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Infrared Studies of Star Formation

Infrared observations make possible the study of stars in early evolutionary stages.

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The lifetime of a massive star before it begins to deplete its nuclear fuel is less than 5 million years (*1*). In contrast, the age of the galaxy is more than 10 billion years (*2*); nevertheless, many massive and short-lived stars have been identified by observations at optical wavelengths. These massive stars must have formed very recently relative to the age of the galaxy, and therefore star formation must be occurring in the galaxy at the present time.

For many years, astronomers and astrophysicists have attempted to understand the stages in the formation and early evolution of a star. These studies have included both observational searches for objects that could be identified as forming stars and theoretical investigations of the mechanisms through which stars are formed (*3*).

In recent years, the relatively new techniques of infrared astronomy have been successfully applied to the observational study of star formation. In this article we review the infrared observations, at wavelengths from a few micrometers to 1 millimeter, which pertain to the problem of star formation. The infrared data include both observations of large clouds of dust and gas within which groups of stars may be forming and detailed studies of individual objects within these clouds.

One of the principal results of the infrared studies has been the discovery of numerous starlike objects with sizes comparable to the size of the solar system, total luminosities in excess of 10^4 solar luminosities ($L_\odot$), and temperatures of 300° to 500°K. These objects, which are very bright in the infrared but invisible at optical wavelengths, have many of the characteristics expected of young and forming stars. Thus the infrared observations permit us to push the empirical study of star formation back to a time preceding the stage at which a young star first becomes visible optically.

Scope of the Observations—Stages of Star Formation

The infrared observations to be discussed here pertain chiefly to massive stars of high luminosity which are observed to be forming in groups within large clouds of gas and dust. These clouds have dimensions of 1 to 10 light years (*4*), masses of 10^3 to 10^5 solar masses ($M_\odot$), and average densities of 10^4 to 10^6 atoms per cubic centimeter. The gas in these clouds has been extensively investigated by radio astronomical studies of emission lines from molecular species such as CO, HCN, and H_2CO (*5*), but the principal gaseous constituent is H_2. The dust represents only about 1 percent of the total mass in both the dense clouds and the diffuse interstellar medium. The dust particles have a characteristic size of 0.1 μm and are thought to be composed of a mixture of materials, including silicate minerals, ices, and graphite (*6*). The dust is of special importance for the present discussion because, as will be described below, most of the infrared radiation from the regions and objects discussed here is produced by thermal emission from heated dust particles. Because the dust particles are so small, they interact less strongly with infrared than with optical radiation, and infrared sources can be detected even when they are embedded within dust clouds that are opaque at optical wavelengths.

In the galactic plane away from these dense clouds, the average interstellar gas density is 0.1 to 10 atom cm^{-3} (*7*). The first step in star formation is compression of this low-density interstellar material into dense clouds of gas and dust with densities of 10^4 to 10^6 atom cm^{-3}, within which stars are observed to form. The physical mechanisms which produce this crucial first step in star formation may be related to the large-scale collective motions which are thought to maintain the spiral structure of the galaxy (*8*), and detailed models of cloud compression based on this idea have been worked out recently (*9*). To form a star, which has an average density of 10^{22} atom cm^{-3}, from a region with a density of 10^4 atom cm^{-3} requires further condensation of the gas and dust. It is thought that this is initiated when a large portion of the cloud of gas and dust becomes unstable and starts to collapse under its own gravitational attraction. Calculations (*10*) suggest that as the collapse proceeds, this initial condensation may break up into a number of collapsing fragments, each of roughly stellar mass, and that this collapse process eventually results in the formation of a group or cluster of main sequence stars; that is, stars in a stable configuration which derive their luminosity from the conversion of hydrogen to helium. A star spends most of its lifetime in this stage, and most stars observed optically are found to be main sequence stars.

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Infrared Emission from Forming Stars

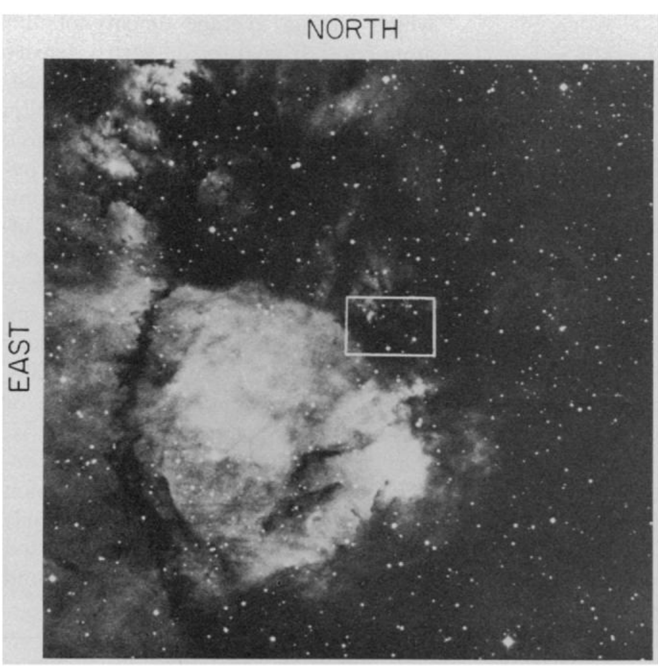
Consider now a single collapsing fragment of mass about 20 $M_\odot$, which is embedded within a much larger cloud of dust and gas. The following arguments suggest that this collapsing fragment will be very luminous and that it should be observable, particularly at infrared wavelengths, as it evolves into a main sequence star. On the main sequence, a 20 $M_\odot$ star has a radius of ten solar radii, or about 5×10^{11} cm. It follows that about 2×10^{50} ergs of gravitational potential energy are released in the contraction associated with the formation of this star. If, as suggested by a number of calculations (*10*), the gravitational energy is released over a formation time scale of 10^5 to 10^6 years, the average luminosity of the star as it forms is 5×10^3 $L_\odot$. This luminosity, which is generated at the center of the collapsing star, diffuses outward and heats the gas and dust in the outer portions of the star to a temperature of several hundred degrees. The dust radiates this power at infrared wavelengths, and consequently a forming star in this pre–main sequence phase will be a luminous, compact infrared source. Even after the star has reached a stable main sequence configuration, it may not yet have emerged from the larger cloud of dust and gas within which it formed. In a cloud with a gas density greater than 10^4 atom cm^{-3}, there is enough dust that the optical and ultraviolet radiation from an embedded main sequence star travels less than 0.5 light year before being absorbed by the dust particles, which reradiate the energy at infrared wavelengths. Thus a main sequence star embedded in a dense dust cloud will appear as an infrared source; however, it may be possible to distinguish the main sequence star from an embedded pre–main sequence object because of the radio continuum emission associated with the main sequence star, which is discussed in the next section.

Figures 1 and 2 illustrate the fact that regions of recent star formation are very bright at infrared wavelengths. These figures show photographs of a region called W3 in the constellation Cassiopeia (*11*). The area enclosed in the box in Fig. 1 shows no unusual optical features; however, as illustrated in Fig. 2, it is the center of a strong source of infrared radiation which has a total luminosity of 10^6 $L_\odot$ in the wavelength range 40 to 350 μm (*12*). This infrared luminosity is radiated by a dense dust cloud that is heated by a group of main sequence and pre–main sequence stars which are buried deep within it and which are not visible at optical wavelengths.

Selection Criteria

Many of the regions which have been found to contain possible pre–main sequence objects, including the W3 region, were selected for detailed study in the infrared because it was deduced that they contain short-lived main sequence stars and are therefore sites of recent star formation. The short-lived main sequence stars have been discovered through radio continuum observations of clouds of ionized gas, called H II regions, which often surround such stars. A 20 $M_\odot$ star has a main sequence lifetime of 5×10^6 years, a luminosity of 3×10^4 $L_\odot$, and a surface temperature of 25,000°K; more massive stars have shorter lifetimes and are more luminous and hotter. Such massive and short-lived stars are therefore hot enough to emit photons with sufficient energy to ionize the surrounding gas and produce an H II region. The H II region has a characteristic continuous emission spectrum which extends from visual to radio wavelengths (*13*). Because the interstellar grains do not absorb radio waves, H II regions can be detected in a radio survey even if they are buried within dust clouds which are opaque at visual wavelengths.

Recently, regions which were selected for study at infrared wavelengths because they show enhanced thermal molecular emission (*14*) or OH and H_2O microwave maser emission (*15, 16*) have also been found to contain possible pre–main sequence objects. The first complete infrared surveys of the sky at wavelengths longer than 2 μm are only now being carried out (*17*). Since these surveys will be free of the selection ef-



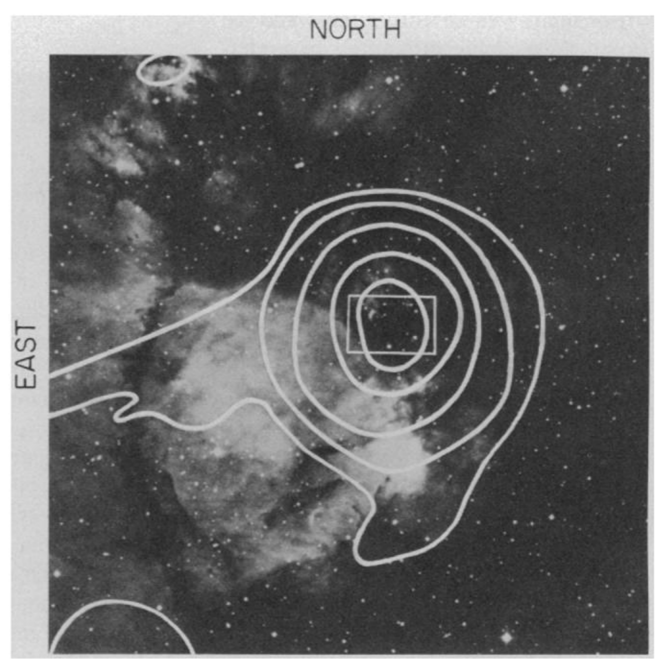


Fig. 1 (left). Photograph of the W3 region. The box encloses the region where infrared and radio observations show that the luminosity due to young stars and forming stars is highest. This region is described in Table 2 and also shown in Fig. 12. Its spectrum is included in Fig. 3. The size of the box corresponds to 3 light years at the distance of W3. Fig. 2 (right). Contours of 40- to 350-μm emission are shown superposed on the photograph of W3 from Fig. 1. [Adapted from (*12*)]

fects which have influenced infrared studies to date, they should stimulate new ideas about the scope and sites of star formation in the galaxy.

The study of pre–main sequence evolution is not confined to infrared and radio wavelengths. Lower-mass stars which form more slowly than the massive stars discussed in this article may wander out of their parent clouds and become visible during the latter stages of their pre–main sequence evolution; such objects have been extensively studied at optical wavelengths (*18*).

Infrared Energy Distributions— The Importance of Dust

The importance of dust within regions in which stars are forming has been established by infrared observations. Typical infrared energy distributions of such regions and of individual sources within them are shown in Fig. 3; Fig. 4 shows higher-resolution spectra of one of the best-studied candidate protostellar objects.

The infrared (1 μm to 1 mm) portion of the spectra in Fig. 3 is attributed to continuous thermal emission from dust particles for the following reasons.

1) Dust emission is an economical and natural hypothesis since dust is a ubiquitous constituent of the interstellar medium which readily absorbs ultraviolet and optical radiation and radiates efficiently at infrared wavelengths.

2) The overall shape of the spectra, which, as shown in Fig. 3, are roughly similar to blackbody spectra, are consistent with this hypothesis.

3) For many sources, the spatial distribution of the radiation is that expected from a cloud of dust heated by a central source (*19*). In particular, at longer wavelengths the regions tend to look larger, as would be expected if the long-wavelength radiation is dominated by a contribution from cool dust at large distances from the embedded luminosity sources.

4) Broad spectral features attributable to ice (*20*) and silicate (*21*) grains are seen at 3 and 10 μm in many sources (Fig. 4a).

5) Although atomic and molecular emission lines are seen in higher-resolution spectra, the spectra are not dominated by these emission lines, even at the highest resolution obtained to date (Fig. 4b).

Because the infrared radiation is produced by heated dust grains, the infrared observations of these regions reflect the

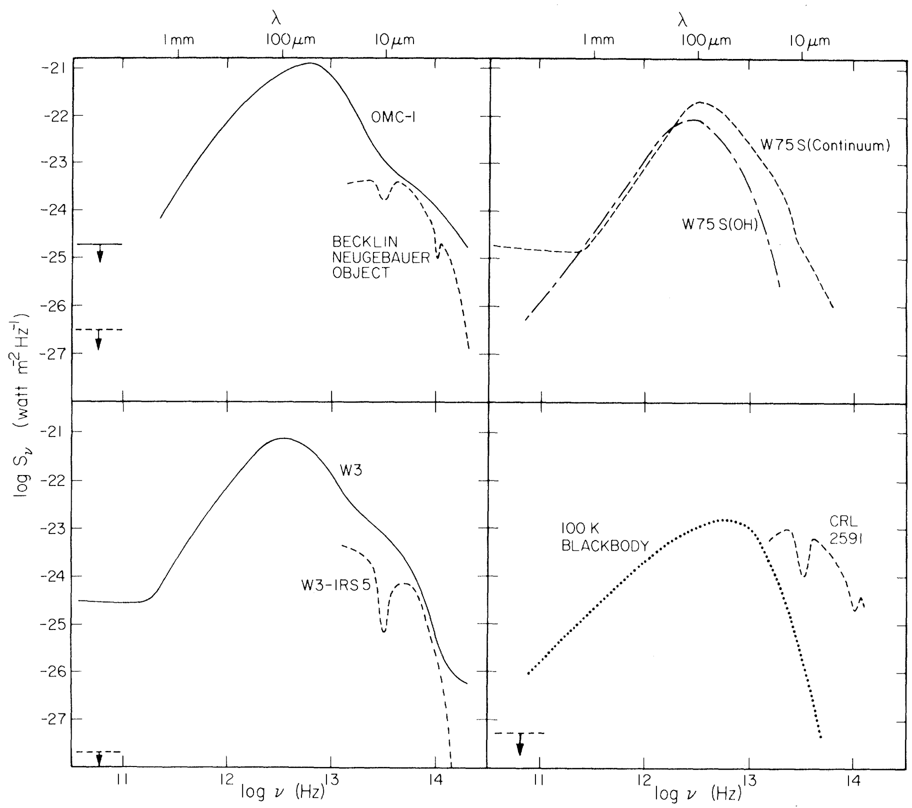


Fig. 3. Infrared energy distributions of prominent regions of recent star formation (solid curves) and of individual sources within them (dashed curves). For reference, the spectrum of the emission from a 100°K blackbody is shown as a dotted line in the lower right panel. The *x*-axis shows both wavelength (λ) and frequency (ν), while the *y*-axis shows flux per unit frequency as observed at the earth. The portion of these spectra from 1 μm to 1 mm is due to thermal emission by dust, as discussed in the text. The flat spectrum longward of 1 mm seen for W75 S and W3 is due to emission by ionized gas. The other regions and objects show only upper limits to any such emission. Most of the regions and sources for which data are shown are discussed in the text. Sources of the data are: OMC-1 (*30, 31, 46*); Becklin-Neugebauer source (*44, 47*); W3 (*46, 48*); W3-IRS 5 (*49, 50*); W75 S (continuum) and W75 S-OH (*51–54*); and CRL 2591 (*55, 56*). The conventions used for naming these objects are discussed in (*11*).

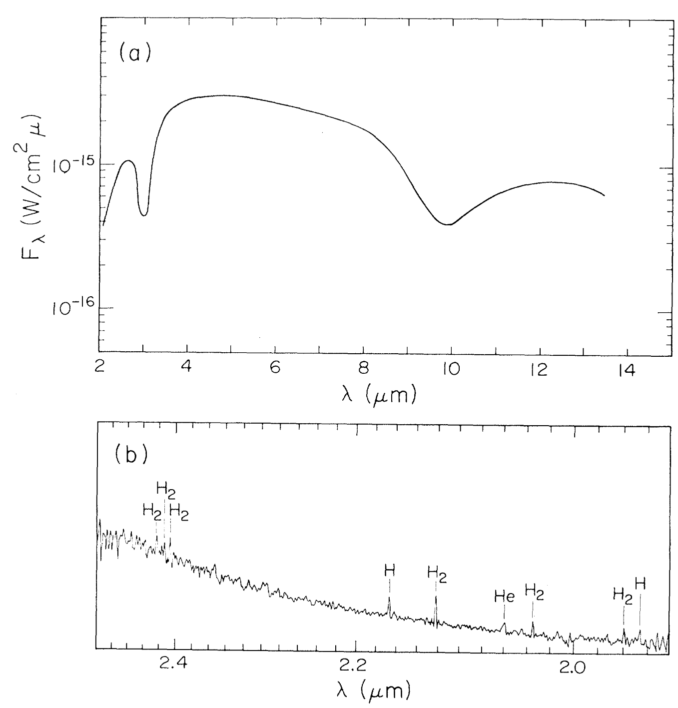


Fig. 4. (a) Spectrum, from 2 to 14 μm, of the emission from the Becklin-Neugebauer object in Orion, which is a well-studied possible protostellar object. The *x*-axis is wavelength and the *y*-axis is flux per unit wavelength as observed at the earth. The spectral resolution is ~ 0.05 μm, and the prominent features at 3.3 and 10 μm are attributed to absorption by ice and silicate grains, respectively [see (*44*) for a detailed discussion]. (b) Spectrum of the emission from the Becklin-Neugebauer object between 1.92 and 2.50 μm. The *x*-axis is wavelength and the *y*-axis is flux in arbitrary units. Spectral resolution is ~ 0.002 μm. Emission lines attributable to helium and hydrogen atoms and to the hydrogen molecule H_2 are seen superposed on the continuum. It is not yet certain whether these emission lines are associated with the Becklin-Neugebauer object itself or with the foreground and background gas clouds of Orion complex. [Adapted from (*45*)]

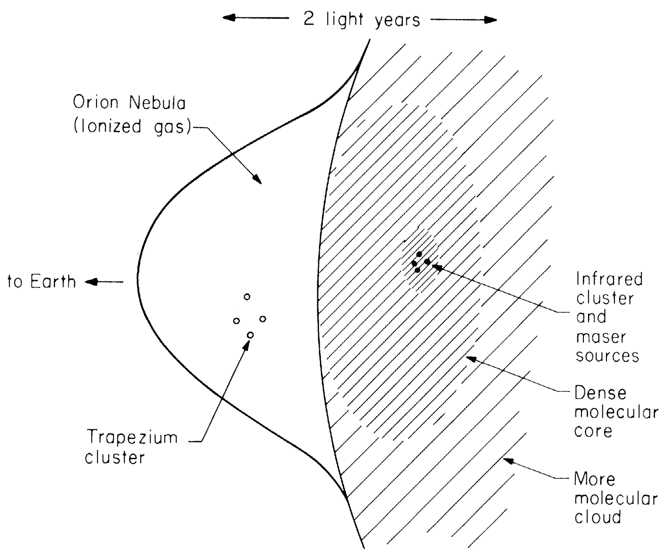


Fig. 5. Schematic representation of the structures and orientation of the OMC-1 region. [After Zuckerman (*28*)]

properties and distribution of the dust rather than of the gas; the latter can be studied directly by observations of molecular and atomic emission lines and of the radio continuum emission from ionized clouds. The gas represents most of the mass, but since most of the energy is radiated by the dust, the dust governs the transport of energy and thereby strongly influences the structure and evolution of these regions.

Orion Molecular Cloud 1—A Case Study

The Orion Molecular Cloud 1 (OMC-1) region, which includes the well-known Orion Nebula, is the nearest known region of recent massive star formation. It offers a unique opportunity for a detailed study of many of the phenomena associated with the early stages of star formation. The OMC-1 region lies about 1500 light years from the earth. Within the core of this region, 2 light years in size, are to be found:

1) The Orion Nebula, a cloud of ionized gas with temperature 10^4°K, density 10^4 atom cm^{-3}, and total mass 10 $M_\odot$.

2) The Trapezium cluster of hot, luminous main sequence stars, with total luminosity 3×10^5 $L_\odot$, which excite and ionize the nebula.

3) A dense cloud of neutral, molecular gas with temperature about 100°K, density in excess of 10^6 molecule cm^{-3}, and total mass 500 $M_\odot$.

4) A cluster of infrared stars which have a total luminosity greater than 10^5 $L_\odot$ but are not visible optically, have the characteristics of pre–main sequence objects, and are located in the densest portion of the molecular cloud.

5) Sources of OH, H_2O, and SiO microwave maser emission which lie close to the infrared cluster.

Figure 5 presents a schematic representation of the OMC-1 complex, showing the relative locations of the components listed above. This representation is constructed on the basis of data such as those presented in Figs. 6 through 11. Figure 6 shows a photograph of the Orion Nebula, while Fig. 7 shows the distribution of the radio continuum emission from the ionized gas in the nebula. This radio emission gives a better idea of the distribution of high-density ionized gas than does the optical photograph because the radio emission is less affected by absorption by intervening dust. Figures 8 through 11 show the center of the OMC-1 complex as observed at 20 and 100 μm, in the 1-mm continuum, and in the 2-cm emission line of the formaldehyde molecule, which is just one of the many molecules that have been observed in this region.

The infrared cluster and its relationship to the maser sources (*22*) and the Trapezium cluster is shown in detail in Fig. 12. The peak of the infrared and molecular emission shown in Figs. 8 through 11 coincides with the infrared cluster and not with the Trapezium cluster or with the region of highest density of ionized gas.

The cloud of ionized gas which produces the radio emission and the optical radiation shown in Figs. 6 and 7 has a particle density of about 10^4 atom cm^{-3} and a total mass of about 10 $M_\odot$ (*23–25*); this density and mass are typical of H II regions associated with newly formed stars. The gas is ionized and excited principally by one of the stars in the Trapezium cluster. The exact age of the nebula and the exciting stars is uncertain, but they are estimated to be 10^5 years old (*25, 26*). The Trapezium cluster makes a significant contribution to the infrared radiation from the region as a whole. For example, it appears that the bar of emission to the lower left in the 100-μm map (Fig. 9) is produced by dust at the edge of the H II region which is heated directly by the Trapezium stars (*27*).

The infrared maps (Figs. 8 through 10) show that several spatially distinct components contribute to the observed infrared emission, and that the overall spatial extent of the emission increases with increasing wavelength. Only at the shortest infrared wavelengths such as 20 μm does the relatively small amount of hot dust inside the region of ionized gas contribute significant radiation. At 100 μm, there is a contribution both from dust at the edge of the region of ionized gas and from material in the molecular cloud. The close correlation between the 1-mm emission (Fig. 10) and the H_2CO emission (Fig. 11) suggests that most of the 1-mm emission is produced by cool dust in the massive molecular cloud.

Although visually the Orion Nebula is very prominent, it is now clear that the bulk of the mass and a significant fraction of the luminosity of the OMC-1 region is contained in the molecular cloud, the core of which lies behind the Orion Nebula as seen from the earth. The proximity on the sky of the Orion Nebula and the molecular cloud shown by Figs. 6 through 11 is not due to an accidental projection. A number of arguments indicate that the Orion Nebula has in fact formed on the front surface of the molecular cloud, as indicated in Fig. 5 (*25, 28*). The core of the molecular cloud is delineated by the 2-cm H_2CO emission (Fig. 11) and the distribution of 1-mm continuum emission (Fig. 10); it is seen as well at 100 μm (Fig. 9). The position of maximum infrared and molecular emission is coincident with the infrared cluster shown in Fig. 12.

The nature and evolutionary status of the objects in the infrared cluster is at once the most important and the most difficult question to be answered about this region. Since this is by far the best-studied object of its type, it is important to review the evidence which suggests that the cluster has formed recently. First of all, the infrared cluster lies in a region which contains a large association of young visible stars, including the Trapezium cluster, and is therefore known to be a site of recent star formation (*29*). The infrared cluster is envisioned as a group of still younger stars which formed recently in the dense core of the molecular cloud and have not had time to disperse from this high-density region where they were born. A physical association between the cluster and the high-density region is suggested by the positional coincidence of the cluster with the peaks in the molecular and 1-mm emission. An accidental projection on the sky is excluded by the fact that the temperature of the emitting grains falls away from the position of the cluster (*30*). These temperature gradients suggest that the infrared cluster is buried within the molecular cloud and is heating the surrounding material. Furthermore, the density distribution in the cloud center inferred from the 1-mm continuum observations (Fig. 10) is similar to that expected in a cloud which is collapsing under its own gravitational forces, and its presence at this position is suggestive of a recent collapse process which led to the formation of the infrared cluster (*31*).

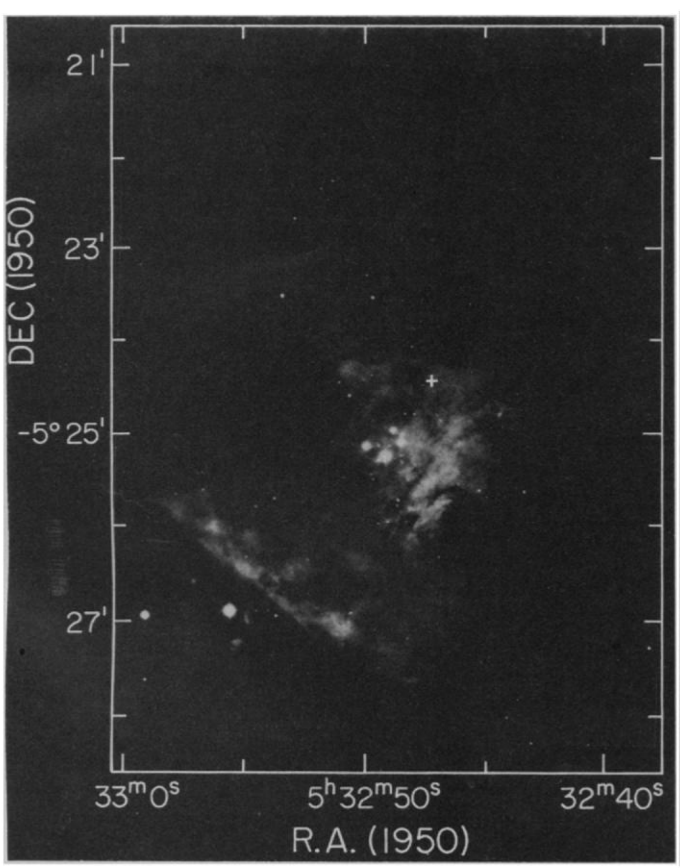
An estimate of the age of the cluster may be obtained from the time scale over which it would dissipate because of random motions. If the cluster size of 0.1 light year is divided by a typical random velocity of a few kilometers per second, this age is found to be around 5×10^4 years, comparable with the pre–main sequence time scale.

Other data support the interpretation that the cluster members are pre–main sequence objects. First, one member of the infrared cluster, the so-called Becklin-Neugebauer object, is a compact source with a luminosity of $10^4\ L_{\odot}$, a temperature of 600°K, and dimensions less than 200 astronomical units. Numerical model calculations show that these parameters are typical of those expected of an object in the latter stages of its pre–main sequence evolution (*10, 32*). Spectra of the Becklin-Neugebauer object are displayed in Fig. 4.

Second, there appears to be no prominent radio continuum emission associated with the infrared cluster. In contrast, the neighboring Trapezium cluster of visible stars ionizes the Orion Nebula, which is a very strong source of radio continuum emission. Since the two clusters have comparable luminosity, the absence of radio emission from the infrared cluster suggests that this cluster is not merely a group of young main sequence stars embedded in the molecular cloud, and that it may be at a significantly earlier evolutionary stage than is the Trapezium cluster. In fact, the data reviewed above support the speculation that the infrared cluster is evolving toward a Trapezium-like configuration. The Trapezium stars, in turn, appear to be the most recently formed members of the extensive association of young main sequence stars which has been identified in the Orion region (*29*).

Additional Examples of Young and Forming Stars

Several dozen compact, dust-embedded sources with properties similar to those of the Orion infrared and Trapezium clusters are known from studies of regions of recent star formation. In Table 1 we list the observed properties of some of these compact sources; the spectra of selected objects are shown in Fig. 3. Of the regions included in Table 1, all but OMC-2, Mon R2, and CRL 2591 were first observed because of association with known H II regions. Orion Molecu-



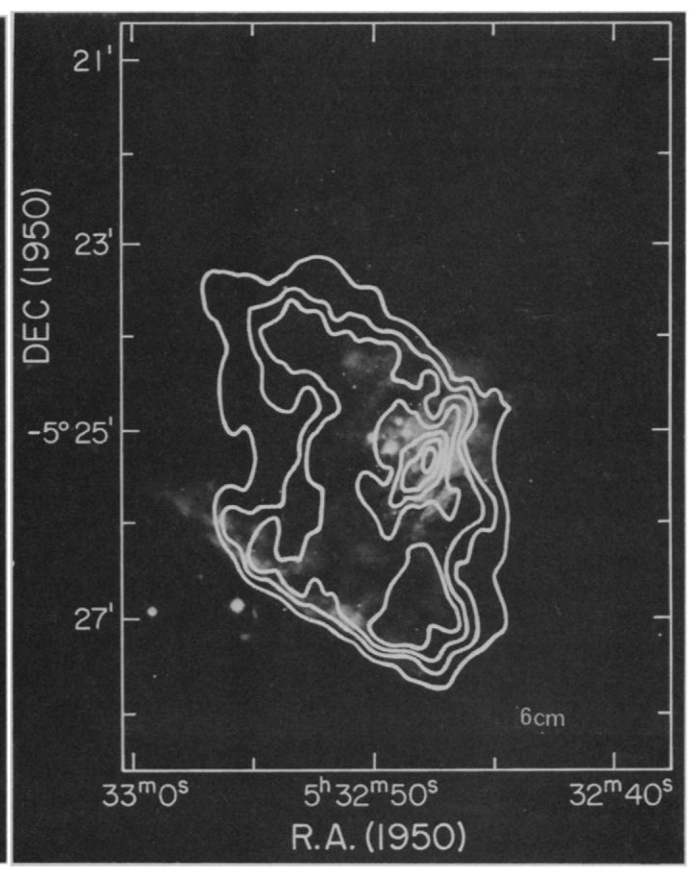
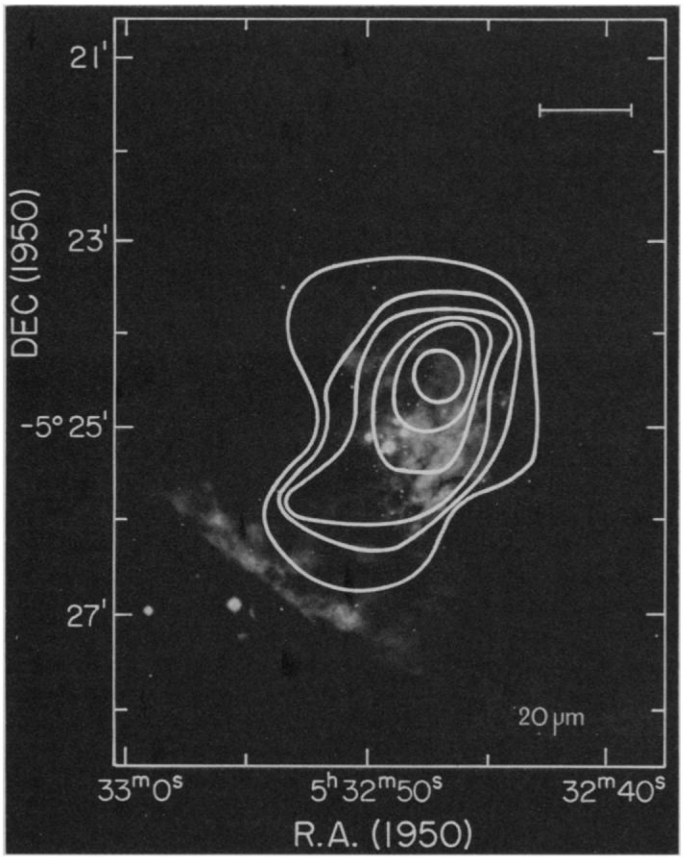


Fig. 6 (left). Photograph of the Orion Nebula as seen in the light of the atomic hydrogen Hα recombination line. The nebula is excited by the Trapezium cluster, the group of bright stars just below the center of the photograph. The cross indicates the position of the infrared cluster shown in detail in Fig. 12. The axes are labeled with the astronomical coordinates, right ascension (*R.A.*) and declination (*DEC*), referred to the year 1950. [Photograph courtesy of G. Münch] Fig. 7 (right). Contours of radio continuum emission at 6 cm from the Orion Nebula are superposed on the photograph of Fig. 6. [Adapted from (*23*)]



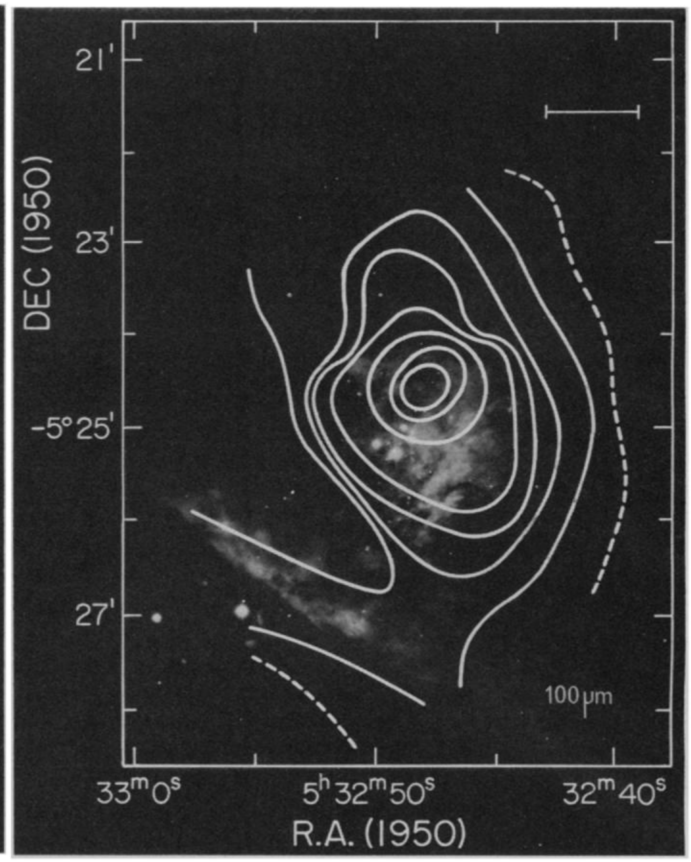
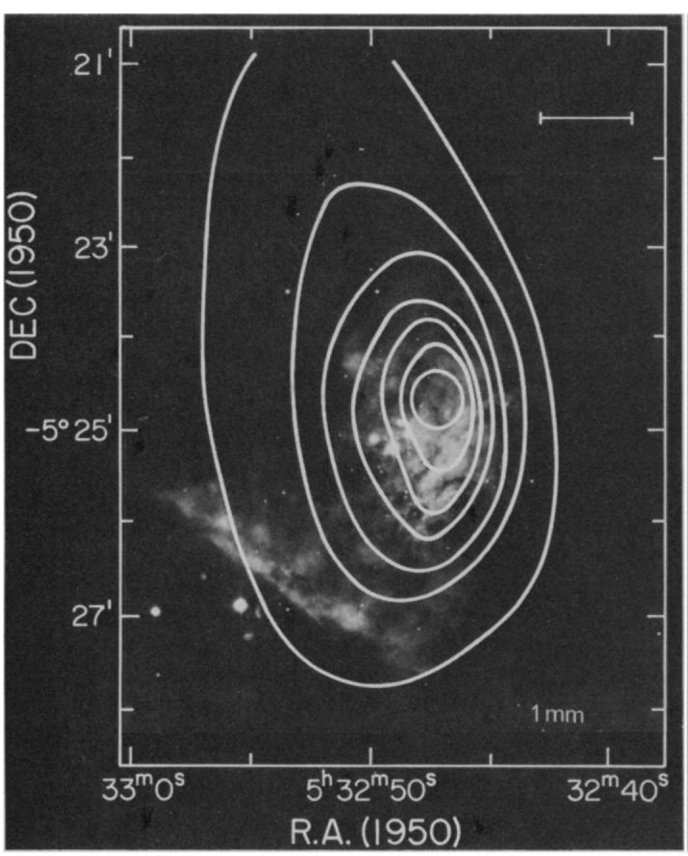


Fig. 8 (left). Contours of infrared emission at 20 μm from the OMC-1 complex are superposed on the photograph of Fig. 6. [Adapted from (*30*); see also (*57*)] In Figs. 8 through 11, the bar in the upper right corner indicates the spatial resolution with which the observations displayed in these figures were made. This corresponds to a distance of 0.51 light year at the distance of OMC-1. Fig. 9 (right). Contours of infrared emission at 100 μm from the OMC-1 complex are superposed on the photograph of Fig. 6. [Adapted from (*30*)]



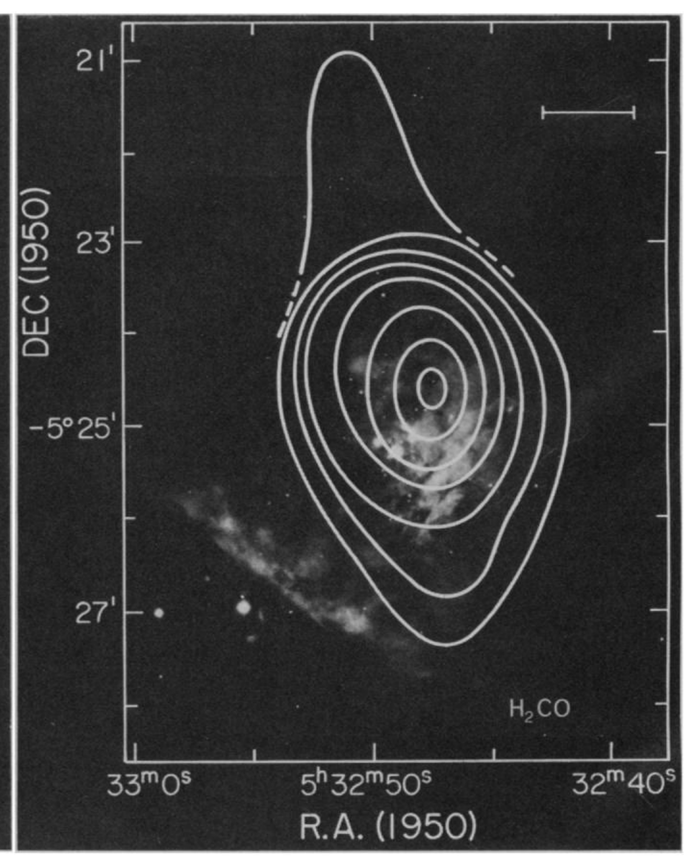


Fig. 10 (left). Contours of infrared emission at 1 mm from the OMC-1 complex are superposed on the photograph of Fig. 6. [Adapted from (*31*)] Fig. 11 (right). Contours of emission from OMC-1 in the 2-cm formaldehyde emission line are superposed on the photograph of Fig. 6. [Adapted from (*58*)]

Table 1. Measured properties of young and forming stars. In object names, IRS means infrared source. Thus, W3-IRS 4 is the fourth infrared source in region W3. The conventions used in naming the regions are discussed in (*11*). Luminosity, at 1 to 25 μm, is corrected for circumstellar extinction by using the 10-μm silicate feature. Under radio continuum emission, "Yes" implies greater than 3×10^{-27} watt m^{-2} $hertz^{-1}$ in a 10-arc-second beam. Under maser emission, "Yes" indicates that OH or H_2O maser emission (or both) is seen coincident with the object. T_{dust} is the observed temperature of the emitting dust.

Region	Object	Distance (light years)	Measured size (A.U.)	Luminosity ($L_\odot$)	T_{dust} (°K)	Radio continuum emission	Maser emission	Reference
W3	IRS 4	9,000		2×10^4	200	Yes	No	(*49, 60*)
	IRS 5	9,000	3,000	1×10^5	300	No	Yes	(*35, 49, 50, 60*)
	OH	9,000		5×10^4	150	Yes	Yes	(*49*)
OMC-2	IRS 3	1,500		1×10^2	600	No	?	(*33*)
OMC-1	Becklin-Neugebauer	1,500	$\lesssim 300$	2×10^3	500	No	Yes	(*35, 44, 47, 61*)
	Kleinmann-Low	1,500	2,000	2×10^3	100	No	Yes	(*35, 62*)
Mon R2	IRS 2	3,000	200	2×10^3	400	?	?	(*14*)
	IRS 3	3,000	400	5×10^4	400	?	?	(*14*)
RCW 57	IRS 1	10,000		1×10^5	400	?	?	(*63*)
M 17	IRS 1	6,000		2×10^3	200	?	?	(*64*)
CRL 2591	CRL 2591	12,000		1×10^5	400	No	?	(*55, 56*)
NGC 7538	IRS 1	10,000		5×10^4	300	Yes	Yes	(*51, 65, 66*)
	East	10,000		5×10^4	300	No	?	(*66, 67*)

lar Cloud 2 was discovered as a result of an accidental detection of the infrared emission from a cluster of compact sources (*33*); the sources in the Mon R2 region were discovered in a rocket-borne infrared sky survey (*17, 34*) and, independently, by ground-based near-infrared studies motivated by the presence of enhanced CO emission at radio wavelengths (*14*); and CRL 2591 was discovered in the rocket survey (*17*). The general characteristics of the objects in Table 1 agree qualitatively with the theoretically predicted appearance of a massive star in its late pre–main sequence or early main sequence stages (*10, 32*); the luminosities are typically thousands of solar luminosities, while the sizes are comparable to that of the solar system and the temperatures are typically several hundred degrees. In some cases, but not all, there is detectable radio continuum emission associated with the compact source, indicating the presence of ionized gas. Each of the sources listed in Table 1 is located in a region of high dust and gas density; this is consistent with the idea that all were formed in relatively recent collapse processes.

It is immediately clear from Table 1 that several compact sources are typically associated with one region. A conspicuous example of special interest is the W3 region, which contains a half-dozen separate sources, which have varying relative amounts of infrared and radio emission. A portion of the W3 region as seen in the infrared at 20 μm and in the radio continuum at 6 cm is shown in Fig. 13; the area shown in Fig. 13 corresponds to that in the box in Figs. 1 and 2. The individual sources shown in Fig. 13 all have luminosities $\gtrsim 10^4$ $L_\odot$; recent high-sensitivity surveys have discovered additional objects of lower luminosity within the region shown (*35*).

The most interesting object in this region is the source W3-IRS 5, which has a luminosity of at least 10^5 $L_\odot$ but shows no associated radio emission down to a very low level (Fig. 3), even though a main sequence star of this luminosity should produce an easily detectable H II region. W3-IRS 5 is extremely compact, with a measured size of 3000 A.U. (*35*); it consists of a small, dense cloud of dust within which a highly luminous object is embedded. Microwave maser emission from H_2O molecules is also associated with W3-IRS 5. The objects W3-IRS 1 and W3-IRS 3, which emit strongly at both 20 μm and 6 cm, are compact H II regions similar to the Orion Nebula, and are excited by stars with main sequence lifetimes less than 10^6 years. The source W3-IRS 4 has properties intermediate between those of W3-IRS 5 and W3-IRS 1; it resembles W3-IRS 5 at infrared wavelengths but also has associated with it a small amount of ionized gas.

These objects in W3 provide a graphic illustration of some of the stages thought to occur as a massive star evolves toward and onto the main sequence. Compact, luminous infrared sources with no associated ionized material, such as W3-IRS 5 and the Becklin-Neugebauer source in Orion, are the most promising candidates to be pre–main sequence objects. Objects such as W3-IRS 4 and NGC 7538-IRS 1 (Table 1) have sizes, temperatures, and infrared energy distributions similar to those of the candidate pre–main sequence objects, but show in addition a small amount of radio continuum emission. These sources may be powered by stars which have reached the main sequence and begun to ionize the surrounding material to form a small H II region, but are still embedded in the dust shell within which they formed. This stage in the early evolution of a massive star has been the subject of several theoretical investigations (*36*), which also suggest that the main sequence star eventually disperses the dust shell and produces a well-developed H II region, as exemplified by W3-IRS 1 and W3-IRS 3 and by the Orion Nebula.

Although this article emphasizes continuum observations, it is important to note that infrared observations of atomic and molecular species at high spectral resolution are becoming increasingly important for probing objects such as W3-IRS 5 and the Becklin-Neugebauer source. For example, an atomic hydrogen emission line at 4.05 μm has recently been detected (*37*) from the Becklin-Neugebauer object, and has been interpreted as indicating that in this case the dust-embedded object may be a star with surface temperature $T \gtrsim 5000$°K, which is in fact in the latter stages of its pre–main sequence evolution. The infrared emission from the Becklin-Neugebauer object has also been observed to be highly polarized (*38*); the polarization is thought to be due to alignment of grains by the magnetic field in the central regions of OMC-1, and detailed studies of the polarization in such regions may clarify the role of the magnetic field in inhibiting or promoting star formation.

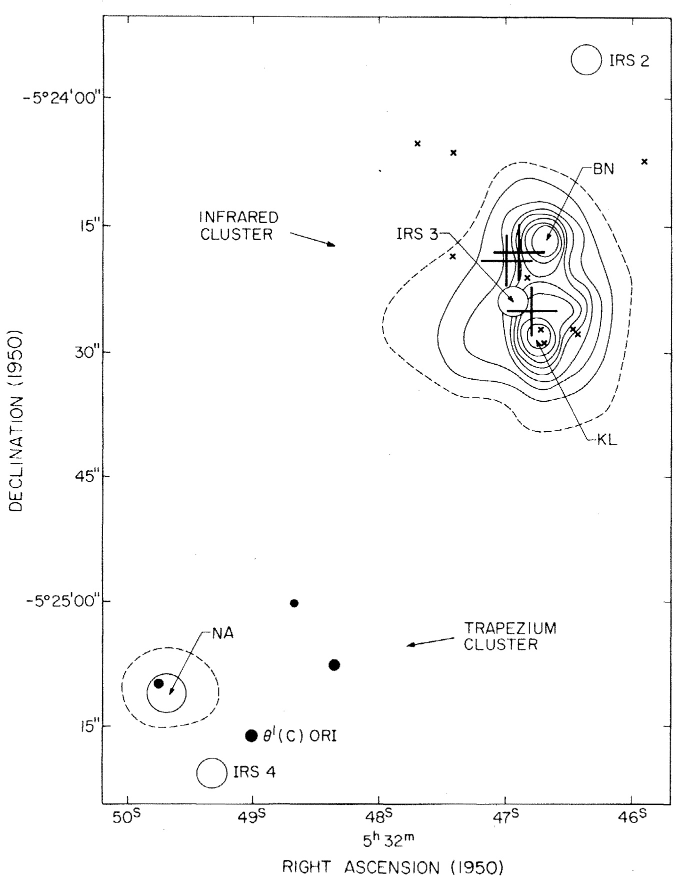
Properties of Regions of Star Formation

Young and forming stars such as those described above are found within dense clouds of dust and gas which often contain a number of objects that appear to be in different early evolutionary stages. It is necessary to study the properties of these regions in their entirety to understand the formation and properties of the individual stars which they contain, since the physical conditions of the region as a whole may represent those under which the stars began to form. In addition, the appearance of the stars may be influenced by the material within which they are embedded, and the luminosity of the embedded stars can only be estimated when their contribution to the heating of the region as a whole has been determined.

An idea of the general properties of such regions is given by Table 2, which lists the overall physical parameters for four regions: W3, OMC-1, OMC-2, and Sagittarius B2, a molecular cloud near the center of the galaxy. These parameters were derived from a variety of infrared and radio observations, as described in Table 2. For each region the

Table 2. Observed properties of regions of star formation. The tabulated properties are derived as follows. The luminosity is obtained from the observed infrared flux and may include contributions from both main sequence and pre-main sequence stars. The gas temperature, T_{gas}, is taken equal to the brightness temperature of the ^{12}CO emission line, and the gas density, N_{gas}, and mass, M_{gas}, are derived from observations of CO and other molecules. The dust temperature is estimated from the wavelength at which the infrared emission peaks, and the mass of dust is derived from the observed emission at 1 mm. The gas and dust densities, masses, and temperatures refer to the neutral components in each region. Regions W3, OMC-1, and Sgr B2 also contain ionized clouds, which are comparable in density to but much less massive than the neutral clouds.

Region	Distance (light years)	Size (light years)	Luminosity ($L_\odot$)	T_{gas} (°K)	N_{gas} (atom cm^{-3})	M_{gas} ($M_\odot$)	T_{dust} (°K)	M_{dust} ($M_\odot$)	Reference
W3	9,000	7	1.1×10^6	30	10^4	2×10^3	80	70	(*31, 46, 49, 60, 68*)
OMC-1	1,500	2	4×10^5	70	10^5	500	85	10	(*23–25, 28, 30, 31, 46, 58, 69*)
OMC-2	1,500	0.5	10^3	55	10^4	5	40	0.1	(*33, 70*)
Sgr B2	30,000	30	10^7	20	5×10^4	5×10^5	35	5×10^3	(*31, 46, 52, 71*)



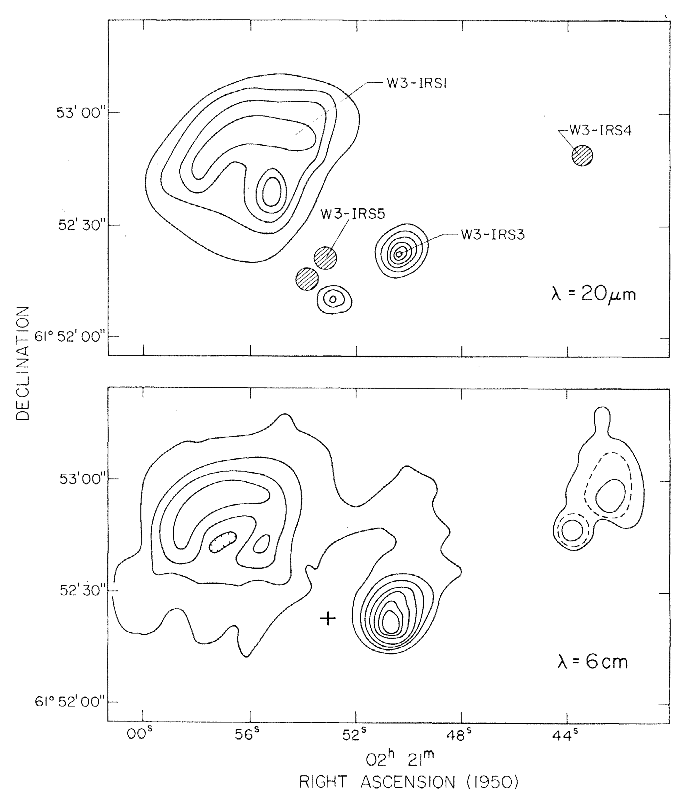


Fig. 12 (left). Schematic representation of the infrared cluster and the Trapezium cluster at the center of the Orion Nebula–OMC-1 complex. This figure corresponds to the central portion of the photograph shown in Fig. 6. The contours show the distribution of 20-μm flux, which has been measured at this high spatial resolution only in the vicinity of the two clusters and not over the entire region shown. The Becklin-Neugebauer (*BN*) and Kleinmann-Low (*KL*) objects are the most prominent members of the infrared cluster, and the open circles *IRS 2*, *IRS 3*, and *IRS 4* are spatially unresolved infrared sources seen at wavelengths shorter than 20 μm. The filled circles show the optically bright Trapezium cluster, the brightest member of which is θ^1 (*C*) *Ori*, and the Ney-Allen (*NA*) source is a region of enhanced 20-μm surface brightness associated with the Trapezium stars. The three large crosses are at the positions of OH microwave maser emission regions, while the nine small crosses are H_2O master emission regions. [Adapted from (*48*); see also (*59*)]

Fig. 13 (right). High-spatial-resolution maps of the W3 region in the infrared at 20 μm and in the radio continuum at 6 cm. At each wavelength, the same region of sky, corresponding to the box in Figs. 1 and 2, is shown. This region is about 3 light years across. The cross on the radio map indicates an H_2O master emission source which coincides with W3-IRS 5. [Adapted from (*49*)] tabulated properties refer to a dense central core which is observed at radio wavelengths to be enveloped by a much larger and more massive cloud of lower-density molecular gas. The central core is the portion of the cloud within which the luminosity due to young and forming stars is observed to be greatest. The tabulated parameters are rough averages over this central region and are of only qualitative significance.

Table 2 shows that these regions are 0.5 to 10 light years in size and have masses in the range 10^2 to 10^6 $M_{\odot}$, luminosities in the range 10^3 to 10^7 $L_{\odot}$, and densities in the range 10^4 to 10^6 atom cm^{-3}. Each contains a number of young and luminous objects which are embedded in the dense clouds of neutral and ionized gas. The luminosity, which is observed principally in the infrared (Fig. 3), is produced by these embedded main sequence and pre–main sequence stars, which heat the surrounding material and cause it to radiate at infrared wavelengths. The mass of the stars required to produce the observed luminosity is typically 0.01 to 0.1 of the mass of the gas.

The specific regions listed in Table 2 were chosen for the following reasons. Orion Molecular Cloud 2 and Sgr B2 represent the exteme ends, in terms of mass and luminosity, of the distribution of known or suspected regions of recent star formation; W3 and OMC-1 are nearby regions with intermediate properties and are among the most intensively studied regions of recent star formation.

Altogether, from a variety of infrared (*12, 17, 39*) and radio (*40, 41*) surveys, roughly 50 regions of star formation having general properties comparable with those described in Table 2 have been discovered at distances of 1,500 to 45,000 light years from the sun. They are confined to the plane of the galaxy and are found preferentially in the spiral arms, where the average density of interstellar matter is highest.

Conclusions

The single most important contribution of the infrared observations to our picture of star formation has been the discovery that compact luminous infrared sources with little or no associated visible radiation or ionized material are frequently found embedded in dense clouds, which also contain young main sequence stars and other signs of recent star formation. These infrared sources are in different, and presumably earlier, evolutionary stages than are the young main sequence stars. Thus they make it possible to push empirical studies of the formation and evolution of a massive star back in time beyond the point at which the star arrives on the main sequence.

Several generalizations can be made from these observations of regions of star formation and of the young stars and forming stars which they contain. A significant observed property of regions of star formation is that possible pre–main sequence objects are found in the densest central portions of larger clouds of gas and dust. This supports the generally accepted premise that gravitational collapse is the driving mechanism for the star formation process. In addition, the properties of these possible pre–main sequence objects agree qualitatively with the predictions of detailed models based on gravitational collapse. A single region often contains stars in several early evolutionary stages, suggesting that the collapse process in these regions occurs through mechanisms which lead to the formation of many stars with comparable properties.

It is now possible to define, observationally, a sequence of objects all of comparable luminosity but which vary in nature from infrared stars with no associated ionized gas to main sequence stars with well-developed H II regions. It is often the case that sources are found within a single region which lie at all points along this sequence. This suggests that stars are still forming in these regions and that further observational studies may reveal objects at evolutionary stages earlier than those which have been identified to date.

Fifteen years ago there was little observational basis for the picture of star formation we have described. Although each advance in infrared and radio astronomy has contributed to our understanding of the process of star formation, identification of specific objects as forming stars still rests largely on circumstantial and statistical evidence. It is clear that further observational and theoretical work is required to establish a detailed understanding of these early stages in the life of a star.

Appendix—Observational Techniques

A discussion of the observational techniques is helpful in defining the limitations of the currently available infrared observations (*42*). At wavelengths shortward of 35 μm the atmosphere is transparent in well-defined windows, and large conventional ground-based optical telescopes can be used effectively. For wavelengths between 35 and 350 μm the earth's atmosphere is opaque and observations are carried out from high-flying aircraft, rockets, and balloons; the telescopes so far flown are no greater than 1 m in diameter. Ground-based telescopes are also used at wavelengths near 1 mm, where the atmosphere again becomes transparent. Cryogenically cooled semiconducting bolometers are generally used as detectors for wavelengths longer than 100 μm; at shorter infrared wavelengths both photoconductive detectors and bolometers are used.

The objects which are discussed in this article lie in the galaxy at distances of 1500 to 6000 light years from the earth—that is, 1/20 to 1/5 the distance to the center of the galaxy. At 10 μm, using a large ground-based telescope at the diffraction limit, structure on the scale of 2500 A.U. or 0.04 light year is resolved in a region located some 3000 light years from the earth, and structure on a finer scale can be discerned by using specialized techniques (*43*). In contrast, for wavelengths between 100 μm and 1 mm limitations due to diffraction are such that it is not possible with the telescopes now available to resolve structure on a scale finer than 1 light year in the same region. A consequence is that observations at these longer wavelengths generally encompass large regions rather than resolving individual pointlike objects.

The detector sensitivity also sets limits on the objects which can be studied. In particular, when mapping or scanning an area 3000 light years from the sun for new sources, it is possible to detect a source with a luminosity ~ 10 times that of the sun if its spectral peak is at 5 μm. A cooler source at the same distance with a spectral peak at 100 μm must have a luminosity greater than 10^3 $L_{\odot}$ to be discovered in a scanning operation. If one is observing at a single point on the sky rather than scanning, it is possible to measure objects 100 times fainter than these limits within reasonable times. Here we have assumed low spectral resolution ($\lambda/\Delta\lambda$ of 2 to 10), which is typical of the data presented in this article. Higher-resolution measurements are just now being achieved (*37, 44, 45*) and undoubtedly will become increasingly important in determining the velocity structure of areas of star formation and in providing detailed information about the characteristics of dust-embedded sources which cannot be obtained from broadband measurements alone.

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11. Astronomical sources are named in a bewildering variety of ways. The confusion is compounded here because infrared sources are often found in regions which were originally identified on the basis of other types of observations. The region W3, for example, is so designated because it is the third source in a catalog of radio sources prepared by Westerhout (*40*). The source W75 shown in Fig. 3 is also taken from this catalog. Other sources mentioned in this article which are designated by numbers from various catalogs are RCW57, M17, CRL 2591, and NGC 7538. Sources may also be labeled by the name of the constellation in which they are found and an additional designation indicating what sort of object they are. Examples include Orion Molecular Clouds 1 and 2; Mon R2, which is a reflection nebula in the constellation Monoceros; and Sgr B2 in the constellation Sagittarius. Finally, some objects, such as the Becklin-Neugebauer and Kleinmann-Low sources in the Orion infrared cluster, have come through popular usage to be identified by the names of their discoverers.
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