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Star formation in the Monoceros OB1 dark cloud

Margulis, Michael Scott, Ph.D.

The University of Arizona, 1987
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UMI
STAR FORMATION IN THE MONOCEROS OB1 DARK CLOUD

by

Michael Scott Margulis

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF ASTRONOMY

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

1987
As members of the Final Examination Committee, we certify that we have read
the dissertation prepared by Michael Scott Margulis
entitled

STAR FORMATION IN THE MONOCEROS OB1 DARK CLOUD

and recommend that it be accepted as fulfilling the dissertation requirement
for the Degree of Doctor of Philosophy.

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ABSTRACT

A survey of the Monoceros OB1 dark cloud has been made for molecular outflows and young stellar objects. In all, nine molecular outflows and thirty far-infrared sources were identified in a portion of the cloud composed of about $3 \times 10^4 \, M_\odot$ of material. Statistical arguments suggest that 90% of the far-infrared sources actually are young stellar objects embedded in the cloud.

If the star formation rate in the Mon OB1 cloud is roughly constant with time then molecular outflows in the cloud should be able to support it against collapse due to gravity. This suggests that the birthrate of outflows in the solar neighborhood is very high. In fact, regardless of considerations of cloud support, the large number of outflows identified in the Mon OB1 cloud and the propensity of the youngest stellar objects in the cloud to be associated with outflows suggest that outflows have a high birthrate in the solar neighborhood and are part of a common stage in early stellar evolution.

The young stellar objects identified in the cloud can be fit into a spectral classification system. In fact, in terms of spectral slopes, far-infrared luminosity, and source size the properties of the objects are consistent with expectations if the system represents an evolutionary sequence.

It is also found that the outflow phase in early stellar evolution tends
to occur at about the time that young stellar objects lose a large fraction of their circumstellar envelopes. As a result it seems likely that outflows play an important role in sweeping out the circumstellar gas around many young stellar objects and may, in fact, play an important part in the evolutionary transition between the protostellar and stellar stages of evolution.
CHAPTER 1

INTRODUCTION

Over the last ten years our understanding of star formation and early stellar evolution has undergone a dramatic revision. It has been discovered that many, perhaps all stars undergo a period of mass outflow during their formation or early evolution. The mechanical energy carried in each outflow is enormous (e.g. $10^{43} - 10^{47}$ ergs), and their frequency of occurrence is very high, perhaps as high as the birthrate of all stars with masses greater than the sun's (Lada 1985). In addition, the outflow phenomenon seems to be associated with the youngest observable stages of stellar evolution (Lada 1985). As a result, it is clear that the existence of outflows must have important implications for both star formation and the structure and dynamics of the dark clouds surrounding young stellar objects.

Because the discovery of the outflow stage of early stellar evolution is so recent, the outflow phenomenon is still something of an enigma. Obvious issues, like the number of outflows in individual dark clouds, the degree to which outflows affect the dynamics of dark clouds, and the place of outflows in the early evolution of young stellar objects have yet to be seriously addressed. In fact, the outflow phenomenon poses a paradox which we have yet to completely solve: outflows are
associated with very young stellar objects which, if our expectations are correct, should be characterized by infall due to gravitational collapse rather than outflow.

A primary reason why many of these questions have not yet been answered is that until now most outflows have been discovered either serendipitously or in surveys of young stellar objects for outflow emission (Edwards and Snell 1982, Calvet, Cantó and Rodriguez 1983, Bally and Lada 1983, Cantó et al. 1984, Levreault 1985). Because of this little is known about how frequently they occur in dark clouds or how often they tend to be associated with young stellar objects. As a result, it is imperative, if our knowledge of this important stage of early stellar evolution is to grow, for us to overcome the limitations of the haphazardly constructed samples of outflows and young stellar objects which have been compiled to date. One way to do this is to perform complete and unbiased surveys of dark clouds for molecular outflows and young stellar objects.

In this thesis I present the results of the first unbiased surveys of a large portion of a dark cloud, the Monoceros OB1 cloud, for both molecular outflows and young stellar objects. The results of these initial surveys are outlined in Chapter 2. The results of detailed follow-up observations made as compliments to the surveys are presented in Chapters 3 and 4. Together these surveys and follow-up observations comprise the first complete census of a dark cloud for star formation activity. As a result they provide us with the first coherent picture of the global star formation activity in a dark cloud and also allow us to investigate a
number of issues concerning the relationships between molecular outflows, young stellar objects, and dark clouds. For example, just from the survey and follow-up observations of the molecular outflows in the cloud alone, it is possible to construct mass and luminosity functions for the outflows in the Mon OB1 cloud, make estimates of the amount of energy and momentum which outflows deposit into the surrounding cloud, and move towards an understanding of the physical conditions in dark clouds which are favorable to outflow formation. In addition, in conjunction with the survey and follow-up observations of the young stellar objects in the cloud it is possible to investigate what types of stars (if not all) go through the outflow phase, and even to find the position of the outflow phase in the evolutionary sequence through which young stellar objects progress. In fact, as an added bonus it is also possible to begin to produce rough luminosity and color functions for the youngest stellar objects in the cloud. Clearly, these surveys and future surveys like them should prove extremely useful for our understanding of molecular outflows. In addition, they should prove useful for our understanding of the global process of star formation in dark clouds as well.

As mentioned above the cloud which I have chosen to survey is the Monoceros OB1 dark cloud. Because of its position in the galaxy with respect to the sun and because of its close proximity to us it is the perfect cloud to be surveyed. Since the constellation Monoceros is in the direction of the galactic anticenter confusion due to foreground and background clouds will be at minimum.
Since the cloud is at a distance of 800 pc (Walker 1956) it is both far enough away so that its molecular emission can be manageably mapped in a few weeks of observing time, and close enough so that the outflows and infrared sources detected will be just slightly resolved. The Mon OB1 cloud is also very well known and has been studied extensively. As a result I am able to rely on a voluminous body of already existing knowledge in order to supplement the survey and follow-up observations taken for this thesis. Molecular emission from the cloud has already been mapped at low resolution (Blitz 1978), the cluster/association NGC2264/Mon OB1 associated with the cloud has already been studied in great detail (Walker 1956, Iben and Talbot 1966, Adams 1981, Adams, Strom, and Strom 1983), the HII region resulting from the interaction of the cluster and cloud has been studied (Rickard et al. 1977), and even the chemistry of the cloud has been studied by a number of authors using continuum emission from dust and molecular line emission and absorption from CS, HCN, H$_2$S, SO, NH$_3$, OH, H$_2$CO, CO, $^{13}$CO, and C$^{18}$O (Blitz 1978, Crutcher, Hartkopf, and Giguere 1978, Gottlieb and Ball 1973, Lang and Willson 1980, Matsakis et al. 1980, Mayer et al. 1973, Rickard et al. 1977, Schwartz 1980, 1982, 1985, Schwartz et al. 1985, Thaddeus et al. 1972, Turner 1971, Turner et al. 1973, Zuckerman et al. 1972). Much of this information comes in handy during the course of this thesis.
History

This thesis is primarily concerned with the intersection of three related fields of study, those of dark clouds, molecular outflows, and young stellar objects. Since a thesis should be useful as a guide to the uninitiated as well as a detailed exposé on a subject, it is worthwhile at this point to give a short historical review of each of these three topics. These reviews will serve the dual purposes of bringing the reader up to date and placing what follows in subsequent chapters into a historical context.

Young Stellar Objects

Although it was not known at the time, the study of young stellar objects began very early in this century. Throughout the 1920's and afterwards as well peculiar variable stars were identified in the direction of dark clouds and patches of obscuration on the sky; many of these strange variable stars were, in fact, found in the direction of the Mon OB1 cloud itself (Hubble 1920, Wolf 1924, Hoffmeister 1949, 1951). Due to their propensity to "burst" in brightness and due to the lack of a pattern in their variability these objects were thought to be very mysterious. In fact, it was only much later in the 1940's, that the first inroads were made towards understanding them. In 1945 Joy identified a subclass of these objects similar to the star T Tauri, and in 1947 Ambartsumian suggested that members of this subclass might be pre-main sequence objects. This last idea took a good ten years
to catch on, but by the 1950's both theoretical and observational studies began to confirm it. With the theoretical work of Henyey, Le Levier, and Levee (1955), in which the first estimates of the expected evolutionary tracks of pre-main sequence stars were made, the study of young stellar objects and early stellar evolution really took off. Subsequent studies of very young open clusters by Walker (1956, 1957, 1959, 1961, 1969) confirmed Henyey et al.'s conclusion that pre-main sequence objects should lie above and to the right of the main sequence in the HR diagram. In addition, in the case of the association/cluster near the Mon OB1 cloud (Walker 1956) star formation was found to be non-coeval and about 30% of the pre-main sequence stars found looked like T Tauri stars (Vasilevskis, Sanders, and Balz 1965). After this, detection of the infrared radiation from young stellar objects began to become possible and with this advance in technology it became apparent that young stellar objects were bright in the infrared. In fact, sometimes they were brighter in the infrared than in the optical. Mendoza (1966, 1968) first discovered the unexpected brightness of T Tauri stars in the infrared. Later Strom, Strom, and Yost (1971) and Walker (1972), in studies of infrared emission from stars near the Mon OB1 cloud, concluded that T Tauri stars are surrounded by circumstellar shells of gas and dust. At this point it began to be suspected that T Tauri stars are objects which have only very recently emerged from their birth clouds. Spurred on by impressive advances in both infrared and millimeter-wave technology, the race was then on to search dark clouds themselves for the youngest of stellar objects.
This race continues today as astronomers frantically try to identify the youngest stars and even "protostars", objects still in the process of accumulating the bulk of the mass they will have when they reach the main sequence. This race has been so frantic, in fact, that protostars have been called the "Holy Grail" of star formation studies (Wynn-Williams 1982). To date, however, perhaps with one exception (Walker et al. 1986), no unambiguous identification of a protostar has yet been made. In fact, it is not even clear exactly how the various types of young stellar objects so far identified fit into an evolutionary sequence (for a summary of the types of young stellar objects identified see Strom, Strom, and Grasdalen 1975). A case in point are the so called "Naked T Tauri stars." These sources occupy nearly the same region of the HR diagram as T Tauri stars themselves, but show no evidence of circumstellar gas or dust (Walter 1987). While clearly young stellar objects it is not clear whether they occur concurrent with or after the T Tauri stage. At this point, then, in our study of young stellar objects we are left with many questions unanswered. A good review on work in these areas and prospects for the future is given in Lada (1987).

Dark Clouds

As in the case of young stellar objects the study of dark clouds began early in this century. Barnard (1919) was the first to systematically search for and photograph these objects, and created a catalog of dark patches on the night
The Mon OB1 cloud was, in fact, first identified in this catalog. However, in spite of the early start very little attention was subsequently paid to these objects except as annoying patches of obscuration which got in the way of astronomer’s work. In fact, in spite of the early detection of molecular absorption lines from CH, CH⁺, and CN in the spectra of stars (Dunham 1937, 1939, 1941, Dunham and Adams 1937, Adams 1941, 1943, Swings and Rosenfeld 1937, McKellar 1940, Douglas and Herzberg 1941), of the realization that an interstellar medium was responsible for the absorption and reddening of starlight (Trumpler 1930), and of the realization that stars probably formed in dark clouds (Whipple 1946, Bok and Reilly 1947), little work was done on the detailed structure and evolution of dark clouds until the 1970’s. The reason for this lack of interest is straightforward; until the advent of millimeter-wave and far-infrared astronomy in the 1970’s it was only possible to study the structure of dark clouds through the unwieldy method of star counting. This method, with its many inherent liabilities was a poor substitute for methods which would come later.

With the development of millimeter-wave astronomy in the 1960’s and 1970’s the study of dark clouds finally came into its own. In the late 1960’s and early 1970’s it was discovered that dark clouds were made primarily of molecules. OH (Heiles 1968), NH₃ (Cheung et al. 1968), and H₂CO (Palmer et al. 1969) were discovered in dark clouds in the late 1960’s. CO was identified in the direction of HII regions (Wilson et al. 1970) and dust clouds (Penzias et al. 1972) in the early
1970's. H$_2$ was then inferred as the dominant constituent of dark clouds; while difficult to detect directly, H$_2$ was the only molecule which could be abundant enough to produce the high gas densities necessary to excite other molecules like CO into emission. Using CO as a probe of the structure of these clouds, then, it was found that they had sizes ranging as large as 100 pc, typical densities of 100 cm$^{-3}$ or more, and total masses ranging as high as $10^6$ M$_\odot$ (see for example Elmegreen 1985 and Solomon and Sanders 1985). Their large sizes and masses earned them the name "Giant Molecular Clouds" and made them the most massive objects identified in the galaxy. It was also discovered that they were intimately related to star formation with many young stellar objects found near them and HII regions found to be essentially blisters on their peripheries (Zuckerman 1973, Israel 1978, Gilmore 1980). Today millimeter emission from many dark clouds has been extensively mapped and a large portion of the galactic plane has been surveyed for CO emission (Cohen and Thaddeus 1977, Sanders, Solomon, and Scoville 1984). As a result, our understanding of the distribution of dark clouds in the galaxy is quickly progressing. However, there are many problems concerning dark clouds still outstanding. One major and longstanding issue is the source of their internal energy. From molecular line observations of dark clouds it has been found that the line-widths observed due to doppler broadening are often ten times the thermal widths that one would expect from the excitation temperatures of gas in the clouds. These large widths in turn imply very large gas velocities in the
clouds, the origins of which are a mystery. Another issue in studies of dark clouds is their structure. Are they smooth or patchy, somewhat organized or purely turbulent? Research by Kleiner and Dickman (1984, 1985) suggests that their velocity and density fields may be random on many size scales. Elmegreen (1985) in turn has suggested that there may be fundamental differences in the character of star formation in clumpy as opposed to smooth clouds. As can be seen, as in the case of the study of young stellar objects there is much that we still do not know.

Molecular Outflows

Finally the last of the triumvirate of topics to be discussed in this thesis has a very short history. In fact, the study of molecular outflows is barely a decade old. Its origins can be traced back to work by Zuckerman and Palmer (1975), Kwan and Scoville (1976), and Zuckerman, Kuiper, and Kuiper (1976), in which it was noticed that molecular emission lines towards the Becklin-Neugebauer object in the Orion OB1 dark cloud consisted of two components, a spatially extended but very narrow spike and a spatially confined but very wide pedestal. At zero intensity the width of the pedestal component was found to be at least 150 km s\(^{-1}\), well in excess of the escape velocity of a typical giant molecular cloud. Clearly rotation or infall could not be responsible for such large line-widths; thus the study of molecular outflows was born.
After the discovery of the Orion outflow numerous other examples of outflow were quickly found, the first few being the outflows near the star LKHα 101 (Knapp et al. 1976), in the dark cloud L1551 (Knapp et al. 1976, Nachmann 1979, Snell, Loren, and Plambeck 1980), and near the embedded sources Cepheus A (Rodriguez, Ho, and Moran 1980), AFGL 961 (Blitz and Thaddeus 1980), and AFGL 490 (Lada and Harvey 1981). With these outflows identified and more on the way it became clear that outflow is a common occurrence in dark clouds. In addition, as the number of identified outflows grew it became clear that they tended to be associated with young stellar objects, particularly those deeply embedded in dark clouds (Bally and Lada 1983). It is possible that sometime in their early evolution all stars may go through the outflow phase. Today, in fact, a primary issue in the study of molecular outflows is whether all or just some stars go through this phase.

A peculiar property of outflows is their morphology. Outflows tend to be bipolar, consisting of spatially separate red and blue shifted lobes of emission on the sky (Rodriguez, Ho, and Moran 1980, Snell, Loren, and Plambeck 1980, Lada and Harvey 1981, Bally and Lada 1983). The two lobes are almost always situated symmetrically opposite each other around a young stellar object. This strange morphology has led investigators to suggest that molecular outflows consist of oppositely directed, collimated jets of material streaming away from the sites of star formation. At the moment the mechanism of collimation is under debate.
Many other issues concerning molecular outflows are also, as yet, unresolved. It is possible that outflows may be the solution to the classic angular momentum problem in astronomy; outflows may carry away the excess angular momentum of young stellar objects ultimately allowing them to be slow rotators like the sun. As mentioned at the beginning of this chapter outflows may also pump a significant amount of mechanical energy into their surroundings. This makes them a possible solution to the internal energy problem in dark clouds. As yet, however, even the structure of outflows is under debate, and where they get their enormous mechanical energies is unknown.

**Summary**

While our picture of the process of star formation is becoming progressively more clear, at this time it is far from complete. Over the last forty years we have come to the firm realization that stars form in dark clouds; over the last ten we have begun, through observations of the molecular outflow phenomenon, to see how young stellar objects and dark clouds interact. Detailed pictures of the global star formation properties of entire, individual dark clouds are a logical next step in these investigations.

In this thesis I make an attempt to solve many of the questions posed in this chapter. In Chapter 2 I outline in a schematic way the global properties of star formation in the Mon OB1 cloud and point out the positions of molecular
outflows and young stellar objects there. In Chapter 3 I highlight the properties of molecular outflows in the Mon OB1 cloud, by comparing them to outflows previously identified, estimating their birthrate, and assessing in detail their ability to affect cloud structure and dynamics. In Chapter 4 I highlight the properties of the young stellar objects in the cloud, by attempting to place them into an evolutionary sequence from young to old objects and by assessing in detail their propensity to be associated with outflow. What I hope emerges in Chapter 5, the concluding chapter, is a better picture of the global properties of star formation in dark clouds.
CHAPTER 2

UNBIASED SURVEYS OF THE MONOCEROS OB1 DARK CLOUD FOR MOLECULAR OUTFLOWS AND YOUNG STELLAR OBJECTS

Of the more than 70 molecular outflow sources now known to exist (e.g. Lada 1985), most have been discovered serendipitously or in surveys of young stellar objects (for example: T Tauri stars, Edwards and Snell 1982, Calvet et al. 1983, and Levreault 1985; Herbig AeBe stars, Cantó et al. 1984; embedded infrared sources, Bally and Lada 1983). As a result of this bias, little is known about the frequency of occurrence of outflows in dark clouds or about the propensity of outflows to be associated with young stellar objects. In order to remedy this situation, I (in collaboration with Charlie Lada) have made the first unbiased survey of a large portion of a dark cloud for both molecular outflows and young stellar objects. In particular, I have obtained a sensitive and complete survey of high-velocity emission from the J=1-0 transition of CO over a large portion of the Monoceros OB1 dark cloud complex in order to search for molecular outflows, and complete maps of the infrared emission from the same region at wavelengths of 12, 25, 60, and 100 μm in order to search for young stellar objects. This survey, and
future surveys like it (for example see Fukui et al. 1986), will be very important for understanding the outflow phenomenon, molecular cloud evolution, and star formation.

Survey and Results

Using the 5 m telescope at the Millimeter Wave Observatory¹ (MWO) during portions of 1984 November and December and 1985 June, I have observed 1319 positions in the direction of the Mon OB1 molecular cloud whose distance is about 800 pc (Walker 1956). A uniformly sampled map of the entire portion of the cloud with peak temperature greater than $T_R = 6$ K was made with 2' spacing (0.46 pc at the distance of Mon OB1) and 2'.3 resolution. A large portion of the cloud where peak temperatures were less than 6 K was also mapped with uniform sampling. Each position in the cloud was observed with a total integration time of 3 minutes (1.5 minutes on source, 1.5 minutes off source) and a spectral resolution of 250 kHz or 0.65 km s⁻¹. The temperature scale on each spectrum was calibrated using the chopper wheel method (Ulich and Haas 1976) and is expressed as $T_R$ (Kutner and Ulich 1981). An additional correction to the temperature scale was made using approximately hourly observations of emission from the position $\alpha_{1950} = 6^h38^m25^s$, $\delta_{1950} = 9^\circ32'27''$ in the Mon OB1 cloud. All spectra in the survey were scaled so that the peak temperature at this position was always 21 K.

¹ The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory, the University of Texas at Austin, with support from the National Science Foundation and McDonald Observatory.
In general, this correction did not result in a change of scale of more than a few percent. As a result I expect errors in the absolute temperature to be no higher than 15%. With only 10 or 20 exceptions, for which quadratic baselines were subtracted, linear baselines were subtracted from each of the spectra. All spectra were taken in position switch mode in order to ensure flat baselines. For a description of the instrumentation used to make these observations and the methods used to calibrate and reduce the millimeter-wave data obtained see Appendix A.

High velocity emission regions were located in the survey by inspecting the two velocity intervals (red and blue) which extended from 4.55 km s\(^{-1}\) to 22.75 km s\(^{-1}\) from the velocity at which peak emission occurred in each of the 1319 spectra. If in either interval the integrated intensity was greater than 2 times the rms noise in the integrated intensity of typical spectra, then that spectrum was considered as a candidate for having high-velocity emission wings. In some cases line profiles tested positive because of multiple-velocity components. These were rejected as not being likely to be due to outflow. This may have introduced a bias into our sample if there are flows which produce "detached wings" such as observed in the Mon R2 outflow (Bally and Lada 1983, Wolf, Lada, and Bally 1985). Finally, to be considered as an outflow candidate all of the regions identified in this manner were reobserved using the NRAO 12 m telescope\(^2\) or FCRAO 14 m

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\(^2\) The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under a contract with the National Science Foundation.
telescope\(^3\) in order to confirm the existence of high-velocity emission. Detailed results of these follow-up observations are included in Chapter 3 of this thesis. Only those candidate sources in which the presence of wings was confirmed in these subsequent observations are considered as outflow sources herein.

From spectra with a typical rms noise of about 0.3 K, nine centers of high-velocity emission were identified in the Mon OB1 molecular cloud. Of these, four showed both red and blue high-velocity emission wings while five showed only a red wing. Four high-velocity emission regions were found to be spatially isolated sources with angular extents less than 10'. Five other high-velocity emission regions were identified as relatively strong, spatially distinct peaks within an extended region of weak, high-velocity emission in the southern portion of the cloud. Figure 2.1 shows the positions and sizes of the newly discovered regions of high-velocity CO emission (*small boxes*), superposed on a red Palomar Sky Survey plate of the region. Also shown are the 6 K peak temperature contour of CO emission from the Mon OB1 molecular cloud and the boundary of the uniformly sampled survey (*large box*). The intermediate-sized box in the figure encloses the area of extended, low-intensity, high-velocity emission. The five sources I have identified as embedded within this region are represented by boxes which outline their sizes measured at half their peak-integrated intensities. The weak and extended com-

\(^3\) The Five College Radio Astronomy Observatory is operated with support from the National Science Foundation under grant AST 82-12252 and with permission of the Metropolitan District Commission of the Commonwealth of Massachusetts.
Figure 2.1: Schematic diagram of the Mon OB1 molecular cloud overlaid on the POSS red plate of the region. The large irregularly shaped box denotes the region mapped. The smooth line is the 6 K peak temperature contour. Small boxes denote positions where strong high-velocity emission was found, and the intermediate-sized box in the southern portion of the cloud denotes the region where nearly continuous low-intensity high-velocity emission was found. Crosses denote the positions of IRAS point sources. The two triangles denote the positions of Herbig-Haro objects identified by Adams, Strom, and Strom (1979). The insert is a peak temperature map of the entire cloud complex adopted from Blitz (1978). The contour interval is 1 K.
Figure 2.1 Schematic diagram of the 403 HID cloud.
ponent of high-velocity emission (hereafter WEC) contains both blueshifted and redshifted high-velocity gas. The blueshifted gas is spatially separated from the redshifted gas, and extends from roughly the position of the southern Herbig-Haro object (triangle) to the IRAS source (cross) at the extreme northeast corner of the region. This weak, blueshifted gas appears to be part of a well-collimated bipolar outflow, the redshifted half of which is the most extended and elongated of the five sources identified in this portion of the cloud. The remaining area of the WEC consists primarily of redshifted high-velocity gas. Altogether 19% by area of the portion of the cloud with peak temperature greater than 6 K shows some evidence of high-velocity emission, while 9% of the entire region mapped shows some evidence of high-velocity emission.

As a check on the sensitivity of the survey the outflow L1551 (Snell, Loren, and Plambeck 1980) was mapped using the 250 kHz filterbanks at the MWO with an integration time of 10 s at each position. Synthetic spectra were then constructed using an appropriate Gaussian convolution of the data to simulate spectra of L1551 (distance = 140 pc, Elias 1979) as it would be observed if it were at the distance of the Mon OB1 molecular cloud. The resulting spectra, displayed in Figure 2.2, show wings which would be spatially extended and just above the limit of detection in the survey.

Sensitive, high-resolution maps of infrared emission at 12, 25, 60, and 100 μm in the Mon OB1 region have also been obtained by co-adding the appropriate
Figure 2.2: Synthetic spectra which simulate observations of the outflow in L1551 if it was at the distance of the Mon OB1 cloud. Spectra are at 6°N, 6°E; 0°N, 0°E; and 6°S, 6°W of the position $\alpha_{1950} = 4^h28^m40^s$, $\delta_{1950} = 18^\circ1'41''$. 
IRAS\textsuperscript{4} survey fields at the Infrared Processing and Analysis Center (IPAC). Spatial resolutions of $0.76 \times 4.45$, $0.76 \times 4.65$, $1.51 \times 4.75$, and $3.03 \times 5.05$, respectively, were obtained in each of the four bands. Additional maps were made by applying a spatial filter to the co-added maps. This filter passed point sources in the fields and suppressed extended emission. Point sources were identified from these filtered maps using the point source extractor program at IPAC. Details of the filtering and extraction procedures can be found in (Kleinmann et al. 1986). In Figure 2.1 the positions of infrared point sources determined from the co-added IRAS survey data are included as crosses. In order to be included in Figure 2.1 each source had to appear as a point source in the filtered 25 $\mu$m map and appear as a point source in either the 12 or 60 $\mu$m filtered maps or the 25 $\mu$m unfiltered map. Using these selection criteria 30 sources were found inside the region mapped in CO. Detailed results concerning the spectral energy distributions, luminosities, and colors of these sources are presented in Chapter 4 of this thesis. A description of the Infrared Astronomical Satellite can be found in Beichmann et al. (1985).

Discussion

From the CO survey nine distinct regions displaying high-velocity emission have been identified as outflow candidates in the Mon OB1 molecular cloud.

\textsuperscript{4} The Infrared Astronomical Satellite was developed and operated by the Netherlands Agency for Aerospace Programs (NIVR), the US National Aeronautics and Space Administration (NASA), and the UK Science and Engineering Research Council (SERC).
To be classified as an outflow source, however, a high-velocity emission region has traditionally been required to meet a number of criteria. Molecular outflow sources are usually required to have velocity widths at zero intensity greater than 10 km s\(^{-1}\) and to be spatially localized within a cloud (Lada 1985). In addition, their morphology is often bipolar. All of the outflow candidates identified in the survey have velocity widths greater than 10 km s\(^{-1}\) and most of the candidates are less than 10' in size at the half intensity level. However, in the data taken for this survey only three show obvious bipolar structure, and only four show evidence of both a red and a blue wing.

It is possible that some of the high-velocity emission in the cloud is not associated with classical molecular outflow. For example, from composite spectra of the Rosette molecular cloud in the \(J = 1-0\) transitions of \(^{12}\)CO and \(^{13}\)CO Blitz and Stark (1986) discovered wings with velocity dispersions about 3 times that of the line cores. These wings were too weak to be detected in individual, short integration spectra. Blitz and Stark interpreted these wings as evidence of a tenuous (average density = 2 cm\(^{-3}\)), but pervasive, molecular interclump medium in which denser molecular clumps are embedded. Presented in Figure 2.3 are three composite spectra of the Mon OB1 cloud: the average of all positions in the survey, the average of all positions in the survey thought to have wings, and the average of all positions in the survey where wings were not detected. From even a casual inspection of the figure one can see that regions exhibiting high-velocity
Figure 2.3: Composite average spectra of (a) all 1319 positions surveyed in the Mon OB1 molecular cloud, (b) only those positions where high-velocity emission was detected, and (c) those positions where high-velocity emission was not detected. Peak temperatures of the spectral lines are 4.3, 7.6, and 4.1 K in (a), (b), and (c), respectively. Note the strong wings in (b) and the lack of wings in (a) and (c).
emission occupy a small enough fraction of the total projected area of the cloud that beam dilution makes them undetectable in the total cloud average. In fact, the total average line profile of the cloud can be fitted with the sum of two narrow (FWHM $\approx 3.5$ km s$^{-1}$ and 4.2 km s$^{-1}$) Gaussian functions, leaving residuals with rms dispersion of less than 0.04 K in amplitude over the velocity range where wings would occur. Therefore, in contrast to the results reported concerning the Rosette molecular cloud, I find no evidence for a pervasive high-velocity molecular component in the Mon OB1 molecular cloud. It is possible that the weak, extended component of high-velocity gas in the southern portion of the cloud could represent such a tenuous interclump medium occupying a smaller region than that observed in the Rosette molecular cloud. However, because the extended high-velocity blue emission in the WEC is associated with a large, well-defined, bipolar flow and the red, high-velocity emission surrounds the five much stronger and distinct high-velocity emission peaks all associated with IRAS sources, it seems more likely that the WEC is a result of the overlap of a number of discrete molecular outflow sources. Moreover, I conclude that all the high-velocity regions identified as outflow candidates are probably molecular outflow sources. It is possible that the wings in the composite spectrum of the observations of the Rosette molecular cloud are also due to outflow activity in that cloud which is of a more vigorous nature than that in the Mon OB1 cloud.

The interpretation, that the extended component of high-velocity gas is a
result of the overlapping of multiple outflows generated in the southern portion of
the cloud, suggests that outflows may have a profound influence on the dynamics
and structure of the Mon OB1 molecular cloud. It is possible that over relatively
large portions of the cloud, its structure is dominated by a clumpy complex of
interacting and overlapping shells or sheets generated by evolved flows. Such a
model could reconcile the apparent paradox that although relatively large densities
(i.e., \( n_{\text{H}_2} > 300-1000 \text{ cm}^{-3} \)) are needed to significantly populate the lowest levels
of the CO molecule, the estimated mean volume density of the cloud is quite
low (\( \approx 50 \text{ cm}^{-3} \)). Furthermore, the outflows may deposit sufficient mechanical
energy to support this cloud against collapse. For example, using a typical velocity
dispersion of 6 km s\(^{-1}\) (FWHM of the spectral line in Figure 2.3c) and a size of
15 pc, the Mon OB1 molecular cloud has a virial mass of \( 3 \times 10^4 M_\odot \), a binding
energy of \( 6 \times 10^{48} \text{ ergs} \), and a dynamical crossing time of \( 5 \times 10^6 \text{ yr} \). Under the
assumption that the time scale for turbulent energy dissipation is short compared
to a dynamical crossing time, turbulent energy must be injected into such a cloud
at a rate of \( 4 \times 10^{34} \text{ ergs s}^{-1} \) to support it against gravitational collapse. A
lower limit to the mechanical luminosity available to be input into the cloud by
flows can be determined from the spectrum in Figure 2.3b by calculating the
mass in each channel in the wings of the line (using a typical flow excitation
temperature of 10 K, a filling factor of 0.5, an abundance ratio of \(^{12}\text{CO}\) to \(^{13}\text{CO}\)
of 89, and a beam/source coupling efficiency of 0.3) and letting the luminosity
in each channel (following Margulis and Lada 1985) be equal to the mass times the cube of the velocity from line center in each channel divided by twice the typical outflow size ($\approx 0.6$ pc). After correcting for low-velocity outflow hidden in the line core and for typical outflow inclination, I find that the total mass and lower limit to the mechanical luminosity in outflows in the Mon OB1 cloud are $76 \, M_\odot$ and $4 \times 10^{34}$ ergs s$^{-1}$, respectively. This mechanical luminosity is enough, in terms of strict energy balance to support the cloud against collapse. Moreover, recent N-body simulations of interacting gas fragments in interstellar clouds suggest that turbulent energy dissipation in molecular clouds may occur on a time scale as much as 10 times longer than a cloud free fall time (Scalo and Pumphrey 1982), indicating that in order for flows to support the Mon OB1 cloud, outflow mechanical luminosity may only have to be injected into the ambient cloud with an efficiency of 10%. Further, my estimate of the total outflow mechanical luminosity is a lower limit and may be as much as an order of magnitude below the actual value. I conclude, therefore, that outflow activity has a significant impact on the dynamical state of the Mon OB1 cloud and that outflows are capable of supporting the cloud against collapse. The results of more detailed calculations which confirm this conclusion are presented in Chapter 3.

On the basis of previous observations, molecular outflows are believed to be driven by young stellar objects. However, most previous searches for molecular outflows have been biased towards those flows associated with such objects. It
is therefore of interest to ask the question whether a survey without this bias will show the same association. The IRAS point source density in the region I surveyed is 20.5 sources per square degree. Since the background point source density in nearby regions of the sky is two sources per square degree, it is likely that 90% of the sources identified using the selection criteria detailed above are young stellar objects embedded in the Mon OB1 molecular cloud. By comparing infrared positions with the positions of outflow candidates it can be seen in Figure 2.1 that seven of the nine regions of high-velocity emission lie near an IRAS point source. However, one of these regions (at $\alpha_{1950} = 6^h 38^m 33^s$, $\delta_{1950} = 9^\circ 58' 28''$) is highly collimated and bipolar and the position of the IRAS source is not between the two lobes. As a result, six of the nine outflow regions might be physically associated with an IRAS source. It is possible that the remaining three outflow sources are associated with objects whose infrared luminosities were too low to be detected by IRAS. For example, I estimate that I could have detected 25 $\mu$m IRAS emission from an object at the distance of the Mon OB1 cloud with an energy distribution similar to L1551 IRS 5 if its bolometric luminosity was greater than 5 $L_\odot$, a luminosity much less than that of IRS 5 itself (i.e., 30 $L_\odot$). Apparently the three outflows without IRAS sources are either associated with sources of significantly lower bolometric luminosity than L1551 IRS 5 or objects of similar or greater luminosity but with more steeply rising energy distributions. Objects of the latter type would be detected in our 60 or 100 $\mu$m maps, but no obvious candidates were
found near the three outflows. Therefore, any sources present probably fall into the former category. Such objects could be either young stellar objects similar in nature to the IRAS sources and known pre-main sequence stars in the cloud but of lower mass or prestellar objects in an extremely early stage of evolution; a stage in which detectable molecular outflow precedes a detectable infrared source. It is interesting to note that the three outflows without associated IRAS sources are all situated in regions where the observed CO line-core temperatures are relatively low. As a result it is possible that even low luminosity sources can drive detectable outflows in these regions since ambient gas densities are also likely to be low.

There are quite a few IRAS point sources in the direction of the Mon OB1 molecular cloud without associated high-velocity molecular emission. In all, 24 of the 30 embedded IRAS point sources in the cloud are not likely to be physically associated with regions of high-velocity emission. If all stars as luminous as the IRAS sources detected in our survey undergo a period of outflow during their early evolution (as has been suggested in previous studies, e.g. Lada 1985) then these numbers suggest that embedded IRAS point sources may spend roughly under a fifth of their lifetimes in the outflow phase. Further, if all flows turn out to be powered by central stars, each of these 24 sources without associated high-velocity emission must either be in the preoutflow or postoutflow periods of their evolution. Preoutflow objects could be extremely young and very possibly protostellar in nature. On the other hand, this result could indicate that the
frequency of outflow activity has been previously overestimated and that only 20% of young stellar objects go through such a phase. Studies of the spectral energy distributions of these sources might enable a distinction between these possibilities. I present the results of such studies in Chapter 4.

Finally I point out that outflows and IRAS sources are found throughout the cloud. This suggests that all stages of star formation are more or less simultaneously present everywhere in the cloud. However, the great majority of the outflows and most of the infrared sources are located in the southern portion of the cloud in a region roughly co-extensive with the open cluster/association (NGC 2264/Mon OB1). This suggests that the overall rate of star formation has been higher in this region. Apparently, the presence of the large nucleus of visible stars in this direction is not merely due to the destruction of the cloud by OB stars and the subsequent unveiling of an underlying embedded population similar in density to that in less disturbed regions of the cloud.

I also conclude that none of the previously suggested objects, i.e. Herbig-Haro objects, IRAS point sources, T Tauri stars, or CO peaks, are particularly good tracers of the distribution of outflow sources. The only way to make unbiased searches for molecular outflows is through observations of emission from the high velocity molecular gas itself.
CHAPTER 3

MOLECULAR OUTFLOWS IN THE MONOCEROS OB1 DARK CLOUD

In this chapter I present follow-up observations of the outflows identified in the survey presented in Chapter 2. Made both with higher resolution and sensitivity than that of the survey, these observations provide a detailed look at the morphologies and energetics of outflows in the Monoceros OB1 dark cloud. In this chapter outflows in the cloud are compared with those in general, the frequency of occurrence of outflows in the Mon OB1 cloud is used to estimate the number and birthrate of outflows in the solar neighborhood, and the question of cloud support by outflows is considered in detail. In addition, the effects of individual outflows on their local environment are considered. These observations are important for our understanding of outflows and molecular clouds since they provide the first detailed view of outflow activity in an entire molecular cloud.

Observations

Using the NRAO 12 m telescope during 1985 October and 1986 June and the FCRAO 14 m telescope during 1985 May and 1986 April, I (in collaboration with Charlie Lada and Ron Snell) have made maps of emission from the $J=1-$
transition of CO in the area surrounding each of the nine molecular outflows identified previously in the Monoceros OB1 dark cloud. These maps were uniformly sampled at 1' spacing and with resolutions of 66'' and 45'' using the NRAO and FCRAO telescopes, respectively. The sources were generally mapped outward from the position of strongest high-velocity emission detected in the original survey until wing emission could not be seen at the boundary of the flows. The weak, extended high-velocity emission identified previously in the southern portion of the cloud and surrounding the outflows identified there was also mapped. Each position in the maps was observed for an integration time of five or ten minutes, dependent on weather conditions and the strength of the high-velocity emission being observed. Observations were made primarily with a spectral resolution of 250 kHz or 0.65 km s⁻¹ although in many cases observations using 500 kHz filter-banks were also obtained. The temperature scale for each spectrum was calibrated using the chopper wheel method (Ulich and Haas 1976) and after correcting for forward scattering and spillover losses is expressed as $T_R$ (Kutner and Ulich 1981). An additional correction to the temperature scale was made using observations of emission from the position $\alpha_{1950} = 6^h38^m25^s$, $\delta_{1950} = 9^\circ32'27''$ in the Mon OB1 cloud. In order to construct a self-consistent database from the data taken on the four telescope runs, all spectra taken on the NRAO 12 m and FCRAO 14 m telescopes were scaled so that the peak temperature at this position was about 20 K. This value was estimated from the peak antenna temperatures ($T_R$) measured
at this position using the NRAO and FCRAO telescopes. In general, presumably because the beamsizes (66'' vs. 45'') and forward spillover and scattering efficiencies (0.75 vs. 0.70) of the NRAO and FCRAO telescopes are not very different, this correction did not result in a relative change of scale between the two data sets of more than a few percent. We expect errors in the absolute temperatures to be no higher than 15%. With only a few exceptions, for which quadratic baselines were subtracted, linear baselines were subtracted from each of the spectra. All spectra were taken in position switch mode in order to ensure flat baselines. The rms noise achieved was typically between 0.1 and 0.3 K. For a short description of the equipment and techniques used to obtain and calibrate this data see Appendix A.

**Results**

Information on the position and morphology of each of the nine outflows identified in the Mon OB1 cloud is displayed in Table 3.1. Outflows names, right ascensions, declinations, major axis radii ($R_{\text{max}}$), minor axis radii ($R_{\text{min}}$), weighted areas ($A_w$), and collimation factors ($R_{\text{coll}} = R_{\text{max}}/R_{\text{min}}$) are listed in columns one through seven, respectively. For the monopolar outflows the right ascensions and declinations listed are the positions at the geometric centers of the high-velocity emission. For bipolar outflows the coordinates given are those for the centroids of the redshifted and blueshifted lobes of emission. The sizes
TABLE 3.1

OUTFLOW POSITIONS AND MORPHOLOGIES

<table>
<thead>
<tr>
<th>Outflow</th>
<th>$\alpha_{1950}$</th>
<th>$\delta_{1950}$</th>
<th>$R_{\text{max}}$ (pc)</th>
<th>$R_{\text{min}}$ (pc)</th>
<th>$A_w$ (pc²)</th>
<th>$R_{\text{coll}}$</th>
<th>Telescopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$6^h39^m58^s$</td>
<td>9°16'20&quot;</td>
<td>0.70</td>
<td>0.46</td>
<td>0.83r</td>
<td>1.5</td>
<td>NRAO</td>
</tr>
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<td>B</td>
<td>$6^h38^m37^s$</td>
<td>9°27'40&quot;</td>
<td>0.38</td>
<td>0.17</td>
<td>0.25r</td>
<td>2.2</td>
<td>FCRAO</td>
</tr>
<tr>
<td>C</td>
<td>$6^h38^m26^s$</td>
<td>9°32'00&quot;</td>
<td>0.24</td>
<td>0.24</td>
<td>0.27r</td>
<td>1.0</td>
<td>FCRAO, NRAO</td>
</tr>
<tr>
<td>D</td>
<td>$6^h38^m19^s$</td>
<td>9°37'32&quot;</td>
<td>1.21</td>
<td>0.64</td>
<td>0.58r</td>
<td>1.9</td>
<td>FCRAO, NRAO</td>
</tr>
<tr>
<td>E</td>
<td>$6^h37^m40^s$</td>
<td>9°39'31&quot;</td>
<td>0.71</td>
<td>0.53</td>
<td>0.61r</td>
<td>1.3</td>
<td>FCRAO, NRAO</td>
</tr>
<tr>
<td>F</td>
<td>$6^h37^m22^s$</td>
<td>9°40'40&quot;</td>
<td>0.46</td>
<td>0.30</td>
<td>0.39r</td>
<td>1.5</td>
<td>FCRAO, NRAO</td>
</tr>
<tr>
<td>G</td>
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<td>0.89</td>
<td>0.21</td>
<td>0.16r</td>
<td>4.2</td>
<td>FCRAO</td>
</tr>
<tr>
<td>H</td>
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<td>10°39'56&quot;</td>
<td>0.29</td>
<td>0.35</td>
<td>0.31r</td>
<td>0.8</td>
<td>FCRAO</td>
</tr>
<tr>
<td>I</td>
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<td>10°52'39&quot;</td>
<td>0.55</td>
<td>0.21</td>
<td>0.11r</td>
<td>2.6</td>
<td>FCRAO</td>
</tr>
</tbody>
</table>

*Weighted Area of Red Wing
bWeighted Area of Blue Wing
were measured using the contours at half of the peak wing integrated intensities of each outflow and have been corrected for a beam 55\".5 in width, a compromise between the beam sizes of the NRAO and FCRAO telescopes. The areas are the apparent emitting areas weighted by the high-velocity \(^{12}\)CO intensity distribution (following Margulis and Lada 1985) as follows:

\[
A_w = \frac{\int_{\text{flow}} T^{12}(\alpha, \delta) \, d\alpha d\delta}{T^{12}(\text{peak})}
\]

where \(T^{12}\) is the integrated intensity distribution of the wings and \(T^{12}(\text{peak})\) is the integrated intensity at the position of peak wing emission. It should be noted that these areas have been calculated without consideration of velocity structure in the sources. All sizes and areas have been expressed in units of parsecs and square parsecs using a distance to the Mon OB1 cloud of 800 pc (Walker 1956).

The telescopes used to observe each outflow are listed in column eight of the table. Note that outflow C has been previously detected (Schwartz et al. 1985) and that another outflow has been detected in the cloud but is outside of the region surveyed (R Mon, Cantó et al. 1981).

Contour maps of the nine outflows are presented in Figures 3.1 through 3.8. Red and blue wing emission are denoted by solid and dashed contours, respectively. Pluses denote the positions of IRAS point sources (identified using the criteria outlined in Chapter 2). A 0.2 pc bar is included in each figure as a fiducial size marker. Spectra showing the strongest wing emission observed from
Figure 3.1: Spectrum and contour map of the red wing of outflow A. The spectrum was taken at $\alpha_{1950} = 6^h39^m58^s$ and $\delta_{1950} = 9^\circ17'26''$. The integrated intensities used to make the contour map were calculated over a range from 12 km s$^{-1}$ to 16 km s$^{-1}$. The contour levels in the map start at 0.6 K km s$^{-1}$ and increase in steps of 0.2 K km s$^{-1}$. The 1$\sigma$ rms noise in the map is 0.17 K km s$^{-1}$. A 0.2 pc fiducial bar has been included in the map for scale.
Figure 3.2: Spectrum and contour map of the red wing of outflow B. The spectrum was taken at $\alpha_{1950} = 6^h 38^m 37^s$ and $\delta_{1950} = 9^\circ 27' 27''$. The integrated intensities used to make the contour map were calculated over a range from 10 km s$^{-1}$ to 16 km s$^{-1}$. The contour levels in the map start at 2.0 K km s$^{-1}$ and increase in steps of 1.0 K km s$^{-1}$. The $1\sigma$ rms noise in the map is 1.21 K km s$^{-1}$. Positions of IRAS point sources identified by Margulis and Lada (1986) are shown in the map as elongated pluses. In addition, a 0.2 pc bar has been included in the map for scale.
Figure 3.3: Spectrum and contour map of the red wing of outflow C. The spectrum was taken at $\alpha_{1950} = 6^h 38^m 25^s$ and $\delta_{1950} = 9^\circ 32' 27''$. The integrated intensities used to make the contour map were calculated over a range from 12 km s$^{-1}$ to 22 km s$^{-1}$. The contour levels in the map start at 2.0 K km s$^{-1}$ and increase in steps of 2.0 K km s$^{-1}$. The $1\sigma$ rms noise in the map is 0.34 K km s$^{-1}$. Positions of IRAS point sources identified by Margulis and Lada (1986) are shown in the map as elongated pluses. In addition, a 0.2 pc bar has been included in the map for scale.
Figure 3.4: Spectra and contour map of the blue and red wings of outflow D. The spectrum showing blue wing emission was taken at $\alpha_{1950} = 6^h38^m25^s$ and $\delta_{1950} = 9^\circ37'27"$. The spectrum showing red wing emission was taken at $\alpha_{1950} = 6^h38^m05^s$ and $\delta_{1950} = 9^\circ35'27"$. The integrated intensities used to make the contour map were calculated over a range from -10 to 2 km s$^{-1}$ for the blue wing emission (dashed contour lines), and over a range from 11 to 21 km s$^{-1}$ for the red wing emission (solid contour lines). The contour levels in the map start at 2.0 K km s$^{-1}$ and increase in steps of 1.0 K km s$^{-1}$ for the blue wing emission, and start at 2.0 K km s$^{-1}$ and increase in steps of 1.0 K km s$^{-1}$ for the red wing emission. The $1\sigma$ rms noise in the map is 0.44 K km s$^{-1}$ for the blue emission and 0.45 K km s$^{-1}$ for the red emission. An IRAS point source identified by Margulis and Lada (1986) is shown in the map as an elongated plus. A 0.2 pc fiducial bar has been included in the map for scale.
Figure 3.5: Spectra and contour map of the blue and red wings of outflow E and the red wing of outflow F. The spectrum at the upper right was taken at $\alpha_{1950} = 6^h37^m45^s$ and $\delta_{1950} = 9^\circ38'27''$. The spectrum at the lower right was taken at $\alpha_{1950} = 6^h37^m33^s$ and $\delta_{1950} = 9^\circ41'28''$. The spectrum at the lower left was taken at $\alpha_{1950} = 6^h37^m24^s$ and $\delta_{1950} = 9^\circ40'27''$. The integrated intensities used to make the contour map were calculated over a range from -2 km s$^{-1}$ to 2 km s$^{-1}$ for the blue emission and from 8 km s$^{-1}$ to 17 km s$^{-1}$ for the red emission. The contours denoting the blue wing emission in the map (dashed lines) start at 0.5 K km s$^{-1}$ (bottom right and top left of the map) and increase in steps of 0.5 K km s$^{-1}$ in the peak in the bottom left and towards the upper right portion of the map. The contours denoting red wing emission in the map (solid lines) start at 1.0 K km s$^{-1}$ and increase in steps of 1.0 K km s$^{-1}$. The blue wing of outflow E is the dashed peak at the bottom left. The red wings of outflows E and F are the solid peaks near the center of the map and right of center, respectively. The 1σ rms noise in the map is 0.34 K km s$^{-1}$ for the blue emission and 0.45 K km s$^{-1}$ for the red emission. IRAS point sources identified by Margulis and Lada (1986) are included in the map as elongated pluses. A 0.2 pc fiducial bar has also been included for scale.
Figure 3.5: Molecular outflows E and F.
Figure 3.6: Spectra and contour map of the blue and red wings of outflow G. The spectrum showing blue wing emission was taken at $\alpha_{1950} = 6^h38^m21^s$ and $\delta_{1950} = 9^\circ58'28''$. The spectrum showing red wing emission was taken at $\alpha_{1950} = 6^h38^m41^s$ and $\delta_{1950} = 9^\circ58'58''$. The integrated intensities used to make the contour map were calculated over a range from -35 km s$^{-1}$ to 0 km s$^{-1}$ for the blue wing emission (dashed contours) and from 10 km s$^{-1}$ to 40 km s$^{-1}$ for the red wing emission (solid contours). The contour levels in the map start at 4.0 K km s$^{-1}$ and increase in steps of 1.0 K km s$^{-1}$ for the blue wing emission, and start at 7.5 K km s$^{-1}$ and increase in steps of 2.5 K km s$^{-1}$ for the red wing emission. The 1$\sigma$ rms noise in the map is 2.85 K km s$^{-1}$ for the blue emission and 2.02 K km s$^{-1}$ for the red emission. A 0.2 pc fiducial bar has been included in the map for scale.
Figure 3.7: Spectra and contour map of the blue and red wings of outflow H. The spectrum showing blue wing emission was taken at $\alpha_{1950} = 6^h38^m17^s$ and $\delta_{1950} = 10^\circ40'27''$. The spectrum showing red wing emission was taken at $\alpha_{1950} = 6^h38^m17^s$ and $\delta_{1950} = 10^\circ39'26''$. The integrated intensities used to make the contour map were calculated over a range from 0 km s$^{-1}$ to 3 km s$^{-1}$ for the blue wing emission, and from 10 km s$^{-1}$ to 30 km s$^{-1}$ for the red wing emission. The contour levels in the map start at 1.5 K km s$^{-1}$ and increase in steps of 0.5 K km s$^{-1}$ for the blue emission, and start at 2.0 K km s$^{-1}$ and increase in steps of 2.0 K km s$^{-1}$ for the red wing emission. The 1$\sigma$ rms noise in the map is 0.65 K km s$^{-1}$ for the blue emission and 2.15 K km s$^{-1}$ for the red emission. An IRAS point source identified by Margulis and Lada (1986) is included in the map as an elongated plus. A 0.2 pc fidicial bar has also been included in the map for scale.
Figure 3.8: Spectra and contour map of the blue and red wing emission of outflow I. The spectrum showing blue wing emission was taken at $\alpha_{1950} = 6^h38^m21^s$ and $\delta_{1950} = 10^\circ54'26"$. The spectrum showing red wing emission was taken at $\alpha_{1950} = 6^h38^m17^s$ and $\delta_{1950} = 10^\circ51'27"$. The integrated intensities used to make the contour map were calculated over a range from -10 km s$^{-1}$ to 2 km s$^{-1}$ for the blue wing emission and from 10 km s$^{-1}$ to 15 km s$^{-1}$ for the red wing emission. The contour levels in the map start at 1.25 K km s$^{-1}$ and increase in steps of 0.75 K km s$^{-1}$ for the blue wing emission, and start at 1.5 K km s$^{-1}$ and increase in steps of 0.75 K km s$^{-1}$ for the red wing emission. The 1$\sigma$ rms noise in the map is 0.89 K km s$^{-1}$ for the blue emission and 0.72 K km s$^{-1}$ for the red emission. A 0.2 pc fiducial bar has been included in the map for scale.
each flow are also shown in the figures and their positions are given in the figure captions. The velocity intervals used to calculate the integrated intensities displayed in these maps are also listed in the figure captions along with the rms noise in the integrated intensities for each map. As is evident from the figures, each of the outflows which was identified in the Mon OB1 cloud is well defined, standing out clearly from the background noise. It should be noted, however, that outflows E and F (shown in Figure 3.5) may, in fact, be portions of a single outflow.

In the original survey described in Chapter 2, these two regions of high-velocity gas appeared to be separate from each other. The higher-sensitivity observations presented here, however, show that there is a bridge of high-velocity emission between the two red wings previously identified. As a result it is not clear whether the observed high-velocity emission in this region arises from one outflow with a somewhat unusual morphology, or from two overlapping but morphologically simpler outflows. Since two IRAS sources have been identified near these wings, and since the angle between the red and blue wings would have to be 135° were this a single outflow, I have chosen to continue to consider these objects as two separate outflows, consistent with the results of the original survey. While doing so does affect the nomenclature in this paper, it has little effect on the conclusions or results concerning the physical conditions in the Mon OB1 cloud.

Information on the masses and energetics of the outflows is presented in Table 3.2. Outflow identifications, velocity widths, dynamical timescales, masses,
TABLE 3.2
OUTFLOW MASSES AND ENERGETICS

<table>
<thead>
<tr>
<th>Outflow</th>
<th>$\Delta v^a$ (km s$^{-1}$)</th>
<th>$\tau_d$ (years)</th>
<th>M ($M_\odot$)</th>
<th>MV ($M_\odot$ km s$^{-1}$)</th>
<th>L ($L_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11.1</td>
<td>9.2x10$^4$</td>
<td>0.58 - 1.1</td>
<td>2.1 - 8.3</td>
<td>.0041 - .056</td>
</tr>
<tr>
<td>B</td>
<td>13.0</td>
<td>4.2x10$^4$</td>
<td>1.4 - 2.9</td>
<td>7.4 - 26.</td>
<td>.056 - .44</td>
</tr>
<tr>
<td>C</td>
<td>31.2</td>
<td>1.1x10$^4$</td>
<td>1.6 - 7.2</td>
<td>11. - 150.</td>
<td>.32 - 25.</td>
</tr>
<tr>
<td>D</td>
<td>26.0</td>
<td>6.9x10$^4$</td>
<td>16. - 30.</td>
<td>92. - 520.</td>
<td>.36 - 11.</td>
</tr>
<tr>
<td>E</td>
<td>11.1</td>
<td>9.7x10$^4$</td>
<td>0.50 - 2.5</td>
<td>2.8 - 18.</td>
<td>.011 - .11</td>
</tr>
<tr>
<td>F</td>
<td>13.0</td>
<td>5.1x10$^4$</td>
<td>1.2 - 1.4</td>
<td>3.9 - 12.</td>
<td>.014 - .17</td>
</tr>
<tr>
<td>G</td>
<td>54.6</td>
<td>1.8x10$^4$</td>
<td>1.3 - 1.9</td>
<td>26. - 93.</td>
<td>1.9 - 21.</td>
</tr>
<tr>
<td>H</td>
<td>27.3</td>
<td>1.2x10$^4$</td>
<td>1.6 - 2.3</td>
<td>17. - 53.</td>
<td>1.1 - 8.2</td>
</tr>
<tr>
<td>I</td>
<td>18.2</td>
<td>3.9x10$^4$</td>
<td>0.14 - 0.22</td>
<td>1.0 - 3.1</td>
<td>.010 - .092</td>
</tr>
</tbody>
</table>

$^a$These values are the greatest velocity widths observed in individual spectra of each outflow. In cases in which the red and blue lobes of an outflow are spatially separate the total red to blue extents may be significantly greater than these values. For example, from the spectra shown in Figure 6 it can be seen that the total red to blue extent of outflow G is 88 km s$^{-1}$, a value much larger than that given in the table.
momenta, and mechanical luminosities are listed in columns one through six. Velocity widths are full widths, measured from the bluest to the reddest velocities at which outflow emission was observed in individual spectra of each outflow. Dynamical timescales listed were calculated by dividing the major axis radius (listed in Table 3.1) by the greatest velocity from line-center observed for each outflow.

Masses in Table 3.2 were calculated by assuming that the excitation temperature \( T_{ex} \) for the J=1-0 transition of the CO gas was the higher of either 10 K or the peak temperature of the CO emission at the position of strongest high-velocity emission for each outflow lobe. It was also assumed that the filling factor \( f \) for each outflow was 0.5, the beam/source coupling efficiency \( \eta_c \) was 0.775, and the abundance ratio of \(^{12}\text{CO} \) to \( \text{H}_2 \) in each flow was \( 2.2 \times 10^{-4} \) (89 x 2.5 x \( 10^{-6} \), Dickman 1978). A filling factor of 0.5 is typical for CO in outflows (Snell et al. 1984, Margulis and Lada 1985). A beam/source coupling efficiency of 0.775 was chosen as a compromise between the main beam efficiencies of the FCRAO (0.73) and NRAO (0.82) telescopes. Adoption of this mean value will cause mass estimates made with the FCRAO and NRAO data to be slight underestimates and overestimates respectively (i.e. by a few percent). In addition, using a main beam coupling efficiency as an approximation to the actual beam/source coupling efficiency probably adds an additional, albeit small error since the outflow sources in the Mon OB1 cloud are generally larger than a telescope beam. This error is likely to be very small since the outflows are not very extended on the sky and
the error patterns of the telescopes at 115 GHz are very weak. In general, these errors are also very small compared to other systematic errors inherent in outflow mass determinations (for a discussion of these errors, which may be as large as factors of two or three, see Margulis and Lada 1985 and Snell 1987) and therefore should not have a significant effect on the results of this paper. Adoption of a $^{12}$CO to $\text{H}_2$ abundance ratio of $2.2 \times 10^{-4}$ is a much more important assumption. A ratio half this value will increase the mass estimates presented here by a factor of two. Furthermore, I have not accounted for hidden gas in the outflow if the $^{12}$CO emission is optically thick. If so, then the values calculated in this paper are underestimates. In any case, the mass of each outflow was calculated according to the following prescription: For the position in each outflow where wing emission in $^{12}$CO spectra was strongest, optical depths ($\tau_{12}$) were calculated for each channel in the wings using:

$$T_R^* = f \eta_c [J(\nu, T_{ex}) - J(\nu, T_{bg})][1 - \exp(-\tau_{12})]$$

where $T_{bg} = 2.7 \text{ K}$, $\nu = 115 \text{ GHz}$, and:

$$J(\nu, T) = \frac{h\nu}{k} [\exp\left(\frac{h\nu}{kT}\right) - 1]^{-1}$$

The column density in each channel was calculated using:

$$N^{12} = 2.38 \times 10^{14} (T_{ex} + 0.91)[1 - \exp\left(-\frac{h\nu}{kT_{ex}}\right)]^{-1} \tau_{12} \Delta \nu \text{ cm}^{-2}$$
where $\Delta v$ is the channel width in km s$^{-1}$. The total mass in each channel was then calculated using the $^{12}$CO to $\text{H}_2$ abundance ratio quoted above and the weighted wing areas ($A_w$) presented in Table 3.1 so that for each channel:

$$M_{ch}(\text{M}_\odot) = 7.2 \times 10^{-17} \text{N}^{12}(\text{cm}^{-2}) A_w (\text{pc}^2)$$

The amount of outflowing mass at low-velocities, the emission from which is hidden by the line-core, was estimated by assuming that the mass in each channel from line-center to the highest velocity in the line-core is equal to the mass calculated for the lowest velocity channel in the line-wing. The total mass of each outflow was then calculated in two ways. A lower limit for the mass was found by summing the masses in the individual channels in the line-wings. In calculating this limit no correction was made in order to account for low-velocity outflow material hidden by the line-core. An upper limit to the mass was found by summing the masses in both the line-core and wings. Both limits are presented in Table 3.2.

The momentum carried by each outflow was also calculated in two ways. One way was to sum over the channels in the line-wings the product of the mass in each channel times its line-of-sight speed (as measured from line-center). Another way was to multiply the total mass (upper limit) of the flow by the highest velocity from line-center at which emission was seen in the line-wings. As discussed in Margulis and Lada (1985) the first method assumes no correction is necessary to account for the inclination of the outflow to the line-of-sight while the second
method assumes that all material is moving at a speed equal to the highest outflow speed observed. Note in addition that in the first method no correction has been made to account for low-velocity outflow emission hidden by the line-core. As a result, the two values calculated for the momentum of each outflow can be taken as lower and upper limits respectively. Both limits are presented in Table 3.2.

The mechanical luminosity of each outflow was calculated in two ways as well: by summing over the channels in the line-wings the product of the mass in each channel and the cube of the line-of-sight speed and then dividing the result by twice the major axis radius (from Table 3.1) of the flow, and by multiplying the total mass (upper limit) of the flow by the cube of the highest velocity from line-center at which emission was seen in the line-wings and dividing this result by twice the major axis radius of the flow. As in the case of the calculated values of the momenta of the outflows, these two methods produced lower and upper limits for the mechanical luminosities of the outflows. Both limits are presented in Table 3.2.

Discussion

The detailed results presented herein have important implications for our understanding of the frequency of occurrence and general properties of outflows. In addition, these results provide a unique opportunity to assess in detail the effects of outflows on molecular clouds and to evaluate whether outflows can support the
Mon OB1 cloud against collapse. These issues are discussed below.

Frequency of Occurrence of Outflows in the Solar Neighborhood

Nine outflows have been identified in the Mon OB1 cloud, a cloud comprised of about $3 \times 10^4$ $M_\odot$ of material (Chapter 2). If the Mon OB1 cloud is a typical molecular cloud, then in the solar neighborhood there is at least one molecular outflow for every $3 \times 10^3$ $M_\odot$ of gas and dust. This suggests that outflows are much more abundant in the solar neighborhood than has been previously thought. For example, before unbiased surveys had been performed, 14 outflows (positions taken from Lada 1985 and Fischer et al. 1985) had been identified in Orion molecular clouds A and B ($M = 1.8 \times 10^5$ $M_\odot$, Maddalena et al. 1986), 2 outflows (Lada 1985) had been identified in the Mon R2 molecular cloud ($M = 9 \times 10^4$ $M_\odot$, Maddalena et al. 1986), 2 outflows (Lada 1985 and Cantó et al. 1981) had been identified in the entire Monoceros OB1 molecular cloud complex ($M = 5 \times 10^4$ $M_\odot$, Blitz 1980), 1 outflow (Lada 1985) had been identified in the Cepheus OB3 molecular cloud complex ($M = 5 \times 10^3$ $M_\odot$, Sargent 1979), 17 outflows (Lada 1985, Goldsmith, Langer, and Wilson 1986, Heyer et al. 1987) had been identified in the Taurus and Perseus clouds ($M = 2 \times 10^5$ $M_\odot$, Ungerechts and Thaddeus 1986), and 2 outflows (Lada 1985) had been identified in the Cygnus R1 and W75N clouds ($M = 2 \times 10^4$ $M_\odot$, Blitz 1980). These numbers suggested that on average for molecular clouds within one kiloparsec of the sun there was only one outflow for every
$2 \times 10^4 \, M_\odot$ of material, a frequency of detection about 6 times lower than that derived from the unbiased survey presented in Chapter 2. The high frequency of occurrence of outflows derived from this unbiased survey suggests that there are at least 6 times as many outflows in the solar neighborhood than has been previously thought. This raises the number of outflows within 1 kpc of the sun from about 50 (Lada 1985) to 300. It should be noted, however, that the number of molecular outflows in particular molecular clouds may go up by a considerably higher or lower factor than this. In the case of the portion of the Mon OB1 cloud searched for this thesis, for example, the number of outflows known was increased by a factor of nine. On the other hand, in the case of the Orion A cloud, a similar unbiased survey (Fukui et al. 1986) only increased the number of known outflows there by at most a factor of two. Prior to unbiased surveys, molecular clouds in the solar neighborhood were searched for molecular outflows in a very haphazard way. As a result the factor of six quoted here must be taken as an average value.

The high frequency of occurrence of outflows in molecular clouds in the solar neighborhood suggests that they also have a very high birthrate. If at least 300 outflows, each with a lifetime of about $5 \times 10^4$ yrs, exist within one kiloparsec of the sun, then their birthrate in the solar neighborhood is at least $2 \times 10^{-3} \, \text{yr}^{-1} \, \text{kpc}^{-2}$. This birthrate is about three times the birthrate of one solar mass stars in the solar neighborhood ($6 \times 10^{-4} \, \text{yr}^{-1} \, \text{kpc}^{-2}$, birthrate extrapolated from those in Ostriker, Richstone, and Thuan 1974) and suggests that outflow
may be part of a stage of early stellar evolution common to all stars with masses much greater than the sun's. It should be noted, however, that the typical outflow lifetime used to calculate this birthrate may be a lower limit to the actual value (Cantó, Dyson, and Rodriguez 1987). It is possible, as suggested by Cantó et al., that the true lifetimes of outflows may be as long as a million years. In this case the birthrate quoted above may be a considerable overestimate. However, even a revised, lower birthrate of very long-lived outflows should still be as high as that for 2 $M_\odot$ stars in the solar neighborhood (Ostriker et al. 1974). Clearly outflow is a common occurrence in the solar neighborhood and is part of a common stage in early stellar evolution as well. Very high rates of detection of outflows in searches conducted toward young stellar objects in dark cloud cores (44%, Myers et al. 1987), embedded infrared objects (71%, Bally and Lada 1983), and objects listed as infrared protostars ($\geq 85\%$, Wynn-Williams 1982) lend support to this conclusion.

Outflows in the Mon OB1 Cloud Compared with those in General

Presented in Figures 3.9 through 3.12 are the frequency distributions of the major axis radii, minor axis radii, collimation factors, and velocity widths of outflows identified in the Mon OB1 cloud (solid lines), and of outflows discovered prior to this survey (dashed lines, data taken from Tables 2 and 3 in Lada 1985). To aid in comparison, the two distributions in each figure are displayed on different
Figure 3.9: Frequency distributions of the major axis radii of outflows in the Mon OB1 cloud (solid line, left axis of ordinates) and of outflows identified prior to unbiased surveys (dashed line, right axis of ordinates).
Figure 3.10: Frequency distributions of the minor axis radii of outflows in the Mon OB1 cloud (solid line, left axis of ordinates) and of outflows identified prior to unbiased surveys (dashed line, right axis of ordinates).
Figure 3.11: Frequency distributions of the collimation factors of outflows in the Mon OB1 cloud (solid line, left axis of ordinates) and of outflows identified prior to unbiased surveys (dashed line, right axis of ordinates).
Figure 3.12: Frequency distributions of the velocity widths of outflows in the Mon OB1 cloud (solid line, left axis of ordinates) and of outflows identified prior to unbiased surveys (dashed line, right axis of ordinates).
scales related by the ratio of the number of sources in each distribution. As is clearly evident in these figures, outflows in the Mon OB1 cloud have morphologies and velocity widths similar to those of outflows in general. In addition, it is clear that the morphological properties and velocity widths of outflows in the Mon OB1 cloud are as diverse as those in general. There is, however, one obvious difference between the outflows observed in the Mon OB1 cloud and those in the general sample. As can be seen from the maps of the outflows (Figures 3.1 through 3.8), only five (outflows D, E, G, H, and I) of the nine observed show evidence of both red and blue high-velocity emission. The rest are monopolar with only red wing emission showing. In contrast, in the general sample (Lada 1985) 82% of the outflows for which morphology is described show evidence of both red and blue high-velocity emission. There are a number of possible reasons for the apparent lack of blue wing emission in outflows in the Mon OB1 cloud. It is possible, for example, that some of the outflows identified in this survey actually have monopolar structure, and that the monopolar outflow is a physically distinct phenomenon from the bipolar outflow. In this case monopolar outflows are likely to be more common than previously supposed since a greater percentage of outflows identified in the unbiased survey of the Mon OB1 cloud are monopolar (44%) than in the general sample (18%). However, in the case of the outflows in the Mon OB1 cloud, this explanation is unappealing since all four sources have only red wings. A second possibility is that the monopolar outflows identified here are
near the front-side surface of the molecular cloud in which they are embedded. Such an explanation has been used before in the case of the monopolar outflow associated with B5-IRS3 (Goldsmith et al. 1986). In this case it is possible that only one of the ionized jets in each of these outflows is impacting the molecular cloud and thus these outflows have only one molecular jet. The fact that the southern portion of this cloud, where all of the monopolar outflows are situated, is a region in which star formation is actively taking place on the near side of the cloud (as evidenced by Mon OB1) lends some credence to this suggestion. However, a high extinction ($A_v \approx 10x(H-K) \approx 26$ mag for Allen’s infrared source, H and K magnitudes taken from Allen 1972) to at least one of the embedded infrared sources in this region suggests that at least some of the sources of outflow in this region are, in fact, deeply embedded in the cloud. This possibility, as an explanation of the monopolar morphology of all four outflows, therefore seems unlikely. A third possibility is that in a number of cases the survey and follow-up observations were just not sensitive enough in order to detect blue high-velocity emission from each of the outflows. It is well known that blue outflow emission is often weaker in intensity than the corresponding red emission (Bally and Lada 1983). The fact that only four outflows (D, E, G, and I) showed evidence of both blue and red wing emission in the original survey (Chapter 2) while five show such evidence in the higher sensitivity, follow-up observations presented here suggests that this possibility may be correct. I suspect, therefore, that this is, in fact, the
correct explanation for the large number of monopolar outflows in the Mon OB1 cloud.

Presented in Figures 3.13 through 3.15 are frequency distributions of the masses, momentum supply rates, and mechanical luminosities of the outflows identified in the Mon OB1 cloud and of outflows in the general sample. The values used for the masses of flows in the Mon OB1 cloud are the upper limits in listed in Table 3.2. The values used for the momentum supply rates of flows in the Mon OB1 cloud were calculated by dividing the upper limits for the momenta of flows by the corresponding dynamical timescales as listed in Table 3.2. The values used for the mechanical luminosities of the flows are the upper limits listed in Table 3.2. These values were calculated in the same way as the corresponding values (taken from Lada 1985) in the general sample. The distributions were scaled in an analogous way to those presented in Figures 3.9 through 3.12. As is evident from the figures, the masses, momentum supply rates, and mechanical luminosities of the outflows discovered in the Mon OB1 cloud are similar to those of outflows in the general sample. However, there is a slight tendency for the lower mass, less energetic sources to be more abundant in the Mon OB1 cloud than in the general sample, while the most energetic, highest mass outflows in the general sample are missing in the Mon OB1 cloud. The fact that low mass, low luminosity outflows appear to be more abundant in the Mon OB1 cloud than in the general sample probably reflects the fact that previous searches for outflows have tended
Figure 3.13: Frequency distributions of the masses of outflows in the Mon OB1 cloud (solid line, left axis of ordinates) and of outflows identified prior to unbiased surveys (dashed line, right axis of ordinates).
Figure 3.14: Frequency distributions of the momentum supply rates of outflows in the Mon OB1 cloud (solid line, left axis of ordinates) and of outflows identified prior to unbiased surveys (dashed line, right axis of ordinates).
Figure 3.15: Frequency distributions of the mechanical luminosities of outflows in the Mon OB1 cloud (solid line, left axis of ordinates) and of outflows identified prior to unbiased surveys (dashed line, right axis of ordinates).
to be made towards luminous young stellar objects. It also suggests that the as yet undetected outflows in the solar neighborhood are more likely to be low luminosity sources than high luminosity ones. On the other hand, the fact that the highest luminosity sources are missing in the Mon OB1 cloud is interesting in that it suggests that the total luminosity of outflows in the cloud is not dominated by any single luminous outflow like, for example, Orion A. Instead the luminosity is spread among a number of the outflows in the cloud. A look at Table 3.2 shows, in fact, that most of the outflow luminosity comes not from one source, but from four (outflows C, D, G, and H) which combined carry well over 95% of the total mechanical luminosity of outflows in the cloud. The fact that the total outflow mechanical luminosity in the Mon OB1 cloud is distributed among a number of outflows has important implications for whether outflows can support their parent molecular clouds against collapse. The ramifications of this will be discussed below.

Outflows and the Dynamical Support of Molecular Clouds

The issue of whether outflows can support the Mon OB1 cloud against gravitational collapse was first considered in Chapter 2. In that chapter, however, the question of cloud support was considered using only the gross properties of outflow emission in the Mon OB1 cloud. In light of the more detailed information available from the follow-up data presented in this chapter, it is worthwhile to
reconsider, here, the dynamical energy balance in the Mon OB1 cloud. It was estimated in Chapter 2 that the total mass of the Mon OB1 cloud is $3 \times 10^4$ $M_\odot$ and that, in terms of strict energy balance, the total mechanical luminosity necessary to support the cloud over a free-fall time (about $5 \times 10^6$ yrs) against collapse due to gravity is $4 \times 10^{34}$ ergs s$^{-1}$. From the follow-up data presented here the total mass of outflow gas in the Mon OB1 cloud is between 24 and 50 $M_\odot$ (from Table 3.2), only 0.1 to 0.2% of the total mass of the cloud. However, the total mechanical luminosity carried by the outflows is enormous, between $1.4 \times 10^{34}$ ergs s$^{-1}$ and $2.5 \times 10^{35}$ ergs s$^{-1}$, and as in the calculation in Chapter 2 is enough, in terms of strict energy balance, to support the cloud against collapse. In fact, the timescale to dissipate the internal energy of the cloud may be greater than a free fall time (Scalo and Pumphrey 1982) making it even easier to support the cloud. The fact that the total mechanical luminosity of outflows in the cloud is so great suggests that in general outflows may indeed be the primary source of dynamical support in the Mon OB1 cloud. However, there are two difficulties associated with this idea. First, the question of whether outflows can support their parent clouds against gravitational collapse depends on the efficiency with which outflows impart energy into the surrounding medium, and second it depends on their ability to spread the mechanical luminosity of outflows throughout an entire cloud.

In order to take these considerations into account and assess most conservatively whether outflows can support the Mon OB1 cloud, it is best to consider
a worst-case scenario. In the worst case the nine molecular outflows which are observed in the Mon OB1 cloud will expand purely according to momentum conservation. In this case their driving engines have already turned off and they are coasting to a stop and sweeping up material along the way. Calculated from Table 3.2, the total radially directed momentum at present of the outflows in the Mon OB1 cloud is at least 160 $M_\odot$ km s$^{-1}$. As a result, by the time the mass in these outflows has reached a velocity of 1 km s$^{-1}$ from line-center, they will have swept up at least 160 $M_\odot$ of material. This mass is roughly 0.5% of the mass of the Mon OB1 cloud ($3 \times 10^4 M_\odot$). In the purely momentum conserving scenario, then, it should take at most 200 episodes of similar outflow activity to sweep up and accelerate to highly supersonic speeds the bulk of the Mon OB1 cloud. Consequently, in the worst-case the ability of outflows to support the Mon OB1 cloud from collapse depends on whether 200 episodes of outflow activity can occur over the time it takes for all of the turbulent energy to be dissipated from the cloud.

In general, the timescale for turbulent energy dissipation in molecular clouds is thought to be equal to or greater than their free-fall times (Scalo and Pumphrey 1982). As a result, 1800 outflows (200 episodes) formed in the Mon OB1 cloud over about $5 \times 10^6$ yrs (cloud free-fall time, Chapter 2) could support it from collapse. We note that this suggests an outflow formation rate in the cloud of $3.6 \times 10^{-4}$ yr$^{-1}$ and to be consistent with the nine presently observed outflows an outflow lifetime of $2.5 \times 10^4$ yrs. This last number is comparable to the observed
dynamical timescales of outflows (see Lada 1985 and timescales in Table 3.1). Thus it seems likely that even in the worst case momentum conserving scenario outflows should be able to pump enough energy into the cloud to support it against collapse due to gravity. In addition, the distribution of this momentum throughout the cloud should not be a problem. The main sources of outflow momentum in the cloud at the present time (outflows C, D, G, and H) are distributed relatively evenly its long north-south axis, with outflow H in the north, outflow G in the middle, and outflow pair C-D in the south near the open cluster NGC2264. The distance between them is 6-9 pc, only about twice the end-to-end size of the largest outflow in the Mon OB1 cloud (3-4 pc, outflow D), and given their present velocities it seems reasonable that by the ends of their lifetimes they may grow to sizes comparable to the typical distances between them. Furthermore, if 1800 individual outflows form over the course of a free-fall time then surely they will be able to distribute momentum evenly throughout the entire Mon OB1 dark cloud.

The purely momentum conserving, worst-case scenario discussed above is, of course, unduly pessimistic. In order to evaluate a more realistic scenario one has to take into account the inclination of the outflows to the line-of-sight, outflowing material at low velocities and hidden by the line-core, the additional energy and momentum still being pumped into the outflows by their driving sources, and the fact that turbulent energy may be dissipated from molecular clouds on timescales much longer than their free-fall times. In order to account for the incli-
nation of the outflows to the line-of-sight one must multiply the radially directed momentum quoted above by one over the average of the sine of the inclination angle or $\frac{\pi}{2}$. In order to correct for low-velocity material hidden in the line-core one must multiply the momentum by a factor of 1.4 (found experimentally by actually taking the line-core channels into account when calculating the momenta of the nine outflows). Moreover, if one assumes that the outflows are still gaining momentum from their driving sources then the momenta of the outflows should be increased by an additional factor of two if the flows are driven for an additional fifty thousand years (i.e. twice their dynamical timescales). In sum these corrections result in an actual momentum to be pumped into the ambient cloud by the nine outflows of $700 \, M_\odot \, km \, s^{-1}$, and this in turn suggests that only 40 episodes of outflow like that observed at present are necessary to sweep up the Mon OB1 cloud to 1 km s$^{-1}$. In fact, in this more realistic case 200 episodes of outflow activity are sufficient to sweep up the Mon OB1 cloud to 4.5 km s$^{-1}$, giving rise to 9 km s$^{-1}$ wide lines throughout the Mon OB1 cloud. Clearly, since this line width is greater than the actual widths observed at most positions in the Mon OB1 cloud, support of this cloud by outflows seems extremely likely. Moreover, if the turbulent energy dissipation times are much longer than their free-fall times (e.g. Scalo and Pumphrey 1982) then even fewer episodes of outflow activity may be necessary to support the cloud against collapse. Even as few as ten or twenty episodes might be able to do the job.
There may, however, be one uncomfortable consequence to the idea that outflows support the Mon OB1 cloud against collapse. If as in the worst-case scenario suggested above it takes 200 episodes of outflow activity over a free-fall time to support the Mon OB1 cloud, then this suggests a high birthrate for outflows in the cloud and perhaps an uncomfortably large star formation efficiency. As noted above, in the worst case an outflow formation rate in the cloud of $3.6 \times 10^{-4}$ yr$^{-1}$ is required. If each of these outflows is driven by a 1 $M_\odot$ star, then this suggests that over a cloud free-fall time ($5 \times 10^6$ yrs) 6% of the mass of the Mon OB1 cloud will be turned into stars. In light of the typical star formation efficiencies for clouds in our galaxy of 0.1 to 5.0% (Blaauw 1964, Duerr, Imhoff, and Lada 1982), this value seems unreasonably high. At first glance it seems to suggest that in the worst case molecular clouds must be dispersed within about a free-fall time, resulting in cloud lifetimes much shorter than current wisdom suggests ($\gtrsim 10^7$ yrs, Blitz and Shu 1980 and references therein). A closer look reveals, however, that there are a number of ways out of this dilemma. In the more optimistic than worst case scenario discussed above a considerably lower star formation rate (by a factor of about 4) is required to support the Mon OB1 cloud. In addition, if the timescale for turbulent energy dissipation in the cloud is much longer than a free-fall time (Scalo and Pumphrey 1982), then the required rate for cloud support may go down by as much as an additional order of magnitude. Finally, it is also possible that some young stellar objects may go through more than one outflow
phase. As a result the number of generations of stars formed in a cloud may be less than the number of episodes of outflows. Each of these possibilities has the potential of lowering the star formation efficiency considerably. In consequence support of the Mon OB1 cloud by outflows still seems very likely.

Consideration of these issues serves as a good illustration of the fact that the ability of outflows to support clouds and outflow birthrates are closely related problems. For example, if as in the worst-case scenario discussed above $3.6 \times 10^{-4}$ outflows per year are required to support the Mon OB1 cloud against collapse, the birthrate of outflows in the solar neighborhood should be at least $2 \times 10^{-3}$ kpc$^{-2}$ yr$^{-1}$ (calculated using the fact that there are roughly 9 large molecular clouds comprised of a total mass of $5 \times 10^5$ M$_\odot$ within a kiloparsec of the sun, see references in the “Frequency of Occurrence...” section in this chapter). This value, as high as that found earlier in this chapter, and slightly higher than that derived from the number of previously known outflows (Snell 1987), suggests that if in general outflows can support their parent clouds against collapse then their birthrates in the solar neighborhood must be relatively high, and outflows are likely to be a common phase in early stellar evolution.

It is interesting to compare the results presented here with those of Fukui et al. (1986) for their unbiased survey of the Orion A molecular cloud for molecular outflows. In that cloud Fukui et al. found nine to eleven molecular outflows inside a region containing roughly $2 \times 10^4$ M$_\odot$. These outflows are distributed over a
large portion of the cloud and have a typical spacing between them of a few parsecs. As in the case of the Mon OB1 cloud and a previous study of the Orion cloud (Bally 1982), it seems that the outflows in the Orion A cloud carry enough mechanical luminosity to support it, in terms of strict energy balance, against collapse. However, in contrast to the results reported here, this cloud is one in which the outflow luminosity is dominated by a single object, Orion A itself. When one includes that outflow in the luminosity balance in the cloud the amount of energy available for cloud support is overwhelmingly large. In fact, it has been shown (Solomon, Huguenin, and Scoville 1981) that even in the purely momentum conserving case this outflow alone may be able to provide a significant fraction of the energy needed to support the cloud. Without it, however, the outflows may only barely be able to do the job, and even then only if the turbulent energy dissipation time scale is an order of magnitude longer than the free-fall time for the cloud. One can see from this that the distribution of outflow luminosities from cloud to cloud varies greatly. In order, therefore, to attempt to settle the issue of cloud support for molecular clouds in general more unbiased surveys of molecular clouds for molecular outflows are needed.

The Weak, Extended Component of High-Velocity Gas

In Chapter 2 it was noted that a weak, extended component of high-velocity emission surrounded five of the outflows (B, C, D, E, and F) in the south-
ern portion of the Mon OB1 molecular cloud. This component of high-velocity emission was also evident in the follow-up observations considered here, and a map of it is presented in Figure 3.16. Because of a strong gradient in the velocity at which peak emission occurred across the region and because the emission being mapped was weak, the details in this figure should be considered with some skepticism. However, in a schematic sense the map does faithfully represent the extent and general morphology of the weak, extended component of high-velocity emission which has been identified in the Mon OB1 cloud. In particular, Figure 3.16 confirms that the weak, extended component both surrounds and is larger than the five outflows identified in the region. As can be seen, it is also composed of both red and blue shifted gas.

There are a number of possible explanations for the origin of the weak, extended component of high-velocity emission. It is possible, for example, that the OB association, Mon OB1, may be imparting mechanical energy to the molecular cloud behind it, giving rise to an extended area of high-velocity emission. At first glance this seems like a likely possibility since an HII region presumably caused by stars in the association is roughly coincident with the region of weak, extended, high-velocity molecular emission (see the 4950 MHz radio continuum map in Rickard et al. 1977). However, a closer look suggests that the association cannot be the source of the energy carried in the weak, extended component. High-velocity emission in the region is both red and blue shifted from line-center,
Figure 3.16: Composite spectrum and contour map showing wing emission from the region of weak, extended, high-velocity emission in the Mon OB1 cloud. The spectrum is an average of individual spectra taken towards 366 positions in the region. The integrated intensities used to make the contour map were calculated over a range from -2 km s\(^{-1}\) to 2 km s\(^{-1}\) for the blue wing emission (dashed lines) and from 10 km s\(^{-1}\) to 13 km s\(^{-1}\) for the red wing emission (solid contour lines). The contour levels in the map are at 0.5, 1, 2, 5, 10, 20, and 40 K km s\(^{-1}\) for both the blue and red emission. The 1σ rms noise is between 0.2 and 0.3 K km s\(^{-1}\) over both the blue and red velocity intervals and over most of the map. However, in the southeast corner of the map the noise is somewhat higher, being in some places as high as 1.0 K km s\(^{-1}\). A 0.2 pc fiducial bar has been included in the contour map for scale. Plus signs denote the positions of the centers of the five outflows in the region.
suggesting that high-velocity molecular gas is moving both away from and *towards* the association. It is difficult to understand how, either through winds or radiation, stars in the association could cause molecular gas in the cloud to move towards them. As a result it is difficult to understand how all of the weak, high-velocity emission could be caused by the association. A second possible explanation for the weak, extended component is the one proposed in Chapter 2; the weak, extended component is just due to the overlapping of the five outflow shells in this portion of the cloud. However, from the follow-up observations of the region presented here it is clear that the region of weak, extended emission is much larger on the sky than the combined half power sizes of the five outflows identified in the region, larger, in fact, by roughly a factor of 3 in area. This too, then, seems an unlikely explanation for the origin of the weak extended component. Finally, a third alternative may explain its origins. It is possible that the weak, extended component is the fossil remains of an old episode of outflow activity in the region. Whether such activity might have been due to earlier outflow bursts from the same sources as those undergoing outflow today, or whether originating from entirely different sources is unclear. However, this explanation does seem like the only obvious one without serious difficulties. If this is, in fact, the correct explanation for the origins of the weak, extended component, then outflows may have a profound effect on the morphology of molecular clouds since old outflows may expand over regions as large as 5-6 pc in size before becoming indistinguishable from gas moving at ambient
velocity. If the blue shifted portion of the weak, extended component, for example, arises from one or two old outflows or old bursts from present day outflow sources then it is possible that outflows may live for as long as $5 \times 10^5$ years ($5$ pc/$13$ km s$^{-1}$) before losing their identity. This is within an order of magnitude of the free-fall time calculated for the Mon OB1 cloud.

Moreover, if outflows do expand over large regions before completely losing their identities then molecular cloud structure may be characterized by a latticework of overlapping outflow shells and sheets. This suggests that molecular clouds should have a much more filamentary appearance than one might suppose if they are characterized by smooth density and temperature gradients and a continuous structure. Recent observations of $^{13}$CO emission from the Orion molecular cloud (Bally et al. 1987) do indeed suggest that molecular clouds are filamentary as opposed to smooth in appearance.

Since the weak, extended component may have an additional dynamical effect on the cloud as a whole, it is worthwhile to compare both the mass and mechanical luminosity of this component with those of the outflows. In order to do this I have constructed an average spectrum from the 366 spectra taken in the direction of the weak, extended component. This spectrum is also shown in Figure 3.16. By comparing the mass and luminosity of the region calculated from this composite spectrum with those derived for the five individual outflows, I am able to assess the importance of the weak, extended component for cloud
support. The mass of gas represented in the composite spectrum was estimated in the same way as was done for the outflows as described earlier in this chapter. The excitation temperature of the gas was assumed to be 10 K and the emitting area used was 19.4 pc². This calculation resulted in a mass of $47 M_\odot$. The mechanical luminosity of the high-velocity gas in the region was also estimated following the methods outlined earlier in this paper and using a size for the region of 1 pc. This resulted in lower and upper limits on the value of the mechanical luminosity of high-velocity gas in the region of 0.4 and 10. $L_\odot$, respectively. In comparison, the total mass and limits on the total mechanical luminosity of the five individual outflows in the region are $44 M_\odot$, 0.76 $L_\odot$, and 36.7 $L_\odot$, respectively. These values are, in general, about equal to or greater than those derived from the composite spectrum of the region. (In fact, in the case of the luminosities the values obtained from the composite spectrum are lower than the sum of the luminosities of the individual outflows. This is because the highest velocity outflow emission in the region is so beam diluted in the composite spectrum that it was not detectable.) This suggests that both the mass and luminosity of the weak, extended component are not significant contributions to the mass and luminosity of the high-velocity gas in the Mon OB1 cloud, and that the weak, extended component observed in the cloud today does not significantly contribute to the total energy balance in the cloud.
Interaction of Individual Outflows with the Mon OB1 Cloud

The great amount of momentum and energy carried by the outflows, and the existence of the weak, extended component of high-velocity emission in the Monoceros OB1 molecular cloud suggests that outflows, in general, have profound effects on the dynamical and morphological structures of their parent clouds. Given that this is true, it is therefore of great interest to ask how, in detail, outflows interact with their parent clouds. In order to address this issue, contour maps of the temperature of peak emission, integrated intensity of line-core emission, and full width at half maximum of the line-core were made from the follow-up data for the region surrounding each outflow in the Mon OB1 cloud. Enhanced peak temperatures, line-core integrated intensities, and core line-widths were found in the direction of three of the brightest flows. I now consider in detail the enhancements in temperatures and line-widths in the regions around these three flows.

Shown in Figures 3.17 through 3.19 are contour maps of the peak temperatures, integrated intensities in the line-core, and full widths at half maximum of the line-core for the three outflows (C, D, and H). As can be seen in each contour map there is a peak denoting a portion of the map where the line-core profiles are generally wider and stronger than those observed towards the surrounding regions. In all of the cases shown these peaks lie within one arcminute of either the peak of one of the outflow lobes or the infrared source thought to be associated with the outflow. In addition, in each of the cases the $^{12}$CO gas in the line-core is likely to
Figure 3.17: Contour map of the full widths at half maximum (top), integrated intensities (middle), and peak temperatures (bottom) in the line-core around outflow C. Contour levels start at 3.00 km s$^{-1}$ and increase in steps of 0.5 km s$^{-1}$ in the FWHM map, start at 50 K km s$^{-1}$ and increase in steps of 10 K km s$^{-1}$ in the integrated intensity map, and start at 10 K and increase in steps of 2 K in the peak temperature map. The integrated intensities used to make the middle map were calculated over a range from 4 km s$^{-1}$ to 12 km s$^{-1}$. 
Figure 3.18: Contour map of the full width at half maximum (top), integrated intensities (middle), and peak temperatures (bottom) in the line-core around outflow D. Contour levels start at 4.0 km s$^{-1}$ and increase in steps of 0.5 km s$^{-1}$ in the FWHM map, start at 20 K km s$^{-1}$ and increase in steps of 10 K km s$^{-1}$ in the integrated intensity map, and start at 6 K and increase in steps of 2 K in the peak temperature map. The integrated intensities used to make the middle map were calculated over a range from 2 km s$^{-1}$ to 11 km s$^{-1}$. 
Figure 3.19: Contour map of the full width at half maximum (top), integrated intensities (middle), and peak temperatures (bottom) in the line-core around outflow H. Contour levels start at 3.0 km s⁻¹ and increase in steps of 0.4 km s⁻¹ in the FWHM map, start at 15 K km s⁻¹ and increase in steps of 5 K km s⁻¹ in the integrated intensity map, and start at 2 K and increase in steps of 2 K in the peak temperature map. The integrated intensities used to make the middle map were calculated over a range from 3 km s⁻¹ to 10 km s⁻¹.
be optically thick. This fact, in combination with the peaks in the maps of peak temperature and integrated intensity, suggests that these outflows are situated in regions of enhanced excitation temperature in the CO gas. Inspection of the spectra in Figures 3.3, 3.4, and 3.7 shows, in addition, that especially in the cases of outflows D and H the observed wing emission does not have an intensity equal to or greater than half that of the peak of the line. This, in combination with the peaks in core line-width, suggests that the outflows are situated in regions of enhanced turbulent motion of the CO gas as well. In each of the cases, the peaks are very localized around the outflows and have sizes not much different from the outflows themselves. This suggests that the regions of enhanced temperature and turbulent motion are intimately associated with the star formation and the presence of outflow in the three regions. Whether the enhancements are related to the causes or effects of the star formation in the regions is unclear. However, it is clear from these observations that where *strong* outflow is present in the Mon OB1 cloud both thermal and mechanical energy in addition to that which has been clearly distinguished as part of high-velocity outflows is being pumped into the ambient gas. From the contour maps it can be seen that line temperatures and widths in the regions around outflows can be enhanced by as much as 10 to 50%. This suggests that the amount of energy being pumped into the ambient gas is enormous, almost of the same order of magnitude as the amount of thermal and dynamical energy which exists in the ambient cloud in their absence.
Since the enhancements in line-width and excitation temperature in the cloud seem somehow to be related to the presence of star formation and outflow in the regions it is worthwhile to assess whether the energy and momentum required to produce the enhancements could possibly be supplied by the star formation and outflow activity. In order to do this I have used $^{12}$CO and $^{13}$CO spectra taken on the FCRAO telescope towards outflows C, D, and H in order to estimate rough masses for the regions of enhanced line-widths and temperatures around the flows. Then I have multiplied these masses by the velocity enhancements observed (see Figures 3.17 through 3.19) in order to determine the momentum required to pump up the line-widths in the regions. Masses were estimated by using the ratios of the peak temperatures of $^{12}$CO and $^{13}$CO in the regions (1.8, 1.8, and 2.0 for outflows C, D, and H respectively) in order to find $^{13}$CO optical depths, by using the temperatures of the $^{12}$CO lines in the regions as the excitation temperatures of the gas (19, 15, and 14 K), and by using estimated areas of the enhanced regions determined from Figures 3.17 through 3.19 (0.71, 7.7, and 0.38 pc$^2$), and $^{13}$CO full widths at half maximum of 3.6, 3.3, and 2.0 km s$^{-1}$ for the three regions. These values resulted in masses of 290., 1700., and 40. M$_\odot$ for the gas in the regions around outflows C, D, and H, respectively. Using Figures 3.17 through 3.19, then, I estimated the amount by which $^{12}$CO line-widths were enhanced in the regions (roughly 1, 2, and 0.6 km s$^{-1}$), assumed these values to be proportional to the amount by which $^{13}$CO line-widths are enhanced (0.5, 1.1, and 0.3 km s$^{-1}$), and
multiplied these values for the $^{13}$CO line-width enhancements by the masses in order to roughly determine the momenta required to produce the observed line-widths. These values resulted in momenta of 140, 1900, and 12 $M_\odot$ km s$^{-1}$ for the three regions. In comparison the momenta (from Table 3.2) carried by the three outflows are 11 to 150, 92 to 520, and 17 to 53 $M_\odot$ km s$^{-1}$ for outflows C, D, and H respectively. It seems, then, that outflows in the regions do carry enough momentum to be responsible for a significant portion of the enhanced line-widths in the regions. In fact, it may mean that a substantial fraction of the outflow momenta and energies has already been distributed to the ambient gas, and that estimates made earlier in this chapter of the momentum and energy input by outflows into the ambient cloud may be smaller than the actual values. This result is consistent with a similar result found by Myers et al. (1987) in which it was shown that outflows could be responsible for enhanced line-widths in ammonia cores in molecular clouds as well. In addition, observations of ammonia (J,K) = (1,1) and (2,2) emission made towards dense cores in molecular clouds by Takano (1986) indicate that star formation may also be responsible for enhanced kinetic temperatures in such regions. Takano has shown that there is a strong correlation between the luminosity of embedded infrared sources and the kinetic temperature of the gas surrounding them. It would be useful, in order to investigate these issues, to map line-core emission from $^{13}$CO and C$^{18}$O in the regions surrounding molecular outflows. From a detailed comparison of excitation temperatures and
line-widths towards and away from outflows it may be possible to determine the efficiency with which energy is transferred between outflows, their driving sources, and the surrounding medium.
CHAPTER 4

YOUNG STELLAR OBJECTS IN THE MONOCEROS OB1

DARK CLOUD

In this chapter I present detailed follow-up studies of the far-infrared sources identified in the survey presented in Chapter 2. Together, the surveys for molecular outflows and far-infrared sources presented in Chapter 2 and the follow-up studies presented here and in Chapter 3 comprise a detailed roadmap of the global star formation activity throughout much of the Monoceros OB1 molecular cloud. In particular, these studies make it possible to address the questions of where stars are forming in the molecular cloud today, how the various types of young stellar objects in the cloud are related, and which young stars or protostars are associated with outflow. In addition, they also make it possible to build up an evolutionary picture for young stellar objects in the Monoceros OB1 molecular cloud. In this chapter, I address these issues and consider the far-infrared fluxes, color temperatures, luminosities, and sizes of far-infrared sources in the cloud as well.

Data Reduction and Results

In this chapter I am primarily concerned with far-infrared sources in the
Monoceros OB1 dark cloud. In order to identify such sources co-added maps of emission from the region at 12, 25, 60, and 100 μm have been constructed from the IRAS database (Beichmann et al. 1985). An example of such a map showing the 25 μm emission from the cloud is displayed in Figure 4.1. The region shown is the same as that surveyed for molecular outflows in the cloud as described in Chapter 2. As can be seen, the morphology of 25 μm emission in the region is very complex. Especially in the southern portion of the cloud the far-infrared emission is extended and many bright sources seem to overlap. As a result of this confusion, which in fact is even more acute at 60 and 100 μm, it was difficult to identify discrete sources from the co-added maps alone. Therefore, in order to identify sources additional maps of emission in the four IRAS bands were also constructed from the four co-added maps. These additional maps were constructed by passing the co-added maps through a spatial filter which suppressed extended emission but passed emission from discrete sources. The details of this filtering procedure are best described in Kleinmann et al. (1986). In the filtered maps sources were almost always clearly defined and were, in fact, easy to identify. In general, sources with flux densities greater than six times the rms noise in both the filtered 25 μm maps and either the 25 μm unfiltered, 12 μm filtered, or 60 μm filtered maps were considered. The 6σ detection limits in the four IRAS bands are 0.24, 0.40, 0.60, and 5.1 Jy at 12, 25, 60, and 100 μm. In all, 30 sources were identified using these somewhat conservative criteria.
Figure 4.1: Contour map of the intensity of 25 μm IRAS emission in the region surveyed for far-infrared sources. Contour levels are at -50.0, -45.0, -40.0, -35.0, -30.0, -25.0, -20.0, -15.0, -12.0, -9.0, -6.0, -3.0, 3.0, 6.0, 9.0, 12.0, 15.0, 20.0, 28.3, 40.0, 56.6, 80.0, 113.1, 160.0, 226.3, 320.0, 452.5, 639.9, 905.0, 1279.8, 1810.0, 2559.6, 3619.9, 5119.2, 7239.2, 10238.2, 14478.8, 20476.0, 28957.1, and 40951.1 times a base level of 2.2x10^5 Jy sr^-1. Solid contours represent positive intensity levels while dashed contours represent negative intensity levels. The IRAS resolution at 25 μm is shown as a hatchmarked box in the figure.
Figure 4.2: Plots of intensity verses position of the 12 and 25 µm emission for a strip running along the inscan direction through source 14.
Fluxes were obtained for the sources identified from plots of intensity versus position made for each source along the IRAS inscan direction in the unfiltered, co-added maps. An example of such a plot is shown in Figure 4.2. The inscan direction, or the direction along which resolution on the sky was highest in the IRAS data, was very nearly parallel to lines of constant right ascension in the portion of the sky including the Mon OB1 molecular cloud. Thus these plots were made along lines running very nearly north-south. Fluxes were calculated from these plots by assuming that all of the sources were unresolved in the cross scan direction (perpendicular to the inscan direction), and by using the brightest source in the region, Allen's infrared source (Allen 1972), as a calibrator. Fluxes for the calibrator were obtained by using the standard IRAS point source extractor on the co-added maps. The details of the extraction procedure can be found in Kleinmann et al. (1986). The resulting fluxes for Allen's source (990 and 1600 Jy at 60 and 100 μm respectively) agree well with previous measurements of these fluxes made by Harvey, Campbell, and Hoffmann (1977; 980 and 1645 Jy at 53 and 100 μm respectively) and with fluxes in the IRAS point source catalog. In general, because essentially all of the sources had sizes in the inscan direction less than the cross scan resolution (source sizes will be discussed in detail later in this chapter), and because Allen's infrared source is a very strong, nearly unresolved source, I expect that for strong, isolated sources this procedure produced observed fluxes accurate to 15%. However, for weak sources in confused regions it is certain
that the errors are larger. This is especially true at 60 and 100 \( \mu m \), bands at which the IRAS observations were made with poor resolution for the purposes of this study. I estimate that in the worst cases the observed fluxes may be in error by as much as 40% or possibly even more.

Color corrections were applied to all of the observed fluxes except those of sources 16, 23, and 30 and the 100 \( \mu m \) fluxes of sources 21 and 26. Sources 21, 26, and 30 have energy distributions so steep that no accurate color correction could be made. For sources 16 and 23 only 12 \( \mu m \) fluxes were obtained so no color information was available. For the rest of the sources the 12 \( \mu m \) color correction was made using the correction obtained from the ratio of observed fluxes in the 12 and 25 \( \mu m \) bands, the 25 \( \mu m \) color correction was made using the average of the corrections obtained from the ratios of fluxes in the 12 and 25 \( \mu m \) bands and the 25 and 60 \( \mu m \) bands, the 60 \( \mu m \) color correction was made using the corrections obtained from the ratios of fluxes in the 25 and 60 \( \mu m \) bands and 60 and 100 \( \mu m \) bands, and the 100 \( \mu m \) color correction was made using the corrections obtained from the observed ratio of fluxes in the 60 and 100 \( \mu m \) bands. The appropriate color corrections as a function of color temperature are listed in Beichman et al. (1985). In all but a few cases the corrections were not more than 20% of the raw fluxes. In fact, in most cases the corrections were not more than 10%.

Flux densities in the four IRAS bands of the far-infrared sources identified are presented in columns 4 through 7 of Table 4.1 along with source names
### TABLE 4.1

**FLUXES OF FAR-INFRARED POINT SOURCES**

<table>
<thead>
<tr>
<th>Source</th>
<th>( \alpha_{1950} )</th>
<th>( \delta_{1950} )</th>
<th>( F_\nu(12\mu\text{m}) ) (Jy)</th>
<th>( F_\nu(25\mu\text{m}) ) (Jy)</th>
<th>( F_\nu(60\mu\text{m}) ) (Jy)</th>
<th>( F_\nu(100\mu\text{m}) ) (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6h39m22s</td>
<td>9°13'15&quot;</td>
<td>0.2</td>
<td>0.9</td>
<td>13.</td>
<td>15.</td>
</tr>
<tr>
<td>2</td>
<td>6h39m28s</td>
<td>9°15'00&quot;</td>
<td>0.3</td>
<td>0.8</td>
<td>2.8</td>
<td>8.0</td>
</tr>
<tr>
<td>3</td>
<td>6h37m08s</td>
<td>9°18'29&quot;</td>
<td>2.5</td>
<td>0.7</td>
<td>1.3</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>6h38m38s</td>
<td>9°24'15&quot;</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>6h38m25s</td>
<td>9°27'30&quot;</td>
<td>0.3</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>6h38m28s</td>
<td>9°29'00&quot;</td>
<td>2.5</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>6h37m45s</td>
<td>9°29'30&quot;</td>
<td>0.7</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>6h37m06s</td>
<td>9°31'59&quot;</td>
<td>0.8</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>6h38m26s</td>
<td>9°32'30&quot;</td>
<td>160</td>
<td>300</td>
<td>990</td>
<td>1600</td>
</tr>
<tr>
<td>10</td>
<td>6h36m50s</td>
<td>9°38'14&quot;</td>
<td>0.3</td>
<td>0.8</td>
<td>4.7</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>6h37m48s</td>
<td>9°38'30&quot;</td>
<td>4.9</td>
<td>6.2</td>
<td>13.</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>6h38m18s</td>
<td>9°39'04&quot;</td>
<td>8.3</td>
<td>10.</td>
<td>210</td>
<td>600</td>
</tr>
<tr>
<td>13</td>
<td>6h38m59s</td>
<td>9°40'30&quot;</td>
<td>1.4</td>
<td>1.6</td>
<td>6.7</td>
<td>20.</td>
</tr>
<tr>
<td>14</td>
<td>6h37m33s</td>
<td>9°42'29&quot;</td>
<td>7.0</td>
<td>6.9</td>
<td>24.</td>
<td>83.</td>
</tr>
<tr>
<td>15</td>
<td>6h38m00s</td>
<td>9°43'45&quot;</td>
<td>0.7</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>6h38m09s</td>
<td>9°46'00&quot;</td>
<td>(1.1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>6h39m04s</td>
<td>9°50'00&quot;</td>
<td>1.2</td>
<td>1.7</td>
<td>8.8</td>
<td>16.</td>
</tr>
<tr>
<td>18</td>
<td>6h37m51s</td>
<td>9°50'15&quot;</td>
<td>53.</td>
<td>65.</td>
<td>730</td>
<td>1100</td>
</tr>
<tr>
<td>19</td>
<td>6h37m36s</td>
<td>9°51'59&quot;</td>
<td>0.2</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>6h38m18s</td>
<td>9°52'00&quot;</td>
<td>13.</td>
<td>9.8</td>
<td>140</td>
<td>450</td>
</tr>
<tr>
<td>21</td>
<td>6h37m51s</td>
<td>9°55'00&quot;</td>
<td>16.</td>
<td>12.</td>
<td>100</td>
<td>(990)</td>
</tr>
<tr>
<td>22</td>
<td>6h37m14s</td>
<td>9°55'43&quot;</td>
<td>8.1</td>
<td>13.</td>
<td>82.</td>
<td>280</td>
</tr>
<tr>
<td>23</td>
<td>6h38m09s</td>
<td>9°58'00&quot;</td>
<td>(0.3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>24</td>
<td>6h37m29s</td>
<td>10°16'44&quot;</td>
<td>-</td>
<td>0.4</td>
<td>2.2</td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>6h38m17s</td>
<td>10°18'00&quot;</td>
<td>3.6</td>
<td>8.5</td>
<td>73.</td>
<td>150</td>
</tr>
<tr>
<td>26</td>
<td>6h38m20s</td>
<td>10°29'30&quot;</td>
<td>1.4</td>
<td>1.8</td>
<td>10.</td>
<td>(88.)</td>
</tr>
<tr>
<td>27</td>
<td>6h38m13s</td>
<td>10°39'45&quot;</td>
<td>0.5</td>
<td>3.2</td>
<td>66.</td>
<td>150</td>
</tr>
<tr>
<td>28</td>
<td>6h37m13s</td>
<td>10°53'59&quot;</td>
<td>0.4</td>
<td>0.6</td>
<td>2.8</td>
<td>8.3</td>
</tr>
<tr>
<td>29</td>
<td>6h38m09s</td>
<td>10°59'30&quot;</td>
<td>0.6</td>
<td>1.1</td>
<td>1.8</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>6h38m33s</td>
<td>11°03'01&quot;</td>
<td>(10.)</td>
<td>(1.9)</td>
<td>(0.3)</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: No color corrections have been applied to entries in parentheses.
(column 1) and positions (columns 2 and 3). Except where noted color corrections have been applied to all flux densities. Because many sources were weak and in regions where the morphology of far-infrared emission was complex, a flux in each band for each source could not always be obtained, and the corresponding entries have been left blank. For source 4, in fact, no fluxes could be obtained. Although this source meets the selection criteria it is possible that it has been erroneously identified. In any case, it is clearly at the limit of detection.

In Table 4.2 source names, IRAS luminosities, 12 to 25 μm, 25 to 60 μm, and 60 to 100 μm color temperatures, and source spectral indices are presented. IRAS luminosities were calculated using the following equation:

\[
L(L_\odot) = 60.1L_\odot Jy^{-1} \mu m [\frac{F_{\nu 12}}{(12 \mu m)^2} (18.5 \mu m - 8.75 \mu m) + \frac{F_{\nu 25}}{(25 \mu m)^2} (42.5 \mu m - 18.5 \mu m) + \frac{F_{\nu 60}}{(60 \mu m)^2} (80 \mu m - 42.5 \mu m) + \frac{F_{\nu 100}}{(100 \mu m)^2} (119.67 \mu m - 80 \mu m)]
\]

where all the flux densities are in Jansky. The color temperatures of the sources were derived from the color corrected flux ratios of the designated bands. Finally, the spectral indices were calculated using:

\[
\text{Spectral Index} = \frac{\log \lambda_1 F_{\lambda_1} - \log \lambda_2 F_{\lambda_2}}{\log \lambda_1 - \log \lambda_2}
\]

with \(\lambda_1\) and \(\lambda_2\) equal to the most blueward and redward IRAS wavelengths at which fluxes could be obtained for each source (see Lada 1987). The values for
### TABLE 4.2

LUMINOSITIES, COLOR TEMPERATURES, AND SPECTRAL INDICES OF POINT SOURCES

<table>
<thead>
<tr>
<th>Source</th>
<th>Luminosity $L_\odot$</th>
<th>$T(12/25)$ (K)</th>
<th>$T(25/60)$ (K)</th>
<th>$T(60/100)$ (K)</th>
<th>Index</th>
<th>Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.</td>
<td>180</td>
<td>65</td>
<td>57</td>
<td>+1.0</td>
<td>12-100</td>
</tr>
<tr>
<td>2</td>
<td>6.7</td>
<td>230</td>
<td>93</td>
<td>37</td>
<td>+0.5</td>
<td>12-100</td>
</tr>
<tr>
<td>3</td>
<td>12.</td>
<td>1900</td>
<td>120</td>
<td></td>
<td>-1.4</td>
<td>12-60</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>5</td>
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<td>290</td>
<td>-</td>
<td>-</td>
<td>-0.5</td>
<td>12-25</td>
</tr>
<tr>
<td>6</td>
<td>12.</td>
<td>790</td>
<td>-</td>
<td>-</td>
<td>-2.2</td>
<td>12-25</td>
</tr>
<tr>
<td>7</td>
<td>7.7</td>
<td>270</td>
<td>96</td>
<td>-</td>
<td>0.0</td>
<td>12-60</td>
</tr>
<tr>
<td>8</td>
<td>3.8</td>
<td>790</td>
<td>-</td>
<td>-</td>
<td>-2.2</td>
<td>12-25</td>
</tr>
<tr>
<td>9</td>
<td>2300</td>
<td>260</td>
<td>95</td>
<td>48</td>
<td>+0.1</td>
<td>12-100</td>
</tr>
<tr>
<td>10</td>
<td>5.7</td>
<td>210</td>
<td>79</td>
<td></td>
<td>+0.8</td>
<td>12-60</td>
</tr>
<tr>
<td>11</td>
<td>42.</td>
<td>310</td>
<td>110</td>
<td>-</td>
<td>-0.4</td>
<td>12-60</td>
</tr>
<tr>
<td>12</td>
<td>330</td>
<td>320</td>
<td>60</td>
<td>35</td>
<td>+1.0</td>
<td>12-100</td>
</tr>
<tr>
<td>13</td>
<td>18.</td>
<td>330</td>
<td>88</td>
<td>36</td>
<td>+0.3</td>
<td>12-100</td>
</tr>
<tr>
<td>14</td>
<td>79.</td>
<td>360</td>
<td>94</td>
<td>&lt;35</td>
<td>+0.2</td>
<td>12-100</td>
</tr>
<tr>
<td>15</td>
<td>5.0</td>
<td>290</td>
<td>-</td>
<td>-</td>
<td>-0.5</td>
<td>12-25</td>
</tr>
<tr>
<td>16</td>
<td>(4.2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>18.</td>
<td>300</td>
<td>82</td>
<td>43</td>
<td>+0.3</td>
<td>12-100</td>
</tr>
<tr>
<td>18</td>
<td>1100</td>
<td>310</td>
<td>68</td>
<td>50</td>
<td>+0.4</td>
<td>12-100</td>
</tr>
<tr>
<td>19</td>
<td>2.2</td>
<td>200</td>
<td>-</td>
<td>-</td>
<td>+0.7</td>
<td>12-25</td>
</tr>
<tr>
<td>20</td>
<td>270</td>
<td>430</td>
<td>65</td>
<td>35</td>
<td>+0.7</td>
<td>12-100</td>
</tr>
<tr>
<td>21</td>
<td>(390)</td>
<td>430</td>
<td>74</td>
<td>(&lt;35)</td>
<td>(+0.9)</td>
<td>12-100</td>
</tr>
<tr>
<td>22</td>
<td>180</td>
<td>270</td>
<td>80</td>
<td>&lt;35</td>
<td>+0.7</td>
<td>12-100</td>
</tr>
<tr>
<td>23</td>
<td>(1.3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>24</td>
<td>2.2</td>
<td>-</td>
<td>79</td>
<td>-</td>
<td>+1.1</td>
<td>25-60</td>
</tr>
<tr>
<td>25</td>
<td>110</td>
<td>230</td>
<td>73</td>
<td>42</td>
<td>+0.7</td>
<td>12-100</td>
</tr>
<tr>
<td>26</td>
<td>(37.)</td>
<td>310</td>
<td>82</td>
<td>(&lt;35)</td>
<td>(+1.0)</td>
<td>12-100</td>
</tr>
<tr>
<td>27</td>
<td>87.</td>
<td>160</td>
<td>60</td>
<td>39</td>
<td>+1.7</td>
<td>12-100</td>
</tr>
<tr>
<td>28</td>
<td>6.7</td>
<td>270</td>
<td>87</td>
<td>35</td>
<td>+0.5</td>
<td>12-100</td>
</tr>
<tr>
<td>29</td>
<td>6.1</td>
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<td>-0.3</td>
<td>12-60</td>
</tr>
<tr>
<td>30</td>
<td>(45.)</td>
<td>(&gt;10^4)</td>
<td>(&gt;10^4)</td>
<td>-</td>
<td>(-3.3)</td>
<td>12-60</td>
</tr>
</tbody>
</table>

Note: Color corrections have not been applied to some of the fluxes used to calculate the entries in parentheses.
$\lambda_1$ and $\lambda_2$ for each source are given in the column labeled "Bands" in Table 4.2. The values of $\lambda_1$, $\lambda_2$, $F_{\lambda_1}$, and $F_{\lambda_2}$ for each source were calculated from the data in Table 4.1.

Presented in Table 4.3 are the half power diameters in the inscan direction of each of the sources in each of the four IRAS bands. These sizes have been corrected for the inscan size of the IRAS beam by assuming that both the inscan beam profile and the source profiles are gaussian in shape. The sizes of point sources in the inscan direction have been entered in the table as zeroes. Dashes have been entered in the table in the cases where, due to confusion, no source size could be determined. Sizes marked with an "m" denote sources whose profiles showed evidence of multiple components.

Also presented in Table 4.3 are possible optical counterparts to the far-infrared sources. In order to search for such counterparts both the SAO catalog of bright stars (1966) and the list of stars in Walker's (1956) classic study of the open cluster NGC2264 were searched in order to find optically visible stars within about an arcminute on the sky of the far-infrared sources identified towards the Mon OB1 cloud. In total nine IRAS sources were found to have optical counterparts. In the northern portion of the cloud source 30 was found to have a bright optical counterpart listed in the SAO catalog. Source 30 is, in fact, HD 47886 (SAO 095997), a star of spectral type M1 III with an apparent visual magnitude of 6.1. At a distance of about 200 pc, this star is a foreground giant. In the southern portion
### TABLE 4.3

**SIZES AND OPTICAL COUNTERPARTS OF FAR-INFRARED POINT SOURCES**

<table>
<thead>
<tr>
<th>Source</th>
<th>Size 12 (arcmin)</th>
<th>Size 25 (arcmin)</th>
<th>Size 60 (arcmin)</th>
<th>Size 100 (arcmin)</th>
<th>Optical Counterparts&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>W183</td>
</tr>
<tr>
<td>7</td>
<td>2.4m</td>
<td>2.7m</td>
<td>2.4</td>
<td>0</td>
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</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
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<td>10</td>
<td>0</td>
<td>0</td>
<td>2.1m</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>2.1m</td>
<td>1.5m</td>
<td>0</td>
<td>0</td>
<td>W55</td>
</tr>
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<td>0.9</td>
<td>0</td>
<td>0</td>
<td>W164</td>
</tr>
<tr>
<td>13</td>
<td>1.6m</td>
<td>1.3m</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>2.3m</td>
<td>2.2m</td>
<td>2.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0.9</td>
<td>2.0m</td>
<td>0</td>
<td>0</td>
<td>W82</td>
</tr>
<tr>
<td>16</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>3.3m</td>
<td>1.8m</td>
<td>2.0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>3.6m</td>
<td>3.1m</td>
<td>3.7</td>
<td>4.8</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>1.3m</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>4.1m</td>
<td>3.7m</td>
<td>4.3m</td>
<td>4.2</td>
<td>W161</td>
</tr>
<tr>
<td>21</td>
<td>1.6</td>
<td>1.7</td>
<td>1.9</td>
<td>4.0m</td>
<td>W78</td>
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<tr>
<td>22</td>
<td>3.3m</td>
<td>4.1m</td>
<td>4.5m</td>
<td>4.5</td>
<td>-</td>
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<tr>
<td>23</td>
<td>0.8</td>
<td>-</td>
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<td>HD 47839</td>
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<tr>
<td>24</td>
<td>-</td>
<td>1.2m</td>
<td>0</td>
<td>-</td>
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<tr>
<td>25</td>
<td>0.9m</td>
<td>0</td>
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<td>2.3</td>
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</tr>
<tr>
<td>26</td>
<td>1.4m</td>
<td>1.4m</td>
<td>2.4</td>
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</tr>
<tr>
<td>27</td>
<td>1.6</td>
<td>0</td>
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<tr>
<td>28</td>
<td>1.3m</td>
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<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>HD 47886</td>
</tr>
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</table>

of the cloud two sources could clearly be identified with bright optical counterparts. Source 3 is probably a foreground giant of spectral type M6 (Iijima and Ishida 1978) and source 23 is HD 47839 (SAO 114258, star number 131 in Walker's study, also known as 15 S Mon), a star of spectral type O5 with an apparent visual magnitude of 4.7. This star is the brightest member of the open cluster NGC2264. Note, however, that for an M giant the former source has an anomalously high flux density at 60 μm. Since this source is in a region dominated by confusion at 60 μm this flux density should be considered with some skeptisism. In addition, the 12 μm flux determined for the latter source is somewhat weaker than would be expected for an O5 star at a distance of 800 pc. Since no color correction has been applied to this flux and since this source is in a region dominated by confusion even at 12 μ this also should not be surprising. It is also not surprising that the O star was not detected in any of the other IRAS bands. Longward of 12 μm the expected flux from an O5 star falls about equal to or lower than the IRAS detection limits quoted in this thesis.

Most other optically bright members of NGC2264 were too dim to be seen in the far-infrared. In Walker's original study of the cluster it was shown that stars with spectral types earlier than A0 lie on the main sequence while stars with spectral types from F0 to A0 lie in a band two magnitudes brighter than the main sequence. Using standard values of the effective temperatures and sizes of main sequence stars (Allen 1973) and using a distance to the cluster of 800 pc (Walker
1956), it can be shown that a main sequence cluster member with a spectral type of B0 or later would not have been detected by IRAS. Therefore, even the stars in the cluster with the next earliest spectral types after the O star should not have been detected. In fact, of the four B2 and B3 stars noted in Walker’s study three have no far-infrared sources near them and the fourth has a nearby source with very cold color temperatures. As a result none of these stars might be physically associated with IRAS sources. The F0 to A0 stars as well, and five yellow giants found in the cluster by Walker were also too dim to be detected in the far-infrared. In a similar way it can be shown that the 12 and 25 \( \mu \)m fluxes from these stars are at least an order of magnitude dimmer than the detection limits stated in this thesis.

While no optically bright star in the cluster other than the O star could be seen by IRAS, it is possible that some of the optically dimmer stars in the cluster might have been detected in the far-infrared. In Walker’s study of the cluster it was noted that many of the redder, dimmer stars were variable in brightness and sources of H\( \alpha \) emission. These stars were identified as T Tauri stars. Since then it has been shown that many of these stars have strong infrared excesses at 2.2 \( \mu \)m (Warner, Strom, Strom 1977), and it is likely that many are considerably brighter than blackbodies longward of 2.2 \( \mu \)m as well. As a result, in addition to the O star a number of other stars considered by Walker might be associated with the far-infrared sources discussed here. It has been shown that stars of this type have
spectral energy distributions which typically fall towards long wavelengths from 12 to 100 \( \mu m \) (Rucinski 1985). In fact the typical spectral index for such stars (calculated from IRAS fluxes in Rucinski 1985 in a similar manner to those in Table 4.2) is -0.55. Using UY Aur, a T Tauri star with a spectral index from 12 to 60 \( \mu m \) of -0.6 (Rucinski 1985), as a typical star of this type, I estimate that in the absence of significant foreground extinction a T Tauri star in the cluster bright enough to be detected by IRAS would have an apparent visual magnitude brighter than about 16 (calculated from a rough \( V \) magnitude for UY Aur taken from Rydgren et al. 1984).

In the direction of the Mon OB1 cloud 25 such sources have been identified by Walker. They are W44, W55, W58, W77, W78, W79, W80, W82, W90, W95, W96, W105, W110, W115, W126, W133, W139, W153, W161, W164, W183, W184, W199, W204, and W217. Of these 6 might be associated with IRAS sources identified herein; three (W183, W55, and W82) are probably the optical counterparts of IRAS sources with negative spectral indices (6, 11, and 15) and three (W164, W161, and W78) might be associated with IRAS sources with positive spectral indices (12, 20, and 21). However, young stellar objects with positive spectral indices are often obscured from view at \( V \). As a result it is not clear whether the \( H\alpha \) stars coincident with the latter three IRAS sources are actually physically associated with them. It is possible that these sources may be double (as noted again later in this section). As a result the optical and very far-infrared
emission may come from different sources coincident on the sky. However, even if all six stars actually have IRAS counterparts, nineteen Hα stars with bright V magnitudes have no IRAS counterparts identified herein. It is possible either that this lack of identification is due to the confused morphology of the IRAS emission in the vicinity of the cluster/association NGC2264/Mon OB1 or that many of the Hα stars listed by Walker have spectral energy distributions in the mid and far-infrared more steeply falling than UY Aur's. In support of the latter possibility I note that if I relax the selection criteria stated earlier in this chapter then as many as four more (W77, W79, W204, and W217) of the Hα stars identified by Walker appear to have weak IRAS counterparts at 12 μm. In any case either possibility would make many of the Hα stars impossible to detect using IRAS data alone.

Three IRAS sources with negative spectral indices (sources 5, 8, and 29) have not been identified as Hα stars. At least in the cases of sources 8 and 29 this is because they lie outside of the portion of the sky considered by Walker. Each of these sources do have optical sources near them, however (as can be seen from the POSS red plate of the region), and it is possible that these sources are Hα stars.

As can be seen few of the sources identified in the far-infrared have optical counterparts. In fact, I have in total listed only nine possible counterparts in Table 4.3. It seems that by selecting sources on the basis of far-infrared brightness I have chosen a sample biased towards young, deeply embedded objects hidden by dust at U, B, and V. As I shall discuss these sources are likely to be very young, in fact
in a pre-T Tauri stage of evolution.

In addition to the tables, the far-infrared data are also presented as four band spectral energy distributions in Figure 4.3. In the figure source spectral energy distributions are displayed in order of increasing spectral index from top to bottom and left to right. In addition the far-infrared spectral energy distributions of UY Aur (Rucinski 1985), Elias 29 (Young, Lada, and Wilking 1986), and L1551 IRS 5 (Cohen and Schwartz 1983, Cohen et al. 1984) are also shown for reference. As can be seen there is a smooth progression from steeply falling sources (top left) through flat sources to steeply rising sources (bottom right) in the figure.

Discussion

Young stellar objects in the Mon OB1 cloud range from zero-age main sequence objects to objects in the earliest stages of star formation. As a result the data presented herein provide a unique opportunity to investigate simultaneously the properties of many of the various manifestations of star formation and early stellar evolution in one cloud. In combination with the complementary survey for molecular outflows made for this cloud (as described in Chapters 2 and 3), the data on the young stellar objects presented herein also provide an opportunity to investigate the nature of the objects which drive molecular outflows. These issues are discussed below.
Figure 4.3: Spectral energy distributions of far-infrared point sources identified in the direction of the Mon OB1 cloud. The distributions have been arranged in order of increasing spectral index from the top left to the bottom right. The positive number next to each distribution is the name of the source. Nine spectral energy distributions have been included in each column of the figure. Nine corresponding tickmarks on the vertical axes of the figure have been included for scale. In general the value next to the tick mark at the top corresponds to the top most spectral energy distribution, the value second from the top corresponds to the second energy distribution from the top, and so on. For all sources the distance between the tickmarks is one order of magnitude in $\lambda F_\lambda$. Also shown in separate boxes at the top of the figure are the far-infrared spectral energy distributions of UY Aur, Elias 29, and L1551 IRS 5. These spectral energy distributions are shown for the purpose of comparison and are displayed on similar scales to the distributions in the bottom half of the figure.
Young Stellar Objects

Many types of young stellar objects can be found in the Mon OB1 cloud and accompanying association (NGC2264/Mon OB1). As can be seen from the spectral energy distributions displayed in Figure 4.3 sources with spectral energy distributions falling, flat, and rising towards the far-infrared have all been identified. In addition, in Walker's classic study (1956) and numerous subsequent studies of the association, main sequence stars, stars lying above and to the right of the main sequence, and stars showing brightness variability, Hα emission, and near-infrared excesses have all been identified. Together these sources make up a large sample of objects containing examples of every type of known young stellar object.

In order to make sense of the many young stellar objects identified in the Mon OB1 cloud and accompanying association it is worthwhile to classify them according to their properties. Recently from observations of the shapes of the spectral energy distributions of young stellar objects embedded in the Ophiuchus molecular cloud core (Lada and Wilking 1984, Lada 1987), it has been shown that almost all such objects can be grouped into three well defined classes numbered I through III. Objects with spectral energy distributions like those of sources deeply enshrouded by dust comprise the sources in Class I. These objects have spectral energy distributions much wider than single blackbodies and positive spectral indices in the near and mid-infrared. Objects with spectral energy distributions
like those of T Tauri stars comprise the sources in Class II. These objects also
have spectral energy distributions wider than single blackbodies but have neg-
ative spectral indices. Objects with spectral energy distributions like those of
reddened photospheres comprise those in Class III. Like sources in Class II these
objects are characterized by negative spectral indices, but have spectral energy
distributions with widths comparable to those of blackbodies. As a first step to-
wards understanding the sources in the Mon OB1 cloud, I will fit them into this
classification scheme as well.

Of the 30 IRAS sources which have been identified in the direction of
the Mon OB1 cloud probably only three are Class III objects. These objects are
sources 3, 23 and 30 in Table 4.1, the O and M stars. Since, as discussed in the
"Data Reduction and Results" section of this chapter, it is very unlikely that the
M stars are actually physically associated with the Mon OB1 cloud they will not
be considered further in most of the discussion which follows. This leaves only one
Class III object identified by IRAS in the Mon OB1 cloud. I note in contrast that
many optically visible Class III objects have been identified in the direction of the
Mon OB1 cloud in the past. In Walker's (1956) study of the association Mon OB1,
for example, many stars lying on the main sequence and lying just above and to
the right of the main sequence were identified. These objects had the UBV colors
of reddened photospheres. They did not, however, exhibit brightness variability
or Hα emission lines, and a subsequent study (Warner et al. 1977) has shown
that few if any exhibit infrared excesses. As a result these objects probably all fit into Class III. In fact, a proper motion survey of the association by Vasilevskis, Sanders, and Balz (1965) has shown that \( \frac{2}{3} \) to \( \frac{3}{4} \) of the optically visible sources are likely to fall into Class III. As discussed earlier, none of these objects but the O star is bright enough in the far-infrared to be detected by IRAS.

IRAS did, however, detect a number of Class II objects in the Mon OB1 cloud. Previous studies of IRAS emission from well-known T Tauri stars (Rucinski 1985) have found that the spectral indices of these sources (calculated in the same way as those in Table 4.2) average around -0.55 and only very rarely are greater than zero. As a result it seems likely that of the thirty sources identified herein any source with a spectral index less than about zero (other than the O and M stars) is likely to be a Class II object. This places sources 5, 6, 8, 11, 15, and 29 into Class II. Note that many of these sources have spectral energy distributions similar to that of UY Aur, a typical T Tauri star (see Figure 4.3). In Walker's (1956) study of Mon OB1, as well, 79 optically visible stars were found to exhibit brightness variability and/or H\( \alpha \) emission and many of these stars at the time were classified as T Tauri stars. In addition, all of the stars of this type subsequently observed in the infrared show strong excesses at 2.2 \( \mu m \) (Warner et al. 1977). With infrared excesses in the near-infrared it is not surprising that some of these Class II sources are bright in the mid and far-infrared as well. In fact, three of the sources identified by Walker as T Tauri stars have also been identified as Class II
sources herein. These sources, W183, W55, and W82, are listed in Table 4.3 as optical counterparts of IRAS sources 6, 11, and 15. However, as mentioned earlier, most of the Hα stars noted by Walker are not bright enough in the far-infrared to be detected by IRAS. In fact at least 19 Hα stars with V magnitudes (and thus luminosities) about the same as the IRAS Class II sources discussed here were not identified in the far-infrared.

In addition to objects in Classes III and II, Class I objects have also been detected by IRAS in the Mon OB1 cloud. In fact, the majority of objects detected by IRAS fall into Class I. It is clear that many of the 30 objects identified have spectral indices greater than zero, meaning that they have more steeply rising far-infrared energy distributions and colder color temperatures than typical T Tauri stars. In addition, the spectral energy distributions of these objects are much wider than blackbodies. In fact, among these (source 9) is the well-known Allen's protostellar object (Allen 1972, Harvey et al. 1977, Wynn-Williams 1982) and an object (source 12) observed previously at 70 and 130 μm by Sargent et al. (1984, source NGC2264FIR) and thought to be deeply embedded in the Mon OB1 molecular cloud. These facts suggest that many of the far-infrared sources identified are, in fact, deeply embedded in the Mon OB1 cloud. As a result it seems likely that sources 1, 2, 7, 9, 10, 12, 13, 14, 17, 18, 19, 20, 21, 22, 25, 26, 27, and 28 all fit into Class I. Note that many of these sources have similar spectral energy distributions to Elias 29 and L1551 IRS 5, typical Class I sources
the spectral energy distributions of which are also displayed in Figure 4.3.

Finally, I note that three sources in the cloud could not be easily categorized. Sources 4 and 16 were too weak for accurate fluxes to be obtained and neither the 12 or 100 μm fluxes could be obtained for source 24. As a result I have left them out of much of the discussion which follows.

In summary I show a histogram in Figure 4.4 of the distribution of spectral indices of sources identified by IRAS. In all 26 sources are shown with sources 4, 16, and 24 left out and source 23 left out as well since no far-infrared spectral index for it could be determined. Source 23 is the O star and almost certainly has a spectral index (not color corrected) less than about -3. As can be seen 3 sources (including the O star) fall into Class III, 6 sources fall into Class II, and 18 sources fall into Class I. The dividing line between Classes III and II is about a spectral index of -3.0. The dividing line between Classes II and I is about a spectral index of zero. Note that source 3, an M giant (as discussed earlier), has a spectral index greater than -3.0 in spite of the fact that it is a Class III object. This inconsistency is probably due to the poorly determined 60 μm flux density of this object. Note also that in contrast to the results of previous studies of optical and near-infrared emission from the sources in the region, the majority of sources in the IRAS selected sample are identified as Class I objects. These sources are likely to be deeply embedded in the Mon OB1 cloud.

It is also worth mentioning that many of the IRAS sources identified are
Figure 4.4: Frequency distribution of spectral indices of far-infrared point sources identified in the Monoceros OB1 molecular cloud. Hatchmarked regions in the figure denote sources associated with outflow.
in fact located in the Mon OB1 cloud behind the Mon OB1 association. This suggests that star formation continues to go on behind the association in spite of the fact that literally hundreds of stars have already formed in the region (see for example the list of young stellar objects in Adams, Strom, and Strom 1983). Clearly, star formation in molecular clouds is a continuous and ongoing process lasting perhaps as long as the lifetimes of the clouds themselves. As noted by a number of authors (Iben and Talbot 1966, Adams 1981, Adams et al. 1983), in the particular case of Mon OB1 star formation has clearly been a non-coeval process.

With the young stellar objects identified in the Mon OB1 region categorized into spectral classes I, II, and III, it is now worthwhile to investigate the relationships between these objects and between the classes of objects which they represent. As in the cases of young stellar objects in the ρ Ophiuchi region (Lada and Wilking 1984) and elsewhere (Lada 1987) objects in the Mon OB1 cloud which fall into each of these classes are significantly different in terms of both their optical and infrared properties. Class III sources in the Mon OB1 region are relatively bright at V, relatively dim in the far-infrared, and have spectral energy distributions which peak in the optical. Class II sources in the region have rising spectral energy distributions in the optical (see photometry in Walker 1956) and falling spectral energy distributions in the far-infrared, suggesting that their spectral energy distributions peak in the near-infrared. Class I sources are dim at V, bright in the far-infrared, and have spectral energy distributions which peak in the far-
infrared. The facts that: 1) Class III objects are bright in the optical and in the past have been identified essentially as regular stars, that 2) Class II objects have colder color temperatures than objects in Class III, are often partially obscured by circumstellar envelopes (Mendoza 1966, Mendoza 1968, Strom, Strom, and Yost 1971, Walker 1972), and in the past have been identified as T Tauri stars, and that 3) Class I objects are often completely obscured from view in the optical and give off most of their radiation in the far-infrared, suggests that there may be an evolutionary sequence from Class I to II to III in which circumstellar matter is progressively stripped from an object as it evolves towards the main sequence. Since this framework was first noted in a qualitative way for sources in the \( \rho \) Oph region (Lada and Wilking 1984), quantitative theoretical models have been produced which provide the detailed physics to support such an evolutionary picture (Adams, Lada, and Shu 1987).

From Figure 4.4 it can be seen that IRAS sources in the Mon OB1 cloud can be placed in Classes I, II, and III based primarily on their far-infrared spectral indices. I now investigate whether there are other obvious differences between the IRAS properties of sources in the classes as well. Displayed in Figure 4.5 are the IRAS luminosity functions of the sources in Classes I and II. As can be seen the brightest sources are clearly in Class I. This is what is expected since, by definition, Class I sources emit most of their luminosity in the far-infrared (Lada 1987). This means that for Class I sources the IRAS luminosities quoted in this
Figure 4.5: IRAS luminosity functions of Class I (top) and Class II (bottom) sources identified towards the Monoceros OB1 molecular cloud.
chapter are very nearly bolometric. In contrast, however, Class II sources emit most of their luminosity in the near-infrared and optical. As a result the IRAS luminosities of these sources are much less than their true bolometric luminosities. Clearly it would be more meaningful and useful to make a comparison between the bolometric luminosities of sources in the two classes. In order to do so one must make a bolometric correction to the IRAS luminosities of the Class II sources. I have attempted to do this. Using a composite spectral energy distribution of seven T Tauri stars presented in Adams et al. (1988) I have calculated the emergent luminosities of a typical T Tauri star in the IRAS, near-infrared, and optical wavelength regimes. From this I find that the bolometric luminosity for a typical Class II source is roughly six times its IRAS luminosity. Making this bolometric correction to the histogram in Figure 4.5 amounts to sliding the IRAS luminosity function for Class II sources a little more than two bins to the right. Note that even with this correction the most luminous sources are still in Class I. In fact if all potential Class II sources with bolometric luminosities above about 5 L⊙ are considered (6 Class II IRAS sources and 22 Walker Hα sources with V<16 but not clearly identified with Class II IRAS sources), then only 2 of these sources (7%) have bolometric luminosities greater than about 60 L⊙. In contrast 9 out of 18 (50%) of the detected Class I sources (all with luminosities above 5 L⊙) are more luminous than 60 L⊙. These facts suggest that there is a true difference between the bolometric luminosity functions of Class I and II sources in the Mon
OB1 cloud.

There are two possible reasons why Class I sources might be more luminous than Class II sources in the Mon OB1 cloud. It is possible, for example, that in general Class I objects actually have an additional source of luminosity which Class II objects lack. One attractive possibility is that this excess luminosity is due to infall of material from a circumstellar envelope. In fact, theoretical models of the observed spectral energy distributions of sources like WL16, Elias 29, and L1551 IRS 5 suggest that Class I sources with relatively large luminosities (≈30-50 $L_\odot$) may ultimately produce only solar mass stars (Adams, Lada, and Shu 1987).

On the other hand, it is equally possible that Class I objects are more luminous because star formation is occurring sequentially in mass in the Mon OB1 cloud. This possibility has been suggested before by Iben and Talbot (1966), Adams (1981), and Adams, Strom, and Strom (1983). They found that the average mass of stars forming in the cloud has increased over the last $10^7$ years. It is interesting to note that there are 7 Class I sources with IRAS luminosities greater than 100 $L_\odot$ identified herein. This is about $\frac{1}{4}$ of the total number of stars with similar luminosities which have ever formed from the cloud (see the HR diagram in Walker 1956). Since the pre-main sequence tracks of high mass stars in the HR diagram are essentially horizontal, this suggests that the rate of high mass star formation in the Mon OB1 cloud today is extremely high, and lends support to the latter possibility.
Another interesting difference between sources in Classes I and II are their sizes. For example, on average sources in Class I have inscan diameters at 25 \( \mu \text{m} \) of 1’.4 while sources in Class II have inscan diameters of 0’.6 (values taken from Table 4.3). The fact that Class I objects tend to be larger in the far-infrared than those in Class II lends further support to the idea that Class I objects are more deeply embedded in circumstellar envelopes than those in Class II and therefore Class I objects are in an earlier stage of stellar evolution. Note, however, that while the relative sizes of objects in Classes I and II are consistent with expectations, the absolute sizes of these objects are puzzling. Few of the sources identified in the Mon OB1 cloud are point sources. For example, at 12 \( \mu \text{m} \) many have half power diameters in the inscan direction greater than 2’ (see Table 4.3 and the sample source profile in Figure 4.2), and corresponding radii (at 800 pc, the distance to the Mon OB1 cloud) greater than about 0.23 pc. In fact, as can be seen from Table 4.3 many sources are extended at longer wavelengths as well. At first glance this presents a problem for our understanding of the physical properties of the material surrounding young stellar objects in the Mon OB1 cloud; these large source sizes cannot be easily explained by standard models of dust grain heating by starlight. However, there is a way out of this dilemma. A simple explanation for these large source extents is that many of the sources identified herein are multiple. In fact in some cases the source profiles actually show slight evidence of having multiple components (as denoted by the letter “m” in Table 4.3). I note that this no doubt
adds uncertainty to the determined spectral indices and luminosities of sources identified herein. Unfortunately, however, without higher resolution studies it is not possible to obtain better estimates of these quantities.

Finally, it is also worthwhile to compare the IRAS luminosity function of sources in the Mon OB1 cloud to those in other regions of star formation. One such region for which an IRAS luminosity function has been compiled is the ρ Ophiuchi region. Presented in Figure 4.6 are the IRAS luminosity functions of young stellar objects in the Mon OB1 cloud (luminosities taken from Table 4.2) and in the ρ Oph cloud core (IRAS luminosities taken from Young et al. 1986). The distributions are clearly different in two respects: the distribution of sources identified in the Mon OB1 cloud has both fewer low luminosity and more high luminosity objects than that of sources in the ρ Oph cloud. Since the Mon OB1 cloud is 5 times farther away from us than the ρ Oph cloud the lack of IRAS detections of low luminosity sources in the Mon OB1 cloud is not surprising. However, the excess of high luminosity sources in the Mon OB1 cloud may represent a fundamental difference between the intrinsic luminosity functions in the two regions. The most likely explanation for this difference has to do with the physical sizes of the two regions surveyed for IRAS sources; the area surveyed in Ophiuchus is less than 2 pc x 1 pc while the area surveyed in Monoceros is roughly 30 pc x 10 pc. As a result, the mass of molecular gas surveyed in Ophiuchus is only a few hundred solar masses (Wilking and Lada 1983) while that surveyed in Monoceros is 3x10^4
Figure 4.6: IRAS luminosity functions of far-infrared point sources identified towards the $\rho$ Ophiuchi molecular cloud core (top) and the Monoceros OB1 molecular cloud (bottom). Hatchmarked regions in the figure denote sources associated with outflow.
$M_\odot$ (Chapter 2). Since the formation of higher mass stars (as opposed to lower mass stars) is a relatively rare occurrence in the interstellar medium, it would seem that by sampling a larger mass of gas for young stellar objects one would have a greater chance of finding high luminosity sources (Elmegreen 1983). As a result, it should come as no surprise that higher luminosity sources have been found in the Mon OB1 cloud.

While not surprising the difference in luminosity functions, however, may have an important consequence. It may suggest that there is a fundamental difference between the ways in which open clusters and associations are formed. The $\rho$ Oph region is a relatively quiescent site of star formation with a relatively high star formation efficiency (perhaps as high as 30%, Wilking and Lada 1983). As a result of these facts a number of authors have suggested that this cloud may be the site of an open cluster in formation (Grasdalen, Strom, and Strom 1973, Vrba et al. 1975, Lada and Wilking 1984, Lada, Margulis, and Dearborn 1984). In contrast, the Mon OB1 cloud is a very active site of star formation with a relatively low star formation efficiency ($M_{\text{cluster}}/M_{\text{cloud}} \approx 10^3 \ M_\odot/3 \times 10^4 \ M_\odot \approx 3\%$). In fact, the cloud has already produced an OB association. Dynamical arguments (Lada et al. 1984) suggest that even the core of this association, the so-called open cluster NGC2264, is not a true long-lived open cluster but will be dispersed over the next few million years. As a result of these facts and the fact that the IRAS sources identified in the Mon OB1 cloud are spread over a region roughly 30 pc
x 10 pc it seems likely that many of these sources will emerge from the cloud in associations rather than clusters. The lack of high luminosity sources in the ρ Oph cloud as compared to the Mon OB1 cloud may then suggest that open clusters are formed with a deficiency of high mass stars compared to associations. It is possible that this is because clusters may be formed from less massive clouds than associations (as suggested in Lada et al. 1984). Comparisons of the bolometric luminosity functions of these regions to the initial luminosity function could help to test these possibilities.

Association with Molecular Outflows

As stated above both the identified IRAS and previously identified optical sources observed towards the Mon OB1 cloud can be categorized into three classes representing reddened photospheres of pre-main-sequence and main sequence stars (Class III), T Tauri stars (Class II), and deeply embedded sources (Class I). Since the portion of the Mon OB1 cloud over which these sources are situated has also been completely surveyed for the presence of molecular outflows (as described in Chapters 2 and 3), it is now possible to compare the positions of these sources with the outflows, and to investigate the nature of the young stellar objects that are typically associated with outflow. First, I note that while only 30 IRAS sources have been identified towards the cloud over 600 optical sources have been identified (Walker 1956, Adams et al. 1983). As a first step, then, towards
identifying the type of source associated with molecular outflows, I must decide whether IRAS sources or optically visible sources are associated with them.

In order to decide this I consider a square region on the sky surveyed by Walker and Adams et al. for optically visible sources. Inside this region (the union of regions a, b, c, and d denoted in Adams et al.) there are five identified molecular outflows (outflows B, C, D, E, and F, Chapter 3), 10 IRAS sources (sources 4, 5, 6, 7, 9, 11, 12, 14, 15, and 16), and over 350 optical sources (Walker 1956, Adams et al. 1983). If I say that any source which falls within 3' of the center of an outflow (positions of outflow centers are given in Table 3.1) is considered to be coincident with it, then I find that in this region each outflow has at least one IRAS and one optical source coincident with it. Clearly there are many more optical sources than IRAS sources in the region. This suggests that by chance, it should be much easier for optical sources to be coincident with the outflows than IRAS sources. In fact, if I calculate the probability that by chance one or more optical sources is coincident with each outflow in the region (see Appendix B), then I find that this probability is almost exactly 1.0000. In contrast, the probability that by chance at least one IRAS source is coincident with each outflow in the region is only 0.0045. Since there are IRAS sources coincident with each of the outflows, these probabilities suggest very strongly that IRAS sources, as opposed to optically visible sources, are actually physically associated with the outflows in the region. Furthermore I note that only three of the outflows (B, D, and E) in
the region are associated with any of the 25 bright Hα stars listed in the region by Walker (and noted earlier) and that in each case the Hα star closest to the outflow center is, in fact, a star which has already been identified with an IRAS counterpart (i.e. Hα stars W183, W164, and W55). This suggests that even in the cases in which optical sources are physically associated with outflows, they are always detectable by IRAS as well.

From the arguments above it seems clear that molecular outflows tend to be associated primarily with IRAS sources rather than optically visible sources in the Mon OB1 cloud. If so, then what type of IRAS sources do they tend to be associated with? From the surveys presented in Chapter 2, it was found that six of the nine outflows identified in the entire Mon OB1 cloud might be associated with far-infrared sources. Outflow B was thought to be associated with IRAS source 6, outflow C with IRAS source 9, outflow D with IRAS source 12, outflow E with IRAS source 11, outflow F with IRAS source 14, and outflow H with IRAS source 27. The positions of these sources with respect to the outflows are shown in Figures 3.2 through 3.7. Since then it has also been discovered that there is an outflow associated with IRAS source 25 (Hasegawa 1987). In summary, then, seven outflows are probably associated with seven far-infrared sources, namely sources 6, 9, 11, 12, 14, 25, and 27.

In order to illustrate the type of source which is associated with a molecular outflow in the Mon OB1 cloud I have denoted by hatchmarks in both Figures
4.4 and 4.6 the sources associated with outflows. From Figure 4.4 it should be possible to discern the spectral indices of sources likely to have outflows while from Figure 4.6 it should be possible to discern the IRAS luminosities of such sources.

As can be seen in Figure 4.4 of the seven sources possibly associated with outflow, 2 (sources 6 and 11) have spectral indices between -3.0 and 0.0 and are likely to be Class II objects. On the other hand 5 (sources 9, 12, 14, 25, and 27) have spectral indices greater than zero and are likely to be Class I objects deeply embedded in the Mon OB1 cloud. The two Class II sources have spectral energy distributions falling towards the far-infrared, were not detected by IRAS at 100 μm, and in fact have been identified as T Tauri stars by Walker (1956). In contrast, the five Class I objects have spectral energy distributions rising towards the far-infrared and were detected in all four IRAS bands. This indicates that molecular outflows are associated with IRAS sources which are both Class I objects presumably in the pre-T Tauri stage of evolution and Class II objects in the T Tauri stage itself. However, it is important to note when considering these statistics that 19 additional T Tauri stars bright at V (V<16) but not detected in the IRAS sample considered here have also been found in the Mon OB1 cloud (as discussed earlier in this chapter). Furthermore, IRAS source 12, presumably a Class I source, actually has an Hα star counterpart. As a result it is possible that this source may actually be a superposition of two sources, one Class I and one Class II. Including this information in the statistics indicates that 4-5 out of 18
Class I sources in the cloud might have associated outflow while only 2-3 out of 25 Class II sources might. This suggests that outflow tends to be associated primarily with the Class I phase of early stellar evolution, i.e., the phase in which young stellar objects are deeply embedded in circumstellar envelopes. I note that in previous surveys of Class I and Class II objects for outflow emission similar results have been found. For example, in a survey of 28 T Tauri stars only 3 were found to have associated molecular outflow emission (Edwards and Snell 1982) while in a survey of 45 embedded infrared sources 32 were found to have associated outflow (Bally and Lada 1983).

Although the majority of the molecular outflows seem to be associated with Class I objects, the fact that molecular outflows seem not to be exclusively associated with them suggests that young stellar objects may go through a very long period in the outflow phase. This period may last some of the time they spend as Class I and some of the time they spend as Class II objects. For example, out of the 18 Class I objects identified in the Mon OB1 cloud 4-5 have associated outflow. If all young stellar objects go through the outflow stage then this may mean that Class I sources spend roughly 22-28% of their lifetimes as sources of molecular outflow. On the other hand, out of the 25 Class II objects identified only 2-3 have associated outflow. This may mean that T Tauri stars spend roughly 8-12% of their lifetimes as sources of molecular outflow. Note that the statistics quoted here are based on a very small sample, that some of the IRAS sources might be
multiple, and that their spectral indices are based on only a few far-infrared fluxes. As a result one might not want to take them too literally. However, from these numbers it does seem likely that on average the molecular outflow stage in early stellar evolution occurs somewhere around the late stages of Class I evolution, not very far from the transition between Classes I and II. The facts that the outflow stage occurs at the end of Class I, or the deeply embedded stage of evolution, and that immediately afterwards young stellar objects tend to emerge from their parent clouds and appear as optically visible T Tauri stars or Class II objects suggests that for many stars outflows may play a fundamental role in sweeping away the circumstellar gas and dust ensnaring them. Furthermore, since Class II objects clearly are stars while Class I objects are in an earlier, possibly protostellar stage of evolution, it is very possible that outflow may occur during the transition between protostar and young star. If so then Class I sources without associated outflow, i.e., sources which may be in the pre-outflow stage of their evolution (sources 1, 2, 7, 10, 13, 17, 18, 19, 20, 21, 22, 26, and 28), might be true protostars, objects whose evolution is dominated by infall.

Inspection of Figure 4.6 shows, in addition, that for the most luminous young stellar objects the outflow stage is extremely common. Almost 50% of the IRAS sources in the cloud with IRAS luminosities above $10 L_\odot$ have associated outflow. In fact, if one makes a bolometric correction to the luminosities of Class II sources one finds that the two Class II sources with outflow move two bins
to the right in the figure. These two sources (the ones with IRAS luminosities between about 10 and 50 \( L_\odot \)) actually have bolometric luminosities greater than 50 \( L_\odot \). This suggests that 7 out of 11 or 64\% of IRAS sources in the cloud with bolometric luminosities greater than about 50 \( L_\odot \) have associated outflow. Similar high detection rates for outflows associated with luminous infrared sources have been found in other studies (50\%, Snell et al. 1988). As a result this high detection rate should come as no surprise. The fact that most outflows in the cloud are associated with high luminosity sources, however, does not necessarily suggest that low luminosity sources in the cloud lack associated outflow. In fact three outflows in the cloud (outflows A, G, and I, see Chapter 3) do not have obvious IRAS or \( \text{H} \alpha \) star counterparts. These outflows must therefore be associated with low luminosity infrared sources. It is also possible that due to sensitivity limitations in the original survey outflows associated with low luminosity IRAS sources may have been missed. More sensitive surveys for outflows and infrared sources in the Mon OB1 cloud could help shed light on these issues.

Finally, it is also possible using the data presented herein to quantify our knowledge of the birthrate of outflow sources in the solar neighborhood. As just mentioned 64\% of young stellar objects more luminous than 50 \( L_\odot \) in the Mon OB1 cloud have associated outflow. This suggests that at least 64\% of all young stellar objects in the solar neighborhood more luminous than 50 \( L_\odot \) must go through the outflow phase sometime during their early evolution. The birthrate of
outflow sources in the solar neighborhood must therefore be at least 64% of that for stars more luminous than 50 L\(_\odot\), or 5x10\(^{-5}\) kpc\(^{-2}\) yr\(^{-1}\) (birthrate calculated from those in Ostriker et al. 1974). This value is about equal to the birthrate in the solar neighborhood of 3 M\(_\odot\) stars, and suggests that the birthrate of outflow driving sources must be at least as high as that of early A stars. It should be noted that this birthrate is determined in a way completely independent from those in which outflow birthrates have been determined before (see for example, Bally and Lada 1983, Lada 1985). In particular, no estimate of a typical outflow lifetime was used in deriving this value.

I note that the birthrate derived here is 40 times less than that derived previously from the number of outflows found in the Mon OB1 cloud (2x10\(^{-3}\) kpc\(^{-2}\) yr\(^{-1}\), Chapter 3). However, since the birthrate derived here is clearly a lower limit the difference between the two values may not be a problem. As a matter of fact the birthrate derived here could easily be increased by an order of magnitude or more if one considers that the luminosity limit, 50 L\(_\odot\), used in order to calculate it is the luminosity of a very young stellar object. Theoretical models of young stellar objects have shown that even solar mass stars may have luminosities around 50 L\(_\odot\) during the earliest stages of their evolution (Adams et al. 1987). Solar mass stars, of course, have a much higher birthrate than used above. Thus if one could ascertain the ultimate main sequence luminosity of a 50 L\(_\odot\) young stellar object then a more accurate and higher birthrate for outflow
sources could be found. In fact, even if there was still a discrepancy after taking this into account it could still be explained. A remaining difference between the birthrate derived here for outflow driving sources and that derived in Chapter 3 for outflows themselves would just suggest that outflow sources go through multiple outflow bursts. Multiple outflow bursts are, in fact, a likely possibility. In spite of the fact that very young stellar objects are often associated with outflow (Bally and Lada 1983, Myers et al. 1987, Snell et al. 1988) the estimated lifetimes of very young stellar objects are thought to be much longer than the dynamical timescales of flows themselves. This suggests that either the estimated lifetimes of these types of objects are greatly in error or that outflow driving sources do go through multiple episodes of outflow.
CHAPTER 5

CONCLUSIONS

In this thesis I have presented the results of a detailed census of star formation activity in the Monoceros OB1 dark cloud. Surveys of a large portion of the cloud have been made for molecular outflows and young stellar objects. Molecular and dust emission from the cloud has also been mapped. The detailed results of this work are as follows:

1) Nine molecular outflows and thirty IRAS sources have been identified towards the Monoceros OB1 dark cloud. The cloud surveyed is composed of $3 \times 10^4 \, M_\odot$ of material. Statistical arguments suggest that 90% of the IRAS sources actually are young stellar objects embedded in the cloud. Only one source, an M star, is clearly not associated with the cloud.

2) The young stellar objects and molecular outflows identified are distributed throughout the cloud. This suggests that in general star formation occurs throughout dark clouds. In the particular case of the Mon OB1 cloud many stars are presently forming behind the association Mon OB1. As a result, star formation in this association is clearly not a coeval process.

3) The large number of outflows identified in the Mon OB1 cloud sug-
gests that there are roughly six times as many outflows in the solar neighborhood than have been discovered to date. This suggests that outflows have a very high birthrate in the solar neighborhood and that they are part of a common phase in the early evolution of stars.

4) The morphologies and energetics of outflows in the Mon OB1 cloud are similar to those of outflows discovered elsewhere.

5) If the star formation rate in the Mon OB1 cloud is roughly constant with time then molecular outflows in the cloud should be able to support it against gravitational collapse.

6) A weak, extended component of high-velocity gas has been identified over a portion of the Mon OB1 cloud. This component may be the fossil remains of a past episode of outflow activity.

7) Molecular line temperatures and widths are enhanced in the directions of three of the strongest outflows in the cloud. This suggests that outflows have a profound effect on the detailed dynamics and morphology of the Mon OB1 cloud. In fact, in combination with results 5 and 6 this suggests that dark clouds may be composed primarily of interacting sheets and shells of material ejected in outflows.

8) Young stellar objects in the Mon OB1 cloud can be placed in three spectral classes representing deeply embedded sources (Class I), T Tauri stars (Class II), and pre-main sequence and main sequence stars (Class III).

9) The spectral slopes, luminosities, and sizes of the IRAS sources in the
cloud are all consistent with the idea that the three spectral classes represent an evolutionary sequence.

10) The molecular outflow stage of early stellar evolution seems to be situated near the end of the Class I stage near the transition between Classes I and II. Since Class I sources are deeply embedded while Class II sources are optically visible, this suggests that outflows may play an important role in sweeping out the circumstellar material around young stellar objects. In fact, outflows may play an important part in the transition between the protostellar and stellar stages of evolution.

At the end of the first chapter of this thesis I stated that it was my goal to present a picture of the global properties of star formation activity in the Monoceros OB1 dark cloud. At this point, then, it seems worthwhile to take a somewhat speculative stab at this. Taken as a whole, the ten results listed above seem to suggest to me that star formation in the Mon OB1 cloud is an ongoing, self-regulated process which occurs in a way not very dissimilar from that first suggested for dark clouds by Norman and Silk (1980) and Franco and Cox (1983). According to these models dark clouds are supported from gravitational collapse by winds from young stellar objects. These winds, in addition, produce a filamentary, clumpy structure in dark clouds, and some of the overdense clumps produced collapse to form new stars. Since, in these models, the star formation
rate controls the total dynamical energy in a dark cloud and visa-versa, the rate of star formation is self-regulated. Many of the results presented above could be easily fit into such a picture for the Mon OB1 cloud. Molecular outflows are both common and energetic enough to support the Mon OB1 cloud and produce its filamentary, clumpy structure. In addition, new stars seem to be forming throughout the cloud as part of a continual process. Furthermore, the fact that to within the measurement errors there is just enough momentum and energy carried in outflows to support it against collapse (see Chapter 3) seems to me to be very fishy; while the results of this thesis do not prove that star formation in the Mon OB1 cloud is a self-regulated process, they are tantamount to a smoking gun.

Finally, I would also like to speculate very briefly on the importance of molecular outflows for stellar, dark cloud, and even galactic evolution. Since as suggested in Chapter 4 outflows probably play an important role in sweeping away the circumstellar material around young stellar objects they may, in fact, have an important regulatory effect on the ultimate main sequence masses of stars. In addition, since they affect the dynamics of dark clouds, it is possible that they have an important regulatory effect on the star formation rate in the galaxy as well. In the future more sensitive and complete surveys of dark clouds for molecular outflows and the signposts of star formation should prove extremely useful in quantifying our knowledge of these possible regulatory mechanisms.
APPENDIX A

ACQUISITION AND CALIBRATION OF
MILLIMETER-WAVE DATA

In general the amount of millimeter-wavelength radiation we receive from an extraterrestrial source is very small. For example, the power incident on the 5 m millimeter-wave telescope when observing emission from the J=1-0 transition of CO at a typical position in the Mon OB1 cloud is only $10^{-16}$ watts. In contrast, the power received from the 300 K background is typically two orders of magnitude greater than this, about $10^{-14}$ watts. As a result, detection and measurement of millimeter-wave radiation from extraterrestrial sources is no small feat, requiring a sophisticated array of electronics and careful thought concerning absolute calibration. In this appendix I will describe in a rough way the techniques and instrumentation used to detect millimeter-wave radiation and the methods used to calibrate the resulting data. More detailed descriptions of radio telescopes and receivers can be found in Kraus (1966) and Steinberg and Lequeux (1963).

Radio Receivers

In a typical transistor radio, amplification and detection of an incoming radio signal (from say your favorite radio station) is a relatively simply affair. The
signal is received with a dipole antenna, is amplified using one or more transistors, and then is detected using a speaker which converts the electromagnetic waves to sound waves in the atmosphere. Detection of millimeter-wave radiation of extraterrestrial origin, however, is more complicated for two reasons: the power from the source incident on the antenna is much lower than in more conventional applications, and there are no electronic amplifiers or detectors which can operate on radiation with such high frequencies (typically around 100 GHz). As a result incoming radiation usually must be collected and focused using a large parabolic antenna and integrated over time to make a detection. In addition, it must be amplified. However, since electronic amplifiers do not work on radiation with frequencies of hundreds of GHz, the incoming radiation must be converted to a different, lower frequency before it can be amplified. Radio receivers which change the frequency of an incoming signal before amplification are called superheterodyne receivers. The device which does the frequency conversion is called a mixer.

Presented in Figure A.1 is a block diagram of a typical superheterodyne receiver. Incoming radiation with a center radiofrequency of $\nu_{RF}$ is gathered and focused using a parabolic antenna and then is channeled down a waveguide and into a mixer. In the mixer the radiofrequency signal is multiplied with a synthetically produced signal with known frequency $\nu_o$. The device which produces this signal is called a local oscillator. The resulting signal with center intermediate frequency $\nu_{IF}$ is produced by the beating of the two input signals to the mixer. In
Figure A.1: Schematic diagram of a superheterodyne receiver.
mathematical language the signals are combined roughly as follows:

$$\sin 2\pi \nu_{RF} t \ast \sin 2\pi \nu_o t = \frac{1}{2} [\cos 2\pi (\nu_{RF} - \nu_o) t - \cos 2\pi (\nu_{RF} + \nu_o) t]$$

and for a known value of $\nu_o$ and desired value of $\nu_{IF}$, superheterodyne receivers are sensitive to two incoming bands of millimeter-wave radiation with center frequencies $\nu_{RF} = \nu_o + \nu_{IF}$ and $\nu_{RF} = \nu_o - \nu_{IF}$. By carefully adjusting the local oscillator frequency, $\nu_o$, a radio receiver can be tuned so that one of the two incoming bands has a center frequency, $\nu_{RF}$, coincident with the frequency of the radiation to be detected. The radiofrequency band in which the signal of interest resides is called the *signal sideband*. The other band is called the *image sideband*. Radio receivers which admit radiation in two sidebands are called *double sideband receivers*. In some cases a filter is placed before the mixer in order to absorb all of the incoming radiation in the image sideband. Receivers of this type are called *single sideband receivers*. In general double sideband receivers have an advantage in sensitivity of a square root of two over their single sideband counterparts. However, double sideband receivers have the disadvantage that one must be very careful not to accidentally place a signal in the image sideband.

After the radiofrequency signal has been mixed down to a lower frequency it can then be amplified by conventional means in an analogous way to that in typical radio receivers. The amplified signal is then split into its various frequency components (in order to create a spectrum) using band-pass filters and
each component is then detected using a square-law detector, an integrator, and a voltmeter. Since a *square law detector* has the property that its output voltage is proportional to its input voltage squared, the voltage measured by the voltmeter in each narrow band is directly proportional to power input into the receiver in that band. Since power as a function of frequency is essentially what we wish to know, the detection of a spectrum from a millimeter-wave radiation source is complete at this stage.

**Absolute Calibration of Millimeter-Wave Data**

The output of a millimeter-wave receiver is voltage as a function of frequency. In order to understand how this output function relates to the physical properties of the source, however, it is necessary to convert these two variables into quantities with more obvious physical meaning. The quantities typically used in order to extract physical meaning from a millimeter-wavelength spectrum are temperature (in particular $T^*_B$) and line-of-sight velocity.

The line-of-sight velocity in a spectrum can be calculated from the frequency in a very straightforward way by using the Doppler formula, which, in the Newtonian limit, is:

$$\frac{\nu_o - \nu}{\nu_o} = \frac{v}{c}$$

where $v$ is the line-of-sight velocity of the emitter with respect to some reference system (usually velocities are given with respect to the Local Standard of Rest).
c is the speed of light, $\nu_0$ is the rest frequency of the spectral line being observed, and $\nu$ is the frequency at which radiation from the source is actually detected.

Conversion of voltage into temperature is a much more complicated procedure than conversion of frequency into velocity. I outline below a simplified treatment of the procedure used to calibrate the temperature scale on millimeter-wave spectra and explain the physical meanings of the various temperature scales ($T_R$, $T_R^*$, $T_A$, and $T_A^*$) which appear in the literature. For a more comprehensive treatment of millimeter-wave calibration see Ulich and Hasse (1976) and Kutner and Ulich (1981). The treatment I present here is similar to the one in Machnik (1981).

In order to be able to deduce the physical characteristics of a source from its spectrum it would be most useful to know the equivalent blackbody temperature, $T_B$, of the radiation emergent from the source at each frequency. This quantity is often parameterized in terms of the effective source radiation temperature, $J(\nu, T_B)$, given by:

$$J(\nu, T) = \frac{h\nu}{k} \left[ \exp\left(\frac{h\nu}{kT}\right) - 1 \right]^{-1}$$

For a source with an optical depth of $\tau(\nu)$, and an excitation temperature $T_{ex}$, which is situated in front of a source of background emission with an effective blackbody temperature $T_{bg}$, the effective radiation temperature (measured as intensity above the background) will be:

$$J(\nu, T_B) = (1 - e^{-\tau(\nu)}) (J(\nu, T_{ex}) - J(\nu, T_{bg}))$$
For most millimeter-wave observations the 2.7 K cosmic background radiation is the sole source of background emission and $T_{bg} = 2.7$ K. The effective source radiation temperature, $J(\nu, T_B)$, as defined here, is often called the brightness temperature, $T_b$, or the radiation temperature, $T_R$, of the source. It has the useful property that, for optically thick emission, the excitation temperature of the transition in the emitting gas can be easily calculated from it using the equation:

$$J(\nu, T_{ex}) = J(\nu, T_B) + J(\nu, T_{bg}) \quad \text{for} \quad \tau(\nu) \gg 1$$

Because the radiation temperature is so simply related to the physical conditions in the source, it is the most useful quantity that one can directly get from a millimeter-wave spectrum.

Unfortunately, the acquisition of $T_R$ as a function of velocity for a source is very difficult. When a millimeter-wave telescope is pointed at a position on the sky, it does not receive radiation only from that position, but instead from that position and a large portion of the sky around it. While millimeter-wave telescopes are always optimized so that they receive radiation primarily from the position at which they are pointed, some radiation from the side always enters the feedhorn and is detected by the receiver. As a result, in order to determine $T_R$ as a function of velocity at a particular position in the sky, one must know both the efficiency with which a telescope picks up radiation at all angles off of its axis (called the telescope beam pattern) and the brightness distribution of emission over a large
portion of the sky around the position of interest. Since the latter is usually not well known, people often choose to measure the quantity $T^*_R$ in lieu of $T_R$. These quantities are related by:

$$T^*_R = \eta_c T_R$$

where $\eta_c$ is the overall efficiency with which the telescope beam pattern couples to the brightness distribution of emission from the sky. $T^*_R$ is therefore the equivalent blackbody temperature of emission from a position on the sky measured as if the sky surrounding that position has a uniform brightness distribution. Fortunately, many objects of interest to millimeter-wave astronomers (molecular clouds, for instance) are large and do, in fact, have relatively uniform brightness distributions. For these objects $\eta_c$ is nearly one and $T^*_R$ is a very useful quantity. For small sources or large sources with very non-uniform brightness distributions an estimation, at least, must be made for $\eta_c$ before physical conditions in a source can be deduced from $T^*_R$. For example, in this thesis I use estimated values of $\eta_c$ in order to calculate the masses of the molecular outflows discovered in my survey. For observations made at 115 GHz of outflows with the sizes listed in Table 3.1 in this thesis, $\eta_c$ is about 0.3 for the MWO telescope (Levreault 1985), 0.82 for the NRAO telescope (Jewell 1987), and 0.73 for the FCRAO telescope (Snell 1985). In the case of the MWO telescope, $\eta_c$ was estimated by assuming that the sources being observed are uniform intensity disks on the sky (following Ulich and Haas 1976). In the latter cases $\eta_c$ was estimated by assuming that the sources being
observed have uniform intensity inside and zero intensity outside of the main beam of the telescope.

Once it is decided that $T_R$ is the best representation of the intensity information in the data, the appropriate conversion factors from the raw output (voltage) of the receiver to $T_R$ must be found. In particular, there are three effects which must be considered in order to correctly make this conversion: the gain of the receiver relating raw blackbody temperature to voltage must be found, absorption of the incoming signal by the atmosphere must be considered, and the percentage of the signal lost due to imperfections in the antenna must be found.

Generally, the gain of the receiver is found by measuring its output voltage when objects with various blackbody temperatures are placed in front of it. The gain is then evaluated using the fact that the input power to the receiver is proportional to the output voltage. In practice two blackbody emitters are used: an object at ambient temperature and the sky. The object at ambient temperature is usually mounted on a rotating wheel which brings it alternately into and out of view of the receiver. When it is out of view the receiver detects the sky. This procedure for calculating gains is called the chopper wheel method (Penzias and Burrus 1973).

With the gains known, the percentage absorption of the incoming signal due to the atmosphere must then be found. In practice, this is done using the chopper wheel method with the telescope pointed at a number of different
elevations. At each elevation one measures the calibration voltage ($V_{CAL}$), the difference between the output voltages when the receiver looks at the object at ambient temperature and the sky. This voltage is given by:

$$V_{CAL} = VT_{CAL} = G \eta_l (T_{AMB} - T_{SKY}) = G \eta_l (T_{AMB} - T_M(1 - \exp(-\tau_z A)))$$

where $G$ is the gain of the receiver, $T_{CAL}$ is the corresponding difference in temperature as seen from the receiver, $T_{AMB}$ and $T_{SKY}$ are the blackbody temperatures of the ambient temperature emitter and the sky respectively, $\eta_l$ is the fraction of the incoming radiation which is not absorbed or blocked by the telescope structure and does not bleed off the antenna in the rearward direction after hitting it, $T_M$ is the mean effective temperature of the sky (for a description of the models used to derive this temperature see Kutner 1978), $\tau_z$ is the zenith optical depth of the atmosphere, and $A (=\csc(elevation))$ is the number of airmasses through which the telescope is looking when pointed at a particular elevation. By measuring $V_{CAL}$ at a number of elevations one finds the variation of $V_{CAL}$ with airmass. From this the two unknown variables, $\eta_l$ and $\tau_z$, can be found. In practice one extrapolates the function $V_{CAL}(\text{elevation})$ to an elevation of zero ($A$ becomes infinite in this limit) in order to find $\eta_l$, and then plugs the newly found value of $\eta_l$ back into the equation for $V_{CAL}$ to find $\tau_z$ by using the equation at non-zero elevations. Once the value of the zenith optical depth is known, the percentage absorption of the incoming signal due to the atmosphere has been found. As a bonus the use of
this method also results in a value for $\eta_1$ which is needed in order to evaluate the total efficiency of the antenna. This procedure for calculating the opacity of the atmosphere and $\eta_1$ is called tipping.

With both the gain of the receiver and the zenith optical depth of the atmosphere known, only the total transmission efficiency of the antenna remains to be found. However, the efficiency against absorption and against rearward scattering and spillover of the incoming signal ($\eta_1$) has already been found by tipping. All that remains to be evaluated is the efficiency against forward scattering and spillover of the incoming signal. This efficiency is called $\eta_{fss}$ and is usually determined by observing continuum emission at the frequency of interest from the moon. This object, which emits like a disk with a diameter of $\frac{1}{2}^\circ$ on the sky, has a well known spectral energy distribution in the radio regime. As a result, an expected value of $T_{R}^*$ for this object can be calculated and $\eta_{fss}$ can be found by comparing this theoretically determined value with the observed temperature which has already been corrected for all of the other antenna losses and attenuation due to the atmosphere.

With the total transmission efficiency of the telescope antenna, the gain of the receiver, and the atmospheric attenuation of the incoming signal evaluated, all of the calibration is complete and one can write down the equation which relates the output voltage ($V_o$) of the receiver (when pointed at a source) to the blackbody temperature ($T_{R}^*$) of the source (ignoring structure in its brightness
distribution). This equation is:

\[ V_s = G T_A = G T_A^* \eta \exp(-\tau_s A) = G T_R^* \eta \eta_{fas} \exp(-\tau_s A) \]

where \( T_A \) is the raw blackbody temperature of the detected radiation as seen from the receiver, \( T_A^* \) is the blackbody temperature of the detected radiation corrected for antenna losses due to absorption and rearward spillover and scattering, and for losses due to atmospheric attenuation of the incoming signal, and \( T_R^* \) is the blackbody temperature of the detected radiation corrected for all antenna losses and atmospheric attenuation.

In practice, all of the quantities involving calibration are usually put together in a quantity called \( T^*_c \). In terms of this quantity \( T_R^* \) is related to the receiver output voltage, \( V_s \), when pointed at a source and the calibration voltage, \( V_{CAL} \), by:

\[ T_R^* = T_c^* \left( \frac{V_s}{V_{CAL}} \right) = \frac{T_{CAL}}{\eta \eta_{fas}} \exp(\tau_s A) \left( \frac{V_s}{V_{CAL}} \right) \]

So, in summary, in order to calibrate receiver output to the \( T_R^* \) scale only the quantities \( T_c^* \) and \( V_{CAL} \) need to be known. These quantities can be measured as a function of elevation and weather conditions by tipping and by making measurements of continuum emission from an object like the moon.
APPENDIX B

PROBABILITIES THAT OUTFLOWS ARE ASSOCIATED WITH OPTICAL OR IRAS SOURCES

For Chapter 4 it was necessary to know the probabilities that optically visible and IRAS sources might by chance be coincident with each of five outflows identified in a particular region on the sky. Here I demonstrate a method by which these probabilities can be obtained and give the equation which results in the probabilities quoted in the text.

Essentially, in producing the probabilities given in the text the question which I ask is as follows: If N point objects are placed at random in a large area A containing smaller areas b, c, d, e, and f (see Figure B.1 for a picture of this situation), what is the probability that at least one object will also lie in each of the smaller areas b, c, d, e, and f? In order to demonstrate the method of solution to this problem I first consider the simpler situation in which only two small areas (b and c) reside in area A. In this case the probability that at least one object will reside in b and at least one object will reside in c is equal to one minus the probability that no objects reside in b and/or no objects reside in c. In mathematical language this probability (at least one in b and one in c) is given
Figure B.1: Schematic diagram showing a large area A with five smaller areas b, c, d, e, and f inside of it.
by:

\[ P = 1 - \left[ \left(1 - \frac{b}{A}\right)^N + \left(1 - \frac{c}{A}\right)^N - \left(1 - \frac{b+c}{A}\right)^N \right] \]

where the term involving b only is the probability that no objects reside in b and the term involving c only is the probability that no objects reside in c. The last term in the equation (the one involving \( b+c \)) is the probability that no objects reside in b or c. This term is necessary as a correction to the first two terms since the case in which no objects reside in b or c was previously counted twice (once in the term involving b only and once in the term involving c only) and I wish to count it once.

In an analogous way a similar equation can be written down for the case of five areas b, c, d, e, and f. In this case the probability that there will reside at least one object in each of areas b, c, d, e, and f is equal to one minus the probability that no objects reside in b and/or no objects reside in c and/or no objects reside in d and/or no objects reside in e and/or no objects reside in f. In mathematical language this probability is given by:

\[ P = 1 - \left[ \left(1 - \frac{b}{A}\right)^N + \left(1 - \frac{c}{A}\right)^N + \left(1 - \frac{d}{A}\right)^N + \left(1 - \frac{e}{A}\right)^N + \left(1 - \frac{f}{A}\right)^N \right. \]
\[ - \left(1 - \frac{b+c}{A}\right)^N - \left(1 - \frac{b+d}{A}\right)^N - \left(1 - \frac{b+e}{A}\right)^N - \left(1 - \frac{b+f}{A}\right)^N \]
\[ - \left(1 - \frac{c+d}{A}\right)^N - \left(1 - \frac{c+e}{A}\right)^N - \left(1 - \frac{c+f}{A}\right)^N - \left(1 - \frac{d+e}{A}\right)^N \]
\[ - \left(1 - \frac{d+f}{A}\right)^N - \left(1 - \frac{e+f}{A}\right)^N + \left(1 - \frac{b+c+d}{A}\right)^N \]
where the first five terms (those involving \( b, c, d, e, \) or \( f \) alone) are the probabilities that no objects reside in each of the areas. As in the case of the two area problem discussed above correction terms are necessary to account for possibilities counted more than once or not at all. The last 26 terms in the equation are these correction terms. Terms 6 through 15 correct for miscounting of situations in which combinations of two areas are left empty, terms 16 through 25 correct for miscounting of situations in which combinations of three areas are left empty, terms 26 through 30 correct for miscounting of situations in which combinations of four areas are left empty, and the last term corrects for miscounting of the situation in which all five areas are left empty. I note that as it should this equation gives a probability of exactly zero if \( N \) is 0, 1, 2, 3, or 4, and that also as they should the results of this equation agree with the results of Monte Carlo simulations of the problem. In addition I note that this equation is also valid in cases in which the small areas overlap. However, in this case one must be careful about the meaning of "\( e + f \)"
for example, in the equation. The mathematical phrase “$e + f$” should be taken to mean the area of the union of the two areas $e$ and $f$. In this way the overlapping portions of $e$ and $f$ will not be counted twice.

In the two examples in Chapter 4 $N$ was 350 or 10 depending on whether optical or IRAS sources were being considered, $A$ was 625 square arcminutes and $b$, $c$, $d$, $e$, and $f$ were all 28.3 square arcminutes. Since areas $b$ and $c$ as well as $e$ and $f$ were slightly overlapping the values used for the expressions “$b + c$” and “$e + f$” were 55.5 square arcminutes and 53.1 square arcminutes, respectively. As discussed in the text the probabilities which resulted from these input values were 1.0000 and 0.0045 for optical and IRAS sources respectively.
LIST OF REFERENCES


Hasegawa, T. 1987, private communication.


Wolf, M. 1924, A. N., 221, 379.


