HYDROGEN CONTENT OF YOUNG STELLAR CLUSTERS

V.* CLUSTERS NGC 6604, 6611, AND 6823

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Abstract

Measurements of the total amount of hydrogen gas associated with the O-type clusters NGC 6604, 6611, and 6823 are reported. Only a small part of the large visible nebula in which NGC 6604 appears to be embedded is associated with the cluster. The small ionized nebula associated with NGC 6604 has a mass of $\sim 600\,M_\odot$ and is part of a larger neutral cloud. The mass of the ionized nebula associated with NGC 6611 is $\sim 5000\,M_\odot$, while a neutral hydrogen shell with a total mass of $\sim 10^5\,M_\odot$ probably surrounds the ionized nebula. The cluster NGC 6823 is embedded in a bright nebula of mass $\sim 1800\,M_\odot$. A neutral hydrogen shell of mass $\sim 2000\,M_\odot$ surrounds the ionized nebula, so that the total mass of hydrogen associated with NGC 6823 is $\sim 4000\,M_\odot$.

INTRODUCTION

This paper concludes the present series in which the results of hydrogen-line and 1410 MHz continuum observations of 16 young stellar clusters are given. The methods of observation and reduction are described in Part I (Tovmassian 1973, present issue pp. 829–35). The clusters NGC 6604, 6611, and 6823 are considered in the present paper. Red plate photographs from the Palomar Sky Survey showing the regions containing these clusters, with 1410 MHz continuum contours superimposed, are given in Figures 1(*a*)–1(*c*).

MEASUREMENTS AND RESULTS

NGC 6604

The cluster NGC 6604 is situated within a large bright emission nebula with which it is thought to be associated. However, the nebula consists of patches of arches centred on a small group of faint stars at $\sim 30'$ arc to the north from the cluster, where the brightest knot of the nebula is situated (Fig. 1(*a*)) and this casts doubt on the real connection between the cluster and the nebula. The contours of equal brightness temperature of the continuum emission shown in Figure 1(*a*) have a rather symmetrical distribution centred on the northern grouping of stars. These stars are probably mainly responsible for the ionization of the observed nebula. The Palomar Sky Survey prints indicate that there is even higher absorption at the position of the

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northern stellar grouping than at the position of NGC 6604, which is sufficiently high at $A_v \approx 3^m$, and this would explain the lack of spectral data on these stars.

The radial velocity of the brightest star of NGC 6604, the O8-type star HD 167971, is $+13$ km s^{-1} (Rubin *et al.* 1962). Dieter (1967) has noted an appreciable discrepancy between the radial velocity of the cluster stars and that of the nebula, which is about $+30$ km s^{-1} from H 158α (Dieter 1967) or $+33$ km s^{-1} from H 109α (Reifenstein *et al.* 1970) recombination-line measurements.

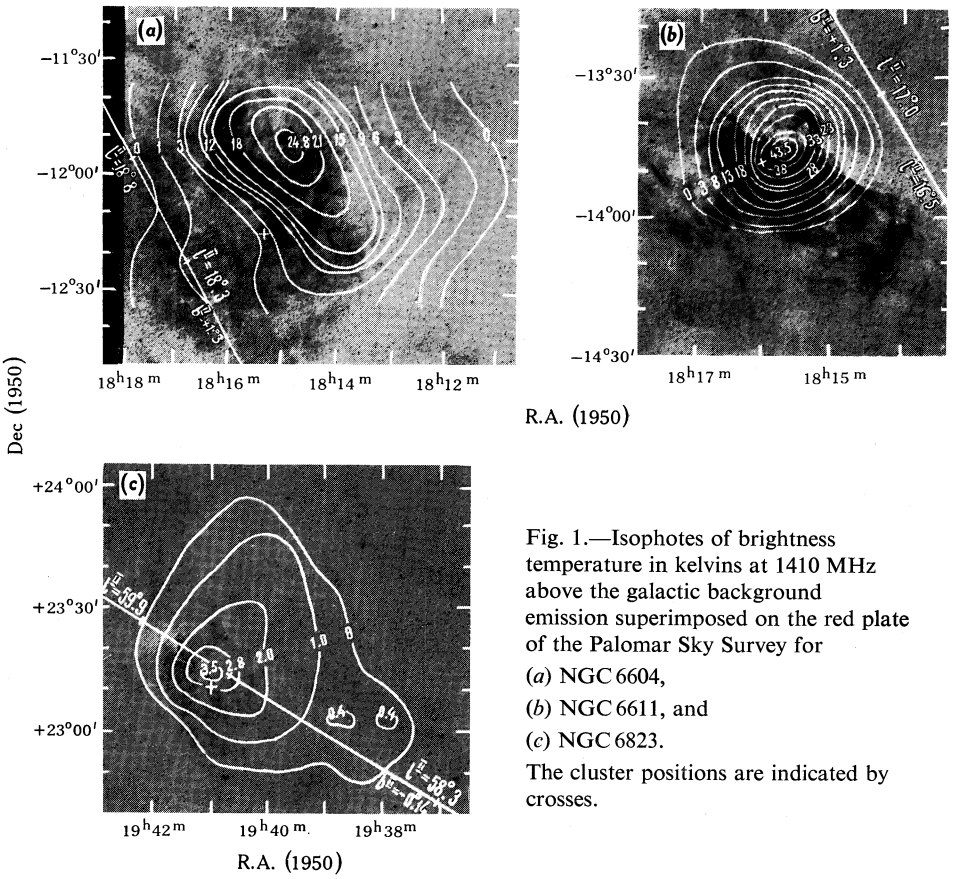

Fig. 1.—Isophotes of brightness temperature in kelvins at 1410 MHz above the galactic background emission superimposed on the red plate of the Palomar Sky Survey for
(*a*) NGC 6604,
(*b*) NGC 6611, and
(*c*) NGC 6823.
The cluster positions are indicated by crosses.

The present hydrogen-line observations help to clarify this situation by revealing the possible presence of two nebulae in the region. The scan along the galactic plane through the cluster (Fig. 2(*a*)) shows a definite deficiency of neutral hydrogen at the cluster position at radial velocities of $+10$ and $+17$ km s^{-1}, which are very close to the radial velocity of the cluster. The total length of this feature, which is apparently associated with NGC 6604, is $\sim 50'$ arc, or about half the size of the corresponding ionized cloud. A similar but less pronounced deficiency is also apparent at radial velocities of $+24$ and $+31$ km s^{-1}. This feature is actually more prominent than the former but it is located $\sim 20'$ arc to the north from the path of the scan, or $\sim 15'$ arc to higher galactic longitudes, which corresponds to the difference in

galactic longitude between NGC 6604 and the northern grouping of stars (or the centre of the continuum source). The scan in galactic latitude through the cluster (Fig. 2(*b*)) shows a pronounced maximum at a radial velocity of $+31$ km s^{-1}, which is probably due to the presence of a neutral portion of the ionized cloud. This would mean that the large nebula is ionization bounded, at least on the side facing the solar system.

To obtain estimates of the densities of both nebulae it is necessary to separate the two sources from each other. Unfortunately this could not be done from the continuum observations, although the distortion of the isophotes at the southern part of the nebula suggests the presence of a second source there. Very rough estimates have been obtained by the approximate method of correcting the hydrogen-line drift curves for the absence of ionization. For an assumed deficiency in brightness temperature of ~20–25 K, a half-power width of ~35′ arc, a linewidth at half-power

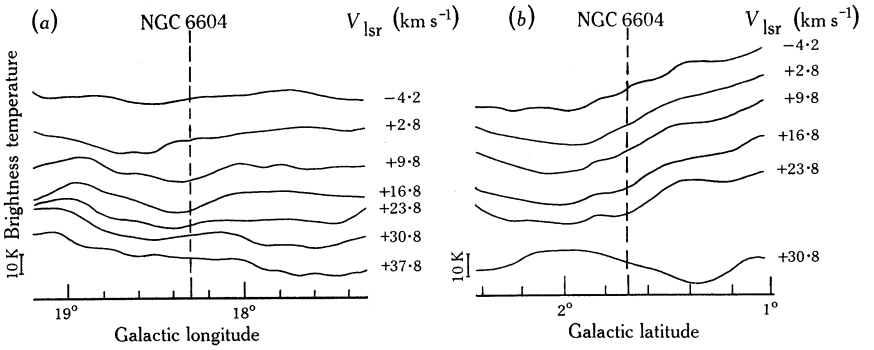

Fig. 2.—NGC 6604. Drift curves of hydrogen-line emission taken with the wide-band receiver through the centre of the cluster: (*a*) along the galactic plane and (*b*) across the galactic plane.

of 15 km s^{-1}, and a distance to NGC 6604 of 1·4 kpc (the distance of the O8-type star HD 167971), the hydrogen atom density of the associated nebula would be ~13–16 cm^{-3} and the Strömgren sphere around the O8-type star would be ~31–26 pc in diameter. The smaller dimension corresponds to the total size of the region deficient in neutral hydrogen.

The above arguments favour the existence in the vicinity of NGC 6604 of two nebulae, only the smaller of which is associated with the cluster. This nebula has a hydrogen atom density of ~16 cm^{-3} and a mass of ~600 $M_{\odot}$, although the total mass of associated hydrogen is greater since we see only the ionized part. In the absence of data relating to the distance of the northern stellar group, it is not possible to estimate the density and mass of the larger nebula associated with it.

NGC 6611

The cluster NGC 6611 is embedded in the well-known nebula M16. In its continuum emission, the nebula appears as a bright compact source (Fig. 1(*b*)) with a total flux density of ~100 f.u. and a mean angular diameter of nearly 20′ arc. For a distance to the nebula of 2·6 kpc (that of the cluster; Buscombe 1963), it would possess a mean electron density of ~35 cm^{-3} and a mass of ~5000 $M_{\odot}$.

Our hydrogen-line observations (Fig. 3(*a*)) taken through the centre of the cluster with the wide-band receiver only, show the presence of pronounced absorption at radial velocities of $+1{\cdot}7$, $+8{\cdot}7$, $+15{\cdot}7$, and $+22{\cdot}7$ km s^{-1}. On the other hand, Gordon *et al.* (1968), who observed the nebula with a better frequency resolution of

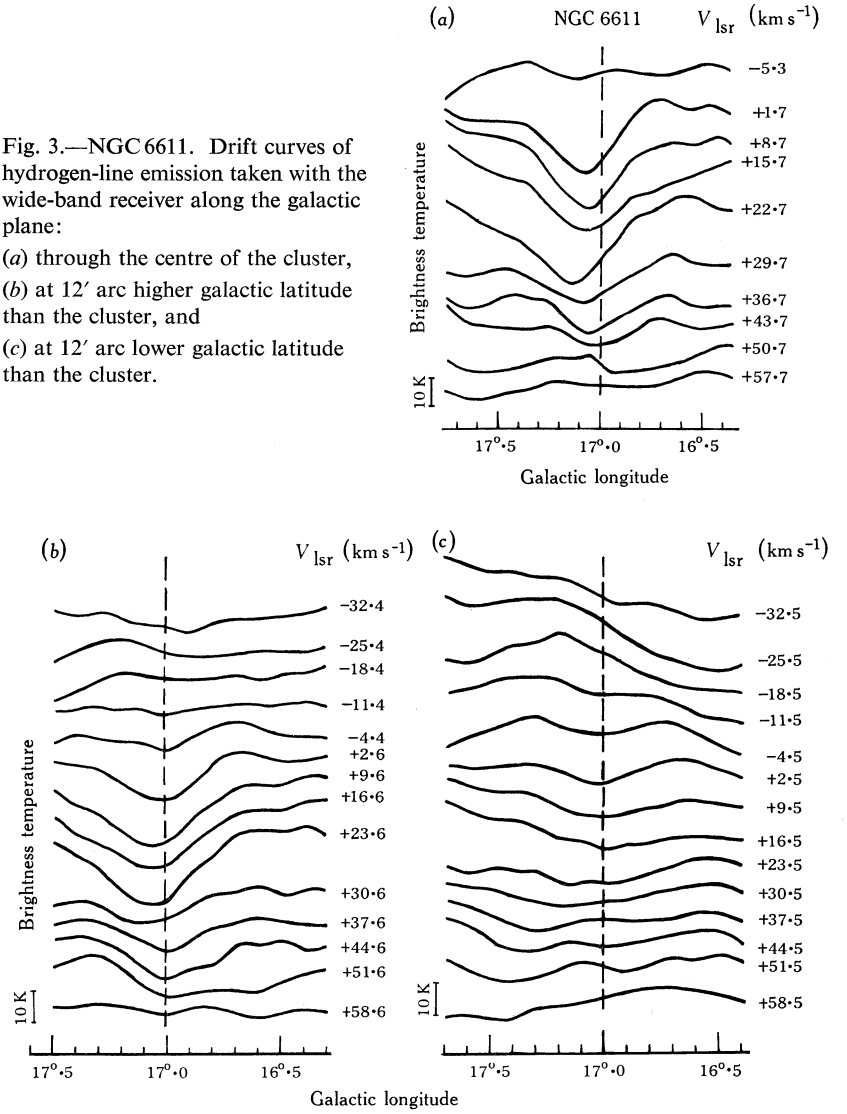

Fig. 3.—NGC 6611. Drift curves of hydrogen-line emission taken with the wide-band receiver along the galactic plane:
(*a*) through the centre of the cluster,
(*b*) at 12′ arc higher galactic latitude than the cluster, and
(*c*) at 12′ arc lower galactic latitude than the cluster.

2 km s^{-1}, recorded decreases in temperature at only the two velocities $+19$ and $+5$ km s^{-1}. However, as these velocities fall between the velocities of two channel pairs of the wide-band receiver, both sets of observations are consistent.

The mean radial velocity of five OB-type stars of the cluster, $+34$ km s^{-1} (Rubin *et al.* 1962), is somewhat higher than that of the ionized nebula, $+24{\cdot}5$ km s^{-1},

which was obtained by H 109α recombination-line measurements (Reifenstein *et al.* 1970). Thus it is possible that the low-temperature features are due to absorbing hydrogen clouds lying in front of M 16 for, at the galactic longitude of the observations, such clouds would probably possess lower mean radial velocities than the cluster.

The absorption features may also be seen on the +12′ arc scan (that made at 12′ arc higher galactic latitude than the cluster; Fig. 3(*b*)). On the other hand, they are barely visible on the −12′ arc scan (Fig. 3(*c*)), which passes almost outside the nebula since the nebula has a radius at half-power points of ∼15′ arc and its centre is at ∼4′ arc higher galactic latitude than the cluster. The central and +12′ arc scans also show dips at the position of the cluster on the drift curves for radial velocities in the range +30 to +45 km s^{-1}, which is close to that of the cluster. It is thus unlikely that the dips are caused by absorption, and it is more natural to assume that they correspond to a region in which the neutral hydrogen has been ionized by the early-type stars of the cluster. A comparison between the temperatures at the longitude of the cluster on the central and −12′ arc scans provides a rough estimate of ∼30 K for the temperature that would be possessed by the missing hydrogen atoms in the absence of ionization. At this temperature, a nebula with a half-power width of ∼20′ arc and a dispersion in radial velocity of ∼20 km s^{-1} would have a minimum density of hydrogen atoms of ∼25 cm^{-3}.

The presence of bumps on either side of the dips on the drift curves at radial velocities +30, +37, and +45 km s^{-1} indicate the probable existence of a shell of neutral hydrogen around the ionized cloud. The outer and inner radii of the shell are ∼20 and 10 pc respectively (∼30′ and 15′ arc at a distance of 2·6 kpc) and the path length in the shell is ∼30 pc. For a temperature of nearly 10 K and a full linewidth at half-power of ∼20 km s^{-1}, the shell would have a hydrogen atom density of 4 cm^{-3} and a total mass of ∼10^5 $M_\odot$. We conclude that the nebula M 16, which is associated with the cluster NGC 6611, is ionization bounded, that the total amount of hydrogen connected with the cluster is ∼10^5 $M_\odot$, and that only a small part of this huge nebula, ∼5% of its mass, is ionized by the hot stars of the cluster.

NGC 6823

The cluster NGC 6823 is embedded within the bright filamentary nebula NGC 6820. On the contour diagram (Fig. 1(*c*)) derived from the continuum observations, the radio source associated with the cluster is somewhat larger than its optical counterpart. The diameter of the source at half-intensity points is ∼25′ arc and its total flux density is nearly 14 f.u. For an assumed distance to the cluster of 2·5 kpc (Becker and Fenkart 1963), the ionized cloud would have an electron density of ∼10 cm^{-3} and a total mass of 1800 $M_\odot$.

Our hydrogen-line observations show the presence of dips at the position of the cluster on drift curves for velocities +31 and +39 km s^{-1} (Fig. 4). This is in agreement with a radial velocity of +30 km s^{-1} for the cluster, as determined from the radial velocities of two of its stars (Rubin *et al.* 1962), and also with a radial velocity of about +35 km s^{-1} for the ionized nebula (Courtés *et al.* 1966; Miller 1968). The coincidence suggests that the observed dips on the hydrogen-line scans correspond to a region of ionized hydrogen in the space occupied by the cluster which possesses an angular dimension of ∼50′ arc in galactic latitude. Similar dips are present on

the drift curves for smaller radial velocities (around $+25\,\mathrm{km\,s^{-1}}$) but these are possibly caused by absorption by a cloud in front of the cluster. A decrease in temperature at $+28\,\mathrm{km\,s^{-1}}$ has also been observed by Gordon *et al.* (1968).

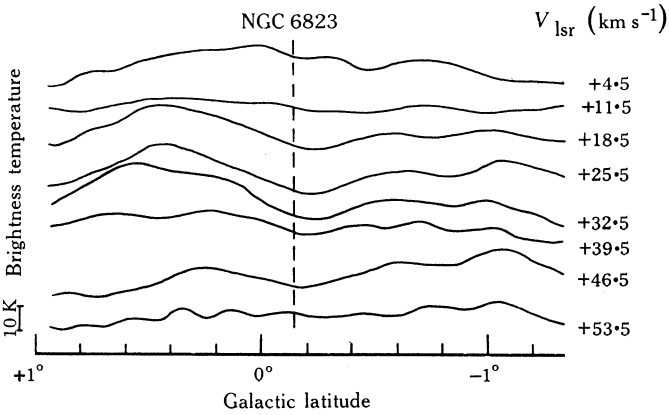

Fig. 4.—NGC 6823. Drift curves of hydrogen-line emission taken with the wide-band receiver across the galactic plane through the centre of the cluster.

A detailed inspection of the central and off-central hydrogen-line scans in both galactic latitude and longitude reveals the presence of a neutral hydrogen shell around the "hole" of ionized hydrogen (Fig. 4). This implies that the emission nebula is ionization bounded rather than density bounded. The shell has a thickness of $\sim 10'$ to $15'$ arc, a temperature of nearly 7 K, and a full linewidth at half-power of no more than $7\,\mathrm{km\,s^{-1}}$. The diameter of the Strömgren sphere around the brightest star of the cluster (of type O7) in a nebula of electron density $10\,\mathrm{cm^{-3}}$ would be ~ 44 pc. This is in excellent agreement with a value of 43 pc for the maximum extent of the continuum source at a distance of 2·5 kpc. The neutral hydrogen atom density of the shell is $\sim 1\,\mathrm{cm^{-3}}$ and its mass is $\sim 2000\,M_\odot$. Consequently the total amount of hydrogen gas associated with the cluster NGC 6823 is $\sim 4000\,M_\odot$, about half of which appears in ionized form and half in neutral form.

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