Multiwavelength observations of the M15 intermediate-velocity cloud

J. V. Smoker, L. M. Haffner, F. P. Keenan, R. D. Davies and D. Pollacco

1 Astrophysics and Planetary Science Division, Department of Pure and Applied Physics, The Queen’s University of Belfast, University Road, Belfast BT7 1NN
2 Department of Astronomy, University of Wisconsin, 5534 Sterling Hall, 475 North Charter Street, Madison, WI 53706, USA
3 Jodrell Bank Observatory, University of Manchester, near Macclesfield, Cheshire SK11 9DL

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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 long-slit echelle Ca II observations, Wisconsin Hα Mapper (WHAM) facility images, and IRAS ISSA 60- and 100-μm co-added images towards the intermediate-velocity cloud (IVC) at +70 km s$^{-1}$, located in the general direction of the M15 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 $\sim 1.5 \times 10^{20}$ cm$^{-2}$, inferred volume density (assuming spherical symmetry) of $\sim 24$ cm$^{-3}$/D (kpc) and a maximum brightness temperature at a resolution of 81 $\times$ 14 arcsec$^2$ of $\sim 14$ K. The major axis of this part of the IVC lies approximately parallel to 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 at half-maximum velocity width of 5 km s$^{-1}$ corresponding to a kinetic temperature, in the absence of turbulence, of $\sim 540$ 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 that there are no unresolved narrow-velocity components, the mean values of $\log_{10}[N(Ca \ II \ K) \ cm^{-2}] \sim 12.0$ and Ca II/H I $\sim 2.5 \times 10^{-8}$ 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 from the main M15 IVC condensation. The main IVC condensation is detected by WHAM in Hα with central local-standard-of-rest velocities of $\sim 60$–70 km s$^{-1}$, and intensities uncorrected for Galactic extinction of up to 1.3 R, indicating that the gas is partially ionized. The FWHM values of the Hα IVC component, at a resolution of 1°, exceed 30 km s$^{-1}$. This is some 10 km s$^{-1}$ larger than the corresponding H I value at a similar resolution, and indicates that the two components may not be mixed. However, the spatial and velocity coincidence of the Hα and H I peaks in emission towards the main IVC component is qualitatively good. If the Hα emission is caused solely by photoionization, the Lyman continuum flux towards the main IVC condensation is $\sim 2.7 \times 10^6$ photon cm$^{-2}$ s$^{-1}$. There is not a corresponding IVC Hα detection towards the halo star HD 203664 at velocities exceeding $\sim 60$ km s$^{-1}$. Finally, both the 60- and 100-μm IRAS images show spatial coincidence, over a 0.675 $\times$ 0.625 deg$^2$ 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 Hα 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.

Key words: ISM: clouds – ISM: general – ISM: individual: Complex gp – ISM: structure – globular clusters: individual: M15 – radio lines: ISM.

1 INTRODUCTION
The study of intermediate-velocity clouds (IVCs) remains one of the most challenging aspects of 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 of whether IVCs are sites of star formation in the halo of the Galaxy (Kuntz & Danly 1996; Christodoulou, Tohline & Keenan 1997; Ivezic & Christodoulou 1997). This latter possibility is underpinned by the fact that within the Galactic halo, there exists a population of early B-type stars where the 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 I aperture synthesis, H I multi-beam wide field mapping, long-slit Ca II observations, Wisconsin H z Mapper (WHAM) facility images, and IRAS sky-survey archive data retrieval towards a particular IVC located in the general direction of the M15 globular cluster [RA = 21h 29m 58.29s, Dec. = +12° 10′ 00.5″ (J2000); l = 65.01°, b = −27.31°]. These observations are amongst the first H I synthesis data to be taken of positive-velocity IVCs, which remain poorly studied as a group of objects.

The M15 H I cloud lies at a velocity of ∼+70 km s⁻¹ in the dynamic local standard of rest (LSR) (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 ∼+70–80 km s⁻¹ is observed in the spectrum of HD 203664, a halo star of distance 3 kpc and ∼3.1° from M15 (Little et al. 1994), combined with the detection of IV H I approximately mid-way between the M15 IVC and HD 203664.

The deviation velocity of the M15 IVC at such a mid-Galactic latitude puts it in on the borderline between the normal definitions for intermediate and high-velocity clouds (cf. fig. 1 of Wakker 1991), although in common with Sembach (1995) and Kennedy et al. (1998) here we classify it as an IVC. The line-of-sight position of the M15 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 M15 IVC is a part of IVC Complex gp (Wakker 2001).

Previous observations in H 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 deg², with structure existing down to the previous resolution limit of ∼3 arcmin. The brightest component is located towards M15 itself and has a peak H I column density at the Arecibo resolution of ∼8 × 10¹⁷ cm⁻². In this paper, we study this part of the IVC at higher spatial resolution. The mass of this particular clump is ∼2 × 10¹² M☉ (where D is the distance in kpc), thus for this particular object, in the absence of H₂, there is insufficient neutral gas to form an early-type star. Low-resolution absorption-line Ca II and Na 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 I D absorption lines (Meyer & Lauroesch 1999), obtaining similar results with structure visible on scales of ∼4 arcsec (velocity resolution ∼16 km s⁻¹). Using empirical relationships between the sodium and hydrogen column densities, Meyer & Lauroesch (1999) derived values of the H I column density towards the cluster centre of ∼5 × 10¹⁹ cm⁻², some six times higher than that found using the Arecibo H I data alone; the difference may be attributable to fine-scale cloud structure. Assuming spherical symmetry, a volume density of ∼10⁰⁰ cm⁻³ is implied by these latter results, similar to values obtained for gas in the local interstellar medium (ISM) (e.g. Faisst 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 M15 IVC to higher resolution and different wavelength regions in order to investigate three areas. First, H I synthesis mapping, WHAM H z and IRAS ISSA survey data retrieval towards the IVC were performed to see whether the H I, H z and infrared properties of the M15 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, the distance from the ionizing field of the Galaxy). Secondly, wide-field medium-resolution H I data were obtained in a search for more IVC components, to trace how the gas kinetic temperature changes with sky position, and possibly to determine the relative distance of cloud components from the Galactic plane (cf. Lehner 2000). Thirdly, long-slit echelle Ca II observations were undertaken, using the centre of M15 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, Section 3 gives the results, Section 4 contains the discussion and Section 5 presents a summary and the conclusions.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Westerbork aperture synthesis H I observations

21-cm aperture synthesis H I observations of the M15 IVC were obtained during two observing sessions, each of 12 h, using the Westerbork Synthesis Radio Telescope (WSRT). The first on 1998 December 19 had a minimum antenna spacing of 32 m and the second on 1999 April 17 had a corresponding separation of 72 m. The velocity resolution for all observations was 1.03 km s⁻¹.

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 and 15.98 Jy, respectively), phase calibration and flagging of bad data, and concatenation of the two ultraviolet (UV) data sets using DBCON. The calibrated data set 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 beamizes of the final images were 111 × 56 and 81 × 14 arcsec² (approximately north–south by east–west), with the corresponding rms noises being 2.3 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

¡ AIPS is distributed by the National Radio Astronomy Observatory, USA.
combining the current observations with the single-dish Arecibo data. For this we used mirad (Sault, Teuben & Wright 1995). The two data sets were first regridded 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 and 150 m in the Fourier domain where the high- and low-resolution images were made to agree. Within this annulus it was found that, where the H I was strong, the flux density scales of the two data sets were the same. Hence the ‘calibration factor’ used when combining the two data sets was set to unity. The resulting combined channel maps were divided by the WSRT single-dish beam to produce the final combined images. These are of the resolution of the WSRT data (111 × 56 arcsec2), but with the correct zero-spacing flux. Finally, moments analysis and Gaussian fitting were performed on the WSRT channel maps and combined cube from +50 to +90 km s\(^{-1}\) in order to determine the H I column densities, velocities and velocity widths of the IVC. H I column densities were derived using the relationship \( N_HI = 1.823 \times 10^{18} \int T_B dv \) (cm\(^{-2}\)), where \( v \) is the velocity in km s\(^{-1}\).

2.2 Lovell telescope multibeam H I observations

Lovell telescope multibeam 21-cm \( H I \) observations covering a \(~4.9 \times 9.3 \text{ deg}^2\) RA--Dec. region, centred upon RA = 21h 22m 47s, Dec. = +10° 00′ 29″ (J2000) were taken during 2000 June 2. The resolution of these data is 12 arcmin spatially and 3.0 km s\(^{-1}\) in velocity. The total integration time was 4 h and the rms noise per channel was \(~0.1 \text{ K}\). 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 live-data and the data being gridded using gridzilla (Barnes et al. 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 (\( v \sim +70 \text{ km s}^{-1} \)) 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 long-slit UES observations

WHT Utrecht Echelle Spectrograph (UES) observations towards the centre of the M15 globular cluster were obtained during bright time over 2000 July 19–21. Twin EEV charge-coupled devices (CCDs) were used. In combination with the E79 grating, this gave nearly complete wavelength coverage from 3800 to 6300 Å, with a slitwidth of 0.85 arcsec, providing an instrumental FWHM resolution of \(~6 \text{ km s}^{-1} \). On the first night of the run, a slit height of 16 arcsec was used; this has the advantage that the full wavelength coverage was obtained with no overlapping orders on either of the CCDs. On the observations of the second and third night, in order to maximize the amount of sky available for the calcium lines at 3933.66 Å, a slit of height 22 arcsec was used, which leads to overlapping orders in the red CCD. ThAr arcs were taken two or three times a night to act as a wavelength calibration with tungsten and sky flats also being obtained. The echelle proved 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 seven parallel cuts through the IVC, separated by 0.7 arcsec, and to use these to make up an RA--Dec. rectangle of size \(~5 \times 20 \text{ arcsec}^2\) within which cloudlet sizes could be obtained. Unfortunately, owing to the presence of Sahara dust and non-ideal seeing conditions (1.5–2.0 arcsec), integration times were somewhat longer than had been hoped for and in the end only two long-slit positions were obtained, offset by a position angle of 85°. Additionally, on the second night we obtained 1200 s of integration towards a blank sky region with a 0.85-arcsec slit and on the third night a total of 5 × 400 s, interleaved with the object exposures and using a slit of width 4.0 arcsec, corresponding to \(~9500 \text{ s}\) of integration with a slit of 0.85 arcsec used for the IVC observations.

Data reduction was performed using standard methods within iraf. The aims were first to obtain a spectrum of the inner part of the globular cluster over the whole wavelength region, and more importantly, to produce long-slit spectra of the Ca II lines alone for the two long-slit positions taken. Data reduction included debiasing, and use of the sky flat-fields to get rid of the vignetting that was clearly visible on many of the orders. Cosmic ray hits near the Ca II line were removed within figaro (Shortridge et al. 1999) using clean. Because of the small pixel-to-pixel variation and pixel size (\(~0.2 \text{ arcsec}\)), no flat-fielding 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.

\(^2\)IRAF is distributed by the National Optical Astronomy Observatories, USA.
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 observations of the third night, where the blank sky exposures were interleaved with the object exposures. For these data, we scaled the high signal-to-noise ratio combined sky flat (taken at twilight with the 0.85-arcsec slit) to produce an image ‘scaled sky’ and then smoothed this in wavelength to a resolution equivalent to a 4-arcsec slit. The scaling factor was chosen so that the resulting image was the same as the blank sky image taken with the 4-arcsec slit for an equivalent of 5400 s of integration. The image ‘scaled sky’ was then subtracted from each 5400 s of the object data. This method has the advantage that in the blank sky images there are clearly no contaminating counts from the object, but it is susceptible to changes in the observing conditions and requires careful removal of the bias strip in both sky and object frames. Fig. 2 shows a cut across the dispersion axis for the sky exposures on night 3. As can be seen, there are few sky counts, although obviously in the outer parts of the slit there are few 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 λ ∼ 3937 Å, there were ∼ 3 ADU sky counts and somewhat fewer at λ ∼ 3933.66 Å, as a result of the ‘sky’ effectively being a solar (G-type) spectrum that has strong Ca II absorption lines.

The method of sky subtraction that we had envisaged performing a priori involved removal of sky using parts of the long-slit image that appeared to be free of emission from the globular cluster. The problem with this method is illustrated by Fig. 3(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 differs by ∼ 3–4 ADU per 5400 s of integration. During night 3, at λ ∼ 3937 Å, position p1 had ∼ 8 ADU as its ‘sky’ value, with the corresponding value for p2 being ∼ 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 λ ∼ 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 ∼ 4 ADU at 3937 Å, compared with a peak continuum value at this point of ∼ 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 ∼ 0.2 arcsec. Wavelength calibration was then undertaken, taking into account the shift in the λ scale along the length of the slit. Finally, normalization and profile fitting were performed within DIPSO (Howarth et al. 1996). The final spectra have a spatial resolution of ∼ 2 arcsec and a velocity resolution of ∼ 7 km s⁻¹.

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 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 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 at half-maximum (FWHM) velocity values for the low-velocity gas and IVC components. These results were compared with 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 II lines taken from Morton (1991) and initial guesses for the Ca 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 data set, 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 tLF and IS fits provide the Ca II number densities and values for the FWHM velocities at each of the positions along the slit.

2.4 Wisconsin Hα Mapper observations

Data were retrieved from the Wisconsin Hα Mapper survey in the range +06° < Dec. < +15° and 20° < RA < 21° (J2000). These data have a resolution 1° spatially and ~12 km s\(^{-1}\) in velocity, with a velocity coverage at this sky position from ~120 to +90 km s\(^{-1}\) in the local standard of rest. Data were reduced using standard methods, which included conversion into the LSR and removal of the geocoronal Hα line that appears at velocities in the range ~30 to +40 km s\(^{-1}\) (Haffner 1999; Haffner et al., in preparation). Owing 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 ~1–3 mR (km s\(^{-1}\))\(^{-1}\). These values are typical for the WHAM survey as a whole. Finally, we note that if the IVC Hα flux originates from above the Galactic plane, then a correction for Galactic extinction of 1.25 would be necessary, calculated from an \(E(B - V) = 0.10\) 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 Hα fluxes may be ~25 per cent too low.

2.5 IRAS ISSA data retrieval

Both the 60- and 100-μm images of a field of size 0.675 × 0.625 deg\(^2\) were extracted from the on-line versions of the IRAS Sky Survey Atlas (ISSA). These images are of resolution ~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\(^{\text{I}}\) results

Fig. 4 shows the H\(^{\text{I}}\) column density map of the IVC for the low-resolution WSRT data alone, with Fig. 5 showing the corresponding map of the combined (WSRT plus Arecibo) image overlaid on the digitized Palomar Observatory Sky Atlas (POSS-I) red image gridded to a 4-arcsec pixel size. The major axis of this part of the IVC lies parallel to the Galactic plane. The H\(^{\text{I}}\) channel maps of the combined WSRT plus Arecibo data set in brightness temperature \((T\(_{\text{B}}\))\) are shown in Fig. 6, where the flux density per beam is related to \(T\(_{\text{B}}\)\) by \(S_{\text{beam}}^{-1} = 0.65\Omega_{\text{be}} T\(_{\text{B}}\)/\(\lambda_{\text{cm}}^2\), where \(\Omega_{\text{be}}\) is the beam area in arcsec\(^2\) and \(\lambda_{\text{cm}}\) is the observed wavelength in centimetres (Braun & Burton 2000). Immediately obvious from each of these figures is the fact that the H\(^{\text{I}}\) 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 ~1.5D\(_{\text{pc}}\) , where D is the IVC distance in kpc. The peak brightness temperature in the combined map (of resolution 111 × 56 arcsec\(^2\)), is ~8 K, rising to ~14 K for the highest-resolution WSRT map with beamsize 81 × 14 arcsec\(^2\).

These values compare with peak values of \(T\(_{\text{B}}\)\) for HVCs of ~25 K towards Complex A at 2-arcmin resolution (Schwarz, Sullivan & Hulsbosch 1976), ~34 K observed towards Complex M at a resolution of 1 arcmin (Wakker & Schwarz 1991) and ~75 K observed to the compact high-velocity cloud CHVC 125 +41–207 (Braun & Burton 2000). Similarly the IVC observed by Weiß et al. (1999) has a peak \(T\(_{\text{B}}\)\) exceeding 7 K, at a resolution of 1 arcmin.

The peak H\(^{\text{I}}\) column density in the combined image is ~1.5 × 10\(^{20}\) cm\(^{-2}\). If we assume that the cloud is spherically symmetric or filamentary (Stoppenburg, Schwarz & van Woerden 1998), and using a cloud size FWHM (cf. Wakker & Schwarz 1991) of ~7 arcmin or 2D\(_{\text{pc}}\) for the brightest point, we obtain a peak volume density of ~24D\(^{-1}\) cm\(^{-3}\). At the assumed distance, this value is a lower limit as it is likely that there will be more structure on smaller scales, as indicated by the spectra of Meyer & Lauroesch (1999).

Fig. 7 shows the brightness temperature \((T\(_{\text{B}}\))\) profile at the position of peak temperature in the uniformly weighted data, with Fig. 8 depicting the combined temperature profiles at a number of positions in the cloud. The FWHM varies from 5 km s\(^{-1}\) at the position of

![Figure 5](https://example.com/f5.png)
Figure 6. WSRT plus Arecibo combined H\textsc{i} brightness temperature channel maps towards the M15 IVC. Velocities are in the LSR and the velocity resolution is 1.03 km s\(^{-1}\). Contour levels are at \(T_B = (-1, 1, 2, 4, 8)\) K. The spatial resolution is \(111 \times 54\) arcsec\(^2\) (\(\sim NS\) by EW).

The three peaks in brightness temperature (Figs 7 and 8a–c), to more than 12 km s\(^{-1}\) at other locations in the IVC (Fig. 8d). Some parts of the cloud (cf. Fig. 8b) are well-fitted by a Gaussian, whereas others, such as Fig. 8(e), appear to be made up of two narrowish components. Although the signal-to-noise ratio in this latter part of the cloud is low, both the WSRT and Arecibo data sets show evidence for a two-component velocity substructure, perhaps indicative of H\textsc{i} cloudlets or of overlapping clouds in the line of sight.

Fig. 9 displays the results of single-component Gaussian fitting to the IVC using XGAUSS and shows how the smaller values of FWHM (and hence the implied kinetic temperature) tend to occur where the H\textsc{i} is brightest in the three cores. At these positions, in the absence of turbulence, the kinematic temperature is of the order of 500 K. The M15 IVC does not show any regular velocity gradients across its field as has been seen in many other HVCs and IVCs (e.g. Weiß et al. 1999; Brüns et al. 2000).

We finally note that an interesting feature of the H\textsc{i} surface density map is that the IVC is approximately centred upon the globular cluster, with the regions of lowest column density being located towards the globular cluster centre. It is tempting to suggest some mechanism whereby the IVC and globular cluster are associated, for example by capture of the IVC by M15, with the gas in the centre being ionized by the cluster itself. However, the existence of other IVC components in the nearby field, combined with the fact that M15 is located at a radial velocity of \(\sim -100\) km s\(^{-1}\) (Harris 1996), compared with the IVC at \(\sim +70\) km s\(^{-1}\), makes it likely that the two objects are simply line-of-sight companions.

3.2 Lovell telescope multibeam H\textsc{i} results

The H\textsc{i} column density map of a 4.9 \(\times\) 9.3 deg\(^2\) field, with a spatial resolution of 12 arcmin, centred to the south-west of M15, integrated from +50 to +90 km s\(^{-1}\), is shown in Fig. 10. No new firm H\textsc{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 \(\sim 0.7\) deg in RA–Dec.
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Figure 7. WSRT uniformly weighted $H\alpha$ brightness temperature profile of the M15 IVC at the position of peak $T_B$. The beamsize is $81\times 14$ arcsec$^2$. The dotted line depicts the Gaussian fit to the spectrum and has FWHM $= 5.2 \pm 0.2$ km s$^{-1}$. The dashed line shows the (data–single-Gaussian fit) residual.

Figure 8. WSRT plus Arecibo combined $H\alpha$ brightness temperature profiles towards selected regions of the M15 IVC. (a) First $T_B$ peak (RA = 21$^h$ 29$^m$ 36$^s$, Dec. = +12$^\circ$ 06$'$ 22$''$). (b) Second $T_B$ peak (RA = 21$^h$ 29$^m$ 36$^s$, Dec. = +12$^\circ$ 06$'$ 22$''$). (c) Third $T_B$ peak (RA = 21$^h$ 30$^m$ 13$^s$, Dec. = +12$^\circ$ 10$'$ 42$''$). (d) High FWHM region (RA = 21$^h$ 29$^m$ 21$^s$, Dec. = +12$^\circ$ 04$'$ 22$''$). (e) Two-component profile (RA = 21$^h$ 29$^m$ 38$^s$, Dec. = +12$^\circ$ 19$'$ 22$''$). The equinox is J2000.

Figure 9. WSRT plus Arecibo $H\alpha$ combined image. Grey-scale; 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, 8) K.

Figure 10. Lovell telescope multibeam $H\alpha$ column density map of resolution 12 arcmin in the general direction of the M15 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 grey-scale levels from 0 to $4 \times 10^{19}$ cm$^{-2}$. For the meaning of the labels see Section 3.2.

at full width half-power in the $N_{H\alpha}$ map. An example $H\alpha$ spectrum in this area is shown in Fig. 1. At this position, a single-component Gaussian fit within DIPSO gives a velocity centroid of $68 \pm 0.5$ km s$^{-1}$, FWHM of $12.0 \pm 1.2$ km s$^{-1}$ and a peak $T_B$ of $\sim 1$ K – similar properties to the main complex studied in this paper. The peak IVC $H\alpha$ column density towards this component (‘D’) is $\sim 3 \times 10^{19}$ cm$^{-2}$.
Also plotted in Fig. 10 are ‘A’, ‘AR’ and ‘HD’. ‘A’ corresponds to the main clump observed by Kennedy et al. (1998), which has FWHM \( \sim 12 - 15 \, \text{km} \, \text{s}^{-1} \) at 12-arcmin resolution. The peak IVC column H I density derived using the current observations towards component ‘A’ of \( 3.7 \times 10^{19} \, \text{cm}^{-2} \) is close to the value of \( 3.9 \times 10^{19} \, \text{cm}^{-2} \) 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 that have \( \text{FWHM} = 12 \, \text{km} \, \text{s}^{-1} \) and \( v_{\text{LSR}} = +61 \, \text{km} \, \text{s}^{-1} \) 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 II K absorption components are seen with \( \text{FWHM} = 2.8 \) and \( 3.2 \, \text{km} \, \text{s}^{-1} \) and \( v_{\text{LSR}} \approx +80 \) and \( +75 \, \text{km} \, \text{s}^{-1} \), respectively (Ryans, Sembach & Keenan 1996). As this is an absorption-line measurement towards a star, the resolution is subarcsecond. Finally, we note that there is a hint of emission at RA \( = 21^h 23m 04s \), Dec. \( = +14^\circ 12' 42" \) (feature ‘E’ in Fig. 10), although this is very close to the noise level and may be a spurious detection.

### 3.3 William Herschel Telescope long-slit UES results

Equivalent widths of some strong stellar lines from the inner 3 arcsec of the first slit position are shown in Table 1. As the core of the cluster is unresolved from the ground, the spectrum obtained is composite. Fig. 11 shows the Ca II K spectra at this position. The equivalent widths of the LV and IV interstellar components at this position are \( \sim 0.3 \) and \( \sim 0.08 \, \text{˚A} \), respectively. The strength of the LV component multiplied by \( \sin(b) \) of \( \sim 135 \, \text{mA} \) compares with a canonical value of \( \sim 110 \, \text{mA} \) integrated EW of the Ca II K perpendicular to the Galactic plane (Bowen 1991).

We now turn to the interstellar Ca 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 ratio in the continuum exceeds \( \sim 10 \). The positions shown are separated by 2 arcsec, 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 primary aim of these long-slit 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 \( \sim +52 \) and \( \sim +66 \, \text{km} \, \text{s}^{-1} \) (Fig. 13). This corresponds to a separation of \( \sim 8 \) pixels, and thus is not an artefact caused by shifts in the echelle over periods of several hours. However, the signal-to-noise

![Figure 11](image1.png)

**Figure 11.** Ca II K central 3 arcsec towards M15.

![Figure 12](image2.png)

**Figure 12.** Normalized spectra each 2 arcsec along the slit. Spectra are offset in units of 1.0 for clarity. (a) Ca II K spectra at slit position 1. (b) Ca II K spectra at slit position 2.

![Figure 13](image3.png)

**Figure 13.** Solid line, Ca 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?.
which is composed of a 12 km s$^{-1}$, take into account the instrumental profile of the instrument, differences between these values.

The current observations could also be used to estimate the IVC Ca II column densities along the slit as explained in Section 2.3.2. Fig. 14 displays the equivalent widths and Ca II column densities for a number of the slit positions for the second slit orientation. Our Ca II K equivalent widths range from 0.06 to 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 I column density of less than $\sim 10^{19}$ cm$^{-2}$), Ryans et al. (1996) measured an IVC Ca II equivalent width of 0.06 ± 0.01 Å. The Ca II/H I ratio for the current data towards the M15 IVC varies from 2.1 to 2.9 x $10^{-3}$. Unfortunately, the poor quality of our measurements caused by a low signal-to-noise ratio, and uncertainties in determining the sky and continuum levels, resulted in our errors being larger than the differences between these values.

3.4 Wisconsin Hα Mapper results

3.4.1 The main IVC towards M15

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 M15 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. 15(c). Fig. 15(a) depicts the locations of these WHAM pointings relative to the Lovell telescope H I surface density map, with integration of velocities from $\sim$+50 to 90 km s$^{-1}$ in the WHAM Hα data also being superimposed. Fig. 15(a) also shows the WHAM data integrated from $\sim$+50 to 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 H I detection ‘E’ (see Fig. 10).

Results of three-component Gaussian fitting at the four positions are shown in Table 2, uncorrected for Galactic extinction. These fits take into account the instrumental profile of the instrument, which is composed 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 because of the slight asymmetry in the LV component, most clearly seen towards position (A7). Table 2 also shows the central velocity and velocity widths observed in H I towards the component (A5), obtained by smoothing the Lovell telescope multibeam data to a resolution of 1°.

The spectrum with the strongest IV Hα emission (A5) is depicted in Fig. 16. This is the nearest grid position to the M15 IVC, the centre of which lies approximately at l = 65.01°, b = −27.31°. The peak IV Hα brightness in this direction obtained using three-component Gaussian fitting is 0.035 R (km s$^{-1}$)$^{-1}$ for the low-velocity gas, and 0.033 R (km s$^{-1}$)$^{-1}$ for the intermediate-velocity gas, where 1 R is $10^{18}/2\pi$ photon cm$^{-2}$ s$^{-1}$. The integrated fluxes are 2.2 ± 0.1 and 1.3 ± 0.1 R for the (total) LV and IV gas, respectively. The Gaussian fit gives centroids of −53.9 ± 4.6, −4.4 ± 0.7 and +64.3 ± 0.4 km s$^{-1}$, and FWHM velocity widths of 26.7 ± 10.4, 47.8 ± 2.6 and 31.5 ± 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 HI data smoothed to the WHAM spatial resolution. This contrasts with the results of Tufte, Reynolds & Haffner (1998) who tentatively found an offset in velocity between Hα and H I velocities of $\sim$10 km s$^{-1}$ towards various HVC complexes. For the position (A5), the velocity width of the IV Hα spectrum of $\sim$32 km s$^{-1}$ is some 10 km s$^{-1}$ greater than the HI data at 1° resolution. For a gas at $\sim$100 K, some $\sim$22 km s$^{-1}$ of this is caused by thermal broadening, with the remaining width being caused by non-thermal motions and beam smearing of different components. The difference between the H I and Hα widths may imply that the two phases are not mixed. However, at least qualitatively, there is reasonable coincidence between the Hα and H I peaks (Fig. 15a), although the mapped area is small.

The second positive detection [towards (A2) in Fig. 15], occurs in a region where the local H I column density, at the Lovell telescope resolution of $\sim$12 arcmin, is lower than 1 x $10^{19}$ cm$^{-2}$. However, when smoothed to a WHAM resolution of 1°, the H I column density at this point is $\sim$1.0 x $10^{19}$ 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 I column density at this point is $\sim$0.4 x $10^{19}$ cm$^{-2}$. We note that this position is close to the Arecibo-measured H I position ‘AR’ (Fig. 10), which has a similar velocity centroid of $v_{LSR} = +61$ km s$^{-1}$.

3.4.2 WHAM pointings towards HD 203664 and position ‘D’

The nearest WHAM Hα pointings in the vicinity of the halo star HD 203664 are some 0.38° and 0.66° from the stellar position and are depicted in Fig. 17. Although there is a slight excess of Hα with velocities exceeding $\sim$+50 km s$^{-1}$, this is very close to the noise level and at lower velocities than the Ca II K absorption seen by Ryans et al. (1996), which had velocities of $\sim$75–80 km s$^{-1}$. Fig. 18 shows the WHAM pointings superimposed on the Lovell telescope multibeam H I column density map for the IVC towards IVC position ‘D’ (cf. Fig. 10). Again, although there is some Hα 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 I velocity of $\sim$+68 km s$^{-1}$ at this point. Even though the WHAM pointing centre is just within the $N_{HI} = 1.1 \times 10^{19}$ cm$^{-2}$ contour, the relatively small size of the ‘D’ component results in the H I column density at this point at 1° resolution being $\sim0.5 \times 10^{19}$ cm$^{-2}$.
3.5 IRAS ISSA results

In this section the IRAS 60- and 100-µm ISSA images are compared with previous Arecibo HI 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-µm image overlaid on the total (LV plus IV) HI column density, with Fig. 20 displaying the corresponding 60-µm data and the IVC HI column density alone. There appears to be a relatively good correlation between the IRAS and HI 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 M15 globular cluster itself, as globular clusters are undetected at the 60- and 100-µm IRAS sensitivity limits (Origlia, Ferraro & Pecci 1996). Plots comparing the low, total and intermediate HI column density with the IRAS flux density are displayed in Fig. 21. Assuming that the observed correlations are in fact real, the current data indicate that this IVC contains dust, as has also been observed in other such objects (Malawi 1989; Weiβ et al. 1999). The fact that the IVC is tentatively detected at 60 µm indicates that the dust may be warm, perhaps heated by collisions. 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 the distance from the heating field of the Galactic plane). HI 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 to differences in temperature.

4 DISCUSSION

4.1 The Hα properties of the M15 IVC

4.1.1 Estimates of the emission measure and H II column density

The detection of Hα towards the main M15 IVC (position A5) with a brightness of ~1.3 R compares with lower values of between 0.06 and 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 photoionized 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 ionization 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 R (Bland-Hawthorn & Maloney 1999) are similar to the range of ~0.1–0.5 R.
Table 2. Wisconsin Hα Mapper results. The values for the velocities and fluxes are the results of three-component Gaussian fitting to the low- and intermediate-velocity gas. Hα brightnesses have not been corrected for Galactic absorption, hence assuming that the IVC lies above the Galactic plane, the tabulated values are likely to be low by $\sim$25 per cent. Lovell telescope Hα multibeam results, smoothed to a WHAM-sized 1′′ beam, provide H I velocity information towards position (A5).

| Position on Fig. 15 | (A7) | (A5) | (A2) | (A0) |
|---------------------|------|------|------|------|
| RA (J2000)          | $21^h 26^m 53^s.3$ | $21^h 29^m 24.9^s$ | $21^h 32^m 00.4^s$ | $21^h 34^m 37.0^s$ |
| Dec. (J2000)        | +11° 28′ 58″ | +12° 14′ 30″ | +13° 00′ 02″ | +13° 44′ 43″ |
| l (deg)             | 63.88 | 64.98 | 66.09 | 67.19 |
| b (deg)             | −27.16 | −27.16 | −27.16 | −27.16 |
| Hα LV $V_c$ (km s$^{-1}$) | −32.0 ± 16.6, +2.7 ± 2.6 | −53.9 ± 4.6, −4.4 ± 0.7 | −43.8 ± 3.7, −5.3 ± 0.6 | −32.4 ± 9.5, −0.7 ± 1.5 |
| Hα LV FWHM (km s$^{-1}$) | 44.6 ± 22.4, 35.1 ± 4.8 | 26.7 ± 10.4, 47.8 ± 2.6 | 18.8 ± 9.4, 35.2 ± 2.0 | 30.3 ± 14.1, 29.5 ± 2.9 |
| Hα LV flux (R)      | 0.27 ± 0.18, 1.02 ± 0.20 | 0.14 ± 0.06, 2.10 ± 0.08 | 0.11 ± 0.04, 1.50 ± 0.06 | 0.20 ± 0.13, 1.26 ± 0.14 |
| Hα LV peak [mR (km s$^{-1}$)$^{-1}$] | 4.8 ± 1.23 ± 1 | 4.2 ± 1.35 ± 1 | 4.7 ± 0.31, 34 ± 1 | 5.2 ± 1.34 ± 1 |
| Hα IV $V_c$ (km s$^{-1}$) | +59.3 ± 1.1 | +64.3 ± 0.4 | +59.4 ± 0.8 | +71.4 ± 0.5 |
| Hα IV FWHM (km s$^{-1}$) | 18.8 ± 3.4 | 31.5 ± 1.4 | 38.1 ± 2.4 | 27.5 ± 1.5 |
| Hα IV flux (R)      | 0.25 ± 0.02 | 1.30 ± 0.04 | 0.95 ± 0.04 | 0.91 ± 0.03 |
| Hα IV peak [mR (km s$^{-1}$)$^{-1}$] | 11 ± 1 | 33 ± 1 | 20 ± 1 | 26 ± 1 |
| H I IV $V_c$ (km s$^{-1}$) | − | 65.7 ± 0.6 | − | − |
| H I IV FWHM (km s$^{-1}$) | − | 22.0 ± 2.0 | − | − |

Figure 16. Solid line, WHAM Hα spectrum towards $l=64.98^\circ$, $b=-27.16^\circ$ (A5). The dotted line shows the results of a three-component Gaussian fit. The dashed line is a (data-three-component Gaussian fit) residual.

detected towards the IVC Complex K (Haffner, Reynolds & Tufte 2001), 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 ionized hydrogen and the electron density. For an optically thin gas, the Hα surface brightness in Rayleigh, $I_o$, is given by

$$I_o = 0.36 \times EM \times \sqrt{T} \times [1 − 0.37 \times \ln(T)]$$

(1)

where $T$ is the gas temperature in units of 10$^4$ K and EM is the emission measure ($\int n_e^2 dl$) in units of pc cm$^{-6}$ (Simonetti, Topasna & Dennisson 1996). Here, $n_e$ is the electron density and integration over $dl$ provides the thickness ($L$) of the ionized region. Assuming the temperature of the H II is 8000 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 $\sim 0.6 \times 0.8$ deg$^2$, 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$^{-3}$ and a column density of ionized hydrogen ($= L_n$) of $\sim 2 \times 10^{19} f^{1/2}$ cm$^{-2}$, where $f$ is the filling fraction of H II in the IVC. Smoothed to a resolution of 1′ (corresponding to the size of the WHAM beam), the H 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 II to H I is of the order of 1.4 $f^{1/2}$, indicating that there is a substantial amount of ionized 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 II column densities of $1.5 \times 10^{19}$ and $0.8 \times 10^{19}$ cm$^{-2}$, corresponding to fractional H II to H I values of the order of $1.5 f^{1/2}$ and $2.0 f^{1/2}$, respectively. These fractional H II to H I ratios towards the current IVC are somewhat higher than derived by Tufte et al. (1998) for a sample of HVCs, which were calculated to be $<0.06 f^{1/2}$. 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 ionization level in both an IVC and HVC of $\sim 90$ per cent. It would be useful to observe this

Figure 17. Nearest two WHAM Hα spectra towards HD 203664 with their angular distances from the star indicated.
cloud using the same methods as described in the current paper and compare the results.

Towards (d3) there is no detection in Hα with velocities corresponding to the H I value of \( \sim +68 \text{ km s}^{-1} \). Assuming a cloud size of 8 pc and an upper limit to the Hα brightness of 0.2 R, gives an estimated upper limit to the IVC H II column density and fractional H II to H I values of \( \sim 4 \times 10^{19} \text{ cm}^{-2} \) and 0.7\(^{1/2} \). Finally, we consider the halo star HD 203664, towards which the limiting column density of neutral hydrogen is \( \sim 10^{18} \text{ cm}^{-2} \). If we take the upper limit to the Hα brightness of 0.2 R, and combine this with a cloud size \( L \) (in pc, where the Arecibo beam is \( \sim 1 \text{ pc FWHM at 1-kpc distance} \), a fractional H II to H I ratio of \( \sim 1.4L_f^{1/2} \) can be set by the current observations.

4.1.2 Estimates of the ionizing radiation field and electron density

Following Tufte et al. (1998), if photoionization is the dominant cause of Hα emission, then the incident Lyman continuum flux \( F_{LC} \) can be estimated, assuming case B recombination:

\[
F_{LC} = 2.1 \times 10^5 \frac{I_\alpha}{0.1 R} \text{ photon cm}^{-2} \text{ s}^{-1},
\]

where \( I_\alpha \) is the Hα intensity in Rayleigh. For the M15 IVC, equation (2) implies an incident flux \( F_{LC} \) of \( 2.7 \times 10^8 \text{ photon cm}^{-2} \text{ s}^{-1} \).

Hence if photoionization is the main cause of Hα production, the derived Lyman-alpha continuum flux towards the main M15 IVC condensation is a factor of 6–22 times higher than the implied incident flux towards the A, C and M HVCs observed by Tufte et al. (1998), and more than twice that observed towards the Complex K IVC by Haffner et al. (2001). We recall that Complex A lies between 4 and 10 kpc, with Complex C being some 5–25 kpc distant and the M15 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 ionizing field.

An alternative possibility is that the Hα is produced by shock ionization, 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 ionized 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 Hz surface brightness ($I_{\text{perp}}$) can be related to the number density of the pre-shocked gas ($n_{0}$), thus

$$I_{\text{perp}} \sim 6.5 \times n_{0}(V_{s}/100)^{1.7} \text{ R.}$$

Given that $I_{\text{perp}} = 1.3$ 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 sightline will increase the observed $I_{\text{th}}$ (Tufte et al. 1998). Of course, given the fact that the transverse component of the velocity of the M15 IVC is unknown, this value is very uncertain. Discriminating between shock and photoionization is difficult, although further progress may be possible via measurements of appropriate emission-line ratios (Tufte et al. 1998).

### 4.2 Ca II number density towards the M15 IVC and HD 203664

Before discussing the Ca II K results, we note that calcium is depleted on to dust and is not the dominant ionization species, hence the absolute metallicity of the M15 IVC is uncertain and awaits high-resolution UV observations. As emphasized by Ryans et al. (1997), differences in resolution between the optical and radio data, combined with the Ca II K results only placing limits on the ion abundances, makes it important not to overinterpret the observed $N$(Ca II)/$N$(H I) ratios.

With that caveat, and assuming that the current observations do not miss any narrow-velocity components, the average IVC Ca II number density and ratio of the IVC compared with H I towards the centre of M15 are $\log_{10}(N(\text{Ca II})/c m^{-2}) = 12.0$ and $N$(Ca II)/$N$(H I) = $2.5 \times 10^{-8}$. The H I column density towards the M15 centre is $4 \times 10^{19}$ cm$^{-2}$ and was obtained using the combined WSR7 plus Arecibo map of resolution 111 $\times$ 56 arcsec$^{2}$. For the nearby sightline towards the halo star HD 203664, we use the results of Ryans et al. (1996) for the total IVC Ca II column density of $\sim 1 \times 10^{22}$ cm$^{-2}$, combined with the upper limit to the H I column density at a resolution of 3 arcmin towards HD 203664 of $\sim 1 \times 10^{21}$ cm$^{-2}$ (Smoker et al. 2001a), giving a much higher value of $N$(Ca II)/$N$(H I) $> 1.0 \times 10^{-6}$.

The current results compare with literature values of $N$(Ca II)/$N$(H I) $\sim 2 \times 10^{-6}$ (Hobbs 1974, 1976) for low-velocity diffuse clouds and of $N$(Ca II)/$N$(H I) in the range 3–300 $\times 10^{-6}$ cm$^{-2}$ for the high latitude clouds studied by Albert et al. (1993). The $N$(Ca II)/$N$(H I) ratios in IVCs and HVCs are thought to be higher than in low-velocity gas, owing to the former having less dust on to which calcium is depleted. Thus the observed $N$(Ca II)/$N$(H I) ratio of $2.5 \times 10^{-8}$ (or $< 0.01$ of the total solar calcium abundance) in the line of sight towards M15 is typical of other high-latitude clouds and also of other HVCs and IVCs (e.g. Wakker et al. 1996a; Ryans et al. 1997).

The lower limit of $N$(Ca II)/$N$(H I) $> 10^{-6}$ towards HD 203664 is, however, on the high side for IVCs/HVCs, being $< 0.5$ of the total solar calcium abundance. There are several possible reasons for this. First, the (currently undetected) H I 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 I column density limit used would be too low and the derived $N$(Ca II)/$N$(H I) ratio too high. Additionally, HST UV observations towards HD 203664 indicate that the H I towards this object is at least partially ionized (Sembach, private communication), either by shock ionization or photoionization. If photoionization, aside from the normal ionizing source being Galactic OB-type stars or the extragalactic UV field, HD 203664 itself (spectral type B0.5) could be a possible ionizing 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 I column density towards the HD 203664 sightline, this appears unlikely.

Alternatively, it could be that the derived value of $N$(Ca II)/$N$(H I) $> 10^{-6}$ 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 of 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 II)/$N$(H I) towards the M15 IVC of 0.01 solar is much lower than towards HD 203664 is likely to be caused by different ionization fractions and dust contents, and/or differing formation mechanisms. Clearly, the latter is speculative and requires follow-up high-resolution UV observations towards the M15 IVC to determine the abundances of elements such as sulphur and zinc that are not depleted on to dust.
4.3 Velocity widths and temperatures towards the M15 IVC and HD 203664

Towards the main M15 IVC condensation (feature ‘A’ in Fig. 10) values of the $H\alpha$ FWHM velocity width at resolutions of $\sim 2 \times 1$ arcmin$^2$ range from 5 to 14 km s$^{-1}$, corresponding to maximum kinetic temperatures in the range $\sim 500$–4000 K. Mid-way between the M15 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’ in Fig. 10). The current observations have additionally observed feature ‘D’ at a resolution 12 arcmin, also with a FWHM velocity width of 12 km s$^{-1}$, indicating gas at a similar temperature. We note that each of these temperatures will be upper limits caused by beam smearing and turbulent velocity components. Finally, towards HD 203664, Ryans et al. (1996) found cloudballs with FWHM of 2.8 and 3.2 km s$^{-1}$ in Ca II K, corresponding to upper limits for the kinetic temperatures of $\sim 8000$–10000 K. Towards the same star, Sembach (1995) used the relative abundances of low-ionization 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 M15 IVC, feature ‘D’ or the intermediate position ‘AR’ could be interpreted as being caused by the former cloud being nearer to the ionizing 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 (e.g. Wolfe et al. 1995), where the two components of 100 and 10000 K are entrained by pressure from the hot Galactic corona. We note that the high-end H1 temperatures observed towards the M15 IVC indeed occur towards its outer parts where the H1 column density is low and the FWHM velocity widths are uncertain.

4.4 Comparison of HI properties with previous Galactic halo IVCs and HVCs

In this section we compare the high-resolution HI properties of the M15 IVC with other IVCs and HVCs known to lie within the Galactic halo and observed at a 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 H1 at high resolution: the M13 IVC (Shaw et al. 1996), the 4-Lac IVC 100–7+100 (Stoppelenburg 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 HI gas clouds known to exist in the Galactic halo. Inspecting the table, there are no clear differences in the HI 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 $\approx 5$ km s$^{-1}$ and indicate 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–H1 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

| Cloud ref. | $l$ (deg) | $b$ (deg) | $D$ (kpc) | $V_{LSR}$ | $V_{GSR}$ | $\Delta V_1$ | $\Delta V_2$ | $T_p$ | $N_{HI}$ | IRAS? | Ca II/H1 | Parallel to Gal. plane? | Res. (arcmin) |
|------------|----------|----------|-----------|-----------|-----------|-------------|-------------|-------|---------|-------|----------|-----------------------|--------------|
| HVC 132+23–211 (SSH76, WPS99) | 123 | 4–10 | –211 | 5–15 | 25 | N | – | Y | ~2 |
| M13E IVC (SBK96) | 59 | <7 | –73 | 27–35 | 0.7 | N | $>1 \times 10^{-7}$ | N | ~3 x 2 |
| M15 IVC (This paper) | 65 | <3 | –70 | 5–15 | 8 | Y? | $2.5 \times 10^{-8}$ | Y | ~2 x 1 |
| M92N IVC (SKD01) | 68 | 5–25 | –101 | 4–7 | 3.4 | N | – | Y | ~6 x 6 |
| HVC100–7+100 (SSW98) | 100 | <1.2 | –106 | 13 | 0.5 | N | – | N | ~2 x 2 |
| IVC135+54–45 (WHMM99) | 135 | 0.29–0.39 | –45 | 4–5 | >7 | Y | – | – | ~1 x 1 |
| PG0859+593 LLIVC (RKS97, WHS96b) | +51 | 1.7–4.0 | –51 | +19 | 2.0 | ? | – | – | ~2 x 2 |
| PG0906+597 LLIVC (RKS97, WHS96b) | +51 | 1.7–4.0 | –48, –53 | 28, 6 | 1.6, 3.9 | ? | – | – | ~2 x 2 |

Table 3. Previous high-resolution H1 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 H1 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. References: RKSD97, Ryans et al. (1997); SSH76, Schwarz et al. (1976); SBK96, Shaw et al. (1996); SSW98, Stoppelenburg et al. (1998); SKD01, Smoker et al. (2001b); WHS96, Wakker et al. (1996b); WPS99, van Woerden et al. (1999); WWHMM99 Weiβ et al. (1999). GSR velocities are calculated via $V_{GSR} = V_{LSR} + 250 \sin(l) \cos(b)$ km s$^{-1}$.
axis near-parallel to 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.

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

5 SUMMARY AND CONCLUSIONS

The current HI WSRT synthesis observations have shown that on scales down to ~1 arcmin, the M15 IVC shows substructure, with variations in the column density of a factor of ~4 on scales of ~5 arcmin being observed, corresponding to scales of ~1.5D pc, where D is 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 that are derived from a combination of low-resolution radio plus optical data. The Lovell telescope HI 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 M15 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 M15 itself. Both the HI emission-line and Ca II absorption-line data showed tentative evidence for velocity substructure, perhaps indicative of cl oudlets. The Ca II/Hi value of ∼2.5 × 10⁻⁶ towards the main M15 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 Hα beam being unfilled or partial ionization of the gas on this sightline. The HI properties of the M15 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 M15 IVC, as in other IVCs, does distinguish it from HVCs, and either points to the M15 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 Hα emission (exceeding 1 R) towards parts of the M15 IVC, if caused by photoionization, may place it closer to the Galaxy than HVCs. Again, however, this finding is uncertain owing to the problem in distinguishing photoionization from shock ionization, uncertainties in dust content, and differences in HI volume densities in different objects studied thus far.

Future work towards this cloud should include higher signal-to-noise ratio observations in the Ca II line in order to determine whether the cloud velocity substructure tentatively found in the current observations is in fact real, and whether the Ca II/HI ratio determined by the current observations is lower than towards the HD 203664 sightline. This should be combined with ¹²CO(1–0) submillimetre observations in order to determine whether molecular material exists towards the peaks in HI column density and out of which stars may form. The determination of the fall-off in HI column density, of the cloud to low column density limits would also indicate the ionization properties of the object and whether or not there is any interaction between the M15 IVC gas and low-velocity material. Finally, UV observations towards M15 globular cluster stars, although difficult, would provide important information on the absolute metallicity of the gas towards this object for comparison with the HD 203664 sightline.

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REFERENCES

Akeson R.L., Blitz L., 1999, ApJ, 523, 163
Albert C.E., Blades J.C., Morton D.C., Lockman F.J., Proulx M., Ferrarese L., 1993, ApJS, 88, 81
Allen C.W., 1973, Astrophysical Quantities, 3rd edn. Athlone Press, London
Barnes D.G. et al., 2001, MNRAS, 322, 486
Bland-Hawthorn J., Maloney P.R., 1999, ApJ, 510, 33
Blitz L., Spergel D.N., Teuben P.J., Hartmann D., Burton W.B., 1999, ApJ, 514, 818
Bluhm H., de Boer K.S., Margraf O., Richter P., 2001, A&A, 367, 299
Bowen D.V., 1991, MNRAS, 251, 649
Braun R., Burton W.B., 2000, A&A, 354, 853
Brits C., Kerp J., Kalberla P.M.W., Mebold U., 2000, A&A, 357, 120
Cardelli J.A., Clayton G.C., Mathis J.S., 1989, ApJ, 345, 245
Christodoulou D.M., Tohline J.E., Keenan FP., 1997, ApJ, 486, 810
Davies R.D., Buhl D., Jafolla J., 1976, A&AS, 23, 181
Durrell P.R., Harris W.E., 1993, AJ, 105, 1420
Dyson J.E., Hartquist T.W., 1983, MNRAS, 203, 1233
Faison M.D., Goss W.M., Diamond P.J., Taylor G.B., 1998, AJ, 116, 2916
Haffner L.M., 1999, PhD thesis, Univ. Wisconsin-Madison
Haffner L.M., Reynolds J.R., Tuft S.L., 2001, ApJ, 566, 33
Harris W.E., 1996, AJ, 112, 1487
Hartmann D., Burton W.B., 1997, Atlas of Galactic Neutral Hydrogen. Cambridge Univ. Press, Cambridge
Heiles C., 1997, ApJ, 481, 193
Hobbs L.M., 1974, ApJ, 191, 381
Hobbs L.M., 1976, ApJ, 203, 143
Howarth I.D., Murray J., Mills D., Berry D.S., 1996, STARNOTE, User Note SUN 50, Rutherford Appleton Laboratory/CCLRC

© 2002 RAS, MNRAS 337, 385–400
Ivezic Z., Christodoulou D.M., 1997, ApJ, 486, 818
Jaschek C., Jaschek M., 1987, The Classification of Stars. Cambridge Univ. Press, Cambridge
Kennedy D.C., Bates B., Keenan F.P., Kemp S.N., Ryans R.S.I., Davies R.D., Sembach K.R., 1998, MNRAS, 297, 849
Kunz K.D., Danly L., 1996, ApJ, 457, 703
Lauroesch J.T., Meyer D.M., Blades J.C., 2000, ApJ, 543, 43
Lehner N., 2000, PhD thesis, The Queen’s Univ. Belfast
Lehner N., Rolleston W.R.J., Ryans R.S.I., Keenan F.P., Bates B., Pollacco D.L., Sembach K.R., 1999, A&AS, 134, 257
Little J.E., Duffton P.L., Keenan F.P., Conlon E.S., Davies R.D., 1994, ApJ, 427, 267
Malawi A., 1989, PhD thesis, Univ. Manchester
Meyer D.M., Lauroesch J.T., 1999, ApJ, 520, 103
Morton D.C., 1991, ApJS, 77, 119
Origlia L., Ferraro F.R., Pecci F.F., 1996, MNRAS, 280, 572
Raymond J.C., 1979, ApJS, 39, 1
Reynolds R.J., 1985, ApJ, 294, 256
Ryans R.S.I., Sembach K.R., Keenan F.P., 1996, A&A, 314, 609
Ryans R.S.I., Keenan F.P., Sembach K.R., Davies R.D., 1997, MNRAS, 289, 83
Sault R.J., Teuben P.J., Wright M.C.H., 1995, in Shaw R., Payne H.E., Hayes J.J.E., eds, ASP Conf. Ser. Vol. 77, Astronomical Data Analysis Software and Systems IV. Astron. Soc. Pac., San Francisco, p. 433
Schwarz U.J., Sullivan W.T. III., Hulsbosch A.N.M., 1976, A&A, 52, 133
Sembach K.R., 1995, ApJ, 445, 314
Shaw C.R., Bates B., Kemp S.N., Keenan F.P., Davies R.D., Roger R.S., 1996, ApJ, 473, 849
Shortridge K. et al., 1999, STARLINK, UserNote SUN/86. Rutherford Appleton Laboratory/CCLRC
Simonetti J.H., Topasna G.A., Dennison B., 1996, AAS, 188, 1201
Smoker J.V., Lehner N., Keenan F.P., Totten E.J., Murphy E., Sembach K.R., Davies R.D., Bates B., 2001a, MNRAS, 322, 13
Smoker J.V., Roger R.S., Keenan F.P., Davies R.D., Lang R.H., 2001b, A&A, 380, 673
Stoppelenburg P.S., Schwarz U.J., van Woerden H., 1998, A&A, 338, 200
Tan J.C., 2000, ApJ, 536, 173
Tuttle S.L., Reynolds R.J., Haffner L.M., 1998, ApJ, 504, 773
van Woerden H., Peletier R.F., Schwarz U.J., Wakker B.P., Kalberla P.M.W., 1999, in Gibson B.K., Putman M.-E., eds, ASP Conf. Ser. Vol. 166, Stromlo Workshop on High-Velocity Clouds. Astron. Soc. Pac., San Francisco, p. 1
Wakker B.P., 1991, A&A, 250, 499
Wakker B.P., 2001, ApJS, 136, 463
Wakker B.P., Boulanger F., 1986, A&A, 170, 84
Wakker B.P., Schwarz U.J., 1991, A&A, 250, 484
Wakker B.P., van Woerden H., Schwarz U.J., Peletier R.F., Douglas N.G., 1996a, A&A, 306, 25
Wakker B., Howk C., Schwarz U., van Woerden H., Beers T., Wilhelm R., Kalberla P., Danly L., 1996b, ApJ, 473, 834
Weiß A., Heithausen A., Herbstmeier U., Mebold U., 1999, A&A, 344, 955
Weiner B.J., Vogel S.N., Williams T.B., 1999, BAAS, 195, 9703 (abstract)
Wölfire M.G., McKee C.F., Hollenbach D., Tielens A.G.G.M., 1995, ApJ, 453, 673
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