High-Resolution Na I and Ca II Absorption Observations toward M13, M15, and M33

BARRY Y. WELSH,1 JONATHAN WHEATLEY,1 AND ROSINE LALLEMENT2

Received 2009 March 18; accepted 2009 April 15; published 2009 May 16

ABSTRACT. We present high resolution ($R = 60000$) measurements of the Na I D1 & D2 (5890 Å) and Ca II K (3933 Å) interstellar absorption line profiles recorded toward several post-AGB stars located within the M13 and M15 globular clusters, supplemented with a lower resolution spectrum of the Ca II K-line observed in absorption toward an Ofpe/WN9 star in the central region of the M33 galaxy. The normalized interstellar absorption profiles have been fit with cloud component velocities, doppler widths, and column densities in order to investigate the kinematics and physical conditions of the neutral and partially ionized gas observed along each sight line. Our Ca II observations toward M13 have revealed three absorption components that can be identified with galactic Intermediate Velocity Clouds (IVCs) spanning the $−50 < V_{\text{lsr}} < −80$ km s$^{-1}$ range. The Na I/Ca II ratio for these IVCs is $<0.2$, which characterizes the gas as being warm ($T \sim 10^3$ K) and partially ionized. Similar observations toward two stars within M15 have revealed absorption due to a galactic IVC at $V_{\text{lsr}} \sim +65$ km s$^{-1}$. This IVC requires at least three different cloud components to fit the observed Na I and Ca II profiles, which is consistent with the theoretical scenario in which possible cloud-to-cloud collisions could result in triggering the star formation process within such complexes. Ca II K-line observations of a sight line toward the center of the M33 galaxy have revealed at least six gas cloud components. A cloud at $V_{\text{lsr}} \sim −130$ km s$^{-1}$ is either an IVC associated with the M33 galaxy occurring at $+45$ km s$^{-1}$ with respect to the M33 local standard of rest, or it is a newly discovered HVC associated with our own Galaxy. In addition, three clouds have been discovered in the $−170 < V_{\text{lsr}} < −205$ km s$^{-1}$ range. Two of these clouds are identified with the disk gas of M33, whereas the cloud at $−202$ km s$^{-1}$ could be IVC gas in the surrounding halo of M33.

1. INTRODUCTION

It has long been known that the Galaxy is surrounded by ionized and neutral gas clouds in the form of a hot and ionized galactic halo (Spitzer 1956), in addition to the numerous neutral intermediate-velocity (IV) and high-velocity (HV) gas clouds (Wakker & van Woerden 1997). These two types of cloud are normally defined by their observed radial velocities, such that IVCs have velocities of $|V_{\text{LSR}}| \sim 30$–90 km s$^{-1}$ and HVCs have velocities of $|V_{\text{LSR}}| > 90$ km s$^{-1}$. Understanding the physical and chemical characteristics of both types of gas cloud is fundamental in defining our current ideas on how matter is exchanged between the Galaxy and the surrounding intergalactic medium. Although the origins of both IVCs and HVCs are still hotly debated (Spitoni et al. 2008), it seems likely that either they are linked to expelled gas from a supernova-driven galactic fountain (Bregman 1980) or they represent accumulations of tidally-stripped or condensed and cooled gas (Putman et al. 2003; Maller & Bullock 2004). Irrespective of their true origin, it is generally agreed that IVCs and HVCs are providing infalling gas, which is theorized to be required in order to sustain both the star formation process and the presence of an interstellar medium in our Galaxy (van den Bergh 1962). If IVCs and HVCs are a major source of this gaseous infall, then knowledge of the mass and chemical composition of each cloud are key input parameters for any model of galactic evolution and star formation (Alibes et al. 2001).

The chemical composition and physical state of gas in HVCs and IVCs are best determined through absorption measurements at ultraviolet wavelengths (Wakker 2001; Richter et al. 2001; Collins et al. 2007). These data suggest that the majority of neutral HVCs have subsolar metallicities, implying that some fraction of the gas is of a primordial extragalactic origin. However, recent observations of a new type of highly ionized HVC that are not associated with neutral H I emission have revealed supersolar metallicity values, which suggests a galactic origin for the gas in these particular HVCs (Fox et al. 2006; Zech et al. 2008). Similarly, the gas associated with IVCs also appears to possess near-solar abundances (Richter et al. 2001), except that the majority of IVCs are relatively nearby objects of distance $<2$ kpc compared with the more distant HVCs of distance $>5$ kpc (Olano 2008). However, we note that all these assumptions are based on relatively few observations of HVCs and IVCs, with the data often being of a low signal-to-noise ratio.

1 Space Sciences Laboratory, University of California, Berkeley, CA 94720.
2 Service d’Aeronomie du CNRS, 91371, Verrieres-le-Buisson, France.
(S/N) because of the relative faintness of the background sources used in the absorption observations.

However, with the advent of high-resolution spectrographs coupled to very large aperture ground-based telescopes, it is now possible to routinely investigate the interstellar gas residing beyond our own Galaxy through classical absorption spectroscopy techniques that involve distant \((d > 5 \text{ kpc})\) background stellar sources. In particular, the well-known interstellar lines of Na I-D (5890 Å) and Ca II-K (3933 Å) have been extremely useful in revealing the presence of, and determining accurate distances to, IVCs and HVCs (Smoker et al. 2004, 2007; Kennedy et al. 1998). In particular, interstellar absorption observations of the sight lines toward hot post-AGB stars within globular clusters of known distance has proven highly fruitful. Their sight lines can provide (a) distance limits to absorption arising within foreground IVCs and HVCs as seen in their visible Na I and Ca II interstellar absorption spectra (Lehner et al. 1999) and (b) metal abundance determinations of foreground IVC and HVC gas, through interstellar absorption spectra of numerous ultraviolet resonance lines (Zech et al. 2008).

In this article we present high-resolution \((R \sim 60000)\) observations of the Na I D-lines and the Ca II-K line seen in absorption toward two post-AGB stars in the globular cluster NGC 7078 (M15) and toward one post-AGB star in NGC 6205 (M13). We also present a lower resolution Ca II K-line spectrum of the hot star UIT-236 which resides in a planetary nebula in the central regions of the M33 galaxy. Using these data we discuss the velocity structure of the interstellar absorption observed along each sight line and attempt to associate these cloud components with a galactic, extended halo or extragalactic origin. These data will also supplement a forthcoming abundance analysis of these four sight lines using ultraviolet absorption observations (with a resolving power of \(\sim 20000\)) using the Cosmic Origins Spectrograph due to be flown in mid-2009 on Servicing Mission 5 to the Hubble Space Telescope.

## 2. OBSERVATIONS AND DATA REDUCTION

We present absorption observations of the interstellar Na I D-line doublet at \(\sim 5890\) Å and the Ca II K-line at 3933 Å recorded toward hot post-AGB stars in the M13 (NGC 6205) and M15 (NGC 7078) globular clusters, in addition to the Of/WN9 star UIT-236 in the M33 galaxy. The four target stars, together with associated astronomical information and appropriate references, are listed in Table 1. These data were obtained during service observing runs performed during 2008 March to July with the High Dispersion Spectrograph (Noguchi et al. 2002) on the 8.2 m Subaru telescope of the National Astronomical Observatory of Japan in Hawaii. The spectrograph was configured with a cross-disperser angle of 5.52° to receive light passing through a 0.6 wide \(\times 5\) cm long slit, with the spectra being recorded on two 4 \(\times 2\) pixel EEV CCDs. Spectra were recorded separately for the Na I lines (using the StdYb instrumental set-up) and the Ca II line (using the StdBc instrumental setup). Unfortunately this setup configuration precluded measurement of the Ca II H-line at 3368 Å, which appeared in an echelle order very close to the edge of the detector.

The raw data were reduced in a similar manner to that described in Sfeir et al. 1999, which includes cosmic ray removal, CCD bias subtraction, flat-fielding, and interorder background subtraction. The spectra were wavelength calibrated using Th-Ar calibration lamp spectra, which resulted in a wavelength accuracy of \(\sim 2\) km s\(^{-1}\). The spectral resolution of the M13 and M15 spectra was determined to be 5 km s\(^{-1}\), whereas the resolution of the spectrum recorded toward M33 (which was recorded with 2 pixel binning) was 9 km s\(^{-1}\). The telluric water vapor lines that contaminate the Na I absorption spectra were removed using a synthetic transmission spectrum described in Lallement et al. 1993. The spectra were all well exposed with typical S/N ratios in excess of 20:1. Finally, the spectral data were converted into velocities in the local standard of rest (LSR) frame.

The calibrated spectra were fit with a high order polynomial to produce local continua in order to establish normalized residual intensities for the absorption lines of interest. These normalized profiles were then fit with multiple absorption components (i.e., interstellar clouds) using a line-fitting program described in Sfeir et al. 1999. This program assigns a three-parameter model fit to the observed profiles using values for the interstellar gas cloud velocity, \(V\), a Gaussian velocity dispersion, \(b\), and a cloud component column density, \(N\). For the case of the Na I D1 and D2 line doublet, the best-fit was performed simultaneously on both line profiles. Fits were carried out using the minimum number of absorption components, with the addition of extra components only being deemed necessary when the fit was not satisfactory.

### Table 1

**Stellar Target Information**

| Star       | R.A. (2000.) | Decl. (2000.) | \(m_\text{B}\) | \(T_{\text{eff}}\) (K) | \(E(B-V)\) | Distance (kpc) | Reference |
|------------|--------------|---------------|----------------|---------------------|-----------|----------------|-----------|
| M13-Barnard 29 | 16:41:3+34.0 | +36:26:08.2 | 13.14 | 20,000 | 0.02 | 7.2 | (1) |
| M15-K648 | 21:29:59.4 | +12:10:26.0 | 14.7 | 39,000 | 0.13 | 10.3 | (2) |
| M15-ZNG1 | 21:29:38.1 | +12:11:44.2 | 14.8 | 28,000 | 0.13 | 10.3 | (3) |
| M33-UIT 236 | 01:33:53.6 | +30:38:51.8 | 18.1 | 33,000 | 0.10 | 820 | (4) |

**References.**—(1) Dixon & Hurwitz 1998; (2) Bianchi et al. 2001; (3) Mooney et al. 2004; (4) Bianchi et al. 2004.
necessary until the residual between the model fit and the data points was approximately equal to the rms error of the data. Due to the large interstellar path lengths involved in these measurements, in which turbulence may well play an important line-broadening role, we have placed no restriction on the derived component $b$-values for these spectral fits. Thus, any gas cloud temperature derived from such values can only be considered as an upper limit. The resultant best-fit values of $V_{lsr}$, $b$ and $N$ for the Na I and Ca II absorption lines are listed in Table 2, and in Figure 1 we show the observed spectra and their respective model fits. We have also included upper limit estimates for certain important IV components where no absorption feature was detected with significance. These values were derived from conservative estimates of the strength of a potential absorption feature appearing at a level $>2.5 - \sigma$ above the rms value of the local continuum. The corresponding upper limit on the column density of such features was determined under the assumption of a linear curve of growth and is reported in Table 2.

3. DISCUSSION

3.1. The Sight Line to Barnard 29 in the M13 Globular Cluster

The 7.2 kpc sight line to Barnard 29 in the M13 globular cluster ($l = 59^\circ, b = +41^\circ$) passes through the galactic Hercules shell (GS 57 + 41) at a distance of $\sim$150 pc (Lilienthal et al. 1992), as well as an Intermediate Velocity Cloud (IVC) first observed in 21 cm H I emission (Kerr & Knapp 1972). The IUE observations of Barnard 29 by de Boer and Savage 1983 revealed IV gas at a velocity centered at $\sim$80 km s$^{-1}$ in

| Star     | $V_{lsr}$ (km s$^{-1}$) | $b$ (10$^{10}$ cm$^{-2}$) | $N$ (10$^{10}$ cm$^{-2}$) | $V_{lsr}$ (km s$^{-1}$) | $b$ (10$^{10}$ cm$^{-2}$) | $N$ (10$^{10}$ cm$^{-2}$) | Na I/Ca II |
|----------|------------------------|-----------------------------|-----------------------------|------------------------|-----------------------------|-----------------------------|------------|
| M13-Barnard 29 |
| Na I     | $<2.5$                 | 6.3                         | 18.6 $\pm$ 2               | $<0.13$                |                             |                             |            |
| Ca II    | $<2.5$                 | 6.4                         | 12.8 $\pm$ 1.5             | $<0.19$                |                             |                             |            |
|         | $<2.5$                 | 6.3                         | 15.9 $\pm$ 2               | $<0.16$                |                             |                             |            |
|         | $<2.5$                 | 5.1                         | 73.1 $\pm$ 7               | -                     |                             |                             |            |
| $-1.3$   | 7.6                    | 20.1 $\pm$ 3               | $+0.9$                      | 3.6                    | 73.1 $\pm$ 6               | 0.28                         |            |
| +11.4    | 3.3                    | 119.9 $\pm$ 14             | $+8.0$                      | 4.2                    | 78.3 $\pm$ 6               | 1.53                         |            |
| M15-K648 |
| Na I     | $-17.7$                | 7.5                         | 28.7 $\pm$ 3.5             | $-27.5$                | 6.3                         | 40.4 $\pm$ 3                |            |
| Ca II    | $-2.2$                 | 4.2                         | 430$^a$                     | $-3.6$                 | 4.6                         | 254 $\pm$ 20                | $>1.7$     |
|         | $+9.8$                 | 3.0                         | 525$^a$                     | $+6.8$                 | 5.0                         | 173 $\pm$ 16                | $>3.0$     |
|         | $+18.1$                | 1.0                         | 30.7 $\pm$ 4               | $+58.5$                | 6.4                         | 65.7 $\pm$ 8                | 0.43       |
|         | $+6.5$                 | 6.5                         | 28.3 $\pm$ 5               | $+68.4$                | 3.1                         | 212 $\pm$ 20                | 0.11       |
| M15-ZNG1 |
| Na I     | $-16.0$                | 5.4                         | 28.1 $\pm$ 4               | $-17.5$                | 6.0                         | 222 $\pm$ 23                | 0.13       |
| Ca II    | $-0.5$                 | 3.2                         | 226.1 $\pm$ 25             | $-3.5$                 | 4.0                         | 173.0 $\pm$ 15              | 1.0        |
|         | $+13.5$                | 2.8                         | 570$^a$                     | $+16.9$                | 2.1                         | 26.5 $\pm$ 4                | $>21.5$    |
|         | $<3.5$                 |                             | $+54.6$                      | 1.0                    | 18.6 $\pm$ 3                | $<0.19$                     |
|         | $+67.0$                | 2.6                         | 66.8 $\pm$ 8               | $+65.0$                | 5.5                         | 200 $\pm$ 18                | 0.33       |
|         | $+73.5$                | 1.0                         | 6.6 $\pm$ 2                | $<3.0$                 |                             | $<2.2$                       |

$^a$ Saturated component.
the Mg II, C II, and O I absorption lines. Due to the similar velocities of the UV and the H I data, it was argued that this absorption arises at an unknown distance within the galactic halo. More recent Leiden-Dwingeloo H I observations have revealed the IV cloud to possess a central velocity of \( \frac{64}{1} \text{ km s}^{-1} \) (Smoker et al. 2006), and the H I maps of Kuntz & Danly (1996) show that M13 lies just off the boundary that defines the spatial extent of the IV Arch, a feature that extends over a large portion of the northern galactic hemisphere. Previous Na I D-line and Ca II K-line observations of sight lines toward several stars within M13 (but not Barnard 29) have revealed IV absorption over the \(-65\) to \(-72\) km s\(^{-1}\) range (Shaw et al. 1996). Observations of the Ca II K-line in the sight line toward Barnard 29 by Bates et al. 1995 have shown a blend of at least

Fig. 1.—Interstellar absorption profiles of the Na I D2, D1, and Ca II K-lines observed towards the stars Barnard 29 (M13), K648 (M15), Zng1 (M15), and UIT 236 (M33). Full lines are the model fits superposed upon the normalized residual intensity data points. Tick marks above the Na I D2 and Ca II-K profiles correspond to the velocity of the fitted cloud components, and the faint dotted lines within the profiles represent the associated unconvolved component fits.
three IV absorption components spanning the $-40, -90$ km s$^{-1}$ range, whereas the more recent measurements of Smoker et al. 2006 have revealed a similarly broad absorption feature that was fit with only one component centered at $V_{lsr} = -48.4$ km s$^{-1}$. Both sets of data are consistent with our present Ca II-K observations that reveal 3 components at $V_{lsr} = -51.0, -65.8,$ and $-76.7$ km s$^{-1}$. Our Na I D-line spectra show no measurable absorption at velocities in the $-40$ to $-90$ km s$^{-1}$ range (to a detection level of $<5$ m Å for the D2 line), in contrast with other (lower S/N) absorption observations of sight lines toward three angular close stars in M13 (Shaw et al. 1996).

Our integrated value of Ca II column density for all 3 IV components is $\log N$(Ca II) = 11.67 cm$^{-2}$, which can be compared with the similar values of $\log N$(Ca II) = 11.65 and 11.92 cm$^{-2}$ measured respectively by Smoker et al.2006 and Bates et al. 1995. Additionally, we note in Figure 3 of Smoker et al. 2006 that there appear to be absorption features in both of the D2 and D1 line spectra of Barnard 29 in the $-20$ to $-80$ km s$^{-1}$ range. Unfortunately the velocities of these features are not common to both Na I lines, suggesting that they may be due to incomplete removal of telluric water vapor lines in this wavelength region. If this is the case, then both of our Na I D-line profiles argue against any measurable IV absorption formed over the same velocity range as the Ca II-K line. There is a large ($\approx$ factor of 100) variation in the abundance of Na for high- and intermediate-velocity gas compared with that measured for low-velocity gas (Wakker 2001), which may explain why, although Na I IV components have been detected along several other sight-lines to M13 (Shaw et al. 1996), we have not been able to detect similar IV Na I toward Barnard 29.

The Na I/Ca II ratio for all three of the presently detected IV components is $<0.2$, which is a value found widely for interstellar clouds that can be characterized as being warm ($T \sim 10^4$ K), of low density ($n_h < 1$ cm$^{-3}$), and partially ionized (Hobbs 1975). It has also been shown that the Na I/Ca II ratio does not depend on velocity for sight lines through IVCs and HVCs, since the ratio depends mostly on $N$(H I), which has lower values at higher velocities (Wakker 2001). The physical conditions of this IV gas can be compared with the main absorbing cloud at $V_{lsr} = +10$ km s$^{-1}$, whose higher Na I/Ca II ratio of 1.53 is typical for clouds that are present in colder, more neutral, and denser interstellar regions.

As discussed in the Introduction, measurement of the distance to IVCs and HVCs is an important parameter. We are able to place a lower limit to the distance of the IV absorption of $d = 265$ pc, based on Ca II absorption measurements toward the star HD 156633 ($l = 56.4^\circ, b = 33.1^\circ$) which does not reveal any measurable absorption components for $V_{lsr} < -30$ km s$^{-1}$ (Welsh & Lallement 2009, in preparation). The upper limit of $d = 7.2$ kpc is obtained from the distance to the M13 globular cluster. Although we did not detect any IV absorption in the Na I lines, we note that this is also consistent with the Na I measurements toward the foreground star HD 147113 ($l = 61^\circ, b = +46^\circ$) of distance $\sim$600 pc (Lilienthal et al. 1992).

3.2. The Sight Lines to K648 and ZNG1 in the M15 Globular Cluster

Both of the 10.3 kpc long sight-lines toward the M15 globular cluster ($l = 65^\circ, b = -27.3^\circ$) pass through a previously known IVC with $V_{lsr} = +70$ km s$^{-1}$ (Cohen 1979; Kerr & Knapp 1972). More recent, higher resolution optical and H I observations of this IV gas (often called the “g1” cloud) have resulted in a distance estimation of between 1.8 to 3.8 kpc to this IVC (Wakker et al. 2008; Smoker et al. 2002a; 2002b). The absorbing gas within this cloud complex has been shown to exhibit significant small-scale structure with Na I column densities varying by up to a factor of 16 across the foreground cloud (Meyer & Lauroesch 1999).

The star ZNG-1 has been previously observed at a spectral resolution of $\sim$7.5 km s$^{-1}$ in both the Na I and Ca II absorption lines (Smoker et al. 2002a; 2002b). These data revealed appreciable low-velocity absorption covering the $-30$ to $+20$ km s$^{-1}$ range, which can be associated with gas in the galactic disk (and perhaps lower halo). An absorption feature centered at $V_{lsr} = +64$ km s$^{-1}$ was observed in both the Na I and Ca II lines, which matched the velocity of the H I emission from the foreground IVC gas recorded toward M15. An extra absorption component at $V_{lsr} = +53$ km s$^{-1}$ was also tentatively suggested by these visible observations. Under the assumption that a value of the H I column density to ZNG-1 is $N$(HI) = $5 \times 10^{19}$ cm$^{-2}$, we derived values of $N$(Ca II)/$N$(HI) $\sim 5 \times 10^{-8}$ and $N$(Na I)/$N$(HI) $\sim 1.3 \times 10^{-8}$ for the entire IV gas cloud.

The star K648, which is thought to be the central star of a planetary nebula lying within M15, has been observed in the ultraviolet and has been shown to possess a significant stellar wind with the nebula expanding at $\sim$$15$ km s$^{-1}$ with respect to the ambient medium (Bianchi et al. 2001). No previous visible interstellar absorption observations exist for this star.

Our present higher resolution Na I and Ca II measurements toward both ZNG-1 and K648 (which are separated by only 1.25’ on the sky) show very similar patterns of visible absorption (see Fig. 1). These profiles are dominated by low-velocity ($-30$ to $+20$ km s$^{-1}$) absorption originating in the galactic disk/halo, in addition to an IVC absorption centered at $V_{lsr} = +65$ km s$^{-1}$. The low-velocity galactic components generally have Na I/Ca II ratios $>1.0$, consistent with the sight lines sampling a cold and neutral diffuse interstellar medium. In contrast, the Na I/Ca II ratios for all of the components associated with the IVC at $V_{lsr} = +65$ km s$^{-1}$ have values $<0.45$, suggestive of a warm, partially ionized, and low-density interstellar cloud medium. Our data also clearly show that the IVC gas sampled toward both stars requires at least three different cloud components to fit the observed Na I and Ca II absorption profiles. This structure of the IVC, in which several clouds with similar velocities are present...
3.3. The Sight Line toward the Star UIT-236 in the M33 Galaxy

M33, the Triangulum spiral galaxy (NGC 598), is a member of the Local Group lying at a distance of \( \sim 820 \) kpc in the direction \((l = 133.6^\circ, b = -31.3^\circ)\) and is about one-quarter the size of both the Milky Way and Andromeda galaxies. It has a systematic velocity of \( V_{\text{lsr}} \sim 180 \) km s\(^{-1}\) and is viewed near face-on. The metallicity of the galaxy is subsolar, with a radial abundance gradient that differs for different elements (Rosolowsky & Joshua 2008).

The interstellar sight line toward the Of-type star UIT-236, which is part of the NGC 588 giant H II region, is close to the nucleus of the galaxy, and low-resolution ultraviolet observations have revealed significant mass-loss (through P-Cygni wind profiles) from this star (Bianchi et al. 2004). Low-resolution far ultraviolet absorption observations of UIT-236 recorded with \textit{FUSE} have revealed the presence of both hot \( 300,000^\circ \) K O VI and lower-temperature C II gas at \( V_{\text{lsr}} \sim 180 \) km s\(^{-1}\) that can be definitely associated with the host galaxy’s ISM (Wakker et al. 2003; Hutchings & Butler 2004). Observations of interstellar molecular H\(_2\) and several low-ionization ions toward the core of NGC 588 (i.e., UIT-236) with \textit{FUSE} have revealed a common absorption at \( V_{\text{lsr}} \sim -140 \) km s\(^{-1}\) (Bluhm et al. 2003). This is a very similar absorption velocity to that of the “weak” component seen in 21 cm H I emission toward M33 by Rogstad et al. 1976.

Our present Ca II-K absorption observations toward UIT-236 shown in Figure 1 reveal five major absorption systems centered at \( V_{\text{lsr}} \sim -200, -180, -130, -35, \) and 0 km s\(^{-1}\). Unfortunately we have no accompanying interstellar Na I observations toward this star. However, we can associate the two sets of components observed at \( V_{\text{lsr}} = 0 \) and \(-35 \) km s\(^{-1}\) with absorption due to foreground galactic (and possibly inner galactic halo) interstellar gas. We note that the component at \( V_{\text{lsr}} \sim -35 \) km s\(^{-1}\) is consistent with the velocity of gas associated with the outer region of the IVC H I gas, which has been termed the PP Arch (Wakker 2001). This stream of IV gas has an implied distance of 1.0 to 2.7 kpc with velocities in the \(-30 \) to \(-60 \) km s\(^{-1}\) range (Wakker et al. 2008). If we assume an integrated H I column density of \( N(\text{HI}) \sim 5 \times 10^{19} \) cm\(^{-2}\) for the IV gas (\(-25 \) to \(-45 \) km s\(^{-1}\)) in this direction, then we obtain a N(Ca II)/N(H I) ratio of \( \sim 6.5 \times 10^{-8} \) for the IV cloud complex. Wakker & Mathis 2000 discovered an empirical relationship between observed values of N(Ca II) and N(H I) along many sight lines, such that for the PP Arch IVC they predict a N(Ca II)/N(H I) ratio that is slightly larger than our observed value. This supports the current notion that IVCs seem deficient in ionized calcium compared with HVCs.

The cloud component observed at \( V_{\text{lsr}} \sim 130 \) km s\(^{-1}\) poses the question as to whether it is a high negative-velocity HVC belonging to the Milky Way galaxy, or an IVC associated with the M33 galaxy that occurs at \( \sim +45 \) km s\(^{-1}\) with respect to the M33 local standard of rest. The observed velocity of this absorption component is very similar to that of both UV molecular H\(_2\) and several low ionization lines measured toward NGC 588 with \textit{FUSE} (Bluhm et al. 2003). This is also very similar velocity to that of the “weak” component seen in 21 cm H I emission by Rogstad et al. 1976, who theorized that this absorption could be due to gas residing above and below the plane of the M33 galaxy. In addition, the all-sky map of galactic HVCs shows only highly negative-velocity (\( V < -300 \) km s\(^{-1}\)) gas present in the general direction of M33 (Wakker et al. 2008). We have not been able to confirm the presence of such HV gas with our present interstellar observations to a level of \( N(\text{Ca II}) < 10^{11} \) cm\(^{-2}\). Until future, more extensive UV absorption observations of the \( V_{\text{lsr}} \sim -130 \) km s\(^{-1}\) component are performed, we favor this component’s association with an IVC of the M33 galaxy.

The three interstellar Ca II gas clouds observed in absorption with velocities in the range \(-170 > V_{\text{lsr}} > -205 \) km s\(^{-1}\) can be directly associated with gas of the M33 galaxy, since such velocities are close to the systemic velocity of the host galaxy. As noted previously, the FUV absorption lines of interstellar molecular hydrogen, C II (1036 Å), Fe II (1144 Å), Ar I (1048 Å), and O VI (1032 Å) have also been detected with similar velocities toward M33 (Bluhm et al. 2003; Hutchings & Butler 2004). The cloud component at \( V_{\text{lsr}} \sim -173 \) km s\(^{-1}\) is saturated and is therefore most probably associated with gas in the disk of M33, which we are viewing almost face-on. The H I emission maps of M33 by Rogstad et al. (1976) show the presence of the main velocity components (\(-150 \) to \(-200 \) km s\(^{-1}\)) occurring in the region within \( \pm 5' \) of the galaxy center. The component with \( V_{\text{lsr}} = -202 \) km s\(^{-1}\) could be an IVC of M33 with a relative velocity of \( \sim 30 \) km s\(^{-1}\) wrt the disk gas. We note that Grossi et al. 2008 have recently found several H I clouds surrounding M33 that fall into this velocity range. The current view of M33 is that it is a satellite of the larger M31 galaxy and the complex of surrounding H I (and H II) clouds may be either debris flowing into M33 from the IGM or from a previous interaction with M31. Gaining gas phase abundances of this component (from forthcoming UV absorption observations) would be extremely informative with respect to a better determination of the origin of this cloud.

4. CONCLUSION

We have presented high resolution (\( R = 60000 \)) absorption measurements of the interstellar lines of Na ID1 & D2 (5890 Å) and Ca II-K (3933 Å) recorded toward post-AGB stars in the M13 and M15 globular clusters, supplemented with a lower resolution spectrum of the Ca II-K line seen toward an O7pe/WN9 star in the central region of the M33 galaxy. The absorption line

(i.e., \( +55 < V_{\text{lsr}} < +75 \) km s\(^{-1}\)), is consistent with the theoretical scenario in which possible cloud-to-cloud collisions could result in triggering the star formation process within such complexes (Christodoulou et al. 1997).
profiles have been fit with cloud component velocities and column densities such that the kinematics and physical conditions of the neutral and partially-ionized gas components can be investigated.

Four Ca II-K absorption components that can be identified with galactic IVCs spanning the −50 to −80 km s⁻¹ range have been detected toward the M13 globular cluster. The associated Na I/Ca II column density ratio for this IVC gas is <0.2, which suggests that the gas is warm (T ∼ 10^3 K) and partially ionized. The observations of two stars within M15 have revealed absorption due to a galactic IVC at V_{lsr} ∼ +65 km s⁻¹, which requires at least three separate cloud components (closely spaced in velocity) to adequately fit the Na I and Ca II profiles.

Ca II K-line observations of the sight line to the M33 galaxy have revealed at least six gas cloud components. A cloud at V_{lsr} ∼ −130 km s⁻¹ is either an IVC associated with the M33 galaxy (occurring at +45 km s⁻¹ with respect to the M33 local standard of rest), or it is a newly discovered HVC associated with our own Galaxy. Also, three gas clouds have been detected in the −170 to −205 km s⁻¹ range, of which at least two are probably associated with the disk gas of M33. The cloud at V_{lsr} = −202 km s⁻¹ could be an IVC residing in the surrounding halo of M33.

Finally, we note that these high-resolution visible data will be extremely useful in providing sight line velocity templates for the forthcoming lower resolution UV absorption studies of these same stars to be carried out with the newly installed Cosmic Origins Spectrograph on the Hubble Space Telescope in mid-2009.

We particularly acknowledge the dedicated team of engineers, technicians, and research staff who recorded these data with the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. This publication makes use of data products from the SIMBAD database, operated at CDS, Strasbourg, France. BYW acknowledges funding for this research through the NSF award AST-0507244.

REFERENCES

Alibes, A., Labay, J., & Canal, R. 2001, A&A, 370, 1103
Bates, B., Shaw, C., & Kemp, S., et al. 1995, ApJ, 444, 672
Bianchi, L., Bohlin, R., & Catanzaro, G., et al. 2001, AJ, 122, 1538
Bianchi, L., Bohlin, R., & Massey, P. 2004, ApJ, 610, 228
Bluhm, H., de Boer, K., & Marggraf, O., et al. 2003, A&A, 398, 983
Bregman, N. 1980, ApJ, 236, 577
Christodoulou, D., Tohline, J., & Keenan, F. 1997, ApJ, 486, 810
Cohen, J. 1979, ApJ, 231, 751
Collins, J., Shull, M., & Giroux, M. 2007, ApJ, 657, 271
de Boer, K., & Savage, B. 1983, ApJ, 265, 210
Dixon, W., & Hurwitz, M. 1998, ApJ, 500, L29
Fox, A., Savage, B., & Wakker, B. 2006, ApJS, 165, 229
Grossi, M., Giovannardi, C., & Corbelli, E., et al. 2008, A&A, 487, 161
Hobbs, L. 1975, ApJ, 202, 628
Hutchings, J., & Butler, K. 2004, AJ, 128, 2234
Kennedy, D., Bates, B., & Kemp, S. 1998, A&A, 336, 315
Kerr, F., & Knapp, G. 1972, AJ, 77, 354
Kuntz, K., & Danly, L. 1996, ApJ, 457, 703
Lallement, R., Bertin, P., Chassefiere, E., & Scott, N. 1993, A&A, 271, 734
Lehner, N., Rolleston, W., & Ryans, R., et al. 1999, A&AS, 134, 257
Lilienthal, D., Hirth, W., Mebold, U., & de Boer, K. 1992, A&A, 255, 323
Maller, A., & Bullock, J. 2004, MNRAS, 355, 694
Meyer, D., & Lauroesch, J. 1999, ApJ, 520, L103
Mooney, C., Rolleston, W., & Keenan, F., et al. 2004, A&A, 419, 1123
Noguchi, K., Aoki, W., & Kawanomoto, S., et al. 2002, PASJ, 54, 855
Olano, C. 2008, A&A, 485, 457
Putman, M., Staveley-Smith, L., & Freeman, K., et al. 2003, ApJ, 586, 170
Richter, P., Sembach, K., & Wakker, B., et al. 2001, ApJ, 559, 318
Rogstad, D., Wright, M., & Lockhart, I. 1976, ApJ, 204, 703
Rosolowsky, E., & Joshua, S. 2008, ApJ, 675, 1213
Sfeir, D. M., Lallement, R., Ciriaco, F., & Welsh, B. Y. 1999, A&A, 346, 785
Shaw, C., Bates, B., & Kemp, S., et al. 1996, ApJ, 473, 849
Smoker, J., Keenan, F., Lehner, N., & Trundle, C. 2002a, A&A, 387, 1057
Smoker, J., Haffner, L., & Keenan, F., et al. 2002b, MNRAS, 337, 385
Smoker, J., Lynn, B., & Rolleston, W., et al. 2004, MNRAS, 352, 1279
Smoker, J., Lynn, B., Christian, D., & Keenan, F. 2006, MNRAS, 370, 151
Smoker, J., Hunter, I., & Kalberla, P., et al. 2007, MNRAS, 378, 947
Spitoni, E., Recchi, S., & Matteucci, F. 2008, A&A, 484, 743
Spitzer, L. J. 1956, ApJ, 124, 20
van den Bergh, S. 1962, AJ, 67, 486
Wakker, B. 2001, ApJS, 136, 463
Wakker, B., & Mathis, J. 2000, ApJ, 544, L107
Wakker, B. P., & van Woerden, H. 1997, ARA&A, 35, 217
Wakker, B., et al. 2003, ApJS, 146, 1
Wakker, B. P., York, D., & Wilhelm, R., et al. 2008, ApJ, 672, 298
Zech, W., Lehner, N., & Howk, C., et al. 2008, ApJ, 679, 460