PHOTOELECTRIC SPECTROPHOTOMETRY OF GASEOUS NEBULAE

III. SCATTERED LIGHT IN THREE BRIGHT H II REGIONS

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ABSTRACT

Three bright diffuse nebulae have been investigated using an interference filter system isolating the emission-line Hβ and the nebular continuum. The results of this photoelectric photometry are used to derive the hydrogen densities and the effective gas-to-dust ratios inside the nebulae. Definite proof is presented for the existence of scattering particles inside H II regions, setting upper limits to the roles played by grain-destruction mechanisms. In two of the nebulae the effective amount of dust is very similar to the amount in the general interstellar medium, while in the third object the amount of dust is some five times greater than normal. The time scales required to push the dust particles radiatively out of the nebulae are estimated, and it is shown that all of these nebulae are too young for this to have occurred. The possible roles of these scattering and absorbing particles in the transfer of trapped Lyman-α radiation and the determination of the ionization structure of a H II region are pointed out.

In this paper we shall present the results of observations of the emission-line and continuum surface brightnesses of three bright galactic nebulae. This third paper reporting on photoelectric investigations of scattered light in diffuse nebulae (O'Dell and Hubbard 1965; O'Dell 1965) is part of a program to provide new and accurate observations of light scattered by small particles in the interstellar medium. These observations should prove to be extremely valuable in accurate discussions of the physical nature, the size distribution, and the theory of formation and destruction of interstellar particles.

Several factors entered into the decision to investigate the three particular diffuse nebulae (NGC 6514, NGC 6523, and NGC 6611): their high surface brightnesses in the central regions, which permit reasonably short observing times (especially important when working in the continuum close to the sky level); the exciting stars are easily identified; they each possess a developed degree of circular symmetry as viewed on the plane of the sky; they are available for observation during the summer observing season from Mount Hamilton, California.

The observations were made in the same manner as those of the Orion Nebula (O'Dell and Hubbard 1965) using an interference filter system selected to isolate spectral regions centered on strong emission lines or the nebular continuum. The observations were reduced to relative absolute energies in the emission lines and the continuum through observations of the stars HD 169454 (B1 Ia) and HD 195592 (O9. 51a) for which the energy distributions in the continua have previously been determined (Code 1961). Observations were made on nine nights, and each field within a nebula was generally measured at least three times. Since adequate equipment for offsetting was not available, the exact position on the nebula probably varied slightly from setting to setting so that all measures were reduced on a relative basis and then an average of the relative measures for that region was taken. The same procedures were followed for each nebula, and each object will be described separately below.

I. NGC 6514

This object is very well suited for such an investigation because of its circular symmetry and the dominance of the radiation field by a single star, HD 164492. The dark lanes marking its surface are probably due to overlying material in the outer regions of the nebula and were largely avoided, as shown in Figure 1, where the regions measured are indicated both by location and size of the diaphragm used (67″). The identification of HD 164492 as the exciting star follows from its early spectral type (O8) and its central location within the nebula. The presence of a surrounding zone of low star count indicates that scattering particles are present outside the ionized zone, which further indicates that we are seeing only the ionized portion of a larger interstellar cloud. The distance to the nebula was determined from the spectroscopic parallax of its exciting star. The observed color ($B - V = 0.00$; Hiltner 1956) indicates a color excess of 0.31 mag. if we assume the intrinsic color to be that listed by Johnson (1965) for an O8 star. For want

TABLE 1

OBSERVATIONS OF NGC 6514

Region	ϕ'	$\log S(H\beta)_{obs}$*	$[F(H\beta)/f(\lambda\ 4861)]_{obs}$ (Å)	$\log s(\lambda\ 4861)_{obs}$†
0	0.5	−3.41	96	−5.43
1	4.3	−4.33	76	−6.25
2	3.0	−3.73	140	−5.92
3	0.8	−3.56	120	−5.68
4	0.8	−3.39	200	−5.78
5	3.5	−3.76	560	−6.79
6	7.0	−4.47	110	−6.54
7	2.4	−3.31	460	−6.19
8	3.5	−3.63	520	−6.60
9	5.1	−4.21	240	−6.69

* Ergs/sec cm² ster.
† Ergs/sec cm² ster Å.

of evidence to the contrary we shall adopt a ratio of total to selective extinction of $A_V/E(B - V) = 3.1$ and the absolute magnitude −5.2 given by Blaauw (1963). This leads to a true distance modulus of 11.84 and a distance of 2340 pc.

The results of the observations are given in Table 1, which is largely self-explanatory. $S(H\beta)$ denotes the surface brightness in the emission line at λ 4861, $s(\lambda\ 4861)$ denotes the surface brightness in the scattered-light continuous radiation for the same region, $F(H\beta)/f(\lambda\ 4861)$ denotes the relative intensity of the emission line and the total continuum, and ϕ is the distance of the region studied from the exciting star in minutes of arc. The ratio of emission-line and continuum flux is an excellent parameter for the strength of the continuum as it denotes the bite out of the continuum that would be required to equal the energy from Hβ.

The observed continuum is a combination of the atomic continuum arising from free-free, two-photon, and free-bound emission of hydrogen and helium superimposed upon light scattered by interstellar particles within the nebula. We are primarily interested in the scattered-light component, which dominates. A correction for the component of the continuum due to atomic sources was made using the emission coefficients given by Seaton (1960), which gave $[f(\lambda\ 4861)/F(H\beta)]_{atomic} = 0.87 \times 10^{-3}$ Å^{-1}.

As suggested by the general appearance of the nebula, we have investigated the expected surface-brightness distribution in Hβ for a model nebula of constant gas density and in the continuum for an optically thin nebula with constant density and

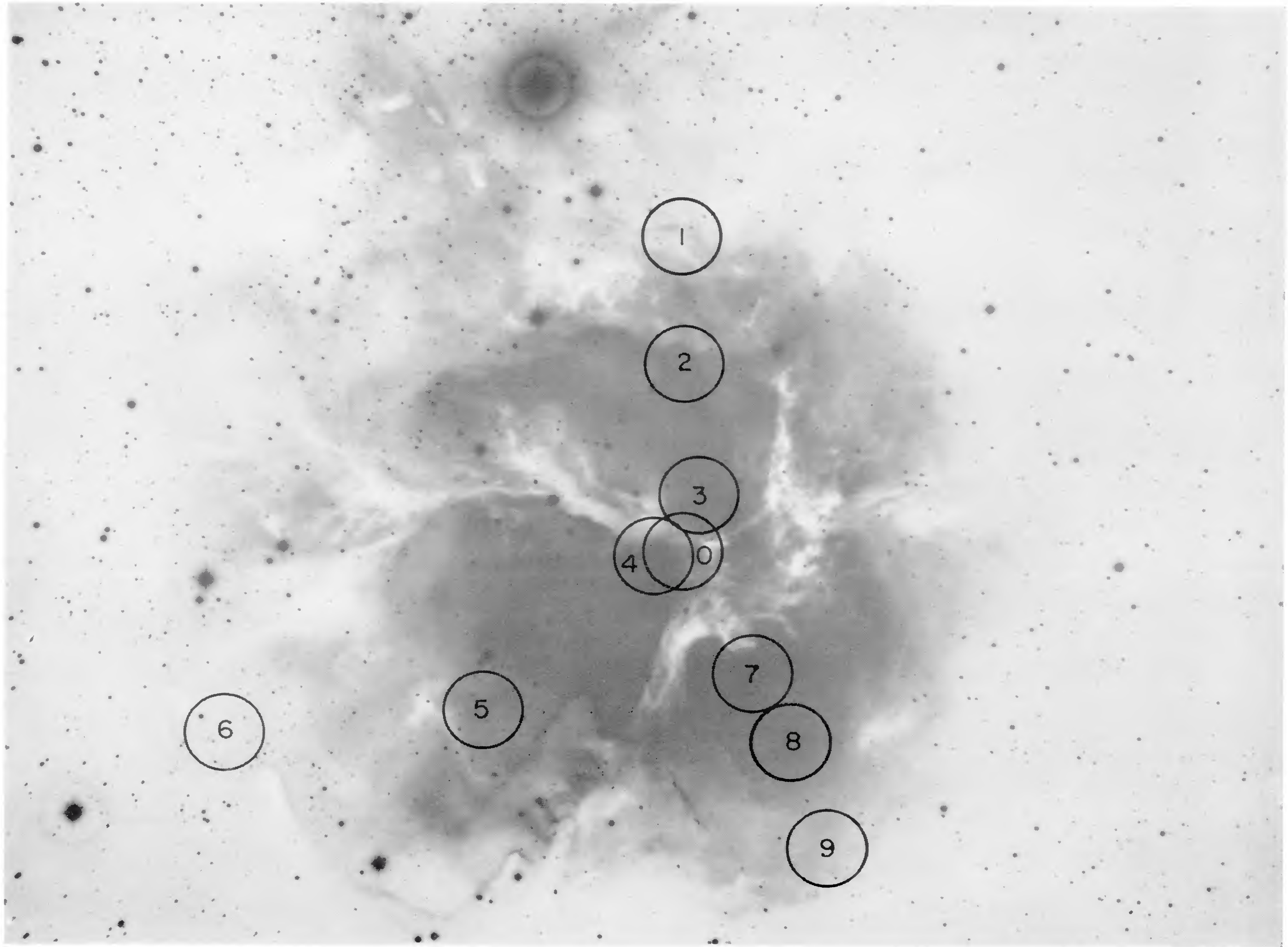

FIG. 1.—Regions studied in NGC 6514 are indicated to scale on this red photograph

size of scattering particles. The expected emission-line surface brightness, compared to that at the center of the nebula, will be

$$\frac{S(\mathrm{H}\beta)}{S_0(\mathrm{H}\beta)}=(1-\phi^2/\phi_S{}^2)^{1/2}\,, \tag{1}$$

where ϕ is the apparent angular displacement and ϕ_S is the apparent distance of the sharp edge of the ionized zone. For the scattered-light continuum we would expect for the surface-brightness distribution

$$\frac{s(\lambda 4861,\phi)}{s(\lambda 4861,\phi_0)}=\frac{\phi_0}{\phi}\frac{\cos^{-1}(\phi/\phi_D)}{\cos^{-1}(\phi_0/\phi_D)}, \tag{2}$$

where ϕ_D is the outer boundary of the cloud of scattering particles (not necessarily the same as ϕ_S) and ϕ_0 is the distance from the center of an inner region to which the dust extends. This normalization is necessary as the formal model treated here would have infinite surface brightness at the center. Equations (1) and (2) can be used to derive expressions for the atomic density

$$N_{\mathrm{H}}N_e = 2\pi S_0(\mathrm{H}\beta)/\phi_{S-\mathrm{rad}}D_{\mathrm{cm}}\alpha_{4,2}h\nu_\beta \tag{3}$$

and the effective gas-to-dust ratio

$$N_{\mathrm{H}}/N_d\sigma_\lambda=\frac{S(\mathrm{H}\beta)\cos^{-1}(\phi/\phi_D)I_0}{s(\lambda 4861)\phi(\phi_S{}^2-\phi^2)^{1/2}N_e\alpha_{4,2}h\nu_\beta}, \tag{4}$$

where N_{H} and N_e are the ion and electron densities, nearly equal; $\alpha_{4,2}$ is the effective emission coefficient for Hβ, taken here to be 3.0×10^{-14} cm^3/sec; D_{cm} is the distance to the nebula in centimeters;

$$N_d\sigma_\lambda=\int_0^\infty Q(a/\lambda)\pi a^2 N(a)\,da$$

is the effective scattering cross-section per unit volume presented by the grains of size distribution $N(a)$; I_0 is the flux that would be observed in the nebula at a distance corresponding to 1′; and the angles are given in minutes of arc. The quantity $N_d\sigma_\lambda$ will be wavelength-dependent, and we shall work at λ 4861.

Figure 2 gives the results of a comparison of these models with the results of the observations of NGC 6514. There appears to be sufficient agreement between these models and the observations to proceed with the method. As an independent check, the values for ϕ_S and ϕ_D agree well with that expected from a cursory examination of the appearance of the nebula. Adopting an observed central surface brightness of log $S(\mathrm{H}\beta) = -3.4$ ergs/sec cm^2 ster, a correction for extinction of $\Delta \log F(\mathrm{H}\beta) = C_{\mathrm{H}\beta} = 0.44$, and $\phi_S = 5\overset{'}{.}6$ we find $N_{\mathrm{H}} = 63$ electrons/cm^3. In turn, this gives for the hydrogen mass in the ionized region $M_{\mathrm{H\,II}} = 2030\, M_\odot$. We have measured the next two brightest members of the cluster and have found that they contribute 41 per cent as much light as HD 164492. I_0 will be the flux from the exciting star(s) observed at the Earth, corrected for extinction, times the square of the number of minutes of arc in a radian, i.e., $I_0 = 1.99\times 10^{-11}\times(3.44\times 10^3)^2 = 2.34\times 10^{-4}$ erg sec cm^2 Å. This value, along with $S(\mathrm{H}\beta)/s(\lambda\, 4861) = 192$ at $\phi = 1'$ and $\phi_D = 10\overset{'}{.}0$ gives $N_{\mathrm{H}}/N_d\sigma_\lambda = 2.8\times 10^{20}$ cm^{-2}.

One can obtain an independent lower limit on this effective gas-to-dust ratio simply from the amount of extinction that has occurred. If all of the scattering has occurred within the nebula, i.e., not in the intervening interstellar medium, the ratio will be

$$\frac{N_{\mathrm{H}}}{N_d\sigma_\lambda}=0.434 N_{\mathrm{H}}\phi_D D/C_{\mathrm{H}\beta}\,, \tag{5}$$

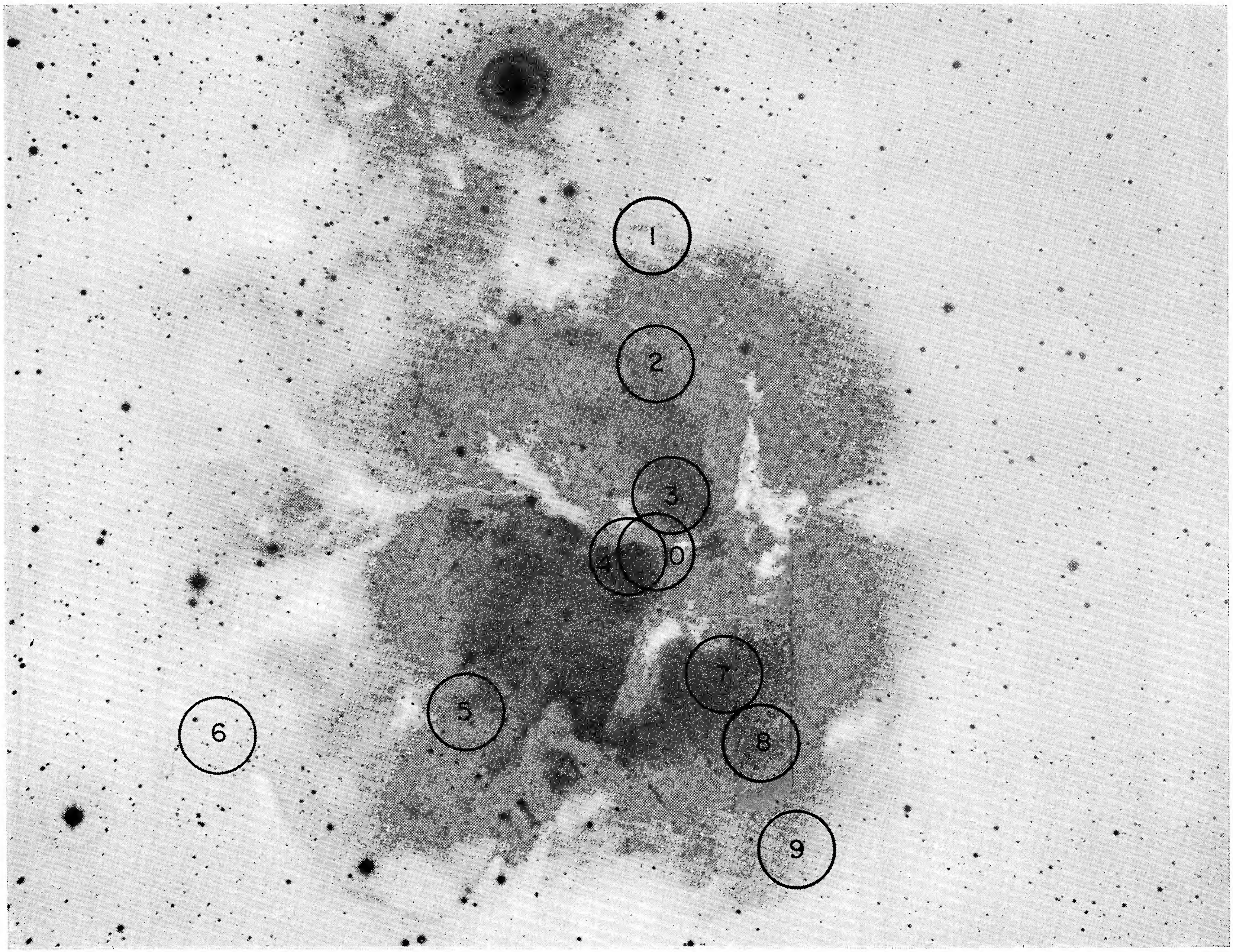

FIG. 1.—Regions studied in NGC 6514 are indicated to scale on this red photograph

which will be a lower limit in the more realistic case at hand. This gives $N_H/N_d\sigma_\lambda \geq 13 \times 10^{20}$ cm^{-2}. The lack of agreement is disconcerting; but, it should be remembered that the method of direct observations is far more reliable since it utilizes the information from a large number of points through the nebula. If the reddening correction applied to the central star were larger, the ratio would increase and the discrepancy diminish. If the ratio of total to selective extinction were 6.2, or twice what is *assumed* above, then the density would be $N_e = 130$ electrons/cm^3, the distance would be $D = 1480$ pc, the gas-to-dust ratio derived from the scattered-light observations would be $N_H/N_d\sigma_\lambda = 3.6 \times 10^{20}$ cm^{-2}, and the ratio derived from the reddening would be $N_H/N_d\sigma_\lambda \geq 8.5 \times 10^{20}$ cm^{-2}, which provides better agreement. This greater extinction correction has the property of placing NGC 6514 very close in the spiral arm to NGC 6530, which agrees well with the appearance of this region. The possibility of an anomalous reddening-curve here is discussed in § IV. If other members of the same cluster of stars also contribute significantly to the radiation, then the derived scattered-light value will be increased accordingly. We shall adopt the value 4×10^{20} cm^{-2}.

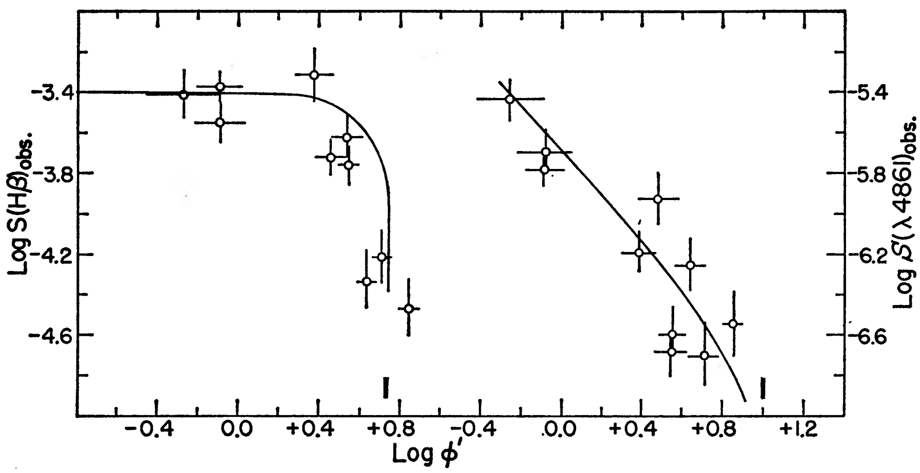

FIG. 2.—Results of the Hβ and scattered-light surface brightness for NGC 6514. The fitted constant-density models are shown as the thin lines, and the limiting sizes of the ionized gas or scattering-particle clouds are shown as the heavy vertical dashes.

II. NGC 6523

Unlike NGC 6514, the previous nebula, M8 is dominated by the presence of a young galactic cluster in its center (NGC 6530; Hiltner, Morgan, and Neff 1965). Other than this, the objects are very similar, with good symmetry and an obvious dust shell surrounding the nebula, indicating that it too is only the ionized part of a larger gas cloud. The density of the shell immediately surrounding the H II region is difficult to ascertain, but certainly the region decreases in density after several Strömgren radii. We have again determined the distance to the nebula by means of the cluster with the spectroscopic parallax, this time using the member spectral types given by Hiltner *et al.* (1965) and Blaauw's (1963) luminosity calibration. First we investigated the ratio of total to selective extinction by the variable-extinction method of Johnson (1965) and using his intrinsic colors. Unfortunately, the range in $B - V$ color excess is small (0.25 mag.), and no firm conclusion can be reached. However, one can say that most of the members of the cluster fit a reddening slope for $A_v/E(B - V) = 3.1$. The data then give an intrinsic distance modulus of 11.00 and a distance of 1600 pc. About one-third of the stars fit a reddening slope of about 6–8, having larger apparent distance moduli but the same intrinsic moduli as the majority of the cluster members. This

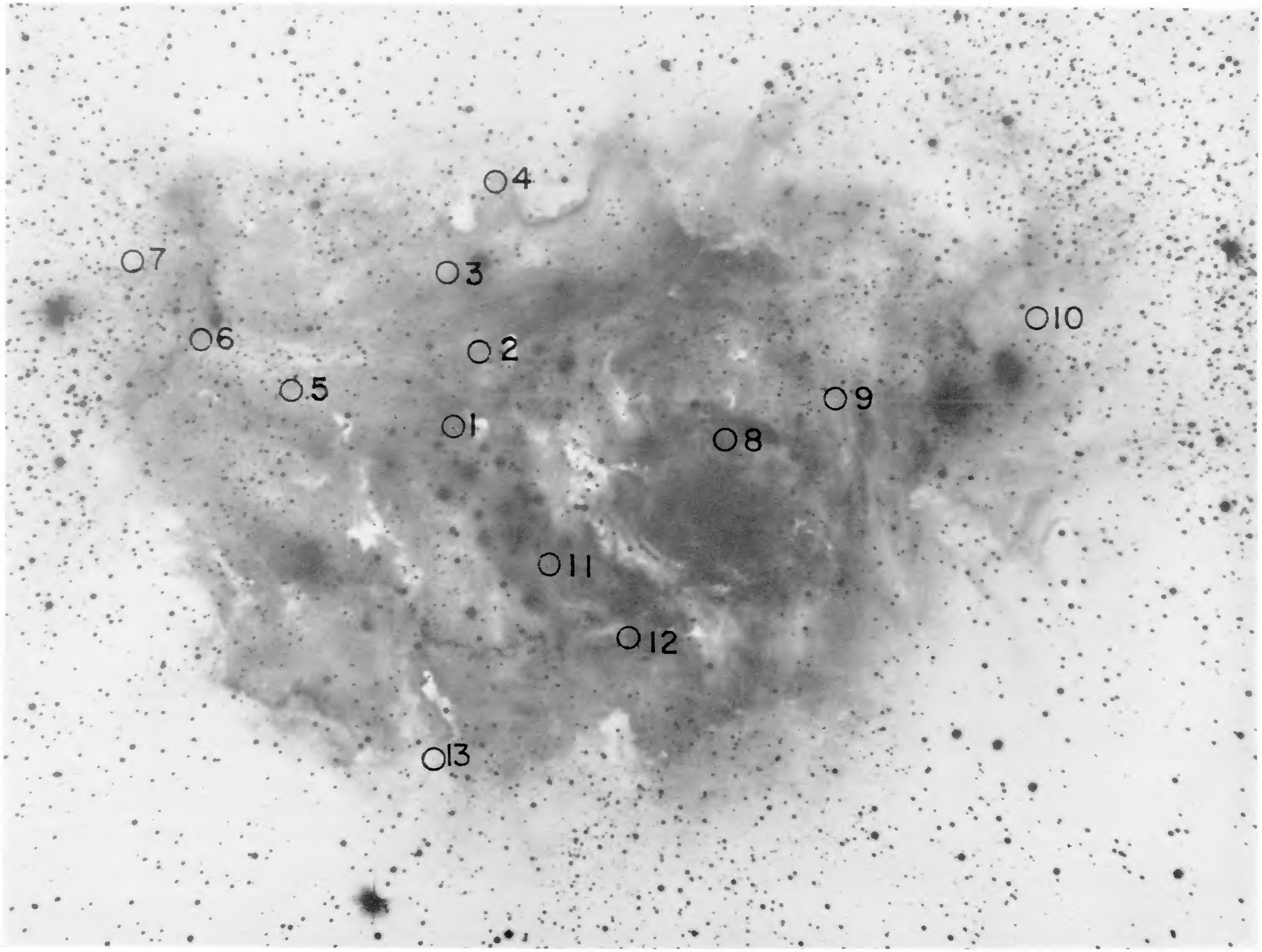

Fig. 3.—Regions studied in NGC 6523 are indicated to scale on this red photograph

curious effect is not connected with the position of the stars in the H-R diagram for the cluster and may indicate that very small-scale deviations in the ratio of total to selective extinction occur in this cluster. This phenomenon can also explain the anomalous results of Miss Loden (1965), who concluded that the inner and outer members of the apparent O association Pup I are actually two groups of stars seen at different distances but the same direction. We shall discuss this point more fully below. For the purpose of the corrections for extinction we shall adopt the "normal" ratio, the mean color excess $E(B - V) = 0.37$ and a value $C_{H\beta} = 0.52$. The cluster shows the peculiar but not unusual structure of having its brightest members in the outlying regions around a well-defined inner cluster. If all members of the cluster are included, then I_0 has the value 2.76×10^{-3} erg cm^2 sec Å and, if only members of the inner cluster are included, then $I_0 = 1.12 \times 10^{-3}$ after correction for extinction.

The regions studied, the results, and the comparison with the optically thin homogeneous model nebula are given in Figures 3 and 4 and Table 2. The adopted center for the nebula was that of the galactic cluster. Again there is a rough agreement between the model and the observed nebula. The electron density was derived using equation (3),

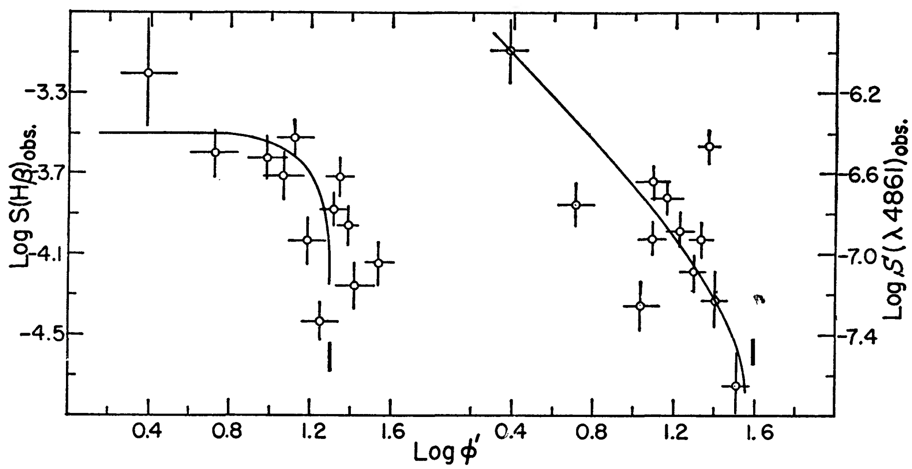

FIG. 4.—Same as Fig. 2 but for NGC 6523

TABLE 2

OBSERVATIONS AT NGC 6523

Region	ϕ'	log $S(\mathrm{H}\beta)_{\mathrm{obs}}$	$[F(\mathrm{H}\beta)/f(\lambda\ 4861)]_{\mathrm{obs}}$ (Å)	log $s(\lambda\ 4861)_{\mathrm{obs}}$
1	5.1	−3.60	640	−6.76
2	9.3	−3.63	1240	....
3	12.5	−3.93	520	−6.92
4	23.7	−3.97	250	−6.47
5	14.6	−4.04	340	−6.72
6	19.4	−3.89	680	−7.10
7	25.3	−4.25	520	−7.23
8	12.7	−3.53	610	−6.64
9	21.6	−3.72	670	−6.93
10	32.5	−4.15	850	−7.66
11	2.4	−3.21	400	−6.00
12	10.9	−3.74	850	−7.26
13	16.8	−4.45	220	−6.88

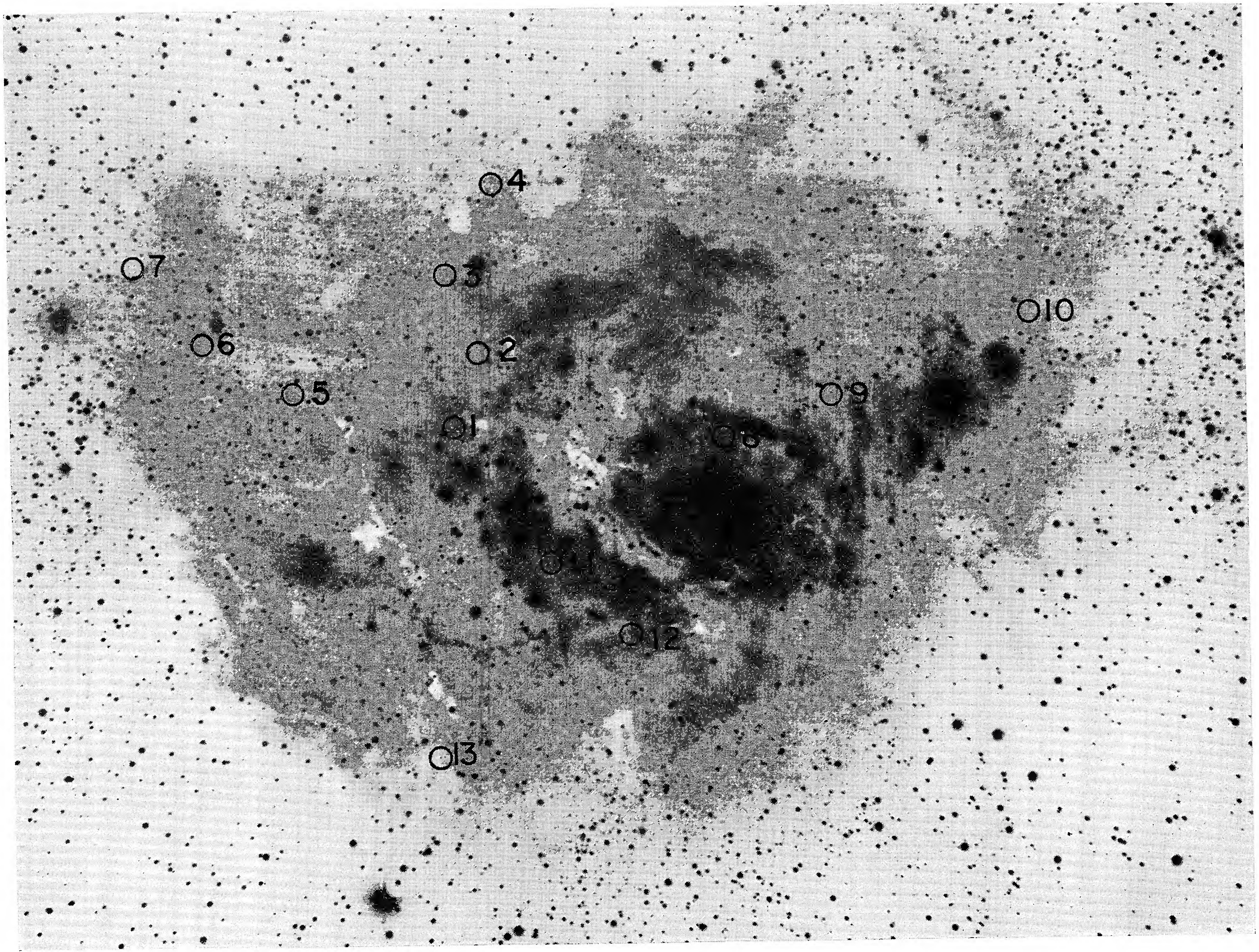

FIG. 3.—Regions studied in NGC 6523 are indicated to scale on this red photograph

$\phi_S = 19'.1$, $D = 1600$ pc, and $\log S(\text{H}\beta) = -2.98$ ergs/sec cm^2 ster. These values gave $N_e = 44$ electrons/cm^3 and an ionized hydrogen mass of $M_{\text{H II}} = 2940\ M_\odot$. The effective gas-to-dust ratio was determined using $\phi_D = 40'$ and $S(\text{H}\beta)/s(\lambda\,4861) = 660$ Å at $\phi = 12'.6$. These values then give $N_\text{H}/N_d\sigma_\lambda = 9.4 \times 10^{20}$ cm^{-2} if only the inner cluster members contribute to the scattered light and 23.0×10^{20} cm^{-2} if all cluster members contribute to the scattered light. Likewise the total extinction method gives $N_\text{H}/N_d\sigma_\lambda \geq 21.2 \times 10^{20}$ cm^{-2}. Since the latter method is more reliable here due to the large number of stars, we shall adopt the value $N_\text{H}/N_d\sigma_\lambda = 22 \times 10^{20}$ cm^{-2}.

III. NGC 6611

This nebula, excited by members of the galactic cluster NGC 6611, is obviously different in many ways from the two nebulae discussed above. Certainly the density distribution is different, being characterized by an inner region of slowly decreasing density surrounded by a region of rapidly diminishing density. The most striking feature is the presence of numerous and well-developed elephant-trunk features. The cluster has been studied in detail by Walker (1961), who concluded that the cluster was quite young and

TABLE 3

OBSERVATIONS OF NGC 6611

Region	ϕ'	$\log S(\text{H}\beta)_\text{obs}$	$[F(\text{H}\beta)/f(\lambda\,4861)]_\text{obs}$ (Å)	$C_{\text{H}\beta}$	$\log S(\text{H}\beta)_\text{corr}$	$\log s(\lambda\,4861)_\text{corr}$
1......	9.2	−4.09	390	0.98	−3.11	−5.89
2......	6.0	−3.75	400	1.09	−2.66	−5.45
3......	6.1	−3.97	300	0.98	−2.99	−5.60
4......	4.8	−3.86	540	1.09	−2.71	−5.71
5......	2.7	−3.99	200	1.09	−2.90	−5.41
6......	4.1	−3.58	440	0.81	−2.77	−5.63
7......	1.7	−4.12	140	1.37	−2.75	−4.94

that there are numerous stars of low luminosity above the main sequence still in a state of gravitational contraction. The nebula has been intensively studied by Terzian (1965) from observations in the radio regions, where the central concentration of ionized matter was outlined. The advantages of working in radio wavelengths are great for this object because of the large and variable amount of extinction suffered across the apparent surface of the nebula (Walker 1961). This shortcoming can be put to good advantage in a determination of the ratio of total to selective extinction for the region. The results of the photometry of Walker (1961) and accurate spectral types for the brighter members (W. W. Morgan, private communication) were used to derive the ratio of total to selective extinction by the variable-extinction method. This ratio, obviously close to the value of 3.1 observed elsewhere, will be adopted here and agrees well with the value 2.9 ± 0.5 determined by Johnson and Borgman (1963). The integrated luminosity of the cluster was determined by applying individual extinction corrections and was found to give $I_0 = 2.0 \times 10^{-3}$ erg cm^2 sec Å. The true distance modulus is 11.49 and the distance is 2000 pc. The results of the observations are given in Table 3 and Figures 5 and 6. The reddening correction for each point was determined from the average color excess for several stars close to that region. The adopted center for the nebula is again that of the cluster, which seems to be different from that of the radio nebula (Terzian 1965). Due to the large variations in the extinction, the corrected surface brightnesses were used for comparison with the constant-density model. The agreement with such a model is good and results from the fact that there is a strongly concentrated central region of diameter 20′ (Terzian 1965). If we take 55 electrons/cm^3 from the radio measures for

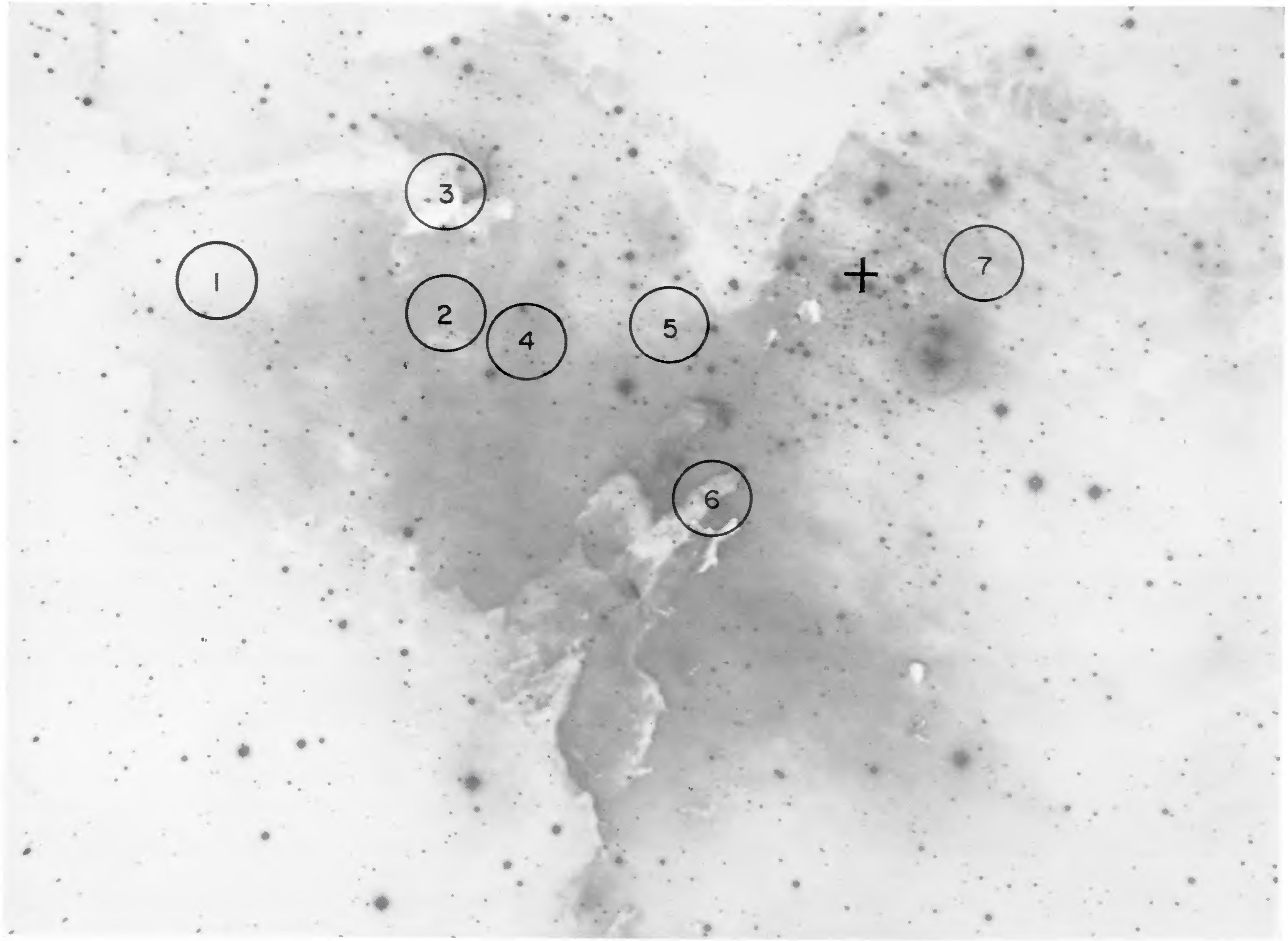

FIG. 5.—Regions studied in NGC 6611 are indicated to scale on this red photograph

the value of the density of this inner region, the extrapolated flux ratio at a distance of 1′ $S(\mathrm{H}\beta)/s(\lambda\,4861) = 115$ Å and $\phi_D = 16'$, the gas/dust ratio becomes $N_{\mathrm{H}}/N_d\sigma_\lambda = 19.1 \times 20^{20}$ cm^{-2}. If we adopt the value $C_{\mathrm{H}\beta} = 1.0$, this gives $N_{\mathrm{H}}/N_d\sigma_\lambda \geq 6.8 \times 10^{20}$ cm^{-2}. We shall adopt the former value, as the lack of agreement is probably due to extinction between the nebula and the observer.

IV. DISCUSSION

It is important to compare the results of this study with the results for the general interstellar medium. The more simple approach is to use equation (5), modified appropriately for extinction per unit distance, and adopt the value of 1 photographic magnitude of extinction per kpc and an average of 1 atom/cm.[3] These values then lead to $N_{\mathrm{H}}/N_d\sigma_\lambda = 30 \times 10^{20}$ cm^{-2} for the general interstellar medium. A more detailed result may be derived from the study by Lilley (1955), where traces were made along the Milky Way at a declination $b^{\mathrm{I}} = -15°$ in H I 21-cm emission. These observations enabled Lilley to derive the total number of hydrogen atoms along a line of sight at

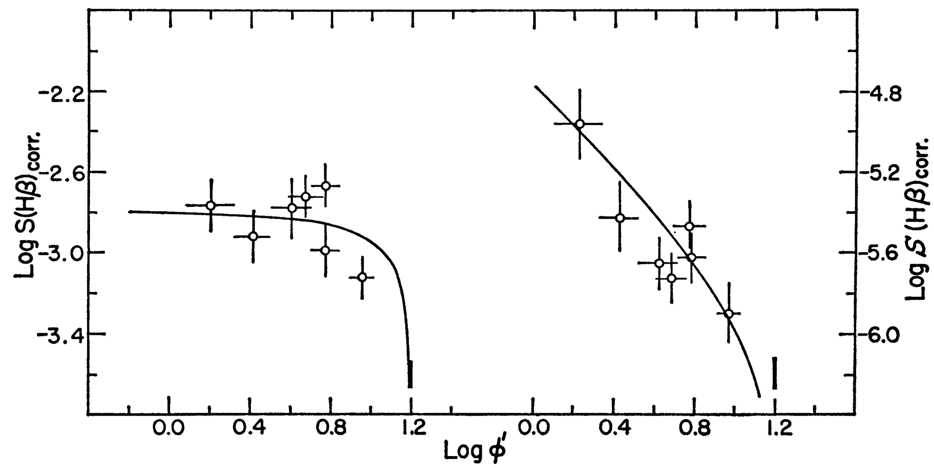

FIG. 6.—Same as Fig. 2 but for NGC 6611

constant galactic latitude. This plane is intersected in several points by extensions of the galactic zone of avoidance where one may, from the rapid decrease in the counts of galaxies, estimate the total extinction. Combining these results from Lilley's investigation, we find $N_{\mathrm{H}}/N_d\sigma_\lambda = 10 \pm 3 \times 10^{20}$ cm^{-2} where the indicated probable error is estimated from the scatter shown between various regions. It is probably not justified to conclude from these two values that the effective gas-to-dust ratio is higher in the anticenter (the region primarily studied by Lilley) than in the general interstellar medium; rather, it is better to take the average of these values as representative of the low-density regions between the field stars. The results of these various methods are given in Table 4. From the values listed in this table we see that there is generally little variation between the various regions in the effective gas-to-dust ratios. The two notable and accurately defined exceptions are the inner regions of the Orion Nebula (near the Trapezium), where there seems to be a deficiency of dust, and NGC 6514, where there seems to be an excess of dust. The deficiency in Orion is well known to be accompanied by a strong anomaly in the wavelength dependence of the reddening law (Johnson and Borgman 1963) while the nature of the reddening law in NGC 6514 has yet to be determined.

In an earlier paper on the Orion Nebula (O'Dell and Hubbard 1965) it was shown that the anomalously low dust abundance and peculiar reddening law might be explained by

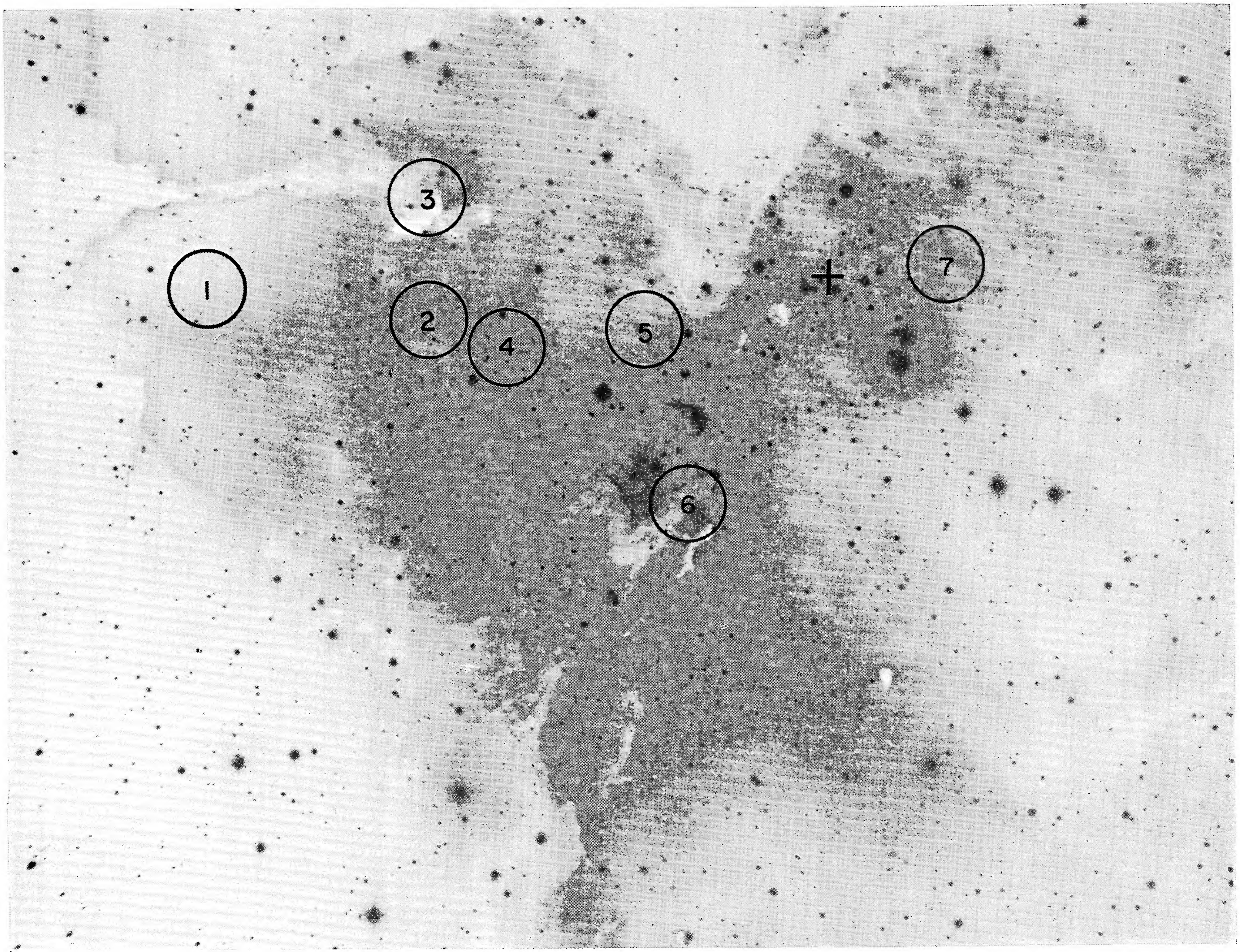

FIG. 5.—Regions studied in NGC 6611 are indicated to scale on this red photograph

selective radiative repulsion by the Trapezium stars if these young stars were at least 5×10^5 years old. It is important to test this interpretation of strong forces of radiation pressure on the several regions studied here. The actual motion of a grain will be a combination of gravitational attraction (negligibly small here), radiative repulsion by the luminous stars, and a viscous drag caused by collisions with the abundant light elements. For a star rapidly becoming luminous in an undisturbed cloud of dust and gas, the dust particles will be subjected to a rapid acceleration outward for a distance 1.5–2.0 times the original distance, after which time the dust will have approached the maximum velocity allowed by the local density and the distance from the exciting stars. Using the equations expressed in the investigation of the Orion Nebula, we may then derive a lower limit for the time that would be required to force the grains out of a spherical, homogeneous nebula,

$$t \geq (M_{\mathrm{H}} c N_e/\sigma)^{1/2} D^2 \phi_D{}^2 / R_{\mathrm{star}} T^2{}_{\mathrm{star}} 3.43^2 \times 10^6 \text{ sec} . \quad (6)$$

This will be a lower limit because the equality would hold only for grains starting in the innermost regions with the maximum allowable velocity. Using the MK spectral types,

TABLE 4

SUMMARY OF RESULTS

Object	$N_{\mathrm{H}}/N_{d}\sigma_{\lambda}$	Spectral Type*	$T_{\mathrm{M.S}}$(yr.)	T†$_{\mathrm{R.P}}$(yr.)
NGC 6514............	4×10^{20} cm^{-2}	O8	$\leq 6\times10^6$‡	$> 8\times10^6$
NGC 6523............	22	O5	$\leq 1\times10^6$§	$>17\times10^6$
NGC 6611............	19	O5	$\leq 3\times10^5$§	$> 8\times10^5$
NGC 1976 (inner)......	144	O6	....	....
NGC 1976 (outer)......	5	O6	....	....
General field..........	20×10^{20} cm^{-2}	....	....	....

* Spectral type of earliest main-sequence star in the cluster.

† Lower limit to the amount of time required to force small particles radiatively out of the nebula.

‡ Upper age of earliest member.

§ Age determined from contraction time for latest cluster members.

absolute magnitudes, effective temperatures, and radii of the early-type stars in the various clusters, we have derived lower limits to the radiative repulsion times for each cluster studied. The results of these calculations are given in Table 4 and are compared with the upper limit for the age for the earliest member star in NGC 6514 as judged by its position on the main sequence and the expected hydrogen-burning lifetimes. Herbig (1962) has shown that there is considerable evidence that all cluster members are not coeval. The sense of the difference is that often the more massive stars were formed more recently. If this is true in NGC 6530 and NGC 6611, the ages calculated from the latest member stars on the main sequence will be better upper limits to the ages of the young stars, as it may be argued that the formation of the hot stars will stop star formation. We have used this method combining the photometry of Walker (1961) and the recent theoretical study of Iben (1965) to estimate the lifetime of the hot stars in NGC 6530 and NGC 6611. It is seen that in all cases there has been insufficient time for significant radiative expulsion to have occurred. Since we have shown that radiative expulsion has not had time to operate in these nebulae, we may draw several major conclusions: First, processes such as electron-impact destruction and evaporation are not acting strongly in these nebulae; second, the nature of the grains has probably not been changed significantly from the original condition; third, the original effective gas-to-dust ratio in NGC 6514 may have been significantly lower than that in many other regions in the Galaxy.

These conclusions are strengthened by the fact that the reddening law that is derived from the observations made by Johnson (1965) for NGC 6523 and NGC 6611 is not strongly deviant from that derived for most other regions that have been thoroughly investigated, i.e., the scattered-light measures indicate that the effective gas-to-dust ratio is anomalously high only for the region (the Orion Nebula) where the reddening law is strongly deviant. This makes it even nore important to investigate in detail the other regions found by Johnson to be anomalous and to derive the reddening law that holds for the stars located within NGC 6514 where there is strong proof of overabundant dust.

The fact that interstellar grains do exist in the H II regions in our Galaxy may be an important factor previously unaccounted for in the formulation of the ionization structure of a region of gas. The size-distribution law for particles derived by Oort and van de Hulst (1946) is consistent with the detailed observations of the reddening law in the low-density regions of the interstellar medium and predicts a rapidly decreasing frequency for particles larger than a critical size r_0. The detailed calculations of Krishna Swamy (1965) indicate that this critical size is about 1200 Å. The expected particle-size distribution for smaller particles is relatively flat so that the effective cross-section rapidly diminishes for these numerous small particles. Since we know the effective scattering cross-section for λ 4861 we can derive the predicted optical depth at λ 4861 for theoretical

TABLE 5

EXPECTED OPTICAL DEPTHS IN H II REGIONS

Spectral Type	$R(N=10^2\ \text{cm}^{-3})$ (pc)	$\tau_{\lambda\,4861}(N=10^2\ \text{cm}^{-3})$
O5	6.5	1.0
O8	2.8	0.5
B0	1.2	0.2
B3	0.5	0.1

nebulae. The results for a single exciting star in a homogeneous medium where the effective gas-to-dust ratio is $N_H/N_d\sigma_\lambda = 20 \times 10^{20}$ cm^{-2} are given in Table 5. The optical depth will roughly increase as $n^{1/3}$, where n is the number of stars of that spectral type in the gas cloud. These optical depths will be lower than those predicted for the far-ultraviolet since the particles important in scattering light at λ 4861 will project even larger cross-sections in addition to the effects of numerous smaller particles being more important. Following the calculations of Krishna Swamy we find for the theoretical ratios of the optical depths $\tau_{\lambda\,1216}/\tau_{\lambda\,4861} = 1.5$. For a very old nebula that has had sufficient time to force out the grains, the optical depths will be lower; but these estimates should hold for the more common young nebulae. Since only the true absorption component of this extinction coefficient will remove ionizing photons, the first effects of the additional internal scattering will not be as great as the simple optical depths might indicate. Even if the true absorption coefficient is only $\frac{1}{4}$ of the total effect, the results will still be important in any considerations of the transfer of Lyman-α photons which are very effectively trapped by the gas. The additional absorption would tend to decrease the predicted Strömgren radius and make the ionization decrease nearly linearly in the inner regions instead of being nearly constant.

The possibility of very small-scale fluctuations in the effective gas-to-dust ratio and the reddening-curve are certainly to be expected through the role of radiation pressure acting selectively on the smaller particles. The selective removal from the initial size distribution has been shown by Krishna Swamy and O'Dell (1966) to be able to generally reproduce the change in the shape of the reddening-curve found in the regions of hot stars where we observe that the ratio of total to selective extinction is larger than the average value. This result is that expected from the process of radiative expulsion and would only be expected for regions where the reddening occurs very close to the star.

The high dust content of NGC 6514 is perhaps significant in our understanding of the formation of interstellar grains. The characteristic time for grain growth by accretion of heavy elements is $T \simeq 6 \times 10^8/N_H$ years if the electron temperature is about 100° K and if the most effective grain size is about 0.2 μ. For NGC 6514 this would give a characteristic time of 10^7 years for the low temperature assumed and 10^6 years for the higher temperatures expected now (about 10^4 ° K). Thus, if the original cloud existed for a period of 10^7 years at its present density, but with no hot stars and hence a low electron temperature, then there would have been appreciable accretion and the effective gas-to-dust ratio would be reduced. If accretion continues to occur when the gas is largely ionized, then the time necessary to build up the grains would be quite short (10^6 years). If this interpretation of recent, rapid buildup in grain sizes is correct, then one might expect to find that the reddening law is different for this region. If it is not greatly different, the information can also be valuable in our understanding of the size distribution of the interstellar particles.

We can summarize the results of this investigation in the following manner: direct evidence by means of observations of the scattered light in H II regions provides proof of the existence of scattering particles, similar to the interstellar grains, in the diffuse nebulae; quantitative interpretation of the observations indicates that the effective gas-to-dust ratio is similar in NGC 6523 and NGC 6611 although the value is some 5 times larger than in NGC 6514; the dust content in the former nebulae is similar to that of the general interstellar medium; the high dust content in the region of NGC 6514 may be due to recent grain growth; true absorption by grains may be important in the transfer of Lyman-α radiation inside the nebulae and the determination of the ionization structure.

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