I am sure that everyone would agree that the modern astrophysical study of diffuse nebulae begins with the pioneering 1939 paper of Strömgren (1939). Many of the ideas of the theory of planetary nebulae due to Menzel, Goldberg, Aller, and others could be taken over and applied to observationally well-known diffuse nebulae. They are different from planetaries, however, in that many of them are optically thick to the ultraviolet ionizing radiation from the star so that their outer boundaries occur where there is no more ionizing radiation ("radiation bounded"), rather than where there is no more gas ("gas bounded" or "density bounded") as in most planetaries. The optical depth, \( \tau_\nu \), at a particular frequency \( \nu \) is a dimensionless quantity, defined by the equation

\[
\tau_\nu = \int_0^\nu N \sigma_\nu \, ds,
\]

where \( N \) is the number per unit volume of absorbing atoms, mostly hydrogen in a typical astronomical situation, and \( \sigma_\nu \) is the absorption cross-section per atom at the frequency in question. Incident radiation at frequency \( \nu \) is then reduced by the factor \( e^{-\tau_\nu} \) in traversing the distance \( l \), so for small optical depth the absorption is negligible, and the ionizing radiation (with \( \nu > \nu_0 \)) can penetrate almost completely unattenuated, while on the other hand for large optical depth the absorption is nearly complete.

* Based on an invited review paper, delivered at the 124th meeting of the American Astronomical Society, Yerkes Observatory, June 13, 1967.

523
The solution of the coupled radiative transfer and ionization equations shows that through most of the nebula the abundant hydrogen is nearly completely ionized, so that the number of neutral atoms \( N_H \) is small, and therefore the optical depth \( \tau_\nu \) remains small. However, near the outer boundary, as the ionization begins to drop the number of neutral atoms increases; so the ultraviolet opacity rises steeply, and the optical depth increases very rapidly. Thus there is a relatively sharp boundary between the central ionized region ("H\,\pi region" or "Strömgren sphere") and the outer neutral region ("H\,\iota region"). The size of the ionized region is fixed by the equilibrium between photoionization and radiative recombination and is given by the equation

\[
Q = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} \, d\nu = N_\pi N_p \alpha(T_\pi) V \equiv N_\iota^2 \sigma_{\text{recap}} \bar{v} V,
\]

where \( Q \) = number of ionizing photons emitted per unit time by the central star or stars, \( V \) = volume of ionized region = \( 4\pi s_0^3/3 \) for a spherical region with radius \( s_0 \), \( N \) = number density of H atoms in H\,\iota region = number density of H ions in H\,\pi region = number density of electrons in H\,\iota region, and \( \alpha(T_\pi) \) = recombination coefficient = \( \sigma_{\text{recap}} \bar{v} \). Plate I shows an especially fine example, the nearly perfectly round Strömgren sphere S 170, surrounding the early-type star BD +63°2093 (Sharpless 1959).

The threshold for ionization, \( h\nu_0 = 13.6 \text{ eV} \), is so large that only very hot stars are effective sources of ionizing radiation, and the size of the H\,\pi region decreases very rapidly for stars of later spectral types. The theory also shows that stars immersed in low-density interstellar matter should be expected to have large, low-surface-brightness H\,\pi regions surrounding them, and in fact this expectation is confirmed by wide-field photographs taken in the wavelength intervals in which nebular emission lines are strong, for instance the red National Geographic Society-Palomar Observatory Sky Survey plates. Plate II shows the complex emission region surrounding the O stars BD +66°1661 and BD +66°1675, including the dense bright region catalogued as NGC 7822, as well as the lower-density fainter part S 171 (Sharpless 1959). In many cases the star is located outside a gas cloud, which is then ionized on the side facing the star (Strömgren 1948). An example is shown in Plate III, a part of the nebula S 29, about one degree east of M 8.
PLATE I

S 170, a small round H II region. Diameter approximately 15'. Plate taken with the 48-inch Schmidt telescope and a deep-red filter, to cut down sky and stars, and to emphasize Hα and [N II] λλ 6548, 6583.

PLATE II

NGC 7822, S 171, a large complex H II region. Diameter approximately 3°. Plate taken with the 48-inch Schmidt telescope and deep-red filter.
S 29, \( \text{H} \, \pi \) region on one side of a dense cloud that extends off to the southeast (lower left). The hot star that supplies the ionizing radiation is to the northwest (upper right). Length of bright ionized region approximately 9'. Plate taken with the 200-inch Hale telescope and deep-red filter.

The ionized and heated gas in an \( \text{H} \, \pi \) region emits an emission-line spectrum, containing recombination lines, particularly of the most abundant elements, hydrogen and helium, and also collisionally excited lines of the ions that have energy levels within a few volts of the ground level, such as [\( \text{O} \, \pi \)], [\( \text{N} \, \pi \)], [\( \text{O} \, \text{III} \)], and [\( \text{Ne} \, \text{III} \)]. Higher ionization occurs close to the star, where the ionizing radiation is strongest, as shown for example in the direct photographs of M 8 in Plate IV, where the relatively high-ionization [\( \text{O} \, \text{III} \)] emission is seen to be much more centrally concentrated than the \( \text{H} \, \pi \) emission, which occurs throughout the entire ionized region.

The \( \text{H} \, \pi \) regions are strongly concentrated to the spiral arms, and
M 8, H II region ionized by several O stars in the densest (most heavily exposed) region near the center. Plates taken with the 48-inch Schmidt telescope, upper with red filter shows Hα and [N II], lower with sharp green filter shows mostly [O III] λλ 4959, 5007. Note how the [O III] is much more concentrated to the source of ionizing radiation than the Hα and [N II] regions.
therefore, as Baade (1951) and Morgan (Morgan, Sharpless, and Osterbrock 1952) particularly emphasized, make good tracers of these structures in our own and other galaxies. A good example is shown in Plate V, of the galaxy NGC 628, taken by Dr. R. F. Garrison with the Yerkes 40-inch telescope using an f/2 reducing camera. In our galaxy the spiral arms in the immediate neighborhood of the sun (say out to 2000 parsecs) have probably been best mapped by the detailed study of distances of individual Hπ regions by the spectroscopic-parallax method (Morgan, Code, and Whitford 1955), though this subject is still far from completely solved. The Hπ regions, being fairly bright and having much of their light concentrated into a relatively few sharp spectral lines, provide the best opportunity we have to study galactic dynamics in other galaxies observationally. In the earlier work by Babcock (1939), Mayall (1951), and Humason, Mayall, and Sandage (1956), the emission lines Hα, Hβ, and [O III] λλ 4959, 5007 were measured for radial velocities, while in the later work by Burbidge, Burbidge, and Pendergast (1959) and Brandt (1960) the longer-wavelength lines Hα and [N II] λλ 6548, 6583 have been used. The galactic dynamics of the Hπ regions in our own galaxy can also be studied observationally in this same way (Courtès 1960; Miller 1967).

Observations within our galaxy are severely limited by the absorption caused by interstellar dust near the galactic plane, but it might in time become possible to make similar radial velocity measurements of the infrared lines of hydrogen such as Paschen α (n=4 to n=3) at 1.876 microns, or Brackett α (n=5 to n=4) at 4.052 microns. These observations of course would have to be made from above the earth's atmosphere, which is completely opaque through most of the infrared spectral region. Within the past few years radio astronomers have begun to observe the very-high-level hydrogen emission lines such as 109α (n=110 to n=109) at 6 cm wavelength and 156α (n=157 to n=156) at 17 cm wavelength. These observations can be made from the ground, are completely unaffected by interstellar absorption, and provide a great opportunity for measuring radial velocities over the entire disk of our galaxy. A maximum amount of information will be derived from these observations if they are combined with distances measured independently, presumably by the method of spectroscopic parallaxes. It would therefore
NGC 628, a spiral galaxy. **Upper**, with deep-red filter, emphasizes H II regions; **lower**, with yellow-orange filter, does not show emission nebulae. Note how the H II regions fall along the spiral arms in the upper plate. Plates taken with the Yerkes 40-inch refractor and f/2 reducing camera.
be quite worth while to begin a program aimed at the discovery of the exciting stars and clusters associated with the H\textsc{ii} regions for which radial velocities have been measured in the radio-frequency region. The spectral classification will probably have to be done in the near infrared, because of the high interstellar obscuration in the ordinary photographic spectral region.

H\textsc{ii} regions can also be observed in the radio-frequency continuum; in fact the observations are somewhat simplified by the facts that the intensity is relatively high in the continuum and that a fairly large bandwidth can be used. The main process responsible for the continuous spectrum is free-free emission, which results in a flat spectrum that enables H\textsc{ii} regions to be distinguished from objects that radiate by the synchrotron process ("nonthermal sources"). The surface brightness in the radio-frequency region depends on the integral of the emission coefficient along the line of sight through the nebula, that is, on the so-called emission measure

$$E.M. = \int_{0}^{n} N_{e} N_{p} \, ds \approx N^{2} \bar{l},$$

where \(\bar{l}\) is a mean dimension along the line of sight. The surface brightness in an optical line, say H\textsc{a} or H\textsc{b}, depends on this same quantity. A radio picture of a nebula usually consists of a line drawing of isophotes at a particular frequency; these radio observations have poorer angular resolution than the optical observations, but are unaffected by interstellar absorption. Comparison of optical and radio pictures of the same nebula shows that in some nebulae the form is chiefly due to the distribution of emitting gas (an example is M 8 in Plate VI), while in other nebulae dense and intrinsically very bright regions are heavily obscured, so that the form of the nebula is largely fixed by the overlying interstellar absorption (an example is M 17 in Plate VII).

Since the size of a radiation-bounded H\textsc{ii} region is fixed by the equilibrium between photoionization and recombination, it is possible to determine observationally the total number of photons absorbed in ionization processes (Zanstra 1927), by measuring the total number of photons emitted in all recombination processes, or more simply, by measuring the number of photons of a specific type emitted in the recombination process, for instance, the number emit-
M 8, H II region. Plate taken with the 48-inch Schmidt telescope and red filter. Superimposed radio-frequency isophotes measured at $\lambda = 6$ cm by Dr. P. Mezger and Dr. B. Högland with the 140-foot NRAO radio telescope. The crosses were made for aligning radio and optical images.

ted in H$\alpha$, which is about 0.43 of the total number of recombinations (Seaton 1960). Equivalently, the number of photons emitted in free-free processes gives the total number of recombinations, so measurement either in the optical or radio-frequency regions may be used to determine the ultraviolet ($v>v_0$) fluxes of hot stars. Such measurements have been made, particularly in the radio-frequency region (because of the freedom from interstellar absorption effects), and the results are that the measured fluxes are in fair agreement with those predicted for black bodies at the effective temperatures of the stars (Pottasch 1965).

One of the most interesting facets of the study of H II regions is the discussion of the physical processes going on within them. In particular, the temperature at a point in a nebula is physically determined by the balance between the energy input due to photoionization, which creates free electrons with initial kinetic energy

$$\frac{1}{2}mv^2 = h(v-v_0),$$
M 17, H II region. Plate taken with the 48-inch Schmidt telescope and red filter. Superimposed radio-frequency isophotes measured at $\lambda = 3.4$ mm by Dr. E. E. Epstein and Mr. J. P. Oliver with the 15-foot Aerospace Corp. radio telescope. The circle represents the half-power beamwidth of the radio observations, approximately 2.8 in diameter.

and the cooling due to radiation, mostly of collisionally excited lines (Spitzer 1948). The lines include not only the well-known forbidden lines in the observable spectral regions, but also additional "fine-structure" lines in the infrared, such as [Ne II] 12.8$\mu$, [Si II] 34.8$\mu$, and [C II] 156$\mu$, as well as other lines in the ultraviolet, some permitted, such as Mg II $\lambda\lambda$ 2796, 2803, C III $\lambda$ 1909, and Si III $\lambda$ 1892. Calculations going back to the early work of Spitzer and Savedoff (1950) predict temperatures of the order of 5000° to 8000° in typical diffuse nebulae, though results are somewhat uncertain because of lack of knowledge of the exact values of the cross-sections for collisional excitation, and of the detailed form of the spectrum of the central star in the far ultraviolet.

In the optical region the temperature can best be measured observationally by comparing two different spectral lines of the same
ion that have different excitation potentials. Measurements of this kind have been made of the [O III] lines $\lambda\lambda$ 5007, 4959, and 4363, but since $\lambda$ 4363 is quite faint these observations are difficult in all but the brightest nebulae.

In the central part of NGC 1976, the Orion Nebula, the temperature found in this way is approximately $T_e = 9000^\circ$ (Aller and Lil-ler 1959). The density in the region measured is known to be high enough so that some of the lines are collisionally de-excited and thus do not contribute to the cooling. The temperature should therefore be expected to be lower in the outer parts of the nebula where the density is lower and collisional de-excitation is less important (Osterbrock 1965). Two somewhat lower-density H II regions, M 8 and M 17, have been measured by O'Dell (1966), and the results are $T_e = 8200^\circ$ and $T_e = 7500^\circ$ respectively. Further observational work on this problem by this method should be carried out using not only [O III] but also [N II], which has a similar electron configuration but somewhat smaller threshold energies, so that the lines are not weakened so much at low temperature. Much-improved cross-sections, which enter the calculated value of the temperature, will very soon be available from detailed calculations of Seaton, Czyzak, and others.

In fainter nebulae it is impossible to measure the weak [O III] $\lambda$ 4363 and [N II] $\lambda$ 5755 lines, and the only optical method for determining the temperature is measurement of two line ratios such as

$$\frac{I(\text{O}^{\text{III}} \, \lambda 5007)}{I(\text{H}\beta)} = \frac{N(O^{++})}{N(H^+)} f_2(T_e),$$
$$\frac{I(\text{O}^{\text{III}} \, \lambda 5727)}{I(\text{H}\beta)} = \frac{N(O^+)}{N(H^+)} f_1(T_e),$$

In this case the results depend on the degree of ionization, and on the abundance ratio of O to H; however, it is a fairly safe assumption that all the oxygen is either singly or doubly ionized, and so use of the two line ratios makes it possible to determine both the degrees of ionization and the temperature (Pronik 1960). The results do depend on the abundance ratio, but not in a very sensitive way. Some results by Gebel from this method indicate temperatures of the order of 9000° for several still lower-density H II regions.

In the radio-frequency region, the ratio of intensities of the free-
free continuum to the high-level lines can be measured to find the
temperature (Mezger and Höglund 1967). However the derived
value of the temperature depends fairly critically on the populations
in the highly excited levels, and as Goldberg (1966) has shown,
even rather small deviations from thermodynamic equilibrium can
lead to rather large uncertainties in the temperature. Considerable
observational and theoretical work is going on in this subject at the
present time.

Another radio method for measuring the temperature of a diffuse
nebula is by low-frequency continuum measurements. The opacity
increases with decreasing frequency (approximately as \(v^{-2}\)), so that
at sufficiently low frequency a nebula is optically thick, and the in-
tensity it radiates is

\[
I_\nu = B_\nu(T_\epsilon) (1 - e^{-\tau_\nu}) \approx B_\nu(T_\epsilon) \approx \frac{2\nu^2 kT_\epsilon}{c^2}.
\]

Thus a measurement of the intensity gives the temperature directly.
By this method Menon (1961) has found that the temperature in the
Orion Nebula drops from \(T_\epsilon \approx 10,000^\circ\) in the central, dense regions
(to which the optical determination quoted previously applies), to
about 7000° in the outer lower-density regions, and Mills, Little, and
Sheridan (1956) have measured temperatures of the order of 6000°
to 7000° in several \(\text{H}_\text{II}\) regions. The difficulties in this method of
temperature measurement are the determination of the absolute cali-
bration and the limited angular resolution of radio telescopes at
long wavelengths. An observing program aimed at this specific prob-
lem, using a carefully selected wavelength (of the order of a few
meters) and an antenna with good angular resolution would yield
very interesting results.

Once "the temperature" in a nebula is known, it is possible to
measure the relative abundance of each ion that gives rise to one or
more observable lines. To find the abundance of a particular ele-
ment in all stages of ionization, since many stages do not have ob-
servable lines it is necessary to use evidence from lines of other ele-
ments, and to make the best possible extrapolations based on theore-
tical ideas of the radiation field (responsible for ionization) in the
nebula. The most comprehensive work available is for the Orion
Nebula, and it appears that in it and in other gaseous nebulae there
are no outstanding abundance anomalies among the ten or twelve most abundant elements.

H II regions contain interstellar dust, and its amount can be measured by its contribution to the continuous spectrum. Measurements of this type (O'Dell and Hubbard 1965; O'Dell, Hubbard, and Peimbert 1966; Boyce 1966) show that the abundance of dust is more or less the same in most of the nebulae studied, and is approximately the same as in the general interstellar H I medium. This observation raises the interesting theoretical question of how the dust particles can survive sputtering by thermal protons and irradiation by ultraviolet photons, particularly Lyman-α photons which have a high density inside a nebula because they are scattered many times before escaping.

So far I have been discussing diffuse nebulae as if they were static equilibrium structures, but actually, since they are much hotter than the surrounding H I regions, they tend to expand (Oort and Spitzer 1955). As a nebula expands, the density within it decreases, and the size of the possible ionized region correspondingly increases, for the reasons described earlier. The ionization front that bounds the H II region therefore also tends to run out into the surrounding neutral material. This front eventually sends a shock wave out ahead, which compresses and sets into motion the H I region (Kahn 1954; Savedoff and Greene 1955). By this process energy derived ultimately from nuclear reactions in the interiors of hot stars is partly converted into kinetic energy of interstellar material, and it has been considered a possibly important source of energy to support the observed turbulent interstellar motions (Oort and Spitzer 1955). Though the numerical values are quite uncertain, recent work by Kahn and Dyson (1965) and Field (unpublished) suggests that the expansion process can in fact just barely account for the energy contained in the interstellar velocity field.

The theoretical problems involved in the expansion of H II regions are quite complicated, involving as they do coupled radiation and hydrodynamics equations. The ionization at a point depends on the radiation field, which in turn is determined by the emitted flux from the hot stars and its interaction with the other material throughout the nebula. Considerable progress has been made on highly idealized versions of this expansion problem by Vandervoort (1964),...
Mathews (1965), Hjellming (1966), and Lasker (1966). The material velocities in the later stages of expansion are expected to range up to a sizable fraction of the velocity of sound, say about ten kilometers per second. The velocities tend to increase outward. Krishna Swamy and O'Dell (1967) and Mathews (1967) have shown that in diffuse nebulae containing reasonable amounts of dust, radiation pressure exerted on the individual dust particles is communicated to the gas and is important in accelerating the expansion.

Attempts have been made to measure the expansion of the surrounding $\text{H}_\text{i}$ region by observing the 21-cm profiles around an $\text{H}_\pi$ region. The most recent work on this problem (Riegel 1967) has concentrated on fairly small nebulae in relatively clear regions to minimize background effects. The part of the $\text{H}_\text{i}$ region that has been set into motion is expected to be rather thin, of the order of 15 percent of the radius of the $\text{H}_\pi$ region. Riegel's observations show broadened 21-cm lines, but it is not clear whether the velocities are a result of simple expansion, integrated over a more or less spherical shell, or random turbulent velocities.

All the theoretical work on expanding nebulae has necessarily been based on highly simplified models in which density homogeneity is assumed. However, inspection of direct photographs of nebulae show that in fact extreme density fluctuations occur. At the ionization fronts at the outer boundary of $\text{H}_\pi$ regions comet-tail or elephant-trunk structures are often seen. One of the best-known examples is the Horsehead Nebula in the $\text{H}_\pi$ region excited by the O9.5 V star $\sigma$ Orionis, shown in Plate VIII. The neutral material within them is evidently denser than average, and it therefore forces the expanding gas to flow around it. It also shields the matter behind it from ionizing radiation from the star. By this process quite high densities evidently can often be built up, and in some nebulae detached "globules" (or dense neutral regions) completely surrounded by ionized gas have been formed, as for example in M 16, shown in Plate IX. Such density fluctuations undoubtedly modify the flow considerably, and theoretical models of expanding nebulae incorporating these features will be necessary before it is possible to understand completely expanding nebulae. A start in this direction has been made by Dyson, but very many problems remain open. The difficulty is that numerical solution of time-dependent partial
Upper, IC 434, H II region excited by σ Orionis, which is to the east (left) of the dense absorbing cloud that extends to the west (right) from the ionized gas. The ionized front is about 50' long. Plate taken with 48-inch Schmidt telescope and red filter. Lower, Horsehead Nebula, a dense detail in IC 434. The "horsehead" is about 3' × 3'. Plate taken with the 200-inch Hale telescope and red filter.
Upper M 16, H ð region showing many “elephant-trunk” or “comet-tail” structures — dense absorption features often bounded on the side toward the source of ionizing radiation by bright, dense, ionization fronts. Diameter of the nebula is about 25'. Plate taken with the 48-inch Schmidt telescope and red filter.

Lower Two “globules,” dense absorption features in M 16 completely surrounded by ionized gas. They must be very close to the side of the nebula nearest us, as there is almost no emitting gas between us and them. They are in the southwest (lower right) part of the whole nebula in the upper picture. Note the ionization fronts on the side toward the central stars. Longer diameter of the larger globule is about 30". Plate taken with the 200-inch Hale telescope and red filter.
differential equations with more than one space coordinate requires extremely large computational capability.

The recent discovery of the OH radio-frequency emission lines has opened up a new and most interesting field of study of interstellar matter (Barrett 1964). The OH emission seems to be particularly associated with bright H II regions containing interstellar dust (Rogers, Moran, Crowther, Burke, Meeks, Ball, and Hyde 1967). The lines are quite sharp and have extremely high central intensities; in addition, the four lines of the “multiplet” have intensity ratios that vary from object to object and that are quite different from the LTE (local thermodynamic equilibrium) values (Weaver, Williams, Dieter, and Lum 1965; McGee, Robinson, Gardner, and Bolton 1965). It therefore appears likely that some kind of maser process is involved in the excitation, though at present no completely satisfactory theoretical explanation is known (Cook 1966; Litvak, McWhorter, Meeks, and Zeiger 1966). An extra complication is that the lines are generally strongly circularly polarized. Individual sources are extremely small, with upper limits to the diameter set by interferometer measurements of the order of 0.1 in some cases, though the numerical values of the limits are modified if coherency effects (which occur in maser processes) are important (Davies, Rowson, Booth, Cooper, Gent, Adgie, and Crowther 1967; Moran, Barrett, Rogers, Burke, Zuckerman, Penfield, and Meeks 1967).

The small angular size of the OH sources suggests they are particularly dense condensations, immersed in a strong radiation field due to the H II region. Molecules would probably be rapidly destroyed by photodissociation, but it seems possible that the OH sources are neutral condensations in the process of being ionized; perhaps the dust particles they contain are in the process of being evaporated, and the OH molecules now emitting will in fact be rapidly broken down to atoms and ions in the near future.

It is possible to measure observationally the electron density $N_e$ in a nebula by measuring the relative strengths of the [O II] $\lambda\lambda 3726, 3729$ doublet (Seaton 1954; Seaton and Osterbrock 1957). These two lines come from two levels with nearly the same excitation energy, but which have different radiative transition probabilities and which therefore are collisionally de-excited at different rates. The method is most sensitive in the density range around $10^8$ electrons
Fig. 1 — Calculated variation of \([\text{O} \text{ I}] \lambda 3727/\lambda 3726\) as a function of \(N_e\) at \(T_e = 10,000^\circ\). At other temperatures, the graph has the same form, but instead of electron density the abscissa gives \(N_e/(10^{-4} T_e)^{1/2}\).

Figure 1 shows. Measurements of the \(\lambda 3729/\lambda 3726\) line ratio show that in most diffuse nebulae the average density is well below 100 electrons cm\(^{-3}\). However, in the Orion Nebula the density at the center goes up to about \(10^4\) cm\(^{-3}\), dropping to about \(10^2\) cm\(^{-3}\) in the outer parts (Osterbrock and Flather 1959). Unpublished measurements show that at an average point in M 16 the electron density is about \(2 \times 10^2\) electrons cm\(^{-3}\), while in the brightest part of a bright ionization front shown in Plate IX the density is about \(1.2 \times 10^3\) electrons cm\(^{-3}\). Within the neutral region included in the elephant trunk, the density must be even higher. In the center of M 8, there is a small, bright, dense object (see Plate X), about 10'' across, which corresponds to a size of about 0.1 parsec. The \(\lambda 3729/\lambda 3726\) ratio here is approximately 0.65, corresponding to an electron density of about \(5 \times 10^3\) electrons cm\(^{-3}\). Several other nebulae, such as NGC 2327, NGC 2175, NGC 6604, and S 157, contain somewhat similar small bright knots, and these probably are only the most extreme cases in a sequence or hierarchy of density fluctuations. Down to the best resolution of large telescopes, say 0''.5 or
Bright, very dense condensation in the central part of M 8. The measured mean electron density \( N_e = 5 \times 10^3 \) per cubic centimeter in the “Hourglass.” Its diameter is about 10”.

Plate taken with the 200-inch Hale telescope and red filter.

about 0.001 parsec in favorable cases, we see more and more detailed fine structure in diffuse nebulae. The smallest, densest knots seem to me to be the most probable sites for future star formation.

In addition to [O II], the [S II] lines \( \lambda \lambda 6717, 6730 \) may also be used to measure the electron density. Little observational work has so far been done with these lines, because the cross-sections (which are used in the conversion of a measured intensity ratio into a calculated density) were only poorly known. However, improved calculations will soon be available, and the [S II] lines, which occur in conditions of relatively low ionization, should be especially valuable in probing ionization fronts and other dense structures near the outer boundaries of H II regions.

It must of course be realized that there is an inescapable averag-
ing along the line of sight involved in determining “the” electron density from a measured line ratio. In the case of a single very bright condensation, the relatively small effects of the rest of the nebula can be corrected for. However, in the Orion Nebula, comparison of \([\text{O} \, \text{II}] \, \lambda \, 3727\) measurements (which determine the “average” density) and radio-frequency continuum measurements (which determine \(N_e^2l\)) shows that there are small-scale large-amplitude density fluctuations throughout the nebula. The “average” density measured by \([\text{O} \, \text{II}]\) is weighted by density in a complicated way, and actually what we should like to know is the entire spectrum of density fluctuations.

The very existence of the density fluctuations poses an interesting theoretical problem. They should be expected to dissipate with velocities of the order of the velocity of sound (about 10 km/sec), and velocities of this order of magnitude are in fact observed in the Orion Nebula. The sizes of some condensations are of the order of (or smaller than) 1” or \(10^{11}\) km, so their lifetimes should be expected to be of the order of \(10^{10}\) sec or 300 years, short in comparison with the age of the nebula, yet the condensations do exist (see for example Plate XI). Thus somehow or other new density fluctuations and new turbulence are continually being regenerated, probably ultimately from the energy of expansion, but in a way that is at present not understood theoretically.

Temperature fluctuations must also occur, due to variations in density and also in the ionizing radiation field. Therefore, as Peimbert (1967) has pointed out, measured temperatures are also averages along a line of sight, and different methods weight different regions differently – for instance the \([\text{O} \, \text{III}]\) and \([\text{N} \, \text{II}]\) methods weight heavily the hottest regions, while the radio-frequency measurements tend to emphasize the cooler regions.

This short review paper is an attempt to give some impression of the work that has been done, and that is now going on, in the field of diffuse nebulae. The problems are very interesting, connected as they are with stellar formation and evolution, and gas dynamics. Looking into the future, it seems to me likely that research in this field will go on at an accelerated pace. More research will be done with specialized instruments, specifically designed for observing...
Complicated density fluctuations just north of central bright part of M 8. Dimensions of whole region shown are about 4' × 5'. Plate taken with the 200-inch Hale telescope and red filter.

gaseous nebulae. High angular resolution combined with speed will be necessary to press the agreement (or lack of agreement) between theory and observation of diffuse nebulae to the limit. Probably the Stratoscope 36-inch telescope photographs will in time give the best optical resolution of ionization fronts and dense condensations. Measurements of internal velocity fields in nebulae other than Orion will be made with fast, high-dispersion, multi-slit instruments. High angular resolution, 21-cm line profiles will be necessary to search for expansion of the H I shells surrounding H II regions. Meter-wave high-resolution measurements of H II regions will give an independent measurement of their temperatures.

On the theoretical side, density fluctuations and internal turbulence will have to be taken into account. The driving mechanism for
small-scale turbulence will presumably have to be sought in the expansion of the nebula, and the way in which this fine structure reacts back on the expansion will have to be included in the calculations. In this way we can hope in time to understand quantitatively as well as qualitatively the structure and evolution of H II regions.

I am most grateful to the many generous colleagues, both here at the University of Wisconsin and at other observatories, who have shared their thinking as well as their research results with me. My own part of the research on which this paper is based has been supported in part by the National Science Foundation.

REFERENCES

Kahn, F. D., and Dyson, J. E. 1965, Annual Rev. Astr. and Astrophysics 3, 47.
Miller, J. S. 1967, A.J. 72, 312.
DIFFUSE NEBULAE

— 1960, Reports Progress Phys. 23, 313.