



The world's second largest steerable radio telescope, during construction of its 210-foot paraboloidal radiation collector. It is being erected at latitude 33° south, near Parkes, New South Wales, Australia, by the Commonwealth Scientific and Industrial Research Organization, for studies of the Milky Way and other galaxies. Photo from Radiophysics Division, C.S.I.R.O.

The Interstellar Medium

BART J. BOK, *Mount Stromlo Observatory*

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Interstellar material associated with hot early-type stars abounds in this part of the Large Magellanic Cloud, which includes at top center the great Tantalus nebula (30 Doradus). The enlargement is from an ultraviolet exposure made by Bengt E. Westerlund with Uppsala Observatory's 20-inch Schmidt telescope, located on the grounds of Mount Stromlo Observatory, Australia.

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ON THE COSMIC SCALE, 10 million years is just an instant. It represents 1/20 of the time that it takes our sun and most of the stars near us to circle once around the center of our Milky Way, and it is no more than 1/500 of the probable age of our solar system. Yet the maximum ages that we assign to some of the apparently very youngest stars are of the order of one to 10 million years. Most of these are stars with masses of 10 to 100 times the sun's, and they evolve quite rapidly.

We are thus forced to consider the pos-

sibility that cosmically very young stars are still being formed today from the matter in interstellar space, that is, from interstellar gas and cosmic dust. In many of the nearby parts of the Milky Way we observe an abundance of interstellar material, and these regions are also relatively rich in young and superluminous *O* and *B* stars. These extensive complexes of gaseous nebulosity appear to possess all the attributes required for star formation.

The most conspicuous manifestations of interstellar gas are the bright and beautiful emission nebulae, large and tenuous

clouds of luminous gas. Among the best examples are the Orion nebula, the Eta Carinae nebulosity, and the 30 Doradus nebula in the Large Magellanic Cloud. What do we know about the emission nebulae, their compositions, their average densities, fluctuations of density; and by what processes are they made to shine?

According to the best available estimates, hydrogen atoms supply about 65 per cent of the total mass of such a nebula, with helium accounting for most of the remainder. Oxygen and calcium are probably next on the list, but their abundance is less than 1/1,000 compared to hydrogen and helium, and the abundances of other elements, sodium, potassium, and titanium, are smaller again by an order of magnitude.

Hydrogen is obviously the key element of interstellar space. Within the large emission nebulae, there are on the average about 50 to 100 hydrogen atoms per cubic centimeter, actually a better vacuum than we can obtain in the physical laboratory. Of vast size, the emission nebulae have diameters often as much as 100 light-years. The total masses of some nebulae and nebulous complexes may be as high as 25,000 to 50,000 suns, and we are thus assured that they contain plenty of gaseous matter for possible condensation into new stars.

Unlike stars, the emission nebulae are not self-luminous. They shine because of hot, blue-white *O* and *B* stars within their boundaries. With surface temperatures of 20,000° Kelvin and higher, these stars emit plentiful ultraviolet radiation, which ionizes the available neutral hydrogen atoms. Not infrequently, the resulting free electrons and protons recombine, the captures often being made in the higher energy levels of hydrogen atoms. The excited states last only a very short time, and as each electron cascades down to the lowest or Lyman level, lines of the familiar series — Paschen, Balmer, and Lyman — are produced in emission, thus making the nebula accessible to observation from the earth.

Best known of the many techniques for the study of emission nebulae is the straightforward optical analysis of their Balmer spectra and the associated background continuum. Additional information is obtained from the lines of other elements in various stages of ionization, notably helium, oxygen, nitrogen, and carbon. We also measure a nebula's total brightness and the distribution of surface brightness over its face. This photometry is best done with the aid of interference filters, which isolate the radiation of a single spectral line or of a small group of neighboring lines.

Radio techniques contribute much useful information. As a by-product of the recombination process between electrons and protons, a gaseous nebula emits strong radio radiation, especially in the wave length range from one to 20 centi-

meters. With some difficulty we may detect this sort of radiation all the way to the meter range. At the longest radio waves that are received from outer space, however, the emission nebulae are in effect absorbers, appearing as dark spots against a sky illuminated by radiation from more remote parts of the Milky Way and from the universe of galaxies.

At the other end of the spectrum, in the far ultraviolet, rockets afford means of observing from above the absorbing layers of the earth's atmosphere. At the Lyman-alpha line (1216 angstroms), the whole sky appears to be bright, but between 1225 and 1350 angstroms the familiar emission nebulae begin to show and some unexpected new regions of emission are detected.

Perhaps the best physical model for a large emission nebula has the mass mostly concentrated in fairly dense small clouds, all of them together occupying only three or four per cent of the nebula's total volume. This model is based wholly on theoretical interpretation of spectral dis-

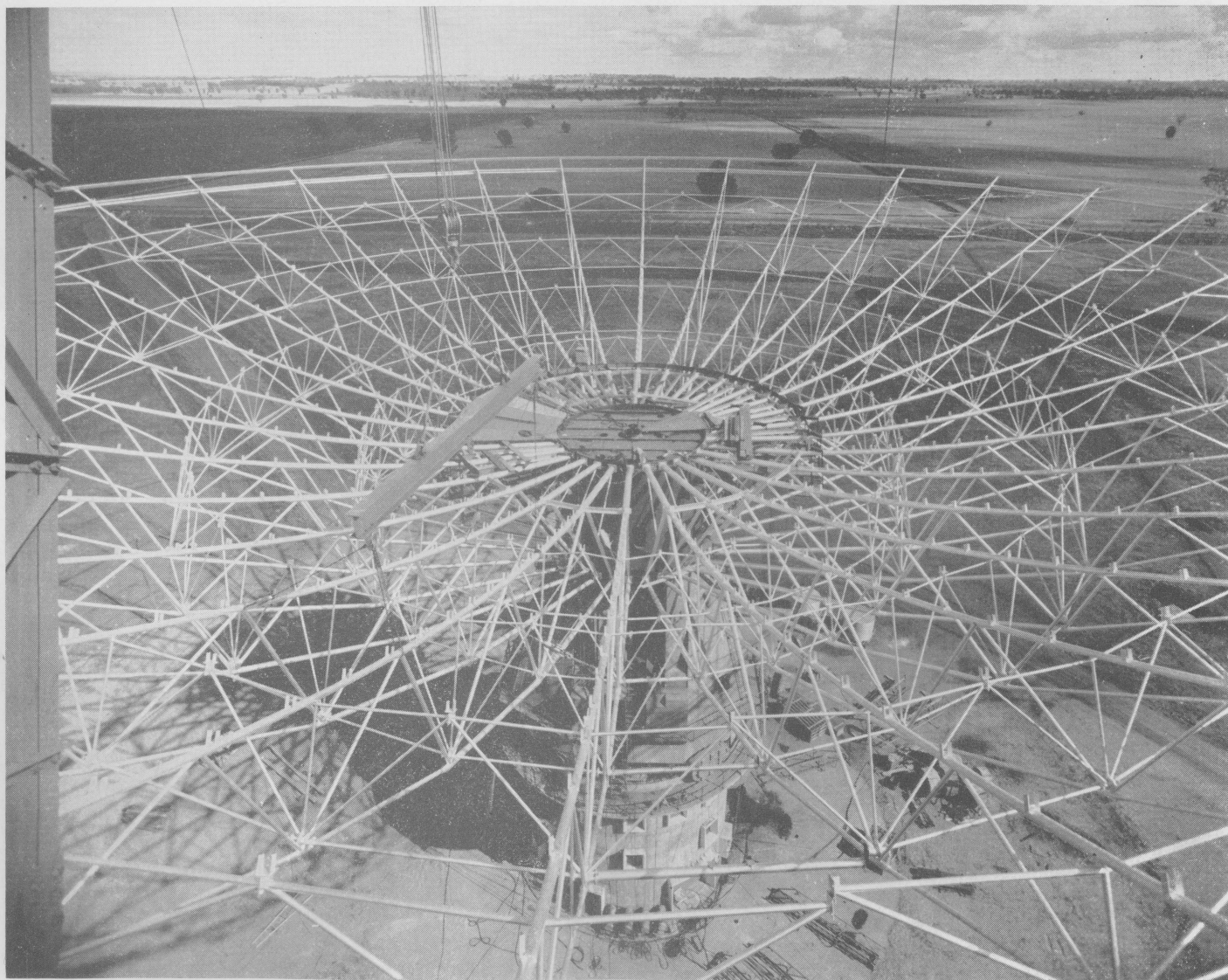
tribution and surface brightness of some large nebulae. Although it requires further observation and analysis, this model is very suggestive of incipient star formation.

Emission nebulae represent concentrations in the interstellar gas, but they are by no means the whole story. In the sun's vicinity, there is much gas outside the nebulae proper, concentrated largely within a layer 1,000 light-years thick near the central plane of the Milky Way. The average gas density is of the order of one hydrogen atom per cubic centimeter, but it is 10 times as great in the spiral arms as between them.

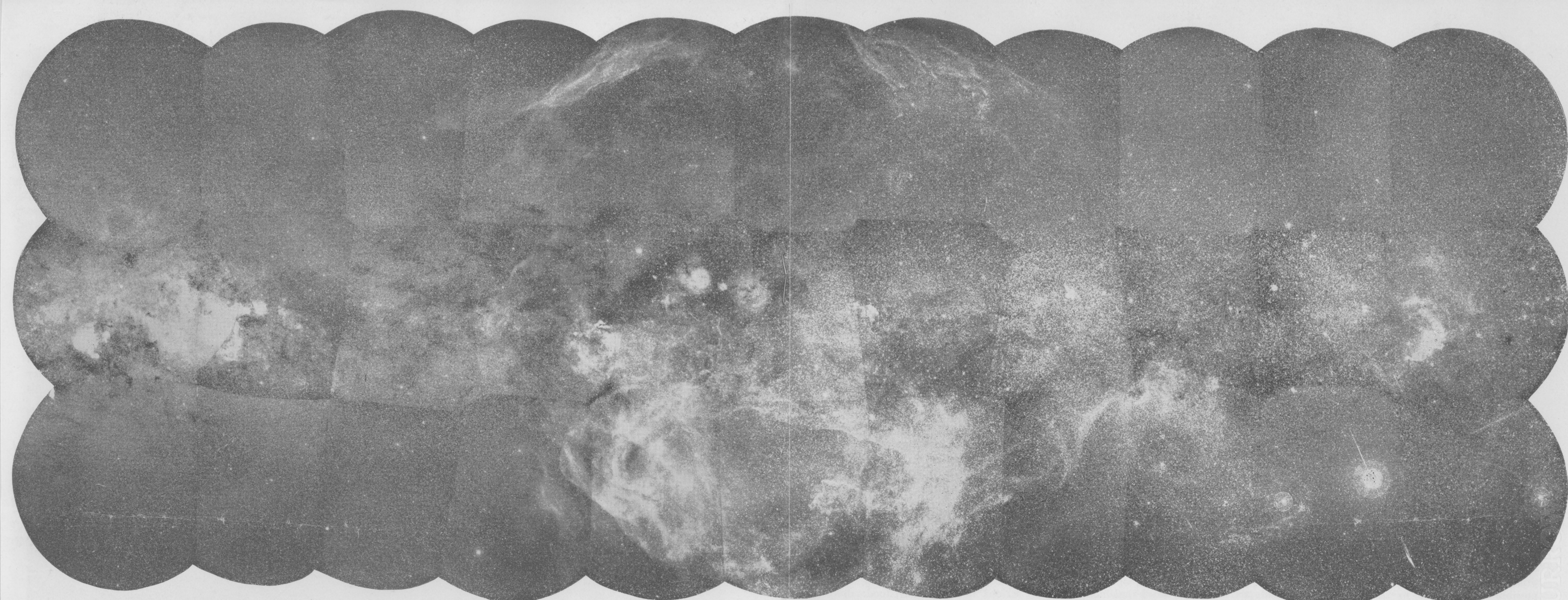
The optical technique of detecting interstellar gas by the absorption lines it produces in stellar spectra was described in the May, 1961, *SKY AND TELESCOPE* by Otto Struve (page 269), so we need not repeat it here. Filter techniques may also be used, as shown by some of the accompanying photographs, but the most recent and striking method of observation is by radio.

In the radio spectrum, emission and absorption at a wave length of 21 centimeters can be produced by the neutral hydrogen atoms of the interstellar gas. The process depends on the hyperfine structure of the atom's lowest (Lyman) energy level. The single electron can have a magnetic spin that is in the same or opposite direction to the spin of the atom's nucleus, the difference of energy in the two situations corresponding to that of the 21-cm. line. A single hydrogen atom probably changes from one of these energy states to the other only once every 300 years, but the number of atoms along almost any line of sight is so great that we receive on earth sufficient radiation at 21 centimeters to detect it with large radio telescopes. The total intensity tells roughly how much hydrogen there is in a particular direction.

If all the hydrogen in the galaxy were at rest relative to the sun, there would be only one very narrow line in the radio spectrum at 21 centimeters. But the Milky Way system rotates, and hydrogen clouds



This is an aerial view of the paraboloidal dish of the 210-foot radio telescope at Parkes, Australia, from high up on the derrick at the left in the front-cover picture. Although it has an altazimuth mounting, the giant reflector will be driven in equatorial co-ordinates by a conversion device and error detector, as described in this magazine's October, 1959, issue, page 666. Photograph from Commonwealth Scientific and Industrial Research Organization.



A composite of Plates 2 and 1 of the Mount Stromlo atlas, overlapping (at the left) a small part of Plate 3 on page 7. The great nebulous complex at bottom center is the Gum nebula, named for its discoverer, the late Colin S. Gum.

at various distances from the galactic center move with different speeds around it. In addition, the clouds have motions of their own, and all these movements combined give us a Doppler pattern of considerable complexity along most lines of sight.

From the appearance of the intensity profile (intensity versus precise wave length) of the 21-cm. line observed for any particular direction, we may deduce how much neutral hydrogen there is present at specific radial velocities of approach and recession. And if we possess — as we do — a rotational model of the galaxy, we can assign to each observed radial velocity a distance from the earth. Similar analyses for many different directions permit building up a picture of the distribution of neutral hydrogen atoms in most parts of the Milky Way system, reaching even to distances far greater than that of the center.

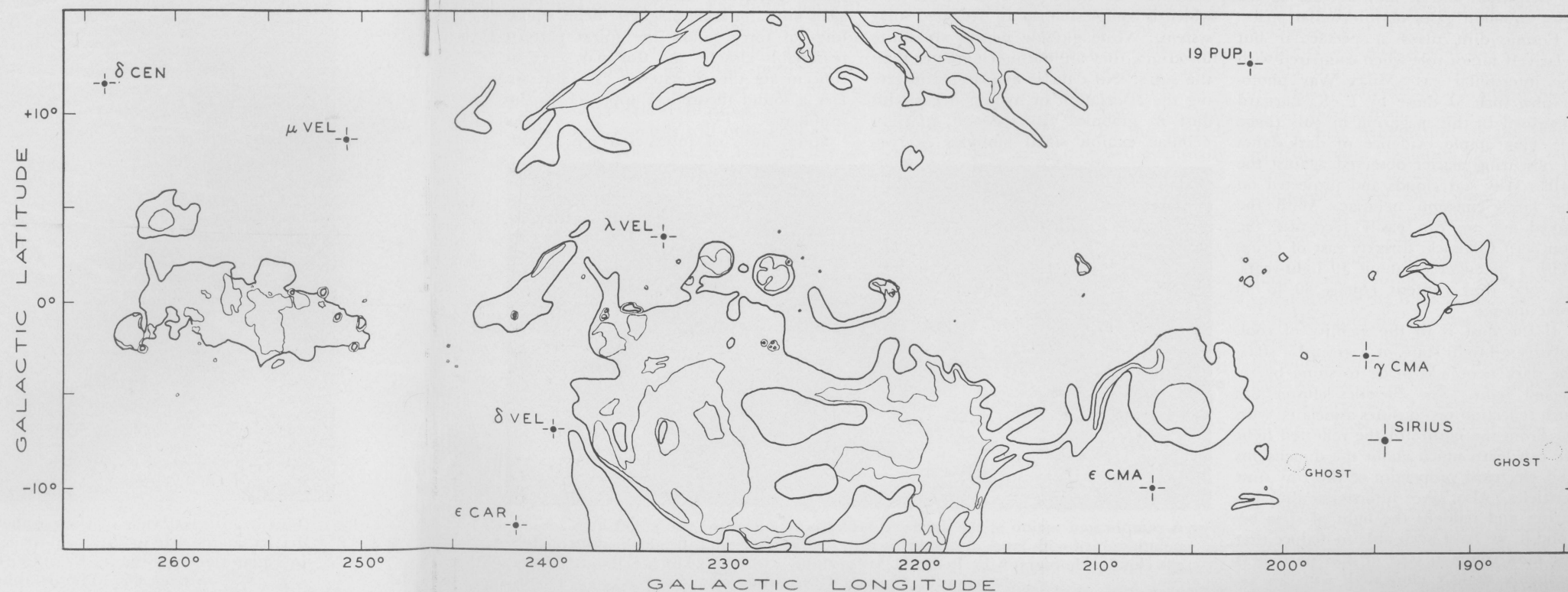
Radio studies have one great advantage over optical observations, for in radio we are not bothered perceptibly by the obscuring effects of cosmic dust. Its presence close to the central plane of the galaxy

limits optical studies for the Milky Way band to distances generally less than 10,000 light-years. Radio waves penetrate cosmic dust without being affected by it, permitting us to reach to the galactic center and beyond.

The 21-cm. observations delineate more clearly than any other type of observation the spiral structure of the galaxy, at the same time providing an increasingly detailed picture of the cloud structure of the interstellar medium. We can obtain data on average densities, temperatures, masses, and motions of the neutral atomic hydrogen clouds. With several large precision radio telescopes under construction, and with improved techniques for recording faint radiations, it should not be many years before the fine structure of interstellar gas clouds will be understood.

These radio observations and other studies enable us to estimate that the total mass of our galaxy, stars, gas, and dust combined, is close to 100 billion solar masses. Only two per cent is interstellar gas, mostly neutral hydrogen, with ionized hydrogen only 1/20 of the gas total. In

As the key chart shows, these 33 exposures with the 8-inch Schmidt camera cover an 80-degree section of the Milky Way, from Sirius on the right to the Carina-Centaurus nebulosities on the left. Mount Stromlo Observatory photograph.





Interstellar gas and dust are inextricably intertwined in Messier 8, a prominent nebula in Sagittarius. Some small, roughly circular dark patches are examples of globules. This is a 30-minute exposure with the 82-inch reflector of McDonald Observatory on Mount Locke in Texas.

the sun's neighborhood, where spiral structure prevails, the interstellar gas may account for 10 or 15 per cent of the total mass. This estimate is uncertain principally because we do not know the possible contribution to the total by molecular hydrogen. Neither optical nor radio techniques provide as yet a way for its detection, and it may be one of the most common gases of interstellar space.

Cosmic dust plays a spectacular but relatively minor role when compared with the interstellar gas. Milky Way photographs, such as those by E. E. Barnard described in this magazine in July (page 14), give ample evidence of dark lanes of obscuring matter observed against the Milky Way star clouds and projected on the large emission nebulae. With the naked eye we can easily recognize the Southern Coalsack, directly east of Crux. With a diameter of about 10 light-years, its total dust content equals 30 to 50 solar masses.

If the dust is in the vicinity of cool, relatively bright stars, or a group of stars, the dark nebula is made to shine by reflected light. The Pleiades cluster has such reflection nebulosities associated with it. From the nature of the reflected light we can learn much about the dimensions and electrical properties of the tiny dust particles. Also, since interstellar dust polarizes and reddens the light of stars beyond it, we have been able to deduce that the most common type of dust particle is probably slightly elongated, with an av-

erage diameter of 1/100,000 inch. In all likelihood it is composed of molecular combinations of familiar elements, such as carbon, nitrogen, oxygen, and the ever-present hydrogen.

There are many very small dark nebulae, some of them highly concentrated features named *globules*. Their dimensions are as small as 1/100 light-year, which is comparable to an oversized solar system. While globule masses are quite uncertain, they are not much greater than the sun's. No data is available concerning the association of hydrogen gas with dust in globules. But several emission nebulae exhibit small globules in con-

siderable numbers at their outer edges, and cosmic dust, as well as bright nebulosity, is abundant in many associations and clusters of *O* and *B* stars.

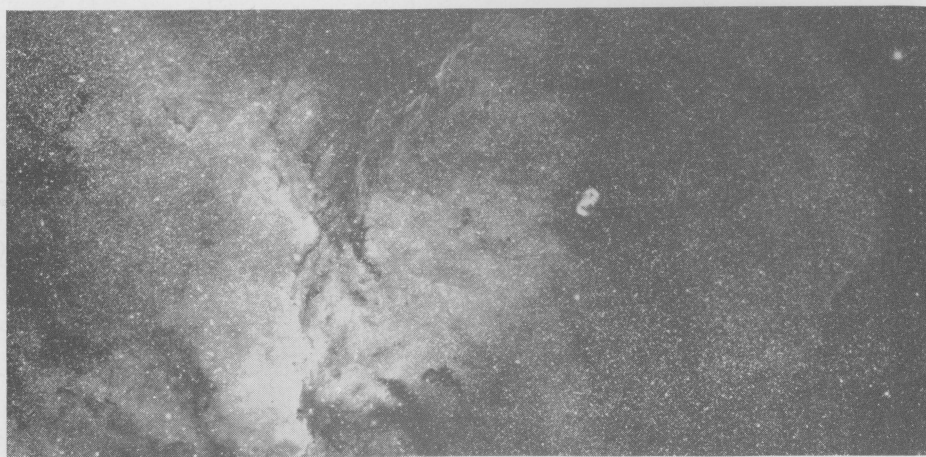
It seems not unlikely that these tiny dark clouds are a mixture of gas and dust now in the process of contraction — the most likely nuclei for the formation of new stars. They will, first of all, tend to contract under their own gravitational action, and a collapse, once started, will be a self-accelerating process. It will be aided by radiation pressure exerted upon a globule from the outside, and probably even more by the high gas pressure exerted by ionized gas at the boundary region between ionized and neutral hydrogen. Finally, magnetic forces may help squeeze globules together.

We do not suppose that all globules collapse in a neat and predictable fashion. More likely many of the observed objects are of a highly temporary nature, to be blown to bits by what we might loosely call the cosmic winds. But an occasional globule should encounter conditions that encourage collapse, which once started will almost surely lead eventually to a thin and very extended star, set on the first steps of its evolutionary path.

In the vicinities of some of the best-known dark nebulae, very faint dwarf variable stars, named after their prototype T Tauri, are generally recognized as the first observed stages of stars in evolution. In two cases we may even have seen a T Tauri variable come into sight before our eyes within a few years (*SKY AND TELESCOPE*, December, 1955, page 59).

For reasons not yet understood, the interstellar gases in the Milky Way and other spiral galaxies seem to follow a spiral pattern. Associated with their arms are large-scale magnetic fields whose lines of force follow the spiral pattern reasonably closely, and this may serve to concentrate the interstellar gas. But we lack a sound theoretical approach to the problem.

Spiral arms of interstellar gas would,



A complicated region of the southern Milky Way, including at the left a gaseous nebula mixed with lanes of obscuring dust and at the right a bright hook-shaped gas cloud. Photograph by Bengt E. Westerlund with the 20-inch Schmidt telescope of Uppsala Observatory.

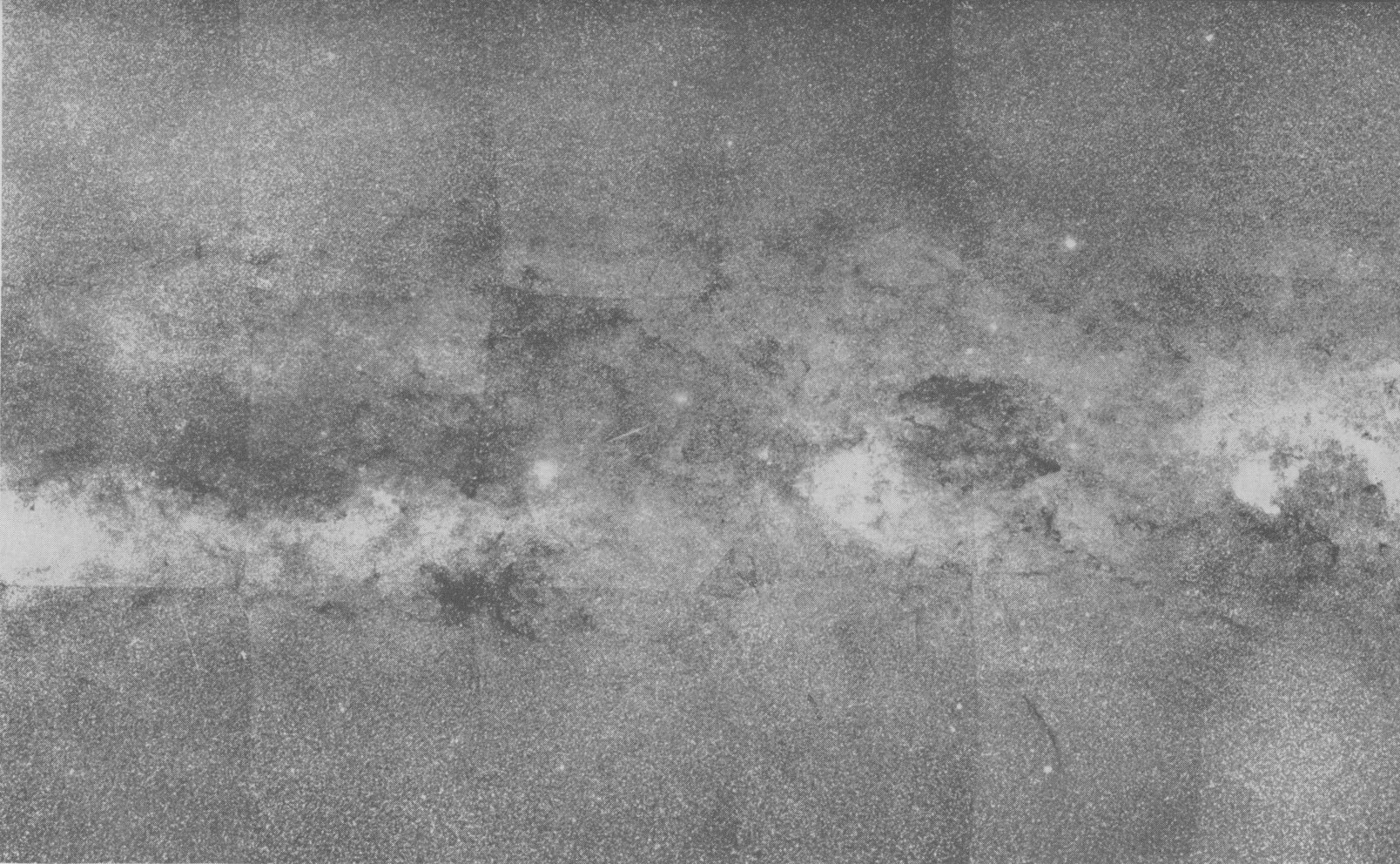


Plate 3 of an atlas of H-II regions in the southern Milky Way, from photographs taken with the 8-inch Schmidt camera at Mount Stromlo Observatory by A. W. Rodgers and J. Whiteoak. The mosaic was assembled by Helen Bailey and V. O. Hunt. From left to right, it covers galactic longitude 300° to about 255° , thus overlapping the section on page 4. To the right of center is the Coalsack, a large dark nebula next to the Southern Cross. The star Beta Centauri is almost centered, with Alpha Centauri overexposed to the left and below it. Constellations Ara, Norma, and Lupus lie along the left edge, where there are relatively few hydrogen emission nebulosities. In the richer region at the right edge is Carina. Triangulum Australe, Circinus, and Musca lie along the bottom central part of the picture. This section of the Milky Way is its southernmost. Reproduced courtesy Australian National University.

however, seem to be rather short-lived features of a galaxy. The inner parts of a spiral arm whirl around the system's center faster than the outer parts. A gradual winding up of the spiral pattern seems almost inevitable, at least in two or three galactic revolutions, say 500 million years, which is still only $1/10$ of the age of the solar system, $1/20$ or less of the age of our universe.

A related problem is the exhaustion of interstellar gas because of the continuing process of condensation into stars, which should also limit a spiral arm's lifetime to two or three galactic revolutions. In galaxies outside our own, the best-developed spiral arms rarely exhibit more than one and a half convolutions — the inner parts cannot have made many more circuits around the centers of these galaxies than have the outer parts.

Although the question of replenishment of spiral arms is unanswered, we may speculate a bit. Radio astronomers in the Netherlands have found considerable amounts of interstellar hydrogen, most of it neutral, some of it ionized, in the central parts of our galaxy. There is even a suggestion of a major spiral arm only one third as far from the galactic

center as the sun is. This "10,000 light-year arm" has the amazing property of moving outward with a speed of 30 miles per second. If this rate were maintained, the whole spiral feature would be carried out to the sun's present position in a little over 100 million years. We may consider the hypothesis that the expanding arms near the center will eventually move outward to take the place of the present spiral arms when the supply of interstellar gas in the latter becomes exhausted.

It is notable that star formation does not seem to take place, at least not on a large scale, in the central regions of the Milky Way and other galaxies; it is an active process only in their outer parts. The Sydney radio astronomer Frank J. Kerr has recently suggested that interstellar hydrogen at the sun's distance from the center moves outward at five miles a second. This indicates that the gas rings expelled from the central regions at 30 miles per second slow down considerably as they advance.

From where, then, would the central regions obtain their fresh supplies of gas to shoot out these expanding "smoke rings"? One suggestion does not seem

very attractive: that Population II stars suffer either very violent or very mild explosions and expel the gases into space. A preferable idea is that gas is supplied by the thin outer gaseous halo indicated by radio observations to surround the Milky Way system.

The best explanation of the general galactic radio radiation in the meter range is that it comes from a low-density ellipsoidal cloud enveloping the Milky Way. With a temperature of perhaps a million degrees Kelvin, the halo's hydrogen is completely ionized, the radio radiation being produced as free electrons spiral around the lines of force that probably lead into the nucleus of the galaxy. Perhaps the expanding gaseous rings in the nuclear regions of our own and other galaxies are produced as a by-product of this large-scale process. These ideas, however, must be considered quite conjectural, serving principally as working mechanisms.

One thing is quite clear. The solution of many problems in star birth and evolution lies in our obtaining as complete information as possible about the distribution, state of motion, and physical conditions in the interstellar medium.

