The Newest Stars in Orion

Clouds of dust and gas in the familiar constellation emit radiation at infrared and radio wavelengths. Some of the denser clouds appear to conceal new stars that are expelling fast-moving streams of gas

by Gareth Wynn-Williams

According to legend, the stars that outline the magnificent winter constellation Orion were put there by Artemis, goddess of the hunt, to commemorate the death of her companion Orion. For present-day astronomers Orion symbolizes birth rather than death; the constellation embraces one of the richest and nearest stellar nurseries in our galaxy. Within a volume a few hundred light-years across and 1,600 light-years away vast cool clouds of hydrogen are slowly collapsing under the influence of their own gravity to give rise to new stars (and presumably new planetary systems). A few of the stars that were formed in the comparatively recent past can be seen with the unaided eye, and many more have long been accessible to optical telescopes. In the past few years, however, advances in the detection of radiation at infrared and millimeter wavelengths have enabled astronomers to study the gas clouds themselves and the very youngest stars hidden deep within them.

In some of these young objects thermonuclear fusion may already have begun at the center even as a thick surrounding cocoon of matter is still radiating at warm infrared temperatures. Astronomers are puzzled by evidence that whereas one would expect such objects to be accreting matter from their immediate environment, some of them appear to be ejecting it.

A "main sequence" star (an ordinary star on the main sequence of stars in a graph of temperature vs. luminosity) shines by virtue of the thermonuclear conversion of hydrogen into helium in its core. The more massive the star is, the faster it consumes its reserves of nuclear fuel; the biggest stars therefore have the shortest lives. For example, stars whose mass exceeds the mass of the sun by a factor of 15 or more are at least 20,000 times more luminous than the sun and convert all their available hydrogen into helium in less than 10 million years, a tiny fraction of the estimated age of the galaxy: 15 billion years. Such massive stars, designated Type O, and the slightly less massive stars of Type B are easily recognized by their brightness, by distinctive lines in their visual spectrum and by their bluish color, indicative of surface temperatures in excess of 10,000 degrees Kelvin. Because of their brief lifetime Type O and Type B stars have little opportunity to stray far from their site of birth. Hence when such stars are found in a cluster, one can be sure that all of them were formed recently in response to conditions prevailing in that small region of the galaxy.

The constellation Orion abounds in stars of types O and B. A particularly prominent group is the Orion I Association, which includes the three bright stars in Orion's belt and the stars that form his sword. The stars in the association have been created at various times over the past 10 million years. The youngest of them, which are probably less than a million years old, lie in and around the glorious Orion Nebula, a cloud of glowing ionized gas heated by a group of four Type O stars known collectively as the Trapezium Cluster. The close connection between hot young stars and visible gas clouds is strong evidence for the hypothesis that new stars form by condensation out of the interstellar gas.

In order for an interstellar cloud to collapse, the pressure exerted by the mutual gravitation of its constituents must exceed the thermal pressure that would cause it to expand. The temperature of the ionized gas in the Orion Nebula is so high (about 10,000 degrees K.), however, that the gas must be expanding rather than contracting. It is therefore unlikely that any new stars are forming within the nebula itself. For evidence of star formation in the Orion region it is necessary to look instead at cooler clouds.

About 90 percent of the atoms in interstellar space are those of hydrogen; most of the rest are those of helium. Under the conditions that favor the gravitational collapse of an interstellar cloud (temperatures below 100 degrees K. and densities greater than 1,000 atoms per cubic centimeter) hydrogen exists mainly in the form of hydrogen molecules rather than as isolated hydrogen atoms or as hydrogen ions (that is, protons). Molecular hydrogen is difficult to detect for several reasons. It is too cool to radiate at visible wavelengths, and unlike atomic hydrogen it emits no characteristic radiation at specific wavelengths that can be detected by radio telescopes. Furthermore, clouds of molecular hydrogen are usually almost completely opaque to light because of the presence in them of tiny dust particles that absorb and scatter electromagnetic radiation of short wavelength. Only radiation with a wavelength considerably longer than that of light is capable of penetrating molecular clouds or escaping from them. Fortunately there are several processes that generate long-wavelength radiation within the clouds and thereby make them visible to modern instruments. Heated dust grains emit broadband thermal radiation in the infrared part of the spectrum, and various molecules other than those of hydrogen emit radiation at specific wavelengths (spectral line emission), mainly at wavelengths of a few millimeters.

By far the most useful of the 40-odd interstellar molecules observed so far is carbon monoxide, which was first detected in space in 1970 by Robert W. Wilson, Keith B. Jefferts and Arno A. Penzias of the Bell Telephone Laboratories with a sensitive receiver tuned to a wavelength of 2.6 millimeters. The energy levels responsible for the electromagnetic radiation from a simple molecule such as hydrogen or carbon monoxide depend on the molecule's electronic structure, on the vibration of the molecule's atoms back and forth along the molecule's axis and on the molecule's end-over-end rotation. In a molecular cloud essentially all the molecules are in the lowest electronic state, and so the only changes of state that need be taken into account are the vibrational and rotational ones.

In general, changes in the vibrational energy of a molecule are much more drastic than changes in rotational ener-
CONJUNCTIONS ORION, shown in a negative print, is speckled with stars that are hot, luminous and young. Many of these Type O and Type B stars, which are less than 10 million years old, are clustered in the Orion I Association. The very youngest of them are found near the Orion Nebula, which is about 1,600 light-years away from the solar system. The contour lines depict the intensity distribution of radiation at a wavelength of 2.6 millimeters from carbon monoxide present in small amounts in clouds of molecular gas that are mainly hydrogen. At the clouds' low temperature (less than 20 degrees Kelvin) there is no detectable emission from hydrogen itself. The carbon monoxide emission was observed with a 1.2-meter radio telescope at Columbia University by Patrick Thaddeus of the Goddard Institute for Space Studies and his co-workers. The concentration of gas that is coincident with the Orion Nebula but that actually lies behind it is called Orion Molecular Cloud 1 (OMC1). It is part of the southern molecular-cloud complex. The small rectangle in the illustration outlines the area in the photograph on the next page. In this photograph and others that follow it north is at the top and east is at the left.
There is therefore a significant fraction of the molecules to be excited to the level $v = 0, J = 2$ (Transitions with $\Delta J = 1$, such as the $v = 0, J = 1 \rightarrow 0$ transition, are extremely rare in a symmetrical molecule such as H$_2$O). In typical interstellar clouds, which are at a temperature of only about 20 degrees K, the mean translational kinetic energy (the energy of motion) corresponds to a photon with a wave number of only 21 cm$^{-1}$. As a result the $v = 0, J = 2$ state, which is at 354 cm$^{-1}$ above the ground state, is almost unpopulated, since collisions rare-

GLOWING GAS IN THE ORION NEBULA (left) has been heated to fluorescence, about 10,000 degrees K., by luminous Type O stars embedded in the nebula. Atoms in the gas are ionized (stripped of electrons) by the stars' ultraviolet radiation. The various colors in this photograph arise from different kinds of ions. The photograph was made with the 3.8-meter telescope at the Kitt Peak National Observatory. The map at the right, covering the same region, depicts the intensity of carbon monoxide emission from OMC1, the invisible cloud of warm molecular gas that lies behind the nebula. The red areas correspond to the most intense emission, the blue areas to the least intensity. The map was prepared by Nicholas Z. Scoville, F. Peter Scherb and Paul F. Goldsmith of the University of Massachusetts at Amherst. Made with a 4-meter radio telescope, the map has a resolution of about 35 seconds of arc, about 10 times higher than the map shown on the preceding page. Rectangle outlines the most luminous regions in OMC1, which are shown in greater detail on the opposite page.
ly excite molecules to levels with energies greater than three to five times their average kinetic energy. Therefore in typical interstellar clouds essentially all the hydrogen molecules are confined to the lowest two levels, and except for a few special hot regions (to which I shall return) molecular hydrogen cannot be directly observed in clouds such as those in Orion.

The difficulties that conceal the cool hydrogen molecule from visibility do not apply to the heavier asymmetric molecule of carbon monoxide. With this molecule transitions are possible between adjacent rotational levels that are much more closely spaced in energy than those of hydrogen. The wavelengths of those transitions form a harmonic progression starting at 2.6 millimeters when molecules in the \( v = 0 \) state drop from \( J = 1 \) to \( J = 0 \) and continuing with spectral lines at 1.3 millimeters, .87 and .65 millimeter for higher transitions. The two longer-wavelength transitions can be observed with high-quality radio telescopes, but the shorter wavelength transitions usually call for the more precise reflecting surfaces of optical or infrared telescopes, which are fitted with special receivers. Various different molecules have been studied by means of their transitions at millimeter wavelengths, but the carbon monoxide molecule (present in the ratio of one molecule for every 2,000 hydrogen molecules) is by far the most abundant of the molecules detected.

An extensive study of the Orion region was done some years ago by a group consisting of Marc L. Kutner of the Rensselaer Polytechnic Institute, Kenneth D. Tucker of Fordham University, Gordon Chin of Columbia University and Patrick Thaddeus of the Goddard Institute for Space Studies. A complete map of the region was made with a 1.2-meter radio telescope at Columbia tuned to detect the lowest rotational transition of carbon monoxide at 2.6 millimeters. It revealed two very large complexes of molecular clouds, each complex about 150 light-years across [see illustration on page 47]. Except for a few patches that are illuminated by bright stars near the edges of the clouds the material appears to be completely dark in optical photographs. Although the clouds are dense by interstellar standards, they consist of only a few hundred molecules per cubic centimeter. Nevertheless, the clouds are so large that they each hold enough matter to make 100,000 stars the mass of the sun.

Measurements of the Doppler shifts in the emission lines from the clouds indicate they cannot have changed greatly in shape in the past million years.

Over most of the area mapped the clouds are cold, less than 20 degrees K.; they are warmed only by the diffuse light that filters in from the neighboring stars. The regions that show the strongest carbon monoxide emission, however, are significantly warmer: between 30 and 100 degrees. Such regions usually turn out to have a higher density than the rest of the cloud. In the southern complex, the better studied of the two, the highest peak of carbon
HEATED DUST AND MOLECULAR HYDROGEN are concentrated in a region only a few tenths of a light-year across in the core of OMC1. The solid contours in color show the distribution of heated dust as it was observed at a wavelength of 20 micrometers with the three-meter infrared telescope on Mauna Kea by Reinhard Genzel, Dennis Downes, Eric F. Becklin and the author. The strongest infrared emission arises from about half a dozen compact sources. They include IRC1 and IRC2, which appear to be at a temperature of about 500 degrees K. The broken-line contours show the emission from molecular hydrogen at 2.12 micrometers, an energy-level transition associated with gas at a temperature of about 2,000 degrees. The hydrogen is probably heated by the collision between gas blown outward from IRC2 and stationary gas in the molecular cloud. The map of hydrogen emission was made with the five-meter telescope on Palomar Mountain by Becklin, Steven V. W. Beckwith, Gerry Neugebauer and S. Eric Persson. Becklin and Neugebauer discovered IRC1, sometimes called the BN object, in 1965. The black spots are the emission peaks of water masers, cloudlets that emit strongly at 1.35 centimeters.
monoxide emission coincides approximately with the Orion Nebula [see illustration on page 49]. Although the Orion Nebula and the carbon monoxide peak appear to be superposed, the glowing gas in the visible nebula consists of fully ionized atoms at a temperature of about 10,000 degrees; the carbon monoxide emission arises from the cloud of molecular hydrogen just behind the nebula. This un-ionized cloud is usually designated OMC1, for Orion Molecular Cloud 1. The nebula is slowly eating its way into OMC1 as the hydrogen, carbon monoxide and other molecules are broken up by the ultraviolet radiation from the hot Type O stars within the nebula.

Although part of the heating of OMC1 can be attributed to the energy absorbed from the Type O stars, the most intense peak in the carbon monoxide emission demands another explanation. By examining emission lines from several different kinds of molecule, each sensitive to density and temperature in a different way, astronomers have found that OMC1 has a core only a few tenths of a light-year across in which the density exceeds 100,000 molecules per cubic centimeter. The mass of the gas in the core is somewhere between a few hundred and a few thousand times the mass of the sun. The strong concentration of gas at this point, the evidence that there must be something within the cloud heating it and the marked broadening of the emission lines (evidence of greater motion than there is elsewhere in the cloud) all suggest that the core is the site of either very recent star formation or current star formation.

The observation of millimeter-wave molecular transitions in interstellar clouds has two shortcomings. First, such transitions reveal nothing about the nature of the stars or the other sources of energy that may be hidden within the cloud. Second, the method suffers from poor angular resolution; the smallest detail that can be mapped by a telescope is governed by the ratio of the wavelength of the radiation to the diameter of the telescope. The resolution that can be achieved when the 2.6-millimeter wavelength of carbon monoxide is collected by a 14-meter radio telescope is 45 seconds of arc, a factor of at least 20 poorer than can be achieved by telescopes at visible wavelengths. Observations at the infrared wavelengths between 7 micrometer and 500 micrometers (3.5 millimeter) are helping to remedy both deficiencies.

The principal source of cosmic infrared emission is the thermal radiation from warm interstellar dust grains. Although the composition and size of the grains are uncertain, they probably include silicate minerals and frozen gases, and at least some of the grains must be about 1 micrometer in diameter. The grains are highly efficient at absorbing the light of stars and reemitting its energy as infrared radiation. The wavelength of the emitted radiation depends on the temperature of the grains. At 500 degrees Kelvin, for example, most of the radiation would lie at wavelengths of between five and 15 micrometers. At lower temperatures longer wavelengths would dominate, following the well-known Planck law for black-body radiation.

In most interstellar clouds the dust grains are well distributed and contribute about .5 percent to the mass of the gas. A Gaussian distribution of grains in which the average diameter is 500 micrometers would contribute about 10 percent. The grain population in a cloud could differ significantly from a Gaussian distribution. The most common dust grains are about one micrometer in diameter, and their thermal radiation is most important in carbon monoxide emission in the interstellar medium.
TRANSITIONS BETWEEN ENERGY LEVELS of the diatomic molecules of hydrogen and carbon monoxide give rise to the radiation that has supplied much of the information about the gas clouds in the vicinity of the Orion Nebula. Diatomic molecules can exist at many different energy levels above the ground level, the minimum energy state of vibration and rotation for a molecule. In that state both the vibration quantum number, \( v \), and the rotation quantum number, \( J \), are zero. In a molecular cloud \( \text{H}_2 \) and CO can acquire energy and be raised to higher vibrational and rotational states by collisions with other molecules. For each vibrational state there are many rotational states. In general more energy is needed to effect a transition between vibrational states with the same \( J \) value than is needed to effect a transition between rotational states with the same \( v \) value. When a molecule falls from a higher state to a lower one, it releases a quantum of radiation in the form of a photon. The wavelength in centimeters of the emitted photon is the reciprocal of the difference in energy levels in wave numbers, shown along the vertical axis. For example, a molecule of hydrogen in the state \( v = 1, J = 2 \) has a wave number of 6,499 inverse centimeters. If the molecule fell to the ground state, \( v = 0, J = 0 \), where the wave number is zero, it would release a photon with a wavelength of 1/6,499 centimeter, or 0.15 micrometers. Radiation at that wavelength is emitted by hydrogen molecules in a few of the hottest regions in OMC1. For \( \text{H}_2 \), whose molecular structure is symmetrical, transitions between adjacent rotational levels are forbidden. Therefore in cool gas clouds energy is lacking to raise hydrogen molecules to levels where transitions can be observed. This does not apply to carbon monoxide molecules, which are asymmetric and free to move between adjacent rotational levels. In cool molecular clouds many transitions can be observed for carbon monoxide molecules in the state \( v = 0 \) and with rotational energies between \( J = 0 \) and \( J = 6 \). The lowest transition of the carbon monoxide molecule, \( J = 1 \) to \( J = 0 \), gives rise to a photon with a wavelength of 2.6 millimeters.
cloud. Jocelyn B. Keene, Roger H. Hillsenbrand and Stanley E. Whitcomb of the University of Chicago mapped the radiation from warm grains in OMC1 at a wavelength of 400 micrometers with the three-meter Infrared Telescope Facility of the University of Hawaii situated at an altitude of 13,600 feet on Mauna Kea. At this comparatively long wavelength and low resolution (about 35 arc-seconds), the infrared radiation appears to originate from a small elliptical region about two light-years in its longest dimension that embraces the core of OMC1. When the infrared source is observed at shorter wavelengths, where radiation from hotter grains becomes dominant, the radiation is found to be concentrated almost entirely within the core of OMC1, which suggests the core itself harbors the source of energy that heats the cloud. Measurements made from aircraft flying at an altitude above 12 kilometers (to reduce the absorption of infrared wavelengths in the earth’s atmosphere) show that most of the radiation from the core of OMC1, amounting to about 100,000 times the power from the sun, is emitted between 20 and 300 micrometers (a range of wavelengths to which the earth’s atmosphere is nearly opaque).

A map of much higher resolution than the one made at 400 micrometers (two arc-seconds compared with 35 arc-seconds) was recently obtained by Reinhard Genzel of the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory, Dennis Downees of the Max Planck Institute for Radio Astronomy in Germany, Eric E. Becklin of the University of Hawaii and me with the three-meter Infrared Telescope Facility on Mauna Kea at a wavelength of 20 micrometers [see illustration on page 50]. The map reveals that the infrared emission arises from a cluster of half a dozen or more objects surrounded by diffuse emission. From the variation of the infrared flux with wavelength we can estimate the apparent temperature of the objects. The hottest, designated IRc1 and IRc2 (for infrared compact source Nos. 1 and 2), radiate strongly in the range between two and 20 micrometers, indicative of a temperature of about 500 degrees K. Several other peaks, including IRc3 and IRc4, are only at about 150 degrees. All these objects have temperatures far below the temperature of the coolest normal star, and so they must represent concentrations of heated dust. The total power radiated by each concentration is hard to calculate because of the attenuating effects of dust in the foreground, but it probably exceeds the output of the sun by a factor of 10,000.

What is the nature of the compact infrared sources that lie within OMC1? Soon after their discovery it was conjectured that they might be protostars: objects intermediate in evolution between interstellar clouds and true stars. The first detailed calculations of the evolution and appearance of protostars were made by Richard B. Larson of Yale University in 1969. His theoretical model shows that a cloud collapsing under the influence of its own gravitational forces initially forms a nucleus of high-density material at its center. As more matter falls into the nucleus the rotational energy that is released heats the dust grains in the outer shell of the protostar, causing them to emit infrared radiation. Meanwhile the density and temperature of the nucleus steadily rise until thermonuclear reactions are kindled at the center. For a protostar with the mass of the sun the entire process takes at least 10 million years; for protostars with the mass of Type O and Type B stars, however, the process is up to 1000 times faster.

More recent work has shown that in high-mass protostars thermonuclear reactions start before the outer regions have had time to fall into the nucleus. The newborn star is surrounded by an infrared-emitting cocoon of gas and dust that is still collapsing. If the compact infrared sources observed in OMC1 are precursors of types O and B stars, their high luminosity is explained. According to this picture, the infrared cluster will eventually emerge as a small group of O and B stars with a size and luminosity similar to the stars of the Trapezium Cluster inside the Orion Nebula itself. The remainder of the molecular cloud will ultimately be heated to thousands of degrees and begin shining as a new ionized nebula.

Problems with this simple picture began to emerge in 1976, when the first moving gas in the core of OMC1 was discovered by Ben M. Zuckerman of the University of Maryland at College Park, Thomas B. H. Kuiper of the California Institute of Technology, Eva N. Rodriguez Kuiper of the University of California at Los Angeles, John Kwan of the State University of New York at Stony Brook and Nicholas Z. Scoville of the University of Massachusetts. They observed Doppler shifts in the carbon monoxide emission from the site of the infrared cluster that indicate gas velocities of plus or minus 50 kilometers per second with respect to the rest of the cloud. Such velocities are more than 10 times higher than those observed elsewhere in OMC1 and are much greater than the velocities that could be induced simply by gravitational collapse. The fast motions are confined within a small volume, about 3 light-year across, and are centered within about 1 light-year from IRc2. The distribution of Doppler velocities suggests a shell of gas expanding in all directions from one source.

Additional evidence of rapid motion in this region came with the discovery, also in 1976, of infrared emission lines from hot hydrogen molecules by T. N. Gautier III, Uwe Fink, Richard R. Tref- fers and Harold P. Larson of the University of Arizona. Their observations were made with the 2.2-meter telescope at the Steward Observatory. More than a dozen molecular-hydrogen transitions have since been observed, most of them between low-lying J levels of the v = 1 and v = 0 vibrational states at wavelengths near two micrometers.

Four things are remarkable about these emissions. First, they are intense, equivalent in total power to at least 100 times the output of the sun at all wavelengths. Second, the temperature of the hydrogen, as deduced from the ratio of the strengths of different emission lines, is about 2,000 degrees K., far hotter than the rest of the gas in OMC1. Third, the Doppler widths of the spectral lines are very wide, implying velocities of between 100 and 150 kilometers per second. Fourth, the hot gas is widely distributed in the OMC1 region, taking the form of clumps around the infrared cluster. These observations all suggest that the molecular-hydrogen emission is the result of a fast-moving “wind” blowing outward from the infrared cluster. As this gas, which probably includes the same material that gives rise to the broad carbon monoxide emission, collides with the surrounding parts of OMC1, it creates a shock wave that heats a thin, dense layer of OMC1 to 2,000 degrees.

A third item of evidence for explosive gas motions in Orion comes from the observation of intense emissions from the water vapor masers. The masers give feedback for microwave amplification by stimulated emission of radiation. A maser operates by raising a large number of atoms or molecules in a gas to a particular energy state and then stimulating them to tumble simultaneously to some lower state. Since the transitions to the lower state occur simultaneously, the rate at which photons can be emitted from a given volume of gas of a given density is enormously greater than the rate arising from the random kinetic processes I have been describing. In a water maser the gas consists of water molecules present in small quantities in the hydrogen gas. The first emission from a celestial water maser was observed at a wavelength of 1.35 centimeters in 1969. Since then water masers have been discovered in more than 100 different regions of the galaxy. In OMC1 at least 50 maser cloudblets are distributed over a region about the same size as the infrared cluster. The emission of a celestial water maser at 1.35 centimeters can be extremely intense. In order to emit an equal amount of energy at that wavelength by ordinary thermal processes a body would have to be at a temperature of more than 10^4 degrees K.

The high intensity of the 1.35-centi-
meter line and the compactness of the water-maser sources enable radio astronomers to measure the distance between various maser cloudlets with great precision. The measurements are carried out by means of very-long-base-line interferometry. Simultaneous observations of the Orion region were made from radio telescopes in California, West Virginia, Massachusetts, Germany, Sweden and the U.S.S.R. by a group that included Downes and Genzel and Mark J. Reid and James M. Moran of the Center for Astrophysics. By observing over a period of two years the group was able to trace minute changes in the distance separating the maser cloudlets in Orion. With very-long-base-line interferometry separation angles were measured to an accuracy of 10^{-3} arc-second, which is about the angle subtended by a small coin at a distance of 4,000 kilometers.

The measurements disclosed that many of the water-maser cloudlets are moving outward from a point somewhere in the vicinity of IRC2 or IRC4 with a velocity of 18 kilometers per second. The identification of IRC2 as the source of the outflow is suggested by the discovery of a second type of maser emission, one from silicon monoxide molecules, coinciding very closely with IRC2 and exhibiting an expansion velocity similar to that of the water masers. A few water-maser regions are moving away from IRC2 at speeds of up to 100 kilometers per second, but it is not yet certain whether they are parts of the same flow that propels the slower-moving water masers and the silicon monoxide maser or whether they emanate from one of the other infrared sources.

In any event the amount of matter involved in the flow from IRC2 is substantial, being equivalent to the loss of between a thousandth and a ten-thousandth the mass of the sun each year from an object unlikely to consist of more than 20 solar masses of material. So far there is no explanation for this enormous rate of mass loss, a loss about 100 times greater than the loss from mature Type O stars and one not predicted by any of the current theories of star formation. The possibilities that are being explored include mass loss driven by radiation pressure, by rotation, by acoustic waves, by magnetic effects and by wind-driven turbulence in the circumstellar disk of a newly formed star (perhaps even a preplanetary disk).

Whatever the mechanism of the mass loss it is clear that much of the activity observed in the core of OMC1 is directly attributable to processes taking place within one or more of the compact infrared sources. What hope is there of examining such processes in more detail and of finding out the nature and evolutionary status of these objects? A powerful tool that has recently been developed is the Fourier-transform spectrometer. This instrument is able to obtain detailed spectra of individual infrared sources at wavelengths of between one micrometer and five micrometers with a resolution that corresponds to a Doppler velocity of a few kilometers per second. Unfortunately IRC2 is faint in that range of wavelengths, but studies of the neighboring bright infrared source IRC1 have been carried out with the Kitt Peak four-meter telescope by Donald N. B. Hall, Stephen T. Ridgway and Fred C. Gillett of the Kitt Peak National Observatory, working with Susan G. Kleinmann of the Massachusetts Institute of Technology and Scoville.

Their spectrum of IRC1 exhibits both emission and absorption lines. Carbon monoxide molecules in various rotational levels of the ground vibrational state \( \nu = 0 \) are excited up to levels in the \( \nu = 1 \) and \( \nu = 2 \) states, giving rise to two series of closely spaced absorption lines, one near 4.6 micrometers and the other near 2.3 micrometers. The absorption was expected: it is due to the gas in the part of OMC1 that lies in front of IRC1. Less expected is the finding that additional absorbing gas is traveling at about 40 kilometers per second away from IRC1 toward us, presumably part of a wind arising from the infrared source or a close neighbor.

Many emission lines are also observed at two to five micrometers in the spectrum of IRC1. Some of the lines represent transitions between the energy levels of atomic hydrogen rather than molecular hydrogen and are identical with lines emitted from interstellar...
clouds that like the Orion Nebula itself are maintained in an almost completely ionized state by ultraviolet radiation from Type O and Type B stars. The fact that IRC1, unlike the Orion Nebula, does not emit continuum radiation (that is, radiation other than line radiation) at wavelengths of a few centimeters implies that the ionized region is highly compact, having a diameter of less than 10 light-hours. Continuum radiation is generated in an ionized gas by the deflection of charged particles as they are accelerated or braked when they approach other particles. The failure of such radiation to emerge from IRC1 must mean that it is being absorbed before it can escape.

The infrared spectrum of IRC1 also includes many emission lines from carbon monoxide. The strongest ones studied are those far arising from transitions in which ν changes by 2, namely ν = 4 → 2, ν = 3 → 1 and ν = 2 → 0 transitions. Many different J levels are involved in these transitions, causing the lines to blur together. The blurring is particularly strong near J = 50 in each vibration level, thus generating in the spectra bands rather than discrete lines. The surprising thing about the band emissions, which appear at wavelengths around 2.3 micrometers, is that they must originate from a region where very high energy levels of carbon monoxide (at least the ν = 4, J = 50 level) are substantially populated. This can happen only if the temperature is above 3,000 degrees K.

Although the compact infrared objects IRC1 and IRC2 are by no means identical in their observed properties, they have enough in common to suggest a possible picture of what is happening in at least some of the infrared sources observed inside OMC1 and in other molecular clouds of similar appearance. Such objects have probably passed beyond the stage of accretion that would justify the use of the term protostar; nevertheless, there is little doubt that the infrared sources are associated with the very early stages of stellar evolution. Their existence as a compact group of objects, their association with dense interstellar clouds and their high rates of mass loss effectively rule out the possibility that they are actually stars in a late stage of evolution that have evolved off the main sequence.

The evidence suggests that lying in the center of the infrared objects is a hot star not unlike a main-sequence Type O or Type B star. Ordinarily such a star would emit enough ultraviolet radiation to maintain a substantial volume of gas surrounding it in a luminous ionized state, as is the case in the Orion Nebula. In the case of an infrared object, however, the star or the disk of material in orbit around it is ejecting so much matter in the form of a dense wind that all the ultraviolet photons are absorbed in a shell of gas very close to the star. The shell is almost totally ionized by the high-energy photons and gives rise to the observed emission lines of atomic hydrogen.

Beyond the range of the ultraviolet radiation the gas continues to flow outward; as its temperature falls the atoms in the gas are able to combine with one another to form molecules and dust grains. Hot molecules of carbon monoxide give rise to the band emission observed around 2.3 micrometers. The dust, which is heated to 500 degrees K. by direct radiation from the star (now a few light-hours, or about the radius of the solar system, away), emits infrared radiation at wavelengths of between two and 20 micrometers. Beyond the shell of dust the wind, now cooled to well below 500 degrees, carries molecules of carbon monoxide that yield a broad band of emission at wavelengths of a few micrometers. At a distance of about a light-month from the newborn star the wind finally collides with the relatively undisturbed part of the surrounding molecular cloud, giving rise to the infrared emission lines of hydrogen molecules heated to about 2,000 degrees. The water masers may be embedded in the wind itself or may be a phenomenon connected with the collision of the wind and the surrounding cloud.

The discovery that at least some of the infrared sources once thought to be protostars are more probably very young, massive stars dramatically shedding mass has some important implications for the understanding of how new stars form. First of all, it means astronomers may have to search afresh for the precursors of typical main-sequence stars. Second, the wind from a large, luminous star may have a strong influence, either positive or negative, on the creation of smaller stars, such as those resembling the sun. On the one hand the wind could so badly disrupt the cloud surrounding it that further star formation would be impossible. On the other hand the pressure of wind on the neighboring parts of the cloud could promote the collapse of further fragments. Third, if a strong wind is a feature of the early evolution of all stars, not just massive ones, it could adversely influence the formation of planetary systems. Calculations of the actual effect, however, are difficult. If some astronomers confess to a slight disappointment that the search for protostars is again inconclusive, they are at least consoled that they may have discovered a new phase in the evolution of massive stars.