NEW H$_2$ JETS IN MONOCEROS R2

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ABSTRACT

We present a wide-field image of the Mon R2 star-forming region obtained with the Wide-Field Camera on UKIRT in the 2.12 μm filter centered on the H$_2$ 1–0 S(1) emission line. We report the discovery of 15 new H$_2$ jets in Mon R2 and 2 in L1646 and confirm most of these discoveries using archival Spitzer IRAC 4.5 and 8.0 μm images. We find that many of these protostellar jets are found in projection against the outflow cavities of the huge CO outflow in Mon R2, suggesting that the jets may be associated with an episode of star formation in Mon R2 triggered by this large, but now fossil, outflow. We also study the spatial distribution of small, localized reflection nebulae and find that these are distributed in the same way as photometrically identified Class I sources.

Key words: ISM: Herbig-Haro objects — ISM: jets and outflows — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

The region studied here was first identified by van den Bergh (1966) as an association of optical reflection nebulae in their list of such objects and was labeled Monoceros R2 (Mon R2). The Mon R2 molecular cloud complex extends over 3° × 6°, and the overall mass of this large molecular cloud has been estimated by Maddalena et al. (1986) to be 9 × 10$^4$ $M_\odot$. The Mon R2 molecular cloud contains several sites of star formation: GGD 11, GGD 12–15 (Gyulbudaghian et al. 1978), L1646 (Carpenter 2000), and the Mon R2 core, the main star formation site that is the subject of this study. The Mon R2 star-forming region lies between the two optical reflection nebulae vdB 67 and vdB 69 (van den Bergh 1966) and has attracted considerable attention as a site of massive star formation, as a young embedded cluster, and as the source of one of the most powerful CO outflows known.

Even though Mon R2 lies close to Orion in projection on the sky, its distance of 830 ± 50 pc based on photometric parallaxes (Herbst & Racine 1976) is almost double that of the Trapezium cluster (e.g., Stanke et al. 2002). Despite its larger distance, it is still close enough for detailed studies of the embedded young objects. The mass of molecular gas in the Mon R2 core has been determined by Ridge et al. (2003) using $^{13}$CO and C$^{18}$O maps. The rarer C$^{18}$O traces denser gas and results in a gas mass of 1826 $M_\odot$, while the more abundant $^{13}$CO also samples the tenuous outer regions of the molecular core and gives a mass of 2550 $M_\odot$. The molecular gas distribution is single-peaked with a slight indication of extended filaments to the south and southwest. To put this region into perspective, Mon R2 is smaller than the Orion Trapezium region in spatial extent, molecular mass, and number and total mass of embedded stars. It is, however, not far behind in many of these parameters.

Mon R2 has been noted as a source of a bipolar CO outflow by Loren (1981). This main Mon R2 molecular outflow was found by Wolf et al. (1990) to be one of the dynamically oldest (1.5 × 10$^5$ yr), largest (7 pc), and most massive (100 $M_\odot$) molecular outflows. Based on CO maps with higher spatial resolution than those of Wolf et al. (1990), Meyers-Rice & Lada (1991) argued that the Mon R2 CO outflow must consist of two bipolar outflows: one component seen almost head-on, to explain the overlapping redshifted and blueshifted velocity components seen in projection against the central cluster, and one component more inclined along the line of sight, to explain the bipolar outflow features. Both components could be modeled as paraboloidal shells with a linear velocity field that could result from velocity sorting of clumpy outflow material. The detailed study of CO emission and multiple transitions of CS by Tafalla et al. (1997) showed that the massive outflow has created an hourglass-shaped cavity in the molecular cloud centered on the cluster of massive young stars. The cavity walls coincide with the limb-brightened shells of the blueshifted outflow lobe. The axis of the paraboloidal outflow shell and cavity are oriented roughly at a position angle of −30°.

The central group of luminous stars and the associated nebulousness were discovered in the near-infrared by Beckwith et al. (1976). Much of the attention has been focused on the ringlike reflection nebula around IRS 1, discovered by Beckwith et al. (1976) and studied in more detail by Hodapp (1987); the details of the cluster’s most luminous individual source (IRS 3), summarized in the most recent work by Preibisch et al. (2002); and the distribution of molecular matter and the large outflow, summarized in Tafalla et al. (1997). In embedded young clusters like Mon R2, near-infrared (J, H, and K) photometry is a very useful tool for identifying young cluster members on the basis of their color excess over the reddened photospheres of old background stars. The first such study of Mon R2 was done by Carpenter et al. (1997). Most recently, the initial mass function in the Mon R2 cluster core was studied in detail by Andersen et al. (2006) on the basis of HST NICMOS data. They find that the ratio of the number of stars below solar mass to the number of objects in the brown dwarf mass range is similar to that found in the Trapezium cluster and in IC 348.

Compared to the widely used J, H, and K images used to characterize the stellar population of young clusters, the Spitzer IRAC images in four bands ranging from 3.6 to 8.0 μm allow the identification of younger and more deeply embedded objects. Further, they also allow the identification of objects with purely longer wavelength infrared excess, indicating passive reprocessing disks, e.g., Gutermuth (2005) and Kumar et al. (2007). On the basis of near-infrared J, H, and K photometry and Spitzer mid-infrared photometry, Gutermuth (2005) found that Class I objects in Mon R2 are distributed in a filamentary pattern, while Class II objects are distributed more widely and evenly. However, even these IRAC bands are not sampling the youngest objects in a

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cluster completely, in particular those Class 0 and I objects that are oriented with their disks seen edge-on. Fortunately, those objects can still be found indirectly. The substantial accretion activity in the Class 0 and I phases of low-mass star formation is invariably associated with outflow activity, as was first noted by André et al. (1993). These outflows easily break out of the dense molecular disk and the envelope enshrouding the young star, and they are therefore readily detected in the near-infrared, due to the shock-excited emission at the interface between the outflow and the ambient molecular material, and in shocks within the outflow. The most easily accessible near-infrared shock-excited emission lines are the [Fe II] line at 1.644 μm and the H₂ 1–0 S(1) line at 2.122 μm, the line studied here. Of these two emission lines, the H₂ 1–0 S(1) line traces lower excitation levels and is excited in virtually all deeply embedded jets propagating in molecular clouds. Therefore, shock-excited emission of molecular hydrogen is the earliest near-infrared signpost of outflow activity in a very young object and is usually observable long before the central star becomes observable in the near- or mid-infrared. Molecular hydrogen jets tend to have morphological features that are distinct from other forms of H₂ emission in star-forming regions and are therefore easily recognized in imaging surveys.

Powerful jet activity is a byproduct of the short-lived main accretion phase of a forming star. When the accretion and jet activity fades after about 10⁵ yr, the envelope of molecular gas around a young star usually has formed two outflow cavities. When properly oriented, scattered light from these cavity walls gives the object the appearance of a bipolar nebula, or a cometary nebula if only one cavity can be seen. Objects of this morphology overlap with the Class I objects that can be identified photometrically using the Spitzer IRAC bands. Therefore, imaging surveys of star-forming regions for protostellar jets and bipolar or cometary nebulae are a powerful tool for discovering very young (Class 0 or I) objects in or soon after their main accretion phase. Thanks to the recent availability of large-format near-infrared cameras, such surveys can now be conducted efficiently.

In this paper we report the discovery of 17 extremely young objects in and around the Mon R2 star-forming region by means of imaging their collimated outflows in the H₂ 1–0 S(1) emission line at 2.12 μm. By comparison of the 2.12 μm image and the Spitzer IRAC 4.5 and 8.0 μm images, we discuss the most plausible identification of the source of each outflow. The large number of outflows indicates that star formation is active all through the Mon R2 molecular cloud. We discuss the spatial distribution of the newly discovered extremely young stars in relation to the large, old molecular outflow in Mon R2.

2. OBSERVATIONS AND DATA REDUCTION

2.1. UKIRT WFCAM 2.12 μm Imaging

The purpose of this project was not the detailed study of any particular jet, but rather the discovery of new objects in the Mon R2 star-forming region that indicate the presence of stars in their youngest phase of evolution. Also, completeness in the discovery of H₂ outflows was not a realistic goal for this survey of a region with such extensive reflection nebulosity and, most likely, also fluorescently excited H₂ emission (e.g., Black & Dalgarno 1976) that both tend to confuse any search for H₂ outflows. Therefore, in the interest of maximizing the scientific return of the observing time used, we did not obtain an image at a continuum wavelength adjacent to the S(1) line or in a broad K-band filter to distinguish between emission-line features and continuum reflection nebulosity. As discussed below, the identification of H₂ jets relied on morphological arguments and confirmation, if possible, by archival Spitzer IRAC images.

Wide-field near-infrared images of the Mon R2 region were obtained on the night of 2005 October 20 UT at the United Kingdom Infrared Telescope (UKIRT). The Wide-Field Camera (WFCAM; Casali et al. 2007) was used with a filter centered at 2.121 μm with Δλ = 0.021 μm that includes the H₂ 1–0 S(1) line. The field was roughly centered on the well-studied Mon R2 cluster of infrared sources. The WFCAM uses four Teledyne (formerly Rockwell) HAWAII-2 2048 × 2048 HgCdTe infrared detector arrays at a pixel scale of 0.4′′ pixel⁻¹, arranged in the camera focal plane with a spacing of 0.94 of the detector size between the devices. To achieve full coverage of a 0.75 deg² region of the sky, four telescope pointings are required, which in WFCAM terminology are called a “tile.” At each tile position, a five-point dither pattern (3.2′′ spacing) was used to avoid bad pixels and other detector array artifacts. Finally, at each dither position, a four-point microstep pattern with a half-pixel (0.2′′) step size was used to oversample the image. For our observations, an on-chip exposure time of 40 s was chosen, and the detectors were read out in nondestructive mode, sampling the accumulating signal 41 times during the integration time. The read noise achieved in this mode of operation was ≈20 e⁻ rms. The on-sky integration time was 800 s, except in the overlap regions of the tile. With a distance to Mon R2 of 830 pc, 1″ in our images corresponds to a projected distance of 0.24 pc.

The data were processed by the Cambridge Astronomical Survey Unit using the procedures described by Dye et al. (2006). Astrometric calibration relative to the 2MASS catalog (Skrutskie et al. 2006) was performed, and a plate solution was written into the file headers. All coordinates in this paper, therefore, are given in J2000.0 and are indirectly based on the 2MASS coordinate system. After retrieval of the reduced data from the WFCAM Science Archive, the final assembly of the full tile image was done with IRAF scripts that used the image header information to assemble the individual images into a tangential projection image of the full tile.

The central region of the resulting image is shown in Figure 1. The image shows the well-known Mon R2 cluster near the center and the two reflection nebulae to the west (vdB 67) and east (vdB 69) of it. Filamentary emission extends mostly to the north and east of the main star-forming region. The lowest contours of the blueshifted and redshifted CO maps of Wolf et al. (1990) are superposed on Figure 1. There is no large-scale feature visible that would be morphologically associated with the main CO outflow centered on IRS 2 (identified in Fig. 2) that has a rather poorly defined outflow axis at P.A. ≈ −45° (Wolf et al. 1990) or with the outflow cavity whose axis is oriented at ≈−30° (Tafalla et al. 1997; Choi et al. 2000).

2.2. Archival Spitzer Images

The IRAC is the main near- and mid-infrared imaging instrument of the Spitzer cryogenically cooled space telescope (Fazio et al. 2004). All four IRAC channels contain emission lines of H₂. Of the four IRAC channels, band 2 centered at 4.5 μm is particularly well suited to detecting H₂ emission. From a discussion of different shock models, Smith & Rosen (2005) concluded that shock-excited H₂ emission in the 4.5 μm band is an order of magnitude brighter than in the other channels for a wide range of shock conditions. IRAC band 2 (4.5 μm) contains the H₂ (0–0) S(9) line at 4.694 μm, and emission in this line shows morphological features nearly identical to those seen in H₂ 1–0 S(1) at 2.122 μm but is less affected by dust extinction. Therefore, despite the fact that the broad IRAC band 2 also contains other important
molecular features, such as CO ($\nu = 1$–0 at 4.45–4.95 $\mu$m) and the atomic hydrogen Br$\alpha$ line at 4.052 $\mu$m, images in this band often show very similar jet morphology to 2.12 $\mu$m $S(1)$ images (Smith et al. 2006). By contrast, Smith & Rosen (2005) find that IRAC band 1 (3.6 $\mu$m) is dominated by vibrationally excited lines with higher excitation energy than the 1–0 $S(1)$ line, so that shock features appear sharper in band 1 than in a 2.12 $\mu$m 1–0 $S(1)$ image. The Spitzer 3.6, 5.8, and 8.0 $\mu$m bands also contain bright PAH emission at 3.3, 6.2, and 7.7 $\mu$m, respectively. In a region like Mon R2, this strong and often filamentary emission tends to mask shock-excited emission from jets.

Spitzer IRAC images were downloaded from the Spitzer Archive. The data used here were originally obtained for a program by G. Fazio. Partial results of their study of the distribution of

![Figure 1](image_url)

**Fig. 1.**—Image of the Mon R2 star-forming region in the 1–0 $S(1)$ emission line of H$_2$ at 2.12 $\mu$m, obtained with the WFCAM at UKIRT. The circles indicate the positions of the newly found H$_2$ jets. The Herbig-Haro object HH 866 is visible in the northwest corner of the image. The small reflection nebula near the eastern edge of the image is GGD 11 (Gyulbudaghian et al. 1978). Newly found small reflection nebulae are indicated by squares. Superposed on this image are the lowest contours of the blueshifted (-2 to 6 km s$^{-1}$, solid line) and redshifted (14–22 km s$^{-1}$, dashed line) CO emission from the map by Wolf et al. (1990).
stars based on JHK and Spitzer IRAC colors have been presented by Gutermuth (2005).

The available archival Spitzer data do not cover the whole field of our WFCAM observations, so we do not have the corresponding longer wavelength data for all of the outflows discovered here. For those objects where all Spitzer bands are available, we discuss the 4.5 and 8.0 μm data. The 4.5 μm data usually show the outflows, but at relatively low signal-to-noise ratio and with poorer spatial resolution that the UKIRT data. The 8.0 μm data do not usually show the outflow itself, but in many cases they show the molecular clump around the driving source either in thermal dust emission or in some cases in absorption against PAH background emission. The 8.0 μm images, therefore, primarily serve to confirm the identification of the driving source. In some cases the band 2 (4.5 μm) data were not available, and for one object band 1 (3.6 μm) data are shown instead for the purpose of source confirmation.

2.3. Criteria for Identifying H2 Jets

This simple imaging project was motivated by the success of similar observations in identifying H2 jets, e.g., the early survey of NGC 1333 by Hodapp & Ladd (1995), the extensive survey of Orion A by Stanke et al. (2002), the survey of the distant massive star-forming region W51 by Hodapp & Davis (2002), and the recent work on DR21/W75 by Davis et al. (2007). Well over 100 of these collimated H2 jets have now been imaged, and their morphology is quite unique and recognizable. Empirically, shock-excited H2 emission can, in most cases, be distinguished from fluorescently excited H2 emission on the basis of morphological arguments. The physical basis for this is that the cooling time of shock-excited molecular hydrogen is typically only a few years (Shull & Hollenback 1978), during which time shock fronts travel only a fraction of an arcsecond in typical star-forming regions. Shock-excited emission, therefore, usually appears as small but resolved knots, filaments, and bow shocks. In contrast, fluorescently excited molecular hydrogen emission varies on the scale of typical density inhomogeneities in molecular clouds and therefore tends to be much more smoothly distributed. The same is true for large-scale continuum reflection nebulosity.

Therefore, our criteria for identifying H2 jets in Mon R2 were the following. They must consist of a string of resolved H2 emission knots. If a bow shock is found at the end of a string of emission knots, this is regarded as additional and convincing evidence for the existence of a jet. In cases where both sides (lobes) of a jet are visible, a high degree of central symmetry in the distribution of emission knots serves as supporting evidence for the identification of a jet. Sometimes, but not always, faint filamentary emission arising from the outflow cavity walls connects the individual emission knots. If such filamentary emission is seen, it serves as additional evidence supporting the identification of a jet. The H2 jets identified by these criteria are listed in Table 1 and identified in Figure 1 (circles).

Finally, many young stars show reflection nebulae of bipolar or cometary morphology or nebulae otherwise clearly associated with individual stars, properties that we summarize by the term “localized.” In addition to their characteristic morphology, they show a more pronounced drop in surface brightness away from the illuminating central star than the shock emission knots in H2 jets. In Table 2 we list such localized nebulae that were found in our 2.12 μm image of Mon R2 but were not classified as likely H2 jets. Nebulous features that are simply knots in the large-scale nebulosity permeating the center of the Mon R2 cluster are not listed in Table 2. Similar to the situation with the H2 jets, this list cannot be expected to be complete, due to sensitivity limits, high extinction in some parts of the molecular cloud, and confusion with the large-scale reflection nebulosity and filamentary emission present in the Mon R2 region. The localized reflection nebulae are indicated by squares in Figures 1 and 2.

The K’ survey of known CO outflow sources by Hodapp (1994) showed that many of these outflow sources are associated with...
the Mon R2 cluster, and vdB 69. These filaments are also oriented along the direction of the local magnetic field, as measured by the R-band polarimetry of Jarrett et al. (1994). Our 2.12 μm S(1) image does not show any emission from these filaments located to the southeast of the embedded cluster.

From the fact that these systems of filaments are readily visible at optical wavelengths, we conclude that they lie on the front side of the Mon R2 molecular core. Since the polarization vectors of more deeply embedded sources in and near the Mon R2 cluster (Hodapp 1987) follow the pattern of the magnetic field measured to the south and west of the cluster, and since the cluster is located at the intersection of the two patterns of magnetic field direction, it can be speculated that the formation of the Mon R2 cluster was triggered by a collision of two molecular clouds, as discussed by Jarrett et al. (1994).

The core of the Mon R2 cluster and the bright reflection nebulae permeating it are shown in more detail in Figure 2. From polarization measurements of this ringlike infrared reflection nebulosity near the core of the Mon R2 cluster by Hodapp (1987), it is clear that IRS 2 is its dominant source of illumination. The brighter source IRS 3 does not significantly contribute to the illumination (as measured by polarization) of the ringlike nebula, and therefore must be located either in front of or behind the nebula and the core of the Mon R2 cluster. Some elongated emission features are seen east of IRS 3 and lie in a direction similar to that of the filaments observed near vdB 69. This would suggest that IRS 3 is illuminating some of these filaments and that it lies in front of the rest of the Mon R2 cluster.

3. RESULTS AND DISCUSSION

3.1. The Environment of the Mon R2 Cluster

Figure 1 shows an extended system of emission filaments to the north and east of the cluster, besides the known reflection nebulae vdB 67 and 69, the nebulosity associated with the Mon R2 cluster, and the individual H2 jets reported here. These filaments coincide with the optical reflection nebula vdB 68 and are strongly visible in all Spitzer IRAC bands, probably indicating a combination of H2 and PAH emission fluoresceingly excited by the illuminating star of vdB 68, a B2 V star (Herbst & Racine 1976). The filaments seen in Figure 1 are oriented at a position angle of ≈35°, similar to some of the filamentary structure seen in the optical reflection nebula. It should be noted that this orientation of the filaments is similar to the polarization angle of background star polarization in the region of vdB 68 as measured by Jarrett et al. (1994) in the R band, which indicates the projected direction of the local magnetic field.

On the Digitized Sky Survey (DSS) blue and red images, an extensive system of filaments is seen in absorption against the background reflection nebulosity in the area south and east of vdB 67, such localized reflection nebulae. Reflection nebulae, in particular of bipolar or cometary morphology, are produced by light scattered from the inside walls of the cavity produced by an outflow in the molecular material surrounding a young star. While the association of reflection nebulae with a young age of an individual star and with outflow activity is less direct than for H2 jets, the presence of large numbers of these localized reflection nebulae nevertheless indicates a population of very young stars, probably stars just after their main accretion and outflow phase.

3.2. Previously Known Outflows

The overwhelming size and total mass of the main Mon R2 CO outflow (Loren 1981) makes it difficult to find evidence for other outflows in the velocity field measured in 12CO(2–1) or 13CO(2–1). It should be noted that Meyers-Rice & Lada (1991) have argued that the distribution of high-velocity CO gas in this main outflow can only be explained by a superposition of two independent outflows with different orientations, one almost head-on and the other more inclined to produce the bipolar appearance. Despite the overwhelming emission from these two main outflows, two additional possible outflows associated with the Mon R2 cluster have been discovered by CO emission-line mapping by Tafalla et al. (1997), and a third possible outflow (a microjet from IRS 3) was found by Preibisch et al. (2002).

The 12CO(2–1) and 13CO(2–1) velocity channel maps of Tafalla et al. (1997; their Figs. 3 and 4) show a redshifted high-velocity component (Mon R2-N) about 80″ to the north of the central cluster, coinciding with “object 1” of Cohen & Frogel (1977). This object is the brightest of a group of embedded stars north of the ringlike reflection nebula and is itself embedded in a reflection nebulosity with a complex filamentary structure shown in Figure 2. The brightest star in this subgroup of the Mon R2 cluster is located at 6h7m45.9s, −6°21′47″. Also, Tafalla et al. (1997) discuss a strongly blueshifted 12CO feature (−100″, −40″) from IRS 1 that also coincides with an enhancement of CS emission, indicating the presence of a deeply embedded object. We refer to this object, using the initials of the authors, as “TBWW97 CO jet.”

The Spitzer 4.5 μm image shows the same object morphology and confirms that the marginally extended 2.12 μm object is not an embedded star. The Spitzer 8.0 μm image shows extended emission in this region. The high-velocity CO gas and the shock-excited...
H$_2$ emission indicate a spatially compact outflow without a clear jet morphology. This object is shown near the western edge of Figure 2 (labeled “CO”) and in the top left panel of Figure 3.

The infrared source IRS 3 was noted by Beckwith et al. (1976) to be extended and was later resolved into a number of sources. The highest spatial resolution images are the speckle interferometry results by Preibisch et al. (2002) that list point sources IRS 3 A–F, of which A, B, and C are associated with strong reflection nebulosity, and B is possibly associated with a microjet of about 0.5" length. The detailed CO velocity maps by Giannakopoulou et al. (1997) show that IRS 3 is not associated with the big Mon R2 CO outflow, but that it is a separate source of very high-velocity CO outflow, even though a clear bipolar feature was not detected.

3.3. The Spatial Distribution of H$_2$ Jets

The newly discovered H$_2$ jets are overlaid in Figure 1 as circles with labels. Also overlaid are the lowest contours of the blueshifted and redshifted features in the CO map of Wolf et al. (1990). Their map was chosen over the higher spatial resolution maps of Meyers-Rice & Lada (1991) and Tafalla et al. (1997), since it covers a larger area with higher sensitivity to faint extended features. The only sites of star formation lying clearly outside of the CO outflow lobes are the newly discovered HOD07 1 to the west of the main cluster and the previously known young object GGD 11. The longest of the newly discovered H$_2$ jets (HOD07 13) lies just south of the redshifted CO lobe.

The CO outflows probably have a shell structure with a relatively empty cavity near the outflow axis (Meyers-Rice & Lada 1991). Since the outflowing material interacts turbulently with the molecular material of the ambient cloud, triggered star formation would be expected near the interface between the shell and the ambient cloud. In projection, the highest density of triggered star formation sites would be expected where we look tangentially along the shell wall and a smaller number where we look onto the front and back sides of the outflow shells. The overall distribution of newly found H$_2$ jets outside of the central cluster roughly matches this expectation. Note in particular that the small cluster associated with HH 866 is projected against the tip of the blueshifted CO contour of Wolf et al. (1990) and that the group of H$_2$ jets HOD07 2, 3, 6, 8, and 9 lie close to the eastern edge of the blueshifted CO contour and behind two secondary blueshifted CO emission maxima. These spatial coincidences strongly suggest that sites of recent star formation outside the main Mon R2 cluster may have been triggered by turbulent interaction of the massive main Mon R2 outflow with ambient molecular material.

In the following we discuss the newly discovered H$_2$ jets individually on the basis of their morphology and, when available, by a comparison of the near-infrared 2.12 $\mu$m S(1) image to longer wavelength Spitzer images. The objects are numbered in sequence of increasing right ascension and labeled by the prefix HOD07. All coordinates are given in the J2000.0 system. To allow easy comparison of their sizes, the overview 2.12 $\mu$m images based on the UKIRT WFCAM data (and Fig. 13) are all shown on the same spatial scale, with the exception of Figures 18 and 19, where this was not practical. Similarly, the detailed views in the figures comparing WFCAM and Spitzer IRAC results are all on the same, but finer, spatial scale.

The small localized reflection nebulae that we found on our 2.12 $\mu$m image but did not classify as jets are listed in Table 2 and are indicated by squares in Figures 1 and 2. These localized reflection nebulae are concentrated to the south of the Mon R2 cluster, closer to the cluster than the H$_2$ jets found to the south and southwest of the cluster. Since the reflection nebulae represent a more advanced state of star formation than the jets, this distribution might indicate a sequence of triggered star formation to the south of the main Mon R2 cluster, in the region where the blueshifted and redshifted CO contours overlap.

3.4. Discussion of Individual H$_2$ Jets

3.4.1. HOD07 1

The H$_2$ jet HOD07 1 has a very symmetric bipolar appearance, as shown in Figure 4. We note a high degree of similarity in the shape and relative intensity of corresponding knots in the two lobes of the jet. We interpret the two extended patches of nebulosity $\approx 3''$ east (labeled 1E) and west (labeled 1W) of the apparent center of symmetry at coordinates $6^h7^m10^s$, $-6^d2^m34^s$ (Fig. 4,
circle) as emission or scattered light from the two outflow cavities, and we assume that the driving source is hidden from direct view and located near that position in the dark region between those two emission knots. From this position, the eastern jet lobe has a position angle of \( \approx 60^{\circ} \). Since HOD07 1 is not included in the publicly released Spitzer images of the Mon R2 region, this position of the central source could not be confirmed by longer wavelength data.

Going symmetrically outward from the assumed position of the driving source, there is a pair of faint emission knots at \( \theta^{h}m^{m}9.5^{s}, -6^{h}26^{m}44^{s} \) (2W) and \( \theta^{h}m^{m}11.6^{s}, -6^{h}26^{m}22^{s} \) (2E). The next pair of relatively faint emission knots is at \( \theta^{h}m^{m}9.0^{s}, -6^{h}26^{m}46^{s} \) (3W) and \( \theta^{h}m^{m}12.4^{s}, -6^{h}26^{m}16^{s} \) (3E). Further away from the central source we find two complex systems of bright emission knots, containing two (west) and three (east) individual knots, centered at \( \theta^{h}m^{m}8.2^{s}, -6^{h}26^{m}52^{s} \) (4W) and \( \theta^{h}m^{m}12.9^{s}, -6^{h}26^{m}11^{s} \) (4E), respectively. Both of these emission regions show a bend of \( \approx 45^{\circ} \) to the left in the direction of motion. To the west of the central source at \( \theta^{h}m^{m}7.5^{s}, -6^{h}26^{m}54^{s} \) (5W) there is one additional very strong emission knot of approximately triangular shape with no detectable counterpart in the east. Finally, the most distant, approximately symmetric set of faint shock emission features is located at \( \theta^{h}m^{m}6.3^{s}, -6^{h}26^{m}57^{s} \) (6W) and \( \theta^{h}m^{m}16.7^{s}, -6^{h}25^{m}53^{s} \) (6E). (On the east side, this faint extended nebulosity coincides with the images of several stars, but there is no evidence to suggest that these stars are physically associated with the outflow.

It is noteworthy that the bend in the otherwise straight bipolar jet coincides with the strongest emission knots. Bent or S-shaped jets as a result of disk precession in a binary system were discussed by Terquem et al. (1999) and Bate et al. (2000). We speculate that the main accretion and outflow event that produced these strong systems of emission knots was triggered by a close stellar encounter, most likely with a binary star component on an elliptical orbit, and that this encounter was also responsible for a change in the disk orientation and therefore the jet direction.

3.4.2. HOD07 2

The extended \( S(1) \) emission with shocklike morphology labeled HOD07 2 in Figure 5 at \( \theta^{h}m^{m}30.5^{s}, -6^{h}11^{m}51^{s} \) consists of two distinct knots of emission, suggesting that this is a short jet (P.A. \( \approx 120^{\circ} \)) originating from a star that itself is too obscured to be directly visible. The position of the more compact shock emission knot is the position given above and in Table 1. The Spitzer \( 8 \mu m \) image (Fig. 6, bottom panel) shows extended emission centered on a point source at \( \theta^{h}m^{m}30.9^{s}, -6^{h}11^{m}48^{s} \). While this point source indicates other ongoing star formation activity in this region, its position does not coincide with the jet HOD07 2, and it therefore cannot be identified with the driving source of this jet.

3.4.3. HOD07 3

The bow shock HOD07 3 (Fig. 5) at \( \theta^{h}m^{m}31.6^{s}, -6^{h}12^{m}47^{s} \) is probably driven by a source some distance away to the southeast of the shock. Projecting back from the bow shock in this direction (P.A. \( \approx 147^{\circ} \)) we find a string of faint, slightly extended knots of \( 2.12 \mu m \) emission. These faint emission features, indicated by arrows in Figure 5, are located at \( \theta^{h}m^{m}33.2^{s}, -6^{h}13^{m}03^{s} \), \( \theta^{h}m^{m}34.1^{s}, -6^{h}13^{m}24^{s} \), and \( \theta^{h}m^{m}39.3^{s}, -6^{h}14^{m}01^{s} \). Overall, they appear to form a jet with multiple, faint internal shocks, ending in the bright bow shock.

3.4.4. HOD07 4

Two knots of \( H_2 \) emission are visible to the west of the star at \( \theta^{h}m^{m}35.3^{s}, -6^{h}20^{m}00^{s} \) in Figure 7 and the top left panel of Figure 8. However, the extended nebulosity associated with the southernmost of these emission knots does not appear to be connected with the star, strongly suggesting that this star may not be physically associated with the \( H_2 \) emission. A second, fainter system of \( H_2 \) emission with a bow shock morphology is visible at \( \theta^{h}m^{m}35.9^{s}, -6^{h}19^{m}56^{s} \), to the east-northeast of this star. The IRAC 3.6 \( \mu m \) (not shown here) and 4.5 \( \mu m \) images (Fig. 8, top middle panel) show faint curved nebulosity connecting the 2.12 \( \mu m \) features with a very faint star at position \( \theta^{h}m^{m}37.6^{s}, -6^{h}19^{m}54^{s} \) that is visible on the 2.12 \( \mu m \) UKIRT image, as well as on the two shorter wavelength IRAC images. There is no evidence for a counterjet, bent or straight, emerging from the position of that faint star. Unfortunately, the longer wavelength IRAC archival images at this position are not of usable quality. From the available data we conclude that the \( S(1) \)
shock emission and the S-shaped feature in the IRAC 3.6 and 4.5 μm images represent the less obscured parts of a jet emerging from the star at \(6^h7^m37.6^s, -6^\circ19'54''\). To explain the bending of the jet, it must be emitted from a precessing disk, similar to the case of IRAS 03256+3055 in NGC 1333 discussed by Hodapp et al. (2005).

### 3.4.5. HOD07 5

The position given here for HOD07 5, \(6^h7^m38.7^s, -6^\circ21'14''\), indicated by a circle in Figure 7 and the middle left panel of Figure 8, is that of a faint extended-emission feature near the apparent symmetry center of a system of shocks oriented at a position angle of \(\approx 32''\). This central object is visible on the UKIRT 2.12 μm image but is much brighter on the Spitzer 4.5 μm image, indicating heavy obscuration. Also, the 2.12 μm image of this central feature shows a marginally detected bifurcation, indicating a disk seen in absorption against the extended emission or a disk shadow. We tentatively conclude that the driving source is not directly visible at near-infrared wavelengths, but that emission and/or scattered light very close to the source has been detected, and that the collimating disk is seen nearly edge-on. From this driving source, the jet extends along a position angle of \(\approx 30''\). The closest pair of shock emission knots is about \(5''\) to the north and south of the driving source. A second pair of emission features \(\approx 20''\) to the north and south appears less symmetric, with the southern shock extending further away from the source.

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**Fig. 6.** — Comparison of 2.12 μm and IRAC 4.5 and 8.0 μm images of two separate systems of H2 knots. HOD07 2 at \(6^h7^m30.5^s, -6^\circ11'51''\) is a small jet with several internal shocks, and the position given is that of the most compact knot. The 8.0 μm Spitzer image shows extended nebulosity and a point source that, however, cannot be identified as the central source of the jet. The bow shock HOD07 3 is located at \(6^h7^m31.6^s, -6^\circ12'46''\). The driving source of this bow shock could not be identified.
3.4.6. **HOD07 6**

To the west of the center of Figure 9 and in the top panels of Figure 10, a faint string of four $2.12\mu m$ $S(1)$ emission knots (labeled 6) and one larger emission knot further to the southwest at $6^h7^m38.7^s, -6^\circ21'14''$ are all roughly aligned at P.A. $\approx 45^\circ$. The position of the central source cannot be determined with any certainty, and the *Spitzer* images do not provide additional information in this case. For lack of any better information, we list this jet by the coordinates of the approximate center of symmetry of the four northernmost emission knots located at $6^h7^m41.2^s, -6^\circ11'14''$, implicitly assuming this as a plausible position of a central source if these knots are, as in many other cases, symmetric shock fronts in a bipolar jet.

3.4.7. **HOD07 7**

The position given for this object in Table 1 is that of a faint star at $6^h7^m41.5^s, -6^\circ21'28''$, roughly between two bright knots of $S(1)$ emission in Figure 7 and the bottom panels of Figure 8 that define a jet axis along P.A. $\approx 30^\circ$. Faint filamentary emission extends back from the shocks to the immediate vicinity of this star, strongly suggesting that it is the source of the jet. On the $2.12\mu m$ image, the northern jet bends to the east and the southern jet to the west about $8''-10''$ from the star, suggesting a strongly precessing jet. The two brightest $S(1)$ emission knots are located near the bend in the jet in the north and slightly beyond it in the south. This jet morphology can be understood by assuming that the bent, contiguous jet was formed by a precessing driving source. The two emission knots lying outside of the contiguous jets could be the product of a single burst of higher outflow velocity. The fact that these higher velocity knots were emitted in the same projected direction as the strongest bend in the jet may indicate that the strong precession of the driving source’s accretion disk that caused this bend may also have caused the higher accretion rate that in turn produced the higher outflow intensity and velocity found in the two brighter knots.

The IRAC $3.6\mu m$ (not shown here) and $4.5\mu m$ (Fig. 8, bottom middle) images show the strongest and spatially extended emission associated with the northern of the two $S(1)$ emission regions.

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**Fig. 7.** — A $2.12\mu m$ $S(1)$ line + continuum image containing three separate systems of H$_2$ knots. HOD07 4 at $6^h7^m35.3^s, -6^\circ20'0''$ appears as a star with nebulous knots. As shown in Fig. 8, this position is most likely not the central source of this outflow. HOD07 5 at $6^h7^m38.7^s, -6^\circ21'14''$ is the likely central star of this bipolar jet. HOD07 7 at $6^h7^m41.5^s, -6^\circ21'28''$ is the likely position of the outflow center of that jet.

**Fig. 8.** — The $2.12\mu m$ $S(1)$, $4.5\mu m$, and $8.0\mu m$ images of the three systems of H$_2$ knots found in the area of Fig. 7. The driving source of HOD07 4 is probably located at $6^h7^m37.6^s, -6^\circ19'54''$, marked by a very faint star and the apex of the jetlike nebulousity of the *Spitzer* $4.5\mu m$ image. HOD07 5 lies at $6^h7^m38.7^s, -6^\circ21'14''$, identified by a faint source at the approximate center of symmetry of the bipolar jet. HOD07 7 at $6^h7^m41.5^s, -6^\circ21'28''$ is the likely position of the driving source of a bipolar jet.
To the east of this object, extended emission is seen both in the S(1) image and in the IRAC 4.5 and 8.0 μm images, and this emission appears to be associated with a filament extending from the Mon R2 central cluster. Whether this filament is physically close to the driving source of the outflow or whether the outflow interacts with the filament cannot be conclusively determined. However, the different emission flux levels in the northern and southern lobe could be understood if the northern jet ran into denser material.

3.4.8. **HOD07 8**

On the 2.12 μm image in Figure 9, this jet extends from an unresolved object at 6$^h$7$^m$43.7$^s$, −6°10′46″ to a knot at 6$^h$7$^m$44.4$^s$, −6°10′11″, a position angle of 16° and distance of 36″ corresponding to a projected length of 0.14 pc. The jet axis is outlined by extended 2.12 μm emission. The only bright 8.0 μm object (Fig. 10) associated with this jet is the southern emission knot. It is therefore likely that this 8.0 μm object is the central star driving a jet where predominantly only one side is visible. The position of this bright mid-infrared source is listed as the position of the jet in Table 1 and shown in Figures 9 and 10. On the 2.12 μm image, emission extends about 2.5″ to the south of the unresolved central source, suggesting that this is part of the jet’s southern lobe.

3.4.9. **HOD07 9**

In Figure 9 a well-developed bow shock is located to the west of a star at 6$^h$7$^m$44.0$^s$, −6°11′2″. An emission feature behind the bow shock, near the center of the arc formed by the bow, could be a Mach disk associated with the bow shock. The driving source of this bow shock cannot be determined with certainty from the data available to us. We are discussing two possible identifications for the driving source. The most plausible candidate for the driving source of this bow shock is the star at 6$^h$7$^m$44.0$^s$, −6°11′02″ that is the second brightest 4.5 and 8.0 μm source in Figure 10 and that shows extended emission on the S(1) image indicating an illuminated outflow cavity opening toward the west. We use this position at 6$^h$7$^m$44.0$^s$, −6°11′2″ as the nominal position of this jet in Table 1.

A much fainter, slightly extended object is visible on the UKIRT S(1) image at 6$^h$7$^m$43.6$^s$, −6°10′58″ and is also detectable, partly blended with the object described just above, on the Spitzer 4.5 μm image. The only reason to consider this object as an alternative candidate for the driving source of the bow shock is that it is more precisely located on the symmetry axis of the bow shock. This object, on the other hand, is also located on the axis of the jet source HOD07 8 and may just be another shock front of the southern part of that jet. The brightest source in Figure 10 at any of the wavelengths discussed here is a cometary reflection nebula at 6$^h$7$^m$43.4$^s$, −6°11′16″ that we list as reflection nebula R5 in Table 2.

3.4.10. **HOD07 10**

Just west of its center, Figure 2 shows 2.12 μm S(1) emission with the morphology of a jet ending in a bow shock at 6$^h$7$^m$43.0$^s$, −6°24′20″. This object is also shown in Figure 3 (bottom panels).
While there are a number of faint features to the northeast of the bipolar nebula, no clear association of these features with the jet source can be established.

The bow shock is strongly detected in the Spitzer IRAC 4.5 μm image and is also indicated in the 8.0 μm image. It is not clear where the driving source for this jet is located. The jet can be traced to an extended feature located at 6\(^{h}\)7\(^{m}\)44.1\(^{s}\), –6°23′59″ and detected in both the 2.12 μm and IRAC 4.5 μm images. It is embedded in the emission surrounding the central Mon R2 cluster. This may be just another knot in a jet emerging from deep inside the molecular cloud, or this may indicate the position of the driving source. There is no enhanced flux in the 8.0 μm image at that position. Nevertheless, we adopt the position of this putative driving source as the formal coordinates of this jet, HOD07 10. A second shock front, located at 6\(^{h}\)7\(^{m}\)43.6\(^{s}\), –6°24′11″, appears as the brightest of a series of internal shocks along the jet axis, which is oriented at a position angle of 220°.

3.4.11. HOD07 11

The region shown in Figure 11 contains two separate systems of H\(_2\) knots shown in more detail in Figure 12. A well-defined bow shock located at 6\(^{h}\)7\(^{m}\)46.6\(^{s}\), –6°19′03″ and several fainter knots of 2.12 μm S(1) emission southwest from it suggest a jet with an axis oriented at P.A. ≈ 23°. The last S(1) emission knot at 6\(^{h}\)7\(^{m}\)46.9\(^{s}\), –6°20′6″ coincides with a faint Spitzer 4.5 μm object (Fig. 12, middle) but is most likely just the 4.5 μm emission of the same emission knot and not the driving source itself. The Spitzer 4.5 and 8.0 μm images in Figure 12 show a stronger mid-infrared source at approximately 6\(^{h}\)7\(^{m}\)46.8°, –6°20′12″, just southwest of the position of the last observed S(1) knot in this string. This object is not detected in our near-infrared S(1) image and therefore must be very deeply embedded. We tentatively identify this mid-infrared source as the driving source of the jet HOD07 11.

3.4.12. HOD07 12

The object at 6\(^{h}\)7\(^{m}\)49.8°, –6°20′43″ in Figure 11, HOD07 12, has the morphology of a faint bipolar nebula seen nearly edge-on, suggesting that it could be the source of a jet. The Spitzer 4.5 μm image in Figure 12 shows this object as an unresolved source, while the 8.0 μm image does not show the object. Two other knots of S(1) emission lie to the southeast at 6\(^{h}\)7\(^{m}\)51.6°, –6°20′58″ and at 6\(^{h}\)7\(^{m}\)54.9°, –6°21′57″, suggesting a jet axis at a position angle 152°. While there are a number of faint emission features to the northeast of the bipolar nebula, e.g., at 6\(^{h}\)7\(^{m}\)48.8°, –6°20′23″, no clear association of these features with the jet source can be established. We tentatively identify the bipolar nebula as the driving source of HOD07 12 based on its morphology. A much brighter star, also associated with extended emission at 2.12 μm and in the Spitzer bands and located at 6\(^{h}\)7\(^{m}\)49.14°, –6°20′33″, also lies on the jet axis and is surrounded by some 2.12 μm emission. It is the brightest source in the area on the Spitzer 8.0 μm image, indicating that it is a luminous, deeply embedded object.

3.4.13. HOD07 13

The nearly symmetric system of H\(_2\) shocks labeled HOD07 13 and located south of the Mon R2 cluster is the largest jet found in our survey. The center of outflow HOD07 13 is clearly identifiable by an object on our S(1) image (Figs. 13 and 14) at position 6\(^{h}\)7\(^{m}\)57.4°, –6°31′6″. From this object, the northern jet extends along a position angle of 13°. Unfortunately, the available 4.5 and 8.0 μm Spitzer images do not extend sufficiently far south to include this object. However, all 2.12 μm features of this object are confirmed by the Spitzer 3.6 μm image (Fig. 13, right) that shows essentially the same outflow shock features.

A magnified view of the central region of this outflow is shown in Figure 14. Immediately north of the central object, a faint string of emission knots is visible, stretching about 15° to the north. There is no counterpart to this knotty jet to the south of the central source, indicating that the jet is inclined with its northern part toward the observer and that the southern counterjet is obscured by molecular material surrounding the central source. However, the IRAC 3.6 μm image shows a faint outline of a paraboloid outflow cavity wall to the south.

More distant S(1) emission shock regions show a remarkable level of symmetry, since they are not affected by the obscuring material surrounding the central source. The first pair of emission

![Fig. 12](image-url)
regions are two complex regions, each showing two strands of emission knots, centered roughly at $6^h7^m56.3^s$, $-6^\circ29'39''$ (labeled 1N) and $6^h7^m57.9^s$, $-6^\circ32'23''$ (labeled 1S). Further out, we find a symmetric pair of fainter shock fronts at $6^h7^m55.7^s$, $-6^\circ29'4''$ (2N) and $6^h7^m58.3^s$, $-6^\circ32'56''$ (2S). The shock fronts farthest removed from the central source show substructure that is again similar in both the northern and southern jet: a symmetric pair of shock fronts at $6^h7^m54.1^s$, $-6^\circ27'33''$ (3N) and $6^h8^m00.2^s$, $-6^\circ34'30''$ (3S). Finally, the leading shock fronts are found at $6^h7^m53.8^s$, $-6^\circ27'19''$ (4N) and $6^h8^m01.0^s$, $-6^\circ34'43''$ (4S). The total projected length of this jet is $\approx 7.5'\text{'},$ corresponding to $1.8\text{ pc}.$

3.4.14. HOD07 14

The compact, bipolar jet HOD07 14 (Fig. 15 and Fig. 16, top panels) is characterized by two bright shock fronts, at $6^h7^m57.8^s$, $-6^\circ25'26''$ and at $6^h8^m00.0^s$, $-6^\circ25'40''$, that define a jet axis at a position angle of $\approx 114^\circ$. The Spitzer 4.5 $\mu m$ image (Fig. 16, top middle panel) confirms the emission seen at $2.12\mu m$ but also shows additional emission, possibly indicative of a second jet parallel to HOD07 14 but more deeply embedded and therefore not visible in the near-infrared. The only indication of the position of the driving source of HOD07 14 is a flux minimum in

![Image](2.12\mu m) ![Image](3.6\mu m)
the Spitzer 8.0 μm image, possibly a dense molecular clump seen in absorption against background emission. This argument would place the driving source at approximately 6ʰ7ᵐ58.9ˢ, -6°25′33″. The central source of HOD07 15 is located near 6ʰ8ᵐ10.0ˢ, -6°24′47″.

3.4.15. HOD07 15

The UKIRT S(1) image (Fig. 15) shows a nearly symmetric, bent system of shock fronts, with two bright shocks both to the north and to the south of the assumed position of the driving source. In addition, on each side, one fainter, extended shock is visible further away from the center of symmetry. The Spitzer 4.5 μm image (Fig. 16, bottom middle panel) shows two additional emission knots in the jet, closer to the center, while the Spitzer 8.0 μm image shows a flux minimum between those two strongly obscured 4.5 μm shocks. We identify this position, approximately 6ʰ8ᵐ10.0ˢ, -6°24′47″, as the position of the driving source of the jet HOD07 15 in Table 1 and Figure 15.

3.5. Other Bipolar and Cometary Nebulae

The area near the Mon R2 cluster contains numerous small patches of nebulosity, often with bipolar or cometary morphology, that did not fit our criteria for identification as shocks or jets. We list those objects in Table 2 and indicate them with squares in Figures 1 and 2. The bipolar or cometary shape of many of these objects suggests that these are young, embedded stars still surrounded by disks and that they have just excavated an outflow cavity in the surrounding molecular material. These objects appear particularly numerous in the area about 2°–3° south of the main Mon R2 cluster and just north of the cluster, as demonstrated in Figures 1 and 2. This finding is consistent with the result by Gutermuth (2005) that the Class I sources in Mon R2, identified by their JHK and Spitzer IRAC colors, are concentrated in a filamentary distribution to the south of the cluster center and to the north and northeast of the cluster. While there is no strict relationship between reflection nebulae of bipolar or cometary morphology and SED Class I, the two criteria cover objects of similar evolutionary status at the trailing edge of their accretion phase. The main difference between the distribution of reflection nebulae and of the Class I sources identified by Gutermuth (2005) is that we find fewer individual reflection nebulae in the region dominated by the large, ringlike reflection nebula and the filamentary emission that dominates the center of the cluster. We attribute this difference largely to the difficulty of identifying small reflection nebulae around individual stars by morphological criteria in this crowded central region of the Mon R2 cluster.

By comparison, Gutermuth (2005) found that the older Class II sources, identified by J-, H-, and K-band colors, are more uniformly distributed around the Mon R2 cluster center, indicating a dynamically more relaxed population of more developed young stars.

4. OTHER INTERESTING OBJECTS IN THE FIELD

4.1. HH 866

The group of Herbig-Haro objects HH 866, found by Wang et al. (2005) in the L1646 cloud, was included in our field (Figs. 1 and 17). The HH objects are associated with the IRAS source 06046−0603. The region was identified by Carpenter (2000) as a region of enhanced star density in 2MASS data and was identified as a
potential CO outflow source by Xu et al. (2001). Our UKIRT WFCAM 2.12 μm image shows a system of features that can be morphologically identified as likely H$_2$ shocks.

The main system of emission knots in the center of Figure 17 is extended roughly in a north-south direction and is probably physically associated with the bow shock at 6$^\text{h}$7$^\text{m}$07.5$^\text{s}$, −6$^\circ$04′36″. The position of the driving source of this jet cannot be determined with certainty. We tentatively list the center of symmetry of the brightest H$_2$ emission knots at 6$^\text{h}$7$^\text{m}$07.9$^\text{s}$, −6$^\circ$03′42″ as the position of the driving source, and we name this jet “HH 866 Jet W” in Table 1. The central parts of this north-south jet coincide closely with knots A, B, and C in the Hα and [S ii] images of Wang et al. (2005). To the east of this position is a large, rather poorly defined bow shock at 6$^\text{h}$7$^\text{m}$08.1$^\text{s}$, −6$^\circ$03′36″ that appears to be associated with more shock emission knots further east of it. A plausible identification of the driving source is a star embedded in nebulosity at 6$^\text{h}$7$^\text{m}$09.8$^\text{s}$, −6$^\circ$03′44″. The nebulosity around this star was also noted by Wang et al. (2005), and the star is labeled “1” in their Hα image. Our image resolves this object into two stars, the eastern and fainter of which is associated with the nebulosity and is the likely outflow source. We list the position of this star as “HH 866 Jet E” in Table 1.

4.2. GGD 11

The bipolar reflection nebula GGD 11 (Gyulbudaghian et al. 1978) was included in our UKIRT WFCAM image and in Figure 1. We show a more detailed view of this object in Figure 18, because our image is, to our knowledge, the best available near-infrared image of GGD 11. This object has the typical morphology of a bipolar nebula, with the eastern lobe being far brighter than the western lobe, due to inclination of the object. The brightness distribution is fairly smooth, in contrast to the knotty and filamentary appearance of typical H$_2$ jets.

4.3. NGC 2182

The NGC 2182 reflection nebula was included in our UKIRT WFCAM image even though it is not included in the image section shown in Figure 1. It is shown in detail in Figure 19. Different from the smooth appearance of this object on optical photographs, e.g., on the red plate of the DSS2, and on the K-band 2MASS image, the UKIRT 2.12 μm S(1) image shows two filamentary regions of enhanced S(1) line emission to the west of the illuminating star. We cannot determine the excitation mechanism of these two filaments just from one image, and both fluorescent excitation and shock excitation are possible.

5. COMPARISON WITH OTHER STAR-FORMING REGIONS

In our 2.12 μm imaging survey of the Mon R2 molecular cloud for H$_2$ jets associated with forming stars, we have found a total of 15 new H$_2$ jets in Mon R2 and two additional H$_2$ jets in the L1646 (HH 866) region. Together with the two outflows detected in CO by Tafalla et al. (1997) and the IRS 3 microjet found by Preibisch et al. (2002), this gives a minimum of 20 active jets and outflows in the larger area of Mon R2 (including the L1646 region), in addition to the huge, but probably inactive, CO outflow found by Loren (1981). The spatial distribution of the H$_2$ jets in Mon R2 along the projected edge of the large CO outflow, in particular the cluster of H$_2$ jets 12′ north of the Mon R2 main cluster, suggests that this star formation activity was triggered by the huge fossil CO outflow in Mon R2, one of the largest outflows known.

By comparison, in a similar survey of Orion A, Stanke et al. (2002) found 44 jets with a high degree of certainty and 29 less certain cases. Considering that their survey area was larger than ours, and the Orion A cloud is more massive than the Mon R2 cloud, this comparison implies a similar specific star formation rate in both clouds. The level of outflow activity in Mon R2 is also similar to that found in the two massive star-forming regions DR21 and W75, where Davis et al. (2007) found a combined number of approximately 50 H$_2$ jet sources based on a similar UKIRT WFCAM image.
NGC 1333 is one of the most active star-forming regions in the solar vicinity, and Bally et al. (1996) list 15 optical Herbig-Haro objects, H$_2$ jets, and CO outflows in this region. This region is closer to the Sun than the other regions discussed before, and the discovery of jets is therefore easier. In the Perseus molecular cloud as a whole, of which NGC 1333 is a part, Walawender et al. (2005b) counted a total of 141 optically (H$_2$ and [Sii]) detectable Herbig-Haro objects that, at the minimum, belong to 30 individual outflows. The smaller Barnard 1 cloud ($\approx$1200 M$_\odot$) was found by Walawender et al. (2005a) to have eight protostars driving outflows. Also, Bally et al. (2006) found a total of at least 20 outflows in the Chamaeleon I molecular cloud, mostly by an optical search supported by Spitzer data. Chamaeleon I is a nearby (165 pc), relatively low-mass (1000 M$_\odot$) cloud. In light of the different techniques used to search for collimated jets from young stars in these different regions, we conclude that the number of such jets discovered in Mon R2 is similar to that found in the other massive star-forming regions.

While it may be argued that the presence of reflection nebulous, fluorescently excited H$_2$ emission, and PAH emission makes the discovery of shock-excited H$_2$ emission near the central cluster of Mon R2 difficult, this is also the region most intensely studied in the past, and only the IRS 3 microjet was found there. By contrast, most of our newly discovered jets are located in the periphery of the central cluster, and the longest collimated jets were found farthest away from the central cluster. The complete absence of large H$_2$ jets near the center of the Mon R2 cluster cannot be explained by observational selection effects alone and suggests that H$_2$ jets do not form in this environment.

This is in agreement with the finding in DR21/W75 by Davis et al. (2007), who conclude that the H$_2$ jets in their sample are usually not associated with young molecular cores detectable at submillimeter wavelengths or with compact infrared clusters. They further conclude that clustering may inhibit disk accretion and the production of extensive flows. A similar conclusion can also be drawn from the extensive survey of the Orion A cloud for H$_2$ jets by Stanke et al. (2002). In Orion A, H$_2$ jets are predominantly found outside the area of the Trapezium cluster and the Orion nebula. Also, Hodapp (1994) noted in their $K'$ imaging survey of CO outflow sources that member objects of large young clusters are less likely to show jets or localized reflection nebulosity than young objects in smaller groupings.

6. CONCLUSIONS

Our UKIRT WFCAM imaging survey of the Mon R2 molecular cloud for H$_2$ jets associated with forming stars was based on a 2.12 $\mu$m H$_2$ 1–0 S(1) plus continuum image. Object identification was based on morphology and confirmation by archival Spitzer images. We have found a total of 17 new H$_2$ jets, including the two in L1646, as well as 27 small reflection nebulae.

We conclude that the number of H$_2$ jet sources in Mon R2 is similar to that found in other star-forming regions of comparable size. We note that the H$_2$ jets appear to be concentrated in projection against the walls of the outflow cavity created by the large Mon R2 CO outflow. This is indicative of a scenario of sequential star formation in Mon R2 triggered by the large outflow.

We confirm the finding in other high-mass star-forming regions that H$_2$ jets tend to be found outside of the dense central cluster in such regions. It appears that the environment of a dense cluster containing some massive stars prevents the formation of large H$_2$ jets.

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