

ON THE CONTINUING FORMATION OF THE ANDROMEDA GALAXY: DETECTION OF H I CLOUDS IN THE M31 HALO

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ABSTRACT

Green Bank Telescope 21 cm observations have revealed a faint, yet extensive H I cloud population surrounding the Andromeda galaxy (M31). The newfound objects are likely analogs to the high-velocity H I clouds seen around the Milky Way. At least 20 discrete features are detected within 50 kpc of the M31 disk, with radial velocities that are comparable to those of outer disk rotation. In addition, a filamentary “halo” component of at least 30 kpc extent is concentrated at the M31 systemic velocity. Some of the discrete features are organized into elongated systems with velocity continuity, suggestive of tidal streams. The discrete population can be characterized by a steep power-law distribution of number versus H I mass in the range between 10^5 and $10^7 M_\odot$. The velocity line width of discrete clouds is correlated with the cloud H I mass such that if the clouds are gravitationally bound this implies a dark matter to H I mass ratio of $\sim 100 : 1$. Possible origins for the discrete and halo M31 features include a Local Group “cooling flow,” tidal debris from recent mergers or interactions, and the gaseous counterparts of low-mass dark matter halos.

Subject headings: dark matter — galaxies: formation — galaxies: individual (M31)

1. INTRODUCTION

Much of the sky is covered with neutral hydrogen clouds whose velocities, although within several hundreds of kilometers per second of zero, are nonetheless anomalous and cannot be explained by the normal rotation of the Galaxy (Muller, Oort, & Raimond 1963; Wakker & van Woerden 1997). It is attractive to consider that these high-velocity H I clouds (HVCs) might be material left over from the formation of the Milky Way, now in the process of being accreted (Oort 1970). If this is the case, other galaxies may be expected to have similar gaseous components. A key advantage of studying such extragalactic clouds is that their distance can be comparatively well constrained. In practice, it has proven difficult to achieve the combination of high spatial resolution, mass sensitivity, and large field of view necessary to detect HVC analogs in external systems. Many nearby galaxies have a few peculiar H I features with H I mass as low as $\sim 10^7 M_\odot$ (e.g., NGC 628; Kamphuis & Briggs 1992), but only recently have instruments had sufficient sensitivity to begin revealing complete systems of peculiar velocity H I (e.g., the slowly rotating “halo” component of NGC 2403; Fraternali et al. 2002). In this Letter, we report on deep, wide-field observations conducted with the Green Bank Telescope (GBT), which have resulted in the detection of a complex system of H I gas extending to at least 50 kpc radius around M31.

2. OBSERVATIONS AND DATA ANALYSIS

The GBT observations were obtained over six nights during 2002 September. The telescope was scanned over a $7^\circ \times 7^\circ$ region around M31 while H I spectra were measured over a heliocentric velocity range between -827 and 226 km s^{-1} at a velocity resolution of 1.25 km s^{-1} . At M31’s distance of 770 kpc (Freedman & Madore 1990), the GBT beam ($9'.1$ FWHM) projects to 2.0 kpc, and our survey covers a $94 \times 94 \text{ kpc}^2$ region. At a resolution of 3 kpc and 18 km s^{-1} , the achieved rms flux sensitivity was $7.2 \text{ mJy beam}^{-1}$, corresponding to an H I column density of $2.5 \times 10^{17} \text{ cm}^{-2}$ in a single channel averaged over the beam.

Our GBT data show many H I clouds surrounding M31 at $-515 \text{ km s}^{-1} \leq v_{\text{hel}} \leq -172 \text{ km s}^{-1}$, which can be compared to the systemic velocity of -300 km s^{-1} . Emission features were identified as discrete sources if they were distinct from the M31 H I disk (which extends over the velocity interval -620 to -20 km s^{-1}), were unconfused with the Galaxy, and were characterized by a peak flux density greater than 5σ . Additional GBT spectra were obtained for the faintest detections to verify the accuracy of our procedures. We limited the investigation to velocities more negative than -160 km s^{-1} in order to exclude contamination from intermediate-velocity Galactic emission.

3. H I CLOUDS AROUND M31

Our 21 cm observations have revealed a population of about 20 discrete clouds together with an extended, filamentary halo component. The data show that these features cannot be instrumental effects related to M31’s bright H I disk, for there is no relationship between the diffuse structures and the brightness of nearby disk gas. GBT images showing the distribution of H I at different velocities are presented in Figure 1. These were taken from a heavily smoothed variant of the data cube. Contours are drawn at 2, 4, and 6 σ . Discrete compact H I clouds appear at velocities between -172 and -515 km s^{-1} . Extended regions of filamentary, low- $N_{\text{H I}}$ gas are found preferentially within $\sim 80 \text{ km s}^{-1}$ of M31’s systemic velocity ($v_{\text{hel}} = -300 \text{ km s}^{-1}$).

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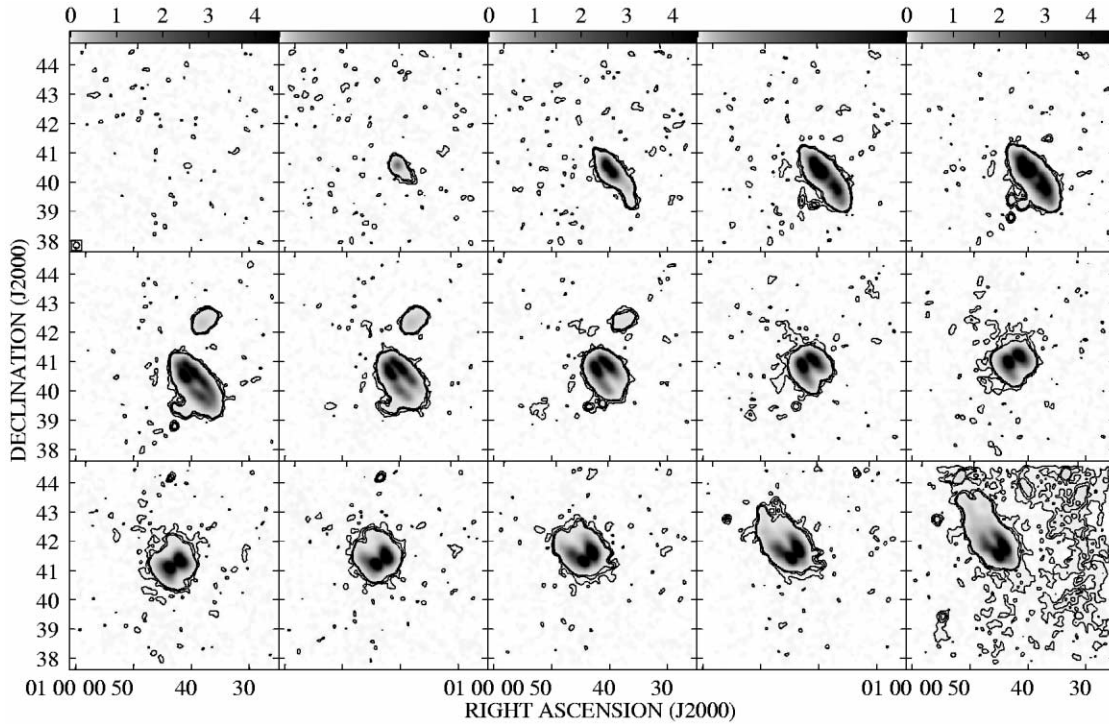


FIG. 1.—Overall distribution of high-velocity H I gas in the GBT survey volume, displayed with a square root transfer function ($0\text{--}4.5 \text{ Jy beam}^{-1}$). Contours are drawn at 2, 4, and 6σ . Our data have been smoothed to ($3 \text{ kpc}, 72 \text{ km s}^{-1}$) resolution for this figure. Note the population of discrete HVCs plus an extended distribution of gas present in the channels near M31's systemic velocity (-300 km s^{-1}). Images for the following heliocentric velocities are shown: -656 km s^{-1} (top left), $-622, \dots, -181 \text{ km s}^{-1}$ (bottom right).

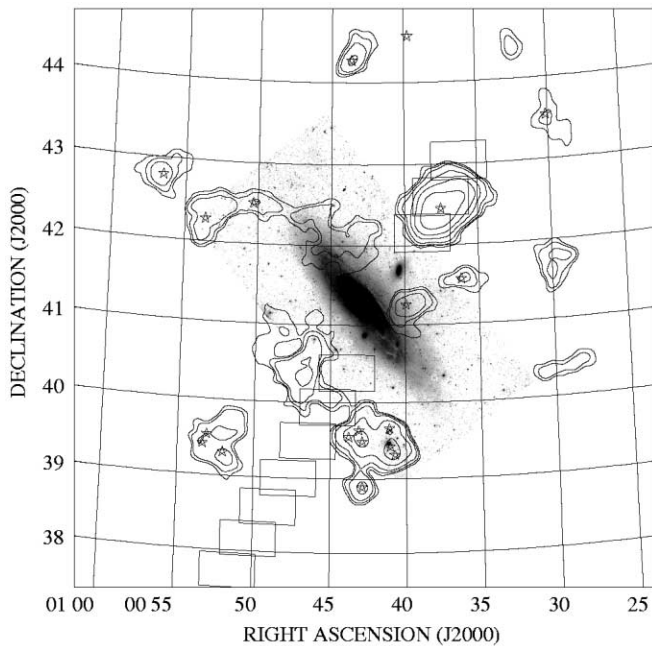


FIG. 2.—Total column density for discrete and diffuse high-velocity H I in the M31 GBT field, after masking emission from Andromeda's inclined, rotating disk. Contours were evaluated at ($3 \text{ kpc}, 72 \text{ km s}^{-1}$) resolution and rendered at $0.5, 1, 2, 10,$ and $20 \times 10^{18} \text{ cm}^{-2}$, then overlaid on a V-band image of M31. The position of each discrete cloud (or distinct substructure) is marked using a star symbol. We indicate the location of the metal-rich stellar stream analyzed by Ferguson et al. (2002) by plotting the imaging fields of McConnachie et al. (2003). H I emission from NGC 205 has been masked.

We believe that this gas is associated with M31, for the following reasons: (1) there is evidence for interaction between several of the clouds and M31 or its companions; (2) cloud velocities match the velocity extent of M31's disk and generally correlate with the pattern of Andromeda's outer disk rotation; (3) the extended H I component is concentrated near M31's systemic velocity; (4) confusion with the foreground Magellanic Stream at this location is unlikely; and (5) dynamical constraints on the mass of M31, assuming a bound cloud population, are in good agreement with independently determined values. We first examine this evidence linking the H I detections to M31, then consider possible origins for the cloud population.

Figure 2 depicts the high-velocity gas in the survey field, which could be cleanly separated from the disk emission of Andromeda. Contours of integrated H I column density at $0.5, 1, 2, 5, 10,$ and $20 \times 10^{18} \text{ cm}^{-2}$ (evaluated using the smoothed cube shown in Fig. 1) are overlaid on an optical image of M31. Star symbols mark discrete clouds meeting our 5σ significance threshold, which are adequately resolved from neighbors in position-velocity space. One discrete cloud near the north edge of the field peaks below the minimum contour after data cube smoothing but has been independently confirmed in follow-up GBT observations. In addition to discrete clouds, there are extended filamentary complexes of low column density H I, most notably at small galactocentric radii southeast and north of Andromeda's stellar disk. Only structures that are cleanly separated from the M31 disk H I emission are included in Figure 2. Additional filaments can be discerned in Figure 1.

The collection of discrete H I clouds extending more than $1^\circ 5$ (20 kpc) to the south of M31's disk near $(\alpha_{J2000.0}, \delta_{J2000.0}) =$

(00:42, 39:15) is suggestive of a tidal stream, based on the elongated distribution and continuously varying radial velocity of the features. These H I clouds are partially coextensive with the metal-rich stellar “Andromeda Stream” (Ibata et al. 2001; Irwin et al. 2002; Ferguson et al. 2002; McConnachie et al. 2003), although they are significantly offset to the southwest. The conclusion that these particular clouds are associated with M31 seems inescapable. A second case of partial correspondence of gaseous and stellar components is the discrete object that is displaced by only 25′ to the southwest of NGC 205 and is overlapping in velocity with that galaxy. This feature also merges in position and velocity with the M31 disk.

The only object in our sample that was known previously is Davies’ Cloud (Davies 1975), which is at least 10 times brighter than the other features. Davies considered that it might be part of the Magellanic Stream rather than M31, but in our complementary wide-field study of a $60^\circ \times 30^\circ$ region centered on M31 (Braun, Thilker, & Walterbos 2003; see also R. Braun & D. A. Thilker 2004, in preparation) we find that the Magellanic Stream comes no closer than 7° to the southwest, where its velocity differs by about 100 km s^{-1} from the diffuse components near M31. It seems likely that Davies’ Cloud and the other detections from our survey are not confused by emission from the Magellanic Stream. A high-resolution imaging study of Davies’ Cloud (de Heij, Braun, & Burton 2002a) has provided additional morphological and kinematic evidence for tidal interaction with M31. We suggest that it is simply the most massive of a population of faint H I clouds around the Andromeda galaxy.

Additional evidence for association of the newly detected clouds with M31 is that the discrete cloud velocities appear partially correlated with the pattern of outer disk rotation in M31, with the most negative velocities occurring in the southwest and the most positive in the northeast. The high negative velocities of some clouds (e.g., -515 km s^{-1}) are also more extreme than any seen previously in Galactic HVC surveys ($v > -466 \text{ km s}^{-1}$; Putman et al. 2002; de Heij, Braun, & Burton 2002b). A straightforward interpretation is that the clouds are collectively under the gravitational influence of the Andromeda galaxy and have interacted dissipatively with M31 in the past.

If the detected clouds represent a circumgalactic population gravitationally bound to Andromeda, their velocity offsets and projected separations should be collectively related to M31’s total mass. Using the virial theorem and representing the discrete GBT clouds as bound test particles orbiting a central mass (eq. [10–22] in Binney & Tremaine 1987), we find that $M_{\text{M31}} = 5.2 \times 10^{11} M_\odot$. This estimate reflects only the mass contained within the radii probed by our clouds. If we instead assume an extended mass distribution (eq. [10–23]) similar to the distribution of clouds, the entire virial mass of Andromeda is then $M_{\text{M31, vir}} = 7.9 \times 10^{11} M_\odot$. These two mass determinations are in good agreement with independent total mass estimates of $4 \times 10^{11} M_\odot$ within a radius of 30 kpc (Brinks & Burton 1984) and $1.6 \times 10^{12} M_\odot$ within Andromeda’s virial radius of 300 kpc (Klypin, Zhao, & Somerville 2002).

From all these considerations, we consider it very likely that the newfound H I clouds reside in the circumgalactic environment of M31.

4. DISCUSSION

At a distance of 770 kpc, most clouds in our sample have H I masses in the range $(0.15\text{--}1.3) \times 10^6 M_\odot$. Such clouds would not have been detected as discrete objects in previous

surveys of more distant galaxies, which generally have probed only the mass range above $\sim 10^7 M_\odot$ (Braun & Burton 2001). An indication for the more general existence of low-mass circumgalactic populations comes from the recent detection of a 15% excess of H I mass found on scales of several hundred kiloparsecs relative to that seen at tens of kiloparsecs in the environment of apparently isolated galaxies (Braun et al. 2003). Placing accurate limits on the total H I mass of the M31 halo cloud population is difficult because we lack a well-measured radial scale length for the population, must cope with potential incompleteness due to Galactic confusion, and have no confirmed minimum cloud mass. To the degree that the observed cloud mass function is consistent with a sensitivity-bounded power law given by $dN(M_{\text{H I}}) \propto M_{\text{H I}}^{-2} dM_{\text{H I}}$, our estimate of H I mass for the halo cloud population within the GBT field is $\sim (3\text{--}4) \times 10^7 M_\odot$. The upper limit of this range is calculated assuming the true population is bounded by a minimum H I cloud mass of $10^5 M_\odot$ and that there are fewer than ~ 100 of such objects, the vast majority of which are not yet detected. We also included an extra 25% to account for clouds confused with Galactic emission, but even so, the H I mass of Andromeda’s discrete halo cloud population in our data amounts to only 1% of the mass of M31’s H I disk. Below, we explore the idea that the halo clouds may trace a more substantial amount of ionized gas and possibly also dark matter.

An obvious source of high-velocity H I is tidal stripping from recent or ongoing mergers. We detect a gaseous feature that is partially coextensive with the stellar Andromeda Stream (McConnachie et al. 2003), and of comparable spatial extent, as well as a component of possibly stripped gas adjacent to NGC 205. However, most of the discrete clouds detected in our GBT survey are rather isolated, lacking any apparent relation to known M31 companion galaxies, and do not have obvious indications of internal tidal distortions. Nevertheless, the faintest dwarf galaxies and stellar streams are notoriously hard to detect (Armandroff, Jacoby, & Davies 1999). One might argue that some dwarfs have yet to be discovered, while others have been entirely consumed by M31. Indeed, the comparatively young (6–8 Gyr) halo stars found by Brown et al. (2003) in the Advanced Camera for Surveys Andromeda deep field do suggest that M31 has seen a major merger (with a massive star-forming galaxy) or several minor mergers.

Cooling of a tenuous intergalactic medium (Oort 1970) is a second viable source of clouds. In this view, halo clouds would condense from, and remain confined by, coronal gas that is located around M31 or perhaps pervades the Local Group. Sembach et al. (2003) presented evidence for an extended and highly ionized Galactic corona or Local Group medium traced by high-velocity O VI absorption. Likewise, Lockman et al. (2002) conducted a sensitive H I survey of 860 sight lines at $\delta > -43^\circ$, which suggested that a low column density “mist” of high-velocity neutral gas surrounds the Milky Way ($N_{\text{H I}} \gtrsim 8 \times 10^{17} \text{ cm}^{-2}$ along 40% of sight lines). Together, these studies show that the Galactic HVC phenomenon extends to much lower column densities than traditionally appreciated and that the classical Galactic HVCs are only part of a more ubiquitous multiphase medium. The filamentary “H I halo” we detect concentrated on the M31 systemic velocity may be a manifestation of an M31 “cooling flow.” In such a scenario, the detected H I may represent only the tip of the iceberg, in terms of baryonic mass, since the gas may well be only of order 1% neutral at the relevant low volume densities (Sembach et al. 1999). The primary source of such coronal gas may

actually be the action of a large-scale “galactic fountain” (Shapiro & Field 1976; Bregman 1980; Savage et al. 2003) in the recent or distant past.

A third component of high-velocity H I near M31 might be the gas associated with a putative population of low-mass dark matter halos. Current simulations of the Local Group in a Λ cold dark matter cosmology predict a large population of low-mass dark matter halos at the present epoch (Klypin et al. 1999; Moore et al. 1999) that dramatically outnumber known dwarf galaxies. If the M31 halo clouds are tracers of substantial dark matter concentrations, this should be reflected in their internal line widths. We plot the observed H I mass versus FWHM line width for discrete clouds in Figure 3. Line width measurements were determined using Gaussian fits to cloud spectra. The line width distribution has an approximate lower bound roughly consistent with thermal broadening for gas at 10^4 K (FWHM = 24 km s^{-1}). A systematic increase in FWHM line width is observed with increasing H I mass, reaching some 70 km s^{-1} for the clouds near $10^6 M_\odot$. Although Davies’ Cloud is significantly offset from the remainder of the distribution in Figure 3, high-resolution imaging has revealed much higher internal line widths in that object as well (de Heij et al. 2002a). To demonstrate the expected distribution of line width with mass, in Figure 3 we show a curve corresponding to $V^2 = 100GM_{\text{H I}}/R$, where the characteristic discrete cloud radius, R , has been held constant at 500 pc, based on our interferometric Westerbork Synthesis Radio Telescope (WSRT) detections of some of the cloud cores (R. Braun et al. 2004, in preparation). This curve, corresponding to a dark matter to H I mass ratio of about 100 : 1, is not intended to fit to the data but merely to provide a basis for comparison. The hypothesis of a kinematically dominant dark matter component appears to be consistent with the observed line widths of the discrete M31 halo clouds.

Another aspect of the dark matter minihalo scenario that can be checked is the expected number of such objects in the appropriate mass range in the vicinity of M31. Sternberg, McKee, & Wolfire (2002) predict ~ 25 dark matter minihalos associated with gravitationally confined H I within a radius of 40 kpc around M31, based on the simulations of Klypin et al. (1999) and Moore et al. (1999). This is fully consistent with the 20 discrete M31 halo clouds we have detected. The Sternberg et al. calculations also suggest that circumgalactic objects of such low mass and peak H I column density should be only $\sim 10\%$

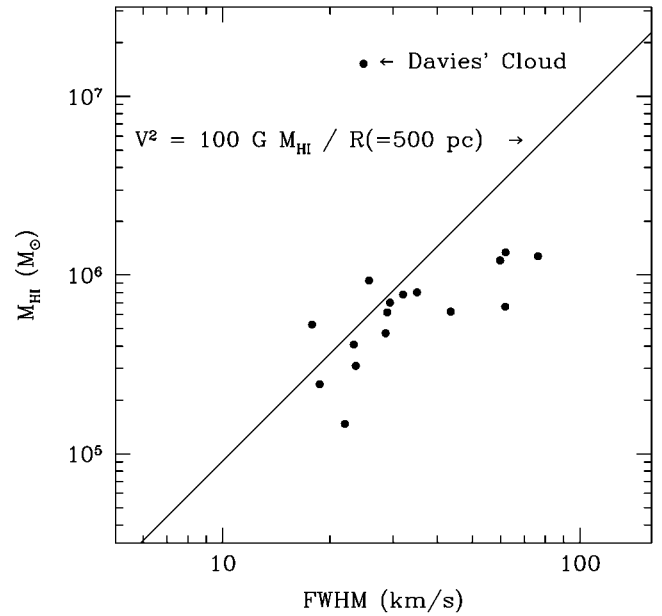


FIG. 3.—Observed H I mass vs. FWHM line width for discrete clouds near M31. Line width was measured using Gaussian fits to flux-weighted average spectra determined over the extent of each cloud. We have also plotted the anticipated relationship between H I mass and line width for gravitationally confined clouds. To first order, our FWHM measurements appear consistent with the hypothesis that the objects are dark matter-dominated, assuming a dark matter to H I mass ratio of 100 : 1 and a characteristic size of 0.5 kpc for each H I cloud core. The later assumption is supported by our WSRT detection of resolved, high column density cores ($N_{\text{H I}} \sim 10^{19} - 10^{20} \text{ cm}^{-2}$) within many of the more centrally located clouds.

neutral, implying $M_{\text{H I} + \text{H II}} \sim 10M_{\text{H I}}$ and $M_{\text{DM}} \sim 10M_{\text{H I} + \text{H II}}$. Associated ionized gas could perhaps be detected via deep Fabry-Pérot imaging (Bland-Hawthorn & Maloney 1999; Tufte et al. 2002) or absorption-line spectroscopy of background quasars (Murphy et al. 2000; Tripp et al. 2003; Sembach et al. 2003).

In summary, our GBT observations of the Andromeda galaxy have revealed the first extensive extragalactic counterpart to the Galactic HVC population. Both discrete and diffuse components are detected. We find some supporting evidence for at least three different possible origins of the high-velocity gas, namely, tidal disruption, halo condensation, and association with low-mass dark matter halos.

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