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ELECTRON DENSITIES IN FOUR H II REGIONS FROM 4-CM OBSERVATIONS

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ABSTRACT

Observations of NGC 6523, NGC 6611, NGC 7000, and IC 410 were made with the University of California 85-foot radio telescope at a wavelength of 4 cm. Using spherical models, one-dimensional rms electron density distributions were computed at an electron temperature of 8000° K. From these density profiles, and assuming that a systematic expansion exists, ages of these diffuse nebulae were estimated. These ages are considerably shorter than the element-burning lifetimes of the exciting stars

I. INTRODUCTION

If the gradient of the pressure and the velocity of expansion in an element of an H II region are known, we can place an upper limit on the time interval during which the pressure gradient has existed (Vandervoort 1963). This time interval may be called the "gradient age" of the H II region.

In the investigation reported here, we observed, at a wavelength of 4 cm, the free-free emission from four H II regions for the purpose of obtaining one-dimensional models of the root-mean-square electron density distributions. These objects are NGC 6523 (M8), NGC 6611 (M16), NGC 7000, and IC 410. Using our observational data, gradient ages for these nebulae were estimated.

II. OBSERVATIONS AND REDUCTIONS

a) Observations

The observations for this program were obtained with the 85-foot paraboloid of the Hat Creek Radio Observatory of the University of California. The half-power beam width was 6ʹ.6 in R.A. and 6ʹ.9 in declination. A Dicke, noise-compensated traveling-wave-tube radiometer was used (Drake 1960). An experiment made to determine the band pass of the radiometer found the mean frequency to be 7.56 GHz, with an effective band width of 205 MHz. The noise temperature of the over-all system was about 5000° K.

The main scanning procedure consisted of two sets of scans: one of east-west scans and one of north-south scans, each through the center of a source; the center-edge emission profile being thus examined at four position angles. The center of the cross pattern was selected on the basis of a preliminary observation program. The main program is summarized in Table 1, the columns of which present (from left to right) the object; the R.A. of scans at constant declination and the declination of scans at constant R.A.; the number of R.A. and declination scans used in the data reduction; the length of the scans, generally symmetric about the center coordinate; the main-beam brightness temperature of a comparison region ("comparison temperature"); the approximate optical dimensions; the center coordinates. The comparison regions for NGC 6523 and NGC 6611 were the centers of the sources. For NGC 7000, the region was Cyg A; for IC 410, Tau A. Comparison temperatures for NGC 6523 and NGC 6611 were determined by a procedure of alternately observing Cyg A and one of the comparison regions. In deriving compari-

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TABLE 1

OBSERVING PARAMETERS

	Scan Coordinates (1950.0)		No. α Scans Used	No. δ Scans Used	α Length	δ Length	T_{comp} (° K)	Dimensions ($\alpha \times \delta$)	Center (1950.0)	
	α	δ							α	δ
NGC 6523 .	$18^h00^m54^s$	−24°22′	10	10	3°2	2°0	4.9	1°0×0°7	$18^h00^m51^s$	−24°24′
NGC 6611 .	18 16 03	−13 47	10	10	2.9	2.0	1.9	1.0×0.8	18 15 58	−13 46
NGC 7000 .	20 50 26	+44 05	12	16	4.1	4.2	28.7	3 0×3 0	20 51 54	+43 55
IC 410. .	05 18 59	+33 24	14	11	2.1	2.0	85.0	0.5×0.5	05 19 01	+33 23

son temperatures from observations of Tau A and Cyg A, we used 4-cm flux densities taken from spectra published by Conway, Kellermann, and Long (1963); source distribution correction factors from Baars, Mezger, and Wendker (1965); and polarization data from Baars, Mezger, and Wendker. No calibration of the radiometer noise tube with a hot-cold load was performed at the time of this observation program, so antenna temperatures are not listed.

b) *Reductions*

The sample time (8 sec for declination scans) was chosen so as to allow each data point, when scanning at a continuous even rate, to correspond to a 2′ interval in the sky.

The reduction of data involved four steps. (1) Digital recordings of each usable scan across an object were calibrated by reference to observations of the comparison regions. In general, each pair of scans across a nebula was preceded and followed by an observation of the appropriate comparison region. (2) Scans were averaged to provide plots of brightness temperature as a function of R.A. and declination. These plots are reproduced in Figure 1, *a–h*. The center coordinates inferred from them are listed in Table 1, last

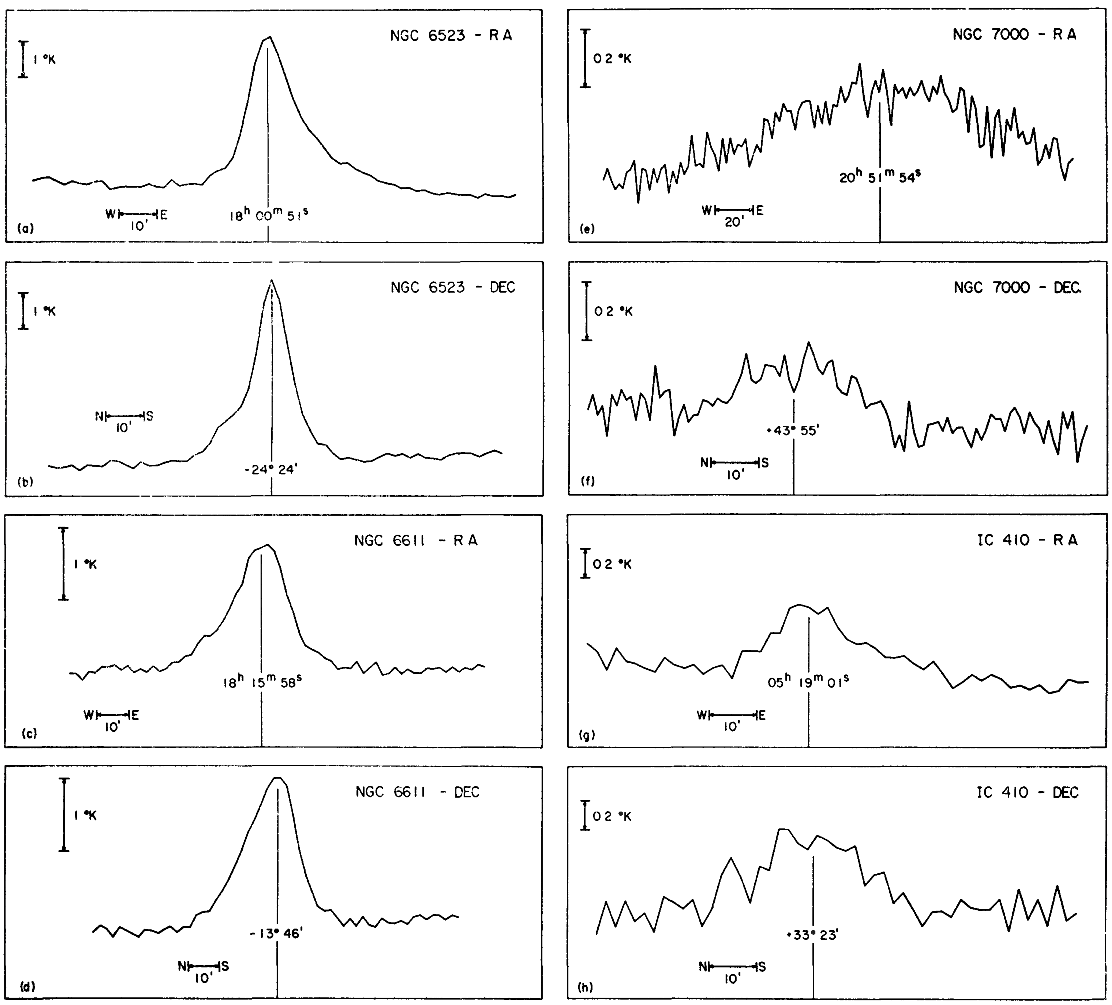

FIG. 1 —Averaged profiles of main-beam brightness temperature These profiles are presented to illustrate the degree of departure from circular symmetry of the objects as observed (*a*) and (*b*), NGC 6523; (*c*) and (*d*), NGC 6611; (*e*) and (*f*), NGC 7000; (*g*) and (*h*), IC 410.

column; the estimated error for NGC 6523 and NGC 6611 is $\pm 3'$. (3) Base lines were subtracted from these plots, which were then smoothed with the aid of probable error values, and adjusted for antenna broadening using Bracewell's (1955) graphical method. The term "base line" implies that the four objects observed are separable from the background of galactic emission and that only the object under study is in the line of sight. For NGC 7000, considerable uncertainty existed as to the base line, and that judged least unreasonable was drawn. (4) The several center-edge temperature profiles for an object were averaged together to provide a single temperature profile to use in constructing a density model.

Mezger and Henderson (1967) have mapped NGC 6523 and NGC 6611 at a wavelength of 6 cm, using a telescope with a half-power beam width approximately equal to 6′.4. Since $T_b \propto \lambda^{2.1}$ for optically thin H II regions, it follows that their peak values of main-beam brightness temperature should be expected to exceed those found in this investigation by a factor of 2.4. The ratios are, in fact, 2.3 for NGC 6523 (taking the mean from Fig. 1, *a* and *b*) and 2.9 for NGC 6611 (taking the mean from Fig. 1, *c* and *d*). This represents agreement to within our estimated errors.

III. DERIVATION OF RESULTS

a) *Electron Densities*

On the basis of our observations as presented in Figure 1, *a–h* and especially from contour maps which have been obtained at the National Radio Astronomy Observatory by Lynds (1961), by Terzian (1965), and by Mezger and Henderson (1967), it is clear

TABLE 2

DISTANCES

	R (pc)	$\Delta R/R$	References
NGC 6523	1400	0 14	Johnson *et al.* (1961)
NGC 6611	2500	18	Johnson *et al.* (1961)
NGC 7000	420	15	Beer (1964)
IC 410	4000	0 14	Johnson *et al* (1961)

that the four nebulae being considered here do not present symmetric circular discs at microwave frequencies. Besides knots and condensations, they exhibit a rough ellipticity, with a ratio of major to minor axes up to about 2 to 1. Nevertheless, we went ahead and fitted our 4-cm data for each object to a spherical model.

We will assume that the nebulae are composed of ionized H plus singly ionized He, that the electron temperatures equal a uniform 8000° K, and that the optical depths at the observing frequency are much less than unity. Then, employing the free-free absorption coefficient given by Oster (1961), we have, for a frequency equal to 7.56 GHz,

$$T_b = 2.25 \times 10^{-5} \int N_e^2 ds \, . \tag{1}$$

Here, T_b = brightness temperature, N_e = electron density, and the units of path length are in parsecs. If a model of a diffuse nebula is specified, the solution of this integral equation yields the rms electron density. Our spherical model was approximated by a set of concentric spherical shells and equation (1) was solved, using a digital computer program, for successive shells, starting with the outermost and working inward. An adaptation of an expression derived for stellar clusters by Wallenquist (1933) was used. The resulting density profiles are plotted in Figure 2, *a–d*. The estimated errors at representative points along the profiles are indicated by the vertical lines.

The distances, R, in pc used in computing N_e are given in Table 2, together with estimated errors and references. NGC 6523 is assigned the distance of the associated cluster

NGC 6530, as listed by Johnson, Hoag, Iriarte, Mitchell, and Hallam (1961); these authors reported a probable error in distance modulus $\Delta(m - M) = \pm 0.3$ mag, corresponding to $\Delta R/R = 0.138$. NGC 6611 is, similarly, assigned the distance of the associated cluster as listed by the same authors, who give $\Delta(m - M) = \pm 0.4$ mag. NGC 7000 is stated in the catalogue of Sharpless (1959) to have HD 199579 as an exciting star; the distance and error adopted for this star is from Beer (1964). IC 410 contains the cluster NGC 1893; the distance and error for NGC 1893 is from Johnson *et al.* (1961). N_e varies as (distance)$^{-1/2}$ and our values for density may be scaled accordingly.

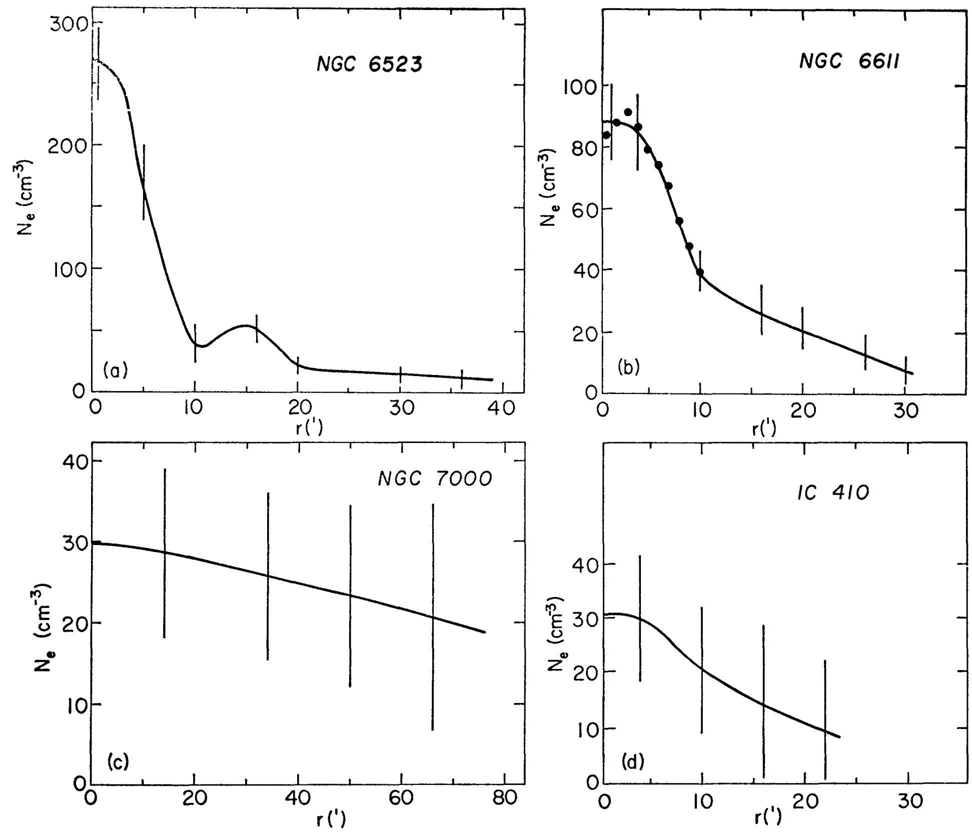

FIG 2.—The rms electron density as a function of radius The vertical lines indicate the estimated errors (*a*), NGC 6523; (*b*), NGC 6611; (*c*), NGC 7000; (*d*) IC 410.

Three factors were considered in estimating errors: (1) error in main-beam brightness temperatures of comparison regions; (2) statistical uncertainty in the T_b profiles illustrated in Figure 1; and (3) distance uncertainty As an absolute calibration of the temperature scale was not made, systematic errors in comparison temperatures may arise from our choice of 4-cm flux densities for Tau A and Cyg A, and, in the case of NGC 6523 and NGC 6611, from our procedure of calibrating the comparison regions for these two objects. We made six observations of the center of NGC 6523; five of the center of NGC 6611, along with eleven of Cyg A. The resulting probable error in the temperatures listed in Table 1 is, for NGC 6523: 21 per cent; for NGC 6611: 18 per cent. These errors are larger than would be expected from our estimates of the system noise-temperature. A possible explanation is discontinuous change in the radiometer gain, when the direction of the antenna beam was shifted. At a given angular distance from the center of an object, the error in N_e from statistical uncertainty in the T_b profiles, and from distance uncertainties, was taken to be a weighted mean calculated from the rms values of $\Delta T_b/T_b$ for the center-edge profiles, and from the distance uncertainties as listed in Table 2. The weighting factor was the N_e factor yielded by equation (1), when applied to the T_b values for a single profile.

Our profiles for NGC 6523, NGC 6611, and IC 410 agree generally with the values reported, on the basis of radio observations, by other investigators (cf. Terzian 1965; Mezger and Henderson 1967). The NGC 6611 profile, shown in Figure 2, *b*, has been somewhat smoothed right at the centeı, where the points given by our computer program are indicated by dots.

In constructing the profile for NGC 7000, illustrated in Figure 2, *c*, only the scans in R.A. were used. The set of scans in declination were probably not made at the R.A. of maximum emission of this low surface-brightness object, as inferred from the 1420 MHz map of Lynds (1961). Our NGC 7000 profile indicates a slow decrease in N_e with radius. The estimated errors show that the possibility of a constant density, or of a central hole, cannot be dismissed. Westerhout (1958) listed a density which, when adjusted for differences in adopted distance, becomes $N_e \simeq 20$. This is similar to the average density from the present investigation.

b) Gradient Ages

We assume: (1) a spherical gas cloud is at rest relative to the exciting stars before it begins to be ionized by the Lyman continuum radiation from the stars; (2) the passage of the ionization front does not change the density distribution or the velocity field; (3) spherically symmetric outward acceleration, constant for a mass element, commences, and this outward acceleration is caused only by the pressure gradient; (4) the ionized nebula is isothermal; (5) the degree of density fluctuation is the same throughout the nebula.

The outward acceleration at radius r is

$$a(r) = \frac{-1}{\mu M_{\rm H} N_e} \frac{dP(r)}{dr}, \tag{2}$$

where $M_{\rm H}$ is the mass of the hydrogen atom and μ = molecular weight. The pressure, $P(r)$, is:

$$P(r) = 2N_e(r)kT_e\,. \tag{3}$$

If $v(r)$ is the present expansion velocity function, the corresponding age $t(r)$ is:

$$t(r) = \frac{v(r)}{a(r)} = -\,v(r)N_e(r)\frac{\mu M_{\rm H}}{2kT_e}\left[\frac{dN_e(r)}{dr}\right]^{-1}. \tag{4}$$

For the calculation of a gradient age, an increment Δr of a density distribution profile was selected, with a corresponding density increment ΔN_e, a value of N_e equal to the density of the midpoint of the increment, and a value of v equal to the expansion velocity at the midpoint. Then we write

$$t = -\,vN_e\frac{\mu M_{\rm H}}{2kT_e}\left(\frac{\Delta N_e}{\Delta r}\right)^{-1}. \tag{5}$$

To apply equation (5), an estimate of expansion velocity is required, a parameter difficult to determine observationally, principally because of differential motions of mass elements in a nebula. We know of no published velocity functions for the four nebulae observed for this study. Courtès (cited by Pottasch 1965) has, however, studied with an interferometer the Hα widths of NGC 6523, NGC 6611, and NGC 7000. These widths are found by Pottasch to be consistent with no expansion, or expansion with $v < 5$ km/sec.

For calculation of the gradient age, itself an upper limit on the time since ionization, we accordingly used 5 km/sec as the present expansion velocity for all four nebulae, in those parts of the nebular volumes selected for the age computations. The parts of the volumes selected were those having the largest density gradients.

The ages calculated from equation (5) are presented in Table 3, together with relevant data. The radii of the midpoints of Δr are listed in the second column; the increments Δr in the third column; ΔN_e in the fourth column; the related mean densities in the fifth column; the ages in the sixth column. Δr is symmetric about r; ΔN_e about N_e. A molecular weight of 0.625 was assumed, as well as $T_e = 8000°$ K. In view of our many assumptions and uncertainties, we have perhaps only an order-of-magnitude estimate of the ages of these nebulae, and we indicate this in the seventh column.

TABLE 3

GRADIENT AGES, ASSUMING A SYSTEMATIC EXPANSION OF 5 KM/SEC

	$r(')$	$\Delta r(')$	ΔN_e	N_e	$t \times 10^{-4}$ yr	Range $\times 10^{-4}$ yr
NGC 6523	6 5	5	160	123	3 7	$1\ 2 < t < 12$
NGC 6611	7	6	46	65	14	$4\ 5 < t < 45$
NGC 7000	40	20	3	24	46	$14 < t < 140$
IC 410	16	12	11	14	42	$13 < t < 130$

V. DISCUSSION

The aim of this investigation has been to obtain electron density profiles of some H II regions and to deduce ages from these profiles. Our ages may be compared with the lifetimes of the exciting stars. For NGC 6523 and NGC 6611, O5 types are the principal exciting stars; for NGC 7000 and IC 410, O6. A 30 $M_\odot$ star may be O6 on the main sequence (Landolt-Bornstein 1965). The evolution of a 30 $M_\odot$ star has been studied by Stothers (1966), who finds that the lifetime (up to iron-core formation) is $\sim 550 \times 10^6$ yr, of which 480×10^6 yr is spent in the hydrogen-burning phase. Thus we conclude, granting the assumptions made in deriving gradient ages, that the four bright H II regions studied here are illuminated by young stars: that is, stars whose ages are of the order of 1–20 per cent of their evolutionary time scales.

Some age determinations based on dynamical theories have been made for H II regions. For the Orion Nebula, Vandervoort (1964) has found a probable age of ~ 20000 yr; our gradient age for NGC 6523 is ~ 40000 yr. Mathews (1967) has deduced an age equal to $\sim 4 \times 10^5$ yr for the Rosette Nebula; the gradient age for IC 410 is of the same order of magnitude.

Walker (1957, 1961) has estimated ages for NGC 6530 (the cluster associated with NGC 6523) and for the NGC 6611 cluster from the points at which the cluster sequence departs from the zero-age main sequence: these ages are 3×10^6 yr (or slightly less) and 1.8×10^6 yr, respectively. Our gradient ages for the H II regions imply that these two objects are, along with their exciting stars, probably considerably younger than the associated clusters. Such a conclusion is in accord with the hypothesis (Herbig 1962) that in our part of the Galaxy, at the present epoch, star formation in a cluster or association may take place over a long interval of time.

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