

GLOBAL STAR FORMATION IN THE L1630 MOLECULAR CLOUD

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ABSTRACT

Recently, the first systematic and coordinated surveys for both dense gas and young stellar objects within a single molecular cloud, the L1630 molecular cloud, have been completed (see recent work by Lada; Lada, Bally, & Stark; Lada et al.) This *Letter* compares these two surveys. As a result, we find that (1) star formation in the L1630 molecular cloud occurs almost exclusively within the dense ($n > 10^4 \text{ cm}^{-3}$) gas; (2) star formation does not occur uniformly throughout the dense gas and is strongly favored in a few very massive ($M > 200 M_{\odot}$) dense cores, where efficient conversion of molecular gas into stars has resulted in the production of rich stellar clusters; and (3) high gas densities and high gas mass may be necessary but not sufficient conditions for the formation of star clusters since two of the five most massive dense cores in the cloud have very low levels of star formation activity.

Subject headings: infrared: stars — ISM: individual: L1630, Orion B — radio lines: molecular: interstellar — stars: formation

1. INTRODUCTION

Understanding the process of stellar birth requires a detailed knowledge of both the prenatal material and recent products of star formation. In our Galaxy stars form within dense, dust enshrouded regions of molecular clouds. However, only recently has technology enabled large-scale, systematic and coordinated studies of both the dense gas and the young stars within molecular clouds. For the first time, extensive, well-sampled searches for dense gas (via the CS $J = 2 \rightarrow 1$ line) and embedded young stellar objects (via their $2 \mu\text{m}$ near-infrared emission) have been completed in a single molecular cloud: the L1630 molecular cloud (Lada 1990; Lada, Bally, & Stark 1991a, hereafter LBS; Lada et al. 1991b, hereafter LDEG). These two surveys have provided the most complete census of dense cores and young stellar objects within a giant molecular cloud to date. In this *Letter*, the results of these two surveys will be compared in order to investigate the relationship between dense molecular gas and star formation.

The L1630 molecular cloud is located in the Orion molecular cloud complex. It is one of two major clouds in this complex, extending northward from the Orion Nebula and containing several well-known star-forming regions such as NGC 2071, NGC 2068, M78, NGC 2024, and NGC 2023. It has a mass of $8 \times 10^4 M_{\odot}$ (Maddalena et al. 1986) and is located at a distance of 400 pc (Anthony-Twarog 1982).

2. OBSERVATIONAL RESULTS: THE MOLECULAR AND INFRARED SURVEYS

2.1. CS $2 \rightarrow 1$ Survey

In order to identify the dense gas, the L1630 molecular cloud was surveyed in the $J = 2 \rightarrow 1$ transition of CS (LBS). This transition traces gas with volume densities on the order of 10^4 cm^{-3} . As described in LBS, the observations were taken using the AT&T Bell Laboratories 7 m telescope. The spatial resolution of the observations equaled 1.8 or 0.2 pc, and the spectral resolution equaled 0.31 km s^{-1} . Thirteen thousand points were surveyed with $1'$ spacing to a rms noise level of 0.2 K. The total area covered by the survey was ~ 3.6 square

degrees or $\sim 20\%$ of the molecular cloud as measured in CO to a detection limit, $T_{\text{R}}^* = 0.8 \text{ K}$ (Maddalena et al. 1986).

The results of the LBS CS($2 \rightarrow 1$) survey are summarized in Figure 1 in the form of an integrated intensity map. CS emission was detected, at a 3σ level above the noise, over $\sim 10\%$ of the area surveyed. This emission is not distributed uniformly throughout the cloud, but rather is confined in dense clumps or cores. The CS emission is bright in all previously known regions of star formation. In addition to these well-known sources, many previously unknown dense cores were found. In fact, 42 individual dense cores were identified at a 5σ level above the noise from analysis of the complete spatial-velocity field of the observed CS emission.

The locations of the 42 CS cores is also shown in Figure 1. The cores appear to be distributed in two large groupings or clusters, located in the northern and southern parts of the cloud, with a mostly empty region in between. These two large groups of cores are elongated, with similar dimensions of $\sim 70'$ N-S by $40'$ E-W, which corresponds to dimensions of $8 \text{ pc} \times 5 \text{ pc}$ at the assumed distance to L1630 of 400 pc. In addition, the two large clusters of cores, themselves, are clearly subclustered.

Most of the CS cores have masses less than $100 M_{\odot}$ and only five cores have masses greater than $200 M_{\odot}$. The distribution of core masses, for $M > 20 M_{\odot}$, follows the power law, $dN/dM \propto M^{-1.6}$, where N equals the number of cores per solar mass interval. It is interesting to note that all clump mass spectra determined to date, for several different molecular clouds, exhibit a similar spectral index (Blitz 1992). Furthermore, this spectral index, $\alpha = -1.6$, implies that a significant amount of the mass of the dense gas within a GMC is contained in the most massive cores. Indeed $\sim 50\%$ of the total core mass in L1630 is found to be contained within the five most massive cores, which have masses greater than $200 M_{\odot}$. These five massive cores cover $\sim 1\%$ of the total area surveyed, which indicates that the dense gas in the surveyed region is confined to a small area and is highly localized on the scale of the GMC. Moreover, the lower mass cores appear to be spatially distributed in groups clustered around the most massive cores (Fig. 1). This further indicates that the dense gas is highly localized or clustered within this cloud.

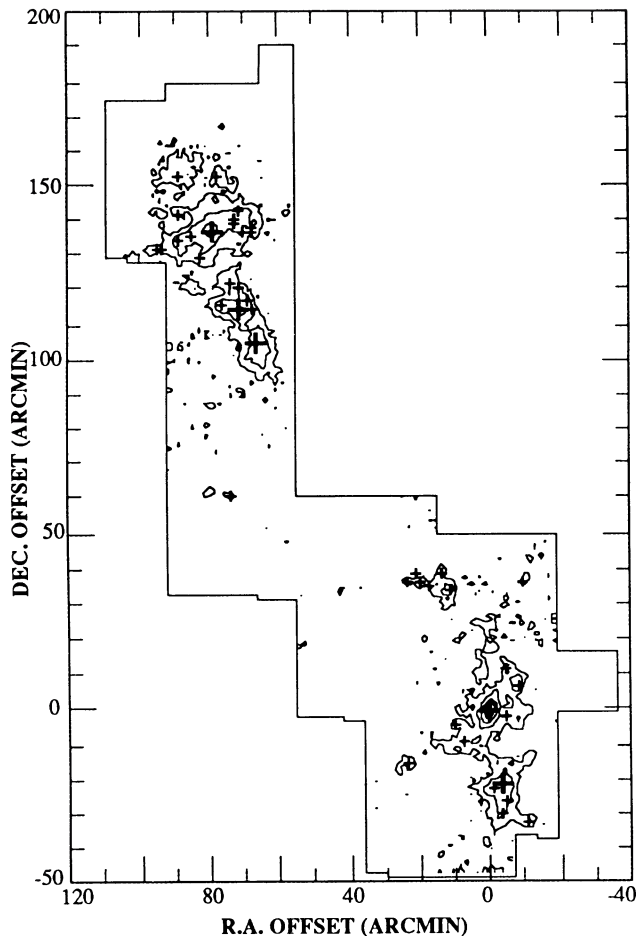


FIG. 1.—The distribution of dense gas in the L1630 molecular cloud. A contour map of CS(2 \rightarrow 1) integrated intensity in the velocity range of 7–13 km s⁻¹ is shown. The (0, 0) position corresponds to R.A. 5^h39^m12^s, Decl. -01°55'42". The lowest contour level is at 0.8 K km s⁻¹, which corresponds to a 3 σ detection above the noise. In addition, the locations of the dense cores identified by LBS are shown as crosses with the five most massive cores ($M > 200 M_{\odot}$) represented by large crosses. The solid lines represent the boundaries of the CS survey.

2.2. Near-Infrared Survey

In order to study the population of young stellar objects, a significant portion of the L1630 molecular cloud was surveyed at near-infrared wavelengths using the NOAO Infrared Array Camera on the Kitt Peak 1.2 m telescope (Lada et al. 1991b). The spatial resolution of these observations was $\sim 1''.3$ pixel⁻¹. Approximately 3000 1' \times 1' fields were surveyed at 2.2 μ m (K band), covering an area of ~ 0.8 square degrees. The regions surveyed included both areas containing CS emission and areas without CS emission. Specifically, 42% of the area observed at 2.2 μ m contained CS emission at a 3 σ level above the noise, and the remaining 58% of the area surveyed contained either no CS emission or emission below the 3 σ noise level.

The LDEG 2.2 μ m survey is estimated to be complete to a K magnitude of 13. At the distance of L1630, assuming no extinction, this would correspond to a 0.6 M_{\odot} main-sequence dwarf. LDEG have shown that the extinction toward regions containing no CS emission is negligible at K. Therefore in such regions the survey would be sensitive to late main-sequence K dwarfs.

In regions of significant CS emission, however, we would expect the extinction to be higher, but even with an extinction, $A_v \sim 15$ mag, we find that the survey is complete to main-sequence stars with masses on the order of 1 M_{\odot} . In addition, the effective sensitivity of the 2.2 μ m survey can be estimated by examining the results of sensitive, near-infrared studies of nearby regions of low-mass star formation. Taurus is a classic example of a region-forming low-mass stars. Myers et al. (1987) have observed 34 *IRAS* sources associated with dense cores at 2.2 μ m. These sources are representative of T Tauri stars and have masses less than 1 M_{\odot} . It is of interest to determine what fraction of the Taurus population would be detected by the LDEG 2.2 μ m survey. If the Taurus sources were placed at the distance of L1630, then 85% of them would be identified. Therefore if L1630 contains a population of stars similar to those in Taurus, the LDEG survey would count the majority of them. We therefore conclude that the 2.2 μ m observations of L1630 were sensitive enough to detect both high- and low-mass young stellar objects.

As a result of this survey, 912 sources having $m_K < 13$ were identified. Based on statistical arguments, LDEG estimate that $\sim 50\%$ of the sources having $m_K < 13$ are associated with the molecular cloud, and the remaining sources are unrelated background stars. Upon examination of the spatial distribution of sources, LDEG found that the sources are not distributed uniformly throughout the cloud but are grouped or clustered. In fact, four spatially distinct, embedded clusters were identified, where an embedded cluster is defined as a region in the sky where the source density significantly increases over the background star density (e.g., Lada & Lada 1991). These clusters are associated with the well-known star formation regions, NGC 2071, 2068, 2024, and 2023.

The most striking result of the 2.2 μ m survey is that the majority of the sources detected are concentrated in these four embedded clusters. Indeed, LDEG find that 58% of the sources detected by the 2.2 μ m survey are located within the four clusters. There are no other concentrations of stars within L1630. Moreover, the number of infrared sources found outside the embedded clusters are consistent with the expected number of background stars not associated with the cloud. After correction for the presence of background/foreground field stars, LDEG estimate that $\sim 96\%$ of the sources associated with the molecular cloud are contained within the four clusters! Furthermore, the total area covered by the four embedded clusters equals only 18% of the total region surveyed, indicating that star formation in L1630 is a highly localized process even for stars whose masses are as low as the mass of the Sun.

3. COMPARISON OF THE CS AND 2.2 MICRON SURVEYS OF L1630

The CS and 2.2 μ m surveys have revealed that both the distribution of the dense gas and the distribution of embedded infrared sources are clustered within the L1630 molecular cloud. What is the relation between these distributions? Figure 2 compares the locations and extents of the embedded infrared clusters with the distribution of dense gas. Comparing the two distributions, we find that the embedded clusters appear to be associated with the dense gas. Since the embedded clusters contain the majority of the infrared sources associated with the L1630 molecular cloud, this result clearly shows that star formation in this molecular cloud occurs almost exclusively in the dense gas.

Even though star formation is confined to the dense regions of the L1630 molecular cloud it is not occurring uniformly throughout the dense gas. As shown in Figure 2, the embedded clusters are coincident or nearly coincident with four of the five most massive ($M > 200 M_{\odot}$) CS cores (NGC 2071, NGC 2068, NGC 2024, and NGC 2023). Furthermore, the majority ($\sim 97\%$) of the embedded cluster sources are found in only three rich clusters ($N > 100$ stars), which are associated with three massive CS cores! These three cores, NGC 2071, NGC 2068, and NGC 2024, have a combined mass of $\sim 1200 M_{\odot}$, which corresponds to only $\sim 30\%$ of the total mass of dense gas within the molecular cloud. One should note, however, that our results do not imply that star formation is *only* occurring in the massive cores. From the present analysis, individual levels of star-forming activity for the lower mass cores have not been determined, and it is quite possible that stars are forming in these cores. However, the results do suggest that the star-forming activity in these cores is considerably lower.

The L1630 cloud was found to contain a massive core, LBS 23, that is not associated with a recognizable embedded cluster. LBS 23 is one of the larger cores in the LBS sample, having an effective radius of 0.52 pc and a mass of $230 M_{\odot}$. Although no obvious cluster is seen in this region, star formation is known to be present (Lada et al. 1974; Strom et al. 1975). Comparison of the CS and $2.2 \mu\text{m}$ results reveals that 18 sources ($m_K < 14$)

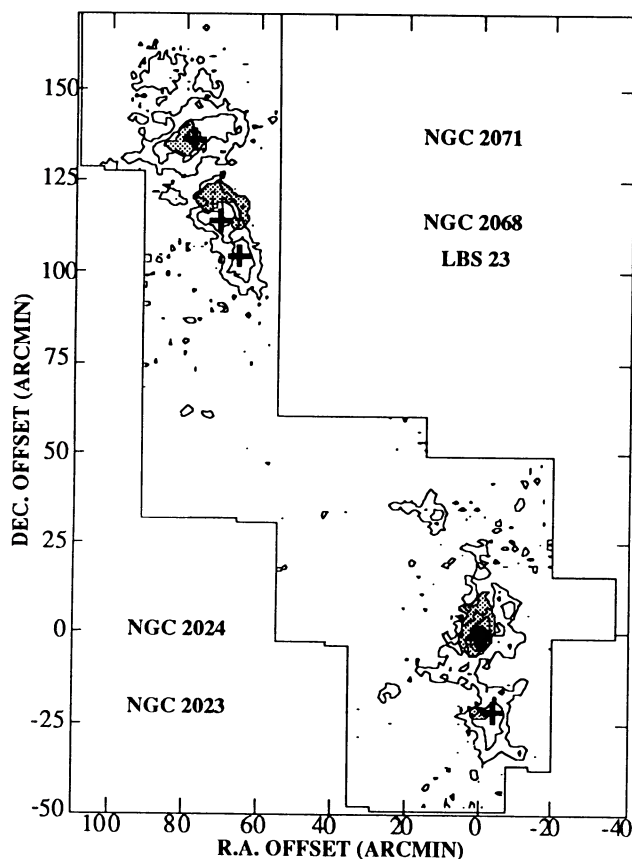


FIG. 2.—Locations of the embedded stellar clusters and dense gas in the L1630 molecular cloud. The shaded regions represent the location and extent of the embedded clusters. The distribution of dense gas is presented as intensity contours of the CS($2 \rightarrow 1$) emission. In addition, the peak intensity positions of the five most massive CS cores ($M > 200 M_{\odot}$) are represented by crosses.

TABLE 1
RELATIVE STAR FORMATION EFFICIENCIES

Core	Number of Sources	Core Mass (M_{\odot})	Number of Sources per Mass (M_{\odot}^{-1})
NGC 2024.....	309	430	0.72
NGC 2068.....	192	266	0.72
NGC 2071.....	106	456	0.23
NGC 2023.....	21	294	0.07
LBS 23.....	18	230	0.08

are contained within the core boundary. These sources appear to be spread throughout the core and therefore did not have a high enough surface density to be identified as a cluster using the criteria of LDEG.

In addition to the LBS 23 core, another massive core, NGC 2023, is associated with only a very poor cluster. NGC 2023 has a core mass of $\sim 290 M_{\odot}$ and is associated with an embedded cluster containing only 20 sources. The level of star formation activity in LBS 23 and NGC 2023 is considerably lower than that in the three other comparable mass cores which are producing rich clusters ($N > 100$ stars). This is reflected in the derived star formation efficiencies. We can estimate effective star-forming efficiencies for the five massive cores by comparing the mass of each core with the number of associated infrared sources. Table 1 summarizes such a comparison. The five massive cores exhibit a range of star formation efficiency. The cores NGC 2024 and NGC 2071 have the highest relative efficiencies, containing 0.7 stars per M_{\odot} , while the cores NGC 2023 and LBS 23 exhibit the lowest relative efficiencies, containing only 0.07 stars per M_{\odot} .

4. DISCUSSION

The surveys for dense cores and embedded infrared sources in L1630 have revealed that stars form almost exclusively from dense gas. In one form or another, this result has long been suspected. What is surprising about our results is that in L1630 not all of the dense gas, which itself only occupies a small fraction of the cloud, is actively participating in the star-forming process. In fact, the vast majority of the stars, located in the surveyed regions, were formed in three rich embedded clusters which in turn formed from three of the largest and most massive dense cores in the cloud. These three cores account for only 30% of the total mass of dense gas in the cloud. This result is quite striking, for it implies that these three massive cores may be distinct from the remainder of the dense gas in either their star-forming properties or their evolutionary states. For example, if all the dense cores had the same star formation efficiency and similar ages, one would expect only 30% of the young stellar objects associated with this cloud to form from these three massive cores and 70% to form from the remainder of the dense gas. This is quite different from what is observed, and it appears that star formation in L1630 not only requires high densities but is also strongly favored in regions having substantial amounts of mass. It is intriguing, given the above results that two massive cores ($M > 200 M_{\odot}$) in the cloud have relatively low levels of star formation activity and are not associated with rich clusters. It is possible that the present low star formation efficiencies of these cores are temporary. If, however, they reflect the final star formation efficiencies for the cores, then high gas density and high mass may

be necessary, but not sufficient conditions for the formation of star clusters.

Observations of GMCs indicate that their overall star formation efficiency [$SFE = M_{\text{stars}}/(M_{\text{stars}} + M_{\text{gas}})$] is low, on the order of a few percent (e.g., Duerr, Imhoff, & Lada 1982; Leisawitz, Bash, & Thaddeus 1989; Evans & Lada 1991). Given the fact that GMCs exceed the threshold for Jeans stability by a large factor, the question arises, why is the star formation efficiency so small? A clue to answering this question may be found by comparing the overall SFE of the region surveyed in L1630 with the SFE of the three massive dense cores, responsible for most of the star-forming activity in the cloud. Assuming a total gas mass of the region surveyed in the L1630 molecular cloud of $1.6 \times 10^4 M_{\odot}$ (LBS 1991) and a mean stellar mass of $1 M_{\odot}$, we find that the overall SFE in the L1630 molecular cloud is only $\sim 3\%$ – 4% , similar to that of other molecular clouds (Evans & Lada 1991). In contrast, the SFE of the three massive cores is $\sim 30\%$ – 40% . This further illustrates that only a small fraction of the mass of a GMC has the conditions needed to form stars.

We have learned that nearly all the star formation in L1630 has occurred in clusters embedded in massive dense cloud cores, a result unanticipated by current theory. Until now most theoretical discussions about star formation have been based on the assumption that the typical low-mass star formed in a *loosely aggregated or distributed mode* of star formation from relatively isolated, low-mass dark cloud cores, as exemplified by the Taurus dark clouds and the streamers of Ophiuchus. These new observations suggest that in the L1630 molecular cloud, most stars, independent of mass, form in a *clustered or tightly packed mode* in which a large group of stars form from a single, well-defined, but massive dense core, similar to the star formation process in the Rho Ophiuchi molecular cloud core (Wilking & Lada 1983). This leads to the conclusion that, if L1630 is a typical GMC, most star formation in GMCs and therefore in the Galaxy may occur in the environment of dense clusters and not in isolated protostellar systems. Indeed, exist-

ing observations of the L1641 GMC suggest that the clustered mode of star formation may also be dominant in this cloud (Lada, Strom, & Myers 1992).

Roberts (1957) estimated that only 10% of all stars in our Galaxy formed in exposed open clusters. This is an order of magnitude lower than the fraction of stars which formed in embedded clusters within the L1630 molecular cloud. If most stars do form in clusters within molecular clouds, why is the observed number of exposed clusters so small? Investigations of the dynamical evolution of young stellar clusters as they emerge from their parent molecular clouds have shown that the evolution of clusters depends sensitively on the evolution of the gas from which they form (e.g., Lada, Margulis, & Dearborn 1984). In cases where the gas is removed rapidly from a cluster (via molecular outflows, stellar winds, etc.), the cluster will only remain bound if the stars contain more than 50% of the original mass of the system (stars + gas). Systems in which the stars contain 20%–50% of the total mass can also evolve into bound groups if the gas dispersal is slow, on the order of a few million years. However, this places strict constraints on the gas dispersal mechanisms (Lada et al. 1984). Consequently, the formation of bound stellar systems is difficult. Since we do not yet have enough information to determine masses for the L1630 clusters, it is difficult to accurately determine whether or not they will evolve into bound stellar systems. However, given the paucity of bound clusters in the Galaxy and the constraints on forming bound systems, it is unlikely that all four embedded clusters in L1630 will remain bound upon their emergence from the molecular cloud. More likely, these clusters will evolve to become unbound associations.

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