Multiwavelength observations of the M 15 intermediate velocity cloud

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ABSTRACT

We present Westerbork Synthesis Radio Telescope H i images, Lovell telescope multibeam H i wide-field mapping, William Herschel Telescope longslit echelle Ca ii observations, Wisconsin H α Mapper (WHAM) facility images, and IRAS ISSA 60 and 100 micron coadded images towards the intermediate velocity cloud (IVC) at +70 km s⁻¹, located in the general direction of the M 15 globular cluster. When combined with previously-published Arecibo data, the H i gas in the IVC is found to be clumpy, with a peak H i column density of ∼ 1.5 × 10²⁰ cm⁻², inferred volume density (assuming spherical symmetry) of ∼ 24 cm⁻³ / D (kpc), and maximum brightness temperature at a resolution of 81″ × 14″ of ∼ 14 K. The major axis of this part of the IVC lies approximately parallel with the Galactic plane, as does the low velocity H i gas and IRAS emission. The H i gas in the cloud is warm, with a minimum value of the full width half maximum (FWHM) velocity width of 5 km s⁻¹ corresponding to a kinetic temperature, in the absence of turbulence, of ∼ 540 K. From the H i data, there are indications of two-component velocity structure. Similarly, the Ca ii spectra, of resolution 7 km s⁻¹, also show tentative evidence of velocity structure, perhaps indicative of cloudlets. Assuming there are no unresolved narrow-velocity components, the mean values of log₁₀(N(Ca ii K) cm⁻²) ∼ 12.0 and Ca ii/H i ∼ 2.5 × 10⁻⁸ are typical of observations of high Galactic latitude clouds. This compares with a value of Ca ii/H i > 10⁻⁶ for IVC absorption towards HD 203664, a halo star of distance 3 kpc, some 3.1 degrees from the main M 15 IVC condensation. The main IVC condensation is detected by WHAM in H α with central LSR velocities of ∼ 60–70 km s⁻¹, and intensities uncorrected for Galactic extinction of up to 1.3 Rayleigh, indicating that the gas is partially ionised. The FWHM values of the H α IVC component, at a resolution of 1 degree, exceed 30 km s⁻¹. This is some 10 km s⁻¹ larger than the corresponding H i value at similar resolution, and indicates that the two components may not be mixed. However, the spatial and velocity coincidence of the H α and H i peaks in emission towards the main IVC component is qualitatively good. If the H i emission is caused solely by photoionisation, the Lyman continuum flux towards the main IVC condensation is ∼ 2.7 × 10⁶ photons cm⁻² s⁻¹. There is not a corresponding IVC Hα detection towards the halo star HD 203664 at velocities exceeding ∼ 60 km s⁻¹. Finally, both the 60 and 100 micron IRAS images show spatial coincidence, over a 0.675° × 0.625° field, with both low and intermediate velocity H i gas (previously observed with the Arecibo telescope), indicating that the IVC may contain dust. Both the H α and tentative IRAS detections discriminate this IVC from High Velocity Clouds although the H i properties do not. When combined with the H i and optical results, these data point to a Galactic origin for at least parts of this IVC.

1 INTRODUCTION

The study of intermediate velocity clouds (IVCs) remains one of the most challenging in contemporary Galactic astronomy, with several issues concerning IVCs remaining unresolved. These include, but are not limited to, the method of their formation, their relationship (if any) with high velocity clouds (HVCs), and the question as to whether IVCs are sites of star formation in the halo of the Galaxy (Kuntz & Danly 1996; Christodoulou, Tohline & Keenan 1997; Izvic & Christodoulou 1997). This latter possibility is underpinned by the fact that within the Galactic halo, there exists a population of early B-type stars whose velocities, ages and distances from the Galactic plane ($z$) are incompatible with them being formed within the disc. A possible site for their formation is IVCs/HVCs via cloud-cloud collisions and subsequent compression of the gas (Dyson & Hartquist 1983). Such collisions are thought to be a viable star formation mechanism within at least the discs of galaxies, albeit where the gas density and cloud-cloud collision rates are somewhat higher than inferred in IVCs/HVCs (Tan 2000).

The solution to both the star formation question and also any possible relationship between HVCs and IVCs requires both the analysis of aggregate parameters of well-defined samples of IVCs and HVCs, and also more detailed studies of individual objects. In this paper we report on radio H\textsc{i} aperture synthesis, H\textsc{i} multibeam wide field mapping, longslit Ca\textsc{ii} observations, Wisconsin H\alpha Mapper (WHAM) facility images, and IRAS sky-survey archive data retrieval towards a particular IVC located in the general direction of the M 15 globular cluster (RA=21° 29′ 58.29", Dec=+12° 10′ 00.5′′ (J2000); l=65.01°, b=−73.31°). These observations are amongst the first H\textsc{i} synthesis data to be taken of positive-velocity IVCs, which remain poorly-studied as a group of objects.

The M 15 H\textsc{i} cloud lies at a velocity of $\sim+70$ km s$^{-1}$ in the dynamical Local Standard of Rest (Allen 1973); its distance tentatively lies between $0.8–3$ kpc (Little et al. 1994; Smoker et al. 2001a). The upper distance limit is gleaned from the fact that IVC absorption at $\sim+70$ to $+80$ km s$^{-1}$ is observed in the spectrum of HD 203664, a halo star of $i_{\odot}$=12.13 (Hillenbrand et al. 1999), hence the M 15 IVC is a part of IVC Complex (c.f. Fig. 1 of Wakker 1991), although in common with Sem-(1995) and Kennedy et al. (1998) here we classify it as an IVC. The line-of-sight position of the M 15 IVC is between the negative-velocity Local Group barycentre cloud Complex G and the Galactic centre clouds (Fig. 8 of Blitz et al. 1999), hence the M 15 IVC is a part of IVC Complex gp (Wakker 2001).

Previous observations in H\textsc{i} emission using the Lovell and Arecibo telescopes (Kennedy et al. 1998; Smoker et al. 2001a) have shown that the IVC consists of several condensations of gas spread out over an area of more than 3 square degrees, with structure existing down to the previous resolution limit of $\sim 3$ arcmin. The brightest component is located towards M 15 itself and has peak H\textsc{i} column density at the Arecibo resolution of $\sim 8\times10^{19}$ cm$^{-2}$. In this paper, we study this part of the IVC at higher spatial resolution. The mass of this particular clump is $\sim 20 D^2 M_\odot$, (where $D$ is the distance in kpc), thus for this particular object, in the absence of H$_2$, there is insufficient neutral gas to form an early-type star. Low-resolution absorption-line Ca\textsc{ii} and Na\textsc{i} spectroscopy (Lehner et al. 1999) towards cluster stars tentatively found cloud structure (or variations in the relative abundance) over scales as small as a few arcsec, with fibre-optic array mapping in the Na\textsc{i} D absorption lines (Meyer & Lauroesch 1999) obtaining similar results with structure visible on scales of $\sim 4$ arcsec (velocity resolution $\sim 16$ km s$^{-1}$).

Using empirical relationships between the sodium and hydrogen column densities, Meyer & Lauroesch (1999) derived values of the H\textsc{i} column density towards the cluster centre of $\sim 5 \times 10^{20}$ cm$^{-2}$, some 6 times higher than that found using the Arecibo H\textsc{i} data alone; the difference may be attributable to fine-scale cloud structure. Assuming spherical symmetry, a volume density of $\sim 1000$ cm$^{-3}$ is implied by these latter results, similar to values obtained for gas in the local ISM (e.g. Faison et al. 1998, although see Lauroesch, Meyer & Blades 2000). Such a high volume density and implied overpressure with respect to the ISM perhaps indicates that the assumption of spherical symmetry is invalid and that there may be some sheet like geometry in the IVC as has been postulated for low-velocity gas (Heiles 1997).

In the current paper, we extend our studies of the M 15 IVC to higher resolution and different wavelength regions in order to investigate three areas. Firstly, H\textsc{i} synthesis mapping, WHAM H\alpha and IRAS ISSA survey data retrieval towards the IVC were performed to see if the H\textsc{i}, H\alpha and infrared properties of the M 15 IVC are compatible with either low velocity gas or HVCs in general, and whether there are any differences between the types of object, perhaps attributable to differences in the formation mechanism or current environment (for example, distance from the ionising field of the Galaxy). Secondly, wide-field medium-resolution H\textsc{i} data were obtained in search of more IVC components, to trace how the gas kinetic temperature changes with sky position, and possibly determine the relative distance of cloud components from the Galactic plane (c.f. Lehner 2000). Thirdly, longslit echelle Ca\textsc{ii} observations were undertaken, using the centre of M 15 as a background continuum source, in order to look for small-scale velocity and column density substructure within the IVC which could indicate the presence of cloudlets, collisions between which in certain IVCs may be responsible for star formation in the Galactic halo.

Section 2 describes the observations and data reduction, Sect. 3 gives the results, Sect. 4 contains the discussion and Sect. 5 presents a summary and the conclusions.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Westerbork aperture synthesis H\textsc{i} observations

21-cm aperture synthesis H\textsc{i} observations of the M 15 IVC were obtained during two observing sessions, each of 12 hours, using the Westerbork Synthesis Radio Telescope (WSRT). The first in 19 December 1998 had a minimum antenna spacing of 32-m, the second in 17 April 1999 had a corresponding separation of 72-m. The velocity resolution for all observations was 1.03 km s$^{-1}$. 

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Standard methods within AIPS were used to reduce the visibility data. Reduction included amplitude calibration using 3C 286 and 3C 48 (assuming flux densities of 14.76 Jy and 15.98 Jy, respectively), phase calibration and flagging of bad data, and concatenation of the two UV datasets using DCON. The calibrated dataset was mapped with IMAGR using both quasi-natural and uniform weightings, with the Arecibo map from Smoker et al. (2001a) being used to set the locations of the CLEAN boxes for each velocity channel interactively. The respective beam sizes of the final images were 111″ × 56″ and 81″ × 14″ (approximately North–South by East–West), with the corresponding rms noises being 2.3 mJy beam⁻¹ and 1.3 mJy beam⁻¹ for the naturally and uniformly-weighted data.

As the WSRT maps suffer from missing short-spacing information, it was decided to create ‘total power’ channel maps by combining the current observations with the single dish Arecibo data. For this we used MIRIAD (Sault, Teuben & Wright 1995). The two datasets were first regrid- ded so that they had the same central coordinate and channel width. Following this, we multiplied the Arecibo data by the WSRT single-dish beam, converted to flux density units, and combined the WSRT and weighted Arecibo maps using IMMERGE. Combination was performed by specifying an annulus of between 50–150-m in the Fourier domain where the H I column densities, velocities and velocity widths of the IVC. H I column densities were derived using the relationship \[ N_{HI} = 1.823 \times 10^{18} \sqrt{T_B dv} \text{ (cm}^{-2}) \text{, where } v \text{ is the velocity in km} \text{s}^{-1}. \]

2.2 Lovell Telescope multibeam H I observations

Lovell telescope multibeam 21-cm H I observations covering a ∼ 4.9×9.3 degree RA–Dec region, centred upon RA=21°26′47″, Dec=+09°16′23″ (J2000) were taken during 2 June 2000. The resolution of these data is 12 arcmin spatially and 3.0 km s⁻¹ in velocity. The total integration time was 4 hours and the RMS noise per channel was ∼ 0.1 K. The observed field is not quite fully sampled, with the spacing between the beams being 10 arcmin, compared with the spatial resolution of 12 arcmin. During observing, data were calibrated in terms of antenna temperature by a frequently-fired noise diode. Off-line, bootstrapping of the flux scale to some previous Lovell telescope H I observations taken during 1996 enabled calibration in terms of brightness temperature (T_B). Data reduction procedures will be discussed in more detail in a future paper. For now, we simply note that most of the process is automated, the bandpass removal being performed within AIPS using LIVEDATA and the data being gridded using GRIDZILLA (Barnes 2001). As the bandpass is simply a running average of the observed spectra in a window, incorrect removal is performed around the low-velocity gas where there is no ‘empty’ region of the sky. However, at the velocity of the IVC (v ∼ +70 km s⁻¹) the baseline subtraction is adequate. An example of a spectrum after automated bandpass removal is shown in Fig. 1.

After gridding, the data were imported into AIPS whence a column density map was made of the entire field between +50 and +90 km s⁻¹ which is presented in section 3.2.

2.3 William Herschel Telescope longslit UES observations

WHT Utrecht Echelle Spectrograph (UES) observations towards the centre of the M 15 globular cluster were taken during bright time on 19–21 July 2000. Twin EEV CCDs were used. In combination with the E79 grating, this gave near-complete wavelength coverage from 3800–6300 Å, with a slit width of 0.85″ providing an instrumental FWHM resolution of ∼ 6 km s⁻¹. On the first night of the run, a slit height of 16 arcseconds was used; this has the advantage that the full wavelength coverage is obtained with no overlapping orders on either of the CCDs. On the second and third night’s observations, in order to maximise the amount of sky available for the calcium lines at 3933.66 Å, a slit of height 22 arcseconds was used which leads to overlapping orders in the red CCD. ThAr arcs were taken two or three times a night to act as the wavelength calibration with Tungsten and sky flats also being obtained. The echelle proved

* AIPS is distributed by the National Radio Astronomy Observatory, U.S.A.
to be remarkably stable with the centres of the arc lines varying by less than 1.5 pixels throughout the whole of the run.

The original intention of the observations was to obtain 7 parallel cuts through the IVC, separated by 0.7 arcsec, and use these to make up an RA-Dec rectangle of size $\sim 5'' \times 20''$ within which cloudlet sizes could be obtained. Unfortunately, due to the presence of Sahara dust and non-ideal seeing conditions ($1.5'' - 2.0''$), integration times were somewhat longer than had been hoped for and in the end only two longslit positions were obtained, offset by a position angle of 85 degrees. Additionally, on the second night we obtained 1200-s of integration towards a blank sky region with a 0.85'' slit and on the third night a total of $5 \times 400$-s, interleaved with the object exposures and using a slit of width 4.0'', corresponding to $\sim 9500$-s of integration with a slit of 0.85'' used for the IVC observations.

Data reduction was performed using standard methods within IRAF. The aims were firstly to obtain a spectrum of the inner part of the globular cluster over the whole wavelength region, and more importantly, produce longslit spectra of the CaII lines alone for the two longslit positions taken. Data reduction included debiasing, and use of the sky flatfields to get rid of the vignetting that was clearly visible on many of the orders. Cosmic ray hits near the CaII line were removed within FIGARO (Shortridge et al. 1999) using clean. Because of the small pixel-to-pixel variation and pixel size ($\sim 0.2''$), no flatfielding to remove the pixel-to-pixel variation was performed on the data. The images were rotated in order to make the cross-dispersion axis occur along the image rows, after which sky subtraction was performed. As expected, this proved to be challenging.

### 2.3.1 Sky subtraction

Two methods were used to estimate the sky value and the results compared. The first used the data from the third nights observation where the blank sky exposures were interleaved with the object exposures. For these data, we scaled the high object counts too, so errors in the equivalent width increase rapidly in the extracted spectra for this region. For an equivalent $5400$-s of integration time, at $\lambda \sim 3937$Å, there were $\sim 3$ ADU sky counts and somewhat less at $\lambda=3933.66$Å, due to the 'sky' effectively being a solar (G-type) spectrum which has strong CaII absorption lines.

The second method involved removal of sky using parts of the longslit that appeared to be free of emission from the globular cluster. The problem with this method is illustrated by Fig.4(a), which shows cuts across the dispersion axis for $5400$-s of data taken on the third night at each of the two slit positions. As is apparent from the Figures, the 'sky' level at the same position on the order at the two different slit positions is different by $\sim 3-4$ ADU per $5400$-s of integration. During night 3, at $\lambda \sim 3937$Å, position p1 had $\sim 8$ ADU as its 'sky' value, with the corresponding value for p2 being $\sim 12$ ADU. These clearly are much larger than the values obtained by exposing on the night sky and combined with the fact that p1 and p2 are different indicates that we are still obtaining counts from the cluster in the outer parts of the slit. This is confirmed by performing an extraction using such counts; in some parts of the spectrum the IVC absorption becomes negative which is unphysical. Because of the lack of object-free emission on the slit, we decided to remove the sky by subtracting the smoothed version of the sky images from our object data. This method relies upon the sky conditions being similar throughout the three nights of observing. This was checked by taking cuts across three places on the dispersion axis of each $5400$-s worth of data and checking for variability. At $\lambda \sim 3937$ Å, the values varied by only $2$ ADU per $5400$-s between nights 1 and 3 for the two slit positions. This variability, combined with the error in removing the bias, gives us an error in the final sky value of $\sim 4$ ADU at 3937Å, compared with a peak continuum value at this point of $\sim 30$ ADU.

### 2.3.2 Extraction and Analysis

The sky-subtracted spectra were extracted within FIGARO by summing over each 10 columns, corresponding to the worst seeing of $\sim 2.0$ arcseconds. Wavelength calibration was then undertaken, taking into account the shift in the $\lambda$ scale along the length of the slit. Finally, normalisation and profile fitting were performed within DIPSO (Howarth et al. 1996). The final spectra have spatial resolution of $\sim 2$ arcseconds and velocity resolution of $\sim 7$ km s$^{-1}$. 

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† IRAF is distributed by the National Optical Astronomy Observatories, U.S.A.
Data were analysed using standard profile fitting methods within DIPSO using the ELF and IS programs. Before fitting, the stellar line was removed by fitting the profile by eye to the lower-wavelength part of the spectrum up to the peak stellar absorption unaffected by LV and IV gas, and creating a mirror of this spectrum for the higher wavelength data. The derived stellar spectrum has a stark-
like line profile, typical of stellar Ca\textsc{ii} lines, and was subtracted from the whole spectrum to leave the interstellar components only. After stellar-line removal, the ELF routines were used to fit Gaussian profiles to input spectra and hence provide the equivalent width, peak absorption and full width half maximum velocity values for the low velocity gas and IVC components. These results were compared to the theoretical absorption profiles computed by the IS suite of programs within DIPSO. These theoretical profiles are derived from the observed b-values (corrected for instrumental broadening), atomic data for the Ca\textsc{ii} lines taken from Morton (1991) and initial guesses for the Ca\textsc{ii} column density. Input parameters were varied until a good fit was produced to match the profiles obtained using ELF. This method is only appropriate in the regime where the lines are not saturated and are resolved in velocity; both caveats apply for a number of positions in the current dataset, although the presence of narrow, unresolved components cannot be ruled out. If present, these would cause our estimated column densities to be too low. The final ELF and IS fits provide the Ca\textsc{ii} number densities and values for the FWHM velocities at each of the positions along the slit.

2.4 Wisconsin H\textsc{o} Mapper observations

Data were retrieved from the Wisconsin H\textsc{o} Mapper (WHAM) survey in the range $+06^\circ < \text{Dec.} < +15^\circ$ and $20^\circ < \text{RA} < 21^\circ$ (J2000). These data are of resolution 1 degree spatially and $\sim 12$ km s$^{-1}$ in velocity, with a velocity coverage at this sky position from $\sim -120$ to $+90$ km s$^{-1}$ in the LSR. Data were reduced using standard methods, which included conversion into the LSR and removal of the geocoronal H\textsc{a} line that appears at velocities in the range $\sim +30$ to $+40$ km s$^{-1}$ (Haffner 1999; Haffner et al. 2001b). Due to the removal of this line, the noise in this part of the spectrum is slightly enhanced compared with the typical RMS noise value (measured for the current spectra) of $\sim 1-3$ mR (km s$^{-1}$)$^{-1}$. These values are typical for the WHAM survey as a whole. Finally, we note if the IVC H\textsc{a} flux originates from above the Galactic plane, then a correction for Galactic extinction of 1.25 would be necessary, calculated from a E(B$-$V)$=0.10 observed towards M15 by Durrell & Harris (1993), combined with the extinction law of Cardelli, Clayton & Mathis (1989). We have not applied this correction to our data so the IVC H\textsc{o} fluxes may be $\sim$ 25 per cent too low.

2.5 IRAS ISSA data retrieval

Both the 60 and 100 micron images of a field of size 0.675$^\circ \times 0.625^\circ$ were extracted from the on-line versions of the IRAS Sky Survey Atlas (ISSA). These images are of resolution $\sim 5$ arcmin and have most of their zodiacal emission removed although they have an arbitrary zero-point.

3 RESULTS

3.1 WSRT aperture synthesis H\textsc{i} results

Fig. 3 shows the H\textsc{i} column density map of the IVC for the low-resolution WSRT data alone, with Fig. 4 showing the corresponding map of the combined (WSRT plus Arecibo) image overlaid on the digitised Palomar Observatory Sky Atlas (POSS-I) red image regridded to a 4 arcsec pixel size. The major axis of this part of the IVC lies parallel with
of the M 15 IVC integrated between +50 and +90 km s\(^{-1}\) at a resolution of 111′′/beam, overlaid on the red POSS-I digital sky survey image towards M 15. Velocities are in the LSR with contour levels being at \(N_{HI}=\{2,4,6,8,10,12,14\}\times10^{19}\) cm\(^{-2}\). Lines of constant Galactic longitude and latitude are also plotted on the figure.

Figure 5. WSRT plus Arecibo combined H\(_i\) column density map of the M 15 IVC integrated between +50 and +90 km s\(^{-1}\) and at a resolution of 111′′×56′′, overlaid on the red POSS-I digital sky survey image towards M 15. Velocities are in the LSR with contour levels being at \(N_{HI}=\{2,4,6,8,10,12,14\}\times10^{19}\) cm\(^{-2}\). Lines of constant Galactic longitude and latitude are also plotted on the figure.

The Galactic plane. The H\(_i\) channel maps of the combined WSRT plus Arecibo dataset in brightness temperature (\(T_B\)) are shown in Fig. 5, where flux density per beam is related to \(T_B\) by \(S_{\text{beam}}=0.65\Omega_{\text{beam}}T_B/\lambda^2_{\text{beam}}\); here \(\Omega_{\text{beam}}\) is the beam area in arcsec\(^2\) and \(\lambda^2_{\text{beam}}\) is the observed wavelength in cm (Braun & Burton 2000). Immediately obvious from each of these figures is the fact that the H\(_i\) is clumpy in nature, as is seen in other intermediate and high velocity clouds observed at a similar resolution (e.g. Weiß et al. 1999; Braun & Burton 2000). Variations in the column density of a factor of \(~4\) on scales of \(~5\) arcmin are observed, corresponding to scales of \(~1.5\) D pc, where \(D\) is the the H\(_i\) distance in kpc. The peak brightness temperature in the combined map (of resolution 111′′×56′′), is \(~8\) K, rising to \(~14\) K for the highest resolution WSRT map with beamsize 81′′×14′′. These values are of the IVC by M 15, with the gas in the centre being ionised by the cloud itself. However, the existence of other IVC components in the nearby field, combined with the fact that M 15 is located at a radial velocity of \(~100\) km s\(^{-1}\) (Harris 1996), compared with the the IVC at \(~70\) km s\(^{-1}\), makes it likely that the two objects are simply line-of-sight companions.

3.2 Lovell telescope multibeam H\(_i\) results

The H\(_i\) column density map of a 4.9×9.3 degree field, with spatial resolution 12 arcmin, centred to the South-West of M 15, integrated from +50 to +90 km s\(^{-1}\), is shown in Fig. 6. No new firm H\(_i\) detections were obtained that are not already given in the Leiden/Dwingeloo survey (Hartmann & Burton 1997), Kennedy et al. (1998) or Smoker et al. (2001a). However, the extent of an IVC component around RA=21\(^h\)27\(^m\), Dec=+09\(^\circ\)10\(^\prime\) (J2000; feature 'D') was determined to be \(~0.7\) degrees in RA-Dec at full width half power in the \(N_{HI}\) map. An example H\(_i\) spectrum in this area is shown in Fig. 6. At this position, a single-component Gaussian fit within DIPOS gives a velocity centroid of \(68\pm0.5\) km s\(^{-1}\), FWHM of \(12\pm1.2\) km s\(^{-1}\) and peak \(T_B\) of \(~1\) K, similar properties to the main complex studied in this paper. The peak IVC H\(_i\) column density towards this component ('D') is \(~3\times10^{19}\) cm\(^{-2}\).

Also plotted on Fig. 6 are ‘A’, ‘AR’ and ‘HD’. ‘A’ corresponds to the main clump observed by Kennedy et al. (1998) which has FWHM \(~12–15\) km s\(^{-1}\) at 12 arcmin resolution.
The peak IVC column H\textsc{i} density derived using the current observations towards component ‘A’ of $3.7\times10^{19}$ cm$^{-2}$ is close to the value of $3.9\times10^{19}$ cm$^{-2}$ observed by Kennedy et al. (1998) with the same telescope and gives us faith in our calibration. ‘AR’ refers to previous IVC detections using the Arecibo telescope which have FWHM=12 km s$^{-1}$ and $v_{\text{LSR}}=+61$ km s$^{-1}$ at a resolution of 3 arcmin. ‘HD’ is the position of the halo star HD 203664 (of distance 3 kpc) in which two strong interstellar IVC Ca\textsc{ii} K absorption components are seen with FWHM=2.8 and 3.2 km s$^{-1}$ and $v\sim+80$ and $+75$ km s$^{-1}$ respectively (Ryans, Sembach & Keenan 1996). As this is an absorption-line measurement towards a star, the resolution is sub-arcsecond. Finally, we note that there is a hint of emission at RA=$21^h23^m04^s$, Dec=$+14^\circ12^\prime42^\prime\prime$ (feature ‘E’ on Fig. 6) although this is very close to the noise and may be a spurious detection.

### 3.3 William Herschel Telescope longslit UES results

Equivalent widths of some strong stellar lines from the inner 3 arcseconds of the first slit position are shown in Table 1.
Figure 7. WSR T uniformly-weighted H\textsc{i} brightness temperature profile of the M 15 IVC at the position of peak T\textsubscript{B}. The beamsize is 81\arcsec\times 14\arcsec. The dotted line depicts the Gaussian fit to the spectrum and has FWHM=5.2±0.2 \text{ km s}^{-1}. The dashed line shows the (data–single Gaussian fit) residual.

Table 1. Equivalent widths of some strong lines towards the centre of M 15. Where there are two values present, these refer to results taken on nights 1 and 2 respectively. Stellar types corresponding to the EWs for that particular line are taken from Jaschek & Jaschek (1987) (JJ87).

<table>
<thead>
<tr>
<th>Species</th>
<th>(\lambda_{\text{rest}}) (Å)</th>
<th>EW (Å)</th>
<th>JJ87 Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca\textsc{ii} K</td>
<td>3933.66</td>
<td>1.6, 1.5</td>
<td>A2</td>
</tr>
<tr>
<td>Fe\textsc{i}</td>
<td>4045.82</td>
<td>0.16, 0.17</td>
<td>A3</td>
</tr>
<tr>
<td>Ca\textsc{i}</td>
<td>4226</td>
<td>0.25, 0.28</td>
<td>F2</td>
</tr>
</tbody>
</table>

As the core of the cluster is unresolved from the ground, the spectrum obtained is composite. Fig. 11 shows the Ca\textsc{ii} K spectra at this position. The equivalent widths of the LV and IV interstellar components at this position are \(\sim 0.3 \text{ Å}\) and \(\sim 0.08 \text{ Å}\) respectively. The strength of the LV component multiplied by \(\sin(b)\) of \(\sim 135 \text{ m}\)\text{Å}\) compares with the canonical value of \(\sim 110 \text{ m}\)\text{Å}\) integrated EW of the Ca\textsc{ii} K perpendicular to the Galactic plane (Bowen 1991).

We now turn to the interstellar Ca\textsc{ii} observations. Fig. 12 shows the extracted spectra at three and five positions along the dispersion axis for slit positions 1 and 2 respectively, where the signal-to-noise in the continuum exceeds \(\sim 10\). The positions shown are separated by 2 arcseconds which corresponds to the worst seeing during the run, and is also the spatial resolution to which the data were smoothed when the extraction was performed.

The prime aim of these longslit observations was to determine whether there is velocity substructure within the IVC. As can be seen from a few of the sightlines, there is tentative evidence for such structure, with two cloudlets being present at LSR velocities of \(\sim +52 \text{ km s}^{-1}\) and \(\sim +66 \text{ km s}^{-1}\) (Fig. 13). This corresponds to a separation of \(\sim 8\) pixels so is not an artefact caused by shifts in the echelle over periods of several hours. However, the signal-to-noise of the data is low, and follow-up observations are required to confirm this finding. We note that although the observations of Meyer & Lauroesch (1999) may have also been expected to find such velocity substructure at their resolution of 14 \text{ km s}^{-1}, their observations were in the Na\textsc{i} D lines, which in some cases do not show velocity components, even when the Ca\textsc{i} lines do (Ryans et al. 1996).

The current observations could also be used to estimate the IVC Ca\textsc{ii} column densities along the slit as explained in section 2.3.2. Figure 14 displays the equivalent widths and Ca\textsc{ii} column densities for a number of the slit positions for the second slit orientation. Our Ca\textsc{ii} K equivalent widths range from 0.06–0.09 Å. These are slightly lower than those measured by Lehner et al. (1999) towards other parts of the IVC with low-resolution data, which are in the range 0.05–0.20 Å, with a median value of 0.10 Å. Towards the nearby halo star HD 203664 (which has an IVC H\textsc{i} column density of less than \(\sim 10^{18} \text{ cm}^{-2}\)), Ryans et al. (1996) measured an IVC Ca\textsc{ii} equivalent width of 0.06±0.01 Å. The Ca\textsc{ii}/H\textsc{i} ratio for the current data towards the M 15 IVC varies from \(2.1\times10^{-4}\) to \(2.9\times10^{-4}\). Unfortunately, poor quality of our measurements caused by low signal-to-noise,
and uncertainties in determining the sky and continuum levels, results in our errors being larger than the differences between these values.

### 3.4 Wisconsin Hα Mapper (WHAM) Results

#### 3.4.1 The main IVC towards M 15

Of the 184 spectra extracted from the WHAM survey, a clearly-defined Hα component at intermediate velocities exceeding +50 km s$^{-1}$ is only obvious at three positions (A0, A2, A5) with a weak detection towards (A7). We note that because M 15 itself is at an LSR velocity of $\sim -100$ km s$^{-1}$, it does not contaminate the observed spectrum. The spectra observed at these positions are shown in Fig. 13c. Fig. 15a depicts the locations of these WHAM points relative to the Lovell telescope Hα surface density map, with integration of velocities from $\sim +50$–$90$ km s$^{-1}$ in the WHAM Hα data also being superimposed. Fig. 15a also shows the WHAM data integrated from $\sim +50$–$90$ km s$^{-1}$, over the whole field mapped by the multibeam observations. The gas with brightness $\sim 0.1$ R is quite extended about the main IVC condensation, with an additional weak signal detected towards the tentative Hα detection ‘E’ (see Fig. 14).

Results of three-component Gaussian fitting at the four positions are shown in Table 3 uncorrected for Galactic extinction. These fits take into account the instrumental profile of the instrument, which is comprised of a 12 km s$^{-1}$ Gaussian with low-level wings superimposed. Although almost equally-well fitted using just two components (for the LV and IV gas), we chose to fit using three components due to the slight asymmetry in the LV component, most clearly seen towards position (A7). Table 2 also shows the

---

**Figure 9.** WSRT plus Arecibo Hα combined image. Greyscale; full width half maxima velocity widths obtained using single-component Gaussian fitting. Contours; peak values of brightness temperature of the same single-component fits with levels at (2,4,6,8) Kelvin.

**Figure 10.** Lovell telescope multibeam Hα column density map of resolution 12 arcmin in the general direction of the M 15 globular cluster integrated from $+50$ to $+90$ km s$^{-1}$ in the LSR. Contour levels are at (1,2,3)$\times 10^{19}$ cm$^{-2}$, with greyscale levels from 0–4$\times 10^{19}$ cm$^{-2}$. For the meaning of the labels see Sect. 3.4.

**Figure 11.** Ca II K central 3′′ towards M 15.
Figure 12. Normalised spectra each 2 arcseconds along the slit. Spectra are offset in units of 1.0 for clarity. (a) Ca\textsc{ii} K spectra at slit position 1. (b) Ca\textsc{ii} K spectra at slit position 2.

Figure 13. Solid line: Ca\textsc{ii} K LV and IV spectrum. Dotted line; ELF multicomponent fit. Dashed line; (data−model) residual plus 1.0. A possible second intermediate velocity component is marked by IV?.

Figure 14. Ca\textsc{ii} fit results along the second slit position.

central velocity and velocity widths observed in H\textsc{i} towards the component (A5), obtained by smoothing the Lovell telescope multibeam data to a resolution of 1 degree.

The spectrum with the strongest IV H\alpha emission (A5) is depicted in Fig. 14. This is the nearest grid position to the M15 IVC, whose centre lies approximately at $l=65.01^\circ$, $b=-27.31^\circ$. The peak IV H\alpha brightness in this direction obtained using three-component Gaussian fitting is 0.035 Rayleighs (km s$^{-1}$)$^{-1}$ for the low velocity gas, and 0.033 Rayleighs (km s$^{-1}$)$^{-1}$ for the intermediate velocity gas, where 1 Rayleigh is $10^6/4\pi$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The integrated fluxes are 2.2$\pm$0.1 and 1.3$\pm$0.1 Rayleighs for the (total) LV and IV gas respectively. The Gaussian fit gives centroids of $-53.9\pm4.6$, $-4.4\pm0.7$ and $+64.3\pm0.4$ km s$^{-1}$, and FWHM velocity widths of 26.7$\pm$10.4, 47.8$\pm$2.6 and 31.5$\pm$1.4 km s$^{-1}$, for the low and intermediate velocity gas respectively. The velocity centroid at this position (A5) agrees within the errors with the H\textsc{i} data smoothed to the WHAM spatial resolution; this contrasts with the results of Tuft, Reynolds & Haffner (1998) who tentatively found an offset in velocity between H\alpha and H\textsc{i} velocities of $\sim 10$ km s$^{-1}$ towards various HVC complexes. For the position (A5), the velocity width of the IV H\alpha spectrum of $\sim 32$ km s$^{-1}$ is some 10 km s$^{-1}$ greater than the H\textsc{i} data at 1 degree resolution. For a gas at $\sim 10^4$ K, some $\sim 22$ km s$^{-1}$ of this is caused by thermal broadening, with the remaining width being due to non-thermal motions and beamsmearing of different components. The difference between the H\textsc{i} and H\alpha widths may imply that the two phases are not mixed. However, at least qualitatively, there is reasonable coincidence between the H\alpha and H\textsc{i} peaks (Fig. 3(a)), although the mapped area is small.

The second positive detection (towards (A2) in Fig. 3), occurs in a region where the local H\textsc{i} column density, at the Lovell telescope resolution of $\sim 12$ arcmin, is lower than $1\times10^{19}$ cm$^{-2}$. However, when smoothed to a WHAM resolution of 1 degree, the H\textsc{i} column density at this point is $\sim 1.0\times10^{19}$ cm$^{-2}$. Finally, towards (A7) there is a weak detection of $\sim 0.25$ R at $\sim +59$ km s$^{-1}$. At the WHAM resolution, the H\textsc{i} column density at this point is $\sim 0.4\times10^{19}$ cm$^{-2}$. We note that this position is close to the Arecibo-measured H\textsc{i} position ‘AR’ (Fig. 10), which has a similar velocity centroid of $v_{lsr}=+61$ km s$^{-1}$.
Figure 15. (a) Lovell-telescope IV H\textsubscript{I} column density map taken from Kennedy et al. (1998) in the vicinity of M 15 with WHAM-observed positions marked (A0)–(A7). Contour levels (full line) are at $N_{H\text{I}}=(1,2,3)\times10^{19}$ cm$^{-2}$. The dashed lines show the H$\alpha$ contours from the WHAM H$\alpha$ observations, integrated from $\sim +50$–90 km s$^{-1}$ with levels at $0.1\times(1,2,3,4,5)$ R. (b) H$\alpha$ brightness integrated from $\sim +50$–90 km s$^{-1}$ for the whole field observed with the Lovell telescope in H\textsubscript{I}. Contour levels are at $0.1\times(1,2,3,4,5)$ R. (c) WHAM H$\alpha$ spectra at the positions (A0)–(A7). Velocities are in the LSR. Where H$\alpha$ is observed (positions A0,A2,A5,A7), a three-component Gaussian fit is indicated by a dotted line with the (data–model) residual shown by the dashed line.

3.4.2 WHAM pointings towards HD 203664 and position ‘D’

The nearest WHAM H$\alpha$ pointings in the vicinity of the halo star HD 203664 are some 0.38 and 0.66 degrees from the stellar position and are depicted in Fig. [17]. Although there is a slight excess of H$\alpha$ with velocities exceeding $\sim +50$ km s$^{-1}$, this is very close to the noise and at lower velocities than the Ca\textsc{ii} K absorption seen by Ryans et al. (1996) which had velocities of +75–80 km s$^{-1}$. Fig. [18] shows the WHAM pointings superimposed on the Lovell telescope multibeam H\textsubscript{I} column density map for the IVC towards IVC position ‘D’ (c.f. Fig. [10]). Again, although there is some H$\alpha$ excess towards position (d3), this is very weak (brightness 0.07 R), and is also at a low-velocity of $\sim +50$ km s$^{-1}$; this compares with the IVC H\textsubscript{I} velocity of $\sim +68$ km s$^{-1}$ at this point. Even though the WHAM pointing centre is just within the $N_{H\text{I}}=1\times10^{19}$ cm$^{-2}$ contour, the relatively small size of the ‘D’ component results in the H\textsubscript{I} column density at this point at 1 degree resolution being $\sim 0.5\times10^{19}$ cm$^{-2}$.

3.5 IRAS ISSA results

In this section the IRAS 60 and 100 micron ISSA images are compared with previous Arecibo H\textsubscript{I} observations of Smoker et al. (2001a). These latter data are of resolution 3 arcmin and contain both low and intermediate velocity gas. Fig. [19] shows the 100 micron image overlaid on the total (LV plus IV) H\textsubscript{I} column density, with Fig. [20] displaying the corresponding 60 micron data and the IVC H\textsubscript{I} column density alone. There appears to be a relatively good correlation between the IRAS and H\textsubscript{I} results, both for the low and intermediate velocity gas; although with such a small field such agreement could have occurred by chance. The emission is not likely to be from the M 15 globular cluster itself, as glob-
The tabulated values are likely to be low by ~25 per cent. Lovell telescope H\textsc{i} multibeam results, smoothed to a WHAM-sized 1 degree beam, provide H\textsc{i} velocity information towards position (A5).

<table>
<thead>
<tr>
<th>Position on Fig. [ ]</th>
<th>(A7)</th>
<th>(A5)</th>
<th>(A2)</th>
<th>(A0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (J2000)</td>
<td>21(^h)26(^m)53.3(^s)</td>
<td>21(^h)29(^m)24.9(^s)</td>
<td>21(^h)32(^m)00.4(^s)</td>
<td>21(^h)34(^m)37.0(^s)</td>
</tr>
<tr>
<td>Dec (J2000)</td>
<td>+11(^\circ)28'58''</td>
<td>+12(^\circ)14'30''</td>
<td>+13(^\circ)00'02''</td>
<td>+13(^\circ)44'43''</td>
</tr>
<tr>
<td>(l) (degrees)</td>
<td>63.88</td>
<td>64.98</td>
<td>66.09</td>
<td>67.19</td>
</tr>
<tr>
<td>(b) (degrees)</td>
<td>-27.16</td>
<td>-27.16</td>
<td>-27.16</td>
<td>-27.16</td>
</tr>
<tr>
<td>H\textsc{i} LV (V_c) (km s(^{-1}))</td>
<td>-32.0±16.6, +2.7±2.6</td>
<td>-53.9±4.6, -4.4±0.7</td>
<td>-43.8±3.7, -5.3±0.6</td>
<td>-32.4±9.5, -0.7±1.5</td>
</tr>
<tr>
<td>H\textsc{i} LV FWHM (km s(^{-1}))</td>
<td>44.6±22.4, 35.1±4.8</td>
<td>26.7±10.4, 47.8±2.6</td>
<td>18.8±9.4, 35.2±2.0</td>
<td>30.3±14.1, 29.5±2.9</td>
</tr>
<tr>
<td>H\textsc{i} LV Flux (R)</td>
<td>0.27±0.18, 1.02±0.20</td>
<td>0.14±0.06, 2.10±0.08</td>
<td>0.11±0.04, 1.50±0.06</td>
<td>0.20±0.13, 1.26±0.14</td>
</tr>
<tr>
<td>H\textsc{i} LV Peak (mR (km s(^{-1}))^(-1))</td>
<td>4.8±1, 23±1</td>
<td>4.2±1, 35±1</td>
<td>4.7±1, 34±1</td>
<td>5.2±1, 34±1</td>
</tr>
<tr>
<td>H\textsc{i} IV (V_c) (km s(^{-1}))</td>
<td>+59.3±1.1</td>
<td>+64.3±0.4</td>
<td>+59.4±0.8</td>
<td>+71.4±0.5</td>
</tr>
<tr>
<td>H\textsc{i} IV FWHM (km s(^{-1}))</td>
<td>18.8±3.4</td>
<td>31.5±1.4</td>
<td>38.1±2.4</td>
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<td>0.95±0.04</td>
<td>0.91±0.03</td>
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<tr>
<td>H\textsc{i} IV Peak (mR (km s(^{-1}))^(-1))</td>
<td>11±1</td>
<td>35±1</td>
<td>29±1</td>
<td>26±1</td>
</tr>
<tr>
<td>H\text{\textsc{I}} IV (V_c) (km s(^{-1}))</td>
<td>–</td>
<td>65.7±0.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>H\text{\textsc{I}} IV FWHM (km s(^{-1}))</td>
<td>–</td>
<td>22.0±2.0</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 16. Solid line: WHAM H\textsc{a} spectrum towards \(l=64.98\), \(b=-27.16\) (A5). The dotted line shows the results of a three-component Gaussian fit. The dashed line is a (data-three component Gaussian fit) residual.

Figure 17. Nearest two WHAM H\textsc{a} spectra towards HD 203664 with their angular distances from the star indicated.

The (tentative) IRAS detection contrasts with the situation in HVCs, which at least at the IRAS sensitivity do not appear to emit at these wavelengths (Wakker & Boulanger 1986). Such a difference indicates either differences in dust content, dust temperature or environment (such as distance from the heating field of the Galactic plane). H\text{\textsc{I}} absorption line spectroscopy towards a number of HVCs by Akeson & Blitz (1999) indicates that the fraction of cold gas is low in these objects. If so, then this would point to the Galactic-halo HVCs containing less dust than the IVCs and not differences in temperature.

4 DISCUSSION

4.1 The H\textsc{a} properties of the M 15 IVC

4.1.1 Estimates of the emission measure and H\text{\textsc{I}} column density

The detection of H\textsc{a} towards the main M 15 IVC (position A5) with brightness of ~1.3 R compares to lower values of
between 0.06 to 0.20 R observed in a number of High Velocity Clouds (Tuft et al. 1998). Similarly, many of the HVCs observed by Weiner, Vogel & Williams (1999) are very faint (<0.03 R), implying that, if they are photoionised by hard photons from the Galaxy, they are 20–60 kpc distant. The relatively high Hα emission from the M15 IVC in turn argues for a closer distance, assuming that shock ionisation is not the dominant factor. This is a big assumption, as detections of Hα in the Magellanic Stream (distance 55 kpc) of are 0.20–0.37 Rayleigh (Bland-Hawthorn & Maloney 1999) are similar to the range of ~ 0.1–0.5 Rayleigh detected towards the IVC Complex K (Haffner, Reynolds & Tuft 2001a) which has a distance bracket of 0.3–7.7 kpc.

Assuming that extinction is negligible and that the cloud is optically thin, the observed Hα brightness of the IVC can be used to estimate both the column density of ionised hydrogen and the electron density. For an optically thin gas, the Hα surface brightness in Rayleigh, $I_\alpha$, is given by:

$$I_\alpha = 0.36 \times \text{EM} \times \sqrt{T} \times (1 - 0.37 \times \ln(T)), \quad (1)$$

where $T$ is the gas temperature in units of $10^4$ K and EM is

Figure 18. Top panel: Lovell telescope multibeam IVC H I surface density map of feature (D) (+50 < $V_{LSR}$ < +80 km s$^{-1}$), with contour levels at $N_{HI}=(1, 2, 3) \times 10^{19}$ cm$^{-2}$ with WHAM pointings (d1)–(d5) marked. Bottom panel: WHAM Hα spectrum towards (d3). The dotted line is a three-component Gaussian fit with the dashed line showing the data-fit residual spectrum.

Figure 19. Arecibo H I and IRAS ISSA data. Greyscale: IRAS 100 micron flux density. Contour: Total (LV plus IV) H I column density at $N_{HI}=(56, 60, 64, 68, 72) \times 10^{19}$ cm$^{-2}$.

Figure 20. Arecibo H I and IRAS ISSA data. Greyscale: IRAS 60 micron flux density. Contour: IVC H I column density at $N_{HI}=(2, 4, 6, 8) \times 10^{19}$ cm$^{-2}$. Note how the peak H I contour corresponds with the IRAS peak.
the emission measure ($\int n_e^2 dl$) in units of pc cm$^{-6}$ (Simonetti, Topasna & Dennison 1996). Here, $n_e$ is the electron density and integration over $dl$ provides the thickness ($L$) of the ionised region. Assuming the temperature of the H\textsc{ii} is 8,000 K, typical of the warm interstellar medium (Reynolds 1985), the resulting emission measure towards position (A5) is 3.7 pc cm$^{-6}$.

Assuming a distance to the main IVC condensation of 1 kpc, the cloud size ($d$) at a column density limit of $N_{HI} = 10^{19}$ cm$^{-2}$ is $\sim 0.6^{\circ} \times 0.8^{\circ}$, corresponding to linear dimensions of $\sim 10 \times 14$ pc. If the cloud is approximately spherically symmetric, this results in an estimated electron density (assuming a size of 12 pc) of $\sqrt{EM/d} \sim 0.6 f^{-1/2}$ cm$^{-2}$ and a column density of ionised hydrogen ($= L \times n_e$) of $\sim 2 \times 10^{19} f^{1/2}$ cm$^{-2}$, where $f$ is the filling fraction of H\textsc{ii} in the IVC. Smoothed to a resolution of 1 degree (corresponding to the size of the WHAM beam), the H\textsc{i} column density at this point derived from the data of Kennedy et al. (1998) is $\sim 1.4 \times 10^{19}$ cm$^{-2}$, hence the fractional ratio of H\textsc{ii} to H\textsc{i} is of order $1.4 \times f^{1/2}$, indicating that there is a substantial amount of ionised gas at intermediate velocities present in this sightline.

For positions (A2) and (A7), and using the same cloud size as above, results in estimated H\textsc{ii} column densities of $1.5 \times 10^{19}$ cm$^{-2}$ and $0.8 \times 10^{19}$ cm$^{-2}$, corresponding to fractional H\textsc{ii} to H\textsc{i} values of order $1.5 \times f^{1/2}$ and $2.0 \times f^{1/2}$ respectively. These fractional H\textsc{ii} to H\textsc{i} ratios towards the current IVC are somewhat higher than derived by Tuft et al. (1998) for a sample of HVCs which were calculated to be $< 0.06 \times f^{1/2}$. However, recent work by Bluhm et al. (2001), in sightlines towards the Large Magellanic Cloud, used the relative underabundance of neutral oxygen to infer an ionisation level in both an IVC and HVC of $\sim 90$ per cent. It would be useful to observe this cloud using the same methods as described in the current paper and compare the results.

Towards (d3) there is no detection in H\textalpha with velocities corresponding to the H\textsc{i} value of $\sim +68$ km s$^{-1}$. Assuming a cloud size of 8pc and upper limit to the H\textalpha brightness of 0.2 R, gives an estimated upper limit to the IVC H\textsc{ii} column density and fractional H\textsc{ii} to H\textsc{i} values of $\sim 4 \times 10^{18}$ cm$^{-2}$ and $0.7 \times f^{1/2}$. Finally, we consider the halo star HD 203664, towards which the limiting column density of neutral hydrogen is $\sim 10^{18}$ cm$^{-2}$. If we take the upper limit to the H\textalpha brightness of 0.2 R, and combine this with a cloud size $L$ (in pc, where the Arecibo beam is $\sim 1$ pc FWHM at 1 kpc distance), a fractional H\textsc{ii} to H\textsc{i} ratio of $\sim 1.4 \times L \times f^{1/2}$ can be set by the current observations.

4.1.2 Estimates of the ionising radiation field and electron density

Following Tuft et al. (1998), if photoionisation is the dominant cause of H\textalpha emission, then the incident Lyman continuum flux $F_{LC}$ can be estimated thus, assuming case B recombination:

$$F_{LC} = 2.1 \times 10^9 \frac{I_\alpha}{0.1^2} \text{photons cm}^{-2} \text{s}^{-1}, \tag{2}$$

where $I_\alpha$ is the H\textalpha intensity in Rayleigh. For the M 15 IVC, equation 3 implies an incident flux ($F_{LC}$) of $2.7 \times 10^6$ photons cm$^{-2}$ s$^{-1}$. Hence if photoionisation is the main cause of H\textalpha production, the derived Lyman-alpha continuum flux towards the main M 15 IVC condensation is a factor 6--22 times higher than the implied incident flux towards the A, C and M HVCs observed by Tuft et al. (1998), and more than twice that observed towards the Complex K IVC by Hauffner et al. (2001a). We recall that Complex A lies between 4--10 kpc, with Complex C being some 5--25 kpc distant and the M 15 IVC being closer than 3 kpc. In the future, comparison of derived Lyman-alpha continuum fluxes for a larger sample of IVC and HVC sightlines with known distances may provide information on the relative contributions of the Galactic and extragalactic ionising field.

An alternative possibility is that the H\textalpha is produced by shock ionisation, caused by interaction of the IVC with LV gas. This is a real possibility given the orientation of the IVC and the fact that its z-distance of less than 1 kpc puts it in the lower Galactic halo. Towards the nearby halo star HD 203664 in which IV absorption is seen, Sembach (1995) postulated that the dust grains in the IVC have been processed by such shocks which also currently produce the highly ionised species. For an ambient temperature of $<3 \times 10^5$ K, a cloud of velocity 50 km s$^{-1}$ will be supersonic and hence shocks may be formed given the right conditions. Using the models of Raymond (1979), which are applicable for shocks with speed $50 < V_s < 140$ km s$^{-1}$, the face-on
Ho surface brightness ($I_{\alpha perp}$) can be related to the number density of the pre-shocked gas ($n_0$), thus:

$$I_{\alpha perp} = 6.5 \times n_0 (V_s / 100)^{1.7} R$$

Given that $I_{\alpha perp}$ = 1.3 R, and assuming a shock speed of 50 km s$^{-1}$, leads to an upper limit to $n_0$ of 0.6 cm$^{-3}$. The value is an upper limit (for this shock speed velocity) as a non-perpendicular sideline will increase the observed $I_\alpha$ (Tuft et al. 1998). Of course, given the fact that the transverse component of the velocity of the M 15 IVC is unknown, this value is very uncertain. Discriminating between shock and photoionisation is difficult, although further progress may be possible via measurements of appropriate emission line ratios (Tuft et al. 1998).

### 4.2 Ca$^{+}$ number density towards the M 15 IVC and HD 203664

Before discussing the Ca$^{+}$ K results, we note that calcium is depleted onto dust and is not the dominant ionisation species, hence the absolute metallicity of the M 15 IVC is uncertain and awaits high resolution UV observations. As emphasized by Ryan et al. (1997), differences in resolution between the optical and radio data, combined with the Ca$^{+}$ K results only placing limits on the ion abundances, makes it important not to over-interpret the observed N(Ca$^{+}$)/N(H$^{+}$) ratios.

With that caveat, and assuming that the current observations do not miss any narrow-velocity components, the average IVC Ca$^{+}$ number density and ratio of the IVC compared to H$^1$ towards the centre of M 15 are log$_{10}$N(Ca$^{+}$)/n$_0$ = 12.0 and N(Ca$^{+}$)/N(H$^{+}$) = 2.5 × 10$^{-8}$. The H$^1$ column density towards the M 15 centre is 4 × 10$^{19}$ cm$^{-2}$ and was obtained using the combined WSRT plus Arecibo map of resolution 117$''$ × 56$''$. For the nearby sightline towards the halo star HD 203664, we use the results of Ryan et al. (1996) for the total IVC Ca$^{+}$ K column density of $\sim$1 × 10$^{12}$ cm$^{-2}$, combined with the upper limit to the H$^1$ column density at a resolution of 3 arcmin towards HD 203664 of $\sim$1 × 10$^{18}$ cm$^{-2}$ (Smoker et al. 2001), giving a much higher value of N(Ca$^{+}$)/N(H$^{+}$) > 10$^{-6}$.

The current results compare with literature values of N(Ca$^{+}$)/N(H$^{+}$) = 2 × 10$^{-9}$ (Hobbs 1974, 1976) for low velocity diffuse clouds and of N(Ca$^{+}$)/N(H$^{+}$) in the range 3–300 × 10$^{-9}$ cm$^{-2}$ for the high latitude clouds studied by Albert et al. (1993). The N(Ca$^{+}$)/N(H$^{+}$) ratios in IVCs and HVCs are thought to be higher than in low velocity gas due to the former having less dust onto which calcium is depleted. Thus the observed N(Ca$^{+}$)/N(H$^{+}$) ratio of 2.5 × 10$^{-8}$ (or $\sim$ 0.01 of the total solar calcium abundance) in the line-of-sight towards M 15 is typical of other high latitude clouds and also of other HVCs and IVCs (e.g. Wakker et al. 1996a; Ryan et al. 1997).

The lower limit of N(Ca$^{+}$)/N(H$^{+}$) > 10$^{-6}$ towards HD 203664 is, however, on the high side for IVCs/HVCs, being $\sim$ 0.5 of the total solar calcium abundance. There are several possible reasons for this. Firstly, the (currently undetected) H$^1$ towards HD 203664 could be in a clump of gas smaller than the Arecibo beamsize of 3 arcmin; if this were the case then the H$^1$ column density limit used would be too low and the derived N(Ca$^{+}$)/N(H$^{+}$) ratio too high. Additionally, HST UV observations towards HD 203664 indicate that the H$^1$ towards this object is at least partially ionised (Sembach, private communication), either by shock ionisation or photoionisation. If photoionisation, aside from the normal ionising source being Galactic OB-type stars or the extragalactic UV field, HD 203664 itself (spectral type B0.5) could be a possible ionising source. The fact that its LSR velocity is +110 km s$^{-1}$ (Little et al. 1994) compared with the IVC at +70 km s$^{-1}$ is inconclusive in determining the relative distance of the line of sight IVC towards HD 203664 with the star itself. Finally, there remains the possibility that the hydrogen is in molecular form. However, given the low H$^1$ column density towards the HD 203664 sightline, this appears unlikely.

Alternatively, it could be that the derived value of N(Ca$^{+}$)/N(H$^{+}$) > 10$^{-6}$ towards HD 203664 is correct. This would tally with the IUE results of Sembach (1995), which found that the majority of the elements in the IV gas, when referenced to sulphur, were within a factor 5 of their solar values and strongly point to a Galactic origin for this part of the IVC. The fact that our derived value for N(Ca$^{+}$)/N(H$^{+}$) towards the M 15 IVC of 0.01 solar is much lower than towards HD 203664 is likely to be caused by different ionisation fractions and dust contents, and/or differing formation mechanisms. Clearly the latter is speculative and requires follow-up high resolution UV observations towards the M 15 IVC to determine the abundances of elements such as sulphur and zinc that are not depleted onto dust.

### 4.3 Velocity widths and temperatures towards the M 15 IVC and HD 203664

Towards the main M 15 IVC condensation, (feature ‘A’ on Fig. 10) values of the H$^1$ FWHM velocity width at resolutions of $\sim$2 × 1 arcmin range from 5–14 km s$^{-1}$, corresponding to maximum kinetic temperatures in the range $\sim$500–4000 K. Mid-way between the M 15 IVC and HD 203664, the FWHM equals 12 km s$^{-1}$ at a resolution of 3 arcmin, which corresponds to $T_k$ $\sim$ 3000 K (feature ‘AR’ on Fig. 10). The current observations have additionally observed feature ‘D’ at a resolution 12 arcmin, with FWHM velocity width also of 12 km s$^{-1}$, indicating gas of similar temperature. We note that each of these temperatures will be upper limits due to beamsmearing and turbulent velocity components. Finally, towards HD 203664, Ryan et al. (1996) found cloudlets with FWHM of 2.8 and 3.2 km s$^{-1}$ in Ca$^{+}$ K, corresponding to upper limits for the kinetic temperatures of $\sim$8000–10,000 K. Towards the same star, Sembach (1995) used the relative abundances of low-ionisation species to derive a temperature for the HD 203664 IVC of 5300–6100 K.

The higher IVC gas temperatures towards HD 203664 than towards the M 15 IVC, feature ‘D’ or the intermediate position ‘AR’ could be interpreted as being caused by the former cloud being nearer to the ionising field of the Galactic plane than the other two IVCs (Lehner 2000). It seems more likely that the lower temperatures seen towards parts of ‘A’ and ‘AR’ are simply caused by shielding of parts of these gas clouds; shielding that is not possible towards the HD 203664 IVC because of the lower gas density there. A two-phase core-envelope structure for halo HVCs has often been proposed within the Galactic corona for 1 < z < 5 kpc.
where the two components of 100 and 10,000 K are entrained by pressure from the hot Galactic corona. We note that the high-end H\textsc{i} temperatures observed towards the M 15 IVC indeed occur towards its outer parts where the H\textsc{i} column density is low and the FWHM velocity widths are uncertain.

### 4.4 Comparison of H\textsc{i} properties with previous Galactic halo IVCs and HVCs

In this section we compare the high-resolution H\textsc{i} properties of the M 15 IVC with other IVCs and HVCs known to lie within the Galactic halo and observed at comparable resolution. We note that it is likely that there are many different types of HVC, with recent work, for example, indicating that a number of the compact HVCs lie at distances of several tens of kpc (Braun & Burton 2000). A literature search found the following objects with known distances and observed in H\textsc{i} at high resolution: the M 13 IVC (Shaw et al. 1996), the 4-Lac HVC 100–7+100 (Stoppenburg et al. 1998), the Low-Latitude Intermediate Velocity Arch (Wakker et al. 1996b), IVC 135+54–45 (Weiβ et al. 1999), HVC 132+23–211 (within Complex A; Schwarz et al. 1976) and the M 92 HVC (within Complex C; Smoker et al. 2001b).

Table 3 compares the properties of these IVC and HVC H\textsc{i} gas clouds known to exist in the Galactic halo. Inspecting the table, there are no clear differences in the H\textsc{i} properties (column density, peak temperature) of the two types of objects, which show a large scatter both within IVCs and HVCs. Similarly, the velocity widths of all of the objects, barring the peculiar HVC100–7 and the Mirabel cloud, all show minimum values of FWHM \(\sim 5\) km s\(^{-1}\) and indicating that gas of temperature less than \(\sim 500\) K is common in these objects. This is in contrast to the situation observed at lower resolution for some northern clouds, where IVCs tend to have smaller velocity widths than their HVC counterparts (Davies, Buhl & Jafolla 1976).

If some IVCs and HVCs are formed from infalling gas, sweeping up high-z H\textsc{i} as they fall towards the plane, or if they are objects within the plane, or if they are formed within a Galactic fountain, it seems plausible that they could be preferentially aligned with the Galactic plane. Of course, it must be taken into consideration that at high resolution, only small parts of cloud complexes are studied, and by chance, some of these components will be aligned with the plane. In any case, of the four objects in the sample with a well-defined axis and at high Galactic latitude, three have their major axis near-parallel with the plane. Although there exist a number of such objects observed at lower resolution with this orientation, to our knowledge no systematic survey has been performed determining the orientation parameters of HVCs. If performed, this could act as a further discriminator between HVCs known to exist in the Galactic halo, and the sample of HVCs postulated to lie at extragalactic distances.

Summarising, at present there are too few high-resolution observations of Galactic halo IVCs and HVCs to determine differences in H\textsc{i} properties and any relationship between the two types of object. However, as previously noted, the IRAS and H\alpha properties do appear to differ, although the number of objects studied in all three wavebands remains small.

### 5 SUMMARY AND CONCLUSIONS

The current H\textsc{i} WSRT synthesis observations have shown that on scales down to \(\sim 1\) arcmin, the M 15 IVC shows substructure, with variations in the column density of a factor of \(\sim 4\) on scales of \(\sim 5\) arcmin being observed, corresponding to scales of \(\sim 1.5\) D, where D is the the IVC distance in kpc. Of course, this is not an unexpected finding, but once again demonstrates that great care must be taken in interpreting quantities such as cloud metallicities which are derived from a combination of low-resolution radio plus optical data. The Lovell telescope H\textsc{i} observations towards this cloud demonstrated how relatively large areas of sky can be mapped with the multibeam system in a short period of time in the search for IVCs and HVCs. These data showed that the M 15 IVC has components spread out over several square degrees, with component ‘D’ being mapped for the first time at medium resolution (12 arcmin) and having a similar column density to the IV gas centred upon M 15 itself. Both the H\textsc{i} emission-line and Ca\textsc{ii} absorption-line data showed tentative evidence for velocity substructure, perhaps indicative of cloudlets. The Ca\textsc{ii}/H\textsc{i} value of \(\sim 2.5\times10^{-8}\) towards the main M 15 condensation is similar to that previously observed in other IVCs and HVCs. Towards HD 203664, the observed lower limit of \(10^{-6}\) is somewhat higher, although this may be caused by factors such as the H\textsc{i} beam being unfilled or partial ionisation of the gas on this sightline. The H\textsc{i} properties of the M 15 IVC are indistinguishable from HVCs, although with the lack of distance information towards most HVCs, comparisons are difficult.

The tentative detection of infrared emission from the M 15 IVC, as in other IVCs, does distinguish it from HVCs, and either points to the M 15 IVC containing more dust, and/or being closer to the heating field of the Galactic plane than HVCs, which as a class of objects are not detected in the IRAS wavebands. Similarly, the relatively strong H\alpha emission (exceeding 1 Rayleigh) towards parts of the M 15 IVC, if caused by photoionization, may place it closer to the Galaxy than HVCs. Again, however, this finding is uncertain due to the problem in distinguishing photoionisation from shock ionisation, uncertainties in dust content, and differences in H\textsc{i} column densities in different objects studied thus far.

Future work towards this cloud should include higher signal-to-noise observations in the Ca\textsc{ii} line in order to determine if the cloud velocity substructure tentatively found in the current observations is in fact real, and whether the Ca\textsc{ii}/H\textsc{i} ratio determined by the current observations is lower than towards the HD 203664 sightline. This should be combined with \(^{12}\)CO(1–0) sub-mm observations in order to determine if molecular material exists towards the peaks in H\textsc{i} column density and out of which stars may form. The determination of the falloff in H\textsc{i} column density, of the cloud to low column density limits would also indicate the ionisation properties of the object and whether or not there is any interaction between the M 15 IVC gas and low velocity material. Finally, UV observations towards M 15 globular cluster stars, although difficult, would provide important in...
Table 3. Previous high-resolution H i observations of IVCs and HVCs known to exist in the halo, compared with the current results. \( T_p \) and \( N_{HI} \) are the peak temperatures in K and peak \( N_{HI} \) column densities in units of \( 10^{19} \) cm\(^{-2} \) respectively. \( \Delta V_1 \) and \( \Delta V_2 \) are the broad and narrow velocity widths in km s\(^{-1} \). The field ‘Parallel to the Gal. plane’ only refers to the object observed at high-resolution and not to the whole complex in the case of the large HVCs.

<table>
<thead>
<tr>
<th>Cloud Ref.</th>
<th>( \theta ) (deg)</th>
<th>( b ) (kpc)</th>
<th>( V_{LSR} ) (km s(^{-1} ))</th>
<th>( \Delta V_1 ) (km s(^{-1} ))</th>
<th>( \Delta V_2 ) (km s(^{-1} ))</th>
<th>( T_p ) (K)</th>
<th>( N_{HI} ) (( 10^{19} ) cm(^{-2} ))</th>
<th>( \mathrm{[CaII/H}] )</th>
<th>Parallel to Gal. plane?</th>
<th>Res.</th>
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<tr>
<td>(SSH76, WPS99)</td>
<td>+23</td>
<td></td>
<td>-329</td>
<td></td>
<td></td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M13 b IVC</td>
<td>50</td>
<td>&lt;7</td>
<td>-70</td>
<td>5–15</td>
<td>8</td>
<td>N</td>
<td>&gt;1\times10^{7}</td>
<td>~ 3x2</td>
<td></td>
<td></td>
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<tr>
<td>(SBK96)</td>
<td>+41</td>
<td></td>
<td>-91</td>
<td></td>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M15 IVC</td>
<td>65</td>
<td>&lt;3</td>
<td>+101</td>
<td>4–7</td>
<td>3.4</td>
<td>N</td>
<td>–</td>
<td>Y</td>
<td>~ 6x6</td>
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</tr>
<tr>
<td>(This paper)</td>
<td>-27</td>
<td></td>
<td>+272</td>
<td></td>
<td></td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M92N IVC</td>
<td>68</td>
<td>5–25</td>
<td>-21</td>
<td></td>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>HVC100–7+100</td>
<td>100</td>
<td>&lt;1.2</td>
<td>+106</td>
<td>13</td>
<td>0.5</td>
<td>N</td>
<td>–</td>
<td>N</td>
<td>~ 2x2</td>
<td></td>
</tr>
<tr>
<td>(SSW98)</td>
<td>-7</td>
<td></td>
<td>+350</td>
<td></td>
<td></td>
<td>0.16</td>
<td></td>
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<tr>
<td>IVC 135+4–45</td>
<td>135</td>
<td>0.29–0.39</td>
<td>-45</td>
<td>4–5</td>
<td>&gt;7</td>
<td>Y</td>
<td>–</td>
<td>~ 1x1</td>
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<tr>
<td>(WHMM99)</td>
<td>+54</td>
<td></td>
<td>+59</td>
<td></td>
<td></td>
<td>30?</td>
<td></td>
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</tr>
<tr>
<td>PG0859+593 LLIVC</td>
<td>+156.9</td>
<td>1.7–4.0</td>
<td>-51</td>
<td>+19</td>
<td>2.0</td>
<td>?</td>
<td>–</td>
<td>–</td>
<td>~ 2x2</td>
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</tr>
<tr>
<td>(RKSD97, WSH96b)</td>
<td>+39.7</td>
<td></td>
<td>+24</td>
<td></td>
<td></td>
<td>5.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>PG0996+597 LLIVC</td>
<td>+156.2</td>
<td>1.7–4.0</td>
<td>-48–53</td>
<td>28, 6</td>
<td>16, 3.9</td>
<td>?</td>
<td>–</td>
<td>–</td>
<td>~ 2x2</td>
<td></td>
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<tr>
<td>(RKSD97, WSH96b)</td>
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<td></td>
<td>+29, +24</td>
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<td></td>
<td>11.0</td>
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formation on the absolute metallicity of the gas towards this object for comparison with the HD 203664 sightline.

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