HYDROGEN CONTENT OF YOUNG STELLAR CLUSTERS

IV.* CLUSTERS NGC 6231, 6383, 6514, AND 6531

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Abstract

The total amount of hydrogen associated with the young stellar clusters NGC 6231, 6383, 6514, and 6531 has been obtained from observations in the continuum at 1410 MHz and in the hydrogen-line emission. NGC 6231 contains in its southern part a cloud of neutral hydrogen atoms of density 6 cm^{-3} and total mass 100 $M_{\odot}$ and in its northern part a small ionized cloud of the same density and a mass of $\sim 50\,M_{\odot}$. NGC 6383 is embedded in a large neutral hydrogen complex, of which a small part of mass $\sim 450\,M_{\odot}$ is ionized. The Trifid nebula is ionized by a single O7-type star at nearly twice the accepted distance of NGC 6514 and the existence of NGC 6514 as a physical cluster appears to be doubtful. The mass of the ionization-bounded Trifid nebula is nearly 5000 $M_{\odot}$. Neither neutral nor ionized hydrogen was found in association with NGC 6531.

Introduction

The results of 21 cm line and continuum observations of the O-type stellar clusters NGC 6231, 6283, 6514, and 6531 are presented. The methods of observation and reduction are described in Part I (Tovmassian 1973, present issue pp. 829–35).

Measurements and Results

NGC 6231

The cluster NGC 6231, which contains several early O-type stars, forms the nucleus of the association Sco. OB1. An unusual HII region in the shape of an elliptical ring, about 4° × 5° in extent, surrounds the association and is centred on the cluster, which is only 26′ arc in diameter (Seggewiss 1968). Bok *et al.* (1955) suggested that the HII region was probably associated with the cluster. The presence of an irregular dark nebulosity in the immediate vicinity of the cluster has been reported by MacRae (1940) and later by Breckinridge and Kron (1963), who found that most of the reddening occurred in the southern part of the cluster. Recently Sanduleak (1968) and Seggewiss (1969) found two extremely red stars in the same region and this would indicate the presence of an appreciable amount of dust matter there.

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Our hydrogen-line observations made with the narrow-band receiver reveal a neutral hydrogen cloud near the cluster position (Fig. 1(*a*)), while the drift curves taken across the galactic plane with the wide-band receiver show that this cloud is located in the southern part of the cluster. The radial velocity of the cloud, about $-24\ \mathrm{km\,s^{-1}}$, is similar to that of the cluster, the mean radial velocity of 13 OB stars of the cluster being $-21\cdot4\ \mathrm{km\,s^{-1}}$ (Rubin *et al.* 1962). We suggest that this neutral hydrogen cloud is associated with the cluster and consider that it is able to survive in a neutral state in the immediate neighbourhood of the O-type stars of the cluster owing to the presence of appreciable amounts of dust. The diameter of the cloud is $\sim 20'$ arc, its brightness temperature nearly 14 K, and the linewidth at half-power $8\ \mathrm{km\,s^{-1}}$. According to recent determinations, the cluster is at a distance of ~ 2 kpc (Buscombe 1963; Bok *et al.* 1966; Feinstein and Ferrer 1968; Seggewiss 1968; Schild *et al.* 1969) and this yields a hydrogen atom density for the cloud of $6\ \mathrm{cm^{-3}}$ and a total mass of $\sim 100\,M_{\odot}$.

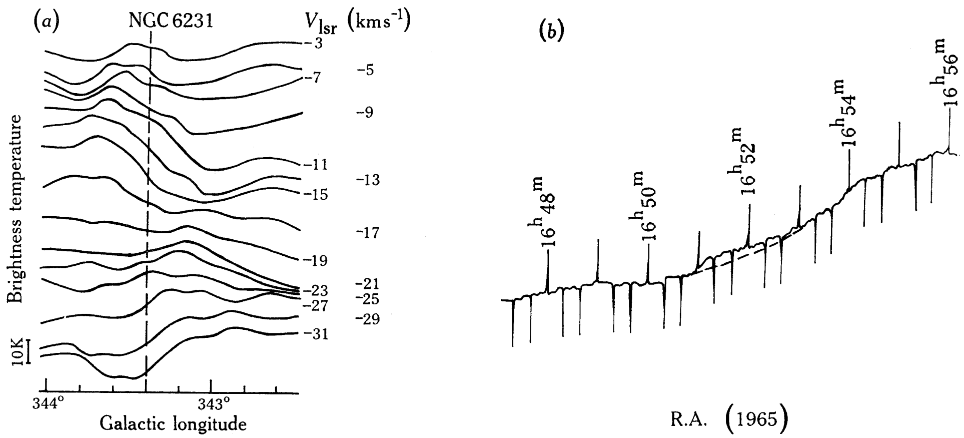


Fig. 1.—NGC 6231. (*a*) Drift curves of hydrogen-line emission taken with the narrow-band receiver along the galactic plane through the centre of the cluster. (*b*) Drift curve of continuum emission taken at 10′ arc north of the cluster centre. The right ascension marks are for the epoch of observations (1965).

Our continuum observations reveal a small weak source in the northern part of the cluster, where the earliest stars are situated (Breckinridge and Kron 1963). This source, which may be seen on the drift curve of continuum emission taken at 10′ arc north of the cluster centre (Fig. 1(*b*)) has a diameter of $\sim 10'$ arc and a total flux density of only $0\cdot3$ f.u. On the assumptions that the source is at the distance of the cluster and that its emission results from ionized hydrogen associated with the cluster, we obtain an electron density of $6\ \mathrm{cm^{-3}}$ and a total mass of $45\,M_{\odot}$. The exact agreement between the densities of the neutral and ionized clouds confirms the suggestion that the latter is the ionized part of the former and that it also is connected with NGC 6231. If the depth of the ionized cloud along the line of sight equals its height in the perpendicular direction, we obtain a value for its emission measure of $\sim 350\ \mathrm{pc\,cm^{-6}}$, which would indicate that the ionized cloud could hardly be observed by optical means. Thus, if the cluster NGC 6231 is connected with both detected clouds, the total gas content in its immediate vicinity would be at most 150 $M_{\odot}$.

NGC 6383

NGC 6383 is a small cluster in the direction toward the galactic centre and this makes the analysis of the observational data particularly difficult. The isophotes of continuum emission in the neighbourhood of the cluster (Fig. 2(*a*)) show several emission features, one of which coincides fairly well with the location of the cluster and is probably associated with it. Rough estimates obtained from the original drift curves yield a total flux density for this source of ~30 f.u. and a diameter of slightly more than 20′ arc. At a distance of 1·2 kpc, that of the cluster (Eggen 1961; Buscombe 1963), the cloud would have a density of ~25 cm^{-3} and a mass of 450 $M_{\odot}$.

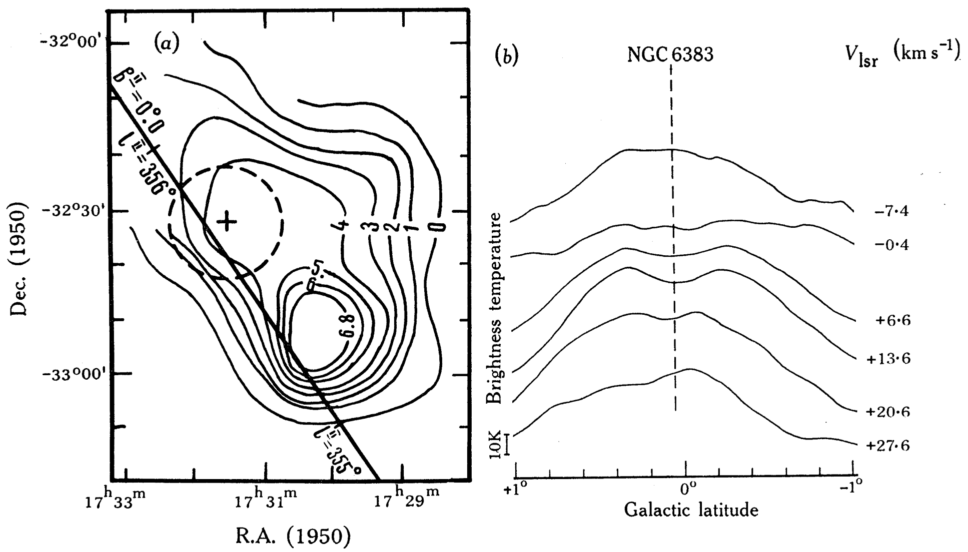


Fig. 2.—NGC 6383. (*a*) Isophotes of brightness temperature in kelvins at 1410 MHz above the galactic background emission, with the position of the cluster indicated by a dashed circle. (*b*) Drift curves of hydrogen-line emission taken with the wide-band receiver across the galactic plane through the centre of the cluster.

Our hydrogen-line observations confirm the association of this cloud with the cluster. Drift curves taken across the galactic plane through the cluster show definite dips (Fig. 2(*b*)) just at the cluster position for radial velocities of +7 and +14 km s^{-1}, which are similar to that of the cluster. The radial velocity of the brightest member, an O7-type star (Markarian 1957; Buscombe 1963), is +5 km s^{-1} (Rubin *et al.* 1962) while that of the associated nebula is about +1 km s^{-1} according to hydrogen recombination-line measurements (Dieter 1967). The angular extent of the region that is deficient in neutral hydrogen agrees well with that of the continuum source, the impression being that the hydrogen in the immediate vicinity of NGC 6383 is ionized by emission from the hot stars of the cluster. The observed dips cannot be caused by absorption as this would affect all clouds in front of the source and so would be present on many velocity contours rather than on a few as is the case. Thus, if the dips are caused by local ionization of the neutral hydrogen, the density of missing neutral hydrogen atoms would be $\sim 25\ \mathrm{cm}^{-3}$, which agrees with the density of ionized atoms.

The sizes of the Strömgren spheres around the cluster stars may be calculated from a knowledge of the hydrogen atom density. The Strömgren radius for the earliest member of the cluster (the O7 star referred to above) is 11·5 pc and is in excellent agreement with the linear radius of the full extent of the continuum source, which is ~12 pc (~35′ arc at ~1·2 kpc). This proves our suggestion and shows that the ionized nebula around NGC 6383 is actually ionization bounded and not density bounded.

The continuum and hydrogen-line results reveal that the cluster is embedded in a large neutral hydrogen complex, of which a small part of mass $\sim 450\,M_{\odot}$ is ionized by the O7-type star of the cluster. We were unable to determine the dimensions of the whole neutral hydrogen complex mainly because the cluster is situated toward the galactic centre, where the gradient of radial velocity with distance is small so that the integrated emission of many neutral hydrogen clouds is observed at all velocities.

NGC 6514

NGC 6514 is another cluster in the direction toward the galactic centre and is situated in an area rich in emission nebulae. It is known to be embedded in the small bright nebula M 20, or Trifid nebula. The isophotes of continuum emission in the region (Fig. 3(*a*)) possess a complicated structure and reveal several emission centres, one of which coincides with the cluster position. Contours of continuum emission for this source (Fig. 3(*b*)) were obtained by subtraction of the background emission and that of nearby sources on the assumption that they have Gaussian brightness distributions, as was done for NGC 3293 and 6193 in Part III (Tovmassian *et al.* 1973, present issue pp. 843–51). The shape of the source matches that of the Trifid nebula although it is somewhat larger. The total flux density from the source is ~30 f.u. and its mean half-width is nearly 25′ arc. The radial velocity of the optical nebula was measured by Courtès *et al.* (1966) to be about $+11\ \mathrm{km\,s^{-1}}$ while hydrogen recombination-line measurements gave $+16\ \mathrm{km\,s^{-1}}$ for the ionized nebula (Reifenstein *et al.* 1970).

Our drift curves of hydrogen-line emission (Fig. 3(*c*)) taken across the galactic plane through the centre of NGC 6514 reveal possible dips at the position of the cluster for radial velocities of 0, +7, and $+14\ \mathrm{km\,s^{-1}}$, which agree well with that of the ionized nebula. The half-width of the dip, ~25′ arc, also agrees with that of the ionized nebula. Such coincidences in radial velocity and size make plausible the suggestion that the dips on the neutral hydrogen contours indicate the existence of an ionized hydrogen nebula. As in the case of NGC 6383, the presence of dips on only a few velocity contours excludes the possibility that they are caused by absorption and thus the Trifid nebula also is ionization bounded rather than density bounded.

The distance of NGC 6514 is estimated to be ~1·6 kpc (Buscombe 1963) but the distances of the six OB stars in the field of the cluster range from 0·4 to 2·8 kpc (Rubin *et al.* 1962) so that not all of them can be members of the cluster. The galactic coordinates, radial velocity, spectral type, and distance given by Rubin *et al.* for each of the six stars is presented below.

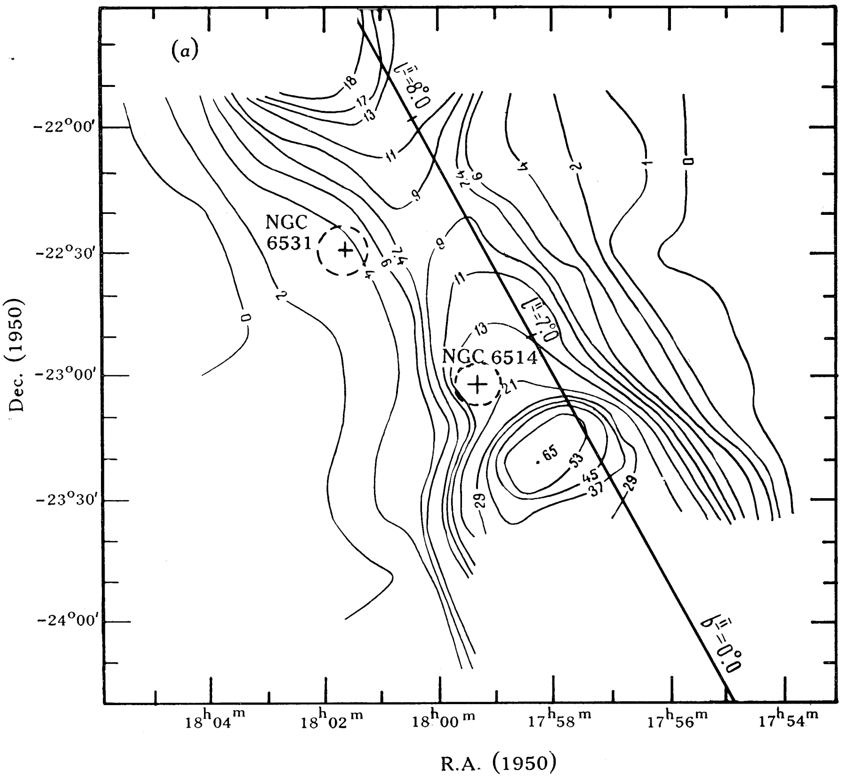
Rubin No.	l^{II}	b^{II}	V_{lsr} (km s^{-1})	Spectrum	d (kpc)
22	6°·99	−0°·24	+10	B2	2·8
23	7°·00	−0°·26	+16	O7	2·8
27	7°·16	−0°·04	−1	B0	1·7
28	7°·24	−0°·37	−7	B5	0·4
29	7°·35	−0°·23	+3	B05	1·7
30	7°·35	−0°·46	−21	B0	1·8

On account of their distances, stars No. 27, 29, and 30 could belong to NGC 6514 although their mean radial velocity of −6 km s^{-1} differs from that of the Trifid nebula by ~20 km s^{-1}. It seems more likely that the ionization of the nebula is caused by the O7-type star No. 23, which has a radial velocity of +16 km s^{-1} similar to that of the nebula. However, at a distance of 2·8 kpc this star is too distant to belong to the cluster. Buscombe (1963) also considered that this star did not belong to NGC 6514 and assumed the brightest member of the cluster to be the B0-type star No. 27. Thus we conclude that the Trifid nebula is not associated with NGC 6514 and is at a distance of ~2·8 kpc, much further than previously accepted.

At a distance of 2·8 kpc the ionized nebula would have a mean electron density of ~13 cm^{-3}. This is in agreement with a value of 11 cm^{-3} for the density of deficient neutral hydrogen atoms as calculated for a brightness temperature of 17 K, a diameter of 25′ arc, and a linewidth at half-power of 20 km s^{-1} for the assumed ionized part of the neutral hydrogen cloud. A mean density of 12 cm^{-3} yields a diameter of ~38 pc for the Strömgren sphere around the O7-type star No. 23. This accords well with the linear dimension of the full extent of the ionized source of ~35 pc (a largest angular size in the north–south direction of 45′ arc at an assumed distance of 2·8 kpc).

On the other hand, if the Trifid nebula were at the distance of the cluster NGC 6514, that is 1·6 kpc, its mean electron density would be ~17 cm^{-3}. In this case the hydrogen-line observations would yield almost the same value, ~18 cm^{-3} for the neutral hydrogen atom density. However, the resulting Strömgren sphere about the B0Ib-type star No. 27 would have a diameter of ~27 pc and the presence of at least one more B0-type star in the cluster would enlarge the sphere, while the maximum linear extent of the nebula at this distance could only be 20 pc. The possibility of the nebula being density bounded is excluded by the shape of the neutral hydrogen drift curves.

Consequently we consider the Trifid nebula to be associated with a single O7-type star No. 23 at a distance of ~2·8 kpc and to bear no relation to the cluster NGC 6514, it being just by chance in the same direction. The probability of a chance coincidence is high as the objects lie only ~7° from the galactic centre. The Trifid nebula is thus the ionized part of a larger cloud. On the assumption of the same brightness temperature, diameter, and linewidth as used in the density calculations, the total ionized mass of the Trifid nebula is ~4700 $M_{\odot}$. The agreement in size with



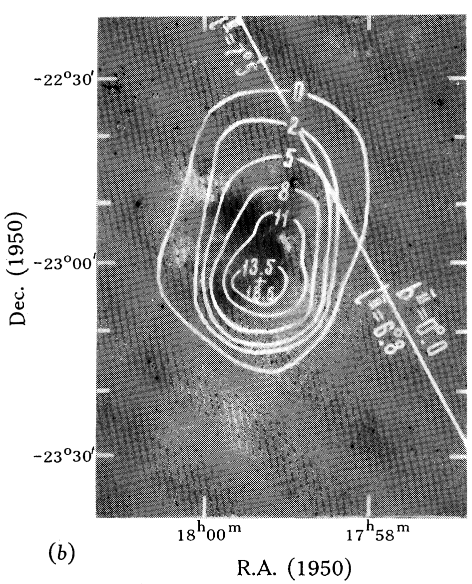


Fig. 3.—NGC 6514. (*a*) Isophotes of brightness temperature in kelvins at 1410 MHz above the galactic background emission, with the position of clusters NGC 6514 and 6531 indicated by dashed circles. (*b*) Isophotes of brightness temperature in kelvins at 1410 MHz obtained by subtracting the emission of the galactic background and nearby strong sources. The contours are superimposed on the red plate of the Palomar Sky Survey, with the cluster centre indicated by a cross. (*c*) Drift curves of hydrogen-line emission taken with the wide-band receiver across the galactic plane through the centre of the cluster.

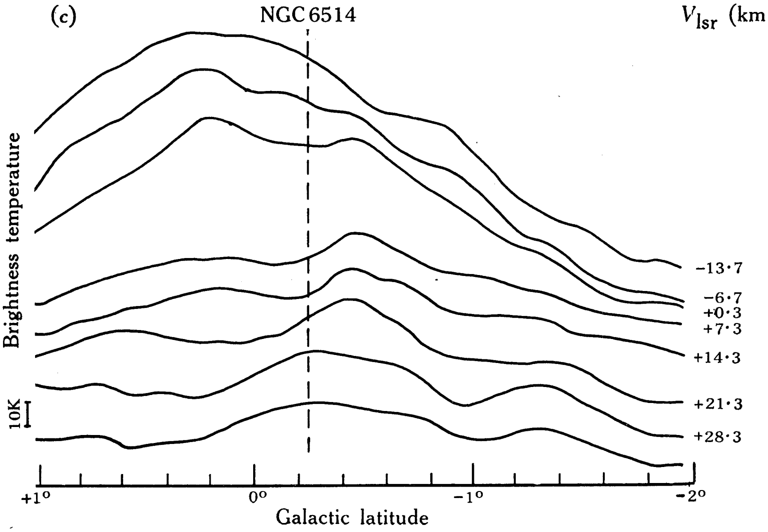


Fig. 3(*c*)

the calculated Strömgren sphere indicates that no ionized hydrogen is connected with the grouping of B-type stars at the position of the cluster, otherwise the integrated flux density from the nebula around the distant O7 star would be overestimated, the real electron density would be smaller, and the Strömgren sphere would be larger. The small number of OB stars left at the distance of NGC 6514, the absence of a concentration of stars there, and the present result concerning the location of the observed ionized gas support the suggestion made by some investigators (see Markarian 1957) that NGC 6514 is not a stellar cluster at all.

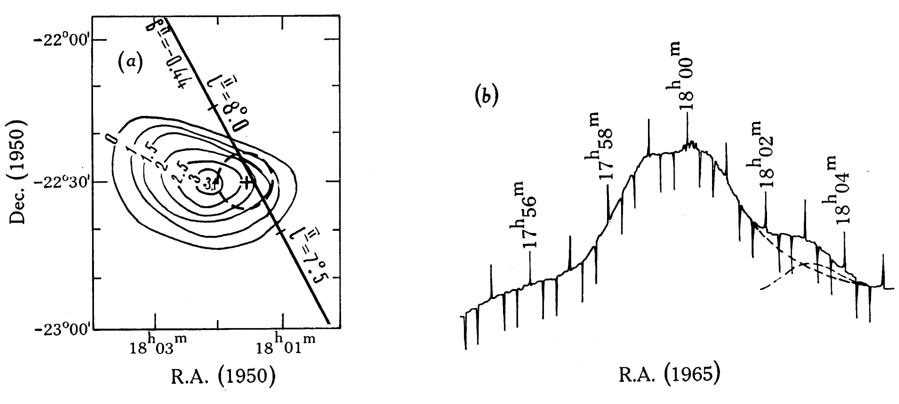


Fig. 4.—NGC 6531. (*a*) Isophotes of brightness temperature in kelvins at 1410 MHz obtained by subtracting the emission of the galactic background and nearby strong sources, with the position of the cluster indicated by a dashed circle. (*b*) Drift curve of continuum emission taken through the centre of the cluster. The right ascension marks are for the epoch of the observations (1965).

NGC 6531

The cluster NGC 6531 is situated near to NGC 6514 in a region rich in sources of continuum emission (see Fig. 3(*a*)). The distortion of the isophotes at the position of NGC 6531 indicates the presence of a weak source there. Contours of continuum emission for this source (Fig. 4(*a*)) were obtained by subtraction of the background emission from the original drift curves (Fig. 4(*b*)). The centre of the source is displaced by $\sim 10'$ arc from that of the cluster, its integrated flux density is less than 6 f.u., and its mean diameter is $\sim 15'$ arc. If the source is at the distance of the cluster, 1·2 kpc (Buscombe 1963), the ionized cloud responsible for the emission would have an electron density of $\sim 20\ \mathrm{cm}^{-3}$. However, the emission measure of the cloud would be $\sim 4000\ \mathrm{pc\,cm}^{-6}$ (the full length of the source being $\sim 32'$ arc, or ~ 10 pc at 1·2 kpc) and the cloud should be detectable by optical means. Consequently the absence of a visible nebula tells against the assumption that the source is connected with NGC 6531. The small amount of absorption in this region, $\sim 0^{m}\!\cdot\!8$ for the cluster stars (Rubin *et al.* 1962), could not prevent an optical nebula from being seen if it were present.

Our hydrogen-line observations also do not show the presence of any hydrogen correlated with NGC 6531. The radial velocity of the cluster, determined by the mean radial velocity of four of its stars (Rubin *et al.* 1962), is about $-3\ \mathrm{km\,s}^{-1}$. There is no feature on the drift curves at this or any adjacent velocity which could be definitely related to the cluster, while any other features present are sufficiently distant from centre of the cluster to be connected with it. Thus neither neutral nor ionized hydrogen has been detected in association with the cluster NGC 6531.

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