investigators think this will provide the best approach to monitoring health effects, since individuals who dispose of toxic wastes are the most likely to have significant exposures. Lilis recommends that similar studies be initiated to monitor the health of workers who clean up dumps on land.

Refining these techniques for monitoring exposure and determining health effects, says James V. Neel of the University of Michigan, "is not an academic exercise but one of the two or three most important challenges to biomedicine in the next decade. Decisions entailing billions of dollars are involved. In this connection, I must once again chide many of my . . . colleagues for talking big but thinking small. We have spoken copiously of the possible risk to future generations of environmental contaminants, but, in my opinion, have thus far failed either to formulate or request funds to pursue proper epidemiologic studies. Hopefully, [these conferences] will be seen in retrospect as the occasions when [scientists] . . . first laid out to Government what had to be done in the nation's interest."

—THOMAS H. MAUGH II

The Hunter and the Starcloud

The great nebula in Orion is a tiny bright patch on an immense dark cloud; that cloud is the best place to study star formation

Orion, son of the sea god Poseidon, was a hunter of great beauty and strength. He was beloved of Artemis, goddess of the hunt. But he was carried off by the dawn goddess Eos, and Artemis slew him in a jealous rage. Later, he was placed in the sky.

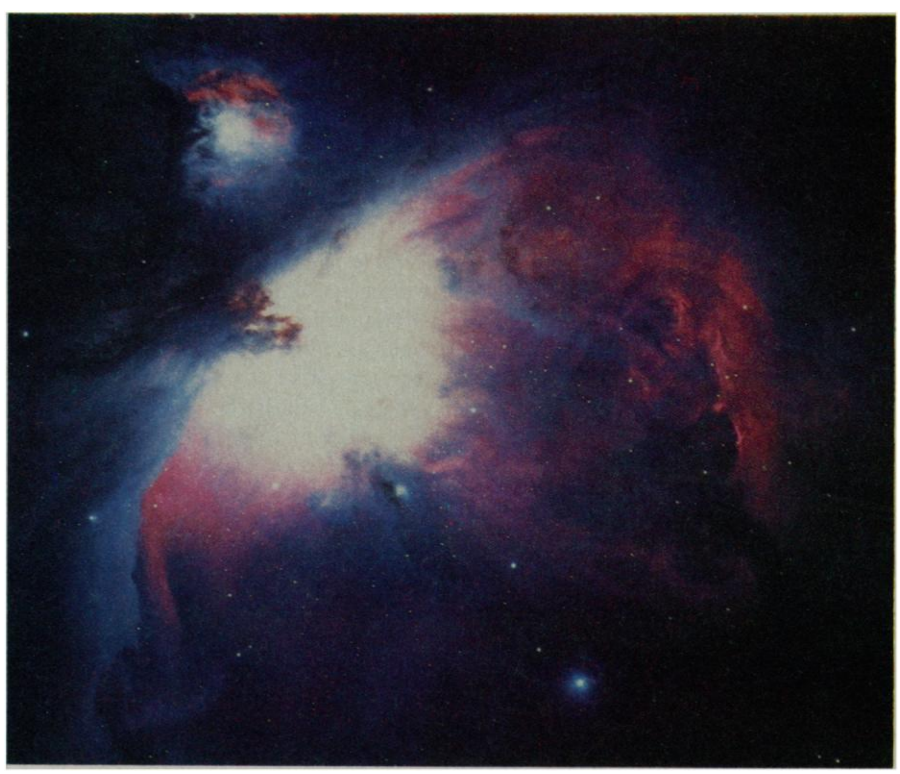
More recently, the legend has undergone a strange inversion: astronomers have come to regard Orion the hunter as a cosmic nursery. It is no accident that the constellation is so bright, they find. Most of the stars there, including all those in the hunter's belt and sword, are very hot and very young. They are blue-white stars of the O and B types, probably no more than a few million years old.*

Just behind those stars lie cold, dense masses of interstellar gas and dust, invisible against the blackness of space. These are the Orion molecular clouds. They sprawl across the hunter's midriff in a vast, broken complex hundreds of light-years across. In aggregate they contain enough material to make hundreds of thousands of stars like the sun. Stars are forming there now as denser clumps of material contract, turn their gravitational energy into heat, and finally ignite by nuclear fusion.

In the middle of Orion's sword, nestled against the face of the densest part of the cloud, lie the four stars of the Trapezium. They are the youngest of the visible stars in Orion. Their ultraviolet radiation is burning a blister in the cloud surface. The ionized atoms there respond by glowing brightly in visible light. This one tiny patch of the cloud complex is what we see as the Orion nebula.

The Orion molecular clouds are made mostly of hydrogen, with small admixtures of carbon, oxygen, nitrogen, and the solid grains of silicate dust. Their densest regions contain a million or more atoms per cubic centimeter. The surrounding interstellar medium contains about one atom per cubic centimeter. No one really understands how or why such giant molecular clouds form, but they are scattered along the spiral arms of the galaxy by the thousands. The Orion complex is neither the largest nor the most active at forming stars. It is, however, the closest to the earth. It lies in the lower fringes of the spiral disk, some 1600 light-years farther out from the center than the sun. Thus, it is by far the most accessible site for studying the poorly understood process of star formation.

Recently, some 200 astronomers interested in star formation gathered at New York University for a symposium on Orion.† The field has begun to develop quite rapidly in the last few years. Some of the data presented at the meeting were only a few months old.



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The great nebula in Orion

The young, hot stars of the Trapezium cluster, which energize the nebula, lie in the overexposed central region.

*Stars are classified according to their temperatures and spectral features. O stars are the hottest, M stars the coolest. Generations of astronomy students have learned to chant "*Oh Be A Fine Girl, Kiss Me*."

†"Symposium on the Orion Nebula to Honor Henry Draper," New York University, 4 and 5 December 1981. Draper (1837–1882) held appointments at New York University in the departments of natural history, philosophy, physiology, analytical chemistry, and chemistry and physics. On the night of 30 September 1880 he made the first successful photograph of a Nebula, the Orion Nebula.

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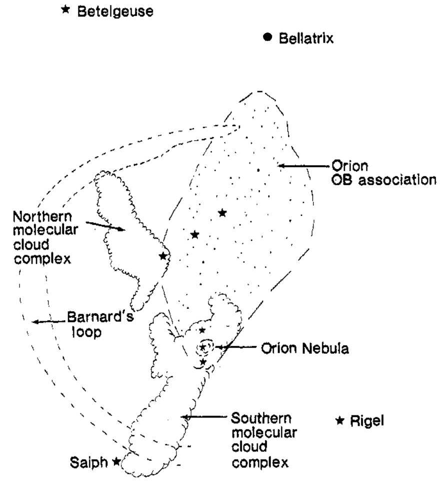
The key to this research was the discovery in the early 1970's that stars are formed in the same clouds that breed interstellar molecules such as water, ammonia, and carbon monoxide. (This is the origin of the name "molecular cloud": As a cloud collapses toward stellar densities, it becomes dense enough for atoms to find each other and combine; it also becomes dense enough to shield the molecules against ultraviolet radiation, which would break them apart again.) By a happy coincidence, the vibrational and rotational emission lines of the molecules tend to lie in the infrared and microwave part of the spectrum, at wavelengths that penetrate the clouds. By another happy coincidence the most intense emission lines, those of carbon monoxide, are also able to penetrate the earth's atmosphere. Thus they can be studied from the ground. (Molecular hydrogen, the most abundant interstellar molecule, has very weak infrared emissions except in regions of particularly high temperature and pressure. It is best observed from sounding rockets or satellites that can detect its absorption lines in the ultraviolet.) During the 1970's interstellar molecules have become the most powerful tool for mapping the interiors of such molecular clouds, for plotting their internal motions, and for taking their internal temperatures.

The surge of activity in the last few years is due primarily to developments in infrared and submillimeter-wavelength detectors and to new instrumentation such as the Very Large Array in New Mexico and the infrared telescopes on Mauna Kea in Hawaii (*Science*, 4 December 1981, p. 1110). "Right now the techniques are just barely able to detect the bright sources," says NYU astronomer Alfred E. Glassgold, one of the organizers of the symposium. This has pretty much confined the observations to Orion, he says. "We're only just beginning to take a look at OB associations that are farther away. In 5 years, perhaps we'll be able to do it, but that will depend on the technical evolution."

Given Orion's observational importance, astrophysicists endlessly debate which features of these molecular clouds are typical of star-forming regions elsewhere in the galaxy, and which are somehow unique. At least one feature is *not* typical: the hunter is wearing an invisible cloak. In less poetic terms, the Orion OB associations and the molecular clouds are surrounded by a tenuous shell of ionized gas some 300 to 600 light-years in diameter. The shell is expanding outward at about 100 kilometers per second. "It's an enormous feature, tens of degrees across," says Lennox L. Cowie of the Massachusetts Institute of Technology, a codiscoverer of the shell. From ultraviolet observations made in the late 1970's by the Copernicus orbiting observatory, Cowie, A. Songaila, and D. G. York estimate the shell's temperature to be about 50,000 K. (The name "Orion's Cloak" is theirs.)



Starclouds

The Orion molecular clouds are shown here behind the field of visible stars. The association of O and B type stars lies in front of the clouds. Barnard's loop, a region of ionized hydrogen that probably marks the inner edge of an expanding shock wave, is a partial shell around the clouds.

Cowie believes that the shell is the outer edge of a shock wave propagating through the interstellar medium from a supernova that erupted among the Orion OB stars about 500,000 years ago. (The lives of the most massive stars are short and fierce. They very quickly burn up all their hydrogen and explode as supernovae. For the collection of stars seen in Orion, says Cowie, one or two supernovae per million years seems like a reasonable average.) On the other hand, it was suggested at the symposium that strong stellar winds from the OB stars, analogous to the solar wind, might collectively drive the shell. Either way, it seems that Barnard's loop, a partial ring of ionized hydrogen discovered in 1898 by E. E. Barnard, is simply the inner rim of this shock wave.

Surprisingly, when Cowie and his colleagues examined 12 other OB associations they found only one, in Carina, that had a shell like Orion's. "We don't understand why they are so rare," he says, but it may be that younger OB associations contain too much intervening material; the shocks cannot break out into the interstellar medium, where they could be seen. Perhaps Orion and Carina are older and less homogeneous, so that the shocks *can* break out.

Star formation seems to have progressed in a remarkably ordered way in Orion. The OB stars are arrayed in a roughly linear chain of subgroups, each one slightly younger, slightly more compact, and slightly more distant from the earth than the one before. The chain leads directly to the Trapezium cluster and continues past the visible nebula into the densest part of the cloud, where the next generation of stars, visible as hot spots in the carbon monoxide emissions, are just igniting.

This same sequential pattern of star formation has been observed in many other OB associations. In 1977, Bruce G. Elmegreen and Charles J. Lada, then at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, proposed a theoretical model for how it could happen. They pointed out that a newly born, massive star ionizes the surrounding molecular cloud and pushes it outward at 5 to 10 kilometers per second. This creates a shock wave that sweeps up cloud material as it expands. After a few million years the swept-up gas becomes dense enough to begin condensing into a second generation of stars. Because many of these will also be hot and massive, they will ionize and push on the cloud to form a third generation, and so on. The sequence of star formation eats its way though the cloud, say Elmegreen and Lada, leaving behind just the chain of OB subgroups observed. (A variant of this model holds that some of the OB stars generate shock waves by becoming supernovae.)

While the Orion observations are generally consistent with the Elmegreen-Lada model, there are problems. The newer star-forming regions are not particularly well lined up with the older subgroups, for example. Most astronomers agree that the model has been a useful framework for asking questions about star formation, and many believe that it holds a kernel of truth. But many also believe that nature is far more chaotic and complex than this orderly model would suggest.

A case in point is Orion's newest cluster of stars, which lies just to the northeast of the visible nebula within the densest core of the molecular cloud. The cluster and its immediate environs are called the KL nebula after Douglas E. Kleinmann and Frank Low, the astronomers who discovered it. It seems to consist of recently ignited O and B stars shrouded in dense cocoons of dust and gas, which show up in the infrared observations as 500 K hot spots.

New, high-resolution observations show that the KL nebula is roiling with turbulence, ionizing radiation, and gusty stellar winds with velocities of hundreds of kilometers per second. Observers still disagree on the details of the cloud's internal motions but it is becoming clear that star formation is not a one-way street. Gestating stars have a profound impact on their surroundings.

This may hold the solution to a long-standing problem with star formation in the galaxy as a whole, noted George B. Field, director of the Center for Astrophysics. There are thousands of molecular clouds in the galaxy. In aggregate, they contain as much as 1 billion solar masses of material. The free-fall time of a typical molecular cloud—the time it would take to collapse under its own gravity—is about 1 million years. Dividing these two numbers, Field said, one would expect about 1000 stars to be born in the galaxy every year. But the actual rate (the total number of stars—billions—divided by the 10-billion-year age of the galaxy) is closer to one new star per year. Why is it so low?

An attractive way out of the contradiction, says Field, is to assume that the molecular clouds are, in fact, very long-lived structures that are being supported against gravitational collapse by their own internal turmoil. For example, John Bally of Bell Laboratories reported on strong stellar outflows found in six separate regions of the Orion molecular cloud. He compared the energy driving those flows to the total amount of turbulent energy in the cloud. An order of magnitude estimate shows that the stellar winds could "pump up" the cloud turbulence in about 1 million years, he said. Perhaps it is no coincidence that this also happens to be the cloud's free-fall time.

The cluster of hot spots in the KL

In the Beginning. . .

Most of what astronomers know about star formation applies only to the hot, massive O and B stars; these are the ones they can see best. But two speakers at the Orion symposium did address the formation of low-mass stars like our own sun.

A Mist of Stars

Scattered among the stars of the Trapezium is a dense swarm of dim, low-mass stars—dim, in this case, meaning about the brightness of the sun. Although the cluster was discovered by R. J. Trumpler in 1931, the stars are difficult to observe against the brilliant veil of atomic emission from the surrounding nebula. Obtaining spectra is even more difficult; no one can say whether these stars are newborn, like the blue-white giants of the Trapezium, or much older.

It is clear, however, that the cluster is extraordinarily dense. A more famous cluster, the Pleiades in the constellation Taurus, contains about one star per cubic parsec (a parsec is 3.26 light-years). The Trapezium cluster contains about 560 stars per cubic parsec.

George H. Herbig of Lick Observatory suggests that the Trapezium cluster is actually only the visible portion of a much vaster array of stars. It may be, he says, that the stars are quite old and that the entire Orion molecular cloud is filled with them. (Presumably, the mass of the cloud is sufficient to keep the stars gravitationally bound inside.) They are visible around the Trapezium only because the Trapezium stars have carved a pocket in the face of the cloud, boiling away the gas and dust that obscures the dimmer stars elsewhere.

Some participants at the Orion symposium were initially skeptical of Herbig's idea—it would imply that these low-mass stars contain most of the cloud's mass, and that seemed a little extreme—but they agreed that it should be taken seriously. They had to take it even more seriously after Ian Gatley of the United Kingdom Infrared Telescope in Hawaii announced his unpublished infrared observations of low-mass stars lying deep within the cloud. If Herbig's model is valid, it could mean that low-mass stars like the sun are calmly and continuously condensing in the cloud like mist, by mechanisms quite different from those that trigger the violent birth of massive stars.

The Fires of Creation

Did a supernova trigger the formation of the solar system? Perhaps. One version of the sequential star formation model holds that new stars condense out of material swept up in a supernova's shock wave propagating through a molecular cloud. Moreover, certain grains of rock found in very primitive meteorites have a different isotopic composition from other material in the solar system—as if they had been injected from outside just before the solar system formed.

University of Chicago astrophysicist David N. Schramm believes he has found new evidence for the supernova trigger. But he inverts the isotope argument. The outside material is not different, he says. The solar system is different.

He starts by modeling the chemical evolution of an Orion-like OB association that forms from a molecular cloud by a chain of supernova explosions. The cloud, he assumes, has the same average composition as the interstellar medium—which is not the same as that of the solar system. (This is well known from the study of cosmic rays and the spectra of interstellar molecules, he says.)

When the first generation of stars form they will process the cloud material by thermonuclear fusion. When they erupt as supernovae they will spew out material with a new suite of isotopes. Assume that this material mixes with the old gas in the edge of the cloud, says Schramm. Then assume that the solar system forms there at the edge among the second generation of stars. How will its isotopic composition differ from the average of the interstellar medium?

Given what is known about nucleosynthesis in supernovae, says Schramm, the solar system should have the following high ratios: neon-20 to neon-22, carbon-12 to carbon-13, oxygen to carbon, and oxygen-16 to oxygen-17. And this is exactly what is observed.

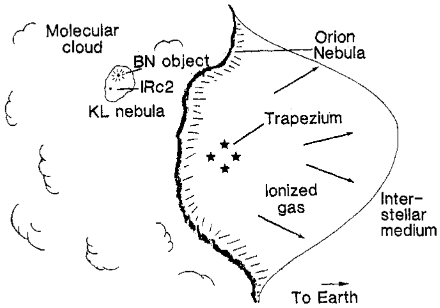
If Schramm's model is correct (it was well received at the Orion symposium) then the birth of the solar system was not at all a calm process. Instead, the skies of the infant earth burned with the actinic light of OB stars, and were seared again and again by the explosive violence of supernovae. When the solar system was born, it was not alone.—M.M.W.

nebula is about 0.1 light-year across. In size and luminosity (about 10^5 times the luminosity of the sun) it resembles the Trapezium. "This suggests that it is evolving toward a Trapezium-like configuration," says Michael W. Werner of NASA's Ames Research Center in Mountain View, California. But he also pointed out that some of the hot spots may just be clumps of gas that shine by scattered light.

There is one source that everyone agrees is a star, says Werner. By far the most luminous of the infrared hot spots, it was discovered in 1965 by Eric E. Becklin, now of the University of Hawaii, and Gerry Neugebauer of the California Institute of Technology; it is variously known as the BN object and as IRc1 (infrared compact source 1). BN's power source is cloaked by silicate dust grains, which form a mantle about the size of the solar system. Nonetheless, BN is bright enough to ionize the surrounding hydrogen, which emits radiation detectable from the earth. Also the Einstein orbiting observatory has detected x-rays from BN, evidence for a hot stellar corona.

IRc2, a source just to the south of BN, was until recently thought to be a true protostar—that is, a slowly shrinking ball of gas that has grown hot enough to retard further contraction, but not yet hot enough to ignite thermonuclear fusion. However, Werner and a number of other speakers at the NYU symposium argued that IRc2 *has* ignited. There are several new pieces of data, said Werner, that can be assembled into the following speculative picture of IRc2.

In the center is the newborn star itself, emitting a strong stellar wind. (Several observers reported evidence for a general outflow of mass from the KL nebula, although it is still not certain that IRc2 is the source.) Surrounding the star is a thick disk of gas and dust; observers from the earth happen to be looking at the star through the plane of the disk, which is why IRc2 looks dimmer than the BN object. Farther out, the wind hits the stationary gas in KL and forms a shock wave. Riding outward with the shock is a swarm of water masers, cloudlets that emit strongly at the 1.35-centimeter wavelength. (Radiation from a nearby star—presumably IRc2—excites the water molecules in the cloudlets; the energy is then reemitted coherently, just as in a laboratory maser. Recent, very accurate measurements of the positions of these maser sources by very long baseline interferometry techniques were reported at NYU by Reinhard Genzel of the University of California, Berkeley.



The nebula in cross section

According to one interpretation, the hot young stars of the Trapezium are boiling away material from the cloud and are raising a blister of ionized gas on its surface. In the process, they are lighting up the visible nebula. Within the cloud, in a dense core of gas and dust called the KL nebula, two stars have just begun to shine: the BN object and IRc2.

The sources are indeed moving outward from the KL nebula at about 18 kilometers per second, he said; a few are moving at up to 100 kilometers per second.)

Finally, Werner suggests that the light from IRc2 is scattering off two nearby clumps of material, which observers on the earth see as the infrared hot spots IRc3 and IRc4. Thus these sources are probably not stars (at least, not yet). This conclusion is based on the recent finding that infrared radiation from these regions is polarized, which is a characteristic of scattered light. The direction of polarization is consistent with a bright source at IRc2.

In one of the final talks at the NYU conference, Richard B. Larson of Yale University, a pioneer in the theory of star formation, reemphasized a ubiquitous theme: complexity. "The available theories of star formation are too rudimentary to compare to observation," he declared. The classical idea, dating from the time of Newton, is that the whole process is dominated by gravity: a continuous distribution of matter is unstable, and gravity will tend to break it up into clumps. Presumably these clumps will fragment still further, with the smallest fragments eventually becoming stars. But it is still not clear that gravity alone can do the job, says Larson. Numerical simulations to date have not supported the idea.

What the data from Orion and other star-forming regions have shown is that hydrodynamic effects play an important or even dominant role. The gas can be compressed by shocks or swept into clumps by turbulence. The stars that have already formed influence the development of newer stars. More realistic models will have to take all the processes into account, Larson says. For example, hydrodynamically formed clumps may well accrete more material from the surrounding cloud by gravity. Much of that infalling material would then spiral into orbit around the star as an accretion disk, like the one around IRc2.

But this model creates another problem. Accretion is a runaway process, says Larson. What keeps the material from building up into supermassive stars far larger than anything now observed? Something must be acting as a cutoff. He finds a likely candidate in the stellar winds. No one has a good explanation for what drives these winds, he says, but some of them deserve to be called stellar hurricanes. The most spectacular winds come from the hottest, most massive newborns, the O stars; some of them are losing material at the rate of 10^{-3} solar mass per year. This kind of activity may well be sufficient to push back the infall in even the densest part of the cloud, says Larson.

Given the chaotic condition of the molecular clouds in Orion, Larson doubts that we are seeing the kind of orderly, sequential process of star formation postulated by Elmegreen and Lada. Looking instead at the distribution of stars in the Orion association, in Taurus, and in another similar cluster, NGC 2264, he noted a tendency for the younger and more massive stars to concentrate toward the center. Perhaps, he said, molecular clouds start out in a relatively dispersed state, like the one in Taurus. Long-lived, low-mass stars form over a wide area. Later, the cloud contracts into denser clumps, where more massive stars form. Finally, the contraction culminates in a cloud complex much like Orion, with a dense core of gas piled up in the center. The stars that form there have to grow very massive before their stellar winds become strong enough to stop the accretion.

In the 1970's astronomers recognized a profound and simple truth, that stars are born in molecular clouds. Yet it was clear at the Orion symposium that the details are anything but simple. Their understanding is tentative at best. In September 1982, NASA will launch the Infrared Astronomy Satellite, a joint European-American effort to perform the first all-sky survey in the infrared. The survey will test the theorists' models of star formation in many new regions. Perhaps because of this the 1980's will bring new insight into the problem, a new synthesis. Perhaps it will take decades. But however long the quest, astronomers will certainly owe a great deal to their study of the starclouds of Orion.

—M. MITCHELL WALDROP