THE SEARCH FOR INFRARED PROTOSTARS

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1. INTRODUCTION

Protostars are the Holy Grail of infrared astronomy. In the 15 years since the discovery of the BN object in Orion by Becklin & Neugebauer (1967) and of the strong infrared emission from R Mon by Mendoza (1966), infrared astronomers have devoted much of their efforts toward trying to understand the birth of stars. They have often hoped, and sometimes believed, that their studies would yield an unambiguous example of a protostar in Spitzer’s (1948) sense of an isolated interstellar cloud undergoing inexorable gravitational contraction to form a single star. These hopes were strongly encouraged by Larson’s (1969) theoretical models, which predicted that protostars would pass through a phase of high infrared luminosity during their accretion stage. The fact that no conclusive identification of such an object has yet been made stems not from a lack of candidate infrared sources, but from the difficulty of establishing the evolutionary status of the 30 or more objects that have already been found associated with dense molecular clouds.

This review describes the searches that have been made for infrared sources in star-forming regions and the detailed studies that have been made of these sources and of the interstellar matter in their immediate vicinity. The emphasis is on those objects manifesting themselves almost exclusively at infrared wavelengths, rather than on the presumably more evolved objects such as compact H II regions and young, visible stars with infrared excesses. Recent work in these latter fields has been described by Habing & Israel (1979), Cohen & Kuhi (1979), and Hyland (1981). Other useful review articles can be found in the conference proceedings on infrared astronomy (Wynn-Williams & Cruikshank 1981), interstellar molecules (Andrew 1980), and on various aspects of star formation (Gehrels 1978, Appenzeller et al. 1980, Roger & Dewdney 1982). Infrared techniques are described by Soifer & Pipher (1978).

The objects attracting the most attention from infrared astronomers almost all have bolometric luminosities in excess of $10^3 L_\odot$. Current theoretical mod-
els indicate that these high luminosities can be achieved only by protostars or mature stars with masses greater than $3 M_\odot$ (Westbrook & Tarter 1975, Yorke & Shustov 1981). Infrared studies of the kind described in this review are therefore directed toward the early evolution of massive rather than solar-type stars.

2. SEARCHES AND SOURCES

2.1 Star Formation Regions

A remarkable variety of strategies have been used to search for infrared sources in molecular clouds. Most of the sources in Table 1 have been found by rastering a single detector over a region of the sky for which independent evidence exists for recent massive star formation. These regions have included young star clusters, H II regions, reflection nebulae, dark clouds, molecular cloud peaks, masers and far-infrared sources. Wavelengths used for infrared searches have generally been in the range 2.2–20 $\mu$m. The shorter wavelengths offer greater sensitivity to warmer and relatively unobscured objects, are less dependent on telescope and site quality, and, because large focal-plane diaphragms can be used, allow large areas to be scanned in a reasonable time. Elias (1978a), for example, scanned 18 square degrees of the Ophiuchus cloud with a 2' beam using a 0.6-m telescope. Surveys at 2.2 $\mu$m, however, tend to become confused by foreground stars and to discriminate against cool sources and those behind large column densities of obscuring matter. Although the current broad-bandwidth detector systems on instruments such as the 3-m Infrared Telescope Facility (IRTF) on Mauna Kea offer sensitivities (in Jy) about 3000 times better at 2.2 $\mu$m than at 20 $\mu$m, observations at the latter wavelength offer an advantage in signal-to-noise if the source has a color temperature below $\sim$400 K or is obscured by more than $\sim$100 mag of visual extinction. Scanning at 10 or 20 $\mu$m is extremely time-consuming because the high thermal background of the telescope limits the size of the focal-plane diaphragm to 10" or less. Beichman's (1979) 20-$\mu$m searches of 19 molecular cloud peaks were therefore confined to a few sq arcmin each.

Surveys of limited regions of the sky have been made at wavelengths longward of 30 $\mu$m using balloon-borne telescopes (e.g. Campbell et al. 1980, Jaffe et al. 1982, Okuda 1981). The spatial resolution of these surveys has been limited by diffraction to a minute of arc or more, so that complementary ground-based observations are necessary in order to separate compact infrared sources from the more diffuse emission from H II regions and molecular clouds.

The only known extragalactic infrared sources with properties similar to those discussed in this review are the compact objects in the LMC and SMC regions N59 and N76B which have been studied in the 1–4 $\mu$m range by Gatley et al. (1981, 1982).
2.2 *Globules and Submillimeter Sources*

There are a small number of objects that belong in a special category by reason of having such low color temperatures that they have very little emission shortward of 100 \( \mu \text{m} \). All the Bok globules observed to date fall into this category (Keene et al. 1980, Keene 1981, Jones et al. 1980). Another intriguing object is the submillimeter source detected in NGC 6334 by Cheung et al. (1978) and further studied by Gezari (1982). This source is so cool (19 \( \pm \) 5 K) that it was not seen in the 40–250 \( \mu \text{m} \) study by McBreen et al. (1979), although it is associated with an H\(_2\)O maser (Moran & Rodríguez 1980). The luminosity of this object is of the order of \( 10^4 L_\odot \), so that unlike the globules, it is probably internally heated.

2.3 *Unbiased Surveys*

An alternative strategy for finding infrared objects is to examine the sources found in unbiased sky surveys. There have been only two infrared surveys that are substantially complete over more than a small fraction of the sky. These are the Caltech survey (Neugebauer & Leighton 1969) and the AFGL survey (Price & Walker 1976, Price et al. 1982). The Caltech (IRC) survey was carried out at 2.2 \( \mu \text{m} \), a much shorter wavelength than those at which the objects discussed in this review emit most of their luminosity. The BN object, for example, lies about 2 mag below the 39 Jy\(^1\) limit of the Caltech survey; of the objects listed in Table 1, only LkH\(\alpha\) 101 appears in the IRC.

The AFGL survey, recently described in detail by Kleinmann et al. (1981), is based on a series of 10 rocket flights using a cryogenic telescope to survey the sky at a number of wavelengths between 4 \( \mu \text{m} \) and 27 \( \mu \text{m} \). Many interesting infrared sources lie above the detection limits of the AFGL catalog, but the survey has been of limited value in discovering new infrared sources in molecular clouds because of the extensive ground-based follow-up required to determine the nature of each object. The low resolution (3' \( \times \) 10') of the survey means that each promising AFGL source must be mapped at both infrared and radio wavelengths in order to eliminate confusion by H II regions and diffuse molecular clouds. This is a slow process that is far from complete even in the northern hemisphere; as a result, only five objects in Table 1 (GL437, 490, 961, 2591, 2789) owe their present fame to their discovery in the AFGL survey.

2.4 *Well-Studied Sources*

Table 1 is a list and selective bibliography of about 30 well-studied compact infrared sources that display convincing evidence of recent formation. Com-

\(^{1}\) 1 Jy = 10\(^{-26}\) W m\(^{-2}\) Hz\(^{-1}\).
Table 1  Infrared sources in molecular clouds

<table>
<thead>
<tr>
<th>Source</th>
<th>Position (1950)</th>
<th>$S_{12}$ (Jy)</th>
<th>$S_{radio}$ (mJy)</th>
<th>H-lines (10^{-16} Wm^{-2})</th>
<th>Distance (kpc)</th>
<th>Luminosity $L_\odot$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL 490</td>
<td>$03^h23^m41^s4.4 \pm 0.3$</td>
<td>110 (27)</td>
<td>$&lt;1$ at 5 GHz</td>
<td>$B\alpha$ 9 (29)</td>
<td>0.9 (30)</td>
<td>$1.4 \times 10^3$</td>
<td>Bipolar CO (31)</td>
</tr>
<tr>
<td></td>
<td>$58^\circ 36'26''(26)$</td>
<td></td>
<td></td>
<td>$B\alpha$ 39 (5)</td>
<td></td>
<td></td>
<td>Faint red star (24)</td>
</tr>
<tr>
<td>NGC 1333-IRS13</td>
<td>$00^h25^m58^s12.2 \pm 0.2$</td>
<td>2 at 4.8 $\mu$m</td>
<td>$&lt;0.5$ at 5 GHz</td>
<td>---</td>
<td>0.5 (35)</td>
<td>$70$</td>
<td>Bipolar CO (14, 36, 198)</td>
</tr>
<tr>
<td>(HH7-11 IR)</td>
<td>$31^\circ 05'46''2''(32)$</td>
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<td></td>
<td>Herbig-Haro objects (35)</td>
</tr>
<tr>
<td>IC 1848A (GL 4029)</td>
<td>$02^h57^m34.7\pm 0.3$</td>
<td>9 (16)</td>
<td>$&lt;8$ at 2.7 GHz</td>
<td>$B\gamma$ 4.1 (17)</td>
<td>2.3 (6)</td>
<td>$2.2 \times 10^4$</td>
<td>Molecular cloud/nebulosity (18-20)</td>
</tr>
<tr>
<td></td>
<td>$+60^\circ 17' 28''3''$</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Unidentified emission features (18)</td>
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<tr>
<td>W3-IRSS</td>
<td>$02^h21^m53.2\pm 0.3$</td>
<td>600 (2, 3, 196)</td>
<td>7 at 15 GHz</td>
<td>$B\alpha$ &lt;12</td>
<td>2.3 (6)</td>
<td>$2 \times 10^5$</td>
<td>1.3&quot; double (8-10)</td>
</tr>
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<td></td>
<td>$+61^\circ 52' 21''3''$</td>
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<td>H$_2$O maser (11)</td>
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<td></td>
<td>(1)</td>
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<td></td>
<td>Molecular cloud (12-15, 194)</td>
</tr>
<tr>
<td>GL 437</td>
<td>$03^h03^m31.3\pm 0.3$</td>
<td>9 (21)</td>
<td>20 at 2.7 GHz</td>
<td>$H\alpha$ 0.26</td>
<td>3 (21)</td>
<td>$3 \times 10^4$</td>
<td>Molecular cloud/nebulosity (23, 24)</td>
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<tr>
<td></td>
<td>$+58^\circ 19' 19''2''$</td>
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<td></td>
<td>Unidentified emission features (21, 25)</td>
</tr>
<tr>
<td></td>
<td>-S</td>
<td>7 (21)</td>
<td>$&lt;1.2$ at 5 GHz</td>
<td>$H\alpha$ 0.41</td>
<td>3 (21)</td>
<td>$3 \times 10^4$</td>
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</tr>
<tr>
<td></td>
<td>$+58^\circ 19' 13''2''$</td>
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<td></td>
<td>-N</td>
<td>8 (23)</td>
<td>$&lt;1.2$ at 5 GHz</td>
<td>---</td>
<td>3 (23)</td>
<td>$3 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$+58^\circ 19' 23''2''$</td>
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</tr>
<tr>
<td></td>
<td>-W</td>
<td>9 (23)</td>
<td>20 at 2.7 GHz</td>
<td>$H\alpha$ 0.26</td>
<td>3 (23)</td>
<td>$3 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>IC 1848A</td>
<td>$02^h57^m34.7\pm 0.3$</td>
<td>9 (16)</td>
<td>$&lt;8$ at 2.7 GHz</td>
<td>$B\gamma$ 4.1 (17)</td>
<td>2.3 (6)</td>
<td>$2.2 \times 10^4$</td>
<td>Molecular cloud/nebulosity (18-20)</td>
</tr>
<tr>
<td></td>
<td>$+60^\circ 17' 28''3''$</td>
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<td>Unidentified emission features (18)</td>
</tr>
<tr>
<td></td>
<td>-S</td>
<td>7 (16)</td>
<td>$&lt;8$ at 2.7 GHz</td>
<td>---</td>
<td>2.3 (6)</td>
<td>$2.2 \times 10^4$</td>
<td></td>
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<tr>
<td></td>
<td>$+60^\circ 17' 31''3''$</td>
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<td></td>
<td>(16)</td>
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<tr>
<td>Object</td>
<td>Coordinates</td>
<td>250</td>
<td>3.5 at 5 GHz</td>
<td>By 420 (40)</td>
<td>Bα 2000 (5)</td>
<td>Position from blue POSS</td>
<td>Emission line star (43)</td>
</tr>
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<tr>
<td>LkHα101</td>
<td>04°26′57″25″±0′04″</td>
<td>0.8</td>
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<td>(IRC+40091)</td>
<td>35° 09′56.0″±0.6″</td>
<td>(38, 197)</td>
<td>(39)</td>
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<td></td>
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<tr>
<td></td>
<td>16° 01′45″±2″</td>
<td>(45)</td>
<td></td>
<td></td>
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<tr>
<td>L1551-IRS5</td>
<td>04°28′40″2″±0′15″</td>
<td>7</td>
<td></td>
<td>—</td>
<td>0.14</td>
<td>25</td>
<td>Part of Taurus dark clouds</td>
</tr>
<tr>
<td></td>
<td>18° 01′45″±2″</td>
<td>(45)</td>
<td></td>
<td>—</td>
<td>(46)</td>
<td>(47)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18° 01′45″±2″</td>
<td>(45)</td>
<td></td>
<td>—</td>
<td>(46)</td>
<td>(47)</td>
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</tr>
<tr>
<td>OMC1</td>
<td>-BN 05°32′49″69″±0″07</td>
<td>600</td>
<td></td>
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<td></td>
<td></td>
<td>IRc4 is core of “KL nebula”</td>
</tr>
<tr>
<td>(=IRc1)</td>
<td>-05° 24′16.6″±1″</td>
<td></td>
<td>8 at 15 GHz</td>
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<td>IR mapping (49, 55–59)</td>
</tr>
<tr>
<td>-IRc2</td>
<td>05°32′47″03″±0″11″</td>
<td>300</td>
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<td>IR/sub-mm spectroscopy (53, 60–62)</td>
</tr>
<tr>
<td></td>
<td>-05° 24′23.2″±1.5″</td>
<td></td>
<td>&lt;2 at 5 GHz</td>
<td></td>
<td></td>
<td></td>
<td>H2 emission (63–65)</td>
</tr>
<tr>
<td>-IRc4</td>
<td>05°32′46″78″±0″11″</td>
<td>300</td>
<td></td>
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<td>Masers (54, 66, 67)</td>
</tr>
<tr>
<td></td>
<td>-05° 24′28.0″±1.5″</td>
<td></td>
<td>&lt;2 at 5 GHz</td>
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<td></td>
<td>Molecular cloud (68–74, 200, 201, 206)</td>
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<tr>
<td></td>
<td>(49)</td>
<td></td>
<td>(28)</td>
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<td>(28)</td>
<td></td>
<td>See also Sections 5 and 6</td>
</tr>
<tr>
<td></td>
<td>05°32′59″1″±0″11″</td>
<td>20</td>
<td></td>
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<td></td>
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<td>Distance assumed equal to OMC1</td>
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<tr>
<td>-IRS3</td>
<td>-5° 12′10″±1″</td>
<td>(2)</td>
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<td>H2O maser (77)</td>
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<td></td>
<td>(75)</td>
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<td>&lt;250 at 8 GHz</td>
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<td>Molecular cloud (78–80)</td>
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<tr>
<td>-IRS4</td>
<td>05°32′59″6″</td>
<td>1.5</td>
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<td></td>
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<td>Nebulosity (81)</td>
</tr>
<tr>
<td></td>
<td>-5° 11′32″</td>
<td>(75)</td>
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<td></td>
<td></td>
<td></td>
<td>H3 emission (82, 205)</td>
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<tr>
<td></td>
<td>(from 75)</td>
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<tr>
<td>S235B</td>
<td>05°37′30″9″±0″16″</td>
<td>3.2</td>
<td></td>
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<td></td>
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<td>Visible spectrophotometry (87)</td>
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<tr>
<td>(M1-82#1)</td>
<td>+35° 40′01″±7″</td>
<td>(84)</td>
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<td>H2O maser (88)</td>
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<tr>
<td>S235-IRS4</td>
<td>05°37′30″9″±0″16″</td>
<td>3.2</td>
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<td>Molecular cloud (83, 89)</td>
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<tr>
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<td>(83)</td>
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<td></td>
<td></td>
<td></td>
<td>Unidentified emission features (202)</td>
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Table 1 (continued)

<table>
<thead>
<tr>
<th>Source</th>
<th>Position (1950)</th>
<th>$S_{13\mu m}$ (Jy)</th>
<th>$S_{radio}$ (mJy)</th>
<th>H-lines ($10^{-16}$ W m$^{-2}$)</th>
<th>Distance (kpc)</th>
<th>Luminosity $L_\odot$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 2071-IRS1</td>
<td>$05^{h}44^{m}30^{s}.6 \pm 0.2$</td>
<td>~30</td>
<td>8 at 5 GHz</td>
<td>B$\gamma &lt;10$</td>
<td>0.5</td>
<td>750</td>
<td>Distance assumed equal to OMC1</td>
</tr>
<tr>
<td>(GL 818)</td>
<td>($00^\circ 20^\prime 42^\prime \pm 1^\prime$ (90))</td>
<td>(30, 90, 91)</td>
<td>(92, 203)</td>
<td>(from 91)</td>
<td>(30, 93)</td>
<td></td>
<td>Bipolar CO, HCO$^+$ (94, 95, 194, 198, 203)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>587</td>
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<td>H$_2$ emission (90,96)</td>
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<td>Multiple system (90, 92)</td>
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<td>Nebulosity (97)</td>
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<td>Masers (77, 98)</td>
</tr>
<tr>
<td>Mon R2-IRS3</td>
<td>$06^{h}05^{m}21^{s}.8$</td>
<td>400</td>
<td>&lt;1 at 5 GHz</td>
<td>B$\alpha &lt;45$ (5)</td>
<td>0.95</td>
<td>$5 \times 10^3$</td>
<td>Multiple system (10, 102)</td>
</tr>
<tr>
<td>(NGC 2170)</td>
<td>($06^\circ 22^\prime 26^\prime$ (from 99))</td>
<td>(2, 196)</td>
<td>(28)</td>
<td>B$\gamma &lt;2$ (100)</td>
<td>(101)</td>
<td>(101)</td>
<td>Bipolar CO (15, 103, 198, 204)</td>
</tr>
<tr>
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<td>Masers (88, 98)</td>
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<td>Nebulosity (81)</td>
</tr>
<tr>
<td>S255-IRS1</td>
<td>$06^{h}09^{m}58^{s}.5 \pm 0.3$</td>
<td>140</td>
<td>&lt;1.6 at 5 GHz</td>
<td>B$\alpha &lt;18$ (5)</td>
<td>2.5</td>
<td>~10$^5$</td>
<td>Total luminosity includes IRS2</td>
</tr>
<tr>
<td>(IC2162, GL 896)</td>
<td>($18^\circ 00^\prime 12^\prime \pm 4^\prime$ (from 104))</td>
<td>(2, 105)</td>
<td>(104)</td>
<td>(5)</td>
<td>(104)</td>
<td>(106, 107)</td>
<td>Molecular cloud (89, 105, 108)</td>
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<td>H$_2$O maser (88)</td>
</tr>
<tr>
<td>GL961</td>
<td>$06^{h}31^{m}58^{s}.9 \pm 0.3$</td>
<td>70</td>
<td>0.9 at 5 GHz</td>
<td>B$\alpha 120$ (5)</td>
<td>1.4</td>
<td>$6 \times 10^3$</td>
<td>Bipolar CO (15, 112, 113, 198)</td>
</tr>
<tr>
<td>(Rosette)</td>
<td>($04^\circ 15^\prime 09^\prime \pm 5^\prime$ (109))</td>
<td>(2, 110)</td>
<td>(92)</td>
<td>(5)</td>
<td>(109)</td>
<td>(111)</td>
<td>H$_2$ emission (96)</td>
</tr>
<tr>
<td>R Mon</td>
<td>$06^{h}36^{m}26^{s}$</td>
<td>50</td>
<td>&lt;5 at 10.7 GHz</td>
<td>B$\alpha 35$ (5)</td>
<td>0.8</td>
<td>860</td>
<td>Variable nebula (116)</td>
</tr>
<tr>
<td>(NGC 2261)</td>
<td>($8^\circ 47^\prime 03^\prime$ (114))</td>
<td>(110)</td>
<td>(115)</td>
<td>(5)</td>
<td>(42)</td>
<td>(42)</td>
<td>Bipolar CO (117)</td>
</tr>
<tr>
<td>GL 989</td>
<td>$06^{h}38^{m}24^{s}.9 \pm 0.3$</td>
<td>170</td>
<td>&lt;5 at 5 GHz</td>
<td>B$\alpha 52$ (5)</td>
<td>0.8</td>
<td>$4 \times 10^3$</td>
<td>Molecular cloud (119, 121,122)</td>
</tr>
<tr>
<td>(NGC 2264)</td>
<td>($+09^\circ 32^\prime 29^\prime \pm 3^\prime$ (118))</td>
<td>(2, 110)</td>
<td>(119)</td>
<td>(5)</td>
<td>(111)</td>
<td>(111)</td>
<td>Herbig-Haro objects (123)</td>
</tr>
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<td></td>
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<td></td>
<td></td>
<td>H$_2$O source (88)</td>
</tr>
<tr>
<td>NGC 6334 IRSV-1</td>
<td>$17^{h}16^{m}36^{s}.6 \pm 0.3$</td>
<td>4</td>
<td>&lt;10 at 5 GHz</td>
<td>B$\alpha &lt;5$</td>
<td>1.7</td>
<td>$2 \times 10^5$</td>
<td>Possibly variable (127)</td>
</tr>
<tr>
<td></td>
<td>($-35^\circ 54^\prime 46^\prime \pm 4^\prime$ (124))</td>
<td>(124)</td>
<td>(124)</td>
<td>(124)</td>
<td>(126)</td>
<td>(127)</td>
<td></td>
</tr>
<tr>
<td>Object</td>
<td>Position</td>
<td>RA</td>
<td>Dec</td>
<td>Observations</td>
<td>Distance</td>
<td>Other Notes</td>
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<tr>
<td>M8 (E)</td>
<td>18°01'48.8&quot;</td>
<td>-24° 26' 56&quot;</td>
<td>170 (2)</td>
<td>4 at 5 GHz</td>
<td>1.5 (6)</td>
<td>2.5×10⁴</td>
<td></td>
</tr>
<tr>
<td>GL 2059</td>
<td></td>
<td></td>
<td>(128)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>G12.4+0.5</td>
<td>18°07'55.8&quot;</td>
<td>-17° 56' 32&quot;</td>
<td>9 (16)</td>
<td>18 at 10.7 GHz</td>
<td>2.3 (131)</td>
<td>2.7×10⁴</td>
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</tr>
<tr>
<td></td>
<td>±0.2</td>
<td>±3&quot;</td>
<td></td>
<td></td>
<td></td>
<td>Very low color temperature (16)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Molecular cloud (132)</td>
<td></td>
</tr>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>H₂O maser (133)</td>
<td></td>
</tr>
<tr>
<td>W33A</td>
<td>18°11'44.2&quot;</td>
<td>-17° 52' 59&quot;</td>
<td>40 (135, 196)</td>
<td>&lt;5 at 5 GHz</td>
<td>3.7 (131)</td>
<td>1.1×10⁵</td>
<td></td>
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<tr>
<td></td>
<td>±0.13</td>
<td>±2&quot;</td>
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<td></td>
<td></td>
<td>Molecular cloud (89, 137)</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Masers (138)</td>
<td></td>
</tr>
<tr>
<td>M17-IRS1</td>
<td>18°17'26.5&quot;</td>
<td>-16° 14' 54&quot;</td>
<td>~40 (139)</td>
<td>4 at 5 GHz</td>
<td>2.5 (140)</td>
<td>≥3×10³</td>
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<tr>
<td></td>
<td>±0.6</td>
<td>±9&quot;</td>
<td></td>
<td></td>
<td></td>
<td>Far-IR confused by H II region (142, 143)</td>
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<td></td>
<td></td>
<td>3.3-μm emission feature (144)</td>
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<td></td>
<td>Molecular cloud (143, 145)</td>
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<td></td>
<td></td>
<td></td>
<td>Embedded cluster (146)</td>
<td></td>
</tr>
<tr>
<td>S106</td>
<td>20°25'33.8&quot;</td>
<td>+37° 12' 52&quot;</td>
<td>80 (147, 148)</td>
<td>4.8 at 5 GHz</td>
<td>0.9 (150)</td>
<td>5×10⁴</td>
<td></td>
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<tr>
<td>GL 2584</td>
<td></td>
<td></td>
<td>(147)</td>
<td></td>
<td></td>
<td>Bipolar nebula (151–153)</td>
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<td>Polarimetry (149, 154–156)</td>
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<td></td>
<td></td>
<td>Molecular cloud (157, 158)</td>
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<td></td>
<td></td>
<td>H₂O maser (159, 160)</td>
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<tr>
<td>GL 2591</td>
<td>20°27'35.9&quot;</td>
<td>+40° 01' 16&quot;</td>
<td>750 (2, 196)</td>
<td>8 at 15 GHz</td>
<td>1.5 (163)</td>
<td>4×10⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>±0.2</td>
<td>±2&quot;</td>
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<td></td>
<td></td>
<td>H₂O maser (161)</td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
<td>Near H II region, nebulosity (161, 165)</td>
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<tr>
<td>GL 2789</td>
<td>21°38'10.4&quot;</td>
<td>+50° 00' 44&quot;</td>
<td>100 (18, 167)</td>
<td>&lt;0.5 at 5 GHz</td>
<td>6 (169)</td>
<td>9×10⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>±0.6</td>
<td>±5&quot;</td>
<td></td>
<td></td>
<td></td>
<td>Bipolar nebula (171)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Unusual &quot;visible spectrum (167)</td>
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<td></td>
<td></td>
<td>Molecular cloud (169, 172)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H₂O maser (170)</td>
<td></td>
</tr>
<tr>
<td>S140-IRS1</td>
<td>22°17'41.3&quot;</td>
<td>+63° 03' 40&quot;</td>
<td>350 (2, 104,</td>
<td>7 at 5 GHz</td>
<td>1.0 (175)</td>
<td>2×10⁴(?)</td>
<td></td>
</tr>
<tr>
<td>(GL 2884)</td>
<td>±0.4</td>
<td>±3&quot;</td>
<td>(173, 196)</td>
<td></td>
<td></td>
<td>Multiple extended source (8, 10, 102, 104)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Molecular cloud (72, 89, 121, 177)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nebulosity (178)</td>
<td></td>
</tr>
<tr>
<td>Source</td>
<td>Position (1950)</td>
<td>S$_{25}$ (Jy)</td>
<td>H-lines</td>
<td>Distance (kpc)</td>
<td>Luminosity (10$^{-6}$ W m$^{-2}$)</td>
<td>Remarks</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>Cep A</td>
<td>22h54m19s ± 0:3 325 ± 8</td>
<td>25 at 5 GHz (104, 179)</td>
<td>—</td>
<td>0.7</td>
<td>2.5 × 10$^4$ (180)</td>
<td>IR source extended (104, 179), H$_2$ emission (96), Radio emission multiple (104, 179, 181), Bipolar CO, HCO$^+$ (182, 194), Molecular cloud (15, 183, 184), Maser (179, 185)</td>
<td></td>
</tr>
<tr>
<td>NGC 7538</td>
<td>23h11m52s ± 0:3 528 ± 2</td>
<td>500 at 15 GHz (187, 188)</td>
<td>By &lt; 3 (186)</td>
<td>3.5 × 10$^4$ (186)</td>
<td>Near-IR emission (19, 81, 146), Molecular cloud (72, 89, 157, 190), IR scattering (154), Maser (188, 193)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**References:**
1. Willis et al. 1972
2. Willer et al. 1972
3. Dickey 1980
5. Colley 1980
7. Thronson et al. 1980b
9. Genzel et al. 1979
10. Lovell et al. 1982
13. Cohen & Kahl 1977
15. Leiden et al. 1981a
16. Thronson et al. 1980b
18. Genzel et al. 1979
19. Lovell et al. 1982
20. Walker 1981
23. Scoville et al. 1978
25. Kleinmann et al. 1977
26. Low et al. 1976
27. Merritt et al. 1976
29. Low et al. 1976
31. Lada et al. 1979
32. Cohen & Scoville 1980
33. Cohen & Scoville 1981
34. Scoville et al. 1978
35. Strickland et al. 1974
36. Snell & Edwards 1981
37. Brown & Woott 1971
38. Cohen & Woott 1970
39. Thompson et al. 1977
40. Thompson et al. 1977
41. Harvey et al. 1975
42. Allen 1973
43. Allen 1973
44. Knapp 1976

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mon features of all the objects in the list are that they emit most of their luminosity longward of 2 µm and are associated with molecular clouds. Most of them are also associated with microwave masers, usually H2O: Compact H II regions, in the sense of an OB star surrounded by an approximation to a Strömgren sphere, have been avoided except for GL437W, which is part of a very compact group, and NGC7538-IRS1, which strongly resembles some radio-quiet infrared sources and is the site of a unique formaldehyde maser. The presence of Brackett lines or faint thermal radio emission, however, has not excluded any source from Table 1. The inclusion of the visible stars R Mon and LkHα101 may be justified on the grounds that their visible luminosities are a minute fraction of their infrared luminosities and that certain of their properties—in particular, an extended infrared envelope for LkHα101 and a bipolar CO flow for R Mon—suggest a strong link with other nonvisible infrared sources. Bipolar nebulae such as IV Zw67 have been excluded from Table 1, although Allen et al. (1980b) argue that at least some of them may be young objects rather than protoplanetary nebulae.

The references in Table 1 are provided as a guide to the recent literature, rather than as an attempt to be comprehensive or to ascribe historical credit. The reader should be able to trace all earlier work on these sources from references in the papers cited. The list of sources in Table 1 is plagued, of course, by selection effects and is useless for statistical purposes. The southern hemisphere is grossly underrepresented, and even in the northern hemisphere most of the listed sources lie toward the anticenter rather than in the more populous first quadrant. In all parts of the sky there are many known infrared sources for which radio, far-infrared, and spectroscopic observations are badly needed in order to ascertain their nature and distinguish them from compact H II regions. In addition to the AFGL sources listed by Kleinmann et al. (1981), there are the southern hemisphere sources found by Frogel & Persson (1974), Moorwood & Salinari (1981a,b), and Epchtein & Lepine (1981), and many new infrared sources in the surveys of dark clouds reviewed by Hyland (1981). Promising regions for future searches would also be in the vicinity of the H II regions listed by Habing & Israel (1979) and Altenhoff et al. (1978), the H2O masers listed by Dinger & Dickinson (1980), and the OH masers listed by Turner (1979).

The IRAS satellite (Walker 1982) due for launch in 1982 will be able to survey the whole sky in four wavebands between 10 and 100 µm, with a sensitivity 10^2–10^3 times better than any large-scale survey to date. This survey is likely to revolutionize our understanding of young infrared sources, particularly at a statistical level, although since the survey beam is of the order of 1 arcmin in diameter, substantial ground-based follow-up will certainly be needed to make full use of the data.
3. CLUSTERING AND LOCATION

Of the objects listed in Table 1, considerably more than half are members of double or multiple groups with overall sizes less than 0.25 pc, although in some cases only one member of the group is listed in the table. This gregarious tendency was stressed by Beichman et al. (1979) in their paper on S140, S255, and Cep A. They pointed out that similar groupings had also been seen in OMC1, OMC2, GL437, Mon R2, W3, and NGC7538. From the sources listed in Table 1, IC1848 and NGC2071 should be added to the list, as well as GL2591 and NGC1333 if their associated compact H II regions or 2-μm infrared sources may be counted as companions.

Wynn-Williams & Becklin (1974) pointed out the similarity in both luminosity and physical size between the Orion OMC1 infrared cluster and the nearby Trapezium cluster of visible OB stars and suggested that the former was evolving to produce a new OB cluster with properties like those of the latter. As discussed by Sharpless (1954), multiple systems like the Trapezium are common in O associations; Beichman (1979) therefore carried out a statistical comparison of the properties of infrared clusters and Trapezium-type multiple systems. He determined the mean nearest-neighbor separation of each type of cluster by calculating the average distance between one object and its two nearest neighbors over all sources in the cluster. His mean values were 0.17 ± 0.04 pc for a group of 14 multiple infrared sources and 0.12 ± 0.01 pc for a group of 31 Trapezium-like systems drawn from the lists of Sharpless (1954) and Salukvadze (1978). Beichman argued that the agreement between these scale sizes is significant despite differences in the selection procedure (such as sensitivity, spatial resolution, and field of view) for the two sets of data, and that this result supports the view that fragmentation during gravitational collapse of the molecular cloud is the best explanation for the formation of Trapezium multiple systems and wide doubles. The scale size for both types of clustering is similar to that found for H₂O maser "centers of activity" by Genzel et al. (1978).

Hierarchical clustering is also seen among infrared sources. The object Mon R2-IRS3, part of a 1' (0.3 pc) diameter cluster of infrared sources and H II regions (Beckwith et al. 1976), is itself a 0.7" (700 AU) double source (Dyck & Howell 1982); W3-IRS5, a member of a considerably larger group of objects (e.g. Colley 1980), is a 1.3" (3000 AU) double, the two components of which have very similar energy distributions (Howell et al. 1981, Neugebauer et al. 1982). It has also been suggested that the high peculiar velocity of the Orion BN object, which is moving at about +12 km s⁻¹ relative to the OMC1 cloud, may be due to its membership in a binary system (Scoville et al. 1982b).
The question of the location of infrared sources within molecular clouds has been discussed recently by Evans (1981) and by Sargent et al. (1981b). It has been claimed (e.g., Habing & Israel 1979) that compact H II regions are preferentially found near the edges rather than at the centers of molecular clouds. Efforts to look for the same phenomenon among radio-quiet infrared sources have been hampered by three selection effects:

1. Searches for infrared sources in the vicinity of nebulosity, or other visible phenomena, are intrinsically biased against highly obscured sources such as those in cloud centers.
2. Searches in the vicinity of compact H II regions sample a volume of the cloud in which considerable dynamical evolution has already taken place since star formation was initiated.
3. Even at 20 μm, where extinction is about 20 times less than at visible wavelengths (Becklin et al. 1978, McCarthy et al. 1980), infrared sources may still be heavily obscured by dust and missed during a search.

Despite these difficulties, Beichman (1979) concluded that there is a strong probability of finding infrared sources near density peaks of molecular clouds. There is no tendency for infrared sources to be found near the edges of molecular clouds, and most infrared sources are too far from the nearest H II region/molecular cloud boundary to be the result of shock-induced star formation of the kind envisaged by Elmegreen & Lada (1977).

There appears to be a tendency for infrared sources to be found at positions of CO self-reversed line profiles in molecular clouds. Of the eight locations of self-reversals quoted by Loren et al. (1981a), five correspond to sources in Table 1. An interesting exception is ρ Oph A, which appears to coincide with neither a 2.2-μm source (Elias 1978a) nor a far-infrared (λ ~ 70 μm) emission feature (Fazio et al. 1976).

4. OBSERVATIONS OF THE DUST

4.1 The Continuum Emission

Many of the sources in Table 1 have had their continuum energy distributions measured over the full range of about 1 μm to 1 mm, although the comparatively poor sensitivity and spatial resolution of airborne instruments severely limit the amount of data available at wavelengths longer than 30 μm. Airborne observations in the 4–8 μm range (Willner et al. 1982) have permitted almost full spectral coverage between 2 and 13 μm for a number of sources, but spectrophotometry longward of 13 μm is presently restricted to only seven sources (Forrest & Soifer 1976, Tokunaga et al. 1978, Erickson et al. 1981, McCarthy et al. 1982). Observations longward of 300 μm may be made from
the ground but tend to be diffraction-limited to about 1' and, in the 300–800 μm range, are severely hampered by atmospheric water vapor.

Figure 1 shows the 1.6–1000 μm energy distributions of NGC2264 and NGC7538-IRS9. These sources were selected because they are well observed and show no signs of multiplicity on the scale of the airborne observations. They demonstrate that, while most of the objects in Table 1 have a broad peak at about 50–200 μm, different objects show substantially different energy distributions shortward of 20 μm; when normalized to their 100-μm flux densities, NGC2264 is 1000 times brighter than NGC7538-IRS9 at 1.6 μm. In fact, the variety of observed energy distributions is considerably wider than is suggested by Figure 1, ranging from the very flat spectrum of visible objects

![Figure 1](image_url)

*Figure 1* The 1.6–1000 μm energy distributions of infrared sources. Solid lines represent spectrophotometry, dashed lines are interpolations. Data for NGC2264 are from Allen (1972), Willner et al. (1982), Simon & Dyck (1977), and Harvey et al. (1977); data for NGC7538-IRS9 are from Werner et al (1979) and Willner et al. (1982). The dotted lines are theoretical blackbody emission from circular sources with the indicated temperature and diameter.
like LkHα 101 (Thompson et al. 1977) to objects like Cep A, which are so cool that they are almost undetectable at wavelengths shortward of 13 μm (Beichman et al. 1979).

In no known case does the energy distribution of an infrared source in a molecular cloud provide a good fit to a single blackbody curve, although in the 2–13 μm range the fits are generally somewhat better than those of compact H II regions (Willner et al. 1982). As may be seen in Figure 1, the emission longward of the peak generally declines more rapidly than the +2 power law of a blackbody, while the emission at short wavelengths lies well above a curve drawn through the peak. The faintness at long wavelengths is readily explicable if the emission at λ ≳ 100 μm is from optically thin dust whose emissivity decreases with wavelength. The strong shortwave emission implies that the source contains dust at more than one temperature, although there is a selection effect operating here, in that a source emitting like a 60 K blackbody would be very hard to discover by searches at wavelengths shortward of 20 μm.

NGC7538-IRS9 is an example of a source that is well fitted by a blackbody curve in the 2–13 μm range. The physical significance of this fit must be treated with great caution, however, because of the tendency for a Planck curve to be mimicked by large amounts of extinction. The reason for this is that in the 2–20 μm range the interstellar extinction varies approximately linearly with frequency, so that an intrinsically gray object will appear to have an energy distribution that varies as exp (−ν/ν₀). Such a curve is hard to distinguish from the “blue” side of the Planck curve, which is dominated by the exp (−hν/kT) term.

From the diameters of the representative blackbodies shown in Figure 1, it can be seen that the hot dust in these infrared sources subtends a smaller solid angle than the cool dust. This conclusion becomes even stronger if, as suggested above, the λ ≳ 100 μm emission is optically thin and if there is foreground extinction. The picture of an infrared source as a small hot core surrounded by a cooler envelope, or as a cloud with a radially decreasing temperature gradient has thus become deservedly popular.

There have been many attempts to calculate the infrared spectra of protostar models. The most ambitious of these attempts (e.g. Larson 1969, Bertout 1976, Yorke 1980) combine hydrodynamical models of protostar collapse with calculation of the radiation transport through the envelope. More commonly, static models have been calculated that comprise a hot energy source embedded in a dusty spherical envelope having a plausible density distribution. This simplified approach is justified by theoretical models for accreting protostars (see e.g. Bertout & Yorke 1978), which show that essentially all the thermal energy generated in a protostar is produced at its core. This is true both for low-mass protostars, in which the source of the luminosity is the accretion
shock between the core and the infalling envelope, and for high-mass protostars where thermonuclear reactions are the dominant heat source. Furthermore, the static radiation transport models have the advantage of being applicable (at least to the first order) to objects that are losing mass rather than accreting it, as long as the density distribution is suitably specified.

Models for radiation transport in a hot-centered spherical cloud have been constructed by Scoville & Kwan (1976), Leung (1976), Jones & Merrill (1976), Finn & Simon (1977), Bedijn et al (1978), Rowan-Robinson (1980), and Mitchell & Robinson (1981). Yorke & Shustov (1981) have made the most successful attempt to relate such models to actual observations of infrared sources, and they discuss which parameters have the greatest effect on infrared energy distributions. Their work suggests that the chief difference between sources such as NGC2264 and NGC7538-IRS9 may be in the column density to the central object, which is higher in NGC7538-IRS9. They also find that changes in the radial density distribution and in the overall size of the cloud tend to have a substantial effect on the long-wavelength parts of the infrared spectrum. Their models are quite insensitive, however, to the spectral distribution of the central hot source.

The usefulness of the long-wavelength measurements ($\lambda \sim 1$ mm) for probing the large-scale density structure of molecular clouds was also pointed out by Scoville & Kwan (1976). They cite two reasons for this. First, a cloud is likely to be optically thin at 1 mm, because grain emissivity decreases with increasing wavelength. Second, in the Rayleigh-Jeans limit, longward of the black-body peak, the volume emissivity in the cloud is proportional to only the first power of the temperature, rather than to an exponential function of it. By making maps at 1-mm wavelength, Westbrook et al. (1976) deduced that several hot-centered clouds have radial density distributions as steep as $r^{-1.5}$ or $r^{-2.0}$.

Little is known about the temporal variability of infrared sources in molecular clouds. McBreen et al. (1979) have reported that the far-infrared emission from NGC6334 IR5 increased by a factor of 2 between 1972 and 1975, but Fischer et al. (1982) detected no $2.2 \mu$m variability in this source over a two-year time span. The source R Mon and its associated nebulosity NGC2261 form a well-known variable visible object (Stockton et al. 1975).

4.2 Sizes and Shapes
As demonstrated by the 470 K blackbody curve fitted to NGC7538-IRS9 in Figure 1, the probable angular diameters of infrared sources in molecular clouds are generally less than or of the order of $1''$ in the 2–13 $\mu$m range. Physical diameters are typically of the order $10–10^3$ AU. Attempts to measure these angular diameters have been made either by direct analysis of slow slit scans across the source (e.g. Neugebauer et al. 1982, Dyck 1980), or by the
"infrared speckle" technique of rapidly scanning the source and examining the shape of the visibility function obtained by Fourier transformation of the scans (Chelli et al. 1979, Foy et al. 1979, Howell et al. 1981, Dyck & Howell 1982, Dyck & Staude 1982). These observations have led to upper limits of about 0.2 being placed on the 2–5 µm diameters of GL490, Orion BN, NGC2264, Mon R2-IRS2, and GL2591. Apart from the double sources W3-IRS5 and Mon R2-IRS3 (see Section 3), only S140-IRS1, NGC7538, and S235B showed signs of structure. In these three cases the extended emission is probably scattered radiation rather than heated dust (Dyck & Howell 1982, Dyck & Staude 1982). In several other cases the upper limits to the angular sizes are fairly close to the expected diameters if the sources are blackbodies at their observed color temperatures. Improvements in technique allowing measurements of the variation in angular size with wavelength would help in distinguishing between models in which the observed energy distribution results from temperature gradients in a hot-centered cloud or from foreground extinction, since hot-centered clouds have a strong variation of apparent diameter with wavelength (Scoville & Kwan 1976).

The shape of an infrared source is even harder to determine than its diameter, but there are a few cases where there is indirect evidence that the emergent radiation field—and hence probably the mass distribution—is anisotropic. Werner et al. (1979) argue that the high integrated brightness of the scattered 2.2-µm radiation seen to the southwest of the source NGC7538-IRS9 can be explained only if the radiation field emerging from the compact object in that direction is stronger than what we observe emerging toward us. In the cases of GL961 and NGC2264, Harvey et al. (1977) invoke a model with bipolar geometry to explain how the sources may simultaneously have a high 100-µm optical depth and yet have a visible appearance as a conical or fan-shaped nebulosity. Additional evidence for anisotropic geometries comes from Scoville et al.'s (1982b) detection of a hot neutral disk in the BN source (see Section 5.2) and from the discovery of bipolar CO flows around several sources (see Section 6.2).

4.3 Absorption and Emission Features

All well-studied infrared sources in molecular clouds show absorption features in their 2–13 µm spectra that are far too broad (λ/Δλ ≲ 100) to be attributable to atoms or ions, and which are therefore either of molecular or (more probably) solid-state origin (see Figure 1). A compilation of these spectra is given by Willner et al. (1982), and a review of the subject has recently been written by Aitken (1981).

The most prominent absorption features are those at 9.7 and 3.07 µm, which are generally attributed to silicate grains and water ice respectively (Gillett & Forrest 1973). Weaker features are also seen at 4.6, 6.0, and 6.8
The shape of the 9.7-μm feature agrees well with that of the emission feature seen in the Trapezium region of the Orion Nebula and in some late-type oxygen-rich stars; it also matches well the laboratory spectra of amorphous and hydrated silicates (Aitken 1981). The 3.07-μm feature, on the other hand, is generally somewhat wider than the laboratory profile of pure water ice and varies from source to source. The variation may be due to differences in particle size, or to the presence of varying amounts of solid ammonia or hydrocarbon ices (Merrill et al. 1976, Hagen et al. 1980).

Some early discussions attempted to explain the silicate absorption feature in terms of foreground extinction of a hot star by cold dust (e.g. Penston et al. 1971), but it soon became clear that such a model was predicting embarrassingly high bolometric luminosities for objects such as W3-IRS5. Kwan & Scoville (1976a) therefore put forward an alternative model in which the silicate feature arises as a result of radiation transfer outward through an optically thick, hot-centered molecular cloud. Due to higher opacity at 9.7 μm, the emission seen at this wavelength will arise farther out from the center (and therefore in a colder region) than the emission at neighboring wavelengths. As discussed in detail by Yorke & Shustov (1981), the silicate feature will finally appear in emission or absorption depending on whether or not the decrease in temperature is compensated by the increased emissivity and surface area of the dust seen at 9.7 μm.

Broad-band emission features, such as those at 3.3 μm, 7.7 μm, and 11.3 μm, have been seen in four of the sources in Table 1, though in each case the feature may be formed in a companion or a surrounding region of the compact object (Willner, private communication). Dwek et al. (1980) have suggested that the emission features arise in volatile mantles surrounding small grains, which, because of their size, are heated to much higher temperatures than their larger companions when exposed to ultraviolet radiation. A different mechanism, however, may be occurring in the envelope of the pre-main-sequence star HD97048 where a 3.5-μm, rather than a 3.3-μm, emission feature is seen (Blades & Whittet 1980, Aitken & Roche 1981).

### 4.4 Polarization

Infrared sources in molecular clouds are among the most highly polarized of all astronomical objects; a review of this subject has recently been published by Dyck & Lonsdale (1981). Most of the objects in Table 1 have now been measured at least one wavelength, usually 2.2 μm (Dyck & Capps 1978, Kobayashi et al. 1978, Dyck & Lonsdale 1979, Heckert & Zeilik 1981, Joyce & Simon 1982b). The 2.2 μm polarizations are often substantial, reaching 24% in the case of GL437N (Dyck & Lonsdale 1979). Outside of the 3.07- and 9.7-μm bands the polarization decreases with increasing wavelength. As discussed by Dyck & Lonsdale (1981), polarization by transmission through
a medium of aligned grains appears to be the best explanation of the polarization of most compact infrared sources. It can account for the polarization of the H$_2$ emission lines in OMC1 (Joyce & Simon 1982a), for the correlation between the percentage polarization and depth of the 3.07-$\mu$m feature in a sample of sources (Joyce & Simon 1982b), for the difference between the wavelengths of maximum extinction and maximum polarization in the ice band (Kobayashi et al. 1980), and for the correlation found by Dyck & Lonsdale (1979) between the direction of polarization of an infrared source with that of visible stars in its neighborhood.

Polarization by scattering, as opposed to absorption, is seen in the vicinity of several infrared sources. These include NGC7538-IRS9 and S106 (Tokunaga et al. 1981, Staude et al. 1981, Lacasse et al. 1981) and, most convincingly, the OMC1 cluster, where approximately 50% polarization is found at 3.8 $\mu$m from regions surrounding BN and IRc2 (Capps et al. 1980, Werner 1982).

5. OBSERVATIONS OF THE GAS

5.1 Ionized Gas

Part of the reason why the term "protostar" became popular among infrared astronomers in the early-1970s was that it appeared to be possible to make a sharp distinction between compact H II regions and "protostars" on the basis of the presence or absence of free-free radio emission. Only a very few sources, such as NGC7538-IRS1 (see Table 1 for references) and W3 (OH) (Thronson & Harper 1979, Scott 1981, Dreher & Welch 1981), appeared to have properties intermediate between the two classes of objects; they were found to be compact ($\leq$3" diameter), to have a very deep silicate absorption feature, and to be closely associated with masers.

The discovery by Grasdalen (1976) of Brackett-$\alpha$ hydrogen line emission from the region of the BN source, the archetypal "protostar," served to confuse this simple classification scheme. Since then, about ten more molecular cloud infrared sources have been found to be sources of atomic hydrogen line emission (see e.g. Thompson 1981, T. Simon et al. 1979, Simon et al. 1981b), while the increased sensitivity of the VLA has led to the discovery of faint radio emission from several of these and other objects (e.g. Beichman et al. 1979, Simon et al. 1981b). Details of these detections are given in Table 1. The 2.21-$\mu$m Na I doublet detected in the BN source by Scoville et al. (1982b) probably also originates in the ionized gas.

For an optically thin, unobscured H II region there is a simple relationship between the strength of the radio free-free emission and of the Brackett lines (see e.g. Wynn-Williams et al. 1978). In the low density limit at a temperature of $10^4$ K, this relation is
100 mJy at 5 GHz \( \equiv 8.8 \times 10^{-16} \text{ W m}^{-2} \) at Brackett-\( \gamma \)
\( \equiv 26 \times 10^{-16} \text{ W m}^{-2} \) at Brackett-\( \alpha \).

These theoretical ratios will alter slightly at very high electron densities (see e.g. Scoville et al. 1982b), but the most important reasons why observed fluxes from H II regions may deviate from these predicted ratios are extinction of the Brackett lines by dust, as in NGC7538-IRS1, and self-absorption of the radio emission, as in GL490 and GL961.

The advent of infrared Fourier transform spectroscopy has made possible the study of Brackett-line profiles in a number of sources. By this means, Scoville et al. (1982b) have shown that the Brackett lines in the BN object consist of a core with a normal H II region FWHM of 38 km s\(^{-1}\), plus high-velocity wings extending to about \( \pm 100 \) km s\(^{-1}\). They propose that the high-velocity emission is due to gas being blown off the edge of a compact H II region or off the central star. Broad lines (FWHM = 150 km s\(^{-1}\)) have also been detected from GL490 and M17-IRS1 by Simon et al. (1981b), who interpret them in terms of a mass flow of order \( 10^{-7} M_\odot \text{ yr}^{-1} \) outward from a central star. They point out that if this interpretation of the velocity profile is correct, most of the recombinations must be taking place in such a small physical volume that the Brackett lines may be substantially optically thick. A similar argument has been made independently by Krolik & Smith (1981), who treat the problem as one of line formation in an outflowing extended stellar atmosphere. Large optical depths in the hydrogen lines have the effect of masking the process causing the excitation of the gas and of altering the relative strengths of the Brackett lines. Under these circumstances, estimates of both the extinction and ionization rates based on the Brackett lines are unreliable. It is possible that this process might also account for the unexpectedly strong Brackett lines seen in some intermediate-luminosity sources, such as GL490 and NGC2264; it would then be unnecessary to invoke exotic ionization sources, such as Thompson’s (1981, 1982) accreting disk, to explain why the apparent recombination rate in these sources far exceeds that of a ZAMS star with the observed luminosity.

Potentially, it is possible to distinguish between the various theories for the origin of hydrogen emission lines by detailed comparison of the various Brackett- and Pfund-line profiles, which should differ if they were found at different optical depths. The only comparison that has been made to date has been in the BN source, where Scoville et al. (1982b) were unable to detect any difference between the Brackett-\( \alpha \) and Brackett-\( \gamma \) line profiles.

5.2 Neutral Gas

The pioneering studies of Hall et al. (1978), Scoville et al. (1979), and Scoville et al. (1982b) demonstrate the enormous amount of information that
may be gleaned from the analysis of the dozens of lines and blends of lines that can be measured in the high-resolution spectra of infrared sources, though as yet only the BN object has been studied in any detail. From Fourier transform spectra of the absorption and emission lines of both $^{12}$CO and $^{13}$CO, Scoville et al. (1982b) were able to deduce the physical conditions in at least four distinct regions of neutral gas close to or in the line of sight to the BN object. Two of the regions are seen only in absorption against the continuum of the BN object. One of these is simply the quiescent but warm ($\sim$150 K) gas of that part of OMC1 between the BN object and us; the other is blueshifted by 39 km s$^{-1}$ with respect to BN and is probably part of an outflow from either BN or IRc2.

The most prominent emission features in the infrared CO spectrum of BN are the $v = 4-2$, 3–1, and 2–0 bandheads at 2.3 $\mu$m. The upper levels for these transitions are at a very high level of excitation (up to $E/k = 19,000$ K) and very short lifetimes ($\sim$6 ms). Scoville et al. (1982b) deduced that the emitting gas has a temperature ranging from 3000 to 5000 K and a density $\geq 10^{13}$ cm$^{-3}$ in a volume with a scale size only a few times larger than a main-sequence B star. The column density of this gas is so high that it would totally obscure the hydrogen emission-line region that produces the Brackett lines of the BN object. Scoville et al. therefore favor a model in which the hot neutral gas comprises the inner region of a rotating disk that is inclined to our line of sight. The mass of this emitting region is in the range of $10^{-3}$ to $10^{-5}$ $M_\odot$, but a considerably greater mass could exist in the outer regions of the disk.

The fourth region of neutral gas that Scoville et al. (1982b) detect has a temperature of about 600° and an inverse P-Cygni profile indicative of gas moving toward BN. The authors interpret this as an inflow at the rate of order $10^{-6} M_\odot$ yr$^{-1}$ onto the outer parts of the disk at a distance of about 25 AU from the central star.

6. GAS FLOWS NEAR INFRARED SOURCES

The most serious challenge to the hypothesis that infrared sources in molecular clouds are protostars in an accretion stage came with the gradual realization that many of these objects are associated with extended (0.01–1 pc) high-velocity gas motions. These velocities, usually in the range of 10–100 km s$^{-1}$, are far higher than can be accounted for purely by gravitational acceleration; gas falling freely toward a 10 $M_\odot$ object would acquire a velocity of only 1 kms$^{-1}$ at a distance of 0.1 pc. High-velocity motions were first seen in H$_2$O masers, but their implications were not widely accepted until the discovery of
broad wings in the 2.6-mm CO emission line and of shock-heated molecular hydrogen.

6.1 Masers

Reid & Moran (1981) have recently reviewed the subject of astrophysical masers. The molecule that has yielded the most information about physical conditions in star-forming regions is undoubtedly H₂O. It is still not certain whether collisional or radiative pumping is the correct mechanism, but in either case it is probable that the H₂ density in the H₂O-masing region is 10⁷–10¹ⁱ cm⁻³, and the temperature is of the order of 1000 K (Goldreich & Kwan 1974, Genzel & Downes 1977b). Water vapor masers thus offer the potential for studying much hotter, denser gas than is generally probed by radiospectroscopy or infrared photometry.

H₂O masers are found associated with more than half of the known regions of OB star formation (Habing & Israel 1979). The association with compact infrared sources is even stronger; Genzel, Downes, Becklin & Wynn-Williams (unpublished), using the IRTF at Mauna Kea, Hawaii, detected 20-μm emission from the vicinity of 17 out of 21 H₂O masers searched. In many cases there is a real displacement of a few arcsec (≈0.1 pc) between the infrared and maser sources; in these cases it is still uncertain whether the H₂O and infrared sources are causally related, or whether they are manifestations of different objects in the same cluster. The latter possibility is a very real one given the clustering tendencies of infrared sources and compact H II regions (Section 3) and of H₂O masers themselves (Genzel et al. 1978).

Very long baseline interferometry has permitted both the detailed mapping of H₂O maser spots and, in a few cases, the measurement of their proper motions. Genzel et al. (1981) detected two expanding flows in OMC1: one is at 18 km s⁻¹ directed outward from a point close to the source IRc2, while the other is a much faster flow (30–100 km s⁻¹) with a less certain point of origin. The identification of IRc2 as the origin of the 18 km s⁻¹ flow is strengthened by its close association with a unique SiO maser (Genzel et al. 1980) and by its unusual infrared energy distribution (Downes et al. 1981). The H₂O maser regions are presumably dense condensations in a wind being blown from one or more infrared sources.

OH masers are often found close to H₂O masers, but they are not necessarily coincident with them. Generally the pattern of velocities in OH masers is confused; only in the Orion OMC1 region has a recognizable outflow pattern been observed (Hansen & Johnston 1980). It appears that almost all class I OH masers are seen projected against an optically thick compact H II region (Turner 1982). This result suggests either that the OH masers occur only in the conditions associated with an ionization front, or that the maser is amplifying
the background free-free radio emission. The only H$_2$CO maser known, NGC7538-IRS1, is also projected against an H II region (Rots et al. 1981).

6.2 Broad mm-Wave Lines

High-velocity molecular line emission in Orion was first seen in the 2.6-mm CO transition (Kwan & Scoville 1976b, Zuckerman et al. 1976). This broad emission, often referred to as the “plateau,” is seen as wide (± 50 km s$^{-1}$) Doppler wings on the edges of the narrow line emitted from the quiescent gas in the same direction. The plateau emission was subsequently seen in higher order CO lines (Phillips et al. 1977, Knapp et al. 1981, van Vliet et al. 1981, Goldsmith et al. 1981) and in a variety of other molecules (see Genzel & Downes 1982 for a recent review). Although a rotational explanation for these velocities has been proposed (Clark et al. 1979), it is now generally accepted that mass outflow of some kind is responsible. Knapp et al. (1981) argue that the flow is energetically too weak to be ascribed to a recent supernova explosion in the molecular cloud; instead, they favor an explanation involving continuous mass loss of order 10$^{-3}$ $M_\odot$ yr$^{-1}$ from one or more young stars or protostars. A similar conclusion is implicit in the work of Phillips & Beckman (1980), Chevalier (1980), Downes et al. (1981), and Kuiper et al. (1981).

Attempts to determine the origin of the outflow by careful positional measurement have been made for CO (Solomon et al. 1981), NH$_3$ (Zuckerman et al. 1981, Bieging et al. 1982, Genzel et al 1982), SO$_2$ (Knapp et al. 1981), SiO (Downes et al. 1982), and SO and HCN (Welch et al. 1981, Plambeck et al. 1982). The results are not conclusive but indicate that one of the infrared sources IRc2 or IRc4 is more likely to be the dominant source of the outflow than the more famous BN object nearby.

Recent improvements in radio telescope and receiver design have led to the discovery of high-velocity CO emission from a further 19 of the regions listed in Table 1, besides OMC1 (Bally 1982a). In 8 cases (noted as “Bipolar CO”) it has been possible to map the spatial distribution of this gas. In each case it is found that the peaks of the redshifted and blueshifted gas lie on opposite sides of the central infrared source, implying that mass ejection is occurring preferentially along one axis of the central object. Several of the authors who have found this double-lobed structure favor a model for these sources in which the expansion of the wind is constrained by a rotating disk of matter in the equatorial plane of the infrared source. Bipolar CO flow is, in fact, one of the strongest pieces of evidence for anisotropy in the matter distribution in the vicinity of molecular cloud infrared sources (see also Section 4.2). It is therefore of particular interest that similar phenomena are seen in objects with bolometric luminosities ranging from 25 $L_\odot$ to $2.5 \times 10^4 L_\odot$. The reason why OMC1 does not show a bipolar character in its CO emission is unclear but might be connected with the fact that it is physically smaller (0.1 pc vs. 1.5
pc for GL961) than the other sources mapped and shows the highest velocity spread of any of those yet measured (P.ully 1982).

6.3 Molecular Hydrogen and Shocked Gas

Emission from the 2-μm ν = 1→0 vibration-rotation lines of H$_2$ was first detected in Orion by Gautier et al. (1976). Subsequent research, which is discussed in detail elsewhere in this volume by Shull & Beckwith (1982), has included detailed studies of these lines in Orion (e.g. Beckwith et al. 1978, Nadeau et al. 1982, Scoville et al. 1982), detections of additional transitions (M. Simon et al. 1979, Knacke & Young 1981, Beck et al. 1979, 1982, Beckwith et al. 1982), and the detection of 2-μm H$_2$ emission from several other regions.

The gas in Orion is extended for over 1' around the OMC1 infrared cluster (Beckwith et al. 1978). It shows a large range in Doppler velocities (Nadeau & Geballe 1979) and a rotational temperature of about 2000 K (Gautier et al. 1976). There is now general agreement that the H$_2$ emission is best explained as arising in shock-heated gas at the boundary between a high-velocity wind and the ambient molecular cloud. The same regions of shocked gas may also give rise to the mm-wave "plateau" source and the high-J transitions of CO detected at far-infrared and submillimeter wavelengths (Storey et al. 1981, Goldsmith et al. 1981, McKee et al. 1982).

7. COMPARISON WITH THEORY

The close physical association of the infrared sources discussed in this review with visible young stars and with dense regions of interstellar matter leaves little room for doubt that they are young objects connected with the birth of stars. With one or two possible exceptions, such as OMC1-IRc4 (Downes et al. 1981), the objects are sufficiently luminous and spatially isolated that they must each have an internal heat source. This energy source could be gravitational or thermonuclear depending on the evolutionary stage of the object; to decide between these alternatives, a comparison with theoretical models of protostar evolution must be made.

Theoretical work on protostar evolution has been reviewed recently by Woodward (1978), Bertout & Yorke (1978), and Stahler et al. (1980). The most detailed studies have been of the precursors of 1-M$_\odot$ stars. The bolometric luminosities of these models are too low at all stages of their evolution to match those of the observed objects discussed in this paper. Models for high-mass (M \geq 3M$_\odot$) protostars must therefore be considered. The evolution of high-mass spherical protostars differs in two major qualitative ways from that of 1-M$_\odot$ objects. First, as pointed out by Kahn (1974), the Kelvin-Helmholtz contraction timescale of the core of a massive protostar soon
becomes shorter than the accretion timescale of its infalling envelope. After this stage, the protostar resembles a thermonuclear-burning main-sequence star surrounded by a dense gas and dust cocoon. The bolometric luminosity and core temperature of such an object rise monotonically toward their final values. Second, the radiation from the core of a massive protostar will eventually become strong enough to stop infall and disperse the remnant envelope either by radiation pressure on the dust or by ionization of the gas (Larson & Starrfield 1971). These predictions have been supported by detailed hydrodynamical calculations of the evolution of massive stars (Appenzeller & Tscharnuter 1974, Yorke & Krügel 1977, Yorke 1979). The implications of these models for the interpretation of the observed sources is (a) that an O or B star achieves a luminosity and surface temperature close to its main-sequence values while still deeply embedded in a dusty envelope, and (b) that the achievement of full luminosity is accompanied by a change from net inflow to net outflow in the envelope. The remaining parts of the envelope manifest themselves first as a luminous infrared source or “cocoon star” and subsequently as a compact H II region (Davidson & Harwit 1967, Kahn 1974, Cochran & Ostriker 1977).

As discussed in Section 4.1, attempts to match the energy distributions of infrared sources with those of model protostars have been reasonably successful (Yorke & Shustov 1981). Unfortunately these comparisons are not very discriminatory about conditions in the core of the object, since the emergent energy distribution depends far more on the optical depth of the dust shell and the properties of the dust grains themselves than on the nature of the central heat source. Further difficulties in comparing theory with observations arise when sources are deeply embedded in molecular clouds, since both the estimated luminosity and the energy distribution can be distorted by the intervening dust.

There are three outstanding phenomena that are not adequately addressed by current theoretical models. First, all models for massive protostars are spherically symmetric, whereas in many cases there is evidence for bipolar or axial symmetry (see Sections 4.2 and 6.2). Several authors have discussed the evolution of low-mass rotating protostars (e.g. Bodenheimer et al. 1980), but by analogy with the spherical case we may expect qualitatively different results for massive protostars. Of particular interest are the origin and properties of the rotating equatorial disks that have been postulated to exist around certain infrared sources.

Second, there is no adequate explanation of the mass outflow seen in a number of sources (Section 6). The mass loss in these sources has a much lower velocity and higher flux than that of mature O stars, so the wind is unlikely to be a radiation-driven wind of the kind described by Castor et al.
(1975). Some possible mechanisms are listed by Downes et al. (1981) and Shull (1982).

Third, protostar models have generally been applicable only to isolated objects, whereas observed infrared sources are frequently clustered on a scale of $10^{16}$–$10^{17}$ cm (Section 3). The close proximity of one source to another may significantly affect its evolution, particularly if their luminosities or formation times are disparate. The implications of the observed clustering on theories of fragmentation have also yet to be fully explored.

8. CONCLUSIONS AND PROSPECTS

The question of whether or not the search for infrared protostars has been successful is as much one of lexicography as astrophysics. If a liberal definition is permitted, such as “a compact infrared source whose major observable characteristics are believed to be a consequence of its current or its very recent accretion of matter” (Wynn-Williams 1977), then most of the sources in Table 1 would easily qualify. If, on the other hand, the word is restricted to objects undergoing current accretion and powered by gravitational rather than thermonuclear energy, it is doubtful whether any would pass. The reason for the lack of protostars in the restricted sense appears to be that the objects studied up to now are sufficiently massive that there is only a very short period of time in which the protostar is luminous enough to be observed before thermonuclear burning dominates the energy production. This condition does not apply to low-mass protostars; our chances of detecting such objects will therefore be greatly improved by the IRAS survey (Walker 1982), which should be capable of detecting $1 L_\odot$, 200 K objects at a distance of 1 kpc.

Our understanding of massive star formation has increased a great deal; we have found where OB stars are born and that they generally form in groups at molecular cloud peaks. We have established that they can reach very large luminosities and start to produce ionizing radiation while still embedded in thick nonspherical dust shells. Finally, we have discovered that both in their embedded stage and later, luminous new stars undergo dramatic anisotropic mass loss. The next few years offer excellent prospects for greatly improving our understanding of the high-luminosity infrared sources discussed in this review. The most rapid progress is likely to come from increased use of high-resolution 1–20 µm spectroscopy, from mapping of cool regions in the submillimeter continuum, from mm-wave aperture synthesis, and from the statistics and follow-up at high spatial resolution of interesting objects found in the IRAS survey.

There are healthy signs that a common ground may be emerging between the two main observational approaches to the study of star formation—namely
the infrared/radio studies of high-luminosity molecular cloud sources and the visible-region studies of stars in young clusters. The discovery of bipolar emission from the low-luminosity source L1551 (Snell et al. 1980), the detection of $\lambda \sim 100$-$\mu$m emission from young visible stars (Harvey et al. 1979b), the detection of CO emission from Ae/Be stars (Loren 1977), the study of the young cluster embedded in OMC1 (Lonsdale et al. 1982), and the discovery of an infrared companion to T Tau (Dyck et al. 1982) all offer signs that a more unified picture of star formation may emerge in the next few years.

ACKNOWLEDGMENTS

I would like to thank the many people who sent me preprints and allowed me to quote unpublished results. I have particularly benefited from suggestions by Eric Becklin, Neal Evans, Tom Geballe, Harry Hyland, Julian Krock, Gerry Neugebauer, Mike Simon, Rodger Thompson, Alan Tokunaga, and Steve Willner. I also thank Linda Peterson for her help in preparing the typescript. This work was performed under NSF grant AST 80-22218.

Literature Cited

Aitken, D. K. 1981. IAU Symp. No. 96, pp. 207–21
Andrew, B. H., ed. 1980. Interstellar Molecules, IAU Symp. No. 87
Gray, W., Hyland, A. R., Jones, T. J. 1982. MNRAS. Submitted for publication
Harvey, P. M., Campbell, M. F., Hoffmann.
SEARCH FOR INFRARED PROTOSTARS

Roger, R. S., Dewdney, P. E., eds. 1982. Regions of Recent Star Formation. Dordrecht: Reidel
Simon, M., Righini-Cohen, G., Fischer, J.,
1982ARA&A..20..587W


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