HYDROGEN CONTENT OF YOUNG STELLAR CLUSTERS

I. METHODS OF OBSERVATION AND REDUCTION

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Abstract

Observations of 16 open galactic clusters in their continuum emission and at the neutral hydrogen line have been made with the Parkes 64 m radio telescope in an attempt to determine the total amount of hydrogen gas associated with them. In this, the first of a series of five papers, the observing procedure and the method of data reduction are described.

Introduction

It is widely accepted that stellar O-associations are regions of recent formation. The youngest members of these associations are O-type stellar clusters (Markarian 1950, 1951), which are found in the nuclei and are distinguished by the presence of an O or at least a B0 star. Markarian (1957) has pointed out that bright emission nebulae are generally associated with O-type stellar clusters if the brightest member of the cluster has a spectrum not later than O8 while, if the cluster contains no stars earlier than spectral type O9, it does not as a rule have a visible nebula in its vicinity. From this, Markarian concluded that the connection between an O-type cluster and an emission nebula was not the result of a random encounter but was of a genetic nature, and that the age of clusters associated with nebulosities was of the order of 10^5 years. These conclusions are consistent with Ambartsumian's (1947) hypothesis of the simultaneous origin of stars and their accompanying gas clouds from superdense protostellar matter. According to this hypothesis, the amount of gas associated with a particular cluster depends upon the peculiar conditions of the origin of that cluster and so may vary in different clusters.

On the other hand, the contraction hypothesis of stellar formation (for references, see Drake 1958) permits an estimate to be made of the minimum amount of associated protostellar gas which, on this hypothesis, has not yet had time to contract to the stellar state. We may therefore expect the relative gas content M_g/M_s (the ratio of gaseous to stellar mass) for O-type stellar clusters to be approximately equal since all such clusters are of roughly equal age. Consequently the determination of the total amount of hydrogen associated with stellar clusters is of great importance as it provides a means of checking the two hypotheses of star formation.

The total gas content of stellar clusters may be determined from observations of both the continuum emission and the hydrogen line. Continuum measurements of ionized clouds have the advantage of not being affected by possible absorption in the galactic plane where open clusters are generally distributed, while 21 cm line observations have the advantage that they reveal the invisible neutral hydrogen content of

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O-type clusters. Observations made in the continuum and at the hydrogen line provide not only measurements of the total amount of ionized and neutral hydrogen but, used in conjunction with each other, they also provide a general means for establishing or rejecting associations between nebulae and stellar clusters.

The first measurements of the neutral hydrogen content of stellar clusters were made by Drake (1958) for five clusters of different ages, while measurements of the masses of ionized hydrogen nebulae were made by Westerhout (1958) and of the total amount of hydrogen gas in several clusters by Davies and Tovmassian (1963). Studies of stellar clusters and associations or of ionized clouds associated with clusters have been made by Terzian (1965), Raimond (1966), Gordon *et al.* (1968), Mezger and Henderson (1967), and others, the observations being made at the 21 cm line, in the continuum, or at hydrogen recombination lines.

TABLE 1

OPTICAL DATA FOR OBSERVED CLUSTERS

Cluster NGC	Position (1950) R.A.	Dec.	Gal. coords. l^{II}	b^{II}	d* (kpc)	V_{lsr}* (km s^{-1})
2175	06^h 06^m·8	+20° 30′	190°·1	+0°·4	2·0	+10
2264	06 38 ·3	+09 56	202 ·9	+2 ·2	0·76	−26
2353	07 12 ·2	−10 13	224 ·7	+0 ·4	1·0	+7
2362	07 16 ·7	−24 51	238 ·0	−5 ·5	1·5	+15
3293	10 33 ·9	−57 58	285 ·8	+0 ·1	2·6	−26
6167	16 30 ·8	−49 40	335 ·2	−1 ·4	1·3?	—
6193	16 37 ·8	−48 40	336 ·7	−1 ·6	1·2	−3
6200	16 40 ·5	−47 28	338 ·0	−1 ·1	2·5?	—
6204	16 42 ·3	−46 56	338 ·5	−1 ·0	2·5	−37
6231	16 50 ·5	−41 43	343 ·4	+1 ·2	2·0	−21
6383	17 31 ·5	−32 32	355 ·7	+0 ·0	1·2	+5
6514	17 59 ·3	−23 02	7 ·0	−0 ·2	1·6	−6
6531	18 01 ·6	−22 30	7 ·7	−0 ·4	1·2	−3
6604	18 15 ·3	−12 15	18 ·3	+1 ·7	1·4	+13
6611	18 16 ·0	−13 48	17 ·0	+0 ·8	2·6	+34
6823	19 41 ·0	+23 11	59 ·4	−0 ·1	2·6	+30

* References for distances and radial velocities are given in the ensuing Parts II–V of this series of papers. The quoted radial velocities are related to the local standard of rest defined by the "standard" solar motion (20 km s^{-1} toward R.A. = 18^h, Dec. = +30° (1900)).

The present observations of 14 O-type clusters in the continuum at 1410 MHz and at the 21 cm line were taken with the 64 m steerable radio telescope of the ANRAO at Parkes in an attempt to determine the total amount of hydrogen gas associated with them. The list of the clusters observed is given in Table 1. The probable clusters NGC 6167 and 6200 have been included because of their close proximity to NGC 6193 and 6204. Although some of the clusters are in the region of a continuum survey made with the same equipment (Hill 1968), it is hard, and sometimes almost impossible, to obtain measurements of the masses of individual clouds from Hill's results. The present clusters were selected for study because they possessed angular dimensions comparable with the telescope's beamwidth, which was $\sim 14'$ arc at 1410 MHz, and because their radial velocities were known from optical measurements. A knowledge of the latter was necessary for establishing associations between the neutral hydrogen nebulae detected and the clusters under investigation.

In the present paper, the continuum and line observations and the methods of data reduction are described. The results of the observations are given in Part II (Tovmassian and Shahbazian 1973, present issue pp. 837–42), Part III (Tovmassian *et al.* 1973*a*, present issue pp. 843–51), Part IV (Tovmassian *et al.* 1973*b*, present issue pp. 853–60), and Part V (Tovmassian and Nersessian 1973, present issue pp. 861–6) of this series of papers. An astrophysical discussion will be given elsewhere.

Observations and Reductions

Continuum Observations

The present continuum observations were taken in August 1965. A 1410 MHz receiver (Gardner and Milne 1963) was used which consisted of a degenerate parametric amplifier followed by a crystal mixer and possessed a bandwidth of 10 MHz and a system noise temperature of 100 K. The receiver was switched between the feed and a backward-looking horn. The observations were smoothed with a 2 s time constant and peak-to-peak noise fluctuations were 0·15 K.

In the course of the observations, several scans in right ascension, declination, or occasionally in both coordinates were made over a region containing each cluster, which usually comprised an area about 100 times that of the cluster. The scans were taken at a rate of $0^\circ{\cdot}5\ \mathrm{min}^{-1}$, with consecutive scans being displaced relative to each other by 10′ arc. After every two or three scans, the scan through the centre of the cluster was repeated as a check on the zero level. An arbitrary zero level was adopted for each cluster since our aim was to search for hydrogen clouds associated with clusters, i.e. to search for excess radiation above the background in the vicinity of the cluster position, and for this reason no absolute measurements of the background temperature were made. The calibration of the equipment was monitored by frequent injection of a known signal from a discharge lamp into the input of the receiver while, for the overall calibration of the system, standard point sources such as Hydra A, 3C 98, 3C 353, etc. were observed. The relative flux densities obtained are most likely accurate to within 3% to 5%.

The flux densities S of the observed sources were derived by integrating the contours of full-beam brightness temperature T_b according to the relationship

$$S = 2k\lambda^{-2} \int_{\mathrm{source}} T_\mathrm{b}\, \mathrm{d}\Omega\,, \qquad (1)$$

where k is Boltzmann's constant, λ the wavelength, and Ω the solid angle. The brightness temperature scale was fixed by observing standard point sources, for which equation (1) reduces to

$$S = 2k\lambda^{-2}\, T_\mathrm{bp}\, \Omega_\mathrm{FB}\,, \qquad (2)$$

where T_bp is the peak apparent brightness temperature of the point source and Ω_FB

is the effective full-beam solid angle obtained by integrating the beam contours for a point source. According to Cooper *et al.* (1965), $\Omega_{FB} = 1\cdot 83\times 10^{-5}$ sr for the present equipment, and this yields $S = 1\cdot 1\, T_{bp}$, where S is expressed in flux units.*

Contours of equal brightness temperature for each of the observed nebulae were drawn after subtracting the background radiation. In most instances, as for NGC 2175 or 6611, this was readily done, since the distribution of background emission was generally smooth. However, for some sources, such as NGC 3293 and 6514, it was hard to distinguish between the radiation of the nebula associated with the cluster and that of the complicated background. Arbitrariness in correcting for the background radiation in these cases increased the errors of flux density measurements and hence of the estimates of electron density and mass of ionized hydrogen in the nebulae.

From a knowledge of the flux density of a thermally emitting nebula together with the assumptions that it is spherical in form and optically thin, we may determine the average electron density N_e (cm^{-3}) and the total mass of ionized hydrogen M_{HII} ($M_\odot$) from expressions given by Mezger and Henderson (1967) or Terzian (1968). Terzian's relations are

$$N_e = 4\cdot 91\times 10^2 (10^{-4}T_e)^{0\cdot 18}\, \nu^{0\cdot 05}\, S_\nu{}^{0\cdot 5}/d^{0\cdot 5}\,\theta^{1\cdot 5} \tag{3}$$

and

$$M_{HII} = 0\cdot 5 (10^{-4}T_e)^{0\cdot 18}\, \nu^{0\cdot 05}\, S_\nu{}^{0\cdot 5}/d^{-2\cdot 5}\,\theta^{-1\cdot 5}, \tag{4}$$

where T_e (K) is the electron temperature of the nebula, ν (GHz) the observing frequency, S_ν (f.u.) the flux density of the nebula, d (kpc) the distance to the nebula, and θ (min arc) the angular half-power width of the nebula as observed in the continuum. The value of θ was computed from the relation $\theta = (\theta_o^2 - \theta_a^2)^{\frac{1}{2}}$, where θ_o is the observed half-width and θ_a is the half-width of the antenna beam. In the case of noncircular sources, the geometric mean value of θ for the nebula was used. For $\nu = 1\cdot 4$ GHz and an assumed value for T_e of 10^4 K,† equations (3) and (4) become

$$N_e = 5\times 10^2\, S_\nu^{\frac{1}{2}}/\theta(\theta d)^{\frac{1}{2}} \tag{5}$$

and

$$M_{HII} = 0\cdot 51\,\theta d^2 (\theta d S_\nu)^{\frac{1}{2}}. \tag{6}$$

Expressions (5) and (6) were used to obtain the electron densities and masses of ionized clouds that are reported in Parts II–V of this series of papers (Tovmassian and Shahbazian 1973; Tovmassian *et al.* 1973*a*; Tovmassian *et al.* 1973*b*; Tovmassian and Nersessian 1973). (In a preliminary report of the present continuum observations (Tovmassian 1967), peak antenna temperatures were used instead of integrated flux densities and the calculated electron densities and cloud masses given were to this extent incorrect.)

The experimental errors in the present integrated flux densities and angular extents of HII regions may be as large as 30% to 50% owing to uncertainties in the correction for the base level and the presence of neighbouring stronger sources.

* 1 f.u. (flux unit) = 10^{-26} W m^{-2} Hz^{-1}.

† It should be noted that expressions (3) and (4) vary as $T_e^{0\cdot 18}$ and so are fairly insensitive to small errors in the value assumed for T_e.

In addition, uncertainties in the cluster distances of about the same order of magnitude result in maximum errors of $\sim 200\%$ in the calculated electron densities and masses of ionized hydrogen, although the actual errors would generally be smaller than this as it is unlikely for all error components to have the same sense.

Hydrogen-line Observations

The hydrogen-line observations were made during three sessions in March, June, and October 1965. All of the clusters reported on in the present series of five papers were observed with the 48-channel wide-band receiver described by McGee and Murray (1963) while, in addition, some of the clusters (NGC 2264, 2362, 3293, 6193, 6204, 6231, and 6531) were also observed with a 15-channel narrow-band receiver during the June session. A circular waveguide horn was installed at the focus of the 64 m telescope. The resultant beam of the telescope was very nearly a circular Gaussian (Kerr 1969) with a half-width of $14' \cdot 5$ arc.

The 48-channel wide-band receiver had channels with bandwidths of 37 kHz that were spaced at $33 \cdot 2$ kHz, or $7 \cdot 0 \text{ km s}^{-1}$ in radial velocity at 21 cm. With an output time constant of 65 s, the r.m.s. noise fluctuations in individual channels were ~ 1 K. The calibration of the receiver was made by injection of a modulated wideband noise signal of about 60 K from an argon discharge lamp into the feed horn. The base level for the profiles was referred to the south celestial pole (hereinafter referred to as SCP). The stability of the local oscillator frequencies and those of the 48 filters permitted the velocities to be determined with an accuracy of about $\pm 0 \cdot 2 \text{ km s}^{-1}$.

As the aim of the present observations was the detection of small-scale hydrogen features in the immediate vicinity of stellar clusters, the scanning was carried out in galactic coordinates. Scans at constant galactic latitude were taken through the centre of each cluster and also through positions shifted in galactic latitude by about $\pm 6'$, $\pm 12'$, $\pm 18'$, $\pm 24'$, and $\pm 30'$ arc. Scans at constant galactic longitude were also taken but these were mainly confined to scans through the cluster centres. Central scans were about $2°$ or more in length while adjacent scans were usually shorter. The scanning rate was $3' \text{ arc min}^{-1}$. As the 48-channel outputs were recorded sequentially over a period of 2 min, one profile was recorded every $6'$ arc, a little less than half a beamwidth.

The 15-channel narrow-band receiver had channels with bandwidths of 10 kHz that were spaced by $9 \cdot 5$ kHz, or 2 km s^{-1} in radial velocity at 21 cm. Despite the use of filters with narrower bandwidths than previously, the same sensitivity was maintained through a compensating increase in observing time, which was achieved by employing sidereal following instead of drift scanning. Each observed point was recorded four times and mean values of the channel outputs were obtained. The observed points were generally spaced $6'$ arc apart, mainly in galactic longitude through the centre of the corresponding cluster. However, for some clusters, observations were also carried out at adjacent positions that were shifted in galactic latitude as previously described for the wide-band observations.

For both receivers, the results were recorded digitally and by a conventional chart recorder, the latter being used for monitoring purposes and for subsequent checking. The digital system has been described by Hindman *et al.* (1963). The initial computer reductions involved correcting the profiles for the gain factor, derived from the noise tube calibrations, and for the SCP baseline. These reductions were carried out on the CDC-3200 computer of the Division of Computing Research, CSIRO, at Sydney, with the program described by Kerr (1969). The analysis was mainly confined to that of the drift contours but, in some cases, computer-drawn contour maps of the velocity-longitude plane were also used (see Kerr 1969). Antenna temperatures were converted to full-beam brightness temperatures by means of the factor $1 \cdot 25$ (Kerr 1969).

The density of neutral hydrogen atoms $N_{\rm HI}$ ($\rm cm^{-3}$) in the nebulae was determined from

$$N_{\rm HI} = 1\cdot 835 \times 10^{13}\, T_{\rm b} \Delta V_{\rm r}/l, \tag{7}$$

where $\Delta V_{\rm r}$ ($\rm cm\,s^{-1}$) is the half-power linewidth of the nebula in radial velocity and l (pc) is the length of the nebula in the line-of-sight direction. If the latter corresponds to the half-width of the observed nebula, equation (7) may be simplified to

$$N_{\rm HI} = 2\cdot 1\, T_{\rm b} \Delta V_{\rm r}/\phi d, \tag{8}$$

where ϕ (min arc) is the angular half-width of the nebula as observed at the hydrogen line. As for the continuum observations, the value of ϕ was computed from the relation $\phi = (\phi_{\rm o}^2 - \phi_{\rm a}^2)^{\frac{1}{2}}$. The maximum error in the neutral hydrogen density due to uncertainties in $T_{\rm b}$ ($\sim 20\%$), $\Delta V_{\rm r}$ ($\sim 20\%$), ϕ ($\sim 20\%$), and d ($\sim 30\%$) is about a factor of two. As for the continuum results, the actual error would usually be smaller, since all its components would rarely have the same sense. The total mass of neutral hydrogen may then be determined, on the assumption of a spherical model for the cloud, from

$$M_{\rm HI} = 6\cdot 6 \times 10^{-4}\, T_{\rm b}\, \phi^2\, d^2\, \Delta V_{\rm r}, \tag{9}$$

with a larger maximum error of $\sim 150\%$. In Parts II–V (Tovmassian and Shahbazian 1973; Tovmassian *et al.* 1973*a*; Tovmassian *et al.* 1973*b*; Tovmassian and Nersessian 1973), equations (8) and (9) are used to derive the density and mass of neutral hydrogen clouds.

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