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Molecular outflows in the L1641 region of Orion.

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MOLECULAR OUTFLOWS IN THE L1641 REGION OF ORION

A Dissertation Presented

by

JAMES ARTHUR MORGAN

Submitted to the Graduate School of the
University of Massachusetts in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

February 1990

Department of Physics and Astronomy

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MOLECULAR OUTFLOWS IN THE L1641 REGION OF ORION

A Dissertation Presented

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JAMES ARTHUR MORGAN

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to me they recall the way some of the best ideas got started. But, perhaps this idea is too Californian....

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Finally, I wish to thank God for creating this magnificent universe and for giving me the ability to study this small section of it. It is to you that I dedicate this work.

ABSTRACT

MOLECULAR OUTFLOWS IN THE L1641 REGION OF ORION

FEBRUARY 1990

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Little is known about the interaction between molecular outflows associated with young stellar objects and the parent molecular cloud that produced them. This is because a) molecular outflows are a recently discovered phenomenon and, so, have not had their global properties studied in great detail and b) molecular clouds have not been mapped to sufficiently high spatial resolution to resolve the interaction. This work addresses the interaction between molecular outflows and the L1641 molecular cloud by both identifying and mapping all the molecular outflows as well as the detailed structure of the cloud. Candidate molecular outflows were found from single point ^{12}CO observations of young stellar objects identified from the IRAS survey data. The candidate sources were then mapped to confirm their molecular outflow nature. From these maps, molecular outflow characteristics such as their morphology, orientation, and energetics were determined. In addition, the Orion molecular cloud was mapped to compare directly with the molecular outflows.

The molecular outflows identified were found to have rising infrared spectra, radio continuum emission that suggests a stellar wind or optically thick H II region, and molecular line strengths that indicate that they are embedded within a very dense environment. The lack of an optical counterpart for many molecular outflows suggests that they occur at the earliest stages of stellar evolution. The orientations of the molecular outflows appear to lie in no preferred direction and they have shapes that indicate that the molecular cloud is responsible for determining their direction and collimation. The energetics derived for the molecular outflows indicate that there is sufficient momentum available to the molecular cloud from the currently present molecular outflows to support the cloud against gravitational collapse. Remnant holes and adjacent multicomponent lines at some locations in the cloud suggest that past molecular outflows may have disrupted the cloud and are evacuating the region around the source.

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CHAPTER 1

INTRODUCTION

1.1 Previous Studies

The first bipolar molecular outflow was discovered by Snell, Loren, and Plambeck (1980). Since then, many additional molecular outflows have been identified through surveys of regions around T Tauri stars (Edwards and Snell 1982), optically identified young stellar objects (Levreault 1988), dark cloud cores (Frerking and Langer 1982), and known Herbig-Haro (HH) objects (Edwards and Snell 1983, 1984). These surveys and their results have been reviewed by Lada (1985), Strom *et al.* (1986), and Fukui (1989). Molecular outflows are found to be associated with a number of signposts of recent star formation, such as optical jets, high velocity HH objects and H₂O masers, shock excited molecular hydrogen emission regions, and embedded infrared sources, which suggests that they occur at the earliest stages of stellar evolution (Lada 1985). To date, over 100 molecular outflows have been confirmed through mapping of the ¹²CO emission around the object (Fukui 1989).

The morphology of most molecular outflows appears bipolar; that is, having two spatially separate lobes of emission with each lobe dominated by either red shifted emission or blue shifted emission with the driving source near the center of symmetry. There are, however, several instances of either monopolar or isotropic outflows. Although there are some instances of highly collimated bipolar outflows, the majority of outflows observed tend not to be highly collimated and Lada (1985) has argued that the lack of collimation of molecular outflows is an intrinsic property of the outflows. Optical

jets of emission are sometimes observed in association with molecular outflows and these jets are much more collimated than the molecular outflow (Strom *et al.* 1986). The orientations of optical jets have also been compared with the magnetic field direction implied from polarimetric observations by Strom *et al.* (1985) and Vrba, Strom, and Strom (1988) and they find that the optical flows and the magnetic field appear to lie in the same direction. This has also been seen in the case of the molecular outflow L1551 (Snell, Loren, and Plambcek 1980).

Most molecular outflows are quite energetic and short lived. Typical dynamical time scales, based on the velocity and spatial extents of the outflows, indicate that molecular outflows last $\sim 10^4 - 10^5$ years (Strom *et al.* 1986). Luminosities based on the masses, velocities, and spatial extents of the high velocity material are quite large and on the order of $\sim 1 - 10\%$ of the bolometric luminosity of the young stellar object. This mechanical luminosity of the outflow tends to correlate with the bolometric luminosity in such a way that the more luminous sources have larger mechanical luminosities (Bally and Lada 1983).

Because molecular outflows have such high mechanical luminosities, it is likely that they can have an important impact on the structure of the parent molecular cloud. Norman and Silk (1979) proposed that winds from newly formed stars are able to provide the turbulence necessary to support a molecular cloud against gravitational collapse. Molecular outflows may be the source of this turbulent energy. Lada (1985) indicates that most of the mass in the high velocity outflow is swept up ambient material and that the presence of shock excited gas associated with molecular outflows suggests an interaction with the surrounding ambient material. Furthermore, HH objects have spectra

that are characterized by shock excited emission and are thought to be either interstellar bullets decelerated by the ambient cloud (Norman and Silk 1979) or clumps of the ambient cloud interacting with the high velocity winds (Schwartz 1975). Seen at large distances (~ 1 pc) away from the origin of some molecular outflows, these objects suggest further that molecular outflows do interact with and may affect the dynamics of the molecular cloud. The question of support by molecular outflows via conservation of momentum has been addressed for the Mon OB1 cloud by Margulis, Lada, and Snell (1988), who find that molecular outflows can provide sufficient support to the cloud if the number of outflows occurring the cloud remains roughly constant over the dispersion time scale of the molecular cloud.

1.2 Motivation

Although the previous studies have come a long way in defining the nature and characteristics of molecular outflows, several important questions remain to be answered about the relationship between molecular outflows and their parent molecular cloud and it is these questions which provide the motivation for this dissertation.

What fraction of young stellar objects have associated molecular outflows?

To properly address this question, a complete inventory of young stellar objects needs to be made to determine how many are associated with molecular outflows. Since young stellar objects could spend only a short part of their pre-main-sequence lifetime in the molecular outflow stage, given current estimates of the life times of outflows, it is likely that many sources that are capable of having molecular outflows would not be currently undergoing outflow. This fraction would indicate the amount of time a young stellar

object spends in the molecular outflow stage if *all* young stellar objects had outflows during their evolution. The number of young stellar objects that are molecular outflows, however, may have characteristics particular only to outflows. These differences may be observed in flux density ratios, spectral energy distribution excesses, or in relationships of derived quantities.

What is the relationship between the morphology of the outflows and the structure of the ambient cloud? Do molecular outflows also have a preferred orientation? Since molecular outflows tend not to be highly collimated, it would be useful to determine if the orientation of the outflows, like the optical jets, is based on properties of the molecular cloud like magnetic fields, high density regions, or cloud geometry. Also, if molecular outflows lose the strong collimation that is observed in optical jets as the high velocity emission extends out into the molecular cloud, then some external source of diversion is necessary to explain the observed morphology of the outflows. One possible explanation might be that inhomogeneities in the molecular cloud alter the shape or divert the direction of the molecular outflow as it moves away from the source. To answer this, high angular resolution observations of the morphology of the ambient cloud and the outflows are needed. Through a comparison of the density structure of the ambient cloud and the shape of the molecular outflow, we may determine if the cloud dominates the structure of the outflow.

What role do molecular outflows play in the evolution of molecular clouds?

A long known problem has been that molecular clouds exist for much longer than their free fall time scales and have ambient line widths that are much greater than due to thermal broadening. One possible explanation is that molecular outflows provide

internal support by transferring their momentum as they expand into the cloud. The presence of HH objects and shock excited gas associated with the molecular outflow suggests that the outflow is interacting with the cloud. Therefore, we can ask to what extent the molecular outflows provide support against gravitational collapse to the host molecular cloud? Does the turbulent energy present in the molecular cloud represent a signature of past or even current molecular outflow activity? Do enough molecular outflows provide sufficient energy to keep the molecular cloud supported over the dispersion time scale? To answer these questions requires knowledge of the locations and energetics of every currently active molecular outflow within a particular molecular cloud. Molecular outflows are needed to be located throughout the entire cloud and not just a small fraction of the total area in order to impact the energy of the cloud because the influence of a particular molecular outflow will only appear on a local scale ($\sim$ few pc). Furthermore, because the luminosity of the outflow is different for each source, the energy production of each currently active molecular outflow is needed to obtain as accurate an assessment as possible of the input available to the cloud.

1.3 Dissertation Description

In order to address the relationship between molecular outflows and the parent molecular cloud, we need a complete inventory of the molecular outflows within one particular molecular cloud. Only by knowing the number, location, and energetics of the molecular outflows can an estimate be made of their impact on the cloud. In addition, it is necessary to have a complete map of the ambient molecular cloud to allow a comparison of the morphology of the molecular outflows with the structure of the cloud.

In this dissertation we will identify all of the molecular outflows within the L1641 region of Orion. Orion is the nearest giant molecular cloud complex with L1641 located within the Orion A cloud about 3 degrees south of the Orion Nebula. The proximity of L1641 (1 arcminute = 0.14 pc; at a distance of 480pc) will enable high angular resolution maps to be made which are necessary in order to make accurate estimates of the masses and energetics of the outflows. Furthermore, L1641 is a site of robust, but low luminosity ($< 10^3 L_{\odot}$), star formation marked by the presence of Herbig Ae/Be stars, over 500 H α emission objects, and several HH objects. Consequently, it would be expected that there should be a large number of young stellar objects, quite possibly with associated molecular outflows, in this molecular cloud.

1.4 Summary of Chapters

The molecular outflows will be identified from a ^{12}CO survey of young stellar objects. The locations of the young stellar objects will be identified from a list of infrared sources from the IRAS survey. Only the L1641 region has been targeted in this young stellar object survey because the strength of the Orion Nebula dominates the infrared emission in the north making unambiguous assignments difficult. Another benefit of surveying the L1641 region for young stellar objects is that it is located between 20 and 30 degrees below the galactic plane reducing the likelihood of confusion from intervening foreground clouds.

The technique of using the IRAS data base for identifying the location of the young stellar objects that are probably associated with molecular outflows in this cloud as well as the molecular line observations themselves will be discussed in chapter 2. In

addition, this sample of sources will allow us to compare infrared and molecular line properties of young stellar objects with and without molecular outflows. The results of chapter 2 will not, however, allow an estimate of the frequency of occurrence of outflow since ^{12}CO mapping of the candidate objects is required to verify that they are actually outflows.

In chapter 3, the observations necessary to determine if the objects identified in chapter 2 are indeed molecular outflows will be described. In addition, chapter 3 will address the general morphological properties of the observed molecular outflows as well as estimate the energy available to the molecular cloud from these outflows. From the estimates of the energetics of the current generation molecular outflows, the extent to which the present day outflows are influencing the present and future evolution of the parent molecular cloud will be discussed.

Chapter 4 presents a radio continuum survey of the sources detected in chapter 2 and discusses their relationship to the molecular outflows in L1641. From these observations, we will describe what type of young stellar object produces radio continuum emission. This may be important in assessing what type of object goes through a molecular outflow stage.

In chapter 5, a general description of the large scale ^{12}CO map of L1641 will be presented. From this map, the structure of the ambient cloud may be determined and compared directly with the location of the known molecular outflows to determine what role the cloud is playing on the structure and evolution of the outflow. Furthermore, from this map, we will be able to discuss the effect that past star formation has had on the shape and structure of the molecular cloud. Finally, the kinematical information in the

map will enable an independent survey for molecular outflows to be made by searching for regions of large ^{12}CO line widths. This can be compared with the sources identified in the previous chapters to confirm that all possibly detected molecular outflow have been found.

Finally, a summary chapter will present the principal results of this dissertation.

CHAPTER 2

THE SURVEY OF IRAS SOURCES

2.1 Introduction

The list of known molecular outflows associated with regions of on-going star formation has grown rapidly in the last few years to over 100 (Lada 1985; Snell *et al.* 1988; Fukui 1988). However, selection effects and the large range in the properties of the flow environment make the general characteristics of the molecular outflow population difficult to determine. In order to investigate properties such as the mechanical and bolometric luminosity function, the age, frequency of occurrence, and the dynamic effects of molecular outflows, a complete sample of sources located in a similar environment and at known distances is highly desirable.

Margulis and Lada (1986) searched for molecular outflows by mapping the entire Mon OB1 molecular cloud. Although Mon OB1 is close (800 pc) and lies in the outer galaxy one to two degrees above the galactic equator, this sample may suffer from contamination from small molecular clouds along the line of sight similar to the recently discovered high-latitude clouds (Magnani, Lada, and Blitz 1986) and confusion by gas that has been accelerated by interaction with the ionized gas in the NGC 2264 region. While this approach samples an entire molecular cloud in an unbiased way, it is time consuming. A search strategy which targets only known regions of recent star formation is desirable.

An alternative approach is to use the Infrared Astronomy Satellite (IRAS) data base to identify the location of protostellar or young stellar objects. As molecular

outflows are expected to be associated with specific sites of star formation, only the immediate vicinity of infrared sources need to be the target for sensitive ^{12}CO observations. In principle, this method can provide a complete inventory of all young stellar objects down to a cut-off infrared luminosity that is determined by cloud distance, density of background sources, extinction, and strength of the diffuse component of the infrared emission. This method has been used by Snell *et al.* (1988) to discover molecular outflows associated with high luminosity infrared sources over much of the second and third quadrants of the Galaxy. Fukui (1988) has searched many intermediate luminosity IRAS sources in the Orion and Monoceros regions. More recently, Wouterloot *et al.* (1989) surveyed IRAS sources associated with H_2O masers and NH_3 emission and found H_2O masers tend to reside around broad ^{12}CO line sources. Although they have led to the identification of many new molecular outflows, each of these studies suffer from incompleteness since they do not make an estimate of the stellar content of an individual cloud complex to a well determined flux cutoff. Furthermore, these studies still fail to provide statistically uniform data which can be used to investigate the group characteristics of molecular outflows.

In this chapter, we present the results of the first complete survey of the embedded infrared source population in a nearby molecular cloud, the L1641 region in Orion. The Orion region contains the nearest complex of giant molecular clouds (GMCs) and has several sites of massive star formation. Located at a distance of 500 pc, in the direction of the galactic anticenter, and well below the galactic plane at $b = -20^\circ$, it is ideally suited for studies of cloud structure and star formation without serious confusion caused by background stars or unrelated gas and dust. By restricting the survey to the southern portion of Orion A, confusion from the ionized gas in the M42 H II

region can be avoided. We have chosen L1641 in the southern part of the Orion A GMC to study the statistical properties of molecular outflows. Because L1641 is situated well below the Galactic plane, confusion from background (or foreground) sources in the Galaxy does not complicate the identification of embedded sources and the large intrinsic line width of the L1641 cloud ($\sim 9 \text{ km s}^{-1}$) eliminates the likelihood of confusion from high latitude clouds (Blitz *et al.* 1988). The large line width the cloud will, however, make the detection of low velocity molecular outflows that might be associated with very low-mass young stars difficult and will also limit the usefulness towards molecular outflows with low projected radial velocities; but this will, of course, be true of *all* searches for molecular outflows.

A list of objects from the *IRAS Point Source Catalog* and co-add survey data was used to determine the positions of infrared sources in this region. Each position was searched for high velocity wing emission in the $J = 1 \rightarrow 0$ transition of ^{12}CO . A subset (defined below) of infrared sources were also observed in the $J = 1 \rightarrow 0$ transition of ^{13}CO , C^{18}O , and the $J = 2 \rightarrow 1$ transition of CS to determine if the source was associated with a cloud core and to delineate the ^{12}CO line widths.

Several complementary projects are being coordinated with this work. Bally *et al.* (1987) have mapped the large scale structure of the Orion A molecular cloud in ^{13}CO , finding the structure to be filamentary and containing many cloud cores and partial shells and bubbles. A similar large scale map in ^{12}CO has been constructed (see Chapter 5) illustrating that regions of large line width correspond very well with the locations of strong IRAS sources and the ^{13}CO cores seen by Bally *et al.* (1987). Observations of the IRAS sources at near-infrared and optical wavelengths has been performed by Strom

et al. (1989). Deep optical searches for optical outflows using Schmidt plates and CCD detectors have led to the discovery of many new reflection nebulae, optical jets, and Herbig-Haro objects (Reipurth and Bally 1986; Reipurth *et al.* 1986; Strom *et al.* 1986; Reipurth 1988). Finally, most of the IRAS source positions and a few of the optical positions have been surveyed at 6 cm and 20 cm to determine if these sources have radio continuum emission (cf. Chapter 4; Yusef-Zadeh, Cornwell, and Reipurth 1989). These studies have made the southern part of Orion A (L1641) one of the most completely investigated molecular clouds in the sky.

2.2 The Selection of the IRAS Sources in L1641

A co-add of the IRAS survey data for a 2.25 by 2.25 degree region of the L1641 cloud centered at $\alpha(1950) = 5^{\text{h}} 35^{\text{m}} 30^{\text{s}}$; $\delta(1950) = -7^{\circ} 25' 30''$ was used (Strom *et al.* 1989) to extract information about the unresolved point-like infrared sources to be used in our survey. The co-add survey data provide a factor of 3 improvement in sensitivity and a factor of 2 improvement in spatial resolution over the IRAS Point Source Catalog, which greatly aids in the discrimination of sources in crowded or confused fields and identifying the location of the source. Application of the point source extraction algorithm used for the IRAS Point Source Catalog to the co-add data base produced a list containing 360 candidate point sources. From this list, a subset of point sources was extracted by a series of steps intended to discard artifacts:

1. The co-add survey images for each of the 4 IRAS bands (centered at 12.5, 25, 60, and 100 μm) were visually inspected in order to reject candidate objects in the list which did not appear to be unresolved, "point-like" infrared sources. Since the

point source extraction algorithm passes the image data through a high-pass filter, it tends to "detect" nonexistent sources in regions having a large flux gradient, such as near the edges of the molecular cloud or near a bright source.

2. Spurious edge effects caused by gradients across the map were avoided by excluding the 10 arcminute region adjacent to the border of the co-add survey map from the search for candidates.
3. The point source extraction algorithm frequently assigned several distinct source names and positions to a single source due to small positional differences in the different IRAS bands. In cases where the objects passed the previous tests, we made an attempt to group these into a single source at the position of the shortest wavelength detection. (Strom *et al.* 1989, found that blending of multiple sources could occur due to the wavelength dependence of the IRAS beam size, and that adjacent sources having different spectral energy distributions sometimes were combined to produce a single source. No attempt to correct for blending has been done in this work.)
4. An estimate was made of the minimum flux density for each band below which the detection completeness was considered to be poor. This was done by analyzing the distribution of the number of sources having flux density greater than S on S . Examining the frequency distribution at each wavelength and assuming that the distribution should continue to rise with decreasing flux density values enabled a lower limit to be estimated. The lower limit on the flux density in each band was 0.3 Jy, 0.3 Jy, 1.5 Jy, and 10.0 Jy for 12 μ m, 25 μ m, 60 μ m, and 100 μ m, respectively. Sources below this flux density limit were eliminated from the final list.

No selection criteria was made on the number of IRAS bands detected nor on the colors (spectral energy distribution) of the candidates. The goal was to create as complete a list with as few spurious sources included as possible. By including sources with only one or two band detections in our sample, we tried to allow for the detection of any very young, cool embedded sources. As a comparison, our list of sources differs from the list of Strom *et al.* (1989) only at the weakest sources and tend to reside off the main cloud.

Our final list was condensed to 67 IRAS sources which we believe, with reasonable confidence, to be compact stellar objects in the sky. Table 2.1 contains the infrared data for the 67 objects sorted by declination. The columns provide the following information: column 1, the object sequence number; column 2, the IRAS name; columns 3 and 4, the right ascension and declination of the IRAS source; and columns 5 to 8, the four infrared flux densities. Column 9 lists the color temperature based on the 60 μ m and 100 μ m flux densities and a dust emissivity that varies as λ^{-1} . Lower limits for the color temperature are given when an upper limit appears in the 100 μ m flux density. If either of the 60 μ m or 100 μ m flux densities are undefined, no color temperature is listed. Finally, column 10 gives comments pertaining to the CO emission (see below) as well as other associated source names.

2.3 Observations

The observations were made with the 7-meter offset Cassegrain millimeter wave telescope located on Crawford Hill at AT&T Bell Laboratories in Holmdel New Jersey. This antenna has a 100 arcsecond diameter beam and is equipped with an SIS receiver

having a receiver temperature ranging from $T_{\text{ssb}} = 130$ to 210 Kelvin for the frequency range from 98 GHz to 116 GHz. We used both a 128 channel 0.25 MHz and a 128 channel 100 kHz filter bank to record spectra. Integration times for all wavelengths observed were automatically adjusted to give a uniform RMS noise level to better than 0.15 Kelvin in the 0.25 MHz filter. All data were calibrated by a hot-cold measurement of the receiver temperature followed by a measurement of the sky emission obtained by comparing the signal from the sky to that produced by a 77 Kelvin load. A plane parallel atmospheric model is used in conjunction with the sky brightness measurements to convert the observed antenna temperatures to values which would have been observed by the same antenna above the atmosphere. Since the antenna primary beam efficiency is about 87%, a small additional correction would be needed to scale observations of point sources to values which would have been measured by a perfect antenna. Since all of our sources are presumed spatially extended, no antenna efficiency correction was applied.

The beam size of 100 arcseconds is ideal for this survey because at the projected distance of Orion this corresponds to a linear scale of 0.24 pc (50,000 AU). This is large enough to detect a molecular outflow positionally offset from an IRAS source yet small enough to be sensitive to a spatially compact molecular outflow. Spatially compact sources may be missed, however, if they are compact enough to have the high velocity emission beamed diluted. This may be the case for 05403-0818, one of the initial 315 sources observed (see discussion below). No ^{12}CO emission was detected below $\text{VLSR} = 0.0 \text{ km s}^{-1}$ at a 1σ level of 245 mK; quite contrary to Wouterloot, Henkel, and Walmsley (1989). (05403-0818 was not observed further because it did not lie within the

selected field of view discussed above.) Even still, this survey was primarily limited by the noise level in the spectra and by confusion caused by the ambient cloud line width.

We observed 315 of the 360 positions produced by the initial IRAS point source extraction algorithm prior to the selection of the subset of 67 sources. All 315 sources were observed in the $J = 1 \rightarrow 0$ transition of ^{12}CO . Figure 2.1 is a histogram of number versus ^{12}CO integrated intensity, number versus the ^{12}CO line width extrapolated to the first crossing (FWZI), and number versus the ^{12}CO line width evaluated at the 200 mK level for both the 315 sources and the subset of 67 sources. The subset of 67 sources is skewed slightly towards the upper end of all three graphs and all sources with a large integrated intensity or large line width are members of this subset. The median values of the line width histograms for the 67 sources is typically 1.3 km s^{-1} greater than for the 315 sources. Several sources at the upper end of Figure 2.1 not included in Table 2.1 are either 1) spatially located outside the selection boundary; 2) strong sources with narrow line widths; 3) within a few beam sizes of a target position; or 4) do not have believable IRAS counterparts and exhibit multicomponent ^{12}CO profiles indicating that two or more unrelated cloud components may be superimposed along our line of sight.

Comparing the ^{12}CO 200 mK line widths to the flux densities at each IRAS wavelength indicates that the line width of the ambient cloud ($\sim 6.0 \text{ km s}^{-1}$) corresponds roughly to the lower limit set (in the previous section) for each IRAS band. This indicates that the lower limit selected for the cutoff flux densities at each wavelength will enable as complete a survey for molecular outflows as is possible in this cloud. Lowering the flux limit of the IRAS data will not enable us to detect weaker molecular

outflows because these sources will have line widths less than or comparable to the ambient cloud.

The 67 sources listed in Table 2.1 were observed in the $J = 1 \rightarrow 0$ transition of ^{13}CO , C^{18}O , and the $J = 2 \rightarrow 1$ transition of CS to obtain information about the properties of the gas surrounding each IRAS source. The characteristics of the molecular line profiles permit us to segregate the sources into three groups: broad ^{12}CO lines indicating molecular outflow (a); moderate ^{12}CO line widths suggesting that an molecular outflow may be present but further observations such as mapping are required to firmly establish the presence of an molecular outflow (b); and sources exhibiting no evidence of a molecular outflow (c). Sources in these categories are identified by designation in column 10 of Table 2.1. Both sources listed as type (c) and sources with no designation are not molecular outflow candidates but sources of type (c) additionally indicate the presence of double peaked lines. A source was classified as type (a) if the ^{12}CO line width was much broader than ^{13}CO and had either C^{18}O or CS emission associated with it. In general, sources with C^{18}O emission were found to have CS emission and, typically, the integrated C^{18}O emission was 1 to 2 times stronger than the integrated CS emission. Sources identified as (b) had line widths not as broad as type (a) and show little or no emission in either C^{18}O or CS. Sources listed as (c) were found to have broad, but generally double peaked ^{12}CO emission. Finally, the one source listed as type (d) in Table 2.1 has been identified as a carbon star by Claussen *et al.* (1987). Of the 67 sources listed in Table 2.1, 14 are type (a) and 19 are type (b). Examples of different types of sources are shown in Figure 2.2 and are identified by their sequence number.

Figure 2.3 is a halftone map of the ^{13}CO emission in the L1641 cloud integrated from $V_{\text{LSR}} = 1$ to 13 km s^{-1} (a subimage from the data of Bally *et al.* 1987). We have identified the positions of the 67 IRAS sources in our final source list by the sequence number given in Table 2.1. The most likely molecular outflow candidates (identified as type (a) sources in Table 2.1) are marked with a triangle, less certain candidates (b) are marked by a square, and all other objects are identified with a circle.

The list of known optical outflows associated with HH objects in this region (Strom *et al.* 1986) were compared with the list of 67 IRAS sources. Every optical outflow was associated with one of the IRAS sources but, with the exception of HH 1 and 2, all lack strong ^{12}CO line widths. This may be due to one of several possible effects. The internal velocity dispersion of the molecular cloud, or the superposition of several unrelated cloud components which can produce ^{12}CO line widths ranging from 2 to 6 km s^{-1} at 0.2 K. Outflows with low radial velocity ^{12}CO emission, due to the inclination of the optical outflow, may remain hidden against the confusing background emission produced by the turbulent motions of the L1641 cloud. Alternatively, by the time the optical outflow is visible, the molecular material may have been removed and the molecular outflow has dispersed into the ambient material.

In some cases, a molecular outflow may lie nearly in the plane of the sky so that the ^{12}CO velocity vector is aimed mostly orthogonal to the line of sight, making detection of the molecular outflow impossible. HH 1 and 2 (Levreault 1988; Bally and Pound 1989) has this geometry and it took nearly 10 years and several different groups to recognize its subtle molecular outflow signature. In other situations, such as HH83 (Reipurth 1989), a high velocity flow may have burst into the intercloud medium where it

does not encounter molecular gas. Despite high velocity atomic and low excitation ionized emission from shocks in the flow, there may be little accelerated molecular gas. Outflows detected by optical means may be prone to the selection of objects lying in low extinction regions with little dust or molecular gas in the path of the flow. Thus, these limitations should be considered and indicate that the ^{12}CO observations can only be used to set a lower limit on the total number of flows present in a cloud complex.

Table 2.2 lists the millimeter wavelength data on the 67 sources listed in Table 2.1. The table gives the following information in each column: column 1, the sequence number; and columns 2 to 5, the integrated intensities measured for ^{12}CO , ^{13}CO , C^{18}O , and CS. Typical uncertainties for the integrated intensities are 0.5, 0.2, 0.1, and 0.3 K km s^{-1} for ^{12}CO , ^{13}CO , C^{18}O , and CS respectively. The ^{12}CO and ^{13}CO line widths are given in columns 6 to 11 at three cutoff levels: the full width at half maximum (FWHM), the full width at the 200 mK level (FW200), and the full width extrapolated to zero intensity (FWZI).

2.4 Results

All previously known molecular outflows in L1641 were re-discovered by our search strategy. This method should identify them since the previously known molecular outflows are associated with strong infrared sources. We have discovered seven new definite molecular outflow candidates in our survey and another 18 objects which may be molecular outflows. All of these objects will have to be carefully mapped to confirm their nature. The difficulty in clearly identifying these 18 sources is that the line widths are approaching the confusion limit set by the parent cloud.

Figure 2.4 is a three band color-color plot showing the relationship between the $12\mu\text{m}$, $25\mu\text{m}$, and $60\mu\text{m}$ flux densities. For sources with upper limits, the ratio is identified with an arrow defining the sense of the limit. If both flux densities in the ratio are upper limits, the ratio has no meaning but is plotted with limit arrows in both directions as a means of identifying the other ratio. Individual sources are identified by their sequence number and are marked according to their type: (a) sources by a triangle; (b) sources by a square; and all others by a circle. Note that most (a) and (b) type sources tend to reside in a quadrant defined by $\log(S_{12}/S_{25}) \leq -0.2$ and $\log(S_{25}/S_{60}) \leq -0.2$.

The four band color-color plot, shown in Figure 2.5, exhibits a higher degree of clustering of the molecular outflow candidates than the three band color-color plot. Upper limits and identifications of the sources are defined as in Figure 2.4. Most (a) and (b) type sources are found at values $\log(S_{12}/S_{25}) \leq 0$ and values between $-0.6 \leq \log(S_{60}/S_{100}) \leq 0$. The region outlined by the four band color-color plot agrees with that defined by Thronson and Bally (1987) as associated with large ($> 10^4 M_{\odot}$) star forming molecular clouds. Furthermore, this region contains few sources not categorized as either type (a) or (b). Hence, the broad and moderate ^{12}CO line width sources tend to extend to redder colors in the $12\mu\text{m}$ to $25\mu\text{m}$ ratio, but to bluer colors in the $60\mu\text{m}$ to $100\mu\text{m}$ ratio, than the other sources.

This is further demonstrated in Figure 2.6 which shows histograms of the number of sources versus the log of the flux density ratio. There is no attempt to account for upper limits in the flux densities for these plots; sources with upper limits are not included. The hatched histograms in each plot represent type (a) (identified with a triangle) and type (b) (a square) sources and the plain histogram represent all other

sources (a circle). Note that the hatched histograms tend to extend to redder colors overall than the non-hatched histograms for the $\log(S_{12}/S_{25})$ plot; to bluer colors for $\log(S_{60}/S_{100})$; and distributed about equally for $\log(S_{25}/S_{60})$. Furthermore, note that type (a) sources appear to be more displaced than type (b) sources from the other sources. Care should be taken with the results of these plots as there are very few points included in each graph. The purpose of Figure 2.6 is only to better illustrate the trends identified in the previous color-color plots; that all broad and moderate line width ^{12}CO sources have a tendency to reside in one region. An IRAS source with colors in this quadrant has a greater probability of being associated with broad ^{12}CO emission.

The integrated CS emission has been found to correlate with the ^{12}CO line widths. Figure 2.7 is a plot of the CS integrated intensity against the ^{12}CO line width at the 200 mK level and shows that sources with large CS integrated intensity also have large ^{12}CO line widths. Furthermore, no source with strong CS emission has a narrow ^{12}CO line width. Thus, sources identified as molecular outflows are associated with dense cores. This agrees with Myers *et al.* (1988) who found that about half of their surveyed dense cores had an associated molecular outflow.

The presence of a source without a large ^{12}CO line width but with strong CS emission would suggest the source is probable an embedded object that has not entered a stage with a molecular outflow. The lack of strong CS sources with small line widths may suggest an absence of these pre-molecular outflow embedded objects. Likewise, a source with a large line width but without strong CS emission would suggest the source is probably an old molecular outflow. The lack of sources with large line widths and no CS emission may indicate that as molecular outflows evolve, they remove both the dense

core traced by the CS and the dust detected by IRAS. If this is so, the infrared emission at this stage would be too weak to be detected (see discussion in the previous section). Furthermore, this would imply that the molecular outflow is the first phenomenon a young stellar object displays prior to the optical appearance of the driving star. Hence, the use of the IRAS data *along with* CS observations is better at identifying molecular outflow candidates than the use of IRAS alone.

Using the ^{12}CO line strength and assuming that the ^{12}CO line is optically thick, the excitation temperature can be found from

$$T_A^* = T_0 [\chi_v(T_{\text{ex}}) - \chi_v(T_{\text{BB}})] [1 - \exp(-\tau_v)], \quad (2.1)$$

where $\chi_v(T) = (\exp(T_0/T) - 1)^{-1}$ arises from the black body definition and $T_0 \equiv h\nu_0/k$. Furthermore, the opacity of the ^{13}CO and C^{18}O lines can be determined from equation (2.1) assuming that $T_{\text{ex}}(^{12}\text{CO}) = T_{\text{ex}}(^{13}\text{CO}) = T_{\text{ex}}(\text{C}^{18}\text{O})$. From the excitation temperature and the line center opacity, the column density of ^{13}CO and C^{18}O is then

$$N = \frac{3k}{4\pi^3 \mu^2 \nu_0} \frac{T_{\text{ex}} \Delta V \tau}{[1 - \exp(-T_0/T_{\text{ex}})]}, \quad (2.2)$$

where $\mu = 0.112$ Debye has been used for the dipole moment for all CO isotopes in this work and ΔV is the full width of the line at the half maximum (FWHM). Table 2.3 lists the calculated parameters for the 67 sources. The table gives the following information in each column: column 1, the source number; columns 2 and 3, the peak temperatures of ^{12}CO and ^{13}CO ; columns 4 and 5, the velocity of peak emission for both ^{12}CO and ^{13}CO ; column 6, the excitation temperature; columns 7 and 8, the opacity for both ^{13}CO

and C¹⁸O; columns 9 and 10, the column density for both ¹³CO and C¹⁸O; and column 11, the infrared luminosity (see below).

The CS integrated intensity has been found to correlate with the ¹³CO line width similar to the relationship found for the ¹²CO line width. In addition, the CS and C¹⁸O integrated intensities also tend to correlate with each other. Thus, lines of sight with large ¹²CO line widths and CS emission should also have large ¹³CO and C¹⁸O column densities. These trends are shown in Figure 2.8. The first part of Figure 2.8 is a plot of the ¹²CO line width at the 200 mK level versus the ¹³CO column density; the second part of Figure 2.8 is the same plot but against C¹⁸O column density. In both cases, line width increases with increasing column density. One possible interpretation for these trends is that regions of large column density are also regions of high volume density.

The luminosity of an IRAS source can be estimated from the flux densities by

$$L(L_{\odot}) = 23.0 \left[\frac{D}{500\text{pc}} \right]^2 \int \frac{S}{\lambda^2} d\lambda, \quad (2.3)$$

where S is the IRAS flux density in Janskys, λ is the wavelength in microns, D is the distance to the source in units of 500pc, and the integration is carried out over the four IRAS wavelengths. The luminosity calculated is based solely on the IRAS flux densities and therefore represents a lower limit to the true luminosity. Figure 2.9 is a plot of the log of the IRAS luminosity versus the CS integrated intensity and versus the 200mK ¹²CO line width. There is a correlation between the source luminosity and the CS integrated intensity and a strong correlation between the luminosity and the ¹²CO line width. There is also a transition, with decreasing luminosity, from type (a) sources, through type (b) sources, to all other sources.

The correlation of ^{12}CO line widths with CS integrated line strength can be explained by two different effects. First, the escape velocity required to overcome the gravitational pull of a cloud core depends on its mass. The mass of a core is expected to be proportional to the average ^{12}CO , ^{13}CO , or C^{18}O line strength. If the velocity of a typical molecular outflow is proportional to the local escape velocity, then the core mass and the integrated intensity of tracers of the core mass may correlate with the flow velocity. Second, Bally and Lada (1983) found a correlation between embedded source bolometric luminosity and the mechanical luminosity of the associated molecular outflow. By fitting the data in Figure 2.9, we found that $L_{\text{IRAS}} \propto \Delta V^{(2.9 \pm 0.4)}$ which is consistent with Bally and Lada (1983). Since the mechanical luminosity depends on ΔV^3 , there is a correlation between mechanical luminosity and flow velocity. The infrared luminosity of an embedded source depends on its mass, which depends on the amount of mass available to produce the protostar. In most star formation models this is, in turn, proportional to the mass of the parent cloud core. Thus the observed correlation between mechanical luminosity and bolometric luminosity can be viewed as a direct consequence of a correlation between the observed ^{12}CO line widths and CS, ^{13}CO , and C^{18}O integrated intensities.

2.5 The L1641 Outflows

We have detected at least 14 probable molecular outflow candidates in the L1641 region of the Orion molecular cloud. The most obvious candidates have all been detected previously in searches motivated by the discovery of either interesting optical nebulosities (Reipurth *et al.* 1986, Reipurth 1988) or near strong infrared sources (Levreault 1985). The three most spectacular molecular outflow candidates in L1641 are

associated with Haro 4-255 (Levreault 1985), Re50 (Reipurth and Bally 1986), and FIRSSE 101 (Price *et al.* 1983). These 3 sources form a small group of intermediate luminosity infrared sources in a 20 arcminute diameter region near $\delta = -7^\circ 30'$.

In the northern portion of L1641, the infrared source density increases and the proximity to the very bright emission from the Orion Nebula region hinders the detection and extraction of IRAS sources. As an example, the area associated with HH 1 and 2 and the NGC 1999 complex is confused. Similarly, the HH34 region, which contains at least 3 or 4 young stellar objects has only a single IRAS counterpart, which in the IRAS Point Source Catalog has been assigned to V801 Orionis, a relatively unobscured star. Thus, source confusion and blending sets a fundamental limit to the usefulness of the IRAS data base in the detection of new candidate young stellar objects. This limit will become even more pronounced as this method is used on molecular clouds situated more in the galactic plane and located at larger distances than Orion.

Table 2.1 shows that in regions having a low source density, the IRAS derived lists are probably complete to source flux density levels of about 10 Jy which at the 500 pc distance of Orion corresponds to a luminosity of order $20 L_\odot$. We note that the brightest infrared sources detected in at least three IRAS bands are all associated with molecular outflows candidates. In addition, several very bright 100 μm sources, which do not have detectable 12 μm or 25 μm emission, also do not have any indication of a molecular outflow. We suspect that these infrared sources may not be young stellar objects but hot dust heated by the ambient radiation field which is much hotter than background cirrus emission. This is supported by the lack of C^{18}O and CS emission along these lines of sight. Near the northern edge of our field, the smooth component of

the dust emission is bright and the ^{12}CO brightness temperature is of order 24 K. The dust temperature derived from IRAS is about 30 K. This part of L1641 lies close to the Orion Nebula and deep optical images show extensive red nebulosity indicating that dust in this region is illuminated by light from the vicinity of the H II region.

2.6 Summary

The 4 square degree region of L1641 has been surveyed for sources with high velocity ^{12}CO emission. The source list was constructed using the IRAS survey co-add data and 14 molecular outflows have been identified. The infrared characteristics of the molecular outflow candidates are that they have redder colors at the short wavelengths and bluer colors at the long wavelengths than non-molecular outflow candidates. The CS integrated intensity was found to correlate with the ^{12}CO and ^{13}CO line widths and with the C^{18}O integrated intensity. This suggests that the most likely molecular outflow candidates tend to reside in dense environments. Finally, the infrared luminosity was compared with the ^{12}CO line width and the CS integrated intensity. The correlation between the infrared luminosity and the ^{12}CO line width appears to be a consequence of the relationship between the mechanical and bolometric luminosity. The greatest limitation in using this method was confusion: in the infrared, the selection of low luminosity objects; and at ^{12}CO , separating the line widths from the ambient cloud.

The success of using the IRAS data base to identify the locations of molecular outflows is limited by:

1. The line width of the ambient molecular cloud. We have shown that the line width of the sources identified is related to their infrared flux density. A molecular cloud

with a larger ambient line width diminishes the likelihood of detecting infrared sources associated with broad line widths.

2. The distance of the molecular cloud. Searching molecular clouds at greater distances effectively reduces the resolution of the IRAS beam and can easily lead to source confusion and spectral distribution blending. This will lead to difficulties with source identification.
3. The presence of strong HII regions. Strong nearby sources can limit the usefulness of the longer wavelength IRAS data.

The merit of this technique is that it does not require extensive ^{12}CO survey mapping of the ambient cloud to identify interesting regions. Furthermore, this method suggests that a working lower limit on the ^{12}CO line width can be estimated based on the luminosity derived from the infrared flux densities prior to observing a cloud. Confirmation of this technique for selecting molecular outflow candidates will require mapping of the sources selected in this work. This will be discussed in the next chapter.

TABLE 2.1

Infrared Source Positions

Source Number (1)	IRAS Name (2)	α (1950) (h m s) (3)	δ (1950) ($^{\circ}$ ' ") (4)	S_{12} (Jy) (5)	S_{25} (Jy) (6)	S_{60} (Jy) (7)	S_{100} (Jy) (8)	T (60/100) (K) (9)	Comments (10)
1	C05398-0621	5 39 50.5	-6 21 55.7	...	...	0.95	26.92	17.8	(b)
2	C05364-0622	5 36 24.2	-6 22 14.8	0.36	0.33	7.91	...	...	(c)
3	C05368-0623	5 36 53.4	-6 23 44.6	0.45	0.72	5.27	...	...	
4	C05325-0623	5 32 31.8	-6 23 57.3	0.15	<0.88	1.11	18.20	19.8	(c)
5	C05338-0623	5 33 51.3	-6 23 59.0	1.33	20.50	220.00	582.00	31.9	(a), L1641-N
6	C05372-0625	5 37 16.2	-6 25 59.3	0.34	0.52	4.85	48.95	22.0	(c)
7	C05361-0626	5 36 06.1	-6 26 14.9	<0.36	<0.49	3.61	<61.07	>19.7	(b)
8	C05339-0626	5 33 57.8	-6 26 44.1	0.89	3.14	17.40	255.00	20.3	(a)
9	C05392-0627	5 39 15.3	-6 27 41.8	...	0.19	3.62	...	...	(a)
10	C05330-0628	5 33 01.7	-6 28 43.1	1.09	8.47	42.30	127.00	30.6	(b), V801 Ori, near HH34
11	C05349-0632	5 34 58.7	-6 32 14.8	0.57	0.81	7.20	20.00	31.4	(c)
12	C05353-0632	5 35 19.8	-6 32 29.9	<0.31	0.34	3.34	20.58	24.9	(b), (c)
13	C05393-0632	5 39 18.7	-6 32 46.6	0.34	0.55	6.08	36.60	25.0	(c)
14	C05337-0633	5 33 44.2	-6 33 43.9	0.17	0.47	10.06	56.36	25.5	(b)
15	C05347-0636	5 34 45.4	-6 36 44.7	1.43	1.63	7.10	46.00	24.5	(c), BF Ori, T432
16	C05317-0637	5 31 45.4	-6 37 56.0	0.35	0.68	4.00	<13.12	>29.8	(a), SW Ori, T108, HH84
17	C05348-0638	5 34 50.6	-6 38 14.8	...	0.44	2.10	26.32	21.0	(c)
18	C05342-0639	5 34 15.4	-6 39 44.4	2.73	3.10	27.20	131.00	26.6	(b)
19	C05353-0644	5 35 20.1	-6 44 15.0	2.10	3.00	4.90	18.30	28.6	HD37357
20	C05339-0644	5 33 56.2	-6 44 44.2	9.40	11.70	60.00	246.00	27.8	(a), V380 Ori, T395, HH35
21	C05339-0646	5 33 57.9	-6 46 29.2	1.83	8.40	74.39	190.19	32.3	(a), NGC1999, HH1&2, N ³ SK50
22	C05390-0649	5 39 04.4	-6 49 57.3	0.27	0.33	2.13	12.04	25.4	
23	C05356-0651	5 35 39.0	-6 51 00.0	3.16	3.89	7.15	56.00	23.4	N ³ SK81

(continued on next page)

TABLE 2.1

(Continued)

Source Number (1)	IRAS Name (2)	α (1950) (h m s) (3)	δ (1950) ($^{\circ}$ ' ") (4)	S_{12} (Jy) (5)	S_{25} (Jy) (6)	S_{60} (Jy) (7)	S_{100} (Jy) (8)	T (60/100) (K) (9)	Comments (10)
24	C05347-0655	5 34 43.5	-6 55 59.8	0.15	0.23	3.40	16.96	26.3	(c)
25	C05354-0658	5 35 28.9	-6 58 15.1	<0.30	0.72	5.06	16.70	29.7	(b), T456
26	C05362-0700	5 36 12.6	-7 00 00.0	2.54	6.02	17.00	40.00	33.2	(b)
27	C05363-0702	5 36 19.3	-7 02 41.2	0.58	6.20	28.40	103.00	28.8	(a), L1641-C
28	C05358-0704	5 35 52.6	-7 04 00.1	53.90	130.30	181.00	144.00	54.7	(b), Haro 13a, N ³ SK83
29	C05357-0710	5 35 42.0	-7 10 07.4	0.38	1.13	4.00	22.00	25.6	(b), Haro 14a
30	C05321-0710	5 32 07.3	-7 10 26.8	<0.37	0.15	2.45	11.33	26.9	
31	C05366-0712	5 36 41.4	-7 12 44.9	0.67	3.42	9.57	18.28	35.9	
32	C05362-0714	5 36 17.6	-7 14 30.0	2.24	3.41	4.15	<73.09	>19.5	(b), Haro4-249, T484, N ³ SK88
33	C05336-0716	5 33 38.0	-7 16 14.0	...	0.12	2.06	14.35	24.1	
34	C05329-0716	5 32 56.6	-7 16 43.1	...	0.16	1.64	...	...	
35	C05379-0717	5 37 58.1	-7 17 58.9	<0.31	0.14	1.58	4.17	31.9	near Re 49
36	C05364-0718	5 36 29.3	-7 18 14.9	1.01	4.45	11.01	<17.76	>38.4	(a), V599 Ori, N ³ SK92
37	C05360-0719	5 36 05.2	-7 19 00.1	0.17	0.25	9.8	20.33	34.8	(b)
38	C05364-0722	5 36 26.3	-7 22 45.0	0.95	1.41	5.50	36.00	24.5	Haro 4-254, T489, N ³ SK90
39	C05369-0728	5 36 56.6	-7 28 05.4	0.20	5.25	70.30	151.00	34.3	(a), Haro 4-255, T497, N ³ SK93
40	C05380-0728	5 38 02.2	-7 28 58.8	29.40	92.20	209.00	242.00	44.5	(a), Re 50, L1641-S
41	C05375-0731	5 37 30.7	-7 31 58.5	0.18	10.80	159.00	298.00	36.1	(a), FIRSSE-101
42	C05365-0734	5 36 32.4	-7 34 29.9	0.13	0.47	4.27	20.10	26.7	
43	C05380-0738	5 38 02.2	-7 38 58.8	0.13	0.87	3.90	<50.86	>20.8	(b)
44	C05375-0738	5 37 35.0	-7 38 59.2	0.51	0.92	<4.05	<42.78	...	
45	C05381-0741	5 38 07.5	-7 41 00.5	0.54	0.21	<3.12	<35.00	...	(b)
46	C05341-0742	5 34 08.1	-7 42 49.1	<0.27	<0.38	2.73	<13.15	>26.6	

(continued on next page)

TABLE 2.1

(Continued)

Source Number (1)	IRAS Name (2)	α (1950) (h m s) (3)	δ (1950) ($^{\circ}$ ' ") (4)	S_{12} (Jy) (5)	S_{25} (Jy) (6)	S_{60} (Jy) (7)	S_{100} (Jy) (8)	T (60/100) (K) (9)	Comments (10)
47	C05349-0743	5 34 56.6	-7 43 59.9	...	0.20	...	13.54	...	
48	C05379-0744	5 37 59.2	-7 44 43.8	<0.29	0.42	2.00	<51.40	>18.1	
49	C05392-0744	5 39 12.9	-7 44 57.1	<0.25	<0.28	2.01	14.73	23.8	
50	C05364-0747	5 36 27.4	-7 47 30.0	...	...	1.68	13.28	23.3	
51	C05378-0750	5 37 52.1	-7 50 07.2	1.20	4.92	11.90	14.00	44.2	(b)
52	C05389-0752	5 38 54.4	-7 52 06.1	0.21	0.74	1.70	<45.51	>18.0	(b)
53	C05389-0756	5 38 54.8	-7 56 42.6	0.47	4.26	16.40	41.20	32.5	(b)
54	C05379-0757	5 37 56.3	-7 57 58.9	1.16	3.13	6.10	21.80	29.0	(a)
55	C05389-0759	5 38 57.8	-7 59 27.6	0.49	1.20	1.40	<44.44	>17.4	
56	C05399-0800	5 39 58.5	-8 00 10.7	0.48	1.00	2.25	11.50	26.1	T529
57	C05364-0801	5 36 25.4	-8 01 00.0	...	0.19	...	17.76	...	(b)
58	C05394-0801	5 39 24.1	-8 01 56.8	0.83	1.00	5.16	<51.12	>22.1	San 6, T527, H7-2
59	C05391-0804	5 39 07.0	-8 04 57.3	1.11	3.39	9.48	<20.33	>34.3	(a)
60	C05382-0805	5 38 12.9	-8 05 28.6	2.36	5.62	3.04	<37.37	>21.1	
61	C05383-0807	5 38 22.6	-8 07 13.4	0.13	1.7	19.5	52.6	31.7	(a)
62	C05390-0807	5 39 00.4	-8 07 27.5	1.98	3.88	5.84	<43.24	>23.7	DL Ori, T523, H7-3, San 5
63	C05380-0808	5 38 00.4	-8 08 58.9	0.42	0.57	0.83	6.00	23.9	T515
64	C05401-0809	5 40 10.7	-8 09 10.2	1.05	1.01	32.79	171.36	26.0	(c)
65	C05391-0809	5 39 10.7	-8 09 42.2	0.24	1.41	2.05	<16.58	>23.2	
66	C05373-0810	5 37 18.9	-8 10 44.5	33.10	9.59	1.95	<40.65	>18.9	(d), AFGL 796
67	C05379-0815	5 37 56.3	-8 15 29.0	0.56	1.18	3.50	14.80	27.6	(b)

(a) - Definite wing profile.

(b) - Possible wing profile.

(c) - Double peaked profile.

(d) - Carbon star.

TABLE 2.2

Millimeter Wavelength Parameters

Source Number (1)	$\int T dV$ (K km sec ⁻¹)				¹² CO Line Width (km sec ⁻¹) [†]			¹³ CO Line Width (km sec ⁻¹) [†]		
	¹² CO (2)	¹³ CO (3)	C ¹⁸ O (4)	CS (5)	FWHM (6)	FW200 (7)	FWZI (8)	FWHM (9)	FW200 (10)	FWZI (11)
1	39.61	10.82	0.78	0.68	1.30	6.50	7.15	1.09	2.99	5.98
2	15.42	1.50	0.28	-0.15	2.60	6.50	7.80	2.18	2.99	3.26
3	15.17	0.94	-0.07	0.46	2.60	5.20	12.35	1.09	1.90	2.99
4	49.70	14.48	0.58	-0.24	3.90	7.80	9.10	1.36	4.62	5.17
5	133.21	36.63	4.87	3.50	5.20	13.65	19.51	2.72	7.89	10.61
6	19.39	2.28	-0.46	-0.08	2.60	5.85	7.80	0.54	2.45	3.54
7	15.25	1.54	0.17	0.33	1.95	6.50	11.70	0.82	2.18	2.99
8	113.99	30.65	5.57	2.41	5.85	12.35	14.30	1.90	7.35	7.62
9	13.10	1.68	0.18	-0.37	1.95	5.85	7.15	0.54	1.09	1.90
10	87.22	21.96	3.21	0.95	1.95	8.45	11.70	1.36	4.62	5.71
11	42.54	7.69	0.44	0.24	1.95	7.80	9.75	0.82	2.18	6.26
12	27.90	4.85	0.42	-0.25	1.30	9.10	11.05	1.09	2.45	4.35
13	23.53	2.74	0.07	-0.76	1.30	6.50	7.15	1.09	1.63	4.62
14	92.75	18.45	1.59	1.41	3.90	8.45	12.35	2.72	5.71	6.26
15	74.79	17.14	0.74	0.83	5.20	8.45	11.05	1.63	6.53	6.80
16	30.54	6.85	0.58	1.10	2.60	7.15	13.00	1.36	2.99	6.80
17	75.05	17.57	1.38	0.42	5.85	8.45	9.10	1.90	7.35	8.71
18	55.42	7.42	0.25	-0.01	3.25	7.80	13.00	1.09	4.62	5.44
19	49.82	10.28	0.14	0.38	3.25	7.15	11.05	2.45	4.90	6.80
20	110.83	30.34	2.33	1.07	3.90	12.35	14.30	1.63	6.80	10.07
21	110.12	36.17	5.34	4.39	3.90	11.05	12.35	2.99	6.53	7.07
22	12.78	1.07	0.01	-0.03	1.95	5.85	6.50	1.09	1.36	2.45
23	39.61	11.79	1.16	-0.51	3.25	7.80	9.75	2.18	4.08	5.44

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TABLE 2.2

(Continued)

Source Number (1)	$\int T dV$ (K km sec ⁻¹)				¹² CO Line Width (km sec ⁻¹) [†]			¹³ CO Line Width (km sec ⁻¹) [†]		
	¹² CO (2)	¹³ CO (3)	C ¹⁸ O (4)	CS (5)	FWHM (6)	FW200 (7)	FWZI (8)	FWHM (9)	FW200 (10)	FWZI (11)
24	52.38	7.39	0.23	0.34	3.25	6.50	6.50	0.54	4.08	5.98
25	62.93	17.78	2.18	1.72	3.25	8.45	9.75	1.36	4.90	6.80
26	75.24	17.91	2.30	0.77	4.55	9.75	10.40	2.45	5.98	7.07
27	69.57	26.61	4.87	1.39	6.50	11.05	19.51	2.45	7.62	8.16
28	62.80	13.77	1.30	0.56	3.90	7.15	7.80	1.09	4.90	5.44
29	58.04	21.54	2.43	2.10	3.90	7.80	9.75	2.72	5.17	7.35
30	5.14	0.18	0.21	0.39	2.60	3.90	11.05	0.54	0.27	0.82
31	54.77	18.31	3.32	1.47	3.90	7.15	10.40	2.72	6.80	7.35
32	49.74	14.82	1.37	0.96	3.90	9.10	11.05	2.45	5.98	6.80
33	20.01	2.25	-0.03	0.45	1.30	5.85	5.85	0.82	1.63	2.99
34	5.12	0.59	0.15	0.28	1.30	2.60	6.50	0.27	0.27	2.72
35	14.17	2.80	0.10	-0.26	2.60	4.55	4.55	2.18	3.26	4.90
36	41.29	7.09	0.24	0.33	3.90	7.80	7.80	1.63	4.35	5.17
37	55.10	17.60	1.82	0.77	3.90	7.80	9.10	1.36	5.44	6.80
38	59.70	16.39	2.02	1.34	5.20	7.80	7.80	2.45	5.44	5.98
39	88.95	21.21	2.28	3.57	5.85	22.11	26.01	2.72	7.89	8.71
40	83.25	21.63	2.25	1.06	6.50	16.90	17.56	2.99	6.80	9.25
41	53.49	17.47	4.69	1.82	3.90	13.65	18.21	2.45	5.44	7.62
42	41.85	7.72	-0.08	-0.33	3.90	7.80	9.10	2.72	4.62	5.44
43	49.27	15.52	2.79	0.15	3.25	11.05	13.65	2.72	5.17	11.15
44	32.87	9.80	1.21	0.43	3.25	7.15	9.75	1.90	4.35	5.17
45	39.67	14.17	2.14	0.22	3.90	8.45	14.95	2.18	5.17	7.62
46	14.16	1.02	-0.08	0.28	1.30	3.90	5.20	0.82	1.36	3.26

(continued on next page)

TABLE 2.2

(Continued)

Source Number (1)	$\int T dV$ (K km sec ⁻¹)				¹² CO Line Width (km sec ⁻¹) [†]			¹³ CO Line Width (km sec ⁻¹) [†]		
	¹² CO (2)	¹³ CO (3)	C ¹⁸ O (4)	CS (5)	FWHM (6)	FW200 (7)	FWZI (8)	FWHM (9)	FW200 (10)	FWZI (11)
47	35.88	10.05	0.72	-0.30	1.95	5.85	6.50	0.82	3.81	5.44
48	35.60	14.35	3.21	-0.26	3.25	6.50	10.40	1.63	4.62	5.71
49	24.00	2.16	0.32	-0.44	1.95	5.20	7.15	0.82	2.99	3.54
50	37.84	8.87	0.42	0.64	3.90	5.85	9.10	2.99	4.62	6.53
51	36.97	14.45	1.90	0.45	2.60	5.85	8.45	1.90	5.17	8.43
52	38.35	13.30	4.58	0.77	3.25	7.80	8.45	2.45	3.81	4.35
53	46.29	16.37	4.29	0.71	3.90	7.15	8.45	2.18	5.17	7.62
54	45.66	11.09	2.11	0.64	3.25	9.10	13.00	2.45	4.62	4.62
55	43.88	16.23	4.88	0.85	3.90	6.50	9.10	2.99	4.90	4.90
56	35.39	4.84	-0.29	-0.23	1.30	7.15	7.80	1.09	4.35	5.17
57	34.41	5.41	0.21	0.48	1.30	9.75	10.40	0.54	3.81	4.62
58	47.63	11.51	1.26	-0.17	2.60	6.50	9.75	1.36	4.08	5.98
59	50.20	14.46	2.41	1.30	3.25	10.40	11.70	2.45	4.35	5.98
60	49.35	9.64	0.70	0.69	3.25	8.45	13.00	2.45	3.81	4.62
61	58.30	15.98	1.82	0.92	3.90	10.40	16.25	1.90	5.44	6.80
62	51.01	18.32	2.91	1.04	3.25	7.80	8.45	2.45	4.62	5.44
63	49.81	8.34	0.37	-0.56	3.25	6.50	8.45	2.18	4.35	4.90
64	65.79	13.72	0.49	0.54	1.95	6.50	6.50	1.36	5.98	8.16
65	43.83	15.06	2.43	1.48	2.60	7.15	7.15	1.90	4.62	6.80
66	15.92	0.77	0.15	0.45	1.95	6.50	7.15	0.82	1.63	2.18
67	58.32	9.86	0.91	0.55	3.25	8.45	9.75	1.36	5.17	5.98

(†) - Line widths are given as Full Widths at the Half Maximum (FWHM), at the 200 mK level (FW200), and extrapolated to the Zero Intensity (FWZI).

TABLE 2.3

Millimeter Wavelength Properties

Source Number (1)	T _{max} (K)			V _{max} (km sec ⁻¹)			T _{ex} (CO) (K) (7)	τ			N (10 ¹⁵ cm ⁻²)			L _{IR} (L _⊙) (12)
	¹² CO (2)	¹³ CO (3)	C ¹⁸ O (4)	¹² CO (5)	¹³ CO (6)			¹³ CO (8)	C ¹⁸ O (9)		¹³ CO (10)	C ¹⁸ O (11)		
1	14.9	7.7	0.9	8.7	8.4		18.4	0.71	0.06		13.84	0.59		0.0
2	3.5	0.7	0.2	6.1	6.3		6.7	0.21	0.07		1.37	0.21		1.5
3	4.1	0.6	0.0	7.9	6.5		7.3	0.15	0.00		0.55	0.00		1.7
4	10.8	6.4	0.7	6.7	6.8		14.2	0.90	0.06		13.39	0.19		0.0
5	21.8	10.0	1.7	8.7	7.4		25.3	0.61	0.08		54.01	7.05		98.9
6	4.6	1.5	0.2	6.1	6.3		7.8	0.41	0.06		0.84	0.06		4.2
7	4.4	1.1	0.2	6.0	5.5		7.6	0.27	0.04		0.82	0.04		0.0
8	19.4	10.5	2.8	6.6	6.8		22.9	0.78	0.16		39.58	5.79		19.6
9	4.1	1.6	0.3	6.6	6.5		7.3	0.50	0.08		0.93	0.16		0.5
10	26.6	11.7	2.6	8.3	8.7		30.1	0.58	0.10		35.37	3.88		24.6
11	11.9	3.4	0.3	9.2	9.5		15.4	0.33	0.03		3.47	0.44		4.0
12	6.9	2.9	0.3	9.2	6.3		10.2	0.54	0.05		3.60	0.17		2.0
13	7.4	1.4	0.2	8.6	8.4		10.8	0.21	0.03		1.56	0.11		4.0
14	21.1	5.6	0.7	9.9	8.2		24.5	0.31	0.03		25.61	2.16		5.6
15	12.7	5.4	0.6	9.2	6.5		16.2	0.55	0.05		12.48	0.56		6.7
16	8.0	3.4	0.3	8.0	8.2		11.3	0.56	0.04		5.60	0.08		1.4
17	13.1	4.1	0.4	6.0	9.5		16.5	0.37	0.03		10.24	0.33		2.0
18	14.8	3.1	0.3	7.4	7.6		18.3	0.23	0.02		4.43	0.09		18.1
19	11.0	3.8	0.2	7.3	7.1		14.4	0.43	0.02		11.79	0.06		6.8
20	24.2	10.6	1.4	9.2	9.0		27.7	0.57	0.06		35.92	1.83		45.8
21	21.8	11.3	2.2	9.2	9.3		25.2	0.73	0.10		70.34	5.58		35.9
22	4.2	0.7	0.2	7.3	7.4		7.4	0.18	0.05		0.68	0.05		1.6
23	9.8	4.6	0.4	7.3	7.1		13.2	0.64	0.04		13.39	0.58		11.0

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TABLE 2.3

(Continued)

Source Number (1)	T _{max} (K)			V _{max} (km sec ⁻¹)		T _{ex} (CO) (K) (7)	τ		N (10 ¹⁵ cm ⁻²)			L _{IR} (L _⊙) (12)
	¹² CO (2)	¹³ CO (3)	C ¹⁸ O (4)	¹² CO (5)	¹³ CO (6)		¹³ CO (8)	C ¹⁸ O (9)	¹³ CO (10)	C ¹⁸ O (11)		
24	13.4	3.6	0.3	8.6	6.8	16.8	0.32	0.02	2.57	0.17	2.0	
25	15.5	7.9	1.4	5.3	5.7	19.0	0.71	0.10	18.10	1.98	2.4	
26	14.2	5.4	1.2	6.0	4.4	17.6	0.48	0.09	19.15	1.59	13.9	
27	10.5	7.4	2.2	6.7	3.8	13.9	1.20	0.23	31.29	3.39	17.6	
28	15.0	7.0	1.0	5.3	5.7	18.4	0.63	0.07	12.18	0.69	220.9	
29	12.8	7.3	1.0	6.0	6.3	16.2	0.84	0.08	32.19	1.82	3.4	
30	1.1	0.3	0.2	7.9	10.9	4.1	0.27	0.25	0.19	0.09	1.2	
31	11.2	5.1	1.5	6.0	3.8	14.6	0.60	0.15	18.93	1.41	6.8	
32	10.2	5.0	0.6	5.3	5.5	13.6	0.67	0.06	16.86	1.12	5.8	
33	8.7	1.7	0.3	6.6	7.4	12.1	0.22	0.03	1.50	0.14	1.2	
34	2.1	0.5	0.2	7.3	7.6	5.2	0.25	0.10	0.14	0.05	0.3	
35	4.9	1.1	0.1	5.3	6.5	8.1	0.26	0.03	2.30	0.06	0.7	
36	9.6	2.5	0.2	5.3	5.2	13.0	0.31	0.03	4.68	0.13	6.2	
37	13.2	7.3	1.0	6.7	6.8	16.6	0.80	0.08	15.94	0.64	2.3	
38	11.0	5.7	1.2	6.6	5.2	14.4	0.72	0.11	19.93	1.05	5.2	
39	12.4	6.6	1.1	3.4	4.9	15.8	0.76	0.09	27.76	1.96	28.6	
40	12.4	5.5	0.9	5.0	4.4	15.8	0.58	0.08	23.22	1.38	173.1	
41	10.9	5.8	2.0	4.8	5.2	14.3	0.76	0.20	20.73	4.24	61.5	
42	9.7	2.6	0.1	6.0	5.7	13.0	0.32	0.01	8.13	0.09	2.5	
43	11.1	5.0	2.1	4.7	5.2	14.6	0.60	0.21	18.67	1.96	1.3	
44	7.5	4.5	0.5	5.3	5.5	10.9	0.90	0.07	11.68	0.95	0.8	
45	8.7	5.7	1.1	4.7	5.2	12.1	1.06	0.13	19.07	1.84	0.6	
46	6.4	0.8	0.2	8.0	7.9	9.8	0.13	0.03	0.58	0.09	0.0	

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TABLE 2.3

(Continued)

Source Number (1)	T _{max} (K)		V _{max} (km sec ⁻¹)		T _{ex} (CO) (K) (7)	τ		N (10 ¹⁵ cm ⁻²)		L _{IR} (L _⊙) (12)
	¹² CO (2)	¹³ CO (3)	¹² CO (5)	¹³ CO (6)		¹³ CO (8)	C ¹⁸ O (9)	¹³ CO (10)	C ¹⁸ O (11)	
47	12.6	6.8	7.3	7.9	16.0	0.78	0.06	8.78	0.67	1.4
48	9.6	5.9	5.3	5.5	13.0	0.94	0.22	14.42	2.28	0.5
49	9.2	1.4	6.0	7.1	12.6	0.16	0.03	1.16	0.06	0.9
50	7.6	3.0	6.6	4.6	10.9	0.49	0.04	10.19	0.24	0.8
51	10.6	6.4	6.0	5.7	14.0	0.92	0.10	18.90	1.77	9.1
52	10.4	5.6	5.3	4.9	13.8	0.77	0.24	19.82	4.88	1.1
53	10.6	6.0	4.7	4.9	14.0	0.83	0.30	19.41	3.50	10.1
54	10.3	4.0	6.0	5.2	13.7	0.48	0.13	12.20	1.51	6.4
55	10.1	4.8	4.7	4.9	13.5	0.65	0.27	19.33	4.39	1.7
56	9.4	3.0	3.4	3.8	12.8	0.38	0.02	3.81	0.05	2.5
57	10.3	4.5	6.7	6.5	13.7	0.56	0.03	3.16	0.15	0.0
58	11.9	5.7	5.3	5.5	15.3	0.65	0.09	11.22	0.65	2.3
59	11.2	5.4	5.3	4.6	14.6	0.66	0.17	18.63	1.59	5.2
60	12.5	3.9	5.3	5.5	15.9	0.37	0.02	12.26	0.45	7.8
61	12.2	6.7	5.3	5.7	15.7	0.78	0.09	19.65	1.64	8.7
62	12.8	6.9	4.7	5.5	16.2	0.76	0.12	26.29	3.29	6.1
63	13.5	3.2	6.0	5.5	16.9	0.27	0.02	8.92	0.33	1.4
64	18.7	5.3	3.4	3.6	22.2	0.33	0.02	11.41	0.22	17.7
65	11.8	6.4	5.3	5.5	15.2	0.78	0.11	18.55	2.20	1.7
66	6.0	0.6	5.3	6.0	9.3	0.10	0.04	0.41	0.05	43.0
67	14.7	4.8	6.0	5.7	18.2	0.39	0.06	9.25	0.88	3.1

Figure 2.1 The distribution of the number of sources with ^{12}CO line parameters. Shown is the full line width at the 200 mK level (*top*), the full line width extrapolated to zero intensity (*middle*), and the ^{12}CO integrated intensity (*bottom*). The hatched histogram in each represents the subset of 67 sources and the plain histogram the other 316 sources.

Figure 2.2 Typical spectra for the various types of sources listed in Table 2.1. Source 39 is a source representative of a molecular outflow; source 45, a source that is a possible outflow; source 15, a double peaked ^{12}CO source; and source 19, a position typical of the ambient molecular cloud. For each source the $J = 1 \rightarrow 0$ transition of ^{12}CO , ^{13}CO , and C^{18}O is drawn. The strongest line strength is given by ^{12}CO , second strongest, ^{13}CO , and the weakest, C^{18}O .

(Figure continued on pages 40 – 43)

Figure 2.3 The locations of the 67 IRAS sources superimposed on a halftone map of the ^{13}CO emission in L1641. The halftone is of the integrated intensity from $V_{\text{LSR}} = 1$ to 13 km s^{-1} and displayed over the range of 0 to 30 K km s^{-1} . The positions of the 67 IRAS point sources are identified by the sequence number assigned in Table 2.1. Triangles mark reliably detected molecular outflows, squares mark outflows with less certain detections, and open circles mark the positions of all other sources.

Figure 2.4 A three band color-color plot of the 12 μ m, 25 μ m, and 60 μ m flux densities. Arrows define the direction of a limit on the ratios. Limit arrows in opposite directions indicate that a ratio is undefined. Sources marked by a triangle belong to the group classified in the text as (a); a square to (b); and a circle to all others. In addition, sources are identified by their sequence number. The dotted line delimits the region defined in the text.

Figure 2.5 A four band color-color plot of the IRAS flux densities. Identifications are the same as in Figure 2.4.

Figure 2.6 A histogram of the number of sources versus the log of the flux density ratio. The bottom hatched histogram in each plot represents type (a) sources, the middle hatched histogram, type (b) sources, and the plain histogram, for the other sources. The first panel is the ratio of $12\mu\text{m}$ to $25\mu\text{m}$, the second, $25\mu\text{m}$ to $60\mu\text{m}$, and the last, $60\mu\text{m}$ to $100\mu\text{m}$.

(Figure continued on pages 51 – 53)

Figure 2.7 A plot of the integrated CS emission versus the ^{12}CO line width evaluated at the 200 mK level. A typical 3σ error bar is shown at the lower right of the plot. The sources are identified as in Figure 2.4.

Figure 2.8 A plot of the ^{12}CO 200 mK line width versus the log of the column density of ^{13}CO and C^{18}O . The sources are identified as in Figure 2.4.

(Figure continued on pages 57 – 58)

Figure 2.9 Plot of the log of the IRAS luminosity (as defined in the text) and the integrated CS emission and the ^{12}CO 200 mK line width. Sources are identified as in Figure 2.4.

(Figure continued on pages 60 – 61)

CHAPTER 3

THE L1641 MOLECULAR OUTFLOWS

3.1 Introduction

In the last few years several observational programs have been directed towards the study of young stellar objects in the L1641 region of the Orion molecular cloud, a region which is characterized by robust, but low luminosity ($< 10^3 L_{\odot}$), star formation. Since molecular outflows are one of the signposts associated with the earliest stages of stellar evolution, many of these programs have included searches for outflows in this region. Some of these searches for molecular outflows have targeted optically visible T-Tauri and other emission line stars (Edwards and Snell 1984; Levreault 1988).

Alternatively, Fukui *et al.* (1988) have completed an unbiased survey of Orion searching for regions of large ^{12}CO line widths. The search strategy followed in Chapter 2 was different in that the positions from a flux limited sample of IRAS sources to determine whether the IRAS survey data could be used, in a systematic way, to locate molecular outflows.

In Chapter 2, many outflow candidates were discovered, but since the observations were limited to only one spatial position, it was difficult to fully determine the nature of the gas motions toward these stars. To identify and characterize a molecular outflow generally requires mapping over a large enough area to delineate the spatial extent of the high velocity emission. Thus, in this paper, detailed mapping observations are reported of the regions most likely to be outflows. These maps permit a more complete description of the outflow to be obtained and allow several additional

questions to be addressed that were not possible in the previous paper. First of all, from the detailed mapping, an assessment may be made of the effect that the parent molecular cloud has in determining the structure and orientation of the outflow. The positions of the optical, infrared, and radio sources can be compared with the location of the red and blue wing emission of the outflow to ascertain their association with these outflows. The maps will also permit an estimate of the collimation and bipolarity of the molecular outflows. Finally, the maps may be used to estimate the outflow masses and energetics and assess their role in the evolution of molecular clouds which surround them.

3.2 Observations and Source Selection

The observations were obtained with the 14 meter telescope of the Five College Radio Astronomy Observatory[†] between 1987 January and 1989 February. A quasi-optical sideband filter and a cryogenic Schottky diode mixer receiver were used along with a 256 channel spectrometer with 100 kHz and 250 kHz resolution per channel to record spectra. Observations were calibrated by the chopper wheel technique which allowed for switching between the sky and an ambient load.

The half power beam width of the 14 meter telescope (45 arcseconds at 2.6 mm) and the efficiency on a spatially extended source ($\eta_{\text{FSS}} = 0.7$) were determined from observations of the Moon and Jupiter. Temperatures quoted in this paper (T_{R}^*) have been corrected by η_{FSS} which includes ambient temperature losses, effects of the Earth's

[†] The Five College Radio Astronomy Observatory is operated with support from the National Science Foundation under grant AST 85-12903 and with permission of the Metropolitan District Commission of the Commonwealth of Massachusetts.

atmosphere, and forward spillover and scattering losses (Kutner and Ulich 1981). The pointing and focus of the telescope were checked on a regular basis using the very high velocity source ($\alpha = 5^{\text{h}}32^{\text{m}}46^{\text{s}}.8$, $\delta = -5^{\circ}24'13''.0$) near Orion KL as a reference. A distance to L1641 of 480 pc has been adopted in this paper.

In Chapter 2, each source was classified according to the shape of the ^{12}CO line profile. If a source had a ^{12}CO line width broader than the ^{13}CO line width and had C^{18}O or CS emission identified at the IRAS position, then it was classified as a definite wing component (Yes). Sources with moderate ^{12}CO line widths that show little or no C^{18}O or CS emission were listed as a possible wing component (Maybe). Sources found to have broad, but generally multiple peaked ^{12}CO lines were designated as double peaked sources (DBL). The remaining sources could be classified by simple gaussian lines (No). The definite wing sources are probably outflows but cannot, based on the information presented in Chapter 2, be confirmed as molecular outflows because they were each only observed at one spatial position. Likewise, the possible wing sources suggest a possible outflow but require further observations to confirm their nature. The double peaked and gaussian line shaped sources have no indications to suggest that an outflow would be found at their position. Thus, all of the sources identified as definite wing profile source and most of the possible wing profile sources were considered as candidates for detailed mapping and are listed in Table 3.1. Column 1 of Table 3.1 lists the source designation from Chapter 2; column 2, the IRAS name; columns 3 and 4, the right ascension and declination of the IRAS source; and column 5, other names for the source (from Strom *et al.* 1989). Columns 6 and 7 are used to identify a source as a molecular outflow. The outflow classification listed in column 6 is the designation given

to the source by Chapter 2 (and described above) and the classification in column 7 is based on the results of this paper.

The sources listed in Table 3.1 were mapped in the $J = 1 \rightarrow 0$ transition of ^{12}CO over a region typically $4'.5$ by $4'.5$ with points spaced at 1.5 arcminutes centered on the infrared position. This initial spacing of the map points is larger than the telescope half power beam width and was selected as a means of quickly determining the spatial extent of the molecular outflows. In cases where a molecular outflow was clearly identified, finer spaced points were obtained and maps were constructed to better define the extent and structure of the outflow. For three of the sources (#39, 40, and 41), small maps were also made of the $J = 1 \rightarrow 0$ transition of C^{18}O in addition to the ^{12}CO observations.

3.3 The L1641 Molecular Outflows

3.3.1 General Results

Chapter 2 lists 14 sources associated with line profiles that have strong evidence for wings and another 13 that are possible wing sources. In general, the criteria used here for establishing a source as an outflow required a total velocity extent at zero intensity in excess of 10 km s^{-1} and that the high velocity be restricted to a small area within the region mapped. Of the original 27 sources studied, 9 are shown to be definite molecular outflows, while two remain undetermined and 16 others show either multicomponent line profiles or no evidence for wing emission. Of the 9 detected molecular outflows, 6 have been previously identified in the literature (#5: L1641-N, Fukui *et al.* 1988; #18 and 21: V380 Ori NE and HH 1-2, Levreault 1988; #20: V380 Ori, Edwards and Snell 1984; #39: Haro 4-255, Levreault 1988; and #40: Re50, Reipurth and

Bally 1986). One additional source, #27 (L1641-C), has been identified by Fukui *et al.* (1988) as an outflow but does not satisfy the criteria of an outflow in this work. The 6 detected outflow sources, source 27, the uncertain outflows, and the previously unidentified sources are discussed individually below.

As a confirmation of the results of Chapter 2, 8 of the 14 "Yes" sources were found to be, in fact, molecular outflows. Furthermore, only one of the sources (#18) listed as "Maybe" in Chapter 2 was found to be a molecular outflow. This suggests that the criteria defined in Chapter 2 for identifying definite wing sources is useful and can be used to locate the positions of the young stellar objects most likely to be associated with molecular outflows. The classification of possible wing sources, however, leads in almost every case to false identifications and should be avoided.

In the following section, we describe the individual objects mapped in this study. Each section will describe 1) the relationship of the outflow to optical, infrared, and radio sources; 2) the structure of the flow relative to the ambient cloud; and 3) the extent of the flow. This information is necessary to determine what role, if any, the molecular cloud plays in the evolution and shape of the outflow. It has been suggested that the dense material near an outflow could be important in diverting and shaping the direction of the high velocity gas (Fukui *et al.* 1988). This could result in the displacement of the outflow from the true origin. Additionally, the orientation of the collimating material may be determined by the direction of the local magnetic field. The implied direction of the magnetic field, obtained from optical polarization measurements, has been seen to be oriented parallel to the direction of optical jets in L1641 (Strom *et al.* 1986; Vrba, Strom, and Strom 1988). Therefore, it will be interesting to compare the directions of the

outflows with each other and with the direction of the magnetic field to determine the global alignment of molecular outflows and the role played by magnetic fields.

3.3.2 Individual Sources

#5 (05338–0623) : L1641–N

Source 5 has been previously identified by Fukui *et al.* (1986) as a compact molecular outflow. Figure 3.1 shows 9 spectra obtained around this region and illustrates the distribution of the high velocity material as a function of position. The center spectrum in the figure is located at the IRAS position and adjacent spectra are spaced 1'.5 apart. The wing emission is delineated by the shaded part of the spectra. It is less than 2 arcminutes in extent and is oriented with a position angle of about 45°. Fukui *et al.* (1988) have identified a dense core centered at the position of the IRAS source and find that it is oriented along the direction of the outflow. Furthermore, they suggest that the shape of the outflow is a direct consequence of the interaction of the outflow with the dense cloud. Our observations confirm source 5 as a bipolar outflow, but the resolution of our map is poorer than that of Fukui *et al.* (1988) and is insufficient to determine the degree of collimation or shape of the outflow.

#8 (05339–0626)

Object 8 is an outflow that has wings that are only slightly more extended than the line width of the ambient cloud in this region. Figure 3.2 is a plot of the spectra located on and around the position of the IRAS source with the high velocity emission shaded. The spectrum at an offset position of (-1.5, 1.5) is identical with the spectrum shown for object 5 (see Figure 3.1) at (0, -1.5). The spatial extent of object 5 does not

extend more than 2 arcminutes south of the source (Fukui *et al.* 1988) suggesting that the high velocity emission seen in Figure 3.2 is probably due to object 8. Further, higher resolution observations will help delineate the high velocity emission originating from object 8 from the emission from the nearby source 5. There is a hint of asymmetry in the lines which appears to be centered on the IRAS source position but object 8 is probably a red wing only source. There are also two velocity components present in the lines that make the wing emission difficult to assign in this region. Object 8 is located 1'5 west and 2'75 south of object 5 with IRAS emission that is distinct from object 5 at the shorter wavelengths but blended at the longer wavelengths. Chapter 2 reported strong CS and C¹⁸O emission at the position of object 8 suggesting a dense core is associated with the infrared source. Recent 6 cm radio continuum observations (see Chapter 4) indicate that the spectral index between 6 and 20 cm of an object 30" south-west of the infrared position is thermal and consistent with the object being an optically thick HII region.

#16 (05317-0637) : HH 84

The ¹²CO emission from this source is suggestive of a double peaked source as can be seen in the spectrum shown in Figure 3.3. The ¹³CO spectrum (from Chapter 2) at the IRAS position shows no emission corresponding to the higher velocity component. Chapter 2 listed object 16 as a definite wing profile but the mapping presented here cannot confirm that this is an outflow. Figure 3.3 demonstrates that this red feature continues for at least several arcminutes but is strongest north of the IRAS source. This IRAS source is near to both SW Ori and HH 84. Reipurth (1985, 1989) has studied HH 84 and finds it is comprised of five small nebulae (Re18 A-E) which extend along the line of sight away from SW Ori. Reipurth does not associate SW Ori as the origin of these

knots. Reipurth could not identify the driving source but suggests that it is along the line of knots in the direction opposite SW Ori. Unfortunately, this is also in the direction away from source 16 indicating that object 16 is probably not the origin of Re18 A-E.

This region is located off the main ridge of the molecular cloud but is marked by moderately strong ^{12}CO and ^{13}CO emission (cf. Chapter 5; Bally *et al.* 1987). No CS or C^{18}O emission was detected towards the IRAS source (Chapter 2). The prominence of the red wing emission makes this region noticeable and, due to the location of HH 84 relative to the main cloud, it is not unlikely that a molecular outflow would be located near the edge of this cloud and only have one component of high velocity emission.

#18 (05342–0639)

No line broadening was observed at the infrared position but, towards the south-west, both red and blue wings are seen. This outflow was first detected by Levreault (1988) who labeled the source V380 Ori NE. Levreault could find no optical or infrared counterpart for this source and finds that the IRAS co-add survey data shows extended and complex emission in this region. If this outflow is associated with the infrared source 05342–0639, then it is displaced about 2 arcminutes south-west from the peak of the infrared position. Also, no CS or C^{18}O emission was detected at the IRAS position by Chapter 2.

Figure 3.4 illustrates the red and blue wings of this source. The two spectra are separated by only 1.5 arcminutes (0.2 pc) and yet a clear delineation of the red and blue emission is present. Also of interest is that the lack of overlap of the red and blue emission between and suggests an almost perpendicular alignment of the outflow with

respect to our line of sight. Further, more highly resolved observations are necessary for this source and they should reveal more about the nature and orientation of this outflow.

*#20 and 21 (05339–0644 and 05339-0646) :
V380 Ori, and HH 1 and 2 and NGC 1999*

This region has been previously observed by Edwards and Snell (1984) and Levreault (1988). The overall structure of the high velocity material, seen in Figure 3.5, is similar to that seen by Levreault (1988). Several radio continuum sources have been associated with the HH 1-2 region (Pravdo *et al.* 1985; cf. Chapter 4; and Rodríguez *et al.* 1990). Levreault identified a distinct outflow associated with both V380 Ori and the HH 1-2 system. In both cases, Levreault could only identify the red wing emission of each outflow. Bally and Pound (private communication) have identified the blue wing of the HH 1-2 outflow to the NW of HH 1-2. The ^{13}CO emission of this region (Chapter 2) indicates that line profiles are composed of at least two components and the double peaked ^{12}CO emission in this region makes it difficult to identify wing emission.

#27 (05363–0702) : L1641–C

Object 27 (L1641–C) was identified as a molecular outflow with line widths of 8 km s^{-1} which extends over 5.5 arcminutes by Fukui (1988). From our observations (shown in Figure 3.6), the ^{12}CO line profile is broadest towards the position of and just south of the IRAS source (0, 0). Figure 3.6 demonstrates that the line width does diminish just slightly with distance from the source, with the narrowest line widths occurring towards the south-east. Our observations also indicate that the line profiles for object 27 are dominated by several strong components at different velocities that extend throughout the map. This multiple line structure is confirmed by the ^{13}CO observation

(Chapter 2) of the IRAS position. Since these multiple components show no localized structure or wing emission, especially over the scale claimed by Fukui, we suggest that L1641-C is not an outflow.

#39 (05369-0728) : Haro 4-255

Haro 4-255 was first identified as a bipolar molecular outflow by Levreault (1988) who also noticed that the IRAS point source position, which was coincident with Haro 4-255, was not spatially coincident with the apparent origin of the outflow. Evans, Levreault, and Harvey (1986) and Levreault (1988) identified an infrared source at 50 and 100 μ m (Haro 4-255 FIR; $\alpha = 5^{\text{h}} 36^{\text{m}} 54^{\text{s}}.5$, $\delta = -7^{\circ} 27' 40''$) located towards the north-west of Haro 4-255. Haro 4-255 FIR dominates the infrared emission at the longer wavelengths and Haro 4-255 at the shorter wavelengths. Levreault concluded that due to the proximity of the two infrared sources, the IRAS Point Source Catalog coincidence criteria was satisfied by both of these sources and the infrared position assigned to the stronger 12 μ m source Haro 4-255. To date, no 2.2 μ m or 6 cm radio continuum source has been detected at the position of Haro 4-255 FIR.

Figure 3.7 is a plot of spectra at three positions around the outflow demonstrating the wing emission. Offsets from the IRAS position are listed for each spectra. The higher angular resolution ^{12}CO map of this source presented in Figure 3.8 suggests that Haro 4-255 FIR is located (within the error of the Evans, Levreault, and Harvey measurements) at the apparent center of the outflow. This outflow is one of the most spectacular examples of a compact bipolar flow in L1641. The outflow of Haro 4-255 is oriented at a position angle of about 90° and, because of the overlap of the wings, is probably directed somewhat along our line of sight.

The $C^{18}O$ observations (shown in Figure 3.9) indicate the highest column density in this region is adjacent to the position of Haro 4-255, not towards Haro 4-255 FIR. It is surprising that the $C^{18}O$ emission does not peak near the position of Haro 4-255 FIR, especially because of the lack of optical or near infrared emission. If the lack of optical and infrared emission was because the source was deeply embedded, then a molecular line that traces column density, like $C^{18}O$, might be expected to be enhanced along the line of sight.

In addition to the peak near Haro 4-255, the $C^{18}O$ emission appears to envelop the southern part of the blue wing emission. One possible interpretation of this is that the high velocity gas is being shaped by the denser regions of the molecular cloud and, thus, is impeding this wing of the outflow. This suggestion has also been made by Fukui *et al.* (1988) to explain the shape of the molecular outflow L1641–N. Another possible interpretation is that the high velocity winds are sweeping up material into a dense ridge as they expand into the cloud (Moriarty–Schieven *et al.* 1987). This would also suggest that the shape of the high column density would conform to the outline of the outflowing material.

#40 (05380–0728) : Re50

The optical nebulosity, Re50, was identified by Reipurth (1985) and, shortly thereafter, Reipurth and Bally (1986) found that the intensity of the optical nebulosity varies dramatically over the time scale of years. There has been no H_2O maser (Wouterloot and Walmsley 1986) nor NH_3 emission (Wouterloot, Walmsley, and Henkel 1988) detected in the direction of the IRAS source associated with Re50. The large scale ^{13}CO map of Orion by Bally *et al.* (1987) reveals that the region around Re50 is located

on a plateau of high column density. Two radio continuum sources in this region have been identified (see Chapter 4). One of the sources is coincident with the IRAS position and the near-infrared source found by Reipurth and Bally (1986). The other (hereafter, Rc50 W) is located 50 arcseconds west. Based on the spectral index between 6 and 20 cm, both radio continuum sources are found to be consistent with a thermal origin and can be understood as originating from either a stellar wind or an optically thick H II region.

Reipurth and Bally (1986) were the first to identify the molecular outflow and suggest a position angle orientation of about 315° . The spectra at the peak of the red and blue wing emission is presented in Figure 3.10. Offset positions are relative to the IRAS source. Our ^{12}CO map (Figure 3.11) reveals that the red wing emission of the outflow is much more spatially extended than was shown by Reipurth and Bally. The red wing emission is seen to peak about 3 arcminutes north of Rc50 and then continue towards the west for 2 arcminutes and then south for another 4 arcminutes. The red wing emission of this outflow is striking because it appears to outline the border of the large ^{13}CO column density region (Bally *et al.* 1987).

The peak of the C^{18}O emission, shown in Figure 3.12, was found at the position of Rc50 (that is, the near-infrared source). In addition, a second C^{18}O peak was observed 2.5 arcminutes south of Rc50 coincident with the blue wing of the molecular outflow and the strongest ^{13}CO emission in this region. The southern optical reflection nebula is coincident with this lower C^{18}O region and appears to outline the boundary of the C^{18}O emission. This agrees with the suggestion of Reipurth and Bally (1986) that

this lower nebula is the result of direct illumination of dense material by the star through the cavity created by the outflow.

One readily apparent feature in Figure 3.11 is that the line connecting the peak integrated red and blue wing emission is displaced west of the position of the near-infrared source. This indicates that either the molecular cloud is shaping the direction of the outflow away from the infrared source or that the infrared source is not the origin of the outflow. Re50 W is located at a better position to be the origin of the outflow than Re50. (This is similar to Haro 4-255 and Haro 4-255 FIR.) The difficulty with assigning Re50 W as the source of the outflow is that there are no optical or infrared detections that would confirm that this source is a young stellar object. Furthermore, C¹⁸O observations reveal the emission peaks at the position of Re50 and not at the position of Re50 W. Hence, it is more likely that the near-infrared source is the origin of the outflow and the dense material of the cloud is directing the shape of high velocity material. Further optical and near-infrared observations at both positions should reveal the solution to the origin of the molecular outflow.

#41 (05375–0731) : FIRSSE 101

The infrared source FIRSSE 101 was first identified as part of a survey in the far-infrared by Price *et al.* (1983). An H₂O maser has been identified by Wouterloot and Walmsley (1986) and an NH₃ core by Wouterloot, Walmsley, and Henkel (1988). But, until recently, the near-infrared counterpart of FIRSSE 101 had remained hidden. Strom, Margulis, and Strom (1989) identified a 2.2μm source located 10 arcseconds south of the H₂O maser source. A 6 cm radio source was found that is coincident with the 2.2μm position (Chapter 4). The spectral index of the radio continuum source between 6 and 20

cm reveals a thermal origin that is consistent with an optically thick H II region or a stellar wind.

FIRSSE 101 is located about 8 arcminutes west and 3 arcminutes south of Re50. The C¹⁸O emission mapped in this region is found to peak at the position of the IRAS source. The ¹²CO emission indicates a very compact molecular outflow extending about 3 arcminutes in a direction oriented perpendicular to the direction of the long axis of the molecular cloud (position angle ~ 45°). Figure 3.13 is a plot of the high velocity ¹²CO emission with the positions of the IRAS, H₂O Maser, and 6 cm source (the 2.2μm source is coincident with the 6 cm source at this scale) identified. The offset positions of the map are relative to Re50 and the contours in the upper left corner are due to the red wing emission of Re50. The ranges for the mass and energetics of FIRSSE 101 (see below) are comparable to Haro 4-255 and yet the two outflows appear strikingly different.

#59 (05391–0804)

Source 59 was identified in Chapter 2 as a definite candidate source because it had weak blue emission detected between -3 and 3.5 km s⁻¹. Our observations indicate that there is no ¹²CO emission below 0 km s⁻¹. While the blue component of the emission appears broader than the corresponding ¹³CO emission (Chapter 2), the distribution of material appears to be uniform over the extent of our map. Hence, these observations cannot determine if source 59 is an outflow.

#61 (05383–0807)

Figure 3.14 shows the high velocity ¹²CO emission around source 61. Both red and blue shifted emission is seen and has a roughly bipolar morphology. The full velocity range observed is 16 km s⁻¹. This outflow appears to be no larger than 3

arcminutes in extent and is oriented east-west (blue-red). Recently, a $2.2\mu\text{m}$ source has been identified in this region associated with this object (Strom, Margulis, and Strom 1989).

3.4 The Structure and Orientation of the Molecular Outflows

Figure 3.15 is a histogram of the orientation of the outflows where the radius represents the number of outflows with a particular orientation and the direction, divided into four directions, illustrates the orientation of the outflow. Outflows not observed to be bipolar are included with the orientation defined as the direction between the IRAS source and the peak of wing emission. Column 2 of Table 3.2 lists the position angle of the outflow which is defined east from north. Figure 3.15 illustrates that the orientation of the 9 outflows mapped shows no preferred direction. A possible trend SW to NE may exist but the number of sources involved is so small that no significance should be assigned to the trend. Furthermore, the 6 optical jets identified by Strom *et al.* (1986) indicate orientations along the length of the cloud (SE to NW).

The outflows that have been observed occur throughout the L1641 cloud but they appear to be clustered, as might be expected if star formation occurs in bursts and the outflow phenomenon is short lived and associated with all stars. Of the 9 detected outflows, 7 appear bipolar but 2 only have red shifted high velocity wing emission. Furthermore, none of the bipolar sources that have been mapped and had their wing emission spatially resolved appear to be highly collimated. That is, in most cases, none of the wing emission appears elongated.

The most prominent feature of the IRAS images of L1641 is the grouping of the three sources 05369-0728 (#39: Haro 4-255), 05380-0728 (#40: Re50), and 05375-0731 (#41: FIRSSE 101). These three objects are located within 16 arcminutes of each other, have strong infrared emission that increases towards longer wavelengths, and each have an associated molecular outflow. It is interesting that each outflow is oriented along a different line of sight direction as random as the entire sample of sources. In other words, there appears there is no preferred orientation of molecular outflows over either small or large scales. Furthermore, the direction of the outflows is different from the implied magnetic field direction suggested by optical polarization observations (Strom *et al.* 1986; Vrba, Strom, and Strom 1988). Thus, this result appears to disagree with the suggestion that the local magnetic field plays a role, at the formation stage, in determining the direction of the outflows (Strom *et al.* 1986). However, the local magnetic field directions are not well enough delineated in this region to conclude that this process does not occur to some extent or that it does not occur at the smallest size scales. The orientation of the outflows and the optical jets may initially be aligned and, then, the outflows may be diverted away from the direction of the jets farther from the origin. Indeed, the observations of objects 39, 40, and 41 suggest that this is probably the case. If local magnetic fields are important in determining the shape of the outflows, then dramatic field direction changes over the size scale of a few parsecs would be required to explain the orientation of these outflows. Furthermore, based on the individual source discussion above, it appears likely that the molecular cloud plays an important role in the shape and orientation of the outflows on the size scale of tenths of parsecs.

3.5 Molecular Outflow Energetics

The mass, momentum, and mechanical luminosity of the high velocity emission has been determined for each of the molecular outflows in this sample following the procedure outlined by Margulis, Lada, and Snell (1988). Throughout, we have assumed the high velocity material completely fills the beam (a beam filling factor, f , of 1) and an abundance ratio of ^{12}CO to ^{13}CO of 89 (terrestrial) and of ^{13}CO to H_2 of 2.5×10^{-6} (Dickman 1978). Since the column density is inversely proportional to the beam filling factor and the mass is directly proportional to both the column density and the beam filling factor, in the optically thin limit, the momentum and energy of the outflow are independent of the beam filling factor. In most cases, the optical depth of the high velocity material was found to be small. Using a more representative value of $f \sim 0.5$ (Snell *et al.* 1984; Margulis, Lada, and Snell 1988) still results in optically thin high velocity emission.

A summary of how the mass, momentum, and mechanical luminosity are determined is given below. In each case, a range of values must be estimated since the space velocity is unknown and only the radial component of the velocity is measured. In addition, the measured size is only the projected size. Another consideration which limits our ability to estimate these quantities is that the outflowing material at low velocities will be lost in the core of the line profile due to confusion with the ambient cloud. Thus, approximations must be made to account for our incomplete knowledge of the amount of high velocity gas and its space velocity.

1) Mass: The lower limit was determined by summing the contribution to the mass in each channel of the line wing. The mass in each channel was estimated from the

LTE calculation of the column density multiplied by the weighted area. The area used was the apparent emitting area of the high velocity material weighted by the integrated wing intensity. The upper limit was computed by summing the mass in each wing channel (as above) and then adding to it the contribution to the mass from the line core. The mass from the line core was derived by first assuming the contribution to the mass in each channel of the core is a constant equal to the mass of the lowest velocity wing component. Then, the mass in each channel from line center to the wing is added together.

2) Momentum: The momentum may be estimated by summing over the wing channels of the product of the mass to the magnitude of the line of sight velocity (offset from line center). However, this estimate is a lower limit since it ignores the inclination of the outflow and the mass in the line core. To determine an upper limit, a measure of the characteristic velocity of the outflowing material is estimated as the largest line of sight velocity extent from line center of the wing emission. The upper limit is then the product of this highest line of sight velocity extent and the upper limit to the total mass, which assumes that all the outflow material is moving at a speed equal to the highest observed outflow velocity.

3) Mechanical Luminosity: A lower limit to the rate at which energy is deposited into the outflow by the source may be determined by summing the product of the mass in a particular channel and the cube of the velocity offset from line center. This is then divided by twice the major axis radius of the outflow. The upper limit to the luminosity may then be estimated as the product of the upper limit of the mass times the cube of the highest velocity extent from line center again divided by twice the

major axis radius of the molecular outflow. Both the upper and lower limit have a form of kinetic energy divided by the dynamical time scale of the outflow.

The derived parameters for each molecular outflow are presented in Table 3.2. Column 1 of Table 3.2 lists the source number; column 2, the position angle of the flow (described above); column 3, the assumed excitation temperature, which was the greater of either the ^{12}CO line center peak temperature of the strongest high velocity spectra or 10K; column 4, the full width extent of the outflow extrapolated to the zero intensity level; columns 5 and 6, the weighted areas of the blue and red wings respectively; column 7, the characteristic dynamical time scales estimated from the maximum spatial and velocity extents of the ^{12}CO wings; column 8, the lower and upper limits of the mass; column 9, the lower and upper limits of the momentum; and column 10, the lower and upper limits of the mechanical luminosity.

Molecular outflows deposit momentum and energy into their parent molecular clouds, and it has been speculated that this energy may play a role in the support of the cloud against gravitational collapse (cf. Norman and Silk 1980). The energetics derived above and shown in Table 3.2 may be used to estimate the dynamic impact that the molecular outflows are having on L1641. However, the uncertainty in the estimates of the momentum and energy imply that only order of magnitude estimates are appropriate.

The rate at which momentum will be needed to be transferred into the cloud by molecular outflows may be estimated as the momentum in the cloud divided by the dissipation time scale. The momentum in the cloud is estimated as the mass of the molecular cloud and the three-dimensional velocity dispersion. Using a typical ambient cloud line width at half maximum of 4 km s^{-1} yields a three-dimensional velocity

dispersion of $\sim 3 \text{ km s}^{-1}$. Using a mass for the L1641 region of $2 \times 10^4 M_{\odot}$ (Fukui *et al.* 1986; Bally *et al.* 1987) and a dissipation time scale on the order of the free fall time scale (Scalo and Pumphrey 1982; Kwan and Sanders 1986), or $\sim 7.4 \times 10^6 \text{ yr}$, we find that the rate at which momentum must be injected into the cloud to support it to be $\sim 8 \times 10^{-3} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$. Using the momentum and dynamic time scale values listed in Table 3.2 suggests that the momentum input into the cloud by the 9 currently active outflows is at a rate between $\sim 3.5 \times 10^{-3}$ and $\sim 1.7 \times 10^{-2} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$. From this estimate it appears that molecular outflows could currently provide sufficient momentum input to support the molecular cloud against gravitational collapse. For the cloud to be supported over several molecular outflow life times, however, requires several episodes of star formation to occur over the dissipation time scale of the cloud. In this order of magnitude estimate, the rate at which momentum is injected into the cloud by outflows could actually be substantially greater if we could take into account the inclination angle of each of the outflows. Also, we note that even if the molecular outflows do not provide enough support to the cloud, there is still enough momentum to substantially affect the evolution of the molecular cloud. This will be more fully discussed in a future work.

3.6 Summary

A group of IRAS selected young stellar objects in the L1641 region of Orion, identified previously in Chapter 2 as having broad ^{12}CO line widths, has been mapped to determine whether they are molecular outflows. The outflows identified in this survey include all previously known outflows and three previously unidentified outflows. No known outflow was omitted by this search strategy (although one previously identified outflow, L1641-C, was found not to be an outflow).

Three of the outflows were observed in C^{18}O and it was found that the regions of highest column densities were typically at the position of the IRAS source. The apparent origin of the outflow, however, does not always agree with the IRAS position. In addition, the direction of the outflows does not correspond with the direction of the magnetic field as suggested by optical polarization observations. Thus, magnetic fields probably have little influence on the direction of the molecular outflows on the size scale of tenths of parsecs. The displacement from the origin of the outflow may, instead, be attributed to the dense regions of the molecular cloud shaping and directing the outflow.

The outflows observed in L1641 appear to be oriented in no preferred direction, and, although the outflows are distributed throughout the molecular cloud, they appear to be clustered in small groups. Based on the energetics derived for the molecular outflows identified in L1641, we find that the outflows can probably provide sufficient momentum to the molecular cloud over the dissipation time scale to support the cloud against gravitational collapse.

TABLE 3.1

Observational Coordinates

Source ^a Number (1)	IRAS Name (2)	α (1950) (h m s) (3)	δ (1950) (° ' ") (4)	Other Name (5)	Outflow Classification ^b	
					Paper I (6)	This work (7)
1	05398-0621	5 39 50.5	-6 21 55.7	L1641-N	Maybe	No
5	05338-0623	5 33 51.3	-6 23 59.0		Yes	Yes
7	05361-0626	5 36 06.1	-6 26 14.9		Maybe	No - DBL
8	05339-0626	5 33 57.8	-6 26 44.1		Yes	Yes
9	05392-0627	5 39 15.3	-6 27 41.8	V801 Ori, near HH34	Yes	No
10	05330-0628	5 33 01.7	-6 28 43.1		Maybe	No
13	05393-0632	5 39 18.7	-6 32 46.6		DBL	No
15	05347-0636	5 34 45.4	-6 36 44.7		DBL	DBL
16	05317-0637	5 31 45.4	-6 37 56.0	BF Ori, T432	DBL	DBL
17	05348-0638	5 34 50.6	-6 38 14.8	SW Ori, T108, HH84	Yes	Maybe
18	05342-0639	5 34 15.4	-6 39 44.4	V380 Ori, T395, HH35	DBL	DBL
20	05339-0644	5 33 56.2	-6 44 44.2		Maybe	Yes
21	05339-0646	5 33 57.9	-6 46 29.2		Yes	Yes
25	05354-0658	5 35 28.9	-6 58 15.1		Yes	Yes
26	05362-0700	5 36 12.6	-7 00 00.0	HH1&2	Maybe	No
27	05363-0702	5 36 19.3	-7 02 41.2	T456	Maybe	DBL
28	05358-0704	5 35 52.6	-7 04 00.1	L1641-C	Yes	DBL
29	05357-0710	5 35 42.0	-7 10 07.4	Haro 13a	Maybe	DBL
32	05362-0714	5 36 17.6	-7 14 30.0	Haro 14a, HH43	Maybe	No
36	05364-0718	5 36 29.3	-7 18 14.9	Haro 4-249, T484	Maybe	No
38	05364-0722	5 36 26.3	-7 22 45.0	V599 Ori	Yes	DBL
39	05369-0728	5 36 56.6	-7 28 05.4	Haro 4-254, T489	...	No
40	05380-0728	5 38 02.2	-7 28 58.8	Haro 4-255, T497	Yes	Yes
41	05375-0731	5 37 30.7	-7 31 58.5	Re 50, L1641-S	Yes	Yes
44	05375-0738	5 37 35.0	-7 38 59.2	FIRSSE-101	Yes	Yes
51	05378-0750	5 37 52.1	-7 50 07.2	T529	...	No
53	05389-0756	5 38 54.8	-7 56 42.6		Maybe	No
54	05379-0757	5 37 56.3	-7 57 58.9		Maybe	No
56	05399-0800	5 39 58.5	-8 00 10.7		Yes	No
57	05364-0801	5 36 25.4	-8 01 00.0	DL Ori, T523, H7-3, San 5	...	DBL
59	05391-0804	5 39 07.0	-8 04 57.3		Maybe	DBL
60	05382-0805	5 38 12.9	-8 05 28.6		Yes	Maybe
61	05383-0807	5 38 22.6	-8 07 13.4		...	No
62	05390-0807	5 39 00.4	-8 07 27.5	DL Ori, T523, H7-3, San 5	Yes	Yes
64	05401-0809	5 40 10.7	-8 09 10.2		...	No
67	05379-0815	5 37 56.3	-8 15 29.0		DBL	DBL
					Maybe	No

a) from Chapter 2.

b) Classifications as defined in the text indicate a definite wing profile (Yes); a possible wing profile (Maybe); a double or multiple peaked profile (DBL); or a gaussian profile (No).

TABLE 3.2
Outflow Parameters, Masses, and Energetics

Source Number	P.A. (°)	T_{ex} (K)	Δv (km s ⁻¹)	$A_{\text{w}}(\text{blue})$ (pc ²)	$A_{\text{w}}(\text{red})$ (pc ²)	τ_{d} (10 ⁴ yrs)	M ($M_{\odot}$)	MV ($M_{\odot}$ km s ⁻¹)	L_{mech} $L_{\odot}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
5	45	20.7	21.0	0.23	0.15	3.6	1.4 – 4.6	7.8 – 50	0.074 – 1.2
8	90	20.7	21.0	0.097	0.12	3.6	1.3 – 4.5	6.9 – 48	0.066 – 1.1
18	0	15.4	27.0	0.044	0.044	2.8	0.095 – 1.4	0.57 – 1.8	0.018 – 0.14
20	90	18.9	20.0	0.20	0.077	3.7	2.1 – 8.4	8.0 – 76	0.036 – 1.2
21	-45	18.9	20.0	0.41	0.070	3.7	1.1 – 5.1	6.4 – 51	0.050 – 1.00
39	90	10.0	30.0	0.039	0.047	3.5	3.5 – 7.2	26 – 107	0.37 – 3.3
40	0	10.0	30.0	0.029	0.073	6.7	7.4 – 17	57 – 245	0.43 – 4.1
41	45	10.0	26.4	0.044	0.099	2.7	4.2 – 8.5	28 – 104	0.42 – 3.2
61	45	10.0	10.5	0.067	0.14	7.4	0.24 – 0.75	0.85 – 4.1	0.0025 – 0.024

Figure 3.1 A plot of the ^{12}CO spectra at and around the position of source 5. Offsets from the position of the IRAS source are identified along with each spectra. The shaded region in each spectra represent the blue and red wings.

Figure 3.2 Same as Figure 3.1 except for source 8.

Figure 3.3 Same as Figure 3.1 except for source 16.

Figure 3.4 A plot of the ^{12}CO spectra near the position of source 18. Shown are the two positions with strong wing emission. Offsets and shading are as for Figure 3.1. The velocity range for the red wing emission is 10 to 21 km s^{-1} and for the blue wing emission, -6 to 4 km s^{-1} .

Figure 3.5 A map of the high velocity ^{12}CO emission for sources 20 and 21. The solid contour represents the blue wing emission and the dashed contours, the red wing emission. The velocity range for the red wing emission is 12 to 20 km s^{-1} and for the blue wing emission, 0 to 6 km s^{-1} . The contour levels are at 2, 2.5, 3, 3.5, 4, 4.5, and 5 K km s^{-1} . The positions of V380 Ori and the HH 1-2 sources (from Levreault 1988 and Pravdo *et al.* 1985) are identified by crosses and labeled.

Figure 3.6 Same as Figure 3.1 except for source 27.

Figure 3.7 Same as Figure 3.1 except for source 39.

Figure 3.8 A map of the high velocity ^{12}CO emission for source 39. The solid contour represents the blue wing emission and the dashed contours, the red wing emission. The blue wing emission ranges between -10 and 0 km s^{-1} and the red wing emission between 9 and 20 km s^{-1} . The first contour level is at 2.9 K km s^{-1} and increases in steps of 1.45 K km s^{-1} . The positions of Haro 4-255 (IRAS) and Haro 4-255 FIR (FIR) are identified by crosses and labeled.

Figure 3.9 Same as Figure 3.8 except the contours shown represent the peak C^{18}O emission. The contour levels are at 1.15, 1.3, 1.45, and 1.6 K.

Figure 3.10 Same as Figure 3.1 except for source 40.

Figure 3.11 A map of the high velocity ^{12}CO emission for source 40. The solid contour represents the blue wing emission and the dashed contours, the red wing emission. The blue wing emission ranges between -10 and 0 km s^{-1} and the red wing emission between 9 and 20 km s^{-1} . The first contour level is at 3 K km s^{-1} and increases in steps of 1.5 K km s^{-1} . The positions of the IRAS source, the $2.2\mu\text{m}$ peak (Reipurth and Bally 1986), and one of the 6 cm sources (see Chapter 4) identified in the text as Re50 W are identified by crosses and labeled. The other 6 cm source listed in chapter 4 is coincident with the IRAS position at this resolution.

Figure 3.12 Same as Figure 3.11 except a grey scale of the peak C¹⁸O emission has been included. The grey scale is shown between 0.6 and 1.9 K.

Figure 3.13 A map of the high velocity ^{12}CO emission for source 41. The solid contour represents the blue wing emission and the dashed contours, the red wing emission. The velocity range for the red wing emission is 8.6 to 16.4 km s^{-1} and for the blue wing emission, -10 to 2 km s^{-1} . The contour levels are at 4.5, 5, 5.5, 6, and 6.5 K km s^{-1} . The IRAS source along with the H_2O Maser (Wouterloot and Walmsley 1986) and 6 cm (see Chapter 4) positions are identified by crosses and labeled.

Figure 3.14 A map of the high velocity ^{12}CO emission for source 61. The solid contour represents the blue wing emission and the dashed contours, the red wing emission. The velocity range for the red wing emission is 8 to 10.5 km s^{-1} and for the blue wing emission, 0 to 2 km s^{-1} . The contour levels are at 0.75, 0.9, 1.05, and 1.2 K km s^{-1} . The position of the IRAS source has been identified by a cross and labeled.

Figure 3.15 A histogram of the orientation of the nine observed outflows. The radius of the histogram represents the number of outflows along a particular orientation and the angle represents the orientation. Sources not observed to be bipolar have their orientation defined as the direction to the outflow peak relative to the infrared source.

1

CHAPTER 4

THE RADIO CONTINUUM SURVEY

4.1 Introduction

Several studies have sought and detected radio continuum emission associated with a number of young stellar objects (Cohen, Bieging, and Schwartz 1982; Simon *et al.* 1983; Bally and Predmore 1983; Bieging, Cohen, and Schwartz 1984; Snell *et al.* 1985; Pravdo *et al.* 1985; and Snell and Bally 1986). The detection of radio continuum emission from low luminosity young stellar objects in these studies was surprising. In fact, the Lyman continuum flux emitted from a zero age main sequence star with the same luminosity as these objects was, in many cases, insufficient by several orders of magnitude to maintain an H II region of the observed radio flux density in photoionization equilibrium. It was also found that the radio spectrum of these sources was consistent with the radio emission being due to thermal free-free emission. In a few of the sources, the observed spectrum was that expected for an optically thick, ionized stellar wind, while, in most sources, the spectrum was that of an optically thin, ionized gas. Thus, either these young stellar objects are producing more Lyman continuum flux relative to their bolometric luminosity than a zero age main sequence star, or the source of ionization is not photoionization by Lyman continuum photons.

A number of additional mechanisms may be at work in young stellar objects capable of producing ionization. First, the luminosity of many young stellar objects may be primarily produced by accretion (Thompson *et al.* 1977; Thompson 1982; Shu, Adams, and Lizano 1986). Evidence for accretion in T-Tauri stars is provided by

observations of an ultraviolet excess thought to originate in the boundary layer where the disk interacts with the stellar surface. This boundary layer emission could significantly enhance the ultraviolet flux from young, low mass stars and thus provide the ionizing radiation needed to explain the observed free-free emission. Secondly, Bally and Predmore (1983) and Snell and Bally (1986) found that, in many cases, the low luminosity young stellar objects associated with molecular outflows and optical jets were sources of radio continuum emission. They suggested that the observed radio emission may arise in a collisionally ionized wind. Lastly, ionization by Balmer continuum photons in a collisionally excited gas in a stellar wind (Simon *et al.* 1983; Alonso-Costa and Kwan 1989) also could produce the radio continuum emission.

All of the mechanisms discussed above that allow low luminosity stars to produce detectable radio continuum emission require the object to be actively accreting material or have a stellar wind; both processes which may occur simultaneously (Shu, Adams, and Lizano 1986). Thus, the detection of radio continuum emission may be indicative of extreme youth, but further observations are required to test this hypothesis.

The previous observational studies have been biased in their object selection. Few surveys have been done on the entire young stellar population of a molecular cloud. In this chapter we present the results of a 6 and 20 cm survey for radio continuum emission from the embedded population of young stellar objects in the L1641 molecular cloud. L1641 extends from 1 to 5 degrees south of the Orion Nebula and is a site of extensive, but relatively low luminosity star formation. In fact, the most luminous young stellar object is Haro 13a ($L = 406 L_{\odot}$), and thus, we would not expect to detect radio continuum emission from any of these objects if they were main sequence stars. Star

formation activity in this region is evidenced by the presence of infrared sources along the length of the molecular cloud, Herbig Haro objects, and several hundred H α -emission line stars (Strom *et al.* 1989). Using the Infrared Astronomy Satellite (IRAS) survey data to identify young stellar objects we should be able, in an unbiased way, to determine the frequency of occurrence and the type of sources that are associated with radio continuum emission.

4.2 Observations and Source Selection

The observations were obtained with the VLA[†] in 1986 November while in the C configuration using two 50 MHz bands centered at frequencies of 4835 and 4885 MHz (6 cm) and 1465 and 1515 MHz (20 cm). The resolution of the VLA in the C configuration at 6 and 20 cm is approximately 3.9 and 12.5 arc seconds, respectively. Observations alternated between sources and the calibrator (0539-057) over as large an hour angle as possible to obtain good UV coverage. The flux density of the sources was established from observations of 3C 286. Flux densities for 3C 286 were assumed to be 7.41, 7.46, 14.27, and 14.51 Jy at 4885, 4835, 1515, and 1465 MHz, respectively.

The Astronomical Image Processing System (AIPS) software package was used for all data processing and map construction. Maps were made over the entire extent of the primary beam (typically $\sim 10'$) for each field observed. In a few cases, a strong source located off the edge of the field of view made the image difficult to clean; these

[†] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

maps were reconstructed and cleaned over a larger spatial extent to include the off edge sources. All maps at 20 cm contained very large amplitude modulations across the image rendering the map useless. We believe this to be due to the proximity and strength of the Orion Nebula. By removing the shortest baselines, most of the modulations could be removed.

The positions observed were selected from an early tabulation of young stellar objects sources identified from the IRAS co-add survey data (the final listing is presented in Strom *et al.* 1989). The observations were chosen to include most of the moderate to strong far infrared emitting sources and many of those with spectra that rise steeply at longer wavelengths. The 55 fields targeted for this survey are listed in Table 4.1. Column 1 lists the IRAS source at the center of the field; columns 2 and 3, the right ascension and declination of the field center; and column 4, the 6 cm 1σ rms of the background fluctuations at field center. All sources within the primary beam of the VLA at 6 cm with flux density greater than ~ 1 mJy should have been detected.

In addition to the above 6 cm observations, three of the IRAS sources (05329–0628, 05369–0728, and 05380–0728) were targeted for observations at 20 cm. These objects were selected because they are associated with molecular outflows. 05329–0628 is near HH 34, an optical jet source (Reipurth and Bally 1986), 05369–0728 is the source coincident with the position of the molecular outflow associated with Haro 4–255 (Levreault 1985), and 05380–0728 is centered on the position of a young stellar object, Re50, which appears to be changing structure at optical wavelengths on the time scale of years and exhibits a strong molecular outflow (Reipurth and Bally 1986).

4.3 Results

4.3.1 General Results

A total of 59 sources have been detected within the 55 fields observed at 6 cm. The larger extent of the primary beam at 20 cm allowed us to map regions of the cloud not mapped at 6 cm and, as a result, 8 additional sources were identified at 20 cm. All 67 detected sources are listed in Table 4.2 ordered by declination. Column 1 of Table 4.2 lists the source sequence number; column 2 and 3, the right ascension and declination of the peak 6 cm emission of the source; column 4, the peak flux density and associated 1σ rms uncertainty; column 5, the spatially integrated flux density and uncertainty; and column 6, an identification of or comments about the source. If no flux density is listed in Table 4.2, the source has been detected at 20 cm and has no corresponding 6 cm observation (20 cm flux densities are given in Table 4.3). Estimates of the 1σ uncertainties in the peak flux density per beam, σ_0 , were determined from the fluctuations in blank fields near the source. Estimates of the uncertainties on the integrated flux density are given by

$$\sigma = \sigma_0 (N_{\text{on}} / \theta)^{1/2}, \quad (4.1)$$

where N_{on} is the number of pixels over which the source was spatially integrated, θ is the number of pixels per beam, and σ_0 is the peak flux density uncertainty defined above.

When two or more fields spatially overlapped and both contained the same source, the data for these sources were combined (weighted by the noise in each field) to more accurately determine the flux density of the source. Positional coordinates for multiple field sources are given for the field with the smallest beam size.

Due to the large extent of the primary beam at 20 cm, many of the sources detected at 6 cm were also observed at 20 cm. Table 4.3 contains the positions and fluxes of the sources detected at 20 cm. 1σ upper limits on the 20 cm peak flux density for 6 cm sources are listed if they were not detected at 20 cm. Column 1 of Table 4.3 lists the sequence number corresponding to the source in Table 4.2. Columns 2 and 3 gives the right ascension and declination of the peak 20 cm emission of the source. If it was not detected, the 6 cm position where the upper limit was established is listed. Column 4 provides the peak flux density at 20 cm and associated 1σ rms uncertainty; column 5, the integrated flux and uncertainty; and column 6, the spectral index (defined below). Sources not listed in Table 4.3 but appearing in Table 4.2 were outside of the primary beams of the three 20 cm maps.

The spectral index, γ , has been defined by $S_\nu \propto \nu^\gamma$ using the 6 and 20 cm integrated flux densities. In cases where 20 cm emission was not detected, but a limit set, an estimated 1σ lower limit to γ has been determined. As a reference, the models of Panagia and Felli (1975) and Wright and Barlow (1975) found that a fully ionized stellar wind will have $\gamma \approx 0.6$. Furthermore, it is expected that an optically thick H II region will have $\gamma = 2.0$ and an optically thin H II region, $\gamma = -0.1$.

Strom *et al.* (1989) list 95 young stellar objects associated with L1641. Of these 95 sources, 75 were within the field of view of our observations and only 3 were detected (objects 20, 38, and 43). Thus, out of the 67 radio sources, only 3 are definitely associated with young stellar objects in the L1641 molecular cloud. Four other radio continuum sources (#6, 19, 21, and 22) are associated with L1641, and HH 1, HH 2, HH 1-2 Center, and the V571 Ori Shock region and are all objects within L1641 that have

been detected previously in radio continuum emission (Pravdo *et al.* 1985, Yusef-Zadeh 1989). One source, HH 1-2 Center, is almost certainly a young stellar object, but the extended and confused far infrared emission in this region make it difficult to separate the IRAS emission into individual sources and, thus, HH 1-2 Center was not listed in Strom *et al.* (1989). Higher angular resolution far infrared maps of the region made by Harvey *et al.* (1986) show clearly that both HH 1-2 Center and HH 1-2 H₂O Maser are distinct sources of emission. We have assumed this source to be a young stellar object in the discussion that follows. In addition, several other radio sources are close to nebulous objects identified by Reipurth (1985) and will be discussed later.

We have attempted to identify optical and far infrared counterparts to the remaining unidentified radio continuum sources. First, optical counterparts were sought for each of the radio sources using R band images obtained by Strom *et al.* (1989). Of the 67 sources, 10 had a possible optical associations, these were objects #6, 15, 19, 20, 21, 22, 25, 30, 38, and 47. Object 15 is a weak 6 cm source with a possible optical source located 9" east of it. Object 25 is a very strong 20 cm source associated with a faint and diffuse optical source. Object 47 was detected only at 20 cm and has an optical counterpart located 8" north of the peak radio continuum emission. No other information is known about these three objects and associations with the radio source are not very convincing; we do not believe that these are young stars in the L1641 region. The remaining optical identifications were of previously known sources (see Table 4.2).

A search for far infrared associations to these radio sources was made using the IRAS ADDSCAN data. To compensate for the poor resolution in the cross scan direction, the positions of the radio sources were also overlaid on the co-add images. In

this way, features in the one dimensional scans could be compared with the two dimensional images clarifying source assignment. No new infrared sources could be associated with the radio continuum sources. The lack of any new infrared sources from the ADDSCAN data is indicative of both the completeness of the Strom *et al.* survey and the confusion problems of the L1641 region.

We conclude that most of the radio sources are not associated with the L1641 molecular cloud. We have used the radio source counts at 6 cm obtained by Bennett *et al.* (1983) to estimate that the number of background radio sources with a flux density > 1 mJy is approximately 0.015 sources per square arc minute. Thus, we would expect approximately 56 background radio continuum sources in the 6 cm fields mapped, consistent with the large number of unidentified sources in our survey. Other than the 4 confirmed young stellar objects, there are a number of other radio sources that, due to their proximity to nebular objects, young stellar objects, or because they have a thermal spectra, are interesting. We discuss these sources and the 4 confirmed young stellar objects in more detail below.

4.3.2 Individual Objects

Objects 3 and 4

These two sources (Figure 4.1) are located at the position of an anonymous object found midway between Reipurth's objects 35 and 43 (see Reipurth 1985, Figure 16). Objects 3 and 4 may, in fact, be just one extended source consisting of as many as three peaks. The integrated flux density at 6 cm is 4.1 mJy. This leads to a spectral index of $\gamma > -0.1$, consistent with a free-free emitting source.

Object 6 : V571 Ori Shock

The region near V571 Ori is easily identified optically by the streamers of emission directed away from the star V571 Ori. Object 6 is shown in Figure 4.2 and is 8'' W of the central shock core (labeled in Figure 4.2 as CS) of V571 Ori (Reipurth and Sandell 1985). Strom *et al.* (1986) have also studied this region and their identification of the location of the apparent crossing of the two most prominent arcs of emission are shown in Figure 4.2 (labeled as "S22"). Note that S22 is coincident with the concave structure of the radio continuum emission. Reipurth and Sandell suggest that the shock complex is a Herbig Haro type shock caused by the stellar wind of the T-Tauri star (V571 Ori; spectral type M0) interacting with the edge of the molecular cloud. The shock region also has prominent Balmer, [NII], [SII], and [OI] lines.

The spectral index of $\gamma = -0.5$ suggests a non-thermal origin for the radio continuum emission. Recently, Yusef-Zadeh, Cornwell, and Reipurth (1989) have detected linearly polarized emission from this source at 6 cm using the VLA. They also classify this source as non-thermal and suggest that a low mass star located at the core of this region, and not V571 Ori, is probably responsible for the HH nebulosity and radio continuum emission.

Object 8

This source is 28'' south-west of an IRAS source (05339-0626; $L_{\text{bol}} = 79 L_{\odot}$) identified in Chapter 1 as having a broad ^{12}CO line width with strong C^{18}O and CS emission. The infrared source and peak C^{18}O and CS emission locations are coincident with each other and are near to the L1641-N (Fukui *et al.* 1986; Fukui *et al.* 1988)

outflow region. These two regions are distinct from each other on the IRAS co-add images at shorter wavelengths but become blended towards longer wavelengths.

The lower limit on the spectral index of object 8 is consistent with that of an optically thick H II region. But the displacement of object 8 from the infrared and molecular peaks is too large to consider the radio continuum emission to be necessarily associated with the young stellar object 05339-0626.

Objects 19 – 22 : The HH 1–2 Region

A more complete study at 6 and 20 cm of this region has been done by Pravdo *et al.* (1985) so we shall only report that our lower limits on the spectral indices are in agreement with Pravdo *et al.* who find $\gamma = -0.11, >0.01, 0.58$, and -0.20 for HH 1, H₂O Maser, HH 1-2 Center (VLA 1), and HH 2 respectively. HH 1-2 Center has also been identified by Pravdo *et al.* as the exciting star for the HH 1-2 nebulae and higher resolution VLA data obtained by Rodríguez (1988) shows a clear elongation along the axis connecting HH 1 and HH 2.

The H₂O maser source is associated with the IRAS source 05338-0647 and has a bolometric luminosity of $103 L_{\odot}$. The long wavelength IRAS emission for this source is confused with that from the HH 1-2 Center source. Harvey *et al.* (1986) estimated that the total far infrared luminosity in their mapped region was $120 L_{\odot}$, of which they estimated that HH 1-2 Center contributed $50 L_{\odot}$. The far infrared emission in this region is extended beyond the region mapped by Harvey *et al.*. Aperture photometry on the co-added IRAS survey data indicates that the far infrared luminosity is at least $180 L_{\odot}$. We estimate the luminosity for HH 1-2 H₂O Maser at $100 L_{\odot}$ and HH 1-2 Center at $80 L_{\odot}$, both probably lower limits to their true bolometric luminosity.

Objects 28 and 29

These two sources are separated by only $25''$. Neither object is spatially extended but object 28 appears to be just resolved at 6 cm. Object 28 has a $\gamma = -0.1$ indicating an optically thin H II region and object 29 has a $\gamma = 0.5$ suggesting a stellar wind. No optical or infrared source has been detected in the immediate area of these two objects.

Object 30 : Re48

Figure 4.3 is the 20 cm map of object 30. This source was observed only at 20 cm and lies $7''$ south of Re48. Reipurth (1985) associates Re48 with a small reflection nebula and object 30 is slightly elongated north-south.

Object 32

This source has a spectral index that is flat ($\gamma = 0.0$). This would suggest an optically thin H II region but object 32 has no associated optical or infrared source.

Objects 34, 37, and 39

At 6 cm, these three objects (Figure 4.4) are distinct from each other but at 20 cm the two northern objects blend into one source. The spectral index for the upper and lower objects suggests a non-thermal origin; no spectral index could be determined for the central source because of the blending at 20 cm. The integrated flux density of all 3 objects yields $\gamma = -0.3$. There is no corresponding infrared source and the source displays a typical radio galaxy behavior of having the lobes stronger than the central source at longer wavelengths and less than or comparable to the center position at shorter wavelengths. Hence, these three objects may be a double lobe radio galaxy.

Objects 38 and 36 : Re50

Object 36 has no known optical or infrared association and is located 50'' west of Object 38. Object 38 is associated with Re50 (Reipurth 1985, Reipurth and Bally 1986) and the associated optical and infrared positions are shown in Figure 4.5. Both objects are unresolved at 6 cm. As discussed before, Re50 ($L_{\text{bol}} = 295 L_{\odot}$) is an object whose optical appearance has changed rapidly at optical wavelengths. It is also the location of a very extended molecular outflow (Reipurth and Bally 1986). Both objects 38 and 36 are faint at 6 cm (see Figure 4.5) and the upper limits at 20 cm result in a lower limit spectral index of $\gamma > 0.5$ and $\gamma > 0.6$ for objects 38 and 36 respectively. The lower limit on γ suggests that the emission from these two objects is similar to a stellar wind or an optically thick H II region.

Object 43 : FIRSSE 101

The peak emission of this source is located 7'' SE of the IRAS source (05375-0731; $L_{\text{bol}} = 123 L_{\odot}$) associated with FIRSSE 101. A 6 cm map of this region is shown in Figure 4.6. FIRSSE 101 was first identified by Price *et al.* (1983) at 10' resolution. Both the IRAS survey and the work of Price *et al.* have resolutions that make a 7'' offset meaningless. Recently, Strom, Margulis, and Strom (1989) have identified a near infrared counterpart to FIRSSE 101 and it is coincident with the peak position at 6 cm (labeled SMS 59 in Figure 4.6). The spectral index lower limit ($\gamma > 0.7$) indicates that object 43 is an optically thick H II region. This region has also been identified both in Chapter 1 and by Fukui (1989, private communication) as being associated with a molecular outflow. Also associated with this source is an H₂O maser (Wouterloot and Walmsley 1986) and an NH₃ core (Wouterloot, Walmsley, and Henkel 1988). The H₂O maser identified by Wouterloot and Walmsley (1986) has a positional uncertainty of

about 5 arc seconds and is located about 10 arc seconds north of the radio continuum peak and 11 arc seconds north of the $2.2\mu\text{m}$ source of Strom, Margulis, and Strom (1989).

4.4 Discussion

We have identified 4 young stellar objects (#20, 21, 38, 43) out of the 67 detected radio continuum sources. The four sources have relatively weak 6 cm emission (see Table 4.2) and are not detected at 20 cm (Table 4.3). While this gave rise to a lower limit on the spectral index for each of the four sources, each appear consistent with an optically thick free-free source.

These 4 young stellar objects have a number of properties in common: first, they are the most luminous of the young stellar objects in L1641; second, they have spectra that steeply rise from 2.2 to $25\mu\text{m}$ (Harvey *et al.* 1986; Strom *et al.* 1989); and last, they are all associated with stellar wind activity. The frequency distribution of the bolometric luminosities of the young stellar objects in Strom *et al.* (1989) is presented in Figure 4.7. The dotted histogram in Figure 4.7 is the distribution of all the young stellar objects; the solid histogram, the young stellar objects within our field of view; and the hatched histogram, the young stellar objects detected in radio continuum. Figure 4.7 illustrates that only the most luminous young stellar objects in the sample are being detected even though a broad range of luminosities were observed.

In Figure 4.8 we have plotted the radio continuum luminosity at 6 cm versus the bolometric luminosity for the four young stellar objects from this survey (Re50, FIRSSE 101, HH 1-2 Center, and HH 1-2 H_2O Maser), along with the young stellar objects in the surveys of Snell and Bally (1986) and Evans *et al.* (1987). The radio continuum

luminosity is defined as $4\pi d^2 S_\nu$, where S_ν is the 6 cm flux density. Although there is significant scatter, a roughly linear relation is found between the radio continuum luminosity and the bolometric luminosity for these young stellar objects. We have also computed the radio continuum luminosity for zero age main sequence stars assuming the H II regions surrounding these stars are optically thin, at a temperature of 10,000 K, and in photoionization equilibrium using the rate of Lyman continuum photon production from Thompson (1984). The position of the zero age main sequence is indicated in Figure 4.8. It is clear that the young stellar objects in L1641 have a radio continuum luminosity several orders of magnitude larger than would be expected for a zero age main sequence star of the same bolometric luminosity. The linear relation between radio continuum luminosity and bolometric luminosity is significantly different than the slope predicted for zero age main sequence stars and suggests that whatever the energy source is for the radio emission in these young stars is a constant fraction of the bolometric luminosity.

If we assume that the young stellar objects in L1641 follow the same relationship between radio continuum luminosity and bolometric luminosity as found for the sources shown in Figure 4.8, then our detection limit of approximately 0.67 mJy corresponds to a bolometric luminosity of roughly $80 L_\odot$. A dashed line is shown in Figure 4.8 at our 5σ detection threshold for the L1641 survey. Only seven sources in L1641 have $L_{\text{bol}} > 80 L_\odot$: the four detected young stellar objects (Re50, FIRSSE 101, HH 1-2 Center, and HH 1-2 H₂O Maser), and V380 Ori (05339–0644; $L_{\text{bol}} = 150 L_\odot$), L1641–N (05338–0624; $L_{\text{bol}} = 224 L_\odot$), and Haro 13a (05358–0704; $L_{\text{bol}} = 406 L_\odot$). The spectral energy distributions between 2.2 and 25 μm (Strom *et al.* 1989) for Re50, FIRSSE 101, HH 1-2 Center, HH 1-2 H₂O Maser, and L1641–N all rise towards the longer wavelengths. In

contrast, V380 Ori and Haro 13a both remain relatively flat between 2.2 and 25 μ m. Furthermore, while V380 Ori, L1641–N, and Haro 13a have been optically identified by Strom *et al.* (1989), none of the four detected young stellar objects have a known optical counterparts. This suggests that young stellar objects with radio continuum emission are more obscured than those objects without radio emission. Thus, we believe that radio emission is associated with young stellar objects at their earliest stages of stellar evolution and the radio continuum luminosity is correlated with the bolometric luminosity.

The lack of radio continuum emission from L1641–N (05338–0624) is surprising since it is a luminous young stellar object with a molecular outflow and with a spectral index similar to Re50 and FIRSSE 101. Strom, Margulis, and Strom (1989) have found the region surrounding the molecular outflow of L1641–N to be filled with over 20 2.2 μ m sources. It is possible that the infrared flux densities at IRAS wavelengths are the result of a blending from several of the 2.2 μ m objects (for a discussion of this effect, see Strom *et al.* 1989). Wood, Fukui, and Churchwell (unpublished data) report a 6 cm detection of L1641–N with the VLA (B configuration) and find it very spatially extended. They report a peak 6 cm flux density of 1 mJy and a spatially integrated flux density of 12 mJy. We did not detect L1641–N at 6 cm to a 1σ limit of 0.18 mJy and, since our observations were made in C configuration, should be more sensitive to large scale structure. This may suggest the source responsible for the 6 cm emission of L1641–N is highly variable.

4.5 Summary

A total of 67 objects were detected at 6 and 20 cm within the L1641 region of Orion. Four of the sources are identified with young stellar objects in L1641; these are Re50, FIRSSE 101, HH 1-2 H₂O Maser, and HH 1-2 Center. Three additional sources are associated with HH or HH like objects and four more sources have thermal radio spectra but no optical or infrared counterparts. The remaining sources are probably background extragalactic sources.

The detected radio continuum sources that are associated with young stellar objects are the more luminous objects in L1641 and a roughly linear relationship has been found between the 6 cm radio luminosity and the bolometric luminosity. The radio spectrum of the four detected sources are consistent with either a stellar wind or an optically thick H II region. Furthermore, these four sources are characterized by a rising spectrum between 2.2 and 25 μ m and have no known optical counterparts. Finally, each of the radio continuum sources associated with a young stellar object is associated with stellar wind activity. This suggests that radio continuum emission from young, low luminosity stellar objects may be associated with the earliest phases of their evolution.

TABLE 4.1

Observational Coordinates

IRAS Name (1)	$\alpha(1950)$ (h m s) (2)	$\delta(1950)$ (° ' ") (3)	1σ rms (mJy/beam) (4)
05340-0603	5 34 01.5	-6 03 06.0	0.13
05342-0613	5 34 12.7	-6 13 37.0	0.14
05344-0623	5 34 28.5	-6 23 14.5	0.14
05369-0623	5 36 52.5	-6 23 35.0	0.18
05338-0624	5 33 52.5	-6 23 53.0	0.18
05329-0628	5 33 00.5	-6 28 40.0	0.13
05345-0635	5 34 33.9	-6 35 13.0	0.12
05342-0635	5 34 15.2	-6 35 46.0	0.13
05348-0636	5 34 47.1	-6 36 44.0	0.14
05342-0639	5 34 14.6	-6 39 50.0	0.12
05353-0644	5 35 21.1	-6 44 13.0	0.13
05339-0644	5 33 59.2	-6 44 45.0	0.13
05335-0645	5 33 31.1	-6 45 31.0	0.13
05339-0646	5 33 59.0	-6 46 30.0	0.13
05338-0647	5 33 52.7	-6 47 21.0	0.14
05357-0650	5 35 43.5	-6 50 57.0	0.12
05355-0658	5 35 28.8	-6 58 27.0	0.14
05362-0659	5 36 14.8	-6 59 57.0	0.13
05350-0700	5 34 58.8	-7 00 16.0	0.14
05363-0702	5 36 23.3	-7 02 21.0	0.13
05358-0704	5 35 53.5	-7 04 07.0	0.13
05357-0710	5 35 42.0	-7 10 12.0	0.12
05367-0712	5 36 42.8	-7 12 18.0	0.13
05363-0714	5 36 17.4	-7 14 21.0	0.19
05365-0718	5 36 33.3	-7 18 22.0	0.11
05364-0722	5 36 27.2	-7 22 46.0	0.14
05369-0728	5 36 57.3	-7 28 19.0	0.09
05380-0728	5 38 03.2	-7 29 01.0	0.09
05375-0731	5 37 31.1	-7 31 59.0	0.14
05365-0735	5 36 33.2	-7 35 01.0	0.13

(continued on next page)

TABLE 4.1

(Continued)

IRAS Name (1)	α (1950) (h m s) (2)	δ (1950) (° ' ") (3)	1σ rms (mJy/beam) (4)
05378-0750	5 37 52.1	-7 50 04.0	
05362-0751	5 36 10.6	-7 51 58.0	0.13
05389-0756	5 38 59.3	-7 56 40.0	0.12
05379-0758	5 37 56.0	-7 58 11.0	0.13
05400-0800	5 40 02.0	-8 00 14.0	0.14
05394-0801	5 39 25.3	-8 01 56.0	0.12
05391-0805	5 39 06.2	-8 05 04.0	0.12
05382-0805	5 38 13.0	-8 05 32.0	0.14
05384-0808	5 38 24.6	-8 08 20.0	0.14
05457-0814	5 45 47.1	-8 14 26.0	0.12
05379-0815	5 37 55.2	-8 15 48.0	0.14
05403-0818	5 40 23.3	-8 18 26.0	0.15
05442-0833	5 44 14.1	-8 33 08.0	0.12
05391-0836	5 39 11.2	-8 36 51.0	0.14
05393-0838	5 39 18.7	-8 38 32.0	0.13
05404-0839	5 40 25.0	-8 39 50.0	0.14
05442-0840	5 44 13.1	-8 40 48.0	0.13
05391-0841	5 39 06.6	-8 41 42.0	0.15
05388-0858	5 38 47.7	-8 58 29.0	0.13
05385-0907	5 38 30.7	-9 07 32.0	0.13
05381-0921	5 38 08.1	-9 21 45.0	0.14
05391-0921	5 39 07.8	-9 21 47.0	0.13
05387-0924	5 38 41.2	-9 24 46.0	0.13
05453-0941	5 45 23.0	-9 41 10.0	0.13
05378-0943	5 37 49.2	-9 43 42.0	0.14

TABLE 4.2
Summary of 6 cm Radio Sources

Source Number (1)	$\alpha(1950)$ (h m s) (2)	$\delta(1950)$ (° ' ") (3)	$S_{\max}$ (mJy) (4)	S (mJy) (5)	Comments (6)
1	5 34 11.6	-6 04 19.2	1.06 ± 0.18	1.91 ± 0.28	
2	5 33 59.7	-6 19 57.8	3.79 ± 0.40	7.43 ± 0.95	20" NE of Re39
3	5 34 01.8	-6 22 59.0	0.80 ± 0.21	0.96 ± 0.30	
4	5 34 00.9	-6 23 00.2	1.42 ± 0.21	1.33 ± 0.33	
5	5 37 12.3	-6 23 50.6	12.76 ± 0.46	16.62 ± 1.01	(1)
6	5 33 15.6	-6 24 54.4	4.07 ± 0.38	8.86 ± 0.90	V571 Ori Shock
7	5 34 47.3	-6 26 12.1	3.48 ± 0.45	3.42 ± 0.67	
8	5 33 56.3	-6 27 01.4	3.94 ± 0.29	4.54 ± 0.60	
9	5 34 42.1	-6 27 04.9	2.30 ± 0.45	3.42 ± 0.81	(2)
10	5 32 45.0	-6 29 38.8	4.32 ± 0.24	4.79 ± 0.48	
11	5 34 44.9	-6 32 46.4	1.00 ± 0.14	1.01 ± 0.24	
12	5 34 60.0	-6 33 28.4	1.70 ± 0.26	2.48 ± 0.51	
13	5 34 44.4	-6 34 17.8	0.81 ± 0.16	0.53 ± 0.26	
14	5 34 45.2	-6 34 38.2	0.63 ± 0.16	0.60 ± 0.23	
15	5 34 20.5	-6 35 08.2	0.88 ± 0.11	0.93 ± 0.21	
16	5 34 16.9	-6 42 12.0	1.70 ± 0.13	2.13 ± 0.24	(3)
17	5 32 35.6	-6 42 33.0	...	...	(4)
18	5 33 50.3	-6 43 22.2	0.75 ± 0.16	1.27 ± 0.36	
19	5 33 54.6	-6 46 57.0	0.42 ± 0.10	0.35 ± 0.16	HH 1
20	5 33 52.9	-6 47 15.0	0.82 ± 0.14	0.74 ± 0.23	HH 1-2 Maser
21	5 33 57.0	-6 47 55.8	1.08 ± 0.10	1.19 ± 0.16	HH 1-2 Center
22	5 33 59.5	-6 48 59.4	1.11 ± 0.10	1.85 ± 0.19	HH 2
23	5 35 24.3	-6 57 21.0	2.45 ± 0.15	4.64 ± 0.32	
24	5 36 09.9	-7 00 52.6	6.33 ± 0.11	7.19 ± 0.24	
25	5 38 23.4	-7 06 58.0	...	...	
26	5 36 31.7	-7 08 40.8	17.85 ± 0.29	23.77 ± 0.74	
27	5 36 20.0	-7 12 06.6	2.46 ± 0.22	5.46 ± 0.44	
28	5 36 43.0	-7 14 41.2	2.41 ± 0.16	2.71 ± 0.27	
29	5 36 41.3	-7 14 42.4	3.92 ± 0.16	4.20 ± 0.29	
30	5 37 54.3	-7 15 36.0	...	...	Re48

(continued on next page)

TABLE 4.2

(Continued)

Source Number (1)	$\alpha(1950)$ (h m s) (2)	$\delta(1950)$ (° ' ") (3)	$S_{\max}$ (mJy) (4)	S (mJy) (5)	Comments (6)
31	5 36 38.0	-7 17 05.2	1.34 ± 0.13	1.32 ± 0.22	
32	5 36 11.4	-7 23 42.4	1.46 ± 0.21	1.64 ± 0.32	
33	5 38 04.5	-7 23 50.6	1.84 ± 0.24	1.74 ± 0.41	
34	5 37 40.5	-7 28 35.0	7.98 ± 0.16	15.87 ± 0.45	
35	5 36 07.9	-7 28 46.8	...	...	(5)
36	5 37 59.1	-7 28 51.4	0.86 ± 0.09	0.90 ± 0.15	
37	5 37 40.2	-7 28 51.8	15.64 ± 0.16	18.74 ± 0.42	(6)
38	5 38 02.4	-7 28 59.4	0.84 ± 0.09	0.82 ± 0.16	(5)
39	5 37 39.4	-7 29 24.2	2.99 ± 0.16	6.93 ± 0.38	Re50
40	5 38 39.9	-7 29 42.9	...	...	(5)
41	5 37 46.8	-7 30 53.0	1.83 ± 0.14	2.12 ± 0.26	
42	5 36 14.0	-7 31 34.9	...	...	
43	5 37 31.1	-7 32 01.4	1.09 ± 0.14	1.23 ± 0.23	
44	5 38 41.8	-7 34 15.9	...	...	FIRSSE 101
45	5 36 28.3	-7 37 25.0	1.02 ± 0.18	1.54 ± 0.28	
46	5 36 21.1	-7 37 56.2	3.90 ± 0.18	5.82 ± 0.50	
47	5 38 00.8	-7 39 17.0	...	...	
48	5 37 32.6	-7 46 54.4	2.92 ± 0.40	4.03 ± 0.71	
49	5 38 57.9	-7 54 53.2	0.88 ± 0.13	0.73 ± 0.15	
50	5 37 34.7	-7 56 47.0	22.58 ± 0.40	32.05 ± 1.10	
51	5 37 34.9	-7 57 57.0	4.20 ± 0.40	3.94 ± 0.69	
52	5 39 09.9	-8 00 40.4	2.33 ± 0.17	2.50 ± 0.25	
53	5 38 57.2	-8 04 04.0	2.84 ± 0.18	5.89 ± 0.40	
54	5 39 28.8	-8 06 18.8	5.30 ± 0.28	5.69 ± 0.43	
55	5 38 06.4	-8 10 20.0	3.10 ± 0.21	3.28 ± 0.26	
56	5 38 07.6	-8 10 22.4	8.01 ± 0.21	10.98 ± 0.42	
57	5 45 47.0	-8 14 59.6	0.60 ± 0.14	0.76 ± 0.21	
58	5 45 36.3	-8 18 24.8	1.40 ± 0.26	1.42 ± 0.37	
59	5 44 15.0	-8 35 06.8	3.87 ± 0.15	4.29 ± 0.33	
60	5 40 18.5	-8 40 48.8	1.14 ± 0.15	1.01 ± 0.21	

(continued on next page)

TABLE 4.2

(Continued)

Source Number (1)	$\alpha(1950)$ (h m s) (2)	$\delta(1950)$ (° ' ") (3)	$S_{\max}$ (mJy) (4)	S (mJy) (5)	Comments (6)
61	5 38 34.1	-8 57 49.4	2.98 ± 0.26	7.58 ± 0.57	
62	5 38 40.9	-9 04 56.0	1.29 ± 0.22	1.39 ± 0.34	
63	5 38 19.6	-9 09 14.0	0.97 ± 0.19	2.44 ± 0.37	
64	5 39 36.3	-9 23 52.9	45.20 ± 1.47	60.71 ± 3.56	
65	5 39 24.7	-9 26 35.0	5.38 ± 0.64	5.49 ± 1.35	
66	5 38 44.0	-9 29 25.6	2.04 ± 0.29	1.77 ± 0.42	
67	5 37 28.6	-9 45 42.4	7.39 ± 0.38	7.71 ± 0.69	

- (1) – Visible in image by Reipurth (1985) between Re35 and Re43.
(2) – Adjacent to source 8 of Chapter 2.
(3) – Could be NE object mentioned by Pravdo *et al.* (1985).
(4) – Coincident with source 25 of Strom *et al.* (1989) but they conclude that source 25 is not a real far infrared source.
(5) – Triple source.
(6) – A second source located 50" W of Re50.

TABLE 4.3

Summary of 20 cm Radio Sources

Source Number (1)	$\alpha(1950)$ (h m s) (2)	$\delta(1950)$ (° ' ") (3)	$S_{\max}$ (mJy) (4)	S (mJy) (5)	γ (6)
2	5 33 59.2	-6 20 01.8	5.59 ± 2.01	22.26 ± 6.41	-0.9
3	5 34 01.8	-6 22 59.0	...	< 4.39	> -1.3
4	5 34 00.9	-6 23 00.2	...	< 4.39	> -1.0
6	5 33 15.5	-6 24 56.0	13.58 ± 0.60	15.34 ± 1.54	-0.5
8	5 33 56.3	-6 27 01.4	...	< 2.13	> 0.6
10	5 32 45.0	-6 29 36.0	10.85 ± 0.60	9.93 ± 1.43	-0.6
17	5 32 35.6	-6 42 33.0	3.57 ± 1.02	17.05 ± 2.64	...
18	5 33 50.3	-6 43 22.2	...	< 3.42	> -0.8
25	5 38 23.4	-7 06 58.0	39.33 ± 1.13	88.92 ± 4.95	...
26	5 36 31.9	-7 08 50.0	33.13 ± 0.71	63.32 ± 2.56	-0.8
27	5 36 19.7	-7 12 05.9	5.20 ± 0.71	9.96 ± 2.04	-0.5
28	5 36 43.2	-7 14 47.0	1.52 ± 0.34	2.89 ± 0.71	-0.1
29	5 36 41.3	-7 14 47.0	2.20 ± 0.34	2.19 ± 0.71	0.5
30	5 37 54.3	-7 15 36.0	5.35 ± 0.48	10.47 ± 1.26	...
31	5 36 38.0	-7 17 07.0	1.57 ± 0.71	3.59 ± 1.45	-0.8
32	5 36 12.1	-7 23 38.9	1.34 ± 0.35	1.62 ± 0.81	0.0
33	5 38 04.6	-7 23 53.0	7.22 ± 0.32	6.05 ± 0.79	-1.0
34	5 37 40.6	-7 28 40.0	37.51 ± 0.32	64.53 ± 1.10	-1.2
35	5 36 07.9	-7 28 46.8	2.83 ± 0.37	4.67 ± 0.99	...
36	5 37 59.1	-7 28 51.4	...	< 0.43	> 0.6
38	5 38 02.4	-7 28 59.4	...	< 0.43	> 0.5
39	5 37 39.7	-7 29 22.0	12.86 ± 0.32	19.35 ± 0.92	-0.9
40	5 38 39.9	-7 29 42.9	2.65 ± 0.45	5.17 ± 1.46	...
41	5 37 46.7	-7 30 53.0	3.52 ± 0.32	3.93 ± 0.60	-0.5
42	5 36 14.0	-7 31 34.9	3.07 ± 0.37	5.13 ± 0.99	...
43	5 37 31.1	-7 32 01.4	...	< 0.56	> 0.7
44	5 38 41.8	-7 34 15.9	6.01 ± 0.37	7.47 ± 1.13	...
45	5 36 28.6	-7 37 24.9	2.76 ± 0.31	3.90 ± 0.70	-0.8
46	5 36 21.0	-7 37 52.9	8.40 ± 0.52	14.98 ± 1.39	-0.8
47	5 38 00.8	-7 39 17.0	3.46 ± 0.37	3.80 ± 0.84	...
48	5 37 32.6	-7 46 51.9	3.13 ± 0.63	12.45 ± 2.36	-0.9

Figure 4.1 Plot of the 6 cm emission from objects 3 and 4. The hatched ellipse in the upper right corner represents the size of the synthesized beam. Axes are the right ascension and declination coordinates for epoch 1950. Contour levels are -0.4, -0.2, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 mJy. Negative contour levels are represented by dashed lines and positive levels by solid lines.

Figure 4.2 Same as Figure 4.1 except for object 6. Contour levels are -1.0, -0.8, 0.8, 1, 1.2, 1.4, 1.6, 2, 2.4, 2.8, 3.2, 3.6, and 4 mJy. Reipurth and Sandell (1985) identify the peak of the Central Shock region (CS) and V571 Orionis and these positions are indicated by plus signs. S22 refers to the identification by Strom *et al.* (1986) of the location of the crossing of two strongest arcs of emission.

Figure 4.3 Same as Figure 4.1 except a plot of the 20 cm emission for object 30. Contour levels are -1, -0.5, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 mJy. The position of Re48 (Reipurth 1985) is marked by a cross.

Figure 4.4 Same as Figure 4.1 except for objects 34, 37, and 39. Contour levels are -0.4, 0.4, 0.8, 1.2, 1.6, 2, 2.4, 2.8, 3.2, 3.6, 4, 5, 6, 7, 8, 9, 10, 12, and 14 mJy.

Figure 4.5 Same as Figure 4.1 except for objects 36 and 38. Contour levels are -0.3, -0.2, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 mJy. Plus signs indicate the positions of the IRAS and 2.2 μ m sources (Reipurth and Bally 1986).

Figure 4.6 Same as Figure 4.1 except for object 43. Contour levels are -0.3, -0.2, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 mJy. The position of the H₂O maser (Wouterloot and Walmsley 1986) is identified by a plus symbol. The 2.2 μ m source identified by Strom, Margulis, and Strom (1989) is also marked by a plus sign and is listed as SMS 59.

Figure 4.7 Plot of the frequency distribution of bolometric luminosities. The dashed histogram is the distribution of all the young stellar objects from the data of Strom *et al.* (1989). The solid histogram is the distribution of the young stellar objects observed in this work and the hatched histogram identify the three objects detected in radio continuum emission.

Figure 4.8 Plot of the 6 cm luminosity versus the bolometric luminosity, where the 6 cm luminosity density is defined as $4\pi d^2 S_\nu$. Filled points represent the four detected sources in our sample and open points represent the 6 cm data from Snell and Bally (1986) and Evans *et al.* (1987). Error bars (1σ) on the 6 cm luminosity are shown for each point unless they are smaller than the symbol size. The dashed horizontal line represents our 5σ detection threshold (~ 0.67 mJy) at the distance of Orion. The solid line represents a least squares fit to the data. Also shown is the 6 cm luminosity and bolometric luminosity for zero age main sequence stars.

CHAPTER 5

THE LARGE SCALE MAP OF ORION

5.1 Introduction

It is well known that stars form in giant molecular clouds (GMCs). What is not clearly understood is the relationship between star formation and the structure and evolution of the GMC. The role that current star formation plays on the evolution of subsequent generations of stars is complex. Elmegreen and Lada (1977) have suggested that present day star formation is the result of past episodes of star formation and that future episodes may be triggered, in part, by the current formation activity. At the same time, observations of GMC structure show that star formation may actually lead to disruption of the cloud and inhibit future star formation.

To understand the role that star formation plays on the evolution of the GMC requires both a knowledge of the structure and kinematics of the GMC and a census of the current and past star formation activity. This paper presents the results of a study of the Orion molecular cloud. Orion was selected because it is the nearest GMC (480 pc) and is known to be a very active site of both high and low mass star formation. Within Orion, massive star formation is concentrated primarily towards the Orion Nebula while low mass stars form throughout the cloud including several degrees to the south in L1641. Because it has been studied in far greater detail than can be addressed in this work, the Orion Nebula region will not be discussed, but, instead, will focus on the low mass star formation occurring in L1641.

In the last few years, L1641 has been studied extensively. Young stellar objects have been identified through the combination of near- and far-infrared observations (Strom *et al.* 1989); several optical HH emission-like objects have been found (Reipurth *et al.* 1986; Reipurth 1988; Strom *et al.* 1986); and surveys have identified several molecular outflows (Fukui *et al.* 1986; cf. this work, Chapter 2). These studies will provide the foundation for the information regarding the star forming regions within L1641.

The global structure of the Orion GMC has been studied as well. The first complete, low resolution, ^{12}CO map of the Orion region was done by Kutner *et al.* (1977) and later by Maddalena *et al.* (1986). Recently, Bally *et al.* (1987) made a map of the ^{13}CO emission and found the L1641 region appeared filamentary. Optical polarization measurements have also been made to identify the direction of the magnetic field across the face of the cloud (Vrba, Strom, and Strom 1988).

Knowing what sources are associated with the present day star formation, we can ask where have these stars formed in the cloud and what are the particular characteristics that are indicative of star forming regions? Furthermore, it will be important to ask if the currently forming stars are primordial or if they are the result of or have already been influenced by past star formation? In order to address these questions, it is important to know what indicates the influence of star formation on the cloud structure. The influence of star formation on the structure of a GMC will likely be seen as 1) holes in the cloud; 2) bright rims of emission; or 3) velocity features. The presence of the holes may suggest that stars are evacuating regions of the cloud. An excellent example of this shaping of the cloud by the presence of an H II region is seen towards S255 (Heyer *et al.* 1989). The

bright rims may be the result of heating of the cloud edge. The velocity features may show as multicomponent lines suggesting possible shock regions (Schloerb and Loren 1982) or high velocity wings suggesting the presence of molecular outflows (Fukui *et al.* 1986; cf. this work, Chapter 2).

In this work we present a high angular resolution, large scale, ^{12}CO map of the Orion molecular cloud. The high angular resolution is needed to resolve the details around the star forming regions. We have selected ^{12}CO for a number of reasons: 1) The line traces the gas temperature so that local heating around stars and near shocks can be identified; 2) It is the most abundant molecular line so it can easily be detected allowing a large region to be mapped quickly; 3) it can be combined with optically thin lines like ^{13}CO to derive the column densities through the cloud; and 4) it is used to identify the presence of broad line wing emission indicative of molecular outflows allowing an unbiased survey for these sources.

The ^{12}CO observations described here will provide us with information regarding the temperature of the gas across the cloud, the velocity of the emission, and the line width at the position observed. Temperature enhancements and multicomponent lines will be investigated for the presence of possible shocks or regions evacuated by stellar winds. The line widths of the cloud will permit identifications of regions of possible molecular outflow activity. These regions will be defined as broad line widths at low intensities observed over a limited area. The identified molecular outflows will be compared with those identified previously in the literature to determine if any new molecular outflows have been found.

5.2 Observations

The observations were obtained with the 14 meter telescope of the Five College Radio Astronomy Observatory[†] between 1984 June and 1988 May. A quasi-optical sideband filter and a cryogenic Schottky diode mixer receiver were used along with a 250 channel spectrometer with 100 kHz and 256 kHz resolution per channel to record spectra. Observations were calibrated by the chopper wheel technique which allowed for switching between the sky and an ambient load. Data were obtained by position switching between the observations on the cloud and a reference position 90 arcminutes west. This reference offset was selected because of the lack of ^{12}CO emission in the low resolution maps of Maddalena *et al.* (1986). Integration times were adjusted to achieve a channel rms noise level in the 256 kHz filters of $\sim 1\text{K}$. Each spectrum had a first order, linear baseline removed and was then sampled at every 0.5 km s^{-1} .

The half power beam width of the 14 meter telescope (45 arcseconds at 2.6 mm) and the efficiency on a spatially extended source ($\eta_{\text{FSS}} = 0.7$) were determined from observations of the Moon and Jupiter. Temperatures quoted in this paper (T_{R}^*) have all been corrected by η_{FSS} which includes ambient temperature losses, effects of the Earth's atmosphere, and for forward spillover and scattering losses (Kutner and Ulich 1981). The pointing and focus of the telescope were checked on a regular basis using the high velocity source ($\alpha = 5^{\text{h}} 32^{\text{m}} 46^{\text{s}}.8$, $\delta = -5^{\circ} 24' 13''.0$) of Orion as a reference. A distance to Orion of 480 pc has been adopted for this paper. The data consist of over 30,000

[†] The Five College Radio Astronomy Observatory is operated with support from the National Science Foundation under grant AST 85-12903 and with permission of the Metropolitan District Commission of the Commonwealth of Massachusetts.

spectra spaced at 45 arcseconds (the HPBW of the FCRAO antenna) centered on the position $\alpha = 5^{\text{h}} 33^{\text{m}} 00^{\text{s}}$, $\delta = -5^{\circ} 30' 00''0$. All offset positions given in this paper are relative to this position.

5.3 Results

5.3.1 Global Cloud Properties

In Figure 5.1, we present a map of the peak ^{12}CO intensity. It reveals small clumps of emission located at the northern end of the map which consist of weak, narrow line width emission that appear only over a small spatial extent. Also, immediately obvious is the very strong and extended emission of the Becklin-Neugebauer Kleinmann-Low (BNKL) region near the origin of the map. Cavities and arcs of emission are apparent near the center of the map and the southern region is marked by relatively diffuse and quiescent gas.

Another way to demonstrate the global properties of the cloud is shown in Figure 5.2, which is a spatial velocity map made along the declination axis. Each spectrum in the spatial velocity map is the composite of all spectra at the same declination averaged together. This process tends to smooth out small perturbations in the line profile that occur only over a small spatial extent and emphasize the overall characteristics of the molecular cloud. The contour shown with the grey scale in Figure 5.2 represents the line width at the 1σ level. The most prominent feature is near the BNKL region ($\Delta\delta = 0$), but what is more immediately obvious is the constancy of the line width over the the extent of the cloud south of $\Delta\delta = -10'$. From Figure 5.2, four parameters can be determined and these are shown in Figure 5.3 as a function of declination offset. The four parameters

shown are a histogram of the full line width at the 1σ intensity level; the velocity corresponding to the peak intensity; the value of the peak line intensity; and the integrated intensity evaluated at the 1σ level.

The distribution of line widths at the 1σ level in Figure 5.3 illustrate that the line width remains relatively flat over ~ 150 arcminutes and then rises very sharply as it approaches the BNKL region. Furthermore, the constancy of the mean line width of ~ 5.5 km s^{-1} over most of the cloud suggests that any line broadening in the southern portion of the cloud must be happening on a very local scale. At the northern end of the cloud, the full width of the line is seen to drop to almost 0 km s^{-1} and then rise again to a value of 4 km s^{-1} . This value of 4 km s^{-1} is lower than the apparent ambient line width seen throughout the rest of the cloud. The corresponding peak temperatures for this northern section suggest that most of the emission is probably from warm, narrow line clumps.

Also of note in Figure 5.3, is that the velocity of the peak emission tends to increase slowly over the entire extent of the cloud. This velocity gradient has been seen previously by Bally *et al.* (1987) in ^{13}CO and by Kutner *et al.* (1977) and Maddalena *et al.* (1986) in ^{12}CO . The abrupt change in the magnitude of the velocity field seen at $\Delta\delta \sim -2'.5$ by Bally *et al.* (1987) is also evident in Figure 5.3. This change in the peak velocity is also matched by a very strong increase in the ^{12}CO line width. The peak temperature, however, does not rise simultaneously with the abrupt velocity change, but occurs further north. What has not been seen in previous studies of Orion is that the direction of the velocity gradient between $\Delta\delta = -50$ and -25 arcminutes changed. This, as well as other specific features in Figure 5.3, will be discussed below.

In Figure 5.4, we present a map of the full line width determined at half the maximum intensity (FWHM) and Figure 5.5 is a map of the full line width evaluated at the 1σ intensity level (FW 1σ). Both maps were determined by summing the channels from the peak intensity to the desired intensity level. If the peak intensity was less than 3σ , the line was rejected and the line width set to 0 km s^{-1} . From Figure 5.5, 16 regions have been identified as having line widths in excess of 7 km s^{-1} at the 1σ level. These 16 regions are outlined in the enlarged scale maps in Figures 5.6 and 5.7. A comparison of the FWHM and FW 1σ maps demonstrates that regions of broad line widths at low intensity are also regions of broad width at the half maximum intensity. Thus, whatever is responsible for creating the broad line widths in the molecular cloud is influencing the entire line and not just the line width in the low intensity wings.

5.3.2 The Relationship Between Line Widths and Molecular Outflows

There are indications of both past and present star formation affecting the structure of the cloud. Upon further investigation of the spectra within the 16 regions identified in the FW 1σ map (Figure 5.5), 10 were found to be dominated by multicomponent line profiles, 1 (#5) has strong lines but no wing structure or profile asymmetry across the region, and 5 have line widths suggestive of a molecular outflow (#1, 3, 7, 9, 13). To help determine which positions in the cloud are associated with known molecular outflows, all previously identified outflows in Orion are listed in Table 5.1 and shown in Figures 5.6 and 5.7. Each of the 5 regions suggestive of being a molecular outflow are associated with previously known molecular outflows and, in each case, the molecular outflow source is at or near the position of the broadest line widths. Thus, no new molecular outflow has been identified from the line widths of this map.

Several known molecular outflows, however, reside in regions with line widths less than 7 km s^{-1} and would not have been identified as outflows if the only selection criteria were broad line widths at the 1σ level. This may be because some outflows only have broad line emission at very low intensity which requires lower rms levels than obtained in this survey. Alternatively, if the outflow has wings that are spatially separated, then the full line width contribution from line center to each of the wings may be significantly less than total line width extent of the outflow as determined from the maximum red wing to the maximum blue wing. Thus, the region around the molecular outflow would appear to be spatially extended, but have only slightly broader line widths than the ambient cloud.

Margulis, Lada, and Snell (1988) found that three of the most energetic outflows in Mon OB1 were characterized by both an increase in line width and an increase in peak temperature. Figure 5.8 is the map of the peak ^{12}CO intensity that was shown in Figure 5.1 but displayed with the outlines of the 16 regions defined from the $\text{FW}1\sigma$ map and the positions of the known molecular outflows from Table 5.1. This is presented to illustrate that below $\delta = -6^\circ$, all known outflows, while they may be marked by regions of increased line width, are *not* necessarily regions of increased temperature.

The positions of the molecular outflows in Table 5.1 have been identified in Figure 5.3. Note that there is an increase in the line width at the positions of the molecular outflows and a marginal increase in the integrated intensity, but no significant increase in the peak line temperature. The increases indicate that although the molecular outflows are spatially limited to the local area, their impact is significant when compared to the ambient cloud.

5.4 The Influence of Star Formation on the Molecular Cloud

It should be expected that the influence of past and present star formation on the morphology of the parent molecular cloud should be identified as coherent structure seen over a size scale of several arcminutes. This is evident in the composite map of the peak intensity and the regions of broad line width (Figure 5.8). The area near $(\Delta\alpha, \Delta\delta) = (35, -120)$ has a low ^{12}CO intensity bordered by two broad line width regions. These two broad line width regions are typically composed of multicomponent lines as might be expected for an expanding shell of material. Another region bordered by broad line widths is seen near $(-10, -35)$. Here, a large cavity of emission is bounded on the east side by broad, multicomponent lines which has, on the western edge, a curvature that mimics the shape of the cavity. This cavity is also apparent in the ^{13}CO channel maps of Bally *et al.* (1987). It is possible that this area is the result of an evacuating wind that has swept up material as it expanded into the cloud and is stirring up the gas into the observed large line width regions. Because of the lack of material at *all* velocities, both of the above examples suggest that the evacuation of material is happening to all the gas and dust along the line of sight. This second region is located at the declination which demonstrates a change in the direction of the velocity of peak emission (Figure 5.3). Again, an expanding shell of material might be evidenced by the shape of the peak velocity seen between $\Delta\delta = -50'$ and $-10'$.

If the outflowing material is directed perpendicular to our line of sight, the influence may appear quite different. The appearance of what looks like bow shocks at the offset positions $(0, -65)$ and $(10, -50)$ both are suggestive of a strong wind or shock

front impacting these regions and heating up the gas and dust. There is also evidence for this bow shock shaped shocked gas in the ^{13}CO map of Bally *et al.* (1987).

5.5 Summary

We have mapped the ^{12}CO emission from the Orion molecular cloud and find the cloud to be composed of a highly active northern region marked with massive star formation and a quiescent southern region restricted to only low mass star formation. The L1641 region of the molecular cloud has line widths that remain constant over 2° with the dominant deviations appearing near the positions of the molecular outflows in the cloud.

Several regions of broad line widths have been identified and found to be mostly consisting of multicomponent lines. Broad line width regions associated with molecular outflows had previously been identified by other authors. No new molecular outflows were identified based on the line width of the cloud at the 1σ level. The regions around some molecular outflows had line widths that were not significantly large and would have been missed if mapping the cloud were the only method of identifying molecular outflows.

The broad ^{12}CO line width regions were also compared with the other properties of the cloud. In two cases, regions of multicomponent lines were adjacent to ^{12}CO holes. The interpretation of these lines is that they are thought to be associated with the presence of an evolved star which is evacuating the gas and dust. The broad ^{12}CO line width regions around known molecular outflows were not always accompanied by enhanced temperatures.

TABLE 5.1
Molecular Outflows in Orion

α (1950) (h m s) (1)	δ (1950) ($^{\circ}$ ' ") (2)	Outflow Type (3)	Name (4)	Reference ^a (5)
5 32 59.6	-5 11 32	bipolar	OMC-2	1
5 32 48.0	-5 24 14	bipolar	Ori KL	2
5 34 11.0	-5 30 03	red	Ori-A East	3
5 30 14.5	-5 37 52	bipolar	Ori-A West	3
5 33 52.7	-6 24 02	bipolar	L1641-N, #5	3, 4
5 33 57.8	-6 26 44	bipolar	#8	4
5 34 09.4	-6 40 44	bipolar	V380 Ori NE, #18	5, 4
5 33 59.4	-6 44 45	red	V380 Ori, #20	5, 4
5 33 57.0	-6 47 55	bipolar	HH 1&2, #21	5, 4
5 36 20.9	-7 02 43	bipolar	L1641-C, #27	6, 4
5 36 56.4	-7 28 14	bipolar	Haro 4-255, #39	5, 4
5 38 02.7	-7 28 59	bipolar	Re50, L1641-S, #40	7, 3, 4
5 37 31.1	-7 31 59	bipolar	FIRSSE 101, #41, L1641-S3	4, 8
5 38 24.6	-8 08 20	bipolar	#61, L1641-S4	4, 8
5 40 23.2	-8 18 26	bipolar	L1641-S2, WHW89	3, 9

a) REFERENCES: (1) Fischer *et al.* 1985. (2) Lada 1985. (3) Fukui *et al.* 1986. (4) This work (Chapter 2). (5) Levreault 1988. (6) Fukui 1988. (7) Reipurth and Bally 1986. (8) Fukui 1989. (9) Wouterloot, Henkel, and Walmsley 1989.

Figure 5.1 A map of the peak ^{12}CO emission of the Orion molecular cloud. Offsets are in arcminutes and are relative to the position given in the text. The solid line represents the limits of the map and the halftone ranges from 4 to 26 K.

Figure 5.2 A spatial velocity plot across the declination of the cloud. Offsets in declination are with respect to the center of the map defined in the text. Each spectrum is the average of all spectra at a particular declination. The halftone represents the line intensity and ranges from 0 to 15 K. The contour illustrates the line width at the 1σ level.

Figure 5.3 A composite of parameters derived from Figure 5.2. The upper panel is the line width at the 1σ intensity level and is in units of km s^{-1} . The second panel from the top illustrates the velocity at the peak emission in km s^{-1} . The third panel is the distribution of peak temperatures across the cloud. The lowest panel is the integrated intensity determined at the 1σ level. The brackets represent regions or features described in the text.

Figure 5.4 A map of the line width determined at half of the maximum intensity. Offsets are as in Figure 5.1. The halftone represents increasing line width and ranges from 2 to 8 km s⁻¹.

Figure 5.5 A map of the line width determined at the 1σ intensity level. The halftone represents increasing line width and ranges from 5 to 10 km s^{-1} . Regions outlined by the contour represent the 16 areas with line widths greater than 7 km s^{-1} .

Figure 5.6 A subsection of Figure 5.5 emphasizing the southern broad line regions. The halftone ranges from 2 to 8 km s⁻¹. The position of the outflows listed in Table 5.1 are shown with open squares.

Figure 5.7 Same as Figure 5.6 except for the northern broad line regions. The halftone ranges from 5 to 15 km s⁻¹.

Figure 5.8 Same as Figure 5.1 except with the broad line width regions identified. The regions of line widths greater than 7 km s^{-1} identified in Figure 5.5 are shown overlaid on a halftone of the peak line intensity. Note that the location of peak temperatures do not appear to correlate with the peak line width regions.

CHAPTER 6

SUMMARY

This dissertation has attempted to understand the interaction between molecular outflows and their parent molecular clouds. In order to address this interaction, we have attempted to identify all the molecular outflows within a single molecular cloud, namely the L1641 region of Orion. The positions of possible molecular outflows were determined from ^{12}CO observations of a sample of young stellar objects identified from the IRAS data base. Single point observations of the molecular lines ^{12}CO , ^{13}CO , C^{18}O , and CS were made to determine if the source had wing emission and densities which indicated that the source was indeed associated with the cloud. The line widths of these candidate outflow sources correlate with the integrated CS and C^{18}O emission, suggesting that the most likely molecular outflow candidates reside in dense environments. The infrared luminosity of each source was found to be related with the ^{12}CO line width suggesting that whatever process is responsible for creating the observed ^{12}CO line widths in the cloud is responsible for adding turbulent energy to the cloud.

A comparison of the infrared and molecular line data taken towards these young stellar objects was made. Based on the infrared colors of the sources observed, the most likely candidate molecular outflow sources have bluer long wavelength colors and redder short wavelength colors than the sources that did not appear to be molecular outflows. Based on these single point observations, we find that candidate molecular outflows can be identified using the IRAS data. The agreement of known outflows with some of the

likely candidates gives us confidence that most of the other candidates will have molecular outflows. The infrared and molecular line data suggests that the dense regions thought to surround the young stellar object responsible for the molecular outflow are intimately coupled with the dust emission further suggesting that molecular outflows occur at the early stages of star formation.

Once a list of candidate molecular outflows was determined, ^{12}CO maps were made to confirm that the candidate was a molecular outflow and to determine the spatial extent of the high velocity material. While single point observations can indicate the presence of a broad ^{12}CO line, the nature of the source is not known until a spatial map around the source is made. Chapter 3 presented the results of mapping the candidate molecular outflow sources and found that the molecular outflows identified were found throughout the cloud but appear to form in clusters. Based on the direction of the high velocity gas relative to the infrared source, the molecular outflows do not appear to be aligned in any preferred direction. This suggests that magnetic fields, which are thought to align the observed optical jets in this region, probably have little effect on the shape and direction of molecular outflows at the size scales discussed here. This led to the need for some large scale shaping mechanism and a role for the parent cloud became apparent.

Based on the measured parameters of the ^{12}CO maps of the observed molecular outflows, estimates were made of the masses, life times, and energetics of the molecular outflows. These estimates were limited by lack of knowledge of the inclination of the molecular outflow, the three dimensional velocity of the high velocity gas, and the amount of outflowing material present in the core of the line profile. As a result,

determinations of the lower and upper limits to the mass, momentum, and mechanical luminosity were made. Even when lower limits on the momentum rate of molecular outflows are compared with the energy requirements of the parent cloud, the molecular outflows were found to be capable of providing sufficient support against the gravitational collapse of the molecular cloud. Thus, even if molecular outflows are not the only means of cloud support, the energetics of the molecular outflows are such that they probably play an important role in the dynamics and future structure of the cloud.

Next, a survey for radio continuum emission was made towards the position of the young stellar objects. This survey was made to determine whether young stellar objects associated with molecular outflows were characteristically different at centimeter wavelengths from the young stellar objects not associated with molecular outflows. Several sources were identified, but most were considered not to be associated with the molecular cloud. Four sources, however, were associated with young stellar objects and each of these young stellar objects had an associated molecular outflow. The detected young stellar objects were the most luminous objects in L1641 and each had a thermal radio spectrum that was consistent with either a stellar wind or an optically thick H II region. Furthermore, these four sources have no known optical counterpart and an infrared spectrum that rises between 2.2 and 25 μ m. This suggested that the young stellar objects that were detected with radio continuum emission are probably at the earliest stage of their evolution.

Finally, a ^{12}CO map of the molecular cloud was made to determine if any new molecular outflows could be identified that were not associated with an IRAS source and to determine if there were indications of interaction with the known molecular outflows.

The cloud was found to be represented by two distinct regions: the north near the Orion Nebula which is marked by massive star formation and disruptive energetics; and the south (L1641), that has only low mass star formation and appears globally quiescent. Overall, the L1641 region has line widths and temperatures that remain roughly constant. Local regions of enhanced line width were identified and found to be either associated with known molecular outflows or thought to be regions affected by past star formation. No new molecular outflow source was found. The lack of temperature enhancements around the positions of the identified molecular outflows relative to the rest of the cloud suggests that the influence of heating by the molecular outflows is either occurring over a very small scale or that it is important over a short time scale. When the shape of the molecular outflow was compared with the structure of the molecular cloud, the molecular outflow morphology, in most cases, was found to fit well with the density structure of the cloud. This suggests that the molecular cloud is directly determining the shape of the molecular outflow.

Now that the molecular outflows have been identified and the structure of the L1641 molecular cloud mapped, we can address the questions that motivated this work. First, what fraction of young stellar objects have associated molecular outflows? The work presented in Chapter 2 was insufficient to address this question because the data presented there were single point observations and, hence, could only suggest possible molecular outflow candidates. In Chapter 3, the candidates were mapped and the presence of a molecular outflow confirmed. The nine molecular outflows identified represent roughly one-tenth of the number of young stellar objects in L1641. This suggests that if *all* young stellar objects pass through a molecular outflow stage during their evolution towards the main sequence, then about 10% of their pre-main sequence

life is spent demonstrating a molecular outflow. Thus, the measured dynamical life time of the observed molecular outflows and the rate of occurrence of 10% suggests a young stellar object spend slightly longer than 10^6 years approaching the main sequence. If all young stellar objects have a molecular outflow stage, then the implied dynamical life time would be longer than that measured for these molecular outflows and this is probably because the objects observed in L1641 have lower masses. Since low mass stars evolve more slowly than high mass stars, perhaps the rate at which a low mass star ejects material during its pre-main-sequence life time occurs over a longer time. Thus, the large fraction of observed molecular outflows may be the result of a relationship between the mass of the molecular outflow and its subsequent dynamical life time. This argument is aided by the limited detectability of the molecular outflows within this cloud. There are probably molecular outflows which lie preferentially perpendicular to our line of sight and have not been detected. These additional molecular outflows, based on the statements above, would increase the percentage of time a young stellar object spends as a molecular outflow.

Next, what is the relationship between the morphology of the molecular outflows and the structure of the ambient cloud? From the maps of the molecular outflows presented in Chapter 3, the orientations and shapes were compared with the structure of the parent cloud (Chapter 5). Most molecular outflows appear to be shaped or have their direction diverted away from the source of the molecular outflow. This was confirmed in three cases where $C^{18}O$ was mapped around the position of the molecular outflow. The $C^{18}O$ indicates that the strongest column density occurs at the position of the infrared source and not at the apparent center of the molecular outflow. Indications that the ambient cloud dominates the direction of the molecular outflow were suggested when the

direction of the observed molecular outflows were found to have no preferred orientation and did not agree with the direction of the long axis of the molecular cloud, the inferred direction of the magnetic field, or the direction of the optical jets that were associated with the molecular outflows. The lack of agreement with the small scale optical jets imposed the necessity for the large scale structure of the molecular cloud to control the direction of the molecular outflow.

Finally, what role do molecular outflows play in the evolution of molecular clouds? By estimating the energetics of the nine observed molecular outflows, and comparing the momentum input into the cloud with the rate required to support the cloud against gravitational collapse, it was found that the molecular outflows present could easily provide this support. For the cloud to be supported over several molecular outflow life times, however, requires several episodes of star formation to occur over the dissipation time scale of the cloud. Based on the energetics derived for the molecular outflows, it was then useful to determine if the molecular outflows are a threat to the future of the cloud. Evidence in the large scale map for holes and cavities around regions of past star formation suggests that vigorous star formation affect the evolution of the molecular cloud. If a sufficient number of star forming episodes occur over the dissipation time scale, it is possible that the cloud will be disrupted by the presence of the formed stars. Alternatively, past star formation can provide a means to push the gas causing it to collapse and start a new episode of star formation. In summary, we have learned that molecular outflows play an important role in the evolution of molecular clouds.

Based on the discussion above, we can now speculate about the evolution of the molecular outflows and their effect on the cloud. Molecular outflow sources form throughout the cloud but appear to form in clusters. The molecular outflows are probably occurring at very earliest stages of stellar evolution and are likely to be embedded deep in a dense medium. The dense material surrounding the molecular outflow and the opacity at infrared wavelengths only allow the longest wavelength infrared emission to escape. As the molecular outflow extends out into the cloud, the density structure of the molecular cloud dominates the path of the high velocity material by shaping and diverting it. Eventually, the source ejects enough material that the molecular outflow will begin to push against the cloud and evacuate the surrounding medium. Around this time, the characteristics of the molecular outflow have become blended with the ambient cloud, and this is an indication of the impact that molecular outflows have on the support of the parent cloud. As the ambient cloud is stirred up by the molecular outflow, the line width of the cloud is increased and the molecular outflow signature becomes "lost" within the surrounding medium.

Finally, the technique of identifying candidate molecular outflows from a survey of IRAS selected young stellar objects was found to be a more complete method than performing a quick survey map of the entire cloud. This is because the large scale map was not sensitive enough to detect the weakest molecular outflow sources. Also, the molecular outflows identified from the survey of IRAS objects included sources that did not appear as a broad line or large integrated intensity regions in the survey map of the cloud. Thus, while the large scale mapping provided the locations of the strongest molecular outflows, the survey of young stellar objects based on the IRAS survey enabled the detection of the strong as well as the weaker molecular outflows. This

suggests that the use of this method for other molecular clouds will be invaluable in the continuing study of molecular outflows and their interaction with molecular clouds.

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