New eyes on the birth of stars

Now and again within the galaxy a cluster of stars is born. The zone known as W3 in Cassiopeia is one recent spawning ground; it was revealed by observations with radio and infrared telescopes.

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So far as we know most of the matter in the Universe is in the form of stars. The majority of stars, including our Sun, are clouds of gas which are maintained at a high temperature by the energy liberated by thermonuclear reactions in their centres. Most of our knowledge of stars and how they evolve comes from the study of the visible light they emit. The birth of stars, however, cannot be followed by an optical telescope, since it takes place in regions of space from which light cannot escape. To study this process, therefore, astronomers have to make use of telescopes operating at other wavelengths. The recent technical developments in radio, millimetre-wave and infrared astronomy have turned the study of star-formation into one of the most exciting areas of astronomy.

The birth of a star is a rare, slow event; all but a very few of the stars visible to the naked eye have existed longer than mankind. We must therefore first consider the evidence that new stars are now being formed at all.

The energy which a normal, so called “main sequence,” star radiates into space is generated by the conversion of hydrogen to helium. If we compare the mass of hydrogen “fuel” in a main-sequence star with the rate at which energy is being emitted we can estimate its potential lifetime. It is found that the main sequence lifetime of a star depends strongly on its mass; low mass stars are small, cool and long-lived, while high mass stars are large, hot and short-lived. Our Sun is now half-way through its total main-sequence lifetime of 10^8 years, but a star with a mass thirty times greater than the Sun would live for only a few million years. The fact that such bright stars are seen to exist now implies that star formation must have taken place over the past few million years; since our Galaxy is some ten thousand million years old it is therefore reasonable to assume that somewhere in the Galaxy the same process is taking place even now. Moreover, the fact that these hot, bright stars are almost always found in the vicinity of interstellar gas clouds leads us to conclude that it is out of such clouds that new stars condense.

The evolution of a cloud of interstellar gas depends on a balance between internal gravitational forces tending to make it contract, and thermal pressure tending to make it expand. James Jeans, in 1926, first showed that a cloud of a given temperature and density can collapse only if its mass is greater than a certain minimum value; a typical cloud with a temperature of 100 K...
and a density of 100 hydrogen atoms per cu cm has to be 3000 times more massive than the Sun in order to start collapsing. However, later theoretical work showed that once the collapse process has started and the density has risen significantly fragmentation into progressively smaller cloudlets (protostars) is possible. These cloudlets eventually collapse to form individual stars. The theory of gravitational condensation therefore predicts, in agreement with observation, that new stars form in clusters containing hundreds or thousands of stars rather than as isolated entities.

The details of the fragmentation process are extremely difficult to calculate. We do not know what determines the proportions of large and small stars produced; nor do we know the effect of the clouds' angular momenta. We cannot yet predict what fraction of a collapsing cloud will end up in stars or what fraction will return to interstellar space. The theoretical approach to the study of star formation leaves so many uncertainties that we must return to observations of the sky in order to progress further. The timescale for star formation, though short by astronomical standards, is generally much too slow for us to see significant changes in a few years. The astronomer must therefore take on the role of a cosmic archaeologist; he finds varied examples of young stars and attempts to put them into the correct evolutionary sequence. The most rewarding clusters for study are those containing bright massive stars, since they evolve comparatively quickly and are easy to observe even at large distances.

There are several well-known regions of recent star formation in our Galaxy; Figure 1 shows one such region of the sky in the constellation of Cassiopeia. Several hundred of the stars in the photograph are all at about the same distance from us and comprise a cluster known as IC 1805. Some of the brightest stars in IC 1805 are marked; they are what astronomers call "class O", being at least 10⁴ times more luminous than the Sun and at a temperature of more than 30 000 K. The delicate filaments of gas which surround the stars are remnants of the cloud of gas out of which IC 1805 condensed. This gas will eventually diffuse away from the stars. It is estimated that the age of the cluster of IC 1805 is about a million years; most of the stars are now "mature", in that they will not alter their properties very much until they start to exhaust their nuclear fuel.

To study stars younger than a million years we come across a fundamental problem. New stars can only form in the centre of a collapsing cloud; it therefore follows that during its infancy a star is surrounded by the remnant of the cloud out of which it condensed. Since all interstellar gas clouds contain minute dust grains, light from the new stars is scattered and absorbed by the enveloping dust; the star at this stage is therefore invisible at optical wavelengths. If the star's surface temperature is greater than about 30 000 K, however, we may detect it indirectly by radio astronomy. The reason that this is possible is that the ultraviolet light from very hot stars can ionise the hydrogen gas surrounding it. This plasma cloud, which has a temperature of about 10 000 K, emits radio radiation as a result of the collisions between ions and electrons. These radio waves penetrate the dusty gas.

**Birth by radio**

Radio emission was first detected from the vicinity of IC 1805 by the Dutch astronomer Gert Westerhout in 1958. He also found a more intense source of radiation about one degree to the north-west of IC 1805 in a region called W3. Some of the radio emission from W3 can be identified with a bright optical nebula called IC 1795; but most of it emanates from a region from which no light can be detected nor stars seen. Westerhout's 21-cm wavelength radio observations had very poor resolving power: he was unable to discern any details finer than about 1/2 degree. Since that time, however, several generations of more sophisticated radio telescopes have studied the details of W3's structure. Figure 2 shows the most recent and most detailed map. It was produced during 1974 by the Cambridge Five-Kilometre aperture synthesis radio telescope at a wavelength of 6 cm. The resolving power is 2 arc seconds, nearly a thousand times better than Westerhout's.

The radio map shows very clearly that most of the ionised gas in W3 is clumped into a cluster of four or five compact condensations; we deduce that each condensation surrounds one or more newly formed stars. From the amount of radio emission coming from each condensation we may conclude the stars at their centres have about the same luminosity (at least at ultraviolet wavelengths) as the brightest class O stars in IC 1805. The invisible star cluster in W3, however, differs from IC 1805 in two important ways: it is more compact, and it is associated with much denser clouds of interstellar gas and dust. This is as we would expect if the stars in W3 were formed more recently than those in IC 1805. A rough estimate of the time since the stars were formed may be made by considering the dynamics of ionised gas clouds. The ionised condensations are hotter and at a higher pressure than their surroundings. They will therefore tend to expand with a velocity somewhere near the velocity of sound, 10 km per sec. The diameters of the larger condensed-
sations in Figure 2 are about one light year, so something like $10^4$ years must have elapsed since the stars began to ionise the gas. The variation in the sizes of the condensations probably reflects a spread in the ages of the enclosed stars.

What lies between the condensations? There are several reasons for believing that these spaces are not empty but are filled with dense molecular hydrogen gas which is too cold to emit radio waves. One reason is that the sharp edges round some of the condensations in Figure 2 show that the expanding ionised gas is pushing its way into dense surrounding material rather than expanding freely into a vacuum. Another reason is that radio telescopes operating at very short wavelengths of a few millimetres have detected emission lines from interstellar molecules in the vicinity of W3. These include carbon monoxide, carbon sulphide and hydrogen cyanide. Molecules such as these are too fragile to exist within the hot ionised condensations; their presence therefore indicates that there are extensive cool regions of unionised gas in W3.

The most abundant molecule in the clouds surrounding the condensations is hydrogen, but we cannot study it directly because it has no spectral lines at easily observable wavelengths. Maps of other molecules, such as carbon monoxide, however, have shown that the cloud out of which the W5 stars are condensing is over a degree in diameter—far larger than the area of Figure 2. By measuring the Doppler shifts of the spectral lines it should be possible to measure the velocity as well as the density and temperature of the gas in different parts of the cloud. These data should help us answer questions such as why most of the class O stars in W3 have formed in a compact group in one part of the cloud, and whether other parts of the cloud are in the process of collapsing. A serious limitation of the technique of millimetre line astronomy, however, is that the spatial resolution is currently limited to about one minute of arc; it is unfortunate that we cannot make maps of molecular hydrogen in W5 in anything like as much detail as that of the ionised hydrogen in Figure 2.

The third of the new techniques being applied to the study of star formation is infrared astronomy. There are two main reasons for this. First, infrared radiation passes through dusty regions of space with less attenuation than does visible light; obscured young stars can sometimes be found this way. Secondly, infrared radiation is given off when dust grains are heated to temperatures of the order of 100 K or more. By using an infrared telescope to look for signs of heated dust we are likely to find regions where forming or newly formed stars are near the material from which they condensed.

Only certain types of infrared radiation can penetrate the Earth's atmosphere. Those that can are usually measured by means of special detectors mounted on large ground-based optical telescopes; much of the wavelength range 1–m to 30–m is accessible by this method. Observations at wavelengths between 30–m and 1–m can only be made from high altitudes, using specially built telescopes mounted under balloons or in high flying aircraft. The US National Aeronautics and Space Administration, for example, is currently flying a C-141 jet transport aircraft modified to carry a 36-inch diameter infrared telescope at an altitude of 45 000 feet. At this height the aircraft is above 99.9 percent of the atmospheric water vapour, which causes attenuation at these wavelengths.

Both types of infrared technique have been used to study W3. Balloon-borne observations covering the wavelength range 30 to 450 $\mu$m showed that the total luminosity of the region is equivalent to a million Suns. Most of this energy comes from the stars at the centres of the condensations in Figure 2, but some probably arises from fainter stars whose location we do not yet know. The most detailed infrared studies of W3 were made at the California Institute of Technology using the Palomar and Mount Wilson telescopes at wavelengths between 1 and 20 $\mu$m. These studies have shown that each of the ionised regions in Figure 2 is a strong infrared source by virtue of the heated dust mixed with plasma. They also led to the discovery of at least one hidden O star. Most significant however, was the discovery of a quite unexpected object, labelled W3-IRSS in Figure 2. This object is 30 000 times more luminous than the Sun, but emits essentially all its energy at wavelengths longer than 3 $\mu$m. Its energy distribution (Figure 3) is like that of an object with a temperature of 350 K, except that near 10 $\mu$m there is a very strong absorption band caused by interstellar silicate particles. W3-IRSS is also a source of intense water-vapour maser emission at a wavelength of 1.35 cm. Several lines of evidence indicate that W3-IRSS is a massive "protostar"—the intermediate stage between a collapsing interstellar cloudlet and a true star. Calculations suggest that W3-IRSS has a core of nuclear-burning material rather like an ordinary star, but is rapidly increasing its mass as more and more interstellar matter falls onto it from its enveloping cloud. The heat produced by the nuclear reactions is absorbed by the infalling gas and dust and reradiated at infrared wavelengths. This process should continue for a few thousand years before W3-IRSS becomes a fully-fledged O star. The most recent observations indicate that W3-IRSS may in fact consist of two stars only a second of arc apart—a proto-binary star.

W5 is just one of several regions of star formation that are being studied in detail by the combination of techniques described in this article. Aperture synthesis radio telescopes lead us to the newly formed O stars and allow us to map the patterns of ionised gas in greater detail. Millimetre-wave spectral line studies delineate the more extensive, cooler neutral clouds, providing information on their temperatures, densities and velocities. Finally, infrared techniques allow us to observe the dust in the clouds and, most important of all, the birth event itself.