

Star Formation in NGC 2023, NGC 2024, and Southern L1630

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Abstract. We review star formation in the southern L1630 molecular cloud (also known as Orion B) as well as the relationship between the young stellar populations and the remnant molecular gas. We begin with an historical introduction to the region, and proceed to discuss recent developments in the study of NGC 2023, NGC 2024, and star formation associated with the Horsehead Nebula. Next we consider the distributed mode of star formation in the L1630 cloud, and conclude with a synthesis of star-forming activity in the region. By comparing and contrasting star formation in Orion B with that found in Orion A, one hopes to discern differences as a function of local initial conditions.

1. Introduction

When T Tauri variables were first recognized as a class of objects by Joy (1949), it was unclear whether their association with dark clouds was due to chance encounters or whether the stars were in the process of forming from the gas and dust in which they were found to be embedded (Herbig 1962). We now know that giant molecular clouds are indeed the sites of active star formation. Characterizing the stellar populations associated with these clouds, as well as their mutual interactions, can help to address a wide range of astrophysical questions related to star formation and early stellar evolution. In addition to investigating the initial mass function of stars, studies aimed at deriving the star forming history of a cluster can discern whether there exists a temporal sequence of star formation as a function of mass or whether high and low mass stars form at the same time. By studying the circumstellar properties of young stars as a function of age, we can estimate the evolutionary timescales for disks which may be the sites of planet formation.

At a distance of 400-500 pc (see chapter by Gibb), Orion is the nearest giant molecular cloud (GMC) complex. As such it offers a unique opportunity to study the

star-forming process at high spatial resolution and sensitivity in a variety of conditions. In particular, understanding the kinematic relationship between the stars and gas can provide constraints on theories of star formation and insight into the lifetimes of GMCs and Galactic star formation efficiencies. Further, Orion is conveniently divided into two main regions: Orion A comprised of OMC-1, OMC-2, and the L1641 cloud; and Orion B, also known as the L1630 cloud, each with total mass of order $1 \times 10^5 M_{\odot}$ with Orion A being slightly more massive (Maddalena et al. 1986).¹ In this contribution, we review the stellar populations found associated with the southern portions of L1630 (see chapter by Gibb for details concerning the northern regions). It is hoped that this synthesis of results for Orion B, when combined with the reviews of Orion A (see chapters by Muench et al., and Allen & Davis) will lead to a better understanding of the similarities and differences between the stellar populations of the two clouds. We can then begin to consider whether differences in the physical conditions in these molecular clouds can help us to understand the results of this comparison. We begin in Section 2 with an historical introduction into studies of the L1630 dark cloud. In Section 3, we discuss the properties of the main embedded stellar populations and associated molecular material. We review the evidence for a distributed population in Section 4. Finally, in Section 5, we discuss the properties of L1630 in the context of star formation throughout the Orion region.

2. Historical Background

Nebulae in the constellation Orion have been a familiar target of star-gazers since the late 18th century. NGC 2023 was discovered by William Herschel (1785) and listed in his catalog as H IV-24. NGC 2024 was discovered later by the same author (Herschel 1786), and is listed in his catalog as H V-28. NGC 2024, also known as the Flame Nebula, is just east of the belt star ζ Ori, while NGC 2023 is located directly to the south of NGC 2024. To the west of NGC 2023, an emission-line nebula excited by σ Ori runs north-south (see chapter by Walter et al.). A dense obscuration midway along this filament is responsible for the Horsehead Nebula. The entire Orion B cloud, as well as the Orion Nebula Cluster and the Orion A cloud, are contained within the atomic shell structure known as Barnard's Loop (Barnard 1894). The orientation of star-forming regions of southern L1630 is shown in Figure 1.

2.1. Early Visible Observations

Studies of the stars in the region known as Lynds 1630 actually pre-date the identification of the complex of dark clouds by B.T. Lynds (1962). Haro & Moreno (1953) conducted the first $H\alpha$ survey of the region and identified several objects in the vicinity of IC 434, the emission-line region against which the Horsehead is projected, as well as a clustering of very red objects near NGC 2024. Herbig & Kuhi (1963) performed an additional $H\alpha$ survey centered on NGC 2068, bringing to several dozen the number of emission-line stars found within the cloud. As noted by Herbig and Kuhi, these objects appear to be located preferentially in regions of extended nebulosity ex-

¹The “A” and “B” designations referred originally to the HII regions associated with the Orion Nebula and NGC 2024 respectively (Howard & Maran 1965). However we follow Maddalena et al. (1986) in referring to the two molecular clouds by these names.



Figure 1. NGC 2024 (The Flame Nebula) is just to the left of the bright star, ζ Ori, with the multi-color reflection nebula NGC 2023 directly below. In this image north is up and east is to the left. The familiar Horsehead Nebula is further to the southwest of NGC 2023, with σ Ori, the bright star toward the edge of the frame, further southwest still. Courtesy Johannes Schedler.

cited by nearby early-type stars rather than randomly distributed throughout the cloud. Sharpless (1962) conducted a photometric survey of stars earlier than F0 from the HD catalogue located within both the “belt region” and the “sword region” of Orion. The belt region included stars from Orion Ia and Ib sub-groups, the latter of which overlaps with the L1630 cloud in the region of NGC 2024 (see chapter by Bally). Based on comparison of color-magnitude diagrams constructed from his lightly reddened sample, Sharpless concluded that the belt region was older than the sword region. However it was not long before the role that extinction played in obscuring important components of the stellar population was appreciated.

2.2. Emergence of Radio and Far-Infrared Astronomy

A variety of studies at radio and infrared wavelengths throughout the 1960s and 70s attempted to discern the nature of the cloud associated with NGC 2024 and its environs. Radio continuum studies at centimeter wavelengths constrained the extent (and centroid) of the HII region observed through electron free-free emission. Recombination line studies elucidated the ionization state, abundances, and velocity dispersions of the atomic material. Observed features atypical for Galactic HII regions include weak He lines, and a narrow emission component (< 5 km/sec) in atomic hydrogen, carbon, and other heavy elements. Several molecules were detected through millimeter wave spectroscopy including CO, CS, NH_3 , H_2CO , and HCN. Low resolution far-infrared maps from this era revealed spatial structures well-matched to the ionized gas emission while comparable sub-millimeter observations correlated strongly with the molecular gas. A two component model was developed that included both warm (100–200 K) and cold (20–50 K) material. This early work is nicely summarized in chapter 5 of “The Orion Complex: A Case Study of Interstellar Matter” by C. Goudis (1982). The hunt to find the source of the ionizing radiation in NGC 2024 began.

2.3. Which is (are) the Ionizing Source(s)?

Johnson & Mendoza (1964) identified the first highly reddened early-type star embedded within the NGC 2024 nebula. At first it was thought that this star might be responsible for exciting the associated optical/radio HII region. However, Gordon (1969; and references therein) pointed out that the star, dubbed IRS # 1, in addition to being located off of the radio centroid position, was not luminous enough. Grasdalen (1974) discovered a nearby, heavily embedded, luminous infrared source (IRS # 2) which he offered as the exciting source of the HII region. Based on the very red near-IR colors of this object, they inferred extinction $A_V > 10^m$ and thus large $2.2 \mu\text{m}$ luminosity, implying a luminous early-type star. However these authors assumed that the observed colors were affected only by the extinction of intervening material, and neglected the effects of infrared excess emission intrinsic to the source. As a result, the extinction (and luminosity) of the source was overestimated.

2.4. Near-IR Astronomy in Transition

Throughout the 1980s, further improvements in IR instrumentation as well as understanding of the nature of pre-main sequence (PMS) stellar evolution provided additional information concerning the stellar population. Sellgren et al. (1983) conducted an infrared survey of NGC 2023 and for most objects detected in the survey, JHK magnitudes were obtained. These authors made use of Galactic models in order to estimate the contamination of field stars as a function of magnitude. Indicators of PMS activity

such as IR excess, photometric variability, and the presence of emission lines were also used to confirm cluster membership. Sellgren et al. concluded that: *i*) a large fraction of the objects detected in her survey ($m_K < 10.5^m$) were indeed association members; *ii*) the objects appeared to be clustered; and *iii*) the derived stellar mass distribution was roughly consistent with that observed for field stars in the solar neighborhood (assuming a main sequence mass–luminosity relationship for the embedded population). Barnes et al. (1989) published the results of an infrared mapping photometer survey of the central $5' \times 5'$ of NGC 2024 ($m_K < 12.0^m$). In trying to identify the origin(s) of ionizing flux responsible for the HII region, a sophisticated model was constructed in which multiple stellar sources create the observed overlapping arcs of ionized material (implying the presence of several early-type stars in the dense molecular cloud core) rather than a single source of ionization.

3. Properties of the Embedded Stellar Population

It was against this backdrop that infrared array detectors burst onto the scene enabling a great leap forward in the study of embedded stellar populations. Taking full advantage of this new technology, Lada et al. (1991) conducted the first near-IR array survey of a large portion of a giant molecular cloud (L1630 Orion B). Over 0.7 square degrees were mapped in the K-band survey covering selected regions from the CS survey of Lada, Bally, & Stark (1991) with a completeness limit of $m_K < 13.0^m$ with additional sources detected down to $m_K < 14.0^m$ (see Figure 4 in chapter by Gibb). Roughly half of the area surveyed contained CS emission from dense gas and half did not. The survey was sensitive enough to detect 1 Myr old stars with masses $> 0.1 M_\odot$ in the absence of extinction (or $1 M_\odot$ with $A_V < 28^m$). The survey identified four embedded clusters, NGC 2024, NGC 2071, NGC 2068 and NGC 2023 associated with previously known regions of star formation within the cloud (see Table 1). The spatial distribution of the stars in L1630 is highly concentrated. More than half the near-infrared sources detected are contained in the three most populous embedded clusters, the extent of which covers less than 18% of the cloud area surveyed. In addition, the number of stars found outside the clusters is consistent with the expected number of background stars not associated with the cloud. After correcting for the presence of field stars, it was estimated that the vast majority ($> 90\%$) of the stars in the L1630 molecular cloud were formed within the three richest clusters!

It what follows we examine the properties of three important star forming regions in the southern portion of L1630: NGC 2023, NGC 2024, and the Horsehead Nebula. For additional information concerning NGC 2068/2071 and other star formation in the northern portion of L1630, the reader is referred to the chapter by A. Gibb. We discuss the young stellar populations, the associated molecular material including outflows, as well as the relationship between them.

3.1. NGC 2023

NGC 2023 is a bright reflection nebula (Figure 2) $20'$ south of NGC 2024 and northeast of the Horsehead nebula, illuminated by the B1.5 star HD 37903 (Abt & Levato 1977).

The Young Stellar Population As a prelude to the survey of Lada et al. (1991), DePoy et al. (1990) published a JHK imaging survey of the cluster of IR sources found by Sellgren et al. (1983). Fewer than 20 sources are observed within a region $5' \times 3'$

Table 1. Properties of L1630 Clusters from Lada et al. (1991)

α (1950)	δ (1950)	Area (amin^2)	R_{eff} (pc)	N ($m_K < 14^m$)	Association
$05^h 44^m 36.0^s$	$00^\circ 19' 42''$	79.6	0.59	105	NGC 2071
$05^h 44^m 08.0^s$	$00^\circ 06' 42''$	171.7	0.86	192	NGC 2068
$05^h 39^m 10.0^s$	$-02^\circ 17' 18''$	21.0	0.30	21	NGC 2023
$05^h 39^m 10.0^s$	$-01^\circ 55' 12''$	180.0	0.88	309	NGC 2024

surrounding the reflection nebula excited by HD 37903. With the enhanced sensitivity of an IR imager ($m_K < 15.0^m$), DePoy et al. were able to determine that the K-band luminosity function of the cluster turns over at $m_K \sim 12.0^m$. Adopting a main sequence mass–luminosity relationship, this implied a mass function with an abrupt cut-off at about $1 M_\odot$. However, re-analysis of their data with more appropriate *pre-main sequence* mass–luminosity relationships yields an IMF consistent with that observed in the solar neighborhood. Several of the sources exhibit near-infrared colors similar to those expected from reddened T Tauri stars. Piché (1993) also presents optical and infrared photometry for several stars in the region with results similar to the DePoy et al. survey. The survey of Lada et al. (1991) covered a slightly larger area and confirmed this result, finding NGC 2023 to be the smallest cluster in L1630 with a membership of 21 sources down to $m_K < 14$. In a pointed ROSAT study of the region surrounding NGC 2023, Freyberg & Schmitt (1995) detected only one source (IRS #16 from DePoy et al.). An ASCA search for hard X-rays in the region by Yamauchi et al. (2000) revealed 13 additional X-ray sources, only one of which (A6, discussed below) lacked a possible counterpart in the visible. Finally, we note that Pouilly et al. (1994) report no new sources detected in a $10 \mu\text{m}$ imaging study of the region, indicating that there are no luminous embedded IR sources hidden by obscuration from the $2 \mu\text{m}$ surveys. Future work using the Spitzer Space Telescope will shed further light on the stellar population associated with NGC 2023 (see Megeath et al. 2005).

The Molecular Content NGC 2023 has long been known to be associated with dense molecular gas (Goudis 1982 and references therein). Due to the special configuration between HD 37903, a local source of ionization, and the background cloud (Harvey, Thronson, & Gatley 1980), NGC 2023 has also been a special target to understand the nature of photo-dissociation (or photon-dominated) regions (PDRs), e.g. Wyrowski et al. (1997), Steiman-Cameron et al. (1997). Sellgren et al. (1985) identified several mid-IR emission features which can be attributed to PAH emission. Based on sub-millimeter and far-IR observations, Jaffe et al. (1990) showed that some of the atomic and molecular emission coinciding with the fluorescent H_2 emission (e.g., Gatley et al. 1987) is associated with the PDR and that some of this gas is warmer than the surrounding dust. Sellgren et al. (1992) used polarimetry to argue that a significant fraction of the foreground near-IR nebulosity is due to scattering. Based on observations with the IRAM telescope, Fuente et al. (1995) presented evidence that CN abundances are enhanced in some of the dense filaments due to the strong UV field. More recent work has focused on the numerous H_2 lines observed toward NGC 2023, which has motivated numerous studies (Hasegawa et al. 1987, Takayanagi & Sakimoto 1987, Field et al. 1994, 1998, Burton et al. 1998, Martini et al. 1999, McCartney et al. 1999), as



Figure 2. Visible image of NGC 2023 using a $15' \times 15'$ field of view (north up and east to the left) centered on the bright star HD 37903. Courtesy Robert Gendler.

well as spatially resolved observations of selected features (Rouan et al. 1997, Takami et al. 2000). Wyrowski et al. (2000) used radio observations to trace C+ emission on the front face of the PDR, and Knauth et al. (2001) did high resolution spectroscopy of HD 37903 to study absorption lines of the gas.

Modern studies of the background molecular cloud core associated with NGC 2023 began with a CS(2-1) survey of L1630 by Lada, Bally, & Stark (1991). They identified several clumps of dense gas in the region including LBS 34, 35, 36, 39, and 42. LBS 36 is one of the 5 most massive clumps in the entire Orion B cloud. Higher resolution, multi-transition CS observations by Lada, Evans, & Falgarone (1997) revealed that there is relatively little dense gas left in the massive clump associated with NGC 2023 compared to other massive clumps (e.g. those associated with NGC 2024 as well as NGC 2071). Their observations also showed that the average column densities in the NGC 2023 region are less than the densities in other massive clumps associated with young clusters. Launhardt et al. (1996) searched the NGC 2023 clumps for pre-stellar cores and protostars using 1.3 mm continuum emission from dust. They found

only extended dust emission toward LBS 34 indicating that most of the star formation in that clump had already occurred. Similarly, toward LBS 36, they also found only extended emission. However, at the southern edge of this core they detected two protostellar condensations which they called LBS 36 SM1 and SM2. Sandell et al. (1999) mapped the region in sub-mm continuum as well as CO, finding a very cold Class 0 source coincident with LBS 36 SM 1 which they label as NGC 2023 MM 1. A strong molecular outflow was seen to the south-west of NGC 2023 in CO (3–2). This outflow extends over $100''$ and has velocities up to 100 km/sec (Sandell et al. 1999). The observed collimation, with an opening angle $< 4^\circ$, suggests it is driven by a jet from an embedded protostar, possibly NGC 2023 MM1. Neither Freyberg & Schmidt (1995) nor Yamauchi et al. (2000) detected X-ray emission from NGC 2023 MM1, consistent with it being a young protostar enshrouded in dense cocoon of gas and dust. The protostar was detected by Reipurth et al. (2004) in their 3.6 cm continuum search for jets in protostellar objects, however, they found no evidence for extended radio emission. Two other radio sources were detected by Reipurth et al., VLA–3 corresponding to ASCA source A6 and VLA–2 having no known counterpart at any wavelength. Most recently, Johnstone, Matthews, & Mitchell (2006) mapped the area encompassing LBS 34, LBS 36 and LBS 39 at $850\ \mu\text{m}$ using SCUBA (Figure 3). They identified 12 individual clumps, two associated with LBS 34 and LBS 36, another associated with LBS 36 SM1/NGC 2023 MM1. No compact submillimeter continuum emission was found to be associated with LBS 39.

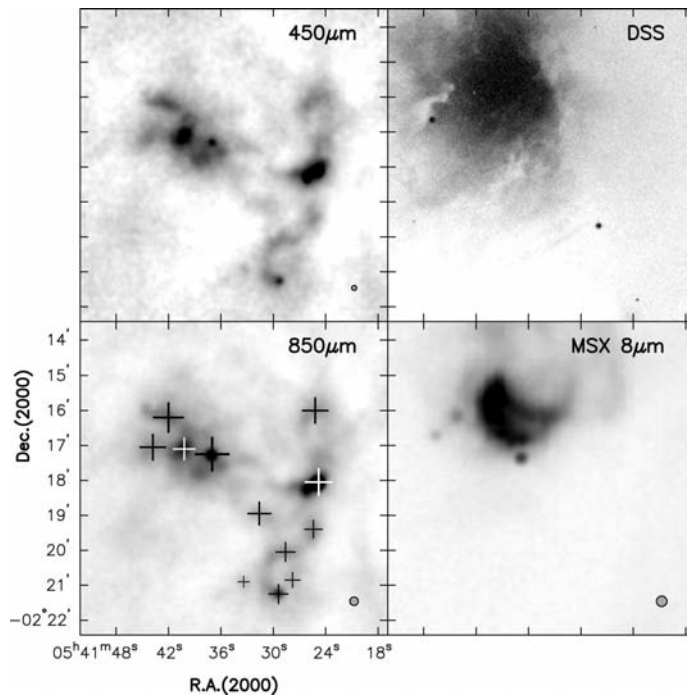


Figure 3. Sub-millimeter observations of NGC 2023 from Johnstone, Matthews, & Mitchell (2006) at $450\ \mu\text{m}$ (upper left) and $850\ \mu\text{m}$ (lower left) shown along with an $8\ \mu\text{m}$ mid-IR image from the MSX satellite (lower right) and a visible light image from the Digitized Sky Survey (DSS) database (upper right).

Malin, Ogura, & Walsh (1987) identified three main groupings of emission-line nebulae within NGC 2023, which are classified as Herbig–Haro (HH) objects. HH 247 consists of multiple knots whose proper motion extends out from NGC 2023, suggesting the driving source is located within the cloud. Sellgren star C (also Sharpless 108) has been suggested as a driving source. This emission-line late G/early K star (Malin, Ogura, & Walsh 1987) is associated with a bipolar nebula (Scarrott, Rolph, & Mannion 1989) though the nebula is slightly misaligned with the HH outflow axis. Two other objects, HH248 and 249, are located further to the south. Based on their proper motions there is no obvious driving source and no associated molecular flow detected (White et al. 1990).

3.2. NGC 2024

Also known as the Flame Nebula, this region is characterized by an extensive HII region, a dark lane that persists from visible to infrared wavelengths, and a ridge of cold dust and molecular gas thought to contain protostellar objects.

The Young Stellar Population The richest of the L1630 clusters (and second in Orion only to the Trapezium cluster), NGC 2024 has attracted great interest in recent years. The cluster is comprised of several hundred stars, many heavily obscured, and is elongated in the N–S direction (Figures 4 and 5). Several groups have undertaken infrared photometric and spectroscopic surveys of the region. Comerón et al. (1996) surveyed 30 square arcminutes in the J, H, and K-bands, avoiding the regions of extensive nebulosity surrounding IRS#1 and IRS#2. Using the near-IR colors to estimate the extinction towards each source, they constructed a luminosity function for the region, taking into account near-IR excess emission commonly found in PMS populations routinely detected in such surveys. Adopting a best-fit mass–luminosity relationship for each source, Comerón et al. derive a mass function for NGC 2024 which extends below the hydrogen-burning limit after making substantial corrections for incompleteness at the low-mass end.

Meyer (1996) presented a near-infrared survey of the inner 0.5 pc ($3.4' \times 3.4'$), sampling $0.1 M_{\odot}$ stars viewed through as much as $A_V \sim 19.0^m$. Combining this photometric survey with near-IR spectra obtained for two dozen sources in the region, an H–R diagram was constructed. The cluster was found to be young $\tau \ll 3 \times 10^6$ yrs and forming intermediate and low mass stars. By estimating the extinction toward each star, a luminosity function can be constructed that is complete over a fixed range of extinction down to some limiting mass (in this case $0.1 M_{\odot}$). Meyer (1996) utilized spectroscopic observations of some representative fraction of cluster members in order to fix the mass–luminosity relationship at crucial points with the aid of pre-main sequence evolutionary models. In this way, the ratio of intermediate ($1.0\text{--}10.0 M_{\odot}$) to low mass ($0.1\text{--}1.0 M_{\odot}$) stars was estimated and found to be consistent with having been drawn from an IMF that characterizes field stars in the solar neighborhood (Liu et al. 2003; Meyer et al. 2000). A similar study was conducted by Ali (1996), who also found that the cluster is extremely young ($\tau < 10^6$ yrs) and is forming a wide range of stellar masses. Levine et al. (2006) used similar techniques combining near-infrared photometric and spectroscopy to study the sub-stellar IMF in the region. Probing down to $0.02 M_{\odot}$ for an extinction-limited sample of $A_V < 15^m$, they find that the ratio of stars to sub-stellar objects is comparable to that observed toward Orion, but lower than that found in less dense star forming regions such as IC 348.

Meyer et al. (1997) reported that nearly 70% of the stars within an extinction-limited sample have infrared excess emission suggesting the presence of active accretion disks. Haisch et al. (2000) performed an L-band imaging study of NGC 2024 that suggested the circumstellar disk fraction was over 80% among the detected sources. Based on the spatial distribution of excess sources as a function of wavelength, they suggested that excess fractions determined from JHK observations alone may be contaminated due to extended nebulosity. A follow-up study based on 10 μ m observations arrived at similar excess statistics (Haisch et al. 2001) and identified several protostellar candidates. Eisner & Carpenter (2003) undertook a sensitive millimeter-wave search for emission attributable to circumstellar disk material. They detected 10 point sources: the embedded intermediate mass star IRS #2, two low mass young stellar objects, and seven with no near-infrared counterparts. Combining local mm-wave maps for each near-IR identified cluster star, they report detection of an “average flux” for association members in excess of that reported for members of the slightly older young cluster IC 348, suggesting significant evolution in the circumstellar disk dust mass. Future studies utilizing the Spitzer Space Telescope in combination with ground-based visible and near-infrared photometry and spectroscopy will deepen our understanding of star formation in NGC 2024 (e.g. Megeath et al. 2005).

Freyberg & Schmitt (1995) present results from pointed ROSAT PSPC observations. Fifty-two separate detections were recorded, 14 of which fall within the inner 0.5 pc survey of Meyer (1996). The spectral properties and X-ray luminosities of the sources are consistent with emission from typical low mass PMS objects obscured through several magnitudes of extinction. Using a single, sensitive *Chandra* observation, Skinner, Gagné, & Belzer (2003) detected 283 X-ray sources in the central 2×2 pc ($16'.9 \times 16'.9$) of NGC 2024. Of these, 248 were identified with known radio, infrared, or optical counterparts and approximately 25% exhibited X-ray variability. Spectral fitting of ~ 100 of the brightest sources yielded a mean plasma temperature of $\langle kT \rangle = 2.8$ keV and a mean visual extinction $\langle A_V \rangle = 10.5$ mag, consistent with A_V estimates from the IR surveys. Skinner, Gagné, & Belzer also calculated the intrinsic X-ray luminosities for 27 bright ($K \leq 10.5$) Class II sources identified in Haisch et al. (2001), finding a correlation between the X-ray and bolometric luminosities for these objects. No significant X-ray emission was detected from any of the sub-millimeter condensations FIR 1-6 (Mezger et al. 1988), consistent with the hypothesis that these sources are a heavily-embedded protostellar population.

NGC 2024 was also one of the main targets in the HST I-band survey of Padgett, Strom, & Ghez (1997) for young binaries in the L1630 cloud. Beck, Simon, & Close (2003) used near-infrared adaptive optics to study the binary frequency of stars in NGC 2024. Liu et al. (2003) performed a similar study utilizing the NICMOS instrument on HST. By characterizing the detection limit as a function of companion brightness and separation they were able to compare the detection statistics with those expected from field star samples (e.g., Duquennoy & Mayor 1991) in an unbiased way. All three studies suggest that the binary frequency in rich clusters is at least as high as that characterizing field stars in the solar neighborhood.

Deep, high resolution 3.6 cm continuum observations of NGC 2024 were presented by Rodríguez et al. (2003). Using the Very Large Array, they detected 25 compact radio sources in a $\sim 4' \times 4'$ region as shown in Figure 6. Fifteen of their detections have X-ray counterparts from Skinner et al. (2003) and thirteen can be identified with objects in the 2MASS catalog. Four sources have no known X-ray or infrared counter-

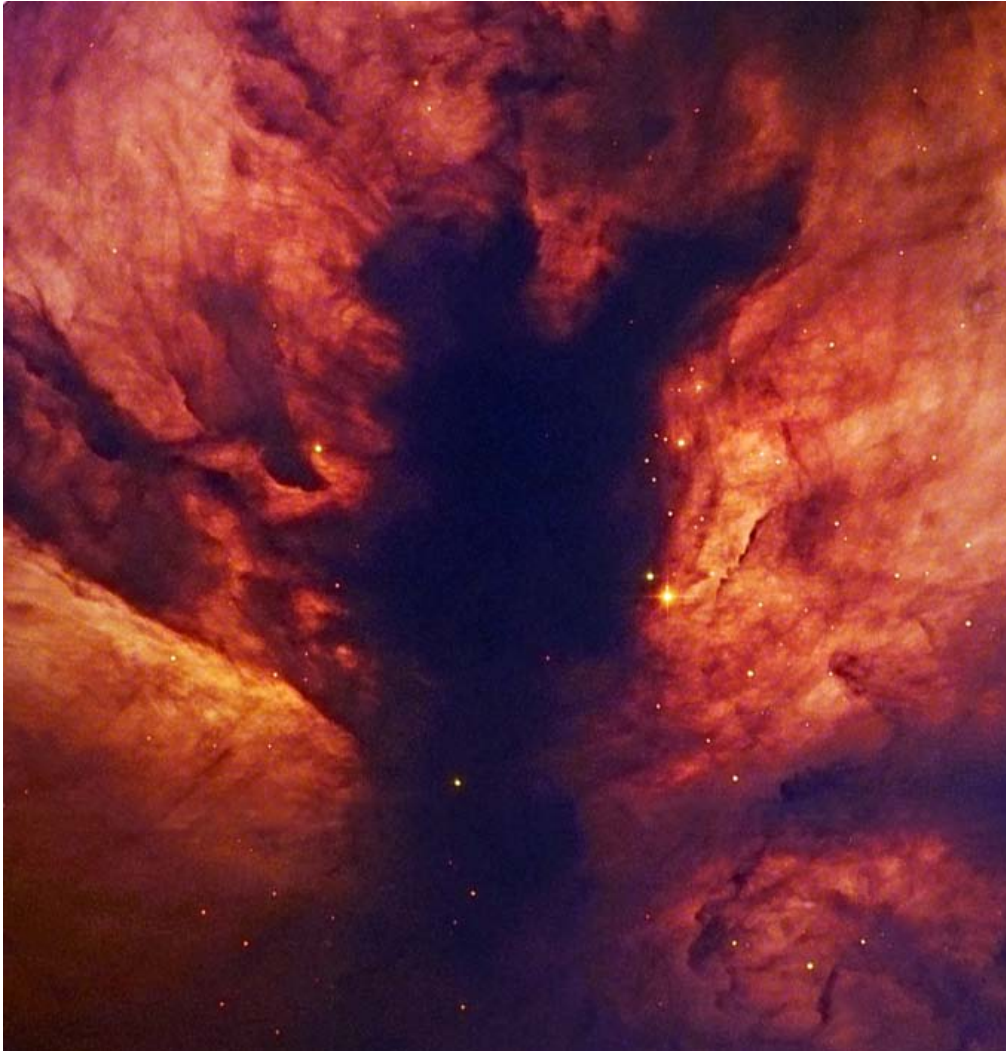


Figure 4. In this visible image of NGC 2024, north is up and east is to the left. In this $10' \times 10'$ field of view, one can see IRS #1 as the bright star below center (south) and just to the right (west) of the dark lane with a fainter companion to its northeast. The image is courtesy of Robert Gendler.

parts, however, three of these are closely associated with sub-millimeter condensations FIR 4-6 from Mezger et al. (1988), again suggesting large extinctions toward these objects. The majority of the radio sources remain unresolved at $0''.2$, with only three objects showing resolved structure. Rodríguez et al. propose that two of these are radio proplyds (VLA-8 and VLA-13). The nature of the third, which coincides with the infrared source IRS 2, remains unclear. Rodríguez et al. also searched for linear and circular polarization in their sample but found only one object showing polarization at the 3% level (VLA-24). This object, along with seven others (VLA 2, 5, 6, 11, 20, 21, and 23), also exhibits fast-time variability, likely indicating gyrosynchrotron emission consistent with detections of activity in young low-mass stars.



Figure 5. This infrared image of NGC 2024 is reproduced at the approximately same scale as Figure 4 (north up and east to the left). The false-color (J = blue, H = green, and K = red) image is courtesy David Thompson. One can clearly see IRS#2 as the bright red source in the heart of the visible dark lane and IRS#1 as the bright blue star to the right (west).

The Molecular Content The molecular gas in the vicinity of NGC 2024 is highly structured. Far-infrared and radio continuum mapping shows a sharp ionization front to the south, as well as two filamentary bubbles to the east and west where the HII region is expanding into the ambient molecular cloud (Thronson et al. 1984, Barnes et al. 1989). Early column density maps derived from multi-transition CS observations revealed a dense core at the center of the optical bar (Snell et al. 1984). Black & Willner (1984) obtained pioneering near-IR spectra of IRS #2 and placed useful constraints on the H_2/CO ratio in the cloud. Lada, Bally, & Stark (1997) independently identified this core (designated LBS 33) using CS(2-1) to trace gas having densities $> 10^4 \text{ cm}^{-3}$ and estimated its radius and virial mass to be 0.4 pc and $\sim 430 M_\odot$, respectively, making it the largest and most massive core in the southern portion of the L1630 cloud. A follow-

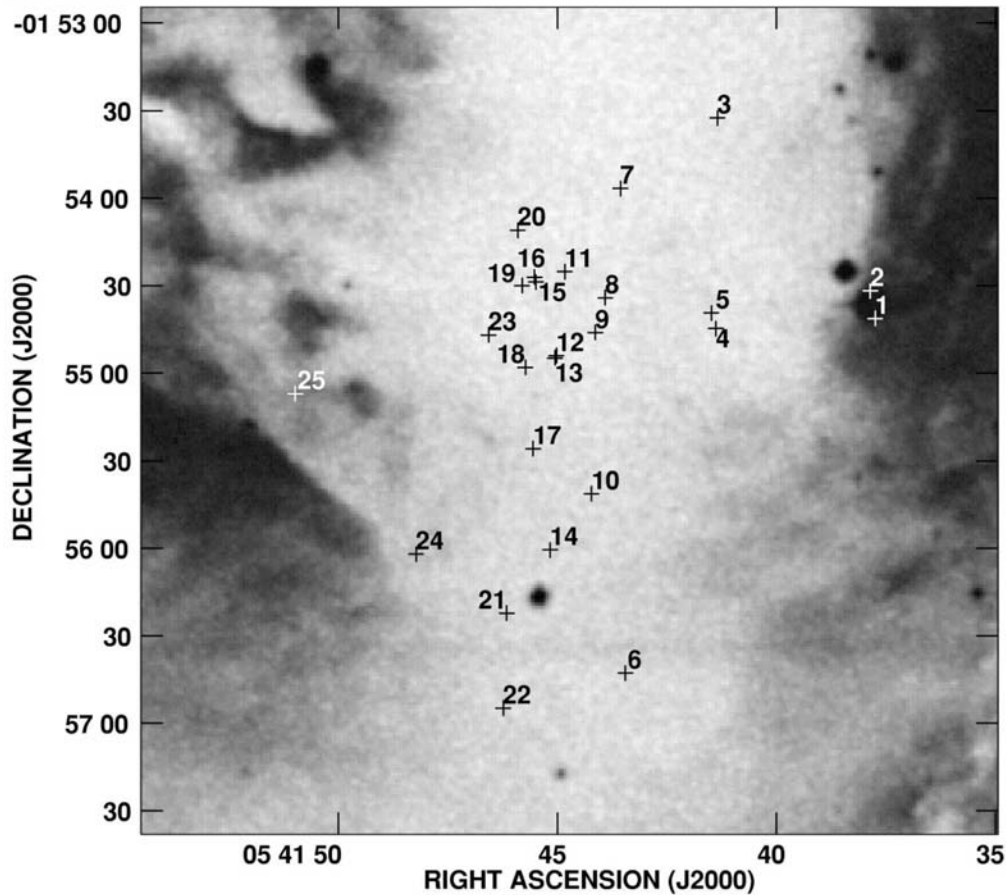


Figure 6. Position of the compact radio sources detected, overlapped on a gray-scale image of the region from the red Digital Sky Survey (DSS). The position and number of some of the sources are shown in white so that they are seen better against the dark background. IRS#1 is denoted as compact radio source 1. Reproduced from Rodríguez, Gómez, & Reipurth (2003).

up study by Lada, Evans, & Falgarone (1991) tracing even denser gas ($> 10^5 \text{ cm}^{-3}$) indicated that NGC 2024 is the most structured core in L1630 and has the highest column density ($\log(N) = 14.0$) and star formation efficiency (30%) in the region.

Multi-line CO observations by Graf et al. (1993) indicate that the bulk of the molecular column density arises from a warm gas (67 K) component located behind but in the immediate vicinity of the HII region, similar to the distribution of the 1.3 mm dust continuum (Mezger et al. 1988). It is likely that both the warm gas and dust are heated by the UV radiation that gives rise to the HII region, with possible additional internal heating from embedded young stellar cores (Moore et al. 1989, Schulz et al. 1991, Lis et al. 1991, Graf et al. 1993). Indeed, 1.3 mm observations reveal 7 protostellar dust condensations FIR 1–7 (Mezger et al. 1988, 1992). Wiesemeyer et al. (1997) present 3 mm interferometry of the region, resolving FIR 5 and FIR 6 and use CS observations to argue for freeze-out of gas onto grains (cf. Mauersberger et al. 1992). Charnley (1997) examined the possibility of such depletions through chemical modelling of the dense

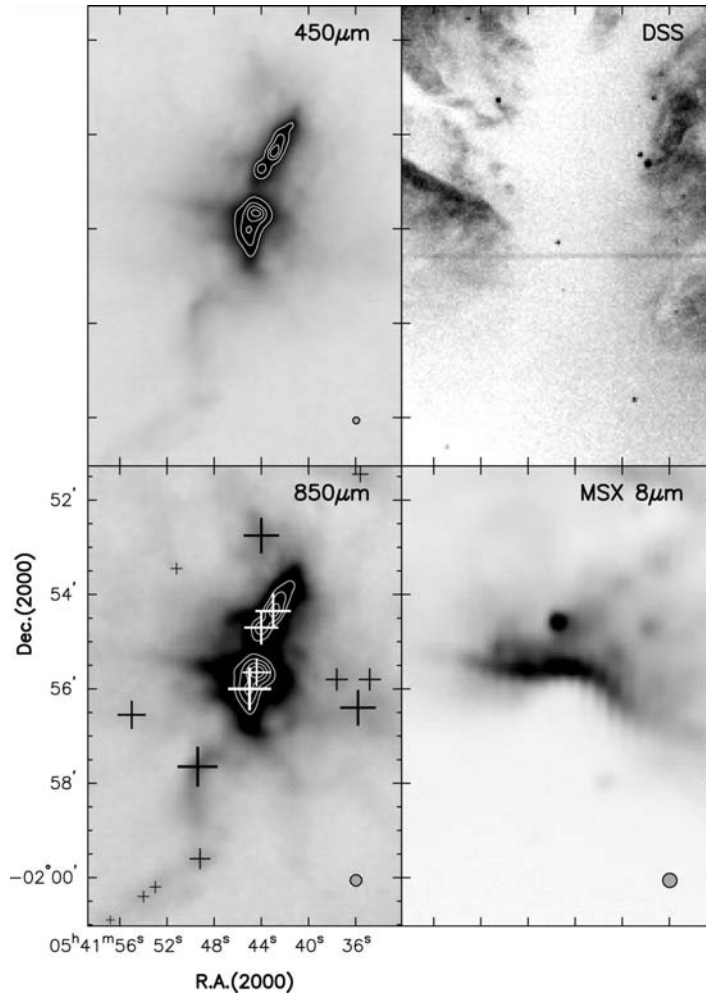


Figure 7. Sub-millimeter observations of NGC 2024 from Johnstone, Matthews, & Mitchell (2006) at $450\ \mu\text{m}$ (upper left) and $850\ \mu\text{m}$ (lower left) shown along with an $8\ \mu\text{m}$ mid-IR image from the MSX satellite (lower right) and a visible light image from the DSS database (upper right).

cores. Wilson et al. report C^{18}O and 2.7 mm continuum observations of the region, and Gaume et al. (1992) used the VLA to obtain high-resolution continuum and NH_3 maps. Several of the sources in this region show evidence for internal heating suggesting they might be more evolved young stellar objects (Ho et al. 1993, Mangum et al. 1999). Recent SCUBA mapping by Johnstone, Matthews, & Mitchell (2006; cf. Visser et al. 1998) at 450 and $850\ \mu\text{m}$ revealed 16 discrete clumps associated with NGC 2024, all with elevated dust temperatures and nine showing centrally condensed structure indicating they may be collapsing into protostars (Figure 7). The picture advocated by Barnes et al. (1989) of an embedded cluster with associated HII region, blowing out from the top (to the north), but still bounded from the front (thus obscured from view along our line-of-sight), back, and both sides is still consistent with all of the extant data.



Figure 8. The HH 92 jet emanates from a deeply embedded source (at α_{2000} : 5 42 27.9, δ_{2000} : $-1^{\circ} 20' 00''$) and shows wiggling indicating that the source may be binary. $H\alpha$ is red and [SII] 6717/6731 is turquoise. The figure is approximately 3 by 4 arcminutes. North is up and east is left. Figure courtesy of Bo Reipurth.

There are a series of HH objects located to the north of the main NGC 2024 nebula (Figure 8). These Herbig–Haro objects were first identified by Reipurth (1985) and subsequently observed by Gredel, Reipurth & Heathcote (1992). Bally, Reipurth & Aspin (2002) suggest that HH 90–93, along with the more recently discovered HH 597, 598 are part of the same jet extending over 10 arcminutes. One Herbig–Haro object, HH67, is located within the NGC 2024 nebula and appears as a series of knots extending over $22''$ (Reipurth & Graham 1988). Numerous molecular outflows have been identified. The largest extends over 1 pc along the north-south direction (Sanders & Willner 1985) and has the following properties: *i*) it is unipolar; *ii*) it is highly collimated with the higher velocity material more collimated than the lower velocity material; and *iii*) it exhibits clumpy structure (Richer 1990, Richer, Hills & Padman 1992). The rotational lines observed from gas in the flow are polarized, due to the Goldreich–Kylafis effect, with a polarization axis consistent with the outflow axis (Greaves, Holland & Ward-Thompson 2001). The gas may be associated with a jet seen in the radio continuum (Subrahmanyam 1992). A more compact jet is also seen on the eastern side of the extended outflow (Richer 1990; Chandler & Carlstrom 1996). The extended and compact outflows are often identified with FIR5 and FIR6, respectively (Richer, Hills, & Padman 1992; Chandler & Carlstrom 1996), although there is some uncertainty with this association (Chernin 1996). A unipolar molecular outflow has also been identified associated

with FIR4 (Chandler & Carlstrom 1996) which is also extended in the near-infrared (Moore & Yamashita 1995 and references therein).

The magnetic field structure of NGC 2024 has been studied by observing: 1) linearly polarized thermal dust emission at $100\ \mu\text{m}$ (Hildebrand et al. 1995; Dotson et al. 2000) and at $850\ \mu\text{m}$ (Mathews et al. 2002); 2) dichroic polarization of point sources at $1.6\ \mu\text{m}$ (Kandori et al. 2007); and 3) Zeeman splitting of OH and HI absorption lines (Crutcher et al. 1999). Though overall magnetic field orientation in NGC 2024 is in the east-west direction as inferred from the far-infrared ($100\ \mu\text{m}$) and near-infrared polarizations, there is a local magnetic field structure along the dense filament containing protostellar condensations FIR 1–7 (Mezger et al. 1988, 1992). Lai et al. (2002) used the BIMA interferometer to study the magnetic field structure in the vicinity of FIR 5. On the basis of the Zeeman splitting observations, the distributions of line-of-sight magnetic field strength are found to smoothly vary from < 8 micro-gauss ($1\ \sigma$) in the northeast to 100 micro-gauss in the southwest, indicating that the line-of-sight orientation of magnetic fields varies across the region. The distribution of the plane-of-sky magnetic field over the dense star-forming ridge, not well resolved at $100\ \mu\text{m}$ and not well penetrated at $1.6\ \mu\text{m}$ was studied in detail at $850\ \mu\text{m}$. On the basis of the polarization map at $850\ \mu\text{m}$ and the Zeeman observation results, the magnetic field structure of the star-forming ridge was successfully modeled in two ways: a) helical magnetic fields surrounding a curved filamentary cloud; and b) magnetic fields swept-up by the ionization front of the expanding HII region (Mathews et al. 2002).

Ionizing Source In contrast to the other HII regions, such as M 42, the dominant source of ionization powering the HII region is not directly identified due to the heavy obscuration by the central dust lane in NGC 2024. Barnes et al. (1989; cf. Crutcher et al. 1986) note that there are two main ionization loops in the region, one to the east and one the west, each exhibiting a distinct velocity signature. IRS #2, a candidate early B-type star (Lenorzer et al. 2004), was thought to be the exciting source of the East Loop (e.g., Grasdalen 1974; see however Thompson et al. 1981). Bik et al. (2003) suggest that the ionizing source is actually IRS 2b located $5''$ north-west of IRS #2. They found that the spectral type of IRS 2b is in the range O8 V – B2 V, which is consistent with the intensities of radio continuum and recombination lines observed toward the HII region (Krügel et al. 1982) as well as the oxygen fine structure lines observed with ISO (Giannini et al. 2000). However, taking into account the contribution of the infrared excess emission to the K-band flux (Meyer, Calvet, & Hillenbrand 1997), the extinction toward IRS 2b may be substantially less than the $A_V = 24^m$ estimated by Bik et al. (2003). With the range of resulting luminosities derived assuming $A_V = 15^m$ (Meyer 1996), early B may be preferred to late O for the spectral type. Thus, while IRS 2b likely contributes significantly to the total ionizing flux, it may not be the dominant source. Recent near-infrared imaging polarimetry constrains the location of ionizing source(s) through the polarization vector analysis assuming that the ionizing source and the illuminating source are the same (Kandori et al. 2007). The location of ionizing source(s) is inferred to be within the circle with 15 arcsec radius at the center of NGC 2024, in which both IRS #2 and IRS 2b are included, but IRS 2b is closer to the center of the symmetric vector pattern. Yet there are several other bright sources within this region that could in principle contribute to the ionizing flux (Liu et al. 2003; Haisch, Lada, & Lada 2000). Ezoe et al. (2006) report detection of diffuse X-ray emission towards NGC 2024 which requires significant energy input, perhaps by strong winds from a number of massive stars. The jury is still out, however the preponderance of the

evidence to date suggests that IRS #2 plus IRS 2b, together with other sources in the cluster core, provide the total ionizing flux.

3.3. The Horsehead Region

The Horsehead Nebula is a dark cloud of dense gas and dust protruding from the L1630 molecular cloud (Figure 9). It is seen in silhouette against the bright HII region IC 434, itself photoionized by the σ Orionis system. The Horsehead is being photoevaporated at its western limb by the nearby (4 pc in projection) O9.5V star σ Ori A and it points radially toward this source of erosion (see the chapter by Walter et al.). The photographic discovery of the Horsehead was made by Harvard College Observatory staff member Williamina Paton Fleming in 1888 as part of a program to image the Orion Nebula (Waldee & Hazen 1990). Photographs were subsequently presented by Pickering (1895), Roberts (1903), Wolf (1903), Keeler (1908), Barnard (1913), Curtis (1918), and Duncan (1921). It soon became evident that the lack of stars in that region was caused by a physical structure blocking background light. This interpretation was advocated by E.E. Barnard in his extensive description of the Horsehead Nebula in 1913 (Barnard 1913; see Pound, Reipurth, & Bally 2003 for an historical account). In the catalog of Barnard (1919), the Horsehead got the name B33 by which it is known today.

The Young Stellar Population Star formation in the IC 434 and Horsehead region was first suspected with the discovery of H α emission line stars (Haro & Moreno 1953; Wiramihardja et al. 1989) and variable stars (Mannino 1959) in that general area. Reipurth & Bouchet (1984) identified a partly embedded young star, which they called B33-1, at the northwestern tip of the Horsehead (also known as IRAS 05383–0228, one of three IRAS sources observed within the Horsehead; Pound, Reipurth, & Bally 2003). Another, IRAS 05386–0229, is noted as having a steeply-rising spectral energy distribution between 12 μ m and 60 μ m. Two X-ray detections with ASCA have been reported in the vicinity of the Horsehead (Nakano et al. 1999), although neither infrared counterpart shows excess emission at IR wavelengths. The combination of near-infrared (J , H , and K_S) and mid-infrared (Spitzer/IRAC 3.6, 4.5, 5.8, and 8.0 μ m) imagery has recently been used to characterize the state of star formation in this region (Bowler et al. 2008; Megeath et al. 2005). Color-color and color-magnitude diagrams reveal two flat-spectrum protostars emerging from the western limb of the Horsehead (one being the young star B33-1) as well as several other candidate young stars displaying modest infrared excesses. The location of the flat-spectrum sources at the interface between the Horsehead and IC 434 suggest a possible interaction between σ Ori and the Horsehead in the context of triggered star formation.

Molecular Gas The formation of the Horsehead has been discussed by various authors. Reipurth & Bouchet (1984) first proposed that the Horsehead is a pre-existing dense cloud core that is emerging as a Bok globule due to the photoevaporation of the surrounding more tenuous material, and at the same time is shielding the material behind it from photoevaporation. Alternatively, a variety of instabilities at a cloud/HII region interface may produce dense structures like the Horsehead. Pound, Reipurth, & Bally (2003) made detailed millimeter interferometric observations of the Horsehead and found that both of the above formation scenarios are consistent with their data. In a theoretical investigation, Gritschneder et al. (2007) used a smoothed particle hydrodynamic code to simulate a massive star's UV radiation interacting with a stable molecular cloud. They found that structures similar in length to the Horsehead emerge in about

0.3 Myr and that the collapse of otherwise stable clumps can occur at their tips. Their work supports the dense clump-shadowing model of pillar formation.

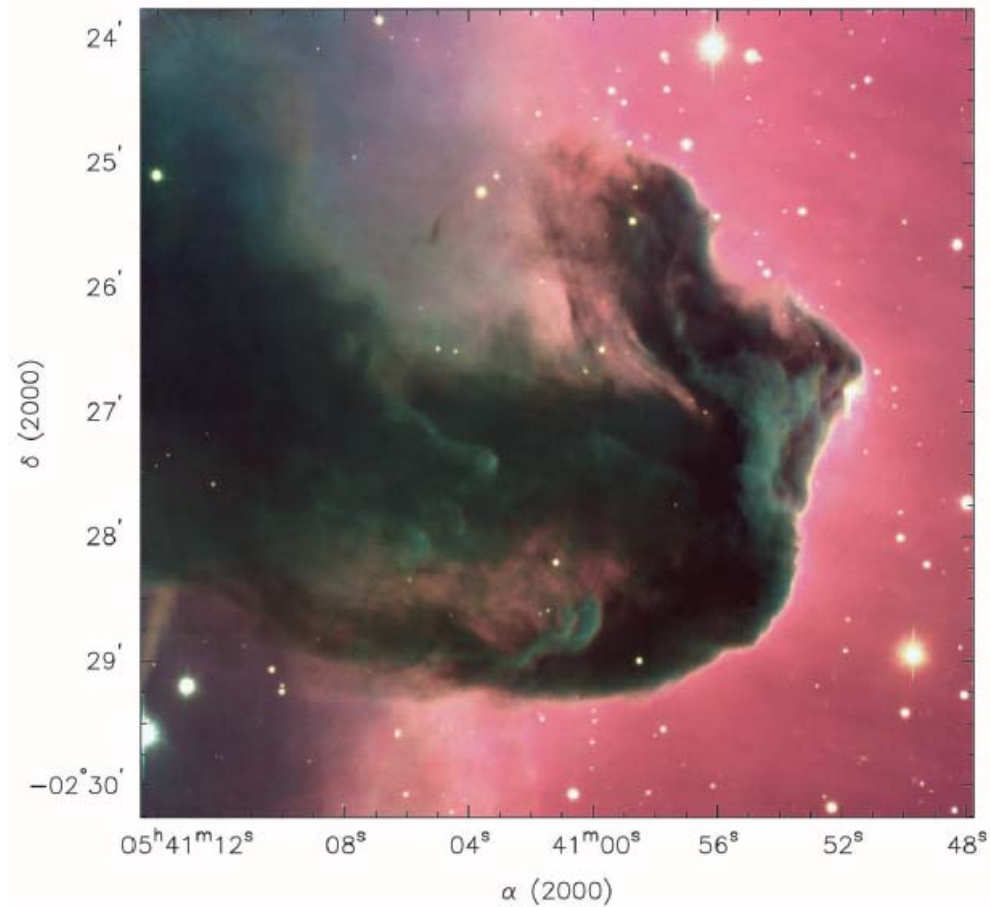


Figure 9. The Horsehead as seen in a B, V, and R-band mosaic obtained at the VLT. The young star B33-1, a visible star embedded in a small bright nebula, is located at the western-most cusp of the Horsehead. Courtesy ESO.

The defining shape of the Horsehead is caused by the physical separation of a denser clump on either side of the main pillar— together these comprise the jaw and mane of the horse (Figure 9). There has been some debate regarding the formation of the jaw cavity and its origin is still unclear (Reipurth & Bouchet 1984; Warren-Smith, Gledhill, & Scarrott 1985; Neckel & Sarcander 1985). Pound, Reipurth, & Bally (2003) found a “U”-shaped feature in CO emission that appears to wrap around the end of the pillar with its northern leg tracing the nose of B33 and its southern leg following the shape of the jaw cavity. They discuss possible origins for this structure and suggest that it may originate from the outflow of an embedded, as yet undiscovered, young star. Hily-Blant et al. (2005) investigated the velocity field of the Horsehead and found a north-east velocity gradient as well as a rotation about the trunk connecting the horse’s head to L1630. This raises the possibility of a pre-existing velocity field through

which centrifugal forces created the nose and mane separations from the main pillar. Its rotational period (about 4 Myr) is similar to its survival timescale (about 5 Myr; Pound, Reipurth, & Bally 2003). The Horsehead has also been found to have fractal structure in an investigation by Datta (2003). Despite the prodigious work focused on these unique substructures of the Horsehead, there is little consensus on the mechanism of their formation.

The physical properties of the Horsehead have been determined by several groups. Zhou et al. (1993) infer a gas density of roughly 10^4 cm^{-3} from molecular CS observations, a value confirmed (and slightly increased) by other authors (Habart et al. 2005; Philipp et al. 2006; Abergel et al. 2003; Kramer, Stutzki, & Winnewisser 1996). Densities are found to increase in the clump cores and immediately behind the cloud/HII interface (Kramer, Stutzki, & Winnewisser 1996). Gas temperatures of 10–20 K are derived inside the cloud core coincident with the Horsehead (Philipp et al. 2006; Pety et al. 2007). The virial mass has been estimated to be $35 M_{\odot}$ (Lada, Bally, & Stark 1991), and the observed molecular mass has been measured at $27 M_{\odot}$ (Pound, Reipurth, & Bally 2003) and $<37 M_{\odot}$ (Philipp et al. 2006).

The proximity of the Horsehead photodissociation region (PDR) and its nearly edge-on orientation make it an excellent laboratory to investigate the interaction of high-energy photons and molecular gas. The excitation, ionization, and photo-erosion of polycyclic aromatic hydrocarbons at the interface between B33 and IC 434 have been studied by numerous authors (Copiègne et al. 2007; Pety et al. 2005; Teyssier et al. 2004; Abergel et al. 2002, 2003). Glowing brightly in the mid-infrared, the western ridge of the Horsehead was found to be the sharpest IR filament in the Milky Way detected by ISOCAM (Abergel et al. 1999, 2002, 2003) and represents a rapid cutoff in gas density. Other work on the PDR includes a study of sulfur depletion (Goicoechea et al. 2006), evidence for deuterium fractionation indicative of cold cloud chemistry (Pety et al. 2007), and a measurement of the cyclic to linear abundance ratio of C_3H_4 (Teyssier et al. 2005). A search for anions in this region has only resulted in upper limits on their abundances; they continue to remain elusive despite a concerted effort to find them (Millar et al. 2007; Agúndez et al. 2008).

Ward-Thompson et al. (2006) mapped the Horsehead at $450 \mu\text{m}$ and $850 \mu\text{m}$ and resolved two extended sub-mm clumps. One is located all along the western limb (B33-SMM1; resolved into two components by Johnstone, Matthews, & Mitchell 2006) while the other resides near the base of the pillar (B33-SMM2). The SMM2 clump is in gravitational equilibrium and is thought to pre-date the emergence of the pillar. On the other hand, SMM1 is not in gravitational equilibrium and may have been compressed by the ionization front at the western surface of B33 (Figure 10).

Triggered Star Formation? Triggered star formation at the western surface of B33 was first proposed by Reipurth & Bouchet (1984) as a model for the formation of the emerging young star B33-1. It has since been echoed by other authors (Pound, Reipurth, & Bally 2003; Ward-Thompson et al. 2006; Bowler et al. 2008) and partially relies on the spatial coincidence of young stars in the pillar. The SMM1 condensation at the western limb seems to be suffering compression by photoevaporation at the surface of the cloud and may be forced into a triggered collapse (Ward-Thompson et al. 2006). This scenario is consistent with the radiation-driven implosion model of induced star formation first proposed by Bertoldi in 1989. In this model the photoionization at the surface of a molecular cloud produces a shock into the cloud and compresses it, forming a clump; later this clump becomes gravitationally unstable and collapses to form new

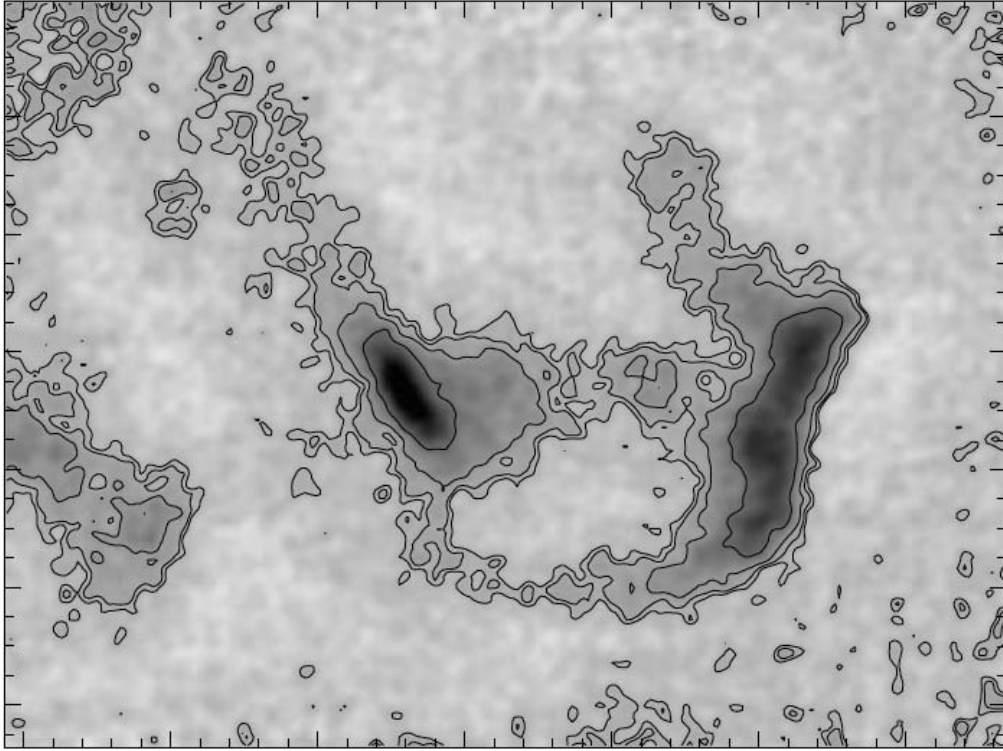


Figure 10. The Horsehead observed at $850\ \mu\text{m}$ by Ward–Thompson et al. (2006). Two regions of cold dust are identified, SMM 1 lies along the western ridge, and SMM 2 is at the base of the Horsehead structure.

stars. While the SMM1 clump is not coincident with either of the two flat-spectrum protostars, the observation of external compression bolsters the notion of induced star formation in this region. This scenario closely resembles recent simulations of triggered star formation in pillars (e.g., Gritschneider et al. 2007). However, it remains to be seen whether triggering is *required* to explain the data, or is merely consistent with the observations. It is notoriously difficult to argue that a given region was induced to collapse through compression as opposed to scenarios where an unstable clump experiences compression, but might have collapsed anyway in the absence of the external forcing.

4. Distributed Young Stars in L1630

The observations of Lada et al. (1991) suggest that most stars in L1630 formed in a clustered mode in which large groups of stars are produced in massive dense cores. In contrast, near-infrared studies of the L1641 molecular cloud present a different picture of the star forming process in GMCs (see chapter by Allen & Davis). Strom, Strom, & Merrill (1993) uncovered a population of isolated PMS stars distributed throughout the

cloud as well as several sparse aggregates ($N_* < 100$)². Based on spectroscopic studies, Allen (1996) suggested that as many as half of the young stars in L1641 (excluding OMC-1/2) may have formed in relative isolation, distributed throughout the cloud. This population may therefore have formed in a manner similar to stars in the Taurus dark clouds. In Taurus, the typical low mass star forms in a loosely aggregated or distributed mode of star formation from relatively isolated low mass dark cloud cores. At present it is still unclear why the star forming processes in the neighboring L1630 and L1641 clouds appear to be different. Could there be a significant distributed population in L1630 similar to that observed in the L1641 cloud?

4.1. Distribution of IRAS Sources

One way of searching for a widely scattered population of very young stars is to make use of the IRAS Point Source Catalogue (PSC). Because of sensitivity and resolution limitations, IRAS studies of the Orion molecular clouds do not probe the entire PMS stellar content (Strom et al. 1989). IRAS is only sensitive to infrared luminous young stellar objects, including embedded protostellar sources (i.e. the Class 0/I objects described in André & Montmerle 1994; see also Lada 1987), T Tauri stars possessing circumstellar disks (Class II sources), as well as more evolved stars lacking IR excesses (Class III) of intrinsically high mass. Further, IRAS source counts in high density regions are confused within the 45'' beam of the 12 and 25 μm detectors. In order to compare the distribution of embedded sources between L1630 and L1641, a search of the PSC was made for sources with $5^{\text{h}}12^{\text{m}} < RA < 6^{\text{h}}08^{\text{m}}$ and $-10.5^\circ < DC < 03.5^\circ$. The criteria of the search were that each source be detected at both 12 and 25 μm with $S_\nu(12)/S_\nu(25) < 1.25$ (indicative of an infrared excess over that expected from a stellar photosphere; e.g. Wilking et al. 1992). 232 sources were identified over the region encompassing the Orion A and B clouds and their spatial distribution is shown in Figure 11. Most of the IRAS sources in Orion B meeting these search criteria are associated with the dense cloud cores associated with the rich clusters identified above. This gives a similar picture concerning the distribution of protostars in L1630 as the study of Launhardt et al. (1996), who conducted a 1.3 mm survey for protostellar condensations in dense clumps. In contrast, the distribution of IRAS sources in L1641 extends from the region of the Trapezium for several degrees along the cloud to the southeast. Note that this IRAS selected sample comprises $< 10\%$ of the known stellar populations in either cloud. Embedded sources in the Orion B cloud appear to be localized in regions containing dense cloud cores (and embedded clusters) while they are more distributed across the face of the Orion A cloud. Future work with the Spitzer Space Telescope will probe an even more deeply embedded population of young stars (cf. Megeath et al. 2005). Based on Spitzer observations, Allen et al. (2007) suggest that the fraction of very young objects in Orion B located in a distributed population could be as large as 25%.

4.2. Near-Infrared Surveys

Li, Evans, & Lada (1997) have searched for a distributed population of PMS stars in L1630 by surveying a 1320 arcmin² region in the J, H, and K-bands. The region sur-

²Most of the aggregates identified by Strom, Strom, & Merrill (1993) have dynamical relaxation times $< 10^6$ yrs suggesting that they will not survive more than a few crossing times. In contrast, the rich clusters ($N_* > 100$) in L1630 as well as Orion A have relaxation times 1–10 Myr.

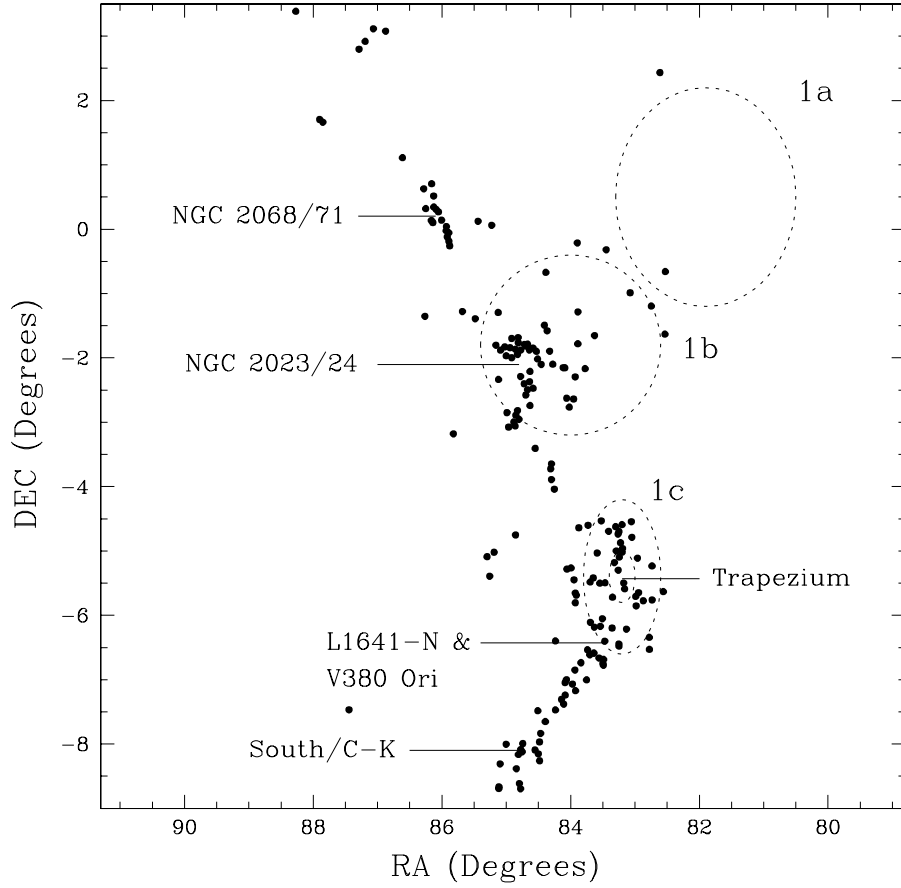


Figure 11. Distribution of IRAS PSC sources detected at both 12 and 25 μm with $S_{\nu}(12)/S_{\nu}(25) < 1.25$ indicating an infrared excess. While the sources in Orion B are largely confined to two groupings near the dense clusters NGC 2068/71 and NGC 2023/24, the distribution in Orion A extends over several degrees from the Trapezium cluster along the filaments of L1641 to the southeast.

veyed concentrated on an area that was away from the dense molecular cores and that exhibited modest visual extinctions ($\leq 10^m$). Two different approaches, near-infrared color and star counting analyses, were used to look for a distributed population. Since many young stars are surrounded by circumstellar accretion disks which emit significant amounts of near-infrared emission, one can search for evidence of recent star formation by looking for sources exhibiting IR excess (e.g. Meyer, Calvet, & Hillenbrand 1997; Haisch, Lada, & Lada 2001). Using this method, Li, Evans, & Lada (1997) estimated the fraction of sources with near-IR excess located outside the cluster areas to be 3% – 8%. In addition, the surface density of near-infrared excess sources is 1/7 of that found in the distributed population of L1641 and 1/20 of that found in the young cluster NGC 2023. The low fraction and low surface density of excess sources indicates that recent star formation activity has been very low in the outlying regions of L1630. The second approach used to search for a distributed population employed near-infrared star counts (Li 1997). Extensive control fields off the molecular cloud were used to es-

tablish the stellar surface densities of field stars and a method was developed using the survey data and a ^{13}CO map to extract foreground stars not associated with the cloud. Comparison of the star counts of the control field with the extinction-corrected on-cloud fields reveals that there are < 0.15 association members arcminute $^{-2}$ observed with $m_K < 14.5^m$ scattered across the region surveyed in L1630, suggesting there is no evidence for a large distributed population. Carpenter (2000) conducted a comprehensive study of several molecular clouds, including the entire L1630 (Orion B) region utilizing the Two Micron All Sky Survey. In agreement with previous work, he finds that nearly 100% of the young stars in Orion B are members of dense clusters with between 300 and 1000 stars (Adams & Myers 2001; Lada & Lada 2003). Results from both the near-IR color and star counting analyses strongly support the assertion that most stars in L1630 formed in rich embedded clusters.

4.3. $\text{H}\alpha$ Surveys

Over several years, astronomers at the Kiso Observatory in Japan utilized their Schmidt telescope to survey nearly 300 square degrees in the direction of Orion (Nakano, Wiramihardja, & Kogure, 1995). The objective-prism survey was targeted at $\text{H}\alpha$ emission-line stars which are comprised of classical and weak-emission T Tauri stars as well as Herbig-Haro emission nebulae associated with energetic mass loss from young stars. With a limiting magnitude of $V < 17.0^m$, this survey was sensitive to 1 Myr old T Tauri stars with masses $> 0.2 M_\odot$ in the absence of extinction (or $1.0 M_\odot$ with $A_V < 4.0^m$) at the distance of Orion. The $\text{H}\alpha$ emission-line strength is rated from 0 (dubious detection) to 5 (very strong). Comparison of the $\text{H}\alpha$ equivalent widths for Kiso $\text{H}\alpha$ sources also listed in the Herbig-Bell Catalogue indicates that most stars classified with $\text{H}\alpha$ strengths 3–5 correspond to classical T Tauri stars with $\text{EW}(\text{H}\alpha) > 10 \text{ \AA}$. There are over 150 emission-line stars projected onto the L1630 cloud (approximately 20 square degrees) in the Kiso survey area A-0904 (Wiramihardja et al. 1989). Several non-stellar emission-line objects are also detected such as the well known outflows HH 24–26 (e.g., Davis et al. 1997). The majority of these $\text{H}\alpha$ sources are associated with the rich clusters NGC 2024, 2068, and 2071; however some are spread across the face of the cloud (Figure 12). In addition, there is a curious cluster of $\text{H}\alpha$ emitters just to the southwest of NGC 2024 near σ Ori. There is no molecular material in this region though the $\text{H}\alpha$ sources are coincident with part of the Ori Ib sub-group of the OB association.

It is interesting to compare the distribution of $\text{H}\alpha$ sources in L1630 with those of L1641. Nakajima et al. (1998) present an analysis of these distributions over the whole of Orion. They divide the Kiso survey data into three regions: the Ori OB (roughly the Ori Ia subgroup of the association), Orion A (including L1641), and Orion B (including L1630). Nakajima et al. compute the average surface density of companions as a function of angular separation following Larson (1995) as well as the distribution of nearest-neighbor distances for each region. The mean surface density of companions in Orion A is $\times 2\text{--}3$ greater than in Orion B over the separation range $6'$ to 1° . However the mean nearest-neighbor distances are comparable. The distribution of $\text{H}\alpha$ emitters in L1630 can be explained as a collection of independent clusters super-posed on a random background with about 50% of the sources in each component (Nakajima et al. 1998). The distribution of $\text{H}\alpha$ sources in L1641 is somewhat similar, being comprised of both a clustered and a more diffuse background component. However, the surface

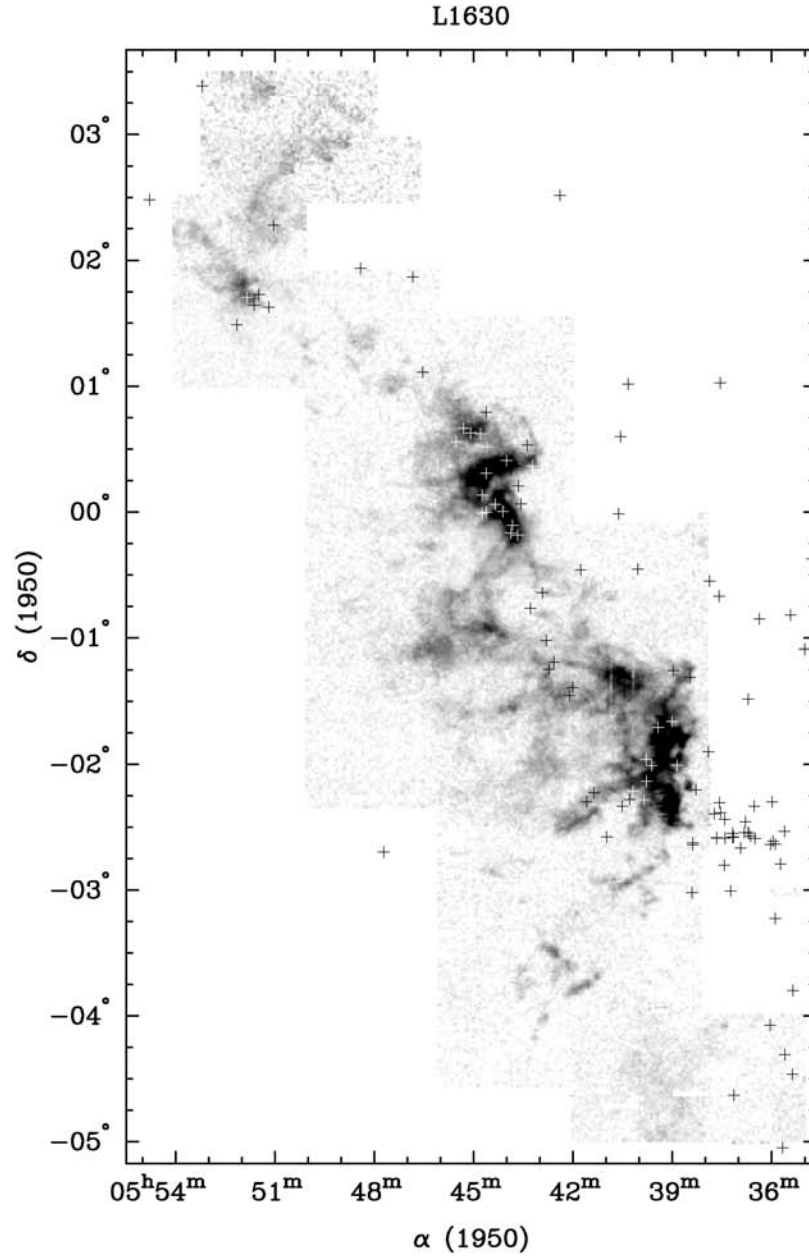


Figure 12. The distribution of $H\alpha$ sources classified 3–5 (i.e. classical T Tauri stars) from the Kiso survey area A-0904 overlaid with CO map of Bally et al. (1991) in greyscale. Most sources are concentrated in regions of dense molecular material although some sources are spread across the face of the cloud. Note the cluster of sources at $(\alpha, \delta) = (5^h37^m, -2^\circ30^m)$ associated with σ Ori.

density of $H\alpha$ sources in L1641 is much higher over a larger spatial area than the $H\alpha$ sources in L1630.

4.4. The ROSAT All Sky Survey

Another method of searching for young stellar populations is to look for X-ray emission associated with PMS activity (e.g., Feigelson et al. 2007). There are approximately 100 ROSAT X-ray sources projected across a 25 square degree region encompassing the L1630 cloud (Sterzik et al. 1995). Inspection of the X-ray source distribution suggests that the source density in L1641 is significantly higher than in L1630. This visual impression is supported by the distribution of weak-emission T Tauri star candidates identified as part of the unbiased spectroscopic follow-up of Alcalá et al. (1996). They selected 15 ± 1 X-ray sources in 12 different regions toward Orion of approximately 35 square degrees each. Of the stars which appear to have LiI absorption based on low resolution spectra, the observed source density in L1641 is $3 \times$ greater than that projected onto L1630. Assuming all of the objects projected onto the cloud are at a distance of 460 pc, Alcalá et al. (1998, 2000) derive masses between $0.8\text{--}3.4 M_{\odot}$ and ages $0.2\text{--}7$ Myr for these sources. If most of these objects are bona fide weak-emission T Tauri stars, this also suggests that recent “distributed-mode” star formation has been much more vigorous in L1641 compared with L1630 in the last 10 Myr.

5. Discussion

5.1. A Dominant Mode of Star Formation?

Based on results from IRAS, near-infrared, $H\alpha$, and X-ray surveys of L1630, it is clear that star formation is not restricted *exclusively* to the dense clusters. However, it does appear that 60–90% of the stars $> 1.0 M_{\odot}$ formed in the last 10 Myr are concentrated in the rich clusters NGC 2024, 2068, and 2071. This stands somewhat in contrast to the results obtained by Strom, Strom, & Merrill (1993; see also Allen 1996) in L1641 where it is estimated that as much as 50% of the on-going star formation (excluding OMC-1/2) occurs in a widely distributed population of young stars (cf. Carpenter 2000). Yet when we attempt to compare the relative importance of different star-forming entities (e.g. cluster, aggregate, and isolated) in both regions in a consistent fashion we find that star formation in Orion A (L1641) and Orion B (L1630) is rather similar.

In order to affect an accurate comparison of Orion A and Orion B we must count OMC-1/2 as part of the stellar population of the former in addition to L1641. After all, we have not excluded NGC 2024 in considering star formation in L1630! Further, some of the aggregates of Strom, Strom, & Merrill (1993) have properties very similar to the clusters identified by Lada et al. (1991). For example, the L1641 South cluster (comprised of 105 stars within an effective radius of 0.65 parsecs) is similar to the NGC 2071 cluster of L1630 even though it is probably older. In addition the aggregate associated with the Cohen-Kuhi group (25 stars within 0.3 pc radius) compares well with NGC 2023. Finally, we note that on-going star formation associated with the dense core LBS 23 bears a striking resemblance to the L1641-N aggregate including outflow activity, and deeply embedded IR/radio sources (e.g. Davis et al. 1997; Moneti &

Reipurth 1995; Bontemps, André, & Ward–Thompson et al. 1995)³. Taking a broader perspective, there appears to be a continuum of star forming events over the whole of Orion, stretching from the extreme Trapezium, to the rich clusters and sparser aggregates of both L1630 and L1641, and finally some distributed or isolated star formation occurring over the face of both clouds. In order to determine the range of plausible events in which a sun–like star forms in Orion, it would be valuable to construct the cumulative distribution of young stars as a function of stellar density, from distributed mode to dense cluster. When one considers the *entire* stellar population of the Orion A cloud, it turns out that $> 2/3$ of the total number of stars < 10 Myr old are part of rich clusters or aggregates (see chapter by Allen & Davis). This seems to be consistent with the results of Lada et al. (1991) for L1630: in both the Orion A as well as the Orion B molecular clouds, most stars form as part of young clusters compared to a minority that form in relative isolation (Carpenter 2000; Allen et al. 2007).

Yet Miller & Scalo (1978) have presented arguments that most of the stars ($\sim 90\%$) found in the Galactic disk were formed as part of unbound associations. How can we reconcile this with the fact that 60–90% of stars forming in both the Orion A and B clouds are cluster members? Lada, Margulis, and Dearborn (1984) point out that unless the star formation efficiency (SFE) is $> 50\%$, embedded clusters such as those observed in Orion B will likely emerge as unbound associations. This result has been confirmed through a number of numerical studies over the past twenty years (e.g. Fellhauer & Kroupa 2005). There is some evidence that the Orion Nebula Cluster (ONC) may evolve into a bound open cluster (Hillenbrand & Hartmann 1998) similar to the Hyades. However, as pointed out by Lada & Lada (2003), given the number of open clusters in the solar neighborhood, it is unlikely that most embedded clusters found in local giant molecular clouds will emerge bound unless we are over–producing bound clusters in the present epoch. It is worth remembering that there are more young stars associated with the ONC than have recently formed in the entire region of L1630 ($N_{ONC} > 3000$ compared to $N_{L1630} < 2000$). If the ONC will evolve into a bound open cluster, it is difficult to see how this region taken as a whole can be considered representative of star formation in the Milky Way. It is often presumed that the richest clusters are those with the largest SFE and therefore are those that are most likely to emerge as bound open clusters. However, Lada & Lada point out that the mass distribution of embedded clusters in the range 10^2 to $10^4 M_{\odot}$ appears to be similar with that observed for massive open and globular clusters in the range 10^3 to $10^6 M_{\odot}$. This implies that equal numbers of stars form over decadal mass ranges regardless of whether the clusters are bound (high SFE leading to open clusters) or not (lower SFE leading to unbound associations). Indeed Goodwin & Bastian (2006) find no relationship between the implied star formation efficiency and mass for extremely young “super star clusters” in nearby galaxies. A picture emerges where there is no preferred mode of star formation and that bound open clusters represent a fraction of stars formed in the disk of the Milky Way, selected on the basis of star formation efficiency, independent of cluster mass. If confirmed, the next challenge is to understand what sets the SFE, critical to determining the fate of a young forming cluster.

³LBS 23 is the fifth most massive CS core catalogued by Lada, Bally, & Stark (1991); see chapter by Gibb.

5.2. Star-forming Histories: L1630 vs. L1641

Despite the fact that most stars forming in L1630 and L1641 are part of rich clusters or aggregates, there is a substantive difference in the star-forming histories of these two regions: the present-day distributed-mode star formation rate in L1630 is a factor of $\times 2 - 7$ lower than that observed in L1641 despite having a very similar total reservoir of molecular material (Maddalena et al. 1986). Given the difference in the spatial distribution of dense gas between the two clouds, perhaps this is not a great surprise. Comparison of the CS (2–1) observations (tracing gas with densities $> 10^4 \text{ cm}^{-3}$) of Orion B (Lada, Bally, & Stark 1991) and Orion A (Tatematsu et al. 1998) show that the distribution of dense cores in Orion B is much more concentrated than in Orion A. This picture is confirmed in the sub-mm surveys of Orion A (Johnstone & Bally 1999) and Orion B (Johnstone, Matthews, & Mitchell 2006) where the dense material in the former is more broadly distributed than dense material in the latter (see also chapters by Gibb, Muench et al., and Allen & Davis). To the extent that stars form in dense cloud cores, one might expect the distributed star formation to be more vigorous in Orion A where there is ample dense gas found over a large portion of the cloud. However that still leaves the question unanswered; why is there any difference between the Orion A and Orion B clouds? The extinction observed toward the OB stars projected against both clouds suggest that the subgroups of the Ori OB association lie in front of the clouds. Ori Ib is offset somewhat from L1630 to the northwest while Ori Ic is centered roughly on OMC–1. Gomez & Lada (1998) point out that the distribution of $\text{H}\alpha$ sources in the northern portion of Orion A (presumably tracing on-going star formation across the face of the cloud) follows closely the distribution of OB stars in the region (presumably tracing the fossil record of a previous episode of star formation). They argue that this fact taken together with other evidence suggests that current star formation in Orion A was triggered. Indeed Brown et al. (1994) estimate that Ori Ic has input $10 \times$ the energy input from Ori Ib into the local interstellar medium through supernovae, W–R, and stellar winds. Perhaps the main difference between the star forming properties of Orion A and Orion B is that the former was triggered by Ori Ic while the latter has not yet been influenced by its local environment.

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