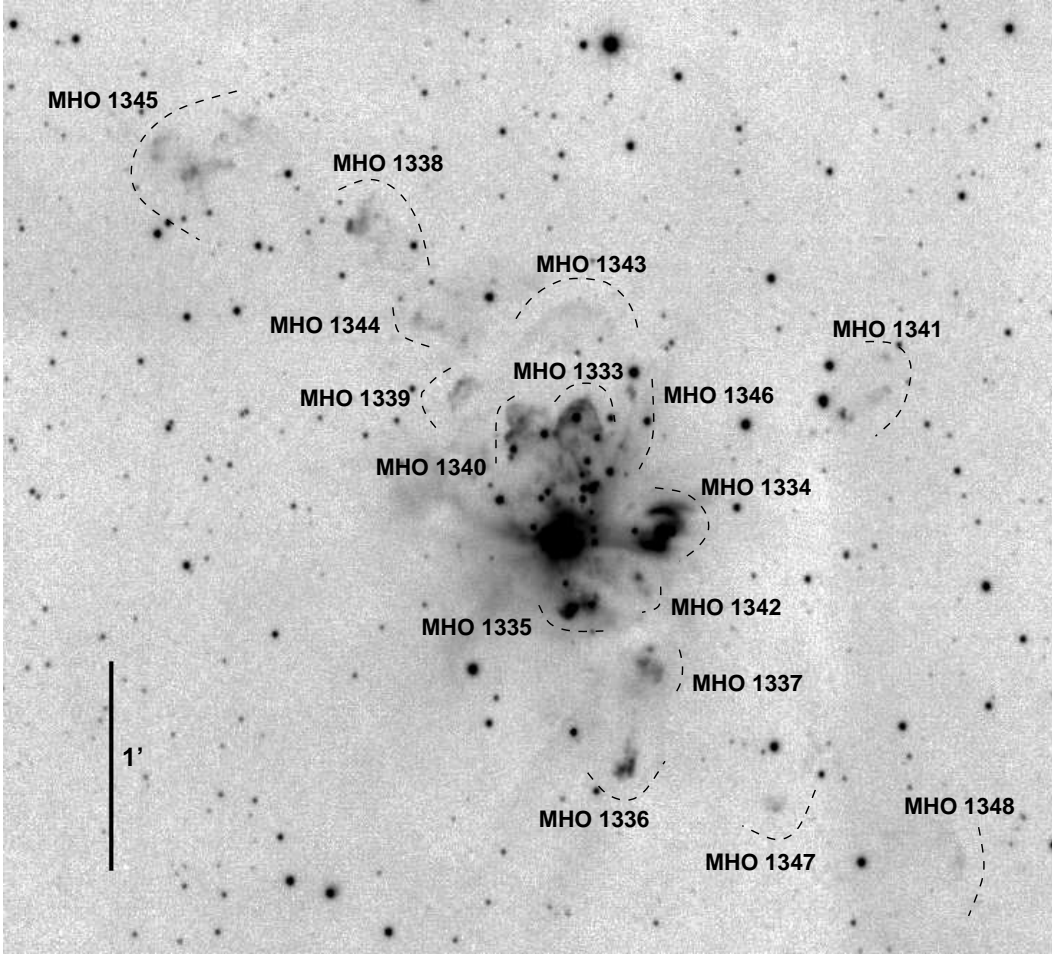
### 3. The MHO Catalogue

#### 3.1. Grouping MHOs by region

There are already almost 1000 objects in the MHO catalogue. In an attempt to bring some semblance of order to the list, we have grouped objects by “region”.

Strictly speaking, there are no official names for, or boundaries to, the star-forming giant molecular clouds in our Galaxy. We have therefore attempted to define large regions based on the well-defined boundaries of the 88 constellations (as outlined by the IAU<sup>2</sup>). MHOs are almost exclusively confined to molecular clouds in and around the Gould Belt and the Galactic Plane (the vast majority of molecular outflows are driven by embedded protostars [Davis et al. 2008, 2009]; relatively few T Tauri stars drive jets that have been detected in molecular hydrogen line emission, and of course H<sub>2</sub> emission, by its very nature, requires the presence of dense molecular gas). We have therefore, in some areas, modified these boundaries slightly to include large groups of clouds. We use the large-scale CO J=1-0 survey of the Milky Way, obtained with 1.2 m telescopes in Cambridge, Massachusetts and Cerro Tololo, Chile (Dame, Hartmann & Thaddeus 2001) to identify these clouds. Even so,

<sup>2</sup> [http://www.iau.org/public\\_press/themes/constellations/](http://www.iau.org/public_press/themes/constellations/)



**Fig. 3.**  $H_2$  (+ continuum) image of AFGL 961 in the Rosette nebula star forming region in Monoceros. Catalogued MHOs are labelled; unpublished data obtained with WFCAM at UKIRT (see Davis et al. 2009 for details of this instrument, the WFCAM data archive and data processing techniques used to create this image).

the boundaries will still pass through some smaller, less massive clouds and so the boundaries should only be considered accurate to within a few arcminutes.

The regions defined in this way are listed in the first column in Table 1. Note that, in the heavily-populated area of Orion, we have split the region up into two sub-regions, Orion A and Orion B, as is the popular convention.

The boundaries of each region are also marked on low-resolution CO  $J=1-0$  maps in Figure 4. M1-M9 in these figures and in Table 1 refer to maps 1 to 9. Note that not all 88 constellations are listed in Table 1, since those at high galactic latitudes do not contain star forming regions and/or known outflows with MHOs. Indeed, five regions; Camelopardalis, Centaurus, Circinus/Lupus, Lyra and Andromeda, as yet contain no MHOs. We include these regions in the catalogue to facilitate the addition of future discoveries.

The MHO number range listed in the final column in Table 1 defines the range of MHO numbers currently being used in each region. To date, not all numbers have been assigned to an MHO (in any of the regions).

The latest version, at the time of writing, of the MHO catalogue is published here in Appendix A.

### 3.2. The on-line database of MHOs

The entire catalogue is also available on-line at

<http://www.jach.hawaii.edu/UKIRT/MHCat>.

This MHO homepage includes the table of regions shown here in Table 1; in the on-line catalogue, links in the first column point to separate tables of MHOs for each region. These tables list the MHO number, Right Ascension and Declination, citations to the discovery paper and subsequent near-IR imaging papers, together with identifications used in the literature, any associated HH objects, and a brief description of each object. A small image of the MHO is also presented with the object clearly marked; example images from the on-line catalogue are shown here in Figure 5.

In the on-line catalogue simple ascii tables are also available. These list only MHO number, Right Ascension and Declination, associated HH object, and region. These very basic tables may be downloaded and used to plot positions of MHOs on images or maps taken at other wavelengths, or to label  $H_2$  emission-line features in new near-IR images of star forming regions already covered by the catalogue.

**Table 1.** Regions used to group MHOs

Region <sup>a</sup>	Map <sup>a</sup>	Approx. RA Range <sup>b</sup>	Approx. Dec Range <sup>b</sup>	MHO Numbers <sup>c</sup>
Perseus	M2	03h 00m → 04h 00m	+25° → +35°	500-699
Auriga	M2	03h 30m → 06h 30m	+30° → +56°	1000-1099
Taurus	M2	03h 00m → 05h 50m	+10° → +30°	700-799
Camelopardalis	M1	04h 00m → 08h 00m	+56° → +90°	1100-1199
Orion A	M3	04h 45m → 06h 00m	-15° → -04°	1-299
Orion B	M3	04h 45m → 06h 00m	-04° → +16°	300-499
Gemini	M3	05h 50m → 08h 00m	+14° → +34°	1200-1299
Monoceros	M3	06h 00m → 08h 30m	-13° → +14°	1300-1399
Puppis	M4	06h 30m → 09h 00m	-38° → -13°	1400-1499
Vela	M4	07h 30m → 11h 00m	-55° → -38°	1500-1599
Carina	M5	08h 00m → 12h 00m	-75° → -55°	1600-1699
Chameleon	M5	08h 00m → 14h 00m	-85° → -70°	3000-3099
Centaurus	M5	12h 00m → 15h 00m	-70° → -30°	1700-1799
Circinus/Lupus	M6	15h 00m → 16h 00m	-70° → -30°	1800-1899
Scorpius	M6	16h 00m → 18h 00m	-60° → -30°	1900-1999
Corona Australis	M6	18h 00m → 19h 30m	-45° → -35°	2000-2099
Ophiuchus	M6	16h 00m → 18h 00m	-30° → +05°	2100-2199
Serpens	M7	17h 30m → 18h 40m	-15° → +05°	2200-2299
Sagittarius	M7	18h 00m → 20h 30m	-35° → -12°	2300-2399
Aquila	M7	18h 40m → 20h 30m	-12° → +15°	2400-2499
Lyra	M8	18h 20m → 19h 00m	+05° → +45°	2500-2599
Vulpecula	M8	19h 00m → 21h 30m	+15° → +30°	2600-2699
Cygnus	M9	19h 00m → 22h 00m	+30° → +55°	800-999
Cepheus	M9	19h 00m → 23h 30m	+55° → +90°	2700-2799
Andromeda	M9	22h 00m → 00h 00m	+30° → +55°	2800-2899
Cassiopeia	M1	23h 00m → 04h 00m	+50° → +90°	2900-2999

<sup>a</sup> The name of each region, and the map used to define each region

<sup>b</sup> Approximate RA and Dec range associated with each region (a more precise range is drawn on each map in Figures 4.

<sup>c</sup> The range of MHO numbers used for objects within each region (note that objects have not yet been assigned to all numbers in each range).

### 3.3. Searching through the catalogue

An easy way to navigate through the catalogue and, in particular, to search for objects by Right Ascension and Declination, was thought to be desirable. A *Perl* script has therefore been developed which allows the user to enter coordinates and a search radius; the script returns an HTML table containing MHOs found within the search area. As with the full region tables, coordinates, references to published observations, a small image and a brief description of each object is returned. This tool is particularly useful for finding MHOs in a star forming cloud or cluster being studied at different wavelengths, or for establishing whether an object is a new discovery, or has in fact already been observed.

### 3.4. Checking the catalogue

Duplicating existing entries and errors associated with the coordinates assigned to each MHO were our two main concerns when compiling the catalogue. To combat both problems, the ascii text files created for each region were imported into the *STARLINK GAIA* graphical display tool (Draper et al. 2008) and plotted over wide field R-band Digitised Sky Survey (DSS) images or, if available, astrometrically-calibrated infrared im-

ages. The infrared images were all obtained from the UKIRT WFCAM archive<sup>3</sup>.

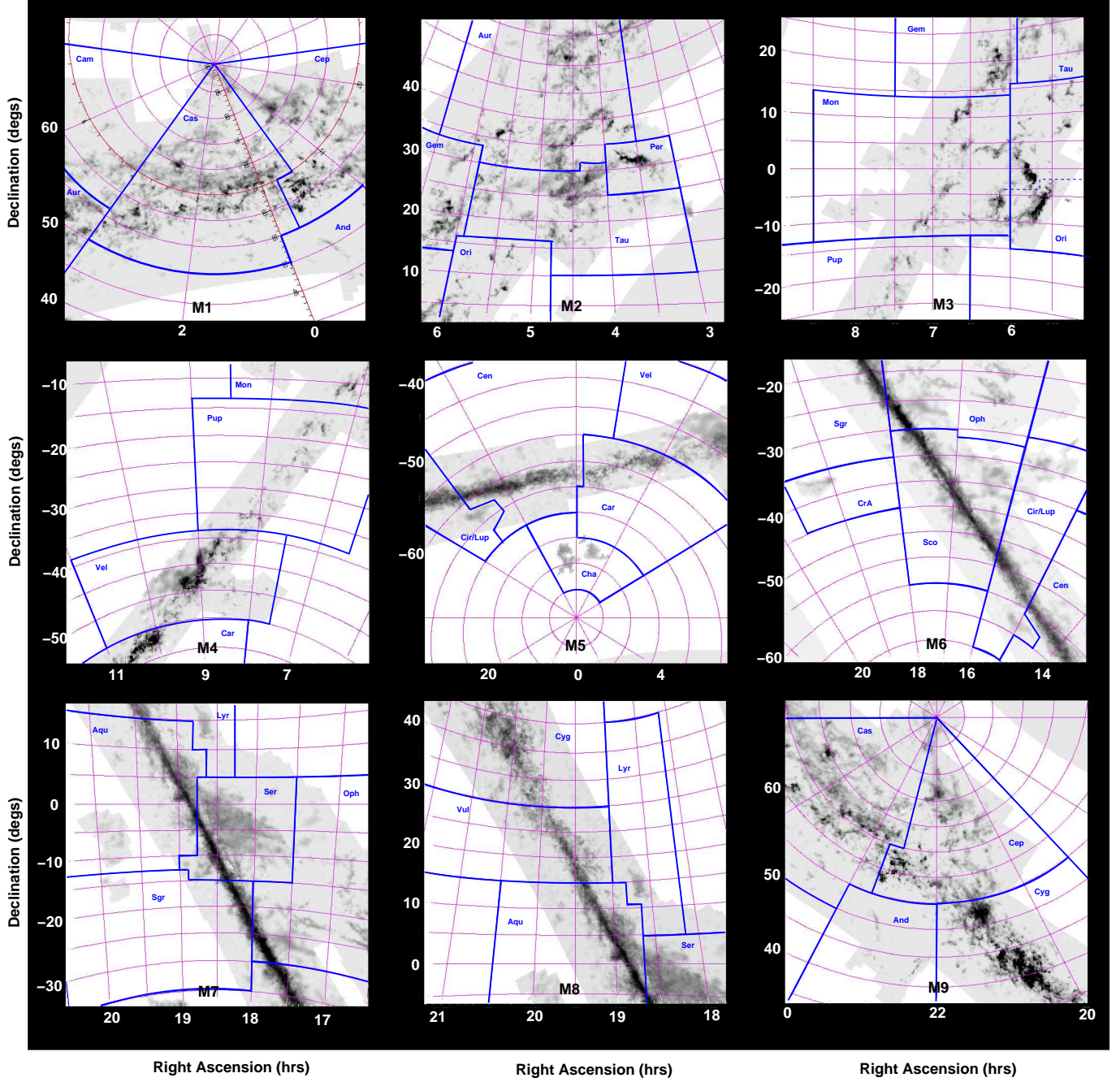
### 3.5. The Future

Our aim is to keep the MHO catalogue as up-to-date as possible. Also, obviously we want to avoid duplication of catalogue numbers (people using the same numbers for different objects). Therefore, we ask that those with new observations please check the catalogue for previous observations, and contact the catalogue organisers (currently Chris Davis: c.davis@jach.hawaii.edu) before papers are written, and certainly before figures and tables of MHOs are finalised, so that new numbers can be assigned.

## 4. Summary

A catalogue of molecular hydrogen emission-line objects (MHOs) has been compiled from the literature. The catalogue includes objects imaged in molecular hydrogen line emission (almost entirely in the 1-0 S(1) line at 2.122  $\mu$ m). It does not include objects observed *only* at UV or mid-IR wavelengths.

<sup>3</sup> <http://surveys.roe.ac.uk/wsa/index.html>



**Fig. 4.** Large-scale maps in CO J=1-0 emission with the boundaries of the regions used to group MHOs marked with thick lines.

The catalogue lists only shock-excited features associated with outflows from young stars. Objects in both low and high-mass star forming regions are included. Similar objects associated with proto-planetary nebulae or extra-galactic sources are not included.

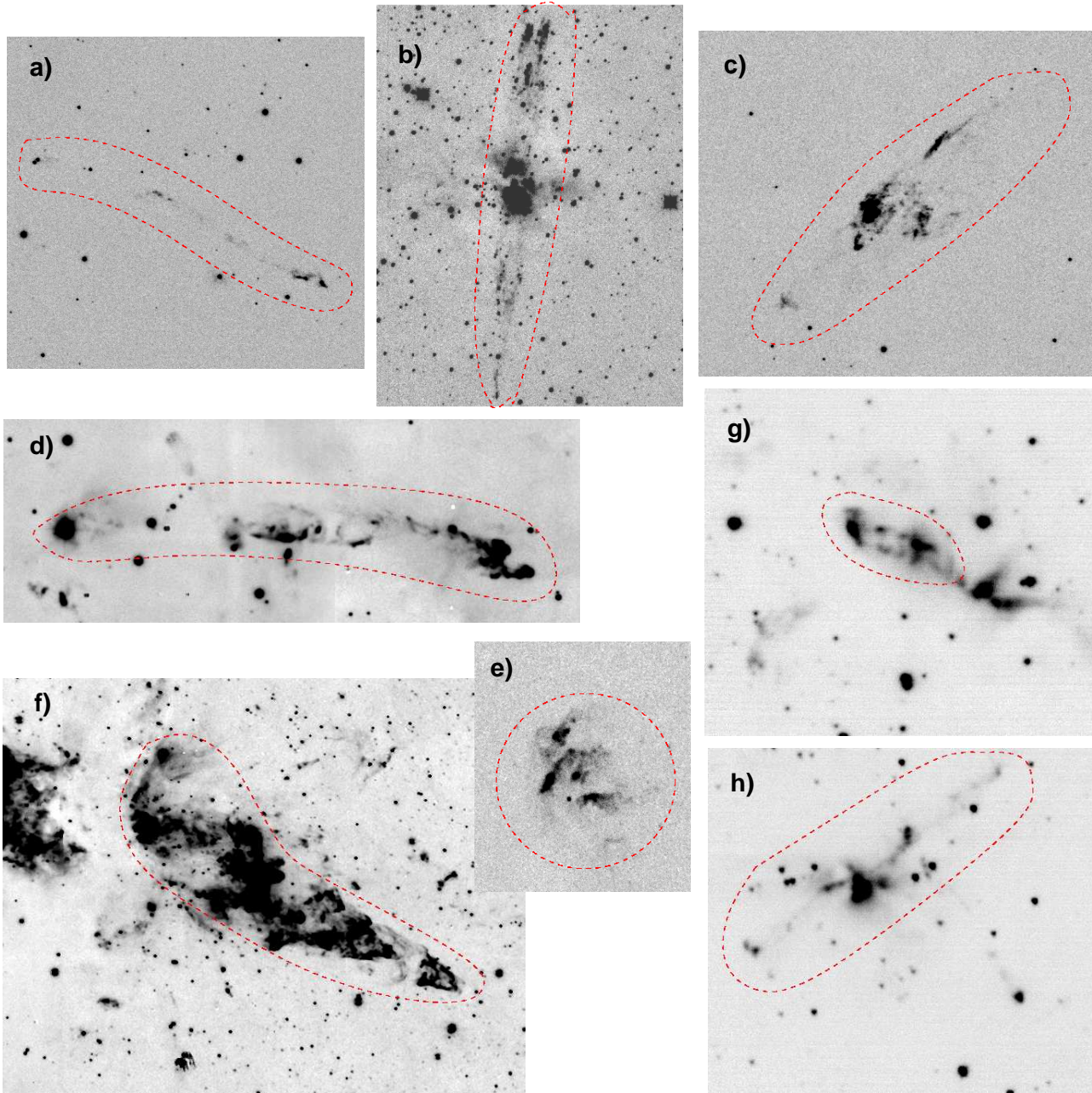
The catalogue currently contains almost 1000 objects. Some are well-known Herbig-Haro objects which we have included for completeness. The catalogue is available on-line at <http://www.jach.hawaii.edu/UKIRT/MHCat/>. With the help of the star formation community, we aim to maintain this catalogue for many years to come, adding new objects as they are discovered. We also hope that in the future, the MHO acronym will be used universally when labelling these enigmatic objects.

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**Fig. 5.** Examples of the small images available at the MHO web site; in each case the MHO is marked with a red dashed ellipse or circle: a) MHO 1300, a curving, collimated jet  $\sim 5'$  SW of the main Mon R2 star forming region in Monoceros (from Hodapp 2007); b) MHO 1510, a bipolar outflow associated with the bright, nebulous source IRS 20 in Vela (Giannini et al. 2007); c) MHO 558 (HH 773), a bright, knotty feature in a bipolar molecular outflow in the B1 ridge in Perseus (Walawender, Reipurth & Bally 2009); d) MHO 18, a spectacular, knotty outflow in the OMC 2/3 region in Orion A (Yu et al. 1997); e) MHO 3000, arcs of emission associated with HH 54 in Chameleon (Zealey, Sutters & Randall 1993); f) MHO 899, the luminous south-western molecular flow lobe associated with DR 21 in Cygnus (Davis & Smith 1996); g) and h) the collimated outflows MHO 2604 and MHO 2201, associated with the high-mass star forming regions IRAS 19410+2336 in Vulpecula and IRAS 18151-1208 in Serpens, respectively (Varricatt et al. 2010).

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## **Appendix A: Tables of MHOs**

In this section we present tables of MHOs separated by region. The regions used to group the MHOs together are defined in Table 1 and in Figure 4. The very latest versions of these tables are also available on-line at: <http://www.jach.hawaii.edu/UKIRT/MHCat/>.