

OBSERVATIONS OF THE EXTENDED DISTRIBUTION OF IONIZED HYDROGEN IN THE PLANE OF M31

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ABSTRACT

We have used the Wisconsin H-Alpha Mapper to observe the spatially extended distribution of ionized hydrogen in M31 beyond the stellar disk. We obtained five sets of observations, centered near the photometric major axis of M31, that extend from the center of the galaxy to just off the edge of the southwestern H I disk. Beyond the bright stellar disk, but within the H I disk, weak H α is detected with an intensity $I_{\text{H}\alpha} = 0.05^{+0.01}_{-0.02}$ R.¹ Since M31 is inclined 77° with respect to the line of sight, this implies that the ambient intergalactic ionizing flux on each side of M31 is $\Phi_0 \leq 1.6 \times 10^4$ photons cm⁻² s⁻¹. Just beyond the outer boundary of the H I disk, we find no significant detection of H α and place an upper limit $I_{\text{H}\alpha} \leq 0.019$ R.

Subject headings: galaxies: individual (M31) — galaxies: ISM — intergalactic medium — ISM: general

1. INTRODUCTION

The distribution of neutral hydrogen (H I) in spiral galaxies often extends well beyond their optical disks (see review by Sancisi & van Albada 1987). Additionally, some spiral systems have neutral hydrogen column densities that sharply truncate at large galactocentric distances (van Gorkom 1991; Corbelli & Salpeter 1993). This may be interpreted as the edge of the gaseous disk of the galaxy; however, recent theoretical arguments and observational evidence suggest that an additional phase of material, ionized hydrogen, may exist beyond the regions of observed H I (Maloney 1993; Bland-Hawthorn, Freeman, & Quinn 1997). Direct observations of this ionized gas would yield important physical information about the true size of spiral galaxies and, with sufficient sensitivity and spectral resolution, could extend the rotation curve of spiral galaxies, yielding more insight into the dynamics of spiral galaxies and their distribution of dark matter. Observations of ionized hydrogen beyond the stellar disk may also lead to information about the sources of ionization, which may be within the galactic system, as in the case of a hot galactic corona, or outside of it. An external source of radiation, the intergalactic Lyman continuum flux, plays an important role in cosmological models. By observing the brightness of the H α in the outer H I disk of a local galaxy, one may constrain the magnitude of the $z = 0$ ionizing background flux.

We have used the Wisconsin H-Alpha Mapper (WHAM) to observe the distribution of diffuse ionized hydrogen in the local spiral galaxy M31. The high sensitivity and large field of view of WHAM make M31 the best galaxy in which to search for an extended disk of ionized hydrogen.

2. OBSERVATIONS

The WHAM instrument is a fully remotely operated facility with a 15 cm, dual-etalon Fabry-Perot spectrometer at the focal

plane of a 0.6 m telescope atop Kitt Peak in Arizona (Reynolds et al. 1998; Tufté 1997). The WHAM spectrometer has a 1° diameter circular field of view on the sky and a velocity resolution of 12 km s⁻¹ within a 200 km s⁻¹ wide spectral window that can be centered on any wavelength between 4800 and 7300 Å. WHAM was designed to detect very weak emission lines from ionized gas.

For the observations of M31, the spectral window was centered at approximately -500 km s⁻¹ with respect to H α , which is the approximate radial velocity of the southwestern half of the galaxy. Spectra were obtained toward a total of nine lines of sight. Five lines of sight (“ONs”) were centered near the photometric major axis of M31 and extended from the center of M31 to just off the edge of the observed southwestern H I disk (see Fig. 1). Four lines of sight (“OFFs”), located a couple of degrees away from M31 (see Table 1) and free of M31 H α emission, were used as comparison spectra. Each direction was observed for 300 s at a time, alternating between OFFs and ONs. The data were obtained over a total of five nights during three different periods separated by almost 1 yr. This was done to take advantage of the motion of the expected M31 H α emission line with respect to fixed weak atmospheric lines. Table 1 summarizes the details of the observations.

The WHAM interferometer produced 128 × 128 pixel ring images from which spectra were extracted via an annular ring summing technique; each position within the 1° beam is equally sampled by each spectral element (Tufté 1997). The resultant spectra were flat-fielded, continuum-subtracted, and intensity-calibrated. Signatures of cosmic rays and physical defects in the interference filter were removed with pixel masking.

Figure 2 shows an average of 44 spectra toward all OFF lines of sight taken on the same night, free of M31 emission. The bright feature in the red side of the spectrum is a well-known OH atmospheric line at 6553.6 Å, which we used for precise wavelength calibration. The feature near -480 km s⁻¹ is a Fabry-Perot ghost from the bright geocoronal H α line near 0 km s⁻¹; the other features are extremely weak, unidentified atmospheric

¹ 1 R = 10⁶/4 π photons cm⁻² s⁻¹ sr⁻¹.

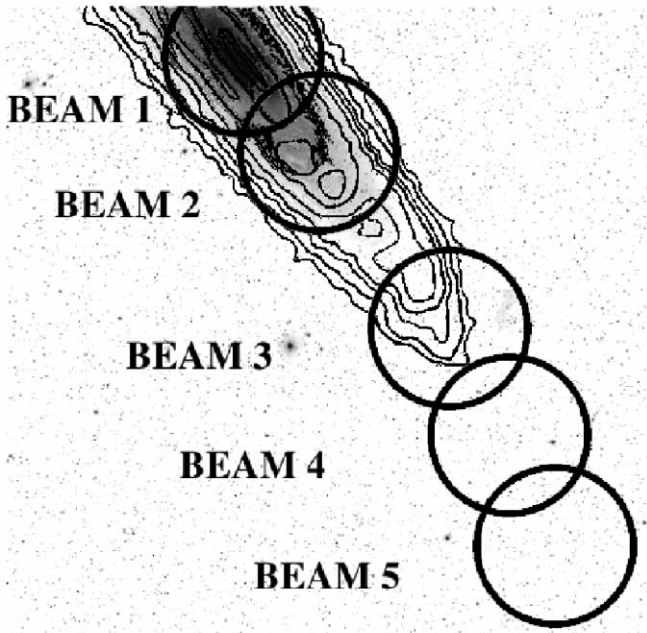


FIG. 1.—Overlay of an optical image of M31, H I contours, and the ON lines of sight considered in this study. The optical image is from the DSS-II at STScI. The H I contour diagram is adapted from Cram et al. (1980). The outermost contour level is at $N_{\text{H I}} = 6.51 \times 10^{19} \text{ cm}^{-2}$. Detectable H I emission extends beyond this last contour to fill beam 3.

lines within the spectral window. The strengths of all of these lines vary both temporally and spatially on the sky, which makes the task of identifying the weak H α emission line from M31 formidable.

To isolate the emission solely due to M31, the spectra obtained in the OFF directions were subtracted from the ON spectra. Due to the complex nature of the intensity variations of the weak atmospheric features, only a subset of the OFF spectra were subtracted from the ONs. This subset satisfied the criteria that the resultant spectra formed a flat baseline around the region of expected M31 emission. This process produces accurate spectra if the OFFs possess no significant extraterrestrial emission features within the spectrum. The potentially incomplete subtraction of the atmospheric lines is the largest source of uncertainty in our results.

3. RESULTS

Beam 1, positioned at the center of M31, reveals significant H α emission. However, due to the dynamical location of the line of sight, the width of the line extended beyond the $\pm 100 \text{ km s}^{-1}$ range of the spectrum. Hence, an accurate spectral baseline and estimate of the emission-line strength was not possible. For the remaining ON beam positions, the expected emission-line width should be relatively narrow, comparable to the thermal and turbulent motion of the emitting gas. This is confirmed by observations of M31's flat rotation curve toward these directions, as seen in the 21 cm spectrum along the major axis (Cram, Roberts, & Whitehurst 1980).

The spectra taken toward beam 2 also reveals significant H α emission, as seen in Figure 3, with an intensity of $I_{\text{H}\alpha} = 0.66^{+0.03}_{-0.09} \text{ R}$. The error in this measurement is due to the uncertainty in the spectral baseline generated by the incomplete subtraction of the weak atmospheric features. Toward the line of sight off of the stellar disk, but within the H I disk (beam

TABLE 1
SUMMARY OF OBSERVATIONS

BEAM	α	δ	DISTANCE		$I_{\text{H}\alpha}$ (R)	$v_{\text{H}\alpha}^c$ (km s^{-1})	FWHM (km s^{-1})
			kpc ^a	R_{25}^b			
ON							
1	0 40 00	41 00 00	...	...	...	...	...
2	0 37 33	40 24 32	10.3	0.47	$0.66^{+0.03}_{-0.09}$	-535 ± 0.5	51 ± 1
3	0 33 16	39 17 54	29.2	1.34	$0.05^{+0.01}_{-0.02}$	-521 ± 1.5	36 ± 5
4	0 31 26	38 37 26	39.5	1.82	≤ 0.019	-521	36
5	0 30 00	37 55 00	49.8	2.29	≤ 0.031	-521	36
OFF							
6	0 08 00	38 15 00	...	...	...	...	...
7	1 00 00	38 00 00	...	...	...	...	...
8	0 20 00	41 00 00	...	...	...	...	...
9	0 55 00	41 30 00	...	...	...	...	...

NOTE.—Coordinates given in (B1950) equinox. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Galactocentric distance, using a distance of 784 kpc to M31 (Stanek & Garnavich 1998).

^b Radius of the $\mu_B = 25 \text{ mag arcsec}^{-2}$ isophote (de Vaucouleurs et al. 1991).

^c Velocity of the H α emission with respect to the LSR.

3), H α emission is detected near the velocity of the H I, with $I_{\text{H}\alpha} = 0.05^{+0.01}_{-0.02} \text{ R}$ (see Fig. 4). Figure 1 shows that this emission arises far from the optical stellar disk.

Toward the two lines of sight just off the edge of the H I disk (beams 4 and 5), no significant H α emission was detected. Upper limits of $I_{\text{H}\alpha} \leq 0.019 \text{ R}$ and $I_{\text{H}\alpha} \leq 0.031 \text{ R}$ were determined for beams 4 and 5, respectively (see Fig. 4). These are the strengths of the strongest emission that can be placed at the H I velocity, with the same width as the H α emission detected in beam 3, and not be discernable in the spectra. Note that the scatter in the

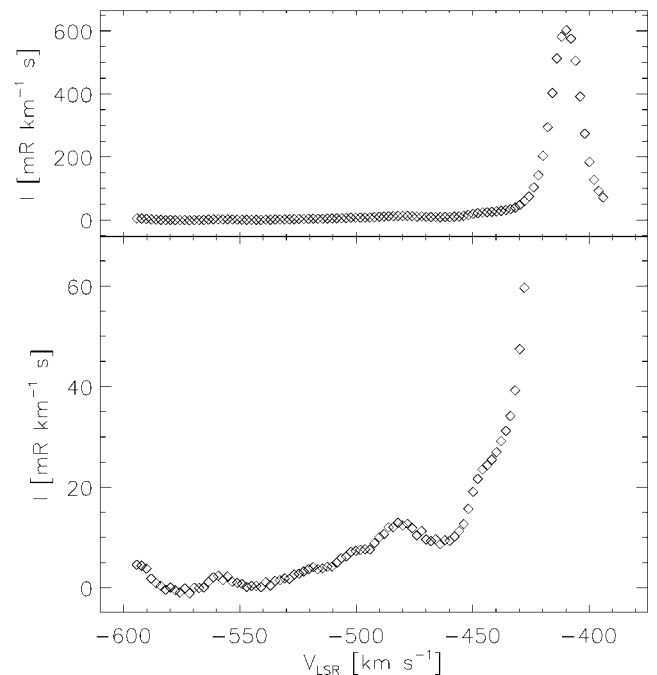


FIG. 2.—Average spectrum of 44 OFF lines of sight, all taken on the same night, for a total integration of 3 hr and 40 minutes. The y-axis is given in units of millirayleighs per kilometers per second. The top graph displays the total spectrum; the bottom graph is an expansion of the full spectrum at low-intensity levels. Note the strong OH line near -410 km s^{-1} , the geocoronal H α ghost at -480 km s^{-1} , and several weaker atmospheric lines.

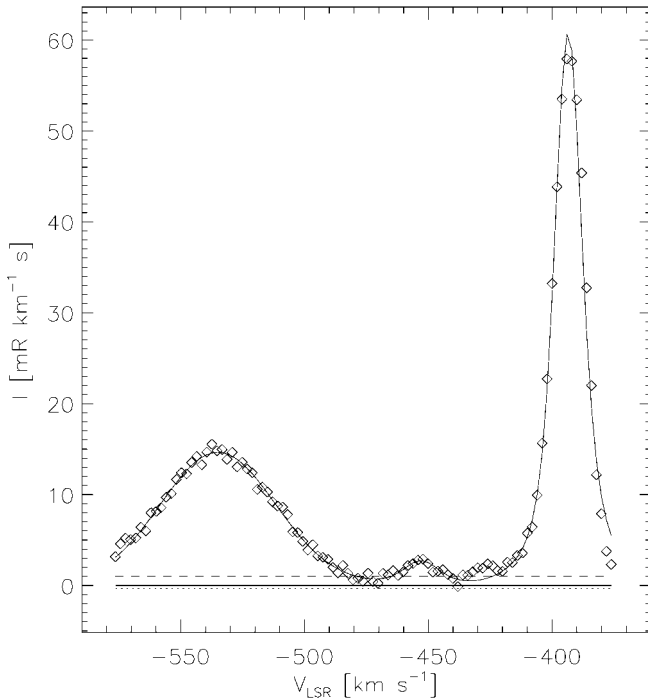


FIG. 3.—Reduced spectrum of the region toward the southwestern stellar disk (beam 2). The M31 H α emission at -535 km s^{-1} has a strength of $I_{\text{H}\alpha} = 0.66^{+0.03}_{-0.09} \text{ R}$. The data are represented as diamonds, and the best fit by a solid line through the data. Note the incomplete subtraction of the OH line and the location of the continuum. The straight solid line is the continuum used for the best fit, whereas the dashed and dotted lines are upper and lower limits to the continuum, respectively, reflected in the upper and lower error limits of $I_{\text{H}\alpha}$.

spectra toward beam 5 is considerably larger than for beam 4. This increase in the scatter arises from intrinsically larger variations in the atmospheric lines in this direction. A more accurate removal of these lines toward beam 4 has provided a stronger upper limit, which we adopt as the largest H α emission strength allowable off the edge of the H I disk in M31. Although the data indicate a somewhat lower limit, we have concluded that the variations in the atmospheric lines, which produce an incomplete subtraction of these features in the ON-OFF spectra, could hide a signal as large as 0.019 R . We note that the 2σ uncertainty due to Poisson noise in the data is much lower, at 0.004 R .

Other deep CCD imaging searches for faint H α emission in external galaxies (Zurita, Rozas, & Beckman 2000; Ferguson, Gallagher, & Wyse 1998a; Martin & Kennicutt 2001; Walterbos & Braun 1992) are sensitive to signals ranging from ≈ 0.5 to 100 R , with typical sensitivities of tens of rayleighs. Our ability to detect emission down to $\sim 0.01 \text{ R}$ is a result of the unique dual-etalon, high-resolution Fabry-Perot design of WHAM combined with the power of the ON-OFF technique.

4. DISCUSSION AND CONCLUSIONS

One of the original motivations for these deep H α observations of M31 was to search for H II extending beyond the radius of the H I cutoff. No such extended emission was found down to our detection limit of 0.019 R . This corresponds to a face-on emission measure $\text{EM}_{\perp} = 0.016 \text{ cm}^{-6} \text{ pc}$ for a temperature of 10^4 K and a column recombination rate of $1.2 \times 10^4 \text{ hydrogen recombinations cm}^{-2} \text{ s}^{-1}$. To calculate the emission measure and recombination rate, we estimated the extinc-

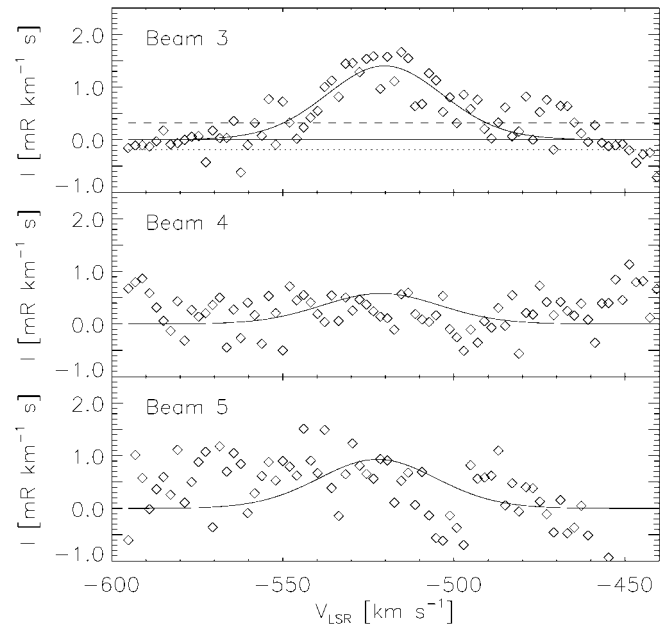


FIG. 4.—Reduced H α spectra away from M31's stellar disk toward beams 3, 4, and 5. H α emission from M31 is present in the top plot toward beam 3 at a velocity of -521 km s^{-1} , with a strength of $I_{\text{H}\alpha} = 0.05^{+0.01}_{-0.02} \text{ R}$ (symbols and lines as in Fig. 3). The middle and bottom plots of spectra toward beams 4 and 5 show no detectable H α emission. The solid lines in these spectra are reasonable lower limits to their continua plus H α emission lines with the same velocity and width as the emission toward beam 3. Lines of strength $I_{\text{H}\alpha} = 0.019 \text{ R}$ and $I_{\text{H}\alpha} = 0.031 \text{ R}$ are overlaid in beams 4 and 5, respectively. Note the scatter in the data and that the vertical scales in all three plots are identical.

tion of the H α photons as they passed through the Milky Way along each of the lines of sight. We used the Galactic neutral hydrogen column density $N_{\text{H I}}$ toward each direction (Hartmann & Burton 1997) and the relationship between $N_{\text{H I}}$ and τ_{λ} given by Bohlin, Savage, & Drake (1978) and Mathis (1990) to increase $I_{\text{H}\alpha}$ by $\approx 30\%$ over the observed $I_{\text{H}\alpha}$. The extinction within the outer disk of M31 is negligible as compared with the foreground Galaxy (Cuillandre et al. 2001), and we therefore have not corrected for that effect.

On the other hand, we did detect ionized hydrogen in the extended H I disk of M31 (beam 3). One possible source of this ionization is young, massive O stars within the H I layer. Cuillandre et al. (2001) recently completed a deep, V - and I -band photometric imaging study of a region within our beam 3 and did find evidence of young B stars. However, they also mention that while an estimate of the threshold for very massive star formation in this region is difficult to ascertain, it is unlikely that the gas disk surface density exceeds the critical density (Martin & Kennicutt 2001). Therefore, while deep H α imaging studies of galaxies of *later type* than M31 (Sb) have revealed sites of massive star formation at comparably large galactocentric distances (Ferguson et al. 1998a, 1998b), it seems unlikely that the observed H α emission toward beam 3 arises from photoionization from massive O stars.

Another possible source of this H II is an external flux of Lyman continuum radiation. Since the H I fills the WHAM beam for position 3 (see Cram et al. 1980), the observed H α intensity of 0.05 R provides a direct estimate of the required ionizing flux (Maloney 1993). Assuming that the H I absorbs all of the incident Lyman continuum photons and that the gas is optically thin to H α , we find that an ionizing flux incident $\Phi_0 = 1.6 \times 10^4 \text{ photons cm}^{-2} \text{ s}^{-1}$ on each side of M31 would

account for the H α . We derived this value assuming case B and an electron temperature $T_e = 10^4$ K, making the small extinction correction described above, and taking into account the 77° inclination of M31's disk from the line of sight. However, since additional sources of ionization may be present, e.g., B stars, planetary nebulae, or hot white dwarf stars in the outer disk and halo of M31 (Cuillandre et al. 2001), this value of Φ_0 must be considered an upper limit on the external ionizing flux. Other authors have derived Φ_0 with various techniques combining both observations and theory and probing a variety of extragalactic environments (see Table 1 of Shull et al. 1999). We find that our value of $\Phi_0 = 1.6 \times 10^4$ photons $\text{cm}^{-2} \text{s}^{-1}$ is among the lowest of these reported values.

Our upper limit on Φ_0 near M31 implies that a spherical, isolated H I cloud bathed only in an *isotropic* intergalactic radiation field of the Local Group would have an H α intensity $I_{\text{H}\alpha} \leq 0.03$ R. This is significantly (approximately a factor of

3) below the observed intensities of high-velocity H I clouds in the Milky Way's halo (Tufté, Reynolds, & Haffner 1998) and in the Magellanic Stream (Weiner & Williams 1996), implying an additional source of ionizing radiation in the halo of the Milky Way, such as Lyman continuum photons from O stars escaping the disk (Bland-Hawthorn & Maloney 1999; Dove, Shull, & Ferrara 2000). H α observations of high-velocity H I clouds may therefore provide important information about the location of clouds within the Local Group. Specifically, clouds far from a galaxy (e.g., Blitz et al. 1999) should have H α intensities ≤ 0.03 R.

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REFERENCES

- Bland-Hawthorn, J., Freeman, K. C., & Quinn, P. J. 1997, ApJ, 490, 143
 Bland-Hawthorn, J., & Maloney, P. R. 1999, ApJ, 510, L33
 Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1999, ApJ, 514, 818
 Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
 Corbelli, E., & Salpeter, E. E. 1993, ApJ, 419, 104
 Cram, T. R., Roberts, M. S., & Whitehurst, R. N. 1980, A&AS, 40, 215
 Cuillandre, J., Lequeux, J., Allen, R. J., Mellier, Y., & Bertin, E. 2001, ApJ, 554, 190
 de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Pasturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer)
 Dove, J. B., Shull, J. M., & Ferrar, A. 2000, ApJ, 531, 846
 Ferguson, A. M. N., Gallagher, J. S., & Wyse, R. F. G. 1998a, AJ, 116, 673
 Ferguson, A. M. N., Wyse, R. F. G., Gallagher, J. S., & Hunter, D. A. 1998b, ApJ, 506, L19
 Hartmann, D., & Burton, W. B. 1997, Atlas of Galactic Neutral Hydrogen (Cambridge: Cambridge Univ. Press)
 Maloney, P. R. 1993, ApJ, 414, 41
 Martin, C. L., & Kennicutt, R. C., Jr. 2001, ApJ, 555, 301
 Mathis, J. S. 1990, ARA&A, 28, 37
 Reynolds, R. J., Tufté, S. L., Haffner, L. M., Jaehnig, K., & Percival, J. W. 1998, Publ. Astron. Soc. Australia, 15, 14
 Sancisi, R., & van Albada, T. S. 1987, in IAU Symp. 117, Dark Matter in the Universe, ed. J. Kormendy & G. R. Knapp (Dordrecht: Reidel), 67
 Shull, J. M., Roberts, D., Giroux, M. L., Penton, S. V., & Fardal, M. A. 1999, AJ, 118, 1450
 Stanek, K. Z., & Garnavich, P. M. 1998, ApJ, 503, L131
 Tufté, S. L. 1997, Ph.D. thesis, Univ. Wisconsin-Madison
 Tufté, S. L., Reynolds, R. J., & Haffner, L. M. 1998, ApJ, 504, 773
 van Gorkom, J. H. 1991, in ASP Conf. Ser. 16, Atoms, Ions, and Molecules: New Results in Spectral Line Astrophysics, ed. A. D. Haschick & P. T. P. Ho (San Francisco: ASP), 1
 Walterbos, R. A. M., & Braun, R. 1992, A&AS, 92, 625
 Weiner, B. J., & Williams, T. B. 1996, AJ, 111, 1156
 Zurita, A., Rozas, M., & Beckman, J. E. 2000, A&A, 363, 9