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DARK NEBULAE, GLOBULES, AND PROTOSTARS

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This lecture is dedicated to the memory of my wonderful wife, Priscilla Fairfield Bok. She was a student of two past Bruce Gold Medalists, W. W. Campbell and A. O. Leuschner, and she admired many of the people selected in the past for this honor, notably Harlow Shapley and Henry Norris Russell. Otto Struve, another of your famous Medalists, was a close friend of ours for many years. So were many Medalists, William Morgan and others; I have known personally 56 of your Medalists. Priscilla would have been terribly pleased to know that her husband was selected by the Astronomical Society of the Pacific to be the recipient of the Bruce Medal.

I am personally feeling much honored indeed. During my nine years as Director of Mount Stromlo Observatory in Australia, I was one of the people who helped the Council of the Astronomical Society of the Pacific with the selection of candidates to receive the Bruce Medal. Hence, I realize how much soul-searching goes into the nominating of each year's Medalist. It makes me feel humble to think that five or six colleagues of mine spent quite a bit of time thinking about good candidates the world over, and that, finally, they came to nominate me.

I shall speak to you on the subject of Dark Nebulae, Globules, and Protostars, which is the title of a little book that my friends in Arizona and elsewhere, led by Beverly Lynds (1971), wrote at the time of my retirement as Director of Steward Observatory. Much has happened in recent years to advance research in this area, and tonight I want to report to you on some of the more important things that have come about during the past decade. The topic is one that combines the best efforts in optical astronomy with the best efforts in radio astronomy. All of us in the field realize that no progress would have been made comparable to what we are seeing today if it had not been for the wonderful discoveries about molecules in interstellar space that were made during the past ten years.

About 30 years ago, I was one of the first to draw attention to the importance of the Barnard Objects (Barnard 1919; Barnard, Frost, and Calvert 1927), dark nebulae of small dimensions, that are observable all along the Milky Way. I was at that time especially interested in the larger one of these Barnard Objects, which are now sometimes referred to as Large Bok Globules. In a way this is a misnomer, for Edward Emerson Barnard published a list of them in 1919, when B. J. Bok was 13 years old! It is interesting to reflect today that these globules received little attention at first, but that gradually they have become accepted as truly physical phenomena in our beautiful Milky Way system. I remember the reaction of one of my rightly famous friends among the people doing research on the Milky Way, when I published in 1937 the little book called: *The Distribution of the Stars in Space*. When the book came out, he wrote me that it was a fine book indeed and that he had enjoyed reading it. At the same time, he warned me against getting too deeply involved with dark nebulae and their problems. He indicated to me that it would have been wiser if I had avoided the dark nebulae. He suggested that it might have been better to concentrate on the regions in between dark clouds where one can explore the fine structure of our Galaxy more directly than in regions in which one is bothered by obscuring nebulosity. I hope to show you tonight that it has proved very useful to have paid attention to the dark nebulae, which have a very special place of their own in the study of our home galaxy, the Milky Way System. They seem to hold the key to star birth within the first 2000 parsecs or so from our sun.

*This paper is essentially the text of my Address delivered upon acceptance of the Catherine Wolfe Bruce Gold Medal of the Society, awarded at the Pomona College Meeting 1977 June 21. Most of the work on the paper was done during a stay of two months in Chile as a Visiting Resident Astronomer, Cerro Tololo Inter-American Observatory, supported by the National Science Foundation under Contract No. C-866.

Star Birth in Our Galaxy

We will remember 1976 in astronomical history as the year during which astronomers arrived at a consensus regarding the early stages of star formation in our Galaxy. The International Astronomical Union sponsored a symposium on the subject at Geneva (De Jong and Maeder 1977) and, even though the conclusions are still highly tentative ones, incomplete and in part probably erroneous, the symposium volume represents the first comprehensive statement on the subject. It is clear that several breakthroughs have occurred in recent years. Star formation has become a topic for serious research by optical and radio astronomers. The theorists can sharpen their pencils and start building and analyzing models for protostars and for the condensed dark nebulae—the proto-protostars—that precede them. Within a few hundred parsecs of our sun, there are several varieties of dark nebulae, clouds of cosmic dust particles containing vast amounts of molecular hydrogen, which are characterized by the presence of CO molecules, observable by radio techniques at 2.6 mm wavelength. In the smaller dark nebulae, especially in the large globules, no stars have yet begun to form; infrared observers cannot detect these compact dark nebulae because of their very low temperatures (see the excellent survey article by Ney (1977)). In the bigger dark complexes, star formation has been in progress for many hundreds of thousands of years. Here the proto-protostars, the protostars, and the cosmically very young stars are found side by side.

Four specific processes of star formation are currently receiving much attention. They are: (1) There is good evidence for recent (and current?) star formation in the large dust complexes, notably in the Ophiuchus and Taurus clouds and inside the dark nebulae associated with and near the Orion nebula. The work of the Stroms, Vrba, and Grasdalen of Kitt Peak National Observatory (Grasdalen, Strom, and Strom 1973; Vrba et al. 1975) apparently indicates the presence of a young highly-obscured OB association within the Ophiuchus complex. This association was detected at a wavelength of 2μ; it represents an OB star grouping that is highly reddened. Chini et al. (1977) have confirmed that 26 of the 60 sources are stellar in nature, most of these having colors comparable with those of highly reddened stars of early spectral type. Dust-embedded young shell stars and T Tauri stars (Herbig 1962) are present in these same regions. (2) Elmegreen and Lada (1976) of the Center for Astrophysics at Harvard have described a "sequential formation mechanism" for star formation, the prototype for which is found in and near the emission nebula Messier 17. Similar situations are found in and near Messier 8, and soon we may have proof that some of the high-excitation far southern emission nebulae behave in a similar fashion. Elmegreen and Lada have shown that "a dense layer of neutral gas will accumulate between the ionization and shock fronts, which are driven into an associated molecular cloud by the nearby OB subgroup." The key to the process lies in the associated molecular cloud, which can be detected most readily by CO observation. The ionization shock front literally "eats" into the adjacent huge cloud of mostly molecular hydrogen. There have over the years been many other suggestions for star formation in nebulae with associated OB stars. One of the most interesting recent suggestions has come from Loren (1976), who has presented evidence for a process involving colliding dust clouds. (3) For many years, there have appeared in the literature papers suggesting that supernova remnants and pulsars create conditions that favor star formation. Early papers that dealt with supernova-associated origins were by Öpik (1953) and Bird (1964). There have been two recent papers on the subject, one by Ögelman and Maran (1976), the other—the most intriguing one yet to appear—by Herbst and Assousa (1977). In the latter paper, the R association Canis Majoris R1 is found to be located on the outer edge of a ring of optical and radio emission, which is coincident with an expanding neutral hydrogen shell shown in the 21-cm map of Weaver and Williams (1974). Herbst and Assousa estimate the ages of the expanding shell and of the stars in CMa R1 to be of the order of only 5×10^5 years. The further hypothesis is made that the expanding shell was produced by a supernova explosion. The presence of a runaway star in CMa OB1 is taken as proof for the supernova origin. The suggested "scenario" is an intriguing one, but various loose ends must be pulled together before the theory can be accepted as a basis for further study. The weakest link in the evidence presented by Herbst and Assousa seems to be the identification of the ring of optical and radio emission as a supernova remnant. (4) Thirty years ago, I drew attention to certain Barnard Objects, compact mostly near-circular dark nebulae, which are now often referred to as Large Globules. The original papers on the subject by Bok and Reilly (1947) and by Bok (1948) identified two varieties of globules, the large and the small ones. In recent years I have done much work on the large globules among the Barnard Objects, which in my opinion are likely proto-protostars. In the present lecture I shall do my best to prove that large globules may evolve into stars in cosmically short times. The result of collapse of a large globule may lead to a single star—often with an associated solar system—or to double or multiple stars, perhaps occasionally to modest clusters. In the present lecture, I shall not discuss the small globules. Herbig (1974) has shown that —at least for the Rosette nebula—these are probably a "late stage in the pinching-off and dissipation of elephant trunks," which are frequently observed in association with emission nebulae.

The majority of the large globules are well-defined, roundish, dark nebulae with diameters in the angle 3′ to 20′. At their estimated distances from the sun, their radii are in the range 0.15 to 0.8 parscs, 30,000 to a little under 200,000 astronomical units. Their masses, determined by both optical and radio methods are in the range 20 to 750 solar masses. The radio data show that their internal temperatures are low—mostly between 7 K and 15 K. Their calculated total kinetic-positive energies are only a fraction of their total potential-negative energies. Gravitational collapse is indicated by the radio data, which suggest collapse times of the order of one million years. I estimate that there are 25,000 large globules in our Galaxy. I doubt that magnetic fields play any appreciable role in their development and collapse. So far, there is no evidence for fragmentation. They seem to be clouds of mostly molecular hydrogen with a density that varies approximately like one over the cube of the distance from the center of the globule. We observe about 200 well-defined large globules within 500 parsecs of the sun.

It is pleasant indeed that globules are there for all to observe! The theorists who study star birth have, in the large globules, objects with well-defined initial properties. When a large globule collapses, it will probably form a single or multiple star with or without a solar system, an object that will initially be embedded in a thick shell of molecular hydrogen with associated cosmic dust.

In the sections that follow, I shall describe the optical and the radio results about the properties of large globules that have been obtained to date. Before I do so, I should speak briefly about one force that may assist in condensing a cloud of dust and molecules on the verge of collapse into a truly collapsing cloud. This may well be brought about by the shock wave associated with the Lin-Shu Density Wave, which is likely responsible for the formation of spiral structure in our own and other galaxies. This shock wave, first studied by W. W. Roberts (1969), should produce local pressures in the interstellar medium that exceed the average pressure by factors 5 to 10. This shock wave is supposed to be present at the insides of spiral arms, where—according to Beverly Lynds (1970)—the dust is generally concentrated. However, I must warn from the start against injudicious use of this convenient factor 5 to 10. One cannot, with the wave of a hand, call on this factor 5 or 10 as a magic factor to squeeze together, without argument, a dark nebula or a globule which seems on the verge of collapse.

Large Globules; Optical Evidence

Sir William Herschel must have been the first astronomer to have viewed one of the large globules through his telescope. He was assisted in his work on "star gauges" by his sister Caroline. On the night when he saw his first globule, he was so surprised that he shouted to Caroline: "Mein Gott, da ist ein Loch in Himmel." Large globules look indeed like holes in the heavens (see Hoskin 1963).

I find that very few astronomers have taken the time to actually *look* at globules through big telescopes. I never cease to marvel at their appearance. Before I select my guide star for photography, I have made it a practice to look at each large globule through the wide-field viewing eyepiece at the prime or Cassegrain focus of a large reflector. If one takes a globule like Barnard 227, 68, or 335, and places it 5′ to 10′ to the east or west of the center of the field, then one observes often a typical Milky Way field with dozens of faint stars and no spectacular side effects. By a slight gradual drifting of the telescope in hour angle, the globule comes into view. When it is at the center of the viewing eyepiece, there are often no stars to be seen within a circle of 5′ to 20′ in diameter. The globule has the appearance of a globular cluster of cosmic dust! It is a truly magnificent sight. Since large globules were a bit slow in gaining acceptance as objects for serious observational study, there must have been two decades at least during which I could say that only William Herschel, Edward Emerson Barnard, and Bart Bok had looked at large globules through fair-sized telescopes! All this is changing now that globules have become accepted as real physical and dynamical units. I hope that in the years to come many astronomers, young and old, may feast their eyes when viewing a large globule as a "Hole in the Heavens."

The cataloguing of large globules is pretty well in hand. Bok and Cordwell (1973), have prepared a list of Barnard Objects of special interest, to which can be added some of the more compact dark nebulae in the list of Beverly Lynds, based on an inspecton of the blue and red Palomar Schmidt Survey Photographs (Lynds 1962). Objects such as Lynds 134, 810, 1262, and 1642 deserve treatment along with the large globules on Barnard's List. For the Southern Hemisphere, a first listing has been prepared by a group of astronomers in Australia, who used the ESO blue Schmidt photographs and the UK Schmidt photographs in their searches for globules. J. W. Brooks, I. J. Danziger, W. M. Goss, K. Hartley, T. G. Hawarden, A. J. Longmore, R. Manchester, G. A. Manefield, and M. W. Sinclair have been involved in these searches. Immediately related to this work have been radio studies of the distribution and properties of formaldehyde and of atomic hydrogen in and near the catalogued objects. There are approximately 200 large globules known within 500 parsecs of the sun. The estimated total number of large globules in our galaxy is at least 25,000—possibly larger. Hawarden (see Bok, Sim, and Hawarden 1977) has listed 32 globules in the Southern Coalsack alone; an earlier (upublished) listing by A. Feinstein of La Plata Observatory confirms Hawarden's count.

It is not always a simple matter to estimate the distance to a specific globule. If the globule is clearly associated with a large dark neblae complex, then its distance is presumably that of the complex. A case in point is Hawarden Globule 2 in the Southern Coalsack (Bok et al. 1977), see Figures 1 and 2. Twenty years ago, Rodgers (1960) gave 175 parsecs as the distance to the Southern Coalsack. This value has not since been questioned and still looks highly acceptable. We shall use 175 parsecs as the distance to Globule 2. If a globule seems either involved in or associated with the Taurus Dark Nebulae Complex, then 125 parsecs is a good distance to assign it, and 200 parsecs is about right for a globule in or near the Ophiuchus Complex. Difficulties arise when one deals with isolated objects, like Barnard 335, which I place at a distance of 400 parsecs (Bok and McCarthy 1974). Globules observed at high galactic latitudes are most likely relatively near to the sun. The globule Lynds 134 at $b = +36°$ has, according to Heiles, a distance of 170 parsecs (Heiles 1968), which places it 100 parsecs above the galactic plane. The situation is a bit more cheerful if, associated with the globule, there is a reflection nebula. A good example is Lynds 810, a globule at an estimated distance of 1500 parsecs (Herbst and Turner 1976), which has a patch of reflection nebulosity. If one can designate a star as being responsible for the reflection nebulosity, then the distance to the globule may be estimated from the absolute magnitude corresponding to the spectral-luminosity class of the star; corrections for interstellar reddening must, of course, be applied.

It may be of interest to review here the results of calculations predicting the number of foreground stars observable against the background of a globule. J. C. Muzzio (see Bok and McCarthy 1974) has calculated these numbers on the basis of the van Rhijn General Luminosity Function for a globule at various distances from the sun measuring 5′ in diameter. The results are as follows.

Distance from Sun (parsecs)	Number of Foreground Stars
100	0.1
200	0.3
400	2
800	15

It is not surprising that Barnard 68, with a diameter of about 4′, and at an estimated distance of 200 parsecs, shows no foreground stars at all and that 10 or more are seen projected against Lynds 810 at 1500 parsecs from the sun, diameter 6′. These simple calculations show that it is generally difficult to detect globules beyond 500 parsecs distance from the sun. A globule like Barnard 68, which is a most conspicuous globule at 200 parsecs distance, will only measure 1′ in diameter at 800 parsecs. Most globules are becoming difficult to detect at 800 parsecs because of the presence of foreground stars and small angular diameter.

The techniques of determining total visual absorptions for large globules have been described by Bok and Cordwell (1973) and especially in the unpublished Doctoral Dissertation of Robert L. Dickman (1975). Starcounts on photographs in *B*, *V*, *R*, and *I* can yield good estimates of A_v, the total visual absorption, for reasonably transparent globules. The paper by Bok and McCarthy (1974) shows that globules with total absorptions $A_v = 10$ magnitudes or smaller can be studied by these methods. It becomes necessary to use emulsions sensitive farther in the near infrared if we wish to obtain total absorptions for globules with 10 magnitudes $< A_v <$ 20 magnitudes.

During a recent visit to Cerro Tolo Inter-American Observatory, I had the opportunity to study four globules with the aid of hyper-sensitized IV N emulsions (silver nitrate process). I photographed the globules at the prime focus of the 4-meter CTIO reflector. The hyper-sensitization process was applied for my use by CTIO's competent photographic technician, Luis Pinto, who also processed my plates. I was assisted in the preparation of internegatives and prints of my plates by Carlos Monsalve. Assisted in this manner, I obtained several beautiful plates, notably one of 200-minutes exposure time of Globules 1, 2, and 3 of Hawarden's list in the Southern Coalsack and another of 200-minutes exposure of Barnard 68 and 72. The results are shown in Figures 1 and 3. Filter RG 695 was used to obtain these photograpic plates.

There is a further requirement that must not be overlooked. For the proper study of large globules, one requires a good standard sequence in *B*, *V*, *R*, and *I* to cover the interval from $V = 10$ to the limit of the 4-meter plates, $V = 23$. This is in itself a major assignment. I solved it by estalishing a sequence adjacent to Globule 2 in the Southern Coalsack by photoelectric photometry in the range $10.50 < V < 16.30$ using the 91-cm and 1.5-meter reflectors at CTIO. There are two photographic methods available for extending the photoelectric sequence to the plate limits of the *B*, *V*, *R*, and *I* plates. In the simplest of the two, one inserts the Racine (1969) prism in the parallel beam of the 4-meter reflector. This produces a companion image, 6.9 magnitudes fainter than the primary image, adjacent to the primary image. The photoelectric standard sequence can be extended to the plate limit for each plate photographed with the Racine prism in place. A second approach is to use the method developed by Harvey Butcher for use with the CTIO 4-meter reflector (Butcher 1977). A progression of faint stars is selected to serve as potential standards beyond the limits of the photoelectric sequence. Since all 4-meter plates are automatically calibrated, we can obtain by integration with the PDS machine total intensities at each wavelength for the additional faint sequence stars and also for a number of the faint photoelectric standards. The standard sequence can thus be extended as desired to the limit of the plate.

I have only just returned from my two months' stay at Cerro Tololo Inter-American Observatory, so there has been no opportunity yet to measure my photographic plates obtained with the 4-meter reflector. This will be done in the coming months with the aid of measuring instruments available at Kitt Peak National Observatory and at Steward Observatory. However, with the photoelectric sequences next to the globules completely reduced, it has been possible to make some fairly reliable estimates of total visual absorptions, A_v, on the basis of rough star counts in Coalsack Globule 2, and in Barnard 68 and 72.

In the letter to *Nature* (Bok et al. 1977), we reported that the total visual absorptions, A_v, in the outer rings of Globule 2 are well-determined from a UK Schmidt infrared plate, hyper-sensitized and of 60-minutes exposure. For the ring with inner radius 1.′6 and outer radius 2.′5, the average absorption A_v is about 5 magnitudes. The absorption within the core region, radius 1.′6, could not be determined because of an absence of observable stars. The 4-meter near-infrared plate (see Figs. 1 and 2) shows approximately 20 very faint stars in the core region, diameter 1.′6. The infrared limit of the plate appears to be at least $I = 20$. The average estimated total infrared absorption in the core region is between $A_I = 7$ and $A_I = 8$ magnitudes. The corresponding value of A_v is about $A_v = 15$ magnitudes. It is of interest to tabulate the provisional values of A_v at various distances from the center of Globule 2. The provisional tabulation follows.

Distance from Center	A_v (Mag)
0′	20
1′	14
2′	5
3′	2.5
4′	1.0
5′	0.0

As viewed in projection against the sky, the value of A_v varies inversely as the square of the distance. Thus, the space density of the cosmic dust varies most likely about inversely as the cube of the distance from the center of Globule 2. This is not unlike the result obtained by Schmidt (1975), who finds that in Barnard 361 the dust density varies approximately inversely as the cube of the distance.

The results for Globule 2 confirm the mass estimates obtained by Bok et al. (1977): 25 solar masses seems like a realistic estimate for the total mass of the molecules and cosmic dust in Globule 2.

We note that the preliminary results reported here give *no* indication whatsoever for the presence of fragmentation in Globule 2. The smooth density gradient seems to show that Globule 2 is a unit object composed of mostly molecular hydrogen with dust as a tracer—an object that reminds one of the polytropic models of stars studied at the turn of the century by Lane (1870) and Emden (1907). Globule 2 is definitely not a conglomerate of five or more interacting separate units.

Barnard 68 (Figs. 3 and 4) is one of the finest globules observed to date. Among its remarkable properties are its kidney shape (two globules interacting with each other?), the unbelievable sharpness of its edges, especially the eastern edge, and the total absence of any stars seen through the globule. The minimum estimated value of A_v amounts to $A_v = 25$ magnitudes, but this may be an underestimate! Barnard 68 deserves careful further study.

Figure 3 shows that Barnard 72 is relatively transparent. On the IV N plate, the snake becomes rather difficult to trace in spots. For the two condensations in its southern belly we find values of A_v of the order of 5 magnitudes, which are somewhat greater, but not much greater, than the values obtained by Bok and McCarthy (1974)

While the photography of globules is in good shape from the blue to the infrared (at 8500 Å), there are as yet no data on their properties at 2μ and farther in the infrared. The techniques used by the Stroms et al. (Grasdalen et al. 1973; Vrba et al. 1975) have not been applied as yet to the study of globules. However, Hyland reports that work is in progress at Siding Spring Observatory on Globules 1, 2, and 3 and surroundings listed by Hawarden (Bok et al. 1977).

Globules have such low temperatures that they cannot be detected as emission objects at wavelengths between 2μ and 50μ. In an unpublished Master's Thesis, David McDavid (1975) concludes that they should be observable in the range 100μ to 500μ. He suggests that the 120-inch (3.05-m) infrared telescope (NASA) at Mauna Kea in Hawaii should be able to detect several globules as far-infrared emitters.

There is an interesting possibility for the study of

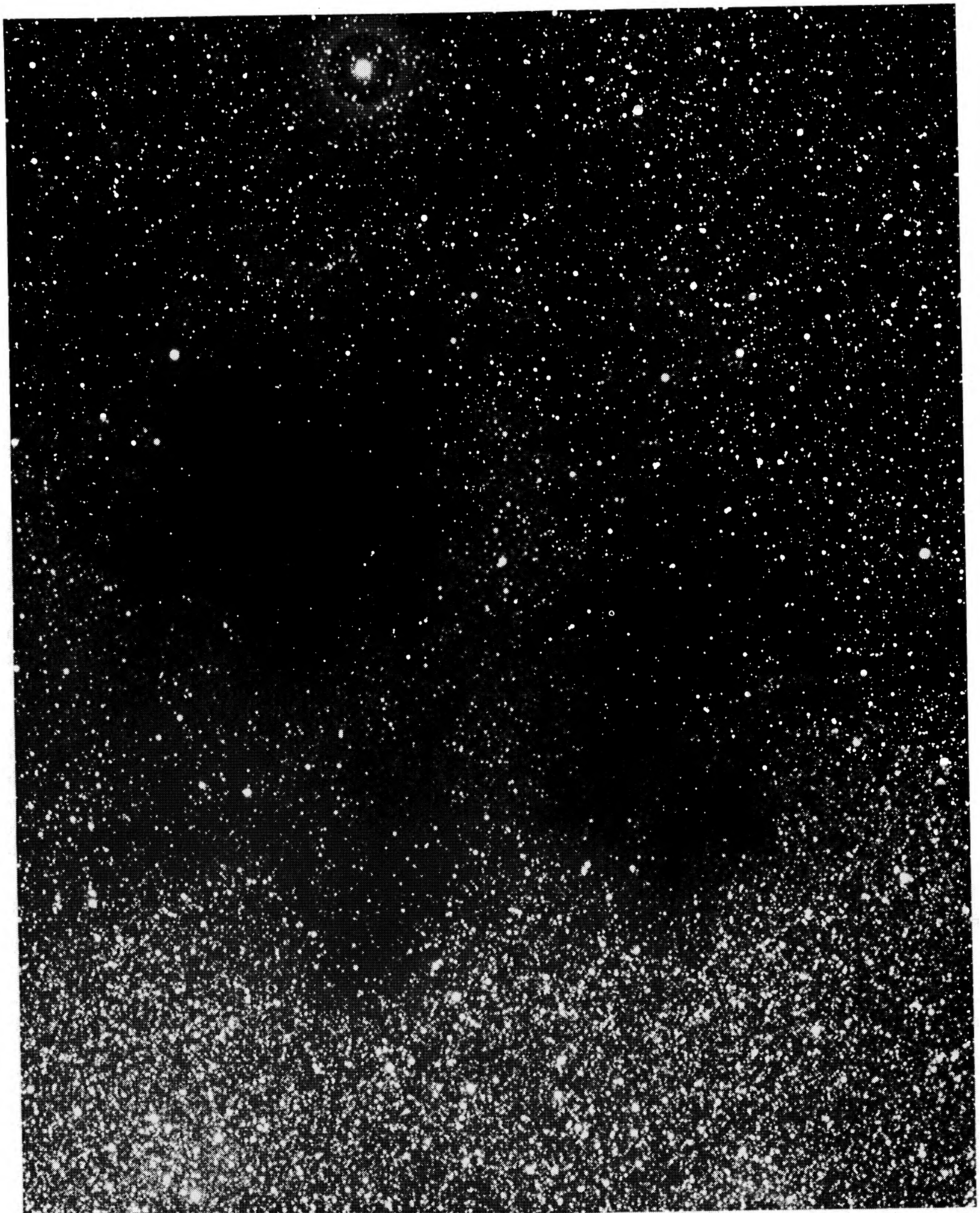

FIG. 1—Hawarden Coalsack Globules 1 (on the right) and 2 (on the left) are shown in this section of a photograph made with the 4-meter Cerro Tololo reflector, prime focus, on a hypersensitized (Luis Pinto) IV N emulsion, filter RC 695, exposure time 200 minutes. Globule 2 is the very dense one. Note that a few faint star images can be seen through the core of the globule, which has an estimated central dust absorption corresponding to $A_v = 20$ magnitudes. Globule 1 is obviously much more transparent than Globule 2. Its central value of A_v equals about 5 magnitudes. *Note:* The five enlargements used as a basis for Figures 1 to 4 were made by Richard Schiff, the Steward Observatory photographer. In all four figures north is up and east on the left. The sides of Figure 1 measure about 35 by 30 arc minutes.

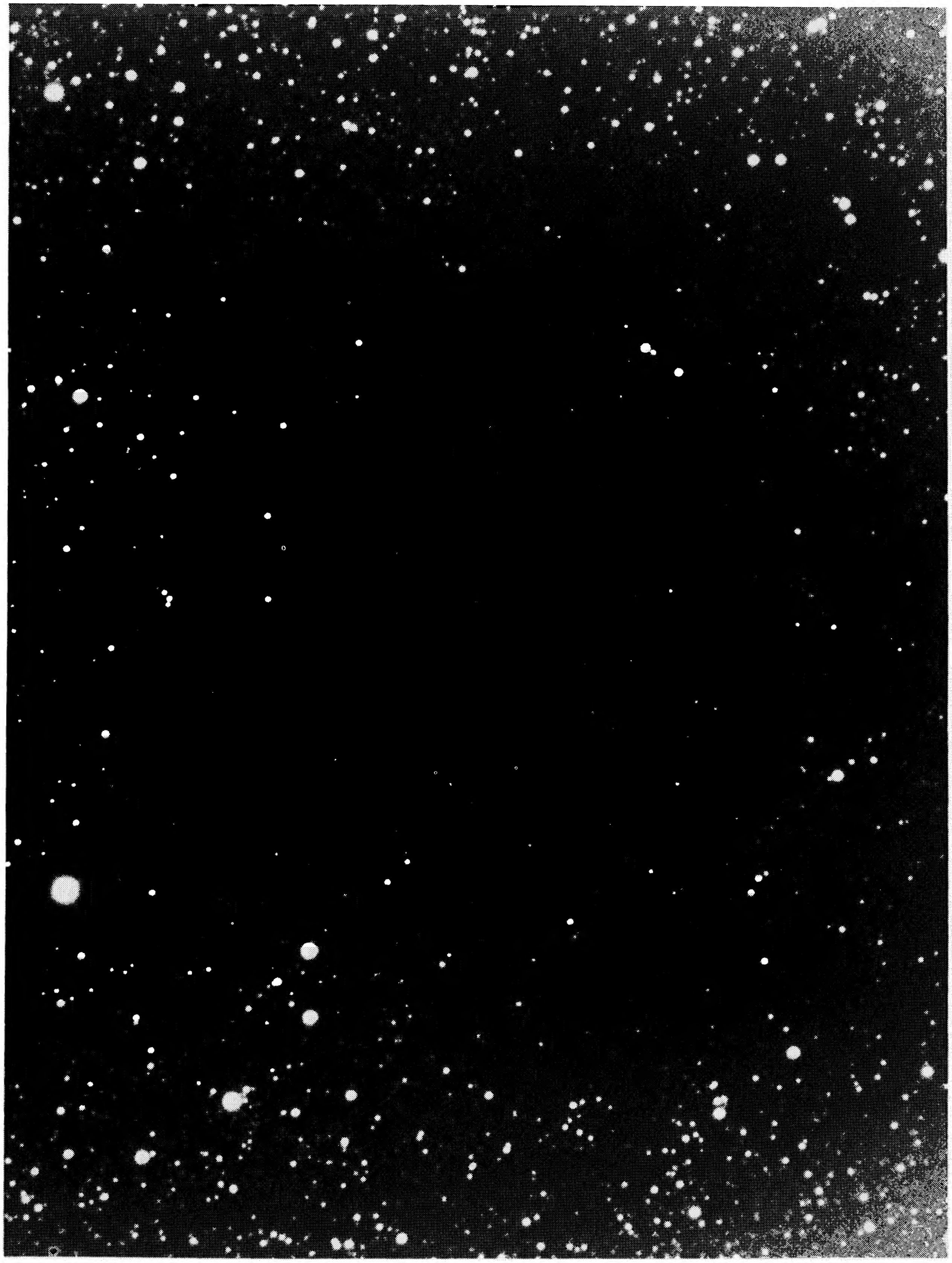

FIG. 2—The enlargement of a section of Figure 1 shows nicely some of the faint stars beyond the globule visible through its core.

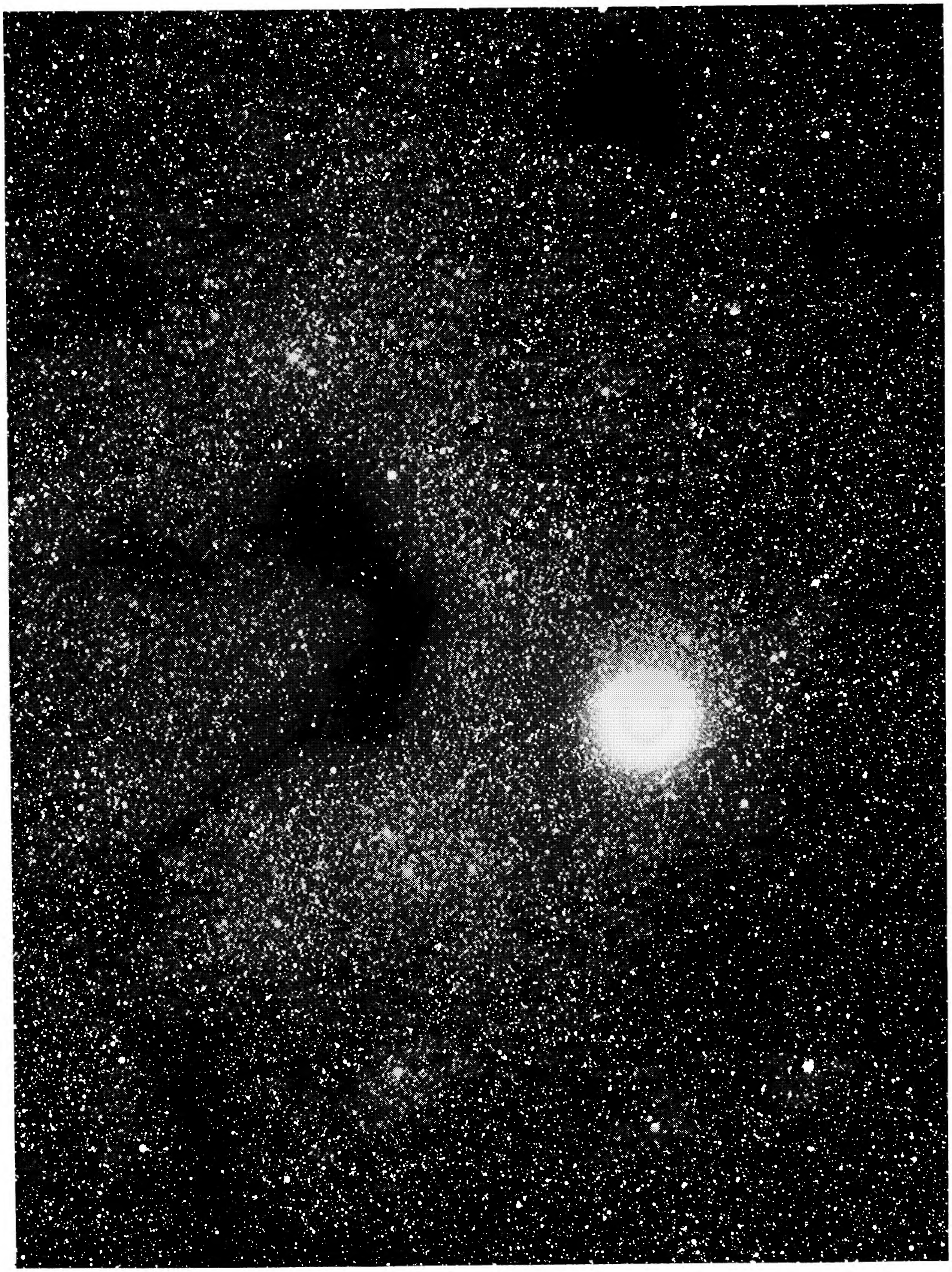

FIG. 3—Barnard Object 68 is the dark kidney-shaped globule on the right. Barnard 72 is the snake-like dark nebula with two globules in its "belly", above and to the right of the bright star 44b Ophiuchi. Exposure time (200 minutes), telescope (4-meter CTIO reflector, prime focus), emulsion and hypersensitization are identical with those for Figure 1. The sides of the photograph measure about 40 by 35 arc minutes. Note the relative transparency of the two globules in Barnard 72 (A_v = 5 magnitudes) and the complete lack of stars in the core of Barnard 68, North is up and east is to the left.

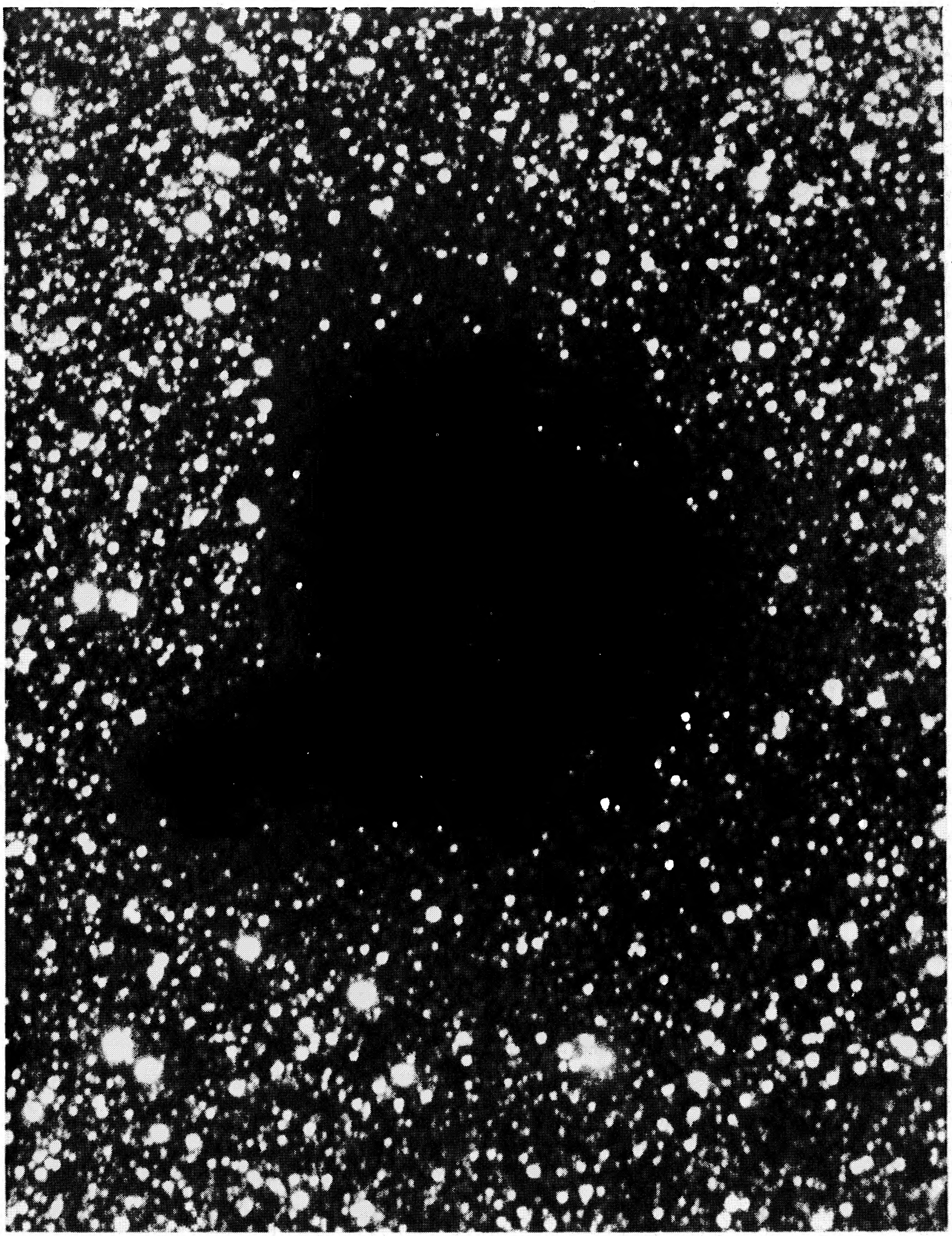

FIG. 4—The enlargement of a section of Figure 3 shows beautifully the sharpness of the edges of Barnard 68 and the total lack of stars in the core of the globule, suggesting $A_v > 25$ magnitudes.

globules in *V*, *R*, *I* and further into the infrared, say at 2μ, 5μ, 10μ, 50μ. . . Globule 2 of the Southern Coalsack seems to be ready-made for the test. Suppose one selects an area of one arc minute diameter centered on the core of the globule. There are obviously no foreground stars within that area and the light that a surface photometer would register in the area of one arc minute diameter centered on the globule would truly be sky background plus the transmitted light from the obscured stars beyond the globule. We should be able to measure the surface brightness within the 1′ diaphragm first for the globule and then for a comparison field (I recommend one 17 minutes south of the globule). The difference between the two readings, the first for the globule center, the other for the comparison field, would be the total absorption produced by the core of the globule. It thus seems like a simple matter to determine the total core absorption at various wavelengths. My personal guess is that at one micron the core absorption will not exceed 7 magnitudes, possibly being smaller. Smaller values will be presumably found at still longer wavelengths. The result of the measurements would be a value for the total core absorption at each wavelength for which the difference in surface brightness is a measurable quantity. Measurements at various infrared wavelengths should yield very useful information regarding the law of reddening at each wavelength.

Large Globules; Radio Evidence

We noted earlier in the present address that radio astronomy has contributed terrifically to our knowledge of dark neblae, especially to our understanding of the physics of large globules, some apparently on the verge of collapse. I can be brief in my summary of radio properties of globules since only a few weeks ago Robert L. Dickman reviewed the subject generally for *Scientific American* (1977).

In the middle 1950s, a few years after the discovery of the 21-cm line of neutral atomic hydrogen by Ewen and Purcell (1951), my Harvard graduate students and I became interested in the H I content of dark nebulae. The subject was studied in a comprehensive manner by A. Edward Lilley (1955), who found that, while there was observed some increase in the H I density in and near the Taurus dark nebulae complex, the increase was not anywhere nearly proportional to the increase in dust density. We argued that most of the hydrogen was probably in molecular form, but there was then no way of proving this. These conclusions were confirmed later. In a few cases, H I self-absorption has recently been associated with dense dark objects. H I self-absorption is present in the Southern Coalsack associated with the densest globules (Kerr, Hawarden, and Bowers 1976). Negative results for several Barnard objects were reported from Argentina (Arnal and Gergely 1977).

Formaldehyde (H_2CO), OH, NH_3, CS, CH, and HCN have all been reported in and near some of the larger globules (Dickman 1975). But the carbon monoxide molecule, CO, has proved to be the best probe for the study of radio properties of globules. The principal studies of CO in globules are reported in the Doctoral Dissertation of Dickman (1975), in a paper by Tucker et al. (1976), and in papers by Martin and Barrett (1976). A comprehensive review of "Microwave Spectral Lines in Galactic Dust Globules" by Barrett and associates will soon appear in the *Astropysical Journal Supplements*. Important contributions to the field have been made by A. S. Milman (1977) at the University of Maryland and by M. Jura, G. R. Knapp, M. Morris and P. C. Wannier at the Owens Valley Radio Observatory.

It is most fortunate for the study of the physics of globules that side by side at wavelength 2.6 millimeters emission lines are observed for two isotopes, ^{12}CO and ^{13}CO. In the majority of globules, the ^{13}CO emission line has about one-third the strength of the ^{12}CO emission line. Since the relative abundance of ^{12}C is somewhere in the range 50 to 80 when compared to ^{13}C, the observations suggest that the ^{12}CO component is saturated and that the ^{13}CO component is not. This happy state of affairs leads to two conclusions:

(1) The strength of the ^{12}CO component is a direct measure of the temperature in the globule. Derived temperatures are quite low, generally in the range 7 K to 15 K.

(2) The strength of the ^{13}CO emission is a direct measure of the number of ^{13}CO molecules in a column with a base of 1 cm^2. We call this number N_{13}. It is generally observed in globules to be in the range $10^{16} < N_{13} < 3 \times 10^{16}$.

Knowing N_{13}, we can make a rough estimate of the number N_{H_2}, the number of hydrogen molecules for a column with a base of 1 cm^2. Dickman (1975) uses the formula

$$N_{H_2}(\text{cm}^{-2}) = 4.6 \times 10^5 \times N_{13} \quad .$$

Since the mass of the H_2 molecule is known, the total column mass in grams per cm^2 can be established. The Dickman (1975) formula is

$$N_{\text{mass}}\ (\text{g} \times \text{cm}^{-2}) = 2.0 \times 10^{-18} \times N_{13} \quad .$$

Since the molecular hydrogen along the line of sight is mostly contained in the globule, the total mass of the globule can be obtained once its area in cm^2 is known. To take an example: Suppose we have a globule at a known distance for which the radio data yield an average value, $N_{13} = 10^{16}$. Let the radius of the globule be 0.5 parsecs = 1.6×10^{18} cm. If we multiply the area of the globule in cm^2 (8×10^{36} cm^2) by the value of N_{mass} from Dickman's formula (2×10^{-2}) we obtain the estimated mass of the globule 1.6×10^{35} grams, which is equivalent to 80 solar masses. Radii, temperatures, and masses for seven globules studied by Dickman (1975) have been reported in his dissertation. His results are as follows.

Object	Radius (pc)	T_K	Mass ($\mathfrak{M}_\odot$)
Barnard 5	1.2	17°	≥740
Barnard 92	0.3	9	≥ 24
Barnard 133	0.6	10	≥ 59
Barnard 134	0.5	9	19
Barnard 335	0.3	9	≥ 22
Barnard 362	0.4	11	33
Lynds 1262	0.5	11	≥ 63

Dickman made careful star counts for each of the seven globules and he obtained at radio positions for which he had a value of N_{13} an average value of the derived visual absorption, A_v. Figure V-2 of the Dickman dissertation shows that the ratio N_{13} over A_v is remarkably constant for the range $1 < A_v < 10$. The corresponding formula is

$$A_v \text{ (mag)} = 3.7 \times 10^{-16} \times N_{13} \quad .$$

It is gratifying indeed that the masses of globules based on derived values of A_v agree nicely with masses for these same globules derived from ^{13}CO observations.

The widths of the CO features are equivalent in most globules to radial velocity dispersions in the range 0.8 to 1.2 km sec^{-1}. Ho et al. (1977) and Rydbeck et al. (1977) have, however, found smaller widths from ammonia observations, suggesting that the turbulence is often quite small. The velocity spreads of the order of 1 km sec^{-1}, quoted above, are probably indicative of collapse of the globules in question. This can be settled in the near future when high-angular resolution CO surveys will become available. In the meantime, the collapse hypothesis can be accepted as most likely the correct one. It seems improbable that turbulence could make much headway in an object the size of the average globule. In the presence of turbulence considerable heating would take place. The low observed temperatures of the globules $7° < T_K < 15°$ speak against any heating effects being present. On the other hand, the total negative-potential energy of the globule, which is readily calculated from its mass and radius, is one to two orders of magnitude greater than the total positive-kinetic energy corresponding to the quoted internal temperatures. Magnetic fields apparently play no role in the physics and evolution of globules. Dickman's article (1977) and the article by Tucker et al. (1976) strongly support collapse of the globule in times of the order of less than one million years as the dominant phenomenon.

Martin and Barrett (1976) were the first to have found indications of rotation in globules. The rotational velocities are small, of the order of a few tenths km sec^{-1}. However, a velocity of rotation at the rim of a globule amounting to 0.2 to 0.3 km sec^{-1} can lead to complications in a rapidly collapsing globule. The presence of any rotation in the original globule probably suggests that, as a result of the collapse, the globule will form either a binary or multiple-star system, *or* that a solar system is formed in the bargain.

Large Globules; Their Evolutionary Status

It is not difficult to estimate that there must be about 25,000 globules near the central plane of our Galaxy. How did these originate? To be perfectly frank; I do not know how the isolated globules were formed. All I can say is that I am glad that the Good Lord put them there and that Edward Emerson Barnard looked systematically for them and prepared his very useful lists of "Barnard Objects" (1919, 1927)!

I think we can be rather definite about their likely future evolution. The globules that have been studied with greatest care (Schmidt 1975; Bok et al. 1977) seem to show a strong negative density gradient for the dust component. The dust density drops roughly inversely proportional to the cube of the distance from the center of the globule. Radio observations suggest that the CO molecules fill about the same volume as the dust, but that some of the rarer molecules concentrate mostly near the globule's center. Our longest-exposure near-infrared photographs give no indication for the presence of fragmentation. No radio evidence for or against fragmentation is yet available. To obtain such evidence, we require radio-millimeter observations with an angular resolution of 1′ or less.

Since the dust and the CO molecules are only tracers for the main component, molecular hydrogen, H_2, we see one of our present-day globules as a large cloud of H_2, with an average internal temperature of the order of 10 K (possibly a bit hotter in the central core). They are objects with roughly spherical symmetry. They resemble in many ways the polytropic star-models of Lane (1870) and Emden (1907).

The evidence for a central core seems strong enough to postulate that most likely the core will collapse faster than the outer parts. In the absence of marked rotation, the process of collapse will probably lead to the formation of a young star at the center, surrounded by a cloud of cosmic dust and various molecules, an object that would be detectable in the infrared as a cool star with a surrounding shell of uncondensed interstellar matter. As the star evolves and becomes hotter, it would tend to blow away its surrounding shell.

In the presence of some initial rotation, the collapse will hopefully be associated with some degree of fragmentation. There might appear either a multiple star, a binary star, or a modest star cluster; or a solar system might be formed to accompany a single star. The latter process seems rather attractive, for the parent-globule does seem to have the basic organic molecules that we have come to associate with the beginnings of life on earth and elsewhere in the universe.

There is probably a variety of processes of star birth in our Galaxy. Several of these were described in the first section of this address. But it does appear that large globules can no longer be ignored as potential proto-protostars.

Star Formation in the Star Clouds of Magellan

In the thin layer of interstellar material near the central plane of our Galaxy, we associate star formation principally with clouds or complexes of moleclar gas (notably H_2, CO, H_2CO, and NH_3) and with cosmic dust. No strong H I (21-cm) concentrations are evident in the radiation received from the densest dust and CO clouds. We have good evidence that star formation is currently taking place, and has occurred within the past few million years, in the Ophiuchus and Taurus dark nebulae, in the Orion complex, and at the edges of large clouds of molecular gas and associated cosmic dust near H II regions (Elmegreen and Lada process). We observe incipient star formation in large globules and in Barnard Objects, which, as we have tried to show, are in all probability isolated molecular-dust clouds on the verge of collapse into proto-protostars or modest star clusters.

The situation seems to be fundamentally different in the Magellanic Clouds. Twelve years ago, I wrote a review paper on the Magellanic Clouds (Bok 1966) and I was surprised (and somewhat saddened!) to note that it still represents a reasonably up-to-date summary.

In my 1966 review paper, I reproduced two photographs by Westerlund, one in near infrared light (IN emulsion), the other in the near ultraviolet (IIa-O emulsion and UG2 filter), which show dramatically the extent of recent star formation in the Large Magellanic Cloud. The near infrared photograph is dominated by the axis of the Cloud, but some of the blue associations register weakly. On the ultraviolet photograph the whole Cloud lights up like a Christmas tree! The Tarantula nebula (30 Doradus) shines forth in all is majesty and, associated with it, we have 100 or so sparkling OB supergiants, some of them with absolute magnitudes as high as $M = -9$. Clusterings of OB supergiants are shown in many places. Some of these are seen in relatively empty sections of the Cloud, with no other special star-formation activity appearing within half a degree (500 parsecs) of the OB association and its emission nebulosity; Harlow Shapley baptized some of these: CONSTELLATIONS. Small amounts of interstellar dust are seen projected against the emission nebulosities, but the unbelievably blue star colors, $(U-B) = -1.00$, show that at present there is relatively little dust in these objects. The Tarantula nebula and the 30 Doradus complex show the greatest dust concentrations, but nowhere do we find complexes with associated cosmic dust similar to our Opiuchus and Taurus Clouds, nor do we find complexes similar to our dusty Orion complex.

The Large Magellanic Cloud is a system rich in young stars, notably OB stars with absolute magnitudes in the range $-3 > M_v > -9$. Cosmic dust is either absent or plays apparently a minor role in several of the most conspicuous isolated young ($\sim 10^7$ years) OB associations. However, 21-cm radio observations indicate that neutral atomic hydrogen is concentrated in vast amounts to some of these centers of young OB groupings.

Constellaton I of Shapley is a case in point (see Fig. 5). The OB stars are concentrated largely in the inner core of Constellation I, where the known OB stars alone (more than 40) have an estimated total mass of the order of 2000 solar masses. The diameter of the core region is 50 parsecs, about 3′ at the distance of the Cloud. The outer shell has a diameter of about 100 parsecs, 6′. Radial-velocity measurements of individual stars show dispersions that are of the order of 10 km sec^{-1}, which means that each star can have traveled no more than 100 parsecs from its place of birth. In other words, the whole show from star birth to the present must have taken place within 10′ of the present center of Constellation I. The *maximum* reddening observed for these stars is of the order of $0^m.7$ in visual light—hence cosmic dust can hardly have played a major role in star formation for Constellation I. Optical and radio observations agree in assigning a total mass of 60,000 solar masses to the associated ionized hydrogen, all of it contained within a diameter of 300 parsecs. Observations at 21 cm show that the total amount of neutral atomic hydrogen associated with Constellation I amounts to 5 *million* solar masses within a diameter of 600 parsecs. Because of the deplorable absence of millimeter radio telescopes in southern latitudes, no estimates for CO content are available, but I would expect at most a mild concentration of CO and presumably small amounts of molecular hydrogen. In other words, associated with Constellation I there is enough neutral atomic hydrogen present for the formation of 200 or more groupings of stars like those contained in Constellation I! We must obviously think in

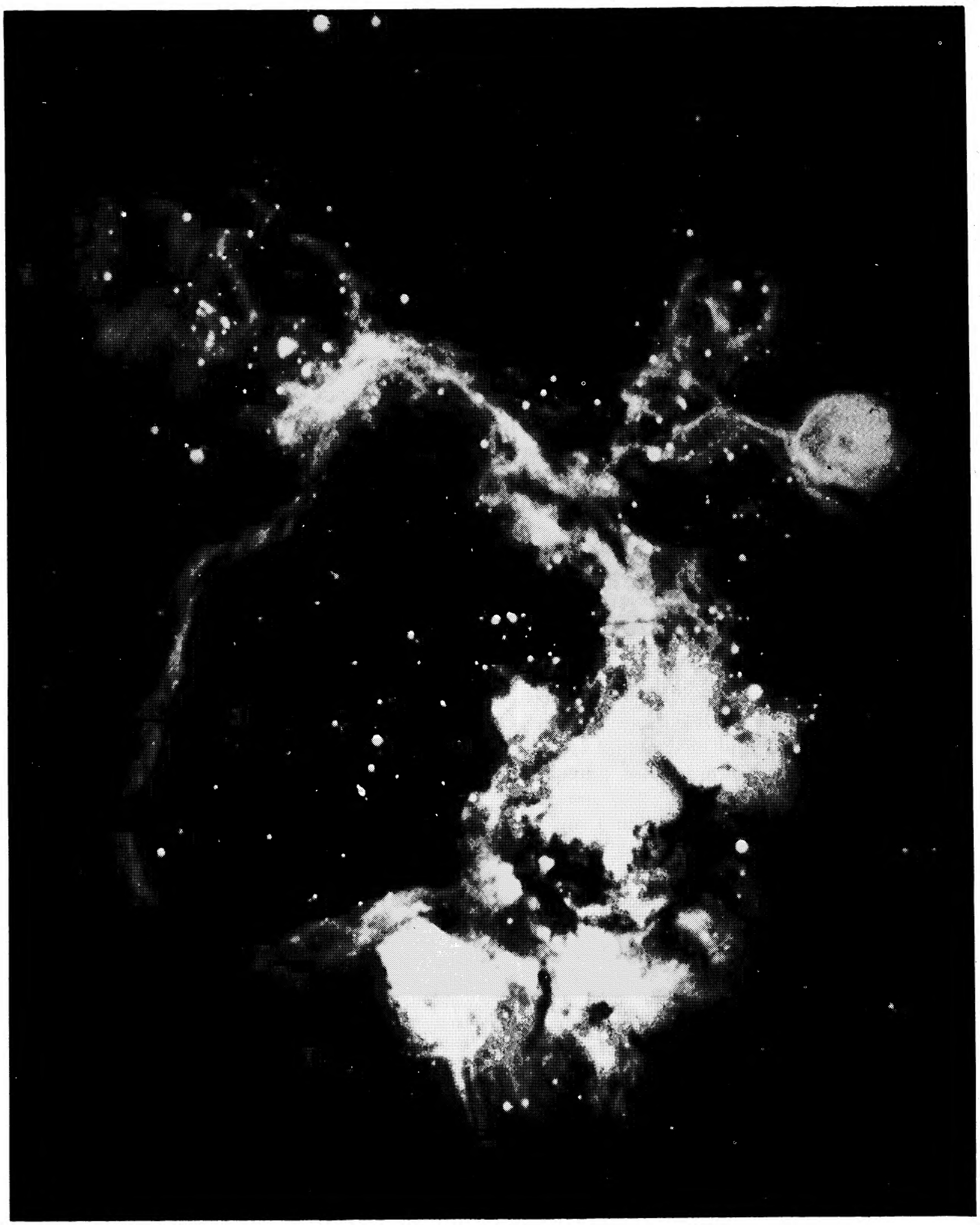

FIG. 5—"Shapley's Constellation I (N44). The CTIO 4-m telescope was used at its $F/2.7$ prime focus for a 45-min exposure on 098-02 emulsion with a 100 Angstrom filter centered on $H\alpha$. This plate, taken by M. G. Smith during the testing phases of the 4-m telescope, has been used extensively by B. Lasker in his study of the bubble-like nature of the nebula. Preliminary analysis of Fabry-Perot data taken in 1976 is consistent with an expansion velocity of about 30 km sec^{-1}. Such an expansion could be driven either by stellar winds from the star cluster inside the bubble or by a supernova explosion. North is up and east is to the left.

terms of processes of star formation here that differ radically from those suggested for our own Galaxy.

Constellation I represents by no means an isolated example of a star-formation process in which dust and molecules play a minor role and in which neutral atomic hydrogen apparently plays a major role. The dozens of young clusters with vertical main sequences of OB stars studied by Westerlund (1961) call for formation processes different from those at work in our own Galaxy. The recent admirable work on blue globular clusters by Freeman also indicates the need for us to think in terms of formation processes that do not enter into our thinking when we limit ourselves to our Milky Way system. The blue globulars present many perplexing evolutionary and dynamical problems. One of these is why they appear to be dynamically relaxed when still quite young on the cosmic scale, probably not much older than 5×10^7 years. It may well be that in their next stage of evolutionary development they will become inconspicuous clusters, difficult to detect and study. How did they originate in the first place?

The situation in the Small Magellanic Cloud differs somewhat from that in the Large Cloud. Here many not-quite-so-spectacular young OB stars are found scattered about rather than in clusters or associations. They occur notably in the central body and in the Shapley Wing of the Small Cloud.

We note that McGee and Milton (1964) have suggested that 9% of the total mass of the Large Cloud and that *fully* 25% of the total mass of the Small Cloud is neutral atomic hydrogen. When a great astronomer said a quarter of a century ago that "it is now clear that the Large Cloud is pure Population I and the Small Cloud pure Population II," he was apparently wrong! It is better to say that both Clouds seem to be cases of retarded evolutionary development, star systems which only just recently have begun to practice star formation on a big scale. Observers must obviously get busy to provide the basic information that theorists will require. This includes much stellar and nebular photometry in both Clouds, as well as photography and especially detailed spectroscopic studies leading to precise knowledge of physical conditions in and near young associations. Above all we shall need detailed studies of atomic abundances. Finally, it is clear that no real progress is possible until suitable radio telescopes for the millimeter range are available to work in close collaboration with the large southern optical telescopes.

It is worth noting in conclusion that Westerlund, Mathewson and others (see Westerlund and Mathewson 1966; Mathewson and Clarke 1973) have found evidence for many past powerful supernova explosions in both Magellanic Clouds. Have the shockwaves produced by these explosions assisted in bringing about concentrations of gas and dust from which at least a fraction of the present OB supergiants have been formed? Have these supernova explosions enriched the heavy-element content of the gas now available for star formation in the Clouds?

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