The Monoceros R2 Molecular Cloud

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Abstract. The Monoceros R2 region was first recognized as a chain of reflection nebulae illuminated by A- and B-type stars. These nebulae are associated with a giant molecular cloud that is one of the closest massive star forming regions to the Sun. This chapter reviews the properties of the Mon R2 region, including the namesake reflection nebulae, the large scale molecular cloud, global star formation activity, and properties of prominent star forming regions in the cloud.

1. The Mon R2 Reflection Nebulae

The Monoceros R2 region is distinguished by a chain of reflection nebulae that extend over 2° on the sky. The brightest of these nebulae were studied as far back as Seares & Hubble (1920), and were included in a larger study of nebulous objects by Hubble (1922), who demonstrated that the extended emission can be attributed to the associated stars. The nebulae are included in the Catalog of Bright Diffuse Galactic Nebulae constructed by Cederblad (1946). Various lists of nebulae identified from inspection of the Palomar Observatory Sky Survey appear in Dorschner & Gürtler (1963, 1966), van den Bergh (1966), and Herbst & Racine (1976). Gyulbudaghian, Glushkov, & Denisyuk (1978) identified seven additional nebulous objects as candidate Herbig-Haro objects, although they were later shown to be reflection nebulae (Cohen & Schwartz 1980). The nomenclature “Mon R2” originated with van den Bergh (1966) to indicate the second association of reflection nebulae in the constellation Monoceros.

Table I lists the nebulous sources in the Mon R2 region identified in the studies mentioned above. Coordinates were determined from the digitized Palomar Sky Survey using previously published finding charts (Downes et al. 1975, Herbst & Racine 1976; Carballo, Eiroa, & Mampaso 1988) and coordinate lists (Rodríguez et al. 1980; Carballo & Eiroa 1992). Figure 1 marks the location of the nebulae on the blue print from the Palomar Observatory Sky Survey. The sources GGD 12 through 15 are located within a small area of the sky and are often collectively referred to as GGD 12-15. The most extensively studied region is the active star forming site embedded in a dense molecular core (identified as the “core” in Fig. 1) that lies midway between the reflection nebulae vdB 67 and vdB 69 (see Fig. 2 for a more detailed optical color image of

1The Mon R1 reflection nebulae are part of the Mon OB1 association, which includes the Galactic cluster NGC 2264.
Table 1. Optical Nebulae in the Mon R2 Region

| Source | α (J2000) | δ | SpT\textsuperscript{a} | vdB | DG | Ced | NGC |
|--------|-----------|---|----------------|-----|----|-----|-----|
| HR 1   | 6:06:58   | −5:55:10 | A0:            |     |    |     |     |
| HR 2   | 6:07:26   | −6:38:13 |                |     |    |     |     |
| HR 3   | 6:07:30   | −6:29:16 |                |     |    |     |     |
| HR 4   | 6:07:32   | −6:24:03 | B2 V           | 67  | 88 | 63  | 2170|
| HR 5a  | 6:07:46   | −6:21:47 | A5:            |     |    |     |     |
| HR 5b  | 6:07:46   | −6:23:02 |                |     |    |     |     |
| HR 6   | 6:07:49   | −6:16:35 |                |     |    |     |     |
| HR 7   | 6:07:48   | −6:26:46 |                |     |    |     |     |
| HR 8\textsuperscript{b} | 6:08:05 | −6:21:34 | B1 V          | 69  | 90 | 66  |     |
| HR 9\textsuperscript{b} | 6:08:04 | −6:13:38 | B2 V          | 68  | 89 | 65  |     |
| HR 10  | 6:08:26   | −6:20:19 | B1 V          | 70  | 91 |     |     |
| HR 11  | 6:09:15   | −6:30:29 |                |     |    |     |     |
| HR 12  | 6:09:25   | −6:18:35 |                |     |    |     |     |
| HR 13  | 6:09:31   | −6:19:36 | B3 V          | 72  | 93 | 68  | 2182|
| HR 14  | 6:09:45   | −6:18:35 | B5 V          |     |    |     |     |
| HR 15  | 6:10:01   | −6:18:42 | B8 V          |     |    |     |     |
| HR 16  | 6:10:15   | −6:27:32 |                |     |    |     |     |
| HR 17  | 6:10:37   | −6:09:58 |                |     |    |     |     |
| HR 18  | 6:10:47   | −6:12:41 |                | 94  | 69 | 2183|     |
| HR 19  | 6:10:56   | −6:14:22 |                |     |    |     |     |
| HR 20  | 6:10:57   | −6:16:21 |                |     |    |     |     |
| HR 21  | 6:11:00   | −6:14:36 |                |     |    |     |     |
| HR 22  | 6:11:06   | −6:12:33 | B8-A0         | 95  | 70 | 2185|     |
| HR 23  | 6:11:49   | −6:09:22 | B4 V          | 74  | 96 | 71  |     |
| HR 24  | 6:12:45   | −6:12:31 |                |     |    |     |     |
| HR 25  | 6:12:46   | −6:10:49 |                |     |    |     |     |
| HR 26  | 6:14:46   | −6:20:36 |                |     |    |     |     |
| HR 27  | 6:14:53   | −6:22:44 | B7 V          | 97  |    |     |     |
| HR 28  | 6:15:21   | −6:25:50 | B5 V          | 98  |    |     |     |
| HR 29\textsuperscript{c} | 6:12:50 | −6:13:11 | K4            |     |    |     |     |
| HR 30  | 6:10:58   | −6:14:39 | Be            |     |    |     |     |
| DG 92  | 6:08:30   | −6:30:30 |                |     |    |     |     |
| GGD 11 | 6:08:33   | −6:18:16 |                |     |    |     |     |
| GGD 12 | 6:10:45   | −6:12:45 |                |     |    |     |     |
| GGD 13 | 6:10:46   | −6:13:04 |                |     |    |     |     |
| GGD 14 | 6:10:50   | −6:12:01 |                |     |    |     |     |
| GGD 15 | 6:10:50   | −6:11:15 |                |     |    |     |     |
| GGD 16 | 6:12:44   | −6:15:24 |                |     |    |     |     |
| GGD 17 | 6:12:50   | −6:12:57 |                |     |    |     |     |

\textsuperscript{a} Spectral types from [Herbst & Racine (1976)] and [Carballo & Eiroa (1992)].

\textsuperscript{b} [Herbst & Racine (1976)] associated HR 8 with vdB 69 and HR 9 with vdB 68. These designations are inconsistent with the coordinates of these sources and the finding chart in that paper (cf. Figure 8 in Downes et al. 1975). We have maintained the same designations in [Herbst & Racine (1976)], and have updated the finding chart in Fig. 1 accordingly.

\textsuperscript{c} T Tauri star also known as Bretz 4 [Herbig & Rao (1972)].

Ced : [Cederblad (1946)]

DG : [Dorschner & Gürtler (1963)]

GGD : [Gyulbudaghian, Glushkov, & Denisyuk (1978)]

HR : [Herbst & Racine (1976)]

vdB : [van den Bergh (1966)]
Figure 1. Location of the optical nebulae in Mon R2 (see Table 1) marked on the blue print from the Palomar Observatory Sky Survey. The regions numbered 1-30 refer to the sources cataloged by Herbst & Racine (1976). The “GGD” and “DG” sources are the nebulous objects identified by Gyalbudaghian, Glushkov, & Denisyuk (1978) and Dorschner & Gürler (1963) respectively. The main Mon R2 star forming cloud core is also indicated.
this region). In many contexts, the name “Mon R2” refers to this particular star forming region.

Racine (1968, see also Herbst & Racine 1976) conducted the first detailed spectroscopic and photometric study of the Mon R2 nebulae and found that the illuminating stars have mainly B spectral types, where B1 V is the earliest type star in the association. Herbst & Racine (1976) estimated an age of 6 to 10 Myr for the association. The lower limit is ascertained since the color-magnitude diagram for the Mon R2 stellar population does not deviate from the zero-age main-sequence for stars with \((B-V)_0 \leq 0.05\) mag, while a pre-main-sequence population is observed for such stars in other clusters such as the Orion Nebula Cluster and NGC 2264. The upper age limit was inferred since the B1 stars in the association still lie on the main-sequence. As noted by Herbst & Racine (1976), the young age for the association suggests that the B-stars likely formed within the cloud, and the reflection nebulae are not the result of a chance encounter of B-stars with a gas-cloud (c.f. the Pleiades; White 2003).

Racine (1968) estimated a distance of 830±50 pc to Mon R2 using spectroscopy and/or \(UBV\) photometry for 10 stars in the reflection nebulae. Using similar techniques, Rojkovskij & Kurchakov (1968, as reported in Downes et al. 1975) derived a distance of 700 pc. Racine & van den Bergh (1970) revised the distance from Racine
(1968) to 950 pc, but did not provide further details on the factors leading to the new estimate. Herbst & Racine (1976) fitted the zero-age-main-sequence locus from Johnson (1963) to dereddened $UBV$ photometry and also obtained a distance of $830 \pm 50$ pc, which is the distance typically adopted for the Mon R2 association.

2. The Mon R2 Molecular Cloud

In addition to bright reflection nebulae, the Mon R2 region is readily identified on optical photographs as an opaque region in silhouette against the backdrop of field stars (see Fig. 2). Lynds (1962) identified 4 prominent “dark nebulae” (L1643, 1644, 1645, and 1646) that form the main part of the molecular cloud that is associated with the reflection nebulae. An extinction map of the Mon R2 region derived from optical star counts by Dobashi et al. (2005) is presented in Figure 3 that clearly delineates the Mon R2 region (labeled TGU 1493 in this map) and dark clouds in its vicinity.

![Figure 3. Extinction map in Galactic coordinates of the Mon R2 cloud and vicinity as derived from star counts in the Digital Sky Survey I database (Dobashi et al., 2005). The lowest contour indicates the $A_V = 0.5$ mag boundary. Symbols indicate identified clouds (filled circles) and clumps within clouds (plus signs). The Mon R2 cloud is object TGU 1493 in the Dobashi et al. (2005) catalog at $(\ell, b \approx 214.3^\circ, -12.9^\circ)$, and includes Lynds (1962) dark nebulae L1643, 1644, 1645, and 1646. The main star forming core is near clump P2, and the GGD 12-15 region is near P8.](image-url)
Figure 4. Overview of the molecular clouds in the vicinity of Mon R2 from Maddalena et al. (1986). The contour show the integrated CO line emission between $-10$ and $20$ km s$^{-1}$ at a level of $1.28$ K km s$^{-1}$. The dots with numbers correspond to CO emission peaks listed in Table 1 in Maddalena et al. (1986).

2.1. Global Characteristics

The Mon R2 region received renewed interest with the first observations of carbon monoxide in the interstellar medium and the discovery of molecular clouds (Wilson, Jefferts, & Penzias 1970). Loren, Peters, & vanden Bout (1974) reported the first $^{12}$CO (J=1-0) detection in Mon R2, and Kutner & Tucker (1975) showed that at least five of the reflection nebulae are associated with local maxima in $^{12}$CO maps. A number of maps have subse-
Figure 5. Molecular line maps of the peak $^{12}$CO J=1-0 antenna temperature (bottom panel; Xie [1992]) and the $^{13}$CO J=1-0 integrated intensity (top panel; Miesch, Scalo, & Bally [1999]). Darker gray scales corresponds to regions of brighter emission.
sequently been made, with ever improving resolution and coverage, and increasing num-
ber of molecular species (Loren 1977; Maddalena et al. 1986; Montalbán et al. 1990; Xie & Goldsmith 1994; Miesch, Scalo, & Bally 1999; Kim et al. 2004; Wilson et al. 2005). A large-scale view of the molecular clouds in Orion and Monoceros as traced by carbon monoxide is shown in Figure 4 (Maddalena et al. 1986). The Mon R2 cloud extends over a \( \sim 3^\circ \times 6^\circ \) (44 pc \( \times \) 88 pc) region roughly parallel to the Galactic plane, but offset from the plane by \( \sim -12^\circ \). Mon R2 is located in projection near the Orion system of molecular clouds, although Orion is a factor of two closer in distance. Heiles (1998) has suggested that the two regions may nonetheless be linked by an expanding superbubble (GSH 238+00+09) that triggered star formation in these regions.

Figure 5 presents images of the J=1–0 emission from \(^{12}\)CO (Xie & Goldsmith 1994) and \(^{13}\)CO (Bally, Langer, & Liu 1991; Miesch, Scalo, & Bally 1999). The \(^{12}\)CO map, tracing approximately the kinetic temperature, shows a bright peak near the Mon R2 core and a sharp filament of gas extending in nearly a north-south direction. The \(^{13}\)CO image traces the molecular column density and shows several peaks in the molecular emission that correspond to the location of reflection nebulae. Xie & Goldsmith (1994) analyzed the global velocity field in the Mon R2 cloud as traced by \(^{12}\)CO and suggested the cloud is an expanding shell of molecular gas with a dynamical time scale of \( \sim 4 \) Myr. No clear energy source driving the expansion was identified, although the center of the shell is near the NGC 2182 reflection nebula. Xie (1992) estimated a cloud mass of \( 4 \times 10^4 \) \( M_\odot \) for the region shown in Figure 5 that has been observed in both \(^{12}\)CO and \(^{13}\)CO using traditional LTE analysis (Dickman 1978). The maps produced by Maddalena et al. (1986) encompass the entire cloud, and they estimated a higher mass of \( 9 \times 10^4 \) \( M_\odot \) by adopting a constant conversion factor from \(^{12}\)CO J=1-0 integrated intensity to \( H_2 \) column density (see, e.g., Strong et al. 1988).

### 2.2. Stellar Content

The global star formation activity in the Mon R2 molecular cloud has been explored at multiple wavelengths, including (1) ROSAT X-ray pointed observations to search for young stars, (2) 2MASS near-infrared and Spitzer mid-infrared observations to identify stellar clusters, (3) IRAS far-infrared images to probe for embedded star forming regions, (4) radio continuum surveys to identify embedded massive stars, and (5) \( H_2 \) imaging surveys to trace jets originating from young stars. The stellar content traced by these diagnostics paint a consistent picture where the Mon R2 and GGD 12-15 region are the two most active star forming sites in the Mon R2 molecular cloud. We now summarize the results from many of these observations.

The lower mass stellar content in the Mon R2 cloud has been investigated by Carpenter (2000), who used the 2MASS point source catalog to identify compact stellar clusters and quantify any stellar population distributed more uniformly over the cloud. Four clusters were found based on enhancements in the stellar surface density relative to the field star population as shown in Figure 6. These four clusters, listed in Table 2, are associated with the Mon R2 core (containing 371 stars brighter than \( K_\text{s}=14.3 \) after subtracting the expected field star population), GGD 12-15 (134 stars), GGD 17 (23 stars), and IRAS 06046-0603 (15 stars). Carpenter (2000) also assessed the magnitude of any distributed stellar population by measuring the surface density of stars toward the molecular cloud relative to the field star surface density. The number of stars contained in the distributed population is between 190 and 790 stars. These results suggest that an
Figure 6.  

**Upper left:** $K_s$-band stellar surface density map of the Mon R2 molecular cloud for stars with magnitudes of $6.0 \text{ mag} \leq m(K_s) \leq 14.3 \text{ mag}$. **Upper right:** The IRAS 60 µm image displayed in a logarithmic stretch. **Lower left:** An image of the average $J-K_s$ color for stars observed by 2MASS. **Lower right:** A map of the integrated $^{13}\text{CO}(J=1-0)$ intensity map (Miesch, Scalo, & Bally 1999). In each panel, darker halftones represent higher intensities. In the $K_s$-band density map and the average $J-K_s$ color image, the white “crosses” are regions around bright stars that were masked out in generating the 2MASS catalog. The sources labeled vdB are reflection nebulae cataloged by van den Bergh (1966), and sources labeled GGD are from the list of small nebulae noted by Gyulbudaghian, Glushkov, & Denisyuk (1978). Figure from Carpenter (2000).
Table 2. Embedded Stellar Clusters in the Mon R2 Molecular Cloud

| Region          | Galactic $\ell$ | Equatorial (J2000) $\alpha$ | Galactic $b$ | Equatorial (J2000) $\delta$ | N$_{stars}$ | $R_{eff}$ [pc] |
|-----------------|----------------|-------------------------------|--------------|-----------------------------|-------------|----------------|
| IRAS 06046-0603 | 213.3381       | 6:07:08.1                     | −12.6029     | −6:03:53                    | 15          | 0.41           |
| MonR2           | 213.6955       | 6:07:47.8                     | −12.5926     | −6:22:20                    | 371         | 1.85           |
| GGD 12-15       | 213.8745       | 6:10:49.1                     | −11.8410     | −6:11:38                    | 134         | 1.13           |
| GGD 17          | 214.1337       | 6:12:48.0                     | −11.4173     | −6:13:56                    | 23          | 0.61           |

Gregorio-Hetem et al. (1998) used ROSAT to conduct an X-ray survey over a 2° diameter region centered on the Mon R2 cloud. The highest resolution and sensitivity was achieved for the inner $\sim 35'$. They detected 41 point sources with a signal to noise ratio greater than 2.5, and possibly seven additional detections at lower confidence levels. The spatial distribution of the 41 X-ray sources are indicated in Figure 7. Based on the observed X-ray hardness ratios and the ratio of the X-ray to stellar bolometric luminosity, Gregorio-Hetem et al. (1998) suggest that most of the detected sources are analogous to Herbig Ae/Be stars and the more X-ray active T Tauri stars. Extended X-ray emission was detected as well, which may originate from partially resolved X-ray emitting young stars within the Mon R2 cloud.

IRAS provided a sensitive survey of the embedded stellar content over the entire Mon R2 molecular cloud. Xie (1992) selected a sample of 36 IRAS point sources having photometric properties consistent with star forming regions (see Beichman et al. 1986) in that (1) the sources are detected at 25 $\mu$m or both 60 $\mu$m and 100 $\mu$m, and (2) $S_\nu(25 \mu m) \geq S_\nu(12 \mu m)$. Table 3 lists the 36 IRAS sources meeting these criteria. The far-infrared luminosity for each source was estimated as $L_{IR}(L_\odot) = 4.7 \times 10^{-6} D^2 \left(\frac{S_\nu(12 \mu m)}{\nu^{3/2}} + \frac{S_\nu(25 \mu m)}{\nu^{3/2}} + \frac{S_\nu(60 \mu m)}{\nu^{3/2}} + \frac{S_\nu(100 \mu m)}{\nu^{3/2}}\right)$, where $D$ is the distance in parsecs and $S_\nu$ is the flux density in Janskys (Casoli et al. 1986; Parker 1991). Column 8 in Table 3 lists the IRAS luminosity computed from the four IRAS bands. For sources where an upper limit to the flux density is listed in the IRAS catalog for one or more bands, column 9 lists the upper limit to the luminosity. The luminosities range from 1.5 $L_\odot$ to 26,000 $L_\odot$. The two most luminous IRAS sources are associated with the Mon R2 core ($L_{IR} \sim 26,000 L_\odot$) and GGD 12-15 (5700 $L_\odot$). Most of the remaining IRAS sources have luminosities less than 1000 $L_\odot$. Figure 7 shows the location of the IRAS sources overlaid on a $^{12}$CO image, where the diameter of the circle is proportional to the far-infrared luminosity. The IRAS sources are spatially distributed in two groups. One group extends east-west along the chain of reflection nebulae. The second group extends north-south along the sharp boundary of the cloud traced by $^{12}$CO emission.

Hughes & Baines (1985) traced the massive embedded stellar content in the Mon R2 molecular cloud by surveying a 16 deg$^2$ region in the radio continuum at 3.2 GHz and 10.55 GHz with angular resolution of 8'.3 and 2'.8, respectively. The sensitivity limit of the survey was 40 mJy at both frequencies, sufficient to detect an H II region excited by a B1 star. Three radio continuum sources with a thermal spectrum were detected. The survey also detected 10 additional radio continuum sources with a non-thermal spectrum that were presumed extragalactic in origin. An additional ten...
Figure 7. Spatial distribution of various tracers of star formation activity overlaid on an image of the peak $^{12}$CO intensity (Xie 1992). The H II regions are from Hughes & Baines (1985), the ROSAT sources from Gregorio-Hetem et al. (1998), and the optical nebulae from Table I. Open circles represent the IRAS point sources listed in Table 3, where the size of the circle is proportional to the infrared luminosity ($L_{IR}$). The dashed circles show the full field of view of the ROSAT pointed observations (outer circle), and the 35′ diameter region that was imaged with high sensitivity and resolution (inner circle).

Sources were detected in only one frequency, and are most likely extragalactic based on the expected radio continuum source counts.

Table 4 lists the positions and flux densities of the three H II regions detected by Hughes & Baines (1985). The location of the H II regions are shown as open triangles in Figure 7. One of the radio continuum sources is located in the Mon R2 core, and a second in the GGD 12-15 region. The third radio continuum source, which has not been well studied, is situated in a hole in the $^{12}$CO emission (see Fig. 7) and has no clear correspondence with a reflection nebula or IRAS source. Assuming that the radio continuum emission is optically thin and the ionization flux is produced by a single star at the distance of Mon R2, the spectral type of the ionizing star for all three radio continuum sources is an early B-type star as listed in Table 4.

Downes et al. (1975) showed that the radio continuum emission in the Mon R2 core extends over a 2′ diameter region, but most of the emission originates from a compact H II region. High resolution observations by Massi, Felli, & Simon (1985).
region where the ionizing star is on the surface of the molecular cloud. The radio edge. Massi, Felli, & Simon (1985) modeled the radio emission as a blister-type H II

| IRAS PSC | \( \alpha_{2000} \) | \( \delta_{2000} \) | 12 \( \mu \)m | 25 \( \mu \)m | 60 \( \mu \)m | 100 \( \mu \)m | \( L_{1R} \) | \( L_{1R\mu} \) |
|----------|-----------------|-----------------|---------|---------|-------|-------|--------|--------|
| 06027-0714 | 06:05:08.2 | -07:14:42 | <0.25 | 0.96 | 4.93 | 6.35 | >7.7 | <8.7 |
| 06045-0554 | 06:06:58.5 | -05:55:08 | 0.76 | 0.99 | 0.98 | 4.96 | 7.1 |
| 06046-0536 | 06:07:06.7 | -05:37:24 | <0.25 | 0.25 | 3.42 | <9.49 | >3.2 | <7.4 |
| 06046-0603 | 06:07:08.5 | -06:03:47 | <0.25 | 2.24 | 15.3 | 28.3 | 25.6 | <26.6 |
| 06047-0546 | 06:07:11.1 | -05:47:21 | <0.25 | 1.66 | 4.83 | 3.96 | 8.0 | <9.0 |
| 06049-0541 | 06:07:21.4 | -05:41:38 | 0.36 | 1.84 | 4.47 | <9.49 | >8.2 | <11.3 |
| 06049-0504 | 06:07:23.4 | -05:04:54 | <0.29 | 0.36 | 1.16 | <10.3 | 1.5 | <6.1 |
| 06050-0623 | 06:07:27.5 | -06:23:47 | 11.8 | 119 | <442 | <20190 | <240 | <7210 |
| 06050-0509 | 06:07:31.6 | -05:10:21 | <0.39 | 1.48 | 4.18 | 10.3 | 9.2 | <10.8 |
| 06051-0653 | 06:07:33.5 | -06:54:26 | <0.25 | 0.25 | 2.18 | <5.21 | 2.2 | <5.0 |
| 06052-0533 | 06:07:43.5 | -05:34:17 | <0.25 | 0.60 | 13.1 | 22.3 | 19.1 | <20.2 |
| 06052-0512 | 06:07:45.0 | -05:12:40 | <0.25 | 0.68 | 2.50 | <15.9 | 3.2 | <9.4 |
| 06053-0622 | 06:07:46.7 | -06:23:00 | 470 | 4095 | 13070 | 20190 | 26008 |
| 06053-0614 | 06:07:48.9 | -06:14:44 | 0.78 | 1.07 | <6.05 | 81.8 | >4.9 | <36.7 |
| 06054-0515 | 06:07:52.7 | -05:16:04 | 0.84 | 1.37 | <2.41 | <34.0 | 5.7 | <18.8 |
| 06055-0524 | 06:07:58.9 | -05:25:03 | <0.45 | 0.44 | 4.80 | <10.4 | >4.7 | <9.9 |
| 06056-0653 | 06:07:58.0 | -06:53:45 | 0.52 | 2.11 | 3.85 | 4.76 | 10.3 |
| 06056-0621 | 06:08:03.8 | -06:21:38 | 7.07 | 29.3 | <13070 | <20190 | 76.4 | <17530 |
| 06057-0700 | 06:08:04.2 | -07:00:38 | <0.26 | 0.69 | 2.24 | <11.2 | 3.0 | <7.7 |
| 06058-0615 | 06:08:14.8 | -06:15:33 | 0.71 | 0.83 | 18.4 | <155 | 19.5 | <70.0 |
| 06059-0632 | 06:08:23.6 | -06:33:02 | 0.38 | 4.42 | 9.64 | 6.52 | 18.9 |
| 06060-0657 | 06:08:27.7 | -06:57:42 | 0.92 | 1.57 | <3.59 | 9.74 | >6.3 | <12.5 |
| 06060-0617 | 06:08:29.5 | -06:18:26 | 0.28 | 1.23 | <18.4 | 39.0 | 15.9 | <31.2 |
| 06068-0643 | 06:09:14.5 | -06:43:57 | 0.73 | 1.35 | 1.91 | <8.47 | 6.8 | <9.5 |
| 06068-0641 | 06:09:19.8 | -06:41:55 | 0.98 | 2.00 | <1.91 | <8.47 | 7.2 | <11.6 |
| 06070-0619 | 06:09:30.0 | -06:19:40 | 2.95 | 15.2 | 178 | 314 | 287 |
| 06084-0611 | 06:10:51.0 | -06:11:54 | 27.1 | 604 | 3613 | 4876 | 5682 |
| 06085-0613 | 06:10:57.8 | -06:14:37 | 2.99 | 3.27 | <3613 | <4876 | >17.5 | <4612 |
| 06086-0611 | 06:11:07.5 | -06:12:32 | 2.38 | 2.57 | <3613 | <4876 | >13.9 | <4608 |
| 06093-0608 | 06:11:48.6 | -06:09:30 | 6.60 | 12.3 | 141 | 249 | 245 |
| 06094-0628 | 06:11:53.3 | -06:29:20 | <0.25 | 0.32 | 7.03 | 25.2 | >14.6 | <15.6 |
| 06103-0612 | 06:12:48.3 | -06:13:19 | 4.02 | 20.8 | 70.3 | 123 | 149 |
| 06111-0624 | 06:13:36.2 | -06:25:01 | 0.44 | 0.48 | 0.69 | <11.2 | >3.1 | <6.8 |
| 06123-0619 | 06:14:44.9 | -06:20:24 | 0.36 | 0.42 | <1.87 | 21.2 | >9.1 | <10.6 |
| 06124-0621 | 06:14:53.1 | -06:22:43 | 1.82 | 2.07 | 15.6 | 53.8 | 41.4 |
| 06125-0658 | 06:15:00.8 | -06:59:15 | <0.25 | 0.19 | <0.51 | 4.12 | >1.6 | <3.1 |

* Flux densities are in units of Janskys and luminosities are in \( L_\odot \).
Table 4. Compact H II Regions in the Mon R2 Cloud from Hughes & Baines (1985)

| Source          | α    | δ    | S_ν (mJy)       | SpT         | Region            |
|-----------------|------|------|-----------------|-------------|-------------------|
|                 | (J2000) | (3.2 GHz) | (10.5 GHz) |             |                   |
| G213.7–12.6^a   | 06:07:46.2 | −6:23:09.3 | 6200±200      | B0 to O9.5  | Mon R2 core       |
| G213.8–12.1^b   | 06:09:39 | −6:15:1 | 120±10         | B0.5 to B1  |                   |
| G213.9–11.8^c   | 06:10:50.6 | −6:11:49.8 | 95±20         | B0.5 to B1  | GGD 12-15         |

^a Coordinates from Wood & Churchwell (1989)
^b Coordinates from Hughes & Baines (1985) and uncertain by 30′′
^c Coordinates from Kurtz, Churchwell, & Wood (1994)

2.3. Magnetic Field

The pattern of polarization angles measured toward field stars was used by Zartisky et al. (1987), Hodapp (1987), and later by Yao et al. (1997) to map the projected magnetic field direction in the Mon R2 molecular cloud. The R-band measurements over a 9′ field by Zartisky et al. (1987) show a projected magnetic field orientation of P.A. = 167°, parallel to the local Galactic magnetic field, and also parallel to the direction of the Mon R2 molecular outflow (Bally & Lada 1983). The studies by Hodapp (1987) based on I- and K-band polarization vectors, and by Yao et al. (1997) based on Ks-band data, concentrated on the region near the cloud core. Both suggested that the projected magnetic field appears to have an hourglass shape, indicative of the collapse of a supercritical cloud where the frozen-in magnetic field lines are bent toward the cloud’s center by the gravitational field of the cloud core. The conclusion that the magnetic field in Mon R2 is bent was confirmed by sub-millimeter (800 µm) emission polarimetry by Greaves, Holland, & Murray (1995) and far-infrared (100 µm) data from Novak et al. (1989).

A study of the polarization pattern in the R-band over a much wider field using three 23′ × 23′ CCD images by Jarrett et al. (1994, see Fig. 8) images confirmed many of the earlier results and demonstrated the continuity between the magnetic field orientation measured in the tenuous parts of the cloud (by R-band polarimetry) and the dense parts (measured by I-band and K-band polarimetry). However, they also showed a second pattern of polarization vectors east of the molecular core that cannot be explained simply by the gravitational pull of the molecular core. Instead, their results are best interpreted in a scenario where a large-scale expanding shell has distorted the magnetic field lines extending from the core to the north.

3. Individual Regions

In this section we review the properties of individual star forming regions in the Mon R2 molecular cloud, including the main Mon R2 core (see Sect. 3.1.), the small group of nebulae in GGD 12-15 (Sect. 3.2.), and the star forming sites associated with HH 866 (Sect. 3.3.) and GGD 16-17 (Sect. 3.4.).

3.1. The Mon R2 Cluster

The Mon R2 core is distinguished by a stellar cluster (see Fig. 9), one of the largest (6.6 pc) and most powerful known molecular outflows (Bally & Lada 1983; Wolf, Lada, & Bally...
Figure 8. $R$-band image of the Mon R2 core region overlaid with $R$-band polarization vectors (Jarrett et al. 1994). The circle represents the area where Jarrett et al. (1994) did not obtain polarization data. In the inner 3′ the $I$- and $K$-band point source measurements from Hodapp (1987) were added. Note that Fig. 12 from Hodapp (1987) shows mostly the polarization vectors of scattered light in the reflection nebula; those polarization vectors are not included here, since they do not trace the magnetic field orientation. The long lines intersecting the circle represent the long-axis of the molecular outflow from the core region (Bally & Lada 1983).

Molecular line (Tafalla et al. 1997; Choi et al. 2000) and submillimeter continuum (Walker, Adams, & Lada 1990; Henning, Chini, & Pfau 1992; Giannakopoulou et al. 1997) observations have shown that the cluster is embedded in a dense core which has a diameter of ∼ 3′ (0.7 pc). The core displays a rich chemical structure that is driven by the high ultraviolet flux from the embedded B-star (Rizzo, Fuente, & García-Burillo 1990; Meyers-Rice & Lada 1994, Xie, Goldsmith, & Patel 1993; Tafalla, Bachiller, & Wright 1994), a compact H II region (Downes et al. 1975; Massi, Felli, & Simon 1985), H$_2$O and OH masers (Downes et al. 1975; Knapp & Brown 1976), and X-ray emission (Hamaguchi, Tsuboi, & Koyama 2000; Kohno, Koyama, & Hamaguchi 2002; Nakajima et al. 2003).
Figure 9. Three-color composite (blue – J; green – H; red – K) of the Mon R2 cluster (Carpenter et al. 1997). The field of view of the image is $\sim 15' \times 15'$; north is up and east to the left. The reflection nebulae vdB 69 and vdB 67 are located to the left and right, respectively, of the central Mon R2 cluster. This infrared image can be compared with the optical image presented in Fig. 2.

The core mass derived from multi-transition CS molecular line observations is $\sim 760 M_\odot$, of which 130 $M_\odot$ is being accelerated by an outflow (Tafalla et al. 1997, where masses and sizes are scaled to a distance of 830 pc). Walker, Adams, & Lada (1990) and Henning, Chini, & Pfau (1992) estimate a core mass of $\sim 200 M_\odot$ within the central 2.7 arcmin$^2$ based on millimeter continuum observations.

Beckwith et al. (1976) discovered the embedded cluster in the Mon R2 core through $H, K, 10 \mu m,$ and $20 \mu m$ scan-maps. Five discrete sources (IRS 1-5) were detected at $10 \mu m$, with two additional sources (IRS 6 and IRS 7) appearing at $H$- and $K$-band only. Figure 10 identifies these sources on modern images of the cluster. IRS 1 has been resolved into two components (Aspin & Walther 1990, Howard, Pipher, & Forrest 1994), but the fainter of the two components in the mid-infrared (IRS 1NE) is a foreground field star. IRS 3 appeared extended in the Beckwith et al. (1976) images, and subsequent observations resolved the source into two point sources (Howell, McCarthy, & Low 2005).
Figure 10. Location of the IRS sources found by Beckwith et al. (1976) identified on the K-band and nbL images from Carpenter et al. (1997). IRS 1 was resolved into two point sources by Aspin & Walther (1990) and Howard, Pipher, & Forrest (1994), where IRS NE is a foreground star unrelated to the cluster. IRS 3 was noted to be extended by Beckwith et al. (1976), and subsequently resolved into multiple sources (see Fig. 11).

Koresko et al. (1993) showed that the bright southern source in IRS 3 is surrounded by a bright conical nebula, which they suggest is produced by starlight scattered from a circumstellar disk. Preibisch et al. (2002) resolved the IRS 3 region into 6 discrete sources. Speckle images from their study are presented in Figure 11. In addition to the conical nebula around IRS 3A, these images reveal three knots of emission distributed along a line connecting to IRS 3B. Preibisch et al. (2002) suggest these knots are related to a jet originating from IRS 3B. The orientation of the possible jet is roughly perpendicular to the large scale molecular outflow originating from the Mon R2 core (Wolf, Lada, & Bally 1990), but it may be related to a second outflow that is inferred from analysis of the gas kinematics (Meyers-Rice & Lada 1991). Infrared spectra of IRS 3 at 3.3 and 11.2 µm reveal absorption features attributed to polycyclic aromatic hydrocarbons (Sellgren et al. 1995; Bregman, Hayward, & Sloan 2000).
results on the illumination by IRS 2, also discuss in detail the scattered light polarization pattern around IRS 3, the brightest of the near-infrared sources. Their measurements show IRS 3 to have the polarization pattern of an object with a multi-scattering disk oriented in SE-NW orientation, and larger degrees of polarization caused by single scattering in the direction perpendicular to the disk, consistent with the details of the spatial structure of IRS 3 revealed by Preibisch et al. (2002).

The 10 µm and 20 µm maps of Hackwell, Grasdalen, & Gehrz (1982) show that, while IRS 2 is the brightest source in the area of the reflection nebula at a wavelength of 10 µm, IRS 1 is, by far, the dominant source at 20 µm, and appears extended. The VLA
observations by Massi, Felli, & Simon (1985) revealed a region of radio-continuum emission coinciding with the near-infrared reflection nebula, but with a sharp concentration of the radio flux near the southeastern edge of the region, in the general area of IRS 1.

Far-infrared (Thronson et al. 1978, 1980) and submillimeter (Henning, Chini, & Pfau 1992) observations have identified IRS 1, IRS 2 and IRS 3 as the most luminous sources in the cluster. From radiative transfer models, Henning, Chini, & Pfau (1992) estimate the luminosities of these three components to be 3000 L_☉, 6500 L_☉, and 14,000 L_☉ respectively. IRS 1 is considered the ionizing source of the radio continuum emission; the K-band position of IRS 1 is offset by ~4'' from the peak radio continuum position, which can be explained in the blister H II region model (Massi, Felli, & Simon 1985). The inferred spectral type of IRS 1 based on the radio continuum emission is B0 ZAMS, which is broadly consistent with the infrared luminosity. Tafalla et al. (1997) did not detect radio continuum emission toward IRS 3 even though it is the most lu-
minous source, and they suggested IRS 3 is in a younger stage of evolution relative to IRS 1.

Near-infrared images with array detectors have identified a cluster of a few hundred stars in the Mon R2 core (Aspin & Walther 1990; Howard, Pipher, & Forrest 1994; Hodapp 1994; Carpenter et al. 1997). Figure 9 presents a 3-color composite image of a $15' \times 15'$ region centered on the cluster from Carpenter et al. (1997). Analysis of the star counts in this image indicates that the cluster extends over a $4.5' \times 8.5'$ (2.1 pc $\times$ 2.1 pc) region elongated in a north-south direction. Many of the cluster members have been detected in X-rays with deep Chandra observations (Kohno, Koyama, & Hamaguchi 2002; Nakajima et al. 2003).

Figure 13. Images of Mon R2 overlayed with the distribution of YSOs identified and classified on the basis on $H$, $K$ and Spitzer 3.6 and 4.5 $\mu$m photometry. The upper left is a $JHK$ false color image with Class II sources marked by green diamonds. The image in the upper right is the Spitzer/IRAC [3.6][4.5][8.0] false color image with Class I sources marked by green circles. The bottom left shows the stellar surface density contours (all YSOs) overlayed on a greyscale $^{13}$CO image. The bottom right shows the distribution of Class I and II source color coded in red and blue, with $^{13}$CO contours overlaid. Figure from Gutermuth (2005).
Based on analysis of the near-infrared photometric data, Carpenter et al. (1997) found that the stellar mass function in the Mon R2 cluster is consistent with the Miller-Scalo mass function for stellar masses $\geq 0.1$ $M_\odot$. No compelling evidence for mass segregation was found within the cluster for stellar masses $\lesssim 2$ $M_\odot$, but as has been noted in NGC 2024 and the Orion Nebula Cluster, the most massive stars are situated near the cluster center (see Carpenter et al. 1997, and references therein). Andersen et al. (2006) used HST NICMOS observations to extend the mass function to $20$ $M_\odot$ by computing the ratio of the number of low mass stars between 0.08 and 1 $M_\odot$ to the number of brown dwarfs between 0.02 and 0.08 $M_\odot$. Their results show that this ratio is similar to that inferred in Taurus, IC 348, the Orion Nebula Cluster, and the system field IMF (Chabrier 2003).

Recently, Gutermuth (2005) studied the distribution of YSOs of different evolutionary states in a number of embedded young clusters, including Mon R2. Figure 13 summarizes these results and compares the YSO spatial distribution to the distribution of $^{13}$CO emission. These results demonstrate that the youngest (Class I) YSOs are distributed in a non-symmetric distribution that strongly resembles the distribution of the gas. In contrast, the presumed older Class II sources appear more widely distributed.

An imaging survey in the 2.12 $\mu$m emission line of $H_2$ 1--0 S(1) by Hodapp (2007) led to the discovery of 15 new $H_2$ jets in Mon R2 that represent the very youngest objects in their main accretion phase (Class 0 and I). The newly discovered $H_2$ jets are overlaid on Figure 14 as open circles with labels. Also overlaid are the lowest contours of the blue and redshifted features in the CO map of Wolf, Lada, & Bally (1990), showing the outline of the huge outflow that dominates the Mon R2 cloud. This outflow is one of the most massive CO outflows known and has carved out a large cavity in the core of the Mon R2 molecular cloud. Only two of the newly found $H_2$ jets are lying clearly outside of the CO outflow contours. The longest of the newly discovered $H_2$ jets (HOD07-13) lies just south of the redshifted CO lobe. It is shown at 2.12 $\mu$m and 3.6 $\mu$m (Spitzer/IRAC) wavelengths in Figure 15. While the Spitzer 4.5 $\mu$m band generally shows $H_2$ shock-excited emission better than the 3.6 $\mu$m band, those longer wavelength data were not available when this figure was prepared.

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. The surface density of triggered star formation sites is expected to be higher in projection along the shell wall compared to the front and back sides of the outflow shell. The overall distribution of newly found $H_2$ jets outside of the central cluster roughly matches this expectation.

Hodapp (2007) also found that the area near the Mon R2 cluster contains numerous small patches of nebulosity, often with bipolar or cometary morphology, that did not fit the adopted criteria for identification as shocks or jets. These are indicated by small square symbols in Fig. 14. 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 that is now observed via scattered light. These objects appear particularly numerous in the area about 2 to 3 arcminutes south of the main Mon R2 cluster, and just north of the cluster. This finding is consistent with the result by Gutermuth (2005) that the Class I sources in Mon R2, identified by their $J$, $H$, and $K$, and Spitzer IRAC colors, are concentrated
Figure 14. Image of the Mon R2 star forming region in the 1–0 S(1) emission line of H$_2$ at 2.12 µm, obtained with 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 north-west corner of the image. The small reflection nebula near the eastern edge of the image is GGD 11 (Gyulbudaghian, Glushkov, & Denisyuk 1978). Newly found small reflection nebulae are indicated by squares. Superposed on this image are lowest contours of the blueshifted (−2 to 6 km s$^{-1}$, solid line) and redshifted (14 to 22 km s$^{-1}$, dashed line) CO emission from the map by Wolf, Lada, & Bally (1990).
Figure 15. The largest of the 15 H$_2$ jets recently found by [Hodapp (2007)] in a 2.12 µm survey of the Mon R2 region. The left panel shows the jet HOD07-13 in the H$_2$ 1–0 S(1) line, and the right panel shows the Spitzer/IRAC 3.6 µm image.
in a filamentary distribution to the south of the cluster center, and to the north and north-east 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 end of their accretion phase.

To the east of the Mon R2 cluster, the isolated object GGD 11 has the morphology of a bipolar reflection nebula, indicating a recently formed young star in relative isolation from the cluster (see Fig. 16).

Figure 16. Image at 2.12 $\mu$m of the bipolar reflection nebula GGD 11 from Hodapp (2007).

3.2. GGD 12-15

The dense core associated with GGD 12-15 possesses similar properties as the main core in the Mon R2 cloud. The core extends over a $\sim 0.7$ pc region as traced by HCO$^+$ and $^{13}$CO J=1-0 with a mass of $\sim 600-800$ M$_\odot$ (Heaton et al. 1988). Submillimeter continuum observations have detected a compact clump (size $\sim 0.15$ pc) in the center of the core with a mass of $\sim 280$ M$_\odot$ (Little, Heaton, & Dent 1990). Rodríguez et al. (1982) detected blue and red shifted CO emission from the core indicative of high velocity gas in a molecular outflow.

The embedded cluster in the GGD 12-15 region began to be uncovered first by Cohen & Schwartz (1980), and, soon after, by Reipurth & Wamsteker (1983) who found a group of seven sources (see also Olofsson & Koomneef 1985). More recent results suggest the cluster population is as high as $\sim 130$ stars (Hodapp 1994; Carpenter 2000). Figure 17 presents an optical and 2MASS $K_s$-band image of the GGD 12-15 region. The various optical nebulae are identified, as well as the position of a compact H II region (cross; Rodríguez et al. 1980; Kurtz, Churchwell, & Wood 1994; Tofani et al. 1995; Gómez et al. 1998) and a water maser (open circle; Rodríguez et al. 1980; Tofani et al. 1995). Recently, Gutermuth (2005) studied the distribution of YSOs of different evolutionary state in GGD 12-15. Figure 18 summarizes the results and demonstrates that the youngest (Class I) YSOs are distributed in a non-symmetric pattern that still strongly resembles the distribution of gas and dust. In contrast, the presumed older Class II sources are distributed more widely.
The compact H II region in GGD 12-15 is coincident with mid- to far-infrared and submillimeter emission (Harvey et al. 1985; Little, Heaton, & Dent 1990; Persi & Tapia 2003). The implied bolometric luminosity is $<6600 \, L_\odot$ for a distance of 830 pc, where the upper limit is implied since multiple sources contribute to the flux within the IRAS beam (Harvey et al. 1985; Persi & Tapia 2003). The inferred spectral type of the ionizing star from the radio continuum flux is B0.5, which is sufficient to produce most of the observed far-infrared luminosity. The water maser in GGD 12-15 is offset from the compact H II region and is coincident with a compact 20$\mu$m source (Harvey et al. 1985). The embedded star associated with the maser is centered between red- and blue-shifted molecular outflow (Rodríguez et al. 1982; Little, Heaton, & Dent 1990) lobes and is the likely source of the outflow (Harvey et al. 1985).

Gómez, Rodríguez, & Garay (2000) report sensitive VLA radio continuum observations of the GGD 12-15 region and detected five new radio continuum sources in addition to the luminous compact H II region detected in previous surveys. They originally suggested these fainter sources are ultracompact H II regions around B2-B3 stars. More sensitive follow-up VLA observations raised the total to ten radio continuum sources in the GGD 14 core (Gómez, Rodríguez, & Garay 2002, see Fig 19). These additional observations showed, however, that several of these sources are time variable, and have negative spectral indices, which led Gómez, Rodríguez, & Garay (2002) to conclude that the radio emission from the fainter sources most likely originates from gyro-synchrotron radiation from an active magnetosphere. The two exceptions are VLA 7, which is possibly a radio jet as implied by the spectral slope of the radio continuum emission (Gómez, Rodríguez, & Garay 2002), and VLA 4, which has a 1-20$\mu$m luminosity of $\sim 240 \, L_\odot$ and may be B-type star (Persi & Tapia 2003).
3.3. HH 866 (IRAS 06046-0603)

The Herbig-Haro object HH 866, discovered by Wang, Stecklum, & Henning (2005), is 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). Images at 2.12 µm (Hodapp 2007) shows a system of emission features that can be morphologically identified as two H$_2$ jets, partly associated with the optical HH objects.
Figure 19. Contour map of the 2MASS \( K_s \)-band image of the GGD 14 star forming region. Crosses mark the position of VLA radio continuum sources from Gómez, Rodríguez, & Garay (2002). VLA 1 is a bright cometary H II region excited by an early B-star. Figure from Gómez, Rodríguez, & Garay (2002).

3.4. GGD 16-17

A smaller site of ongoing star formation in the Mon R2 molecular cloud are the objects associated with GGD 16 and 17 (Gyulbudaghian, Glushkov, & Denisyuk 1978). To the south of GGD 17, the T Tauri star Bretz 4 is probably associated with the GGD object. This star has been studied spectroscopically by Herbig & Rao (1972) and was classified by Carballo & Eiroa (1992) as a K4 spectral type with a class 5 (Herbig 1962) emission spectrum. The embedded objects associated with GGD 16 and 17 were first studied by Reipurth & Wamsteker (1983) and confirmed by Carballo, Eiroa, & Mampaso (1988). The infrared source IRS 2 is positionally coincident with Bretz 4, while the more deeply embedded IRS 1 has no optical counterpart and lies between the GGD objects. A detailed optical study by Carballo & Eiroa (1992) showed that GGD 17 is part of a curved jet extending north of the star Bretz 4 and consisting of HH 271 (also known as GGD 17 HH1) and HH 272 (GGD 17 HH2), and possibly also HH 273 (GGD 17 HH3). Nebulosity close to the star shows the typical morphology of scattered light from an outflow cavity wall. The embedded infrared objects and optical reflection nebulosity in the general GGD 16-17 region is associated with 850 \( \mu m \) emission (Jenness, Scott, & Padman 1995). Beltrán et al. (2001) present VLA 6 cm radio continuum images of the GGD 16-17 region. Their radio continuum map, reproduced in Figure [20] shows the locations of the radio sources with respect to a water maser, an IRAS source, and HH 271.
Figure 20. VLA 6 cm contour map of the GGD 16-17 region (also known as Mon R2E). The ellipse denotes the position uncertainty of the IRAS source. The symbols represent the location of the Herbig-Haro object HH 271 (triangle), near-infrared sources (plus signs), H$_2$O masers (squares), and the T Tauri star (star). Figure from Beltrán et al. (2001).

Acknowledgments. We would like to thank Bo Reipurth and the referee, Rob Gutermuth, for valuable comments on this manuscript. We also thank Russell Croman (http://www.rc-astro.com) for granting permission to reproduce Figure 2.

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