A HIGH-RESOLUTION STUDY OF THE ATOMIC HYDROGEN IN CO-RICH EARLY-TYPE GALAXIES

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Received 2012 May 30; accepted 2012 November 20; published 2013 January 22

ABSTRACT

We present an analysis of new and archival Very Large Array H\textsc{i} observations of a sample of 11 early-type galaxies rich in CO, with detailed comparisons of CO and H\textsc{i} distributions and kinematics. The early-type sample consists of both lenticular and elliptical galaxies in a variety of environments. A range of morphologies and environments were selected in order to give a broader understanding of the origins, distribution, and fate of the cold gas in early-type galaxies. Six of the eleven galaxies in the sample are detected in both H\textsc{i} and CO. The H\textsc{2} to H\textsc{i} mass ratios for this sample range from 0.2 to 120. The H\textsc{i} morphologies of the sample are consistent with that of recent H\textsc{i} surveys of early-type galaxies, which also find a mix of H\textsc{i} morphologies and masses, low H\textsc{i} peak surface densities, and a lack of H\textsc{i} in early-type galaxies that reside in high-density environments. The HI-detected galaxies have a wide range of H\textsc{i} masses (1.4 × 10\textsuperscript{6} to 1.1 × 10\textsuperscript{10} \(M_\odot\)). There does not appear to be any correlation between the H\textsc{i} mass and morphology (E versus S0). When H\textsc{i} is detected, it is centrally peaked—there are no central kiloparsec-scale central H\textsc{i} depressions like those observed for early-type spiral galaxies at similar spatial resolutions and scales. A kinematic comparison between the H\textsc{i} and CO indicates that both cold gas components share the same origin. The primary goal of this and a series of future papers is to better understand the relationship between the atomic and molecular gas in early-type galaxies, and to compare the observed relationships with those of spiral galaxies where this relationship has been studied in depth.

Key words: atomic data – galaxies: elliptical and lenticular; cD – galaxies: individual (NGC 83, UGC 1503, NGC 807, NGC 2320, NGC 3032, NGC 3656, NGC 4459, NGC 4476, NGC 4526, NGC 5666) – ISM: atoms – ISM: kinematics and dynamics – radio lines: ISM

Online-only material: color figures

1. INTRODUCTION

It is well known that many early-type galaxies (E and S0) contain significant amounts of cold gas (Wiklind et al. 1995; Young 2002; Welch & Sage 2003; Sage & Welch 2006; Morganti et al. 2006; Sage et al. 2007; Combes et al. 2007; Oosterloo et al. 2007; di Serego Alighieri et al. 2007; Welch et al. 2010; Young et al. 2011). The evolutionary pathway of early-type galaxies is thought to be driven in part by the acquisition and transformation of this cold gas into new stars. To the best of our knowledge, stars form only from the molecular gas phase. Clearly, knowledge of the amount of cold gas in the molecular phase versus the atomic phase is an important constraint for theoretical models of star formation and galaxy evolution.

Currently, the physical processes that determine the balance of the atomic and molecular gas are poorly understood in early-type galaxies. The question of molecule formation has been thoroughly studied in the literature mostly through two different methods. The first is an empirical study using the CO and H\textsc{i} maps of nearby disk galaxies (Blitz & Rosolowsky 2004a, 2004b, 2006; Leroy et al. 2008). These studies infer that the molecular to atomic surface density ratio in disks is entirely a function of the hydrostatic midplane pressure, which is in turn a function of the stellar and gas volume densities (hereafter BR06 model). The second method also utilizes gas maps and a first principles approach which models the chemical and physical processes that regulate the balance between the formation and dissociation of H\textsc{2} molecules (Elmegreen 1993; Krumholz et al. 2008, 2009; McKee & Krumholz 2010). Interestingly, both of these approaches predict values of the molecular fraction, 

\[ F_{\text{mol}} = \frac{\Sigma_{\text{mol}}}{\Sigma_{g}}, \]

where \( \Sigma_{g} = \Sigma_{\text{H}_2} + \Sigma_{\text{H}_1} \), that are roughly consistent with molecular and atomic observations in nearby disk galaxies (Krumholz et al. 2009). Fumagalli et al. (2010) suggest that the two approaches yield similar values of the molecular fraction, because Blitz & Rosolowsky (2006) use a fixed stellar density typical of nearby disk galaxies and in effect both formalisms become a sole function of the total gas column density.

Testing whether photodissociation and star formation laws (empirical and theoretical) hold in early-type galaxies requires detailed information about the spatial distribution, column density, and kinematics of both the atomic and molecular gas components. There has been a recent explosion in the number of available H\textsc{i} and CO maps of early-type galaxies (e.g., Serra et al. 2012; di Serego Alighieri et al. 2007; Oosterloo et al. 2007; Alatalo et al. 2013). However, most of these H\textsc{i} maps have resolutions \( \geq 45'' \) and so are not at high enough resolution to make an adequate comparison with existing CO interferometric observations, which typically have resolutions \( \leq 7'' \). In this paper, we present the first comparison of high-resolution H\textsc{i} and CO observations in a sample of 11 early-type galaxies. The new H\textsc{i} observations have 2–16 times better resolution than the current H\textsc{i} surveys.

Higher resolution observations of the H\textsc{i} can also help us to better constrain the origins of the cold gas. There are two basic models for the origin of the cold gas in early-type galaxies: internal and external. The internal origin means mass loss from the stars in the galaxy itself. Estimates of the stellar mass-loss rate are certainly more than enough to reproduce the cold gas contents in early-types over a Hubble time (Faber & Gallagher 1976; Ciotti et al. 1991; Brighenti & Mathews 1997; Athey et al. 2002). However, recent observational studies of the cold gas in nearby early-type galaxies show that on average the total...
observed gas masses add up to only about 10% of what is expected from mass loss after the first 0.5 Gyr regardless of luminosity (e.g., Sage & Welch 2006; Welch et al. 2010). It has been speculated that most of the returned stellar mass is either quickly depleted in star formation, used to fuel a central active galactic nucleus (AGN), stripped, or heated into an ionized phase. Possible external origins include gas accretion from mergers or accretion of primordial gas from the intergalactic medium.

A large amount of evidence is accumulating that suggests that the bulk of the cold gas in local early-type galaxies is likely supplied via external processes (e.g., Davis et al. 2011; Morganti et al. 2006; Serra et al. 2012; Emsellem et al. 2004; McDermid et al. 2006). Arguments for an external origin are supported by the fact that the cold gas mass in early-type galaxies only weakly correlate with other optical properties such as stellar luminosity and stellar velocity dispersion (e.g., Davis et al. 2011), the existence of tidal features in H i maps (Morganti et al. 2006; Serra et al. 2012), kinematic mismatch between cold gas and stars (Davis et al. 2011), and the existence of kinematically decoupled stellar cores (Emsellem et al. 2004; McDermid et al. 2006). Some early-type galaxies do sometimes contain stellar disks that correlate with nuclear and global galaxy properties, suggesting that the gas that formed these stars was produced via internal mass loss (Davis et al. 2011). However, in these cases it may be that galaxy wide processes in the most massive early-types or the early-types host environment are effectively destroying any signatures of an external origin (Davis et al. 2011).

Recent single-dish observations of H i and CO in a volume-limited (decl. \(\lesssim 10^\circ\), and distances \(\lesssim 20\) Mpc) sample of early-type galaxies indicate that the atomic and molecular cold gas phases themselves could have separate origins (Welch & Sage 2003; Sage & Welch 2006; Sage et al. 2007; Welch et al. 2010). The key piece of evidence that supports their hypothesis is that the H i and CO kinematics (line profiles) for many of their lenticular galaxies do not match. Sage & Welch (2006) speculate that the two cold gas phases in early-type galaxies are separate, because the molecular gas originates from stellar mass loss while the atomic gas has been acquired from an outside source (primordial or through mergers). This single-dish survey compares H i data with angular resolutions \(\geq 45''\) to CO data with angular resolutions of \(55''\). A more recent ATLAS\textsuperscript{3D} volume-limited multiwavelength survey of 260 early-type galaxies compares \(45''\) resolution H i data to CO data with resolutions ranging from \(3''\) to \(10''\). Their data show that the ionized, atomic, and molecular gas in local early-type galaxies always have similar kinematics and so likely have a common origin (Davis et al. 2011; Alatalo et al. 2013). Resolving the discrepancy between these two studies requires closely matched high-resolution H i and CO data.

This is the first in a series of papers that aim to: (1) use the cold gas kinematics and gas morphologies of our sample to look for indications of separate origins for the H i and CO in early-type galaxies. (2) Test theoretical models of star formation known for spiral galaxies. Is there evidence of star formation where star formation models predict it to occur? (3) Test whether the theoretical H\textsubscript{2} molecule formation models of Elmegreen (1993), Krumholz et al. (2008, 2009), and McKee & Krumholz (2010) and the empirical models of Blitz & Rosolowsky (2004a, 2004b) can predict the observed molecular fraction in early-type galaxies.

In Paper I we present the results of the new H i observations. Paper I is organized as follows: In Section 2 the sample description is presented. In Section 3 we present the 21 cm H i observations and data reduction. In Sections 4.1 and 4.3 we present the results of the observations, and the H i fluxes and masses. In Section 5 we compare the H i and CO morphologies. In Section 6 we present the H i kinematics and the dynamical masses. In Section 7 we discuss the role of the environment on the H i morphology and the origin of the cold gas in early-type galaxies. In Section 8 we present the conclusions.

2. SELECTION AND GALAXY PROPERTIES

Testing whether photodissociation and star formation laws (empirical and theoretical) hold in early-type galaxies requires detailed information about the spatial distribution, column density, and kinematics of both the atomic and molecular gas components. Recently it has been found that the most CO rich early-type galaxies are more likely to have high column density H i (Serra et al. 2012). Therefore, in order to maximize our chances of detecting and resolving H i we begin this preliminary study using a sample of early-types already known to be CO-rich. Our galaxy sample includes 11 of the 14 galaxies recently mapped in \(^{12}\)CO 1–0 line with the Berkeley–Illinois–Maryland Association (BIMA) millimeter interferometer at Hat Creek, CA, by Young (2002, 2005) and Young et al. (2008). The molecular gas in these 11 galaxies is located in very regular, symmetric rotating disks with diameters ranging from 0.7 to 12 kpc and they have H\textsubscript{2} masses in the range of \(1.0 \times 10^8\) to \(4.7 \times 10^9\) M\(_\odot\) (Young 2002, 2005; Young et al. 2008).

All of the galaxies in our sample have an \(r^{1/4}\) profile or a classification as E, E/SO, or S0 in several catalogs. In some cases, these classifications are based on photographic evidence. In the case of NGC 5666, CCD imaging suggests that one of our sample galaxies may have a more complicated morphology (Donzelli & Davoust 2003).

Additionally, all of our early-type sample galaxies have estimates on the amount and location of star formation derived from high-resolution radio continuum (5''), 24\textmu FIR, and UV maps that make them ideal objects for this preliminary study (Lucero & Young 2007; Young et al. 2009).

The sample galaxies have a wide variety of properties and environments. About half the galaxies are isolated, and the other half are located in loose groups or clusters (Virgo and A569). Some have very smooth, regular morphologies, whereas others are classified as ‘peculiar’ because of dust lanes, stellar shells and ripples, etc. The targets’ distances range up to 80 Mpc and optical luminosities are in the range \(-25.80 \leq M_K \leq -21.7\). Thus, a study of these objects should give us a broad understanding of how the H i and CO are distributed in early-type galaxies.

The sample galaxies discussed in this paper have a similar range in K-band stellar luminosity and \(M(H i)/L_K\) as those in the ATLAS\textsuperscript{3D} survey. However, our sample is heavily biased toward objects with H\textsubscript{2} masses above \(10^9\) M\(_\odot\). Additionally about half of our galaxy sample reside at distances greater than 40 Mpc with a few a factor of two more distant. Table 1 contains ephemeris information for the galaxy sample.

One potential danger in making comparisons from single-dish surveys is the large discrepancy of the fields of view between instruments used to observe H i and CO (e.g., 20'' for CO from the IRAM 30 m, versus 3' for H i from the Arecibo 300 m). However, for early-type galaxies at the distances of our sample,
the evidence suggests there is little CO flux missing beyond the available fields of view. For example, Welch & Sage (2003) made multiple pointings on early-type galaxies with the 30 m telescope but rarely found CO emission outside the central kpc. Consistent with that result, a recent comparison of the CO fluxes from the IRAM 30 m and the Combined Array for Millimeter Wave Astronomy (CARMA) for a subsample of the ATLAS3D early-type galaxies shows that the CO is often slightly more extended than the IRAM 30 m primary beam (Alatalo et al. 2013), but a single pointing with the 30 m usually recovers at least 50% of the total flux. Interferometric surveys carried out with the Berkeley–Maryland–Illinois Array (BIMA) and CARMA find that the CO in early-type galaxies rarely extends outside their respective primary beams (e.g., Young 2002, 2005; Alatalo et al. 2013).

3. OBSERVATIONS AND DATA REDUCTION

In order to test the current photodissociation and star formation models, we require H1 column density maps of the 11 early-type galaxies at angular resolutions comparable to what has already been obtained in CO. These column density maps will allow us to calculate the surface density ratio $\Sigma_{H}/\Sigma_{H1}$, as a function of radius. Therefore, new neutral hydrogen Very Large Array (VLA) observations were obtained for eight galaxies (NGC 83, UGC 1503, NGC 807, NGC 2320, NGC 3032, NGC 4526, NGC 4459, and NGC 4150), and five of these galaxies (NGC 83, UGC 1503, NGC 807, NGC 2320, and NGC 3032) were observed in the C configuration (projected baselines 0–15 k\lambda) between 1992 February and 2005 August. The VLA’s C configuration and its 15° beam is the best compromise between sensitivity and resolution for the purpose of comparisons between the atomic and molecular gas in our sample galaxies, and is a factor of three better than recent HI surveys with the Westerbork Synthesis Radio Telescope (WSRT; e.g., Serra et al. 2012), NGC 4150, NGC 4459, and NGC 4526 were observed in the VLA D configuration (projected baselines 0–5 k\lambda) in 2005 December. These three galaxies were observed in the lower resolution D array because they were observed with single-dish telescopes (NGC 4150: Arecibo 305 m; NGC 4459 and NGC 4526: Effelsberg 100 m; Huchtmeier & Richter 1986), but were not detected. The new VLA D configuration observations for these three galaxies are about a factor of 10 deeper than what was done at the single dish. Recent WSRT H1 observations for NGC 4150 produce a clear detection (Morganti et al. 2006). The WSRT data for NGC 4150 have a similar resolution to that of our new D array data (70′ × 35′ 1)), velocity resolution (16 km s$^{-1}$), and an rms noise of 0.6 mJy beam$^{-1}$. VLA D configuration H1 data for NGC 4476 were previously published by Lucero et al. (2005) and resulted in a non-detection. We obtained and re-reduced this data using similar techniques described in Section 3.1 of Lucero et al. (2005) and were able to achieve a slightly better rms noise of 1 mJy beam$^{-1}$ in a primary beam corrected cube. We derive a new upper limit to the H1 mass of $<6.7 \times 10^6 M_\odot$.

High-resolution (≤15′) VLA H1 maps already exist for NGC 3656 and NGC 5666. We have obtained a high-resolution H1 image of NGC 3656 from Jacqueline van Gorkom that was originally published by Balcells et al. (2001). This image was made by combining VLA D, C, and B array data and yielded an H1 mass of 2.0 × 10$^9 M_\odot$. High-resolution H1 data for NGC 4476 were previously published by Lucero et al. (2005) and resulted in a non-detection and an upper limit to the H1 mass of $<6.7 \times 10^6 M_\odot$. We have re-reduced this data using similar techniques outlined in Section 3.1 of Lucero et al. (2005) and were able to achieve a slightly lower rms noise of 1 mJy beam$^{-1}$ in a primary beam corrected cube. Four hours of VLA C array data for NGC 5666 were published by Lake et al. (1987), but no H1 flux or mass is quoted in that paper. Additional time on NGC 5666 was obtained (~9 hr in C array) but never published (J. van Gorkom 2007, private communication). Analysis of the full 13 hr of VLA C array data for NGC 5666 is presented in this paper.

Table 2 gives specific dates, configurations, and time on-source for archive data as well as the new H1 data. All data calibration and image formation was done using standard calibration tasks in the Astronomical Image Processing System (AIPS) package (Greisen 2003). Each galaxy was observed in one pointing centered roughly on the optical center of the galaxy. Phase drifts as a function of time are corrected by means of nearby point sources observed every 30–45 minutes. The absolute flux scale was set by observations of the sources 0137+331 or 1331+305 (whichever was closer to the galaxy in question). These two sources are also used to correct variations in the gain.

| Galaxy | Type | R.A. (J2000.0) | Decl. (J2000.0) | $V_{hel}$ (km s$^{-1}$) | D (Mpc) | $M_H$ (mag) | Environ |
|--------|------|---------------|----------------|------------------------|---------|------------|---------|
| N83    | E    | 00:21:22.4    | 22:26:01.4     | 6359 (27)              | 85.6(1.6)| −23.55     | Group   |
| U1503  | E    | 02:01:19.8    | 33:19:46.4     | 5086 (6)               | 71(5)   | −23.69     | Field   |
| N907   | E    | 02:04:55.7    | 28:59:15.5     | 4764 (12)              | 66.5(1) | −24.74     | Field   |
| N2320  | E    | 07:08:42.0    | 50:34:52.1     | 5944 (15)              | 84.7(5) | −25.77     | AS69    |
| N3032  | S0   | 09:52:08.2    | 29:14:10.6     | 1533 (5)               | 21.2(1.9)| −21.98     | Field   |
| N3656  | S0p  | 11:23:38.4    | 53:50:31.4     | 2869 (13)              | 40(3)   | −23.74     | Merg rem |
| N4150  | S0−  | 12:10:33.6    | 30:24:06.4     | 226 (22)               | 13.7(1.6)| −21.70     | Coma Group |
| N4476  | S0   | 12:20:59.1    | 12:20:55.3     | 1978 (12)              | 17.6(0.6)| −21.76     | Virgo cloud |
| N4526  | S0   | 12:54:03.0    | 07:41:57.3     | 575 (24)               | 17.3(1.5)| −24.71     | Virgo cloud |
| N4459  | S0+  | 12:29:00.0    | 13:58:53.3     | 1210 (16)              | 16.1(0.4)| −23.88     | Virgo cloud |
| N5666  | ?    | 14:33:09.2    | 10:30:39.1     | 2226 (6)               | 31(2)   | −22.28     | Field   |

Notes. Environments and classifications are taken from (1) Young 2002, (2) Young et al. 2008, and (3) RC3. Distances are taken from (4) Young et al. 2009, (5) NASA’s Extragalactic Database (NED), and (6) Lyon Extragalactic Database (LEDA). Velocities are taken exclusively from NED; they refer to H1 where available or to stellar velocities. K-Band magnitudes are taken from integrated magnitudes in the 2MASS catalog (Skrutskie et al. 2006).
as a function of frequency (bandpass calibration). Comparisons of flux measurements on all the observed calibrators suggest that the absolute flux uncertainties are on the order of 10%. Variations in the bandpass are on the order of 1%. Initial imaging revealed which channel ranges were free of H\textsc{i} line emission. Continuum emission was subtracted directly from the raw UV data by making first-order fits to the line-free channels using the AIPS task UVLIN. For the cases where no line emission is visible in any of the channels, the line width of the CO is derived from a conservative 6\sigma of the rms noise in one channel.

### Tables

#### Table 2

| Galaxy | Config | Obs. Dates | Program ID | Flux Cal | Velocity Range (km s\(^{-1}\)) | TOS (hr) | Beam (\arcsec) | Linear Resolution (kpc) | Channel (km s\(^{-1}\)) | Noise (mJy beam\(^{-1}\)) | \(N_{\text{HI}}\) Limit (10\(^{19}\) cm\(^{-2}\)) |
|--------|--------|------------|------------|----------|-------------------------------|----------|----------------|-------------------------|-----------------------------|----------------|-----------------------------|
| N83    | C      | 2005 Aug   | YA159      | 0137+331 | 5900–6700                      | 6.6      | 19.2 ± 17.3  | 7.9 ± 7.1               | 21                          | 0.3             | 13                          |
| U1503  | C      | 2002 Dec   | YA135      | 0137+331 | 4800–5400                      | 8.4      | 13.8 ± 13.0  | 4.8 ± 4.5               | 21                          | 0.3             | 23                          |
| NGC 807| D\(^b\) | 1985 Dec   | AD174      | 3C48     | 4100–5400                      | 16       | 48.5 ± 44.2  | 15.5 ± 14.1             | 42                          | 0.5             | 13                          |
|       | C      | 2002 Jul   | YA135      | 0137+331 | 4100–5400                      | 9.0      | 13.8 ± 13.1  | 5.9 ± 5.5               | 21                          | 0.2             | 15                          |
|       | C&D\(^c\) |        |            |          | 4100–5400                      | 25       | 32.9 ± 31.5  | 10.5 ± 10.1             | 42                          | 0.2             | 5.3                         |
| N2320  | C      | 2005 Sep   | YA159      | 0137+331 | 5200–6600                      | 7.5      | 16.9 ± 15.8  | 6.9 ± 6.4               | 21                          | 0.3             | 16                          |
| N3032c | C      | 1992 Feb   | AL263      | 1228–1873 | 18.9 ± 16.5                  | 9.3      | 18.9 ± 16.5  | 1.9 ± 1.7               | 10                          | 0.6             | 13                          |
| N3656\(^d\) | BCD   | 1996/7    | AB819/791  | 1328+307 | 2365–3521                      | 28       | 7.4 ± 7.2    | 1.4 ± 1.4               | 21                          | 0.16            | 42                          |
| N4476  | D      | 2002 Jan   | YA128      | 1331+305 | 1637–2284                      | 4.6      | 46.2 ± 46.2  | 3.9 ± 3.5               | 10.4                        | 1.0             | 3.4                         |
| N4526  | D      | 2005 Dec   | YA161      | 1331+305 | 0–1300                         | 1.1      | 64.0 ± 50.5  | 5.4 ± 4.2               | 21                          | 0.7             | 3.0                         |
| N4459  | D      | 2005 Dec   | YA161      | 1331+305 | 600–1800                       | 1.1      | 45.0 ± 43.3  | 3.3 ± 3.4               | 21                          | 1.0             | 7.1                         |
| N4150  | D      | 2005 Dec   | YA161      | 1331+305 | −100–600                       | 1.1      | 54.5 ± 52.0  | 3.6 ± 3.5               | 21                          | 1.0             | 4.9                         |
| N5666\(^e\) | AD    | 1986 Feb   | AL111      | 3C286   | 1906–2533                      | 4.8      | 55.0 ± 44.7  | 8.3 ± 6.7               | 21                          | 0.4             | 2.3                         |
| C&DAD |        | 1986 Dec   | AL111      | 3C286   | 1906–2533                      | 13.3     | 16.0 ± 14.5  | 2.4 ± 2.2               | 21                          | 0.5             | 36                          |

Notes.
- \(^a\) Combined C and D VLA configuration data. \(^*\) A array transition into D array.
- \(^b\) Lower resolution data for NGC 807 and NGC 5666 are dominated by errors due to the bright continuum source associated with M87 (~1.6 to the south of the phase center). The following methods were used to try and remove these errors. First, we fit and subtracted the radio continuum using UVLIN on a cube whose phase center has been shifted to the position of M87. This produced a cube with an rms of ~0.7 mJy beam\(^{-1}\), but with unstable baselines. The task UVLIN is known to leave residuals at the position of strong continuum sources resulting in unstable baselines. In order to minimize the residuals, we next tried using the AIPS task IMLIN followed by UVLIN again shifting the phase center to the position on M87. UVSUB subtracts from the visibility data a Fourier sum of the clean components estimated by deconvolution of the continuum image. The use of UVSUB produced no improvement. We next subtracted the continuum in the image plane using the AIPS task IMLIN. IMLIN fits a low-order polynomial to the line-free part of the spectrum of each pixel in an image cube (Cornwell et al. 1992). In this case the continuum model fit is derived from the line-free channels using a first-order polynomial. Both UVLIN and IMLIN have similar problems dealing with point sources that are far from the phase center. However, IMLIN may produce better results than UVLIN, because its errors scale with distance from the bright continuum source rather than from the phase center as they do when fitting with UVLIN. Indeed IMLIN was much more successful at removing the side lobes of M87, but produced an rms noise 1.4 times larger than that of the previous two methods (~1 mJy beam\(^{-1}\)). H\textsc{i} upper limits in the following sections are derived from the IMLIN’d cube.
- \(^c\) Observations by Ernest Sequist but not published.
- \(^d\) Balcells et al. (2001).
- \(^e\) Lake et al. (1987).
- \(^f\) Dressel (1987).
continuum-subtracted C array data are smoothed to the velocity resolution of the lower resolution data using the VLA task SPECR. The lower resolution data are then shifted in frequency space using the AIPS task CVEL, which corrects topocentric to heliocentric velocities and resamples so that channel frequencies in the lower resolution data set correspond to the same channels as in the higher resolution data set. Next, the high- and low-resolution frequency corrected data sets are combined together using the AIPS task DBCON and then imaged using similar methods as those described above. The two data sets are combined such that they contribute equally to the final cleaned image.

4. RESULTS

4.1. H\textsc{i} Non-detections

No H\textsc{i} emission or absorption is visible in the data cubes for NGC 83, NGC 4476, and NGC 4526. Often the H\textsc{i} structures in early-type galaxies are much more extended than the CO emission, and in some cases a central H\textsc{i} hole may be present (Roberts & Haynes 1994; van Driel & van Woerden 1991; Serra et al. 2012). Therefore, two sets of primary beam corrected spectra were made for each of these galaxies. For both spectra we assume that the H\textsc{i} covers the same velocity range as the CO. The first spectrum is constructed by first using the CO maps to define a rectangular mask region within which “all” of the detected CO emission is located. In the case of NGC 83 and NGC 4526 all of the detected CO emission fits within the central H\textsc{i} beam and so only a single pixel spectrum is extracted. The intensity is then integrated over the same spatial region over the velocity range of the CO. The second spectrum is made in a similar manner except emission is summed over a square box with a side length approximately equal to the diameter D_{25} (de Vaucouleurs et al. 1991). These larger boxes are typically 10 times the size of the CO diameter and 2.3–5.5 times the effective radius as defined in Cappellari et al. (2011), and they may reveal any extended, low surface brightness H\textsc{i} emission. The primary beam corrected H\textsc{i} spectra for the H\textsc{i} non-detected galaxies are depicted in Figures 1–3. Spatial smoothing has not been employed, since the CO emission is smaller than the 15′′ beam of the C configuration for NGC 83 and the 45′′ beam of the D configuration for NGC 4526 and NGC 4476.

Upper limits to the H\textsc{i} fluxes for NGC 83, NGC 4476, and NGC 4526 are determined from the unresolved/CO-like spectra (see Table 3). The uncertainty in the sum is calculated from the rms noise in the spectrum and the number of channels summed. This estimate assumes that the channels are uncorrelated. H\textsc{i} column densities and masses are obtained from 3σ upper limits of the uncertainty in the integrated intensity. Numerically, this mass limit (a 3σ limit on a sum over one beam and 20–30 channels) is within a factor of two of that proposed by Serra et al. (2012), which is a 3σ limit on a sum over six beams and 40 km s\(^{-1}\) (1–4 of our channels). Thus, the mass limit we quote here is appropriate either for an H\textsc{i} distribution that is spatially compact and follows the CO emission in velocity, or for a modestly extended but narrow line width “cloud” of the type observed around some nearby early-type galaxies by Serra et al. (2012). H\textsc{i} column density and mass limits are obtained using “standard” formula, \(N_{\text{HI}} = (1.1 \times 10^{21} \text{ cm}^{-2}) S_{\text{HI}}/\theta_{\text{maj}} \times \theta_{\text{min}}\) and \(M(\text{HI}) = (2.36 \times 10^{5} \text{ M}_\odot \text{D}^2 S_{\text{HI}}, \text{where} S_{\text{HI}} \text{ is the H}\text{i} \text{ flux in units of Jy km s}^{-1}, \theta_{\text{maj}} \text{ and } \theta_{\text{min}} \text{ are the major and minor axis of the synthesized beam in arcseconds, and D is the distance in Mpc. All derived parameters for the H\text{i} non-detections can be found in Table 3. No correction has been made for the presence of helium or effects due to inclination.}

4.2. NGC 4459: A Tentative Detection?

For NGC 4459, spectra extracted from the central pixel (Figure 4) appear to show low-level H\textsc{i} emission. The IDL task GAUSSFIT is used to make a linear least square fit of Gaussian to the spectrum in Figure 4. The resulting fit produced a peak H\textsc{i} flux of 0.14 ± 0.04 mJy, an FWHM of 143 ± 45 km s\(^{-1}\) centered on 1307 ± 19 km s\(^{-1}\). The H\textsc{i} column density and H\textsc{i} mass derived from the fitted parameters are 1.1 \times 10^{20} \text{ cm}^{-2} and 1.2 \times 10^{6} \text{ M}_\odot, respectively. The derived H\textsc{i} mass is consistent with a recent Westerbork Synthesis Telescope observation of similar resolution and slightly better rms noise (0.64 mJy beam\(^{-1}\)), which produces an upper limit to the H\textsc{i} mass of <7.41 \times 10^{6} \text{ M}_\odot (Serra et al. 2012).

We regard this as a tentative detection for several reasons. First, the Gaussian fit is not in good agreement with the CO observations, which give a CO line width of 400 km s\(^{-1}\) centered on 1210 ± 20 km s\(^{-1}\) (Young 2005), or with estimates of the systemic stellar velocities 1232 ± 40 km s\(^{-1}\) from Falco et al. (1999) and 1200 ± 10 km s\(^{-1}\) from Emsellem et al. (2004). Second, existing residual problems with the continuum subtraction produces spurious emission over large portions of the data cube (see Section 3.1). H\textsc{i} column density and mass upper limits from our VLA data are also obtained using the methods described in Section 4.1 (see Table 3).

| Galaxy | \(\Delta v_{\text{CO}}\) \(^{a}\) (km s\(^{-1}\)) | \(I_B\) \(^{b}\) (Jy km s\(^{-1}\)) | \(S_s\) \(^{c}\) (Jy km s\(^{-1}\)) | \(N_{\text{HI}}\) \(^{d}\) (10\(^{20}\) cm\(^{-2}\)) | \(M_{\text{HI}}\) \(^{e}\) (10\(^{15}\) \text{ M}_\odot) | \(\log (M_{\text{HI}}/L_K)\) | \(M_{\text{H}_2}\) \(^{(M_{\text{HI}}/M_{\text{H}_2})}\) (10\(^{8}\) \text{ M}_\odot) | H\text{\textsc{i}} Ref |
|---|---|---|---|---|---|---|---|---|
| N83 | 6047–6464 | 0.043(0.030) | 0.09 | <3.0 | <15 | <−3.3 | 19(3) | >29 | 1 |
| N4459 | 1029–1392 | 0.054(0.092) | 0.28 | <1.6 | <1.7 | <−3.6 | 1.70(3.3) | >21 | 2 |
| N4476 | 1870–2050 | 0.12(0.03) | 0.09 | <12 | <0.66 | <−3.2 | 1.00(1.1) | >15 | 3 |
| N4526 | 287–970 | 0.30(0.09) | 0.27 | <0.91 | <1.9 | <−3.9 | 6.41(5) | >100 | 2 |

Notes. No correction is made for the presence of helium or inclination effects in either the H\textsc{i} or the H\textsc{2} masses. H\textsc{2} mass references: (1) Young 2005; (2) Young et al. 2008; (3) Lucero et al. 2005.

\(^{a}\) The observed width of the CO line.

\(^{b}\) H\textsc{i} Intensity integrated over the CO line width.

\(^{c}\) Upper limit of the H\textsc{i} flux for an unresolved source derived from three times the uncertainty in the integrated intensity.

\(^{d}\) Estimated upper limit to the peak H\textsc{i} column density derived from \(S_s\).

\(^{e}\) Estimated upper limit to the H\textsc{i} Mass derived from \(S_s\).

Table 3

H\textsc{i} Non-detections: Flux, Gas Masses, and Ratio Limits
Figure 1. NGC 83: (a) H\textsubscript{i} spectrum of a square region, 5\arcsec on a side, centered on the optical center of NGC 83. The spectrum was constructed by first using the CO image to define a rectangular mask region within which the CO emission is located. The intensity was then integrated over the same spatial region for every channel, so the noise in the line-free regions should be indicative of the noise on the line as well. (b) H\textsubscript{i} spectrum of a square region, 1.5 on a side, centered on the optical center of NGC 83. Integrated intensities quoted in the text are obtained from panel (a).
4.3. H observers: Fluxes and Line Widths

4.3.1. H observers Absorption

We detect no H observers in emission for NGC 2320. There is H observers emission present in the data cube for NGC 2320, but is associated with the spiral galaxy NGC 2321 (see the Appendix). Despite the fact that the data cube for NGC 2320 still contains some residual side lobes from a nearby bright continuum source, the continuum flux is consistent with that of the value quoted in NRAO VLA Sky Survey (19.3 ± 0.7 mJy; Condon et al. 1998). Figure 5 shows a spectrum extracted from the pixel containing the radio continuum peak. This spectrum appears to show the presence of low-level H observers absorption. The absorption is asymmetric with a peak of \(-0.9 \pm 0.3\) mJy beam\(^{-1}\) centered near 6000 km s\(^{-1}\) and a weaker tail out to 5600 km s\(^{-1}\). The absorption peak is only three times the rms noise, and the broader portion of the absorption is at or below noise level. Thus, we investigated the possibility that the absorption feature is just an instrumental effect by also inspecting continuum subtracted images of the phase and flux calibrators, but we find no similar central absorption features or other artifact associated with those cubes. There is an H observers absorption artifact associated with a spiral galaxy, NGC 2321, that is located 10' from the phase center (see Appendix A.1). However, the channels that contain this artifact are offset by more than 100 km s\(^{-1}\) from the absorption feature associated with NGC 2320 and so both features are probably not due to an interference spike. We believe that the absorption artifact in NGC 2321 is probably caused either by problems with the continuum subtraction and/or imaging of a source that is far from the phase center; in other words, it is not related to the feature in NGC 2320. It is also interesting to note here that the
Figure 3. NGC 4526: as in Figure 1 but using box sizes of (a) 36″ on a side and (b) 6′6″ on a side, centered on the optical center of NGC 4526.
CO emission shows a small extension southwest of the galaxy center, and the CO extension has similar velocities to the H\textsc{i} emission peak (6032–6282 km s$^{-1}$; see Figure 12 of Young 2005). This fact strengthens the possibility that at least the peak H\textsc{i} absorption is real. We proceed now with the assumption that the entire absorption is real.

We fit a two component Gaussian to the usable portion of the absorption spectrum in Figure 5. The narrow component has a peak intensity of $-0.72 \pm 0.17$ mJy beam$^{-1}$ and a line width of $101 \pm 31$ km s$^{-1}$ centered on $5964 \pm 13$ km s$^{-1}$. The broader component has a peak intensity of $-0.38 \pm 0.14$ mJy beam$^{-1}$ and a line width of $168 \pm 80$ km s$^{-1}$ centered on $5755 \pm 31$ km s$^{-1}$. The total velocity width of the two component fit is $425$ km s$^{-1}$ centered on $5862$ km s$^{-1}$. The center velocity of the two component fit is in close agreement with both the systemic velocity of the CO ($5886 \pm 20$ km s$^{-1}$; Young 2005) as well as measurements of the optical velocity (5944 $\pm$ 15 km s$^{-1}$; Smith et al. 2000; 5725 $\pm$ 60 km s$^{-1}$; de Vaucouleurs et al. 1991).

The optical depth calculated from the narrow and broad Gaussian fits are $0.043 \pm 0.013$ and $0.022 \pm 0.007$, respectively. The estimated column density of the two components are $N_{H_1} = 8.4 \pm 2.1 \times 10^{20}$ cm$^{-2}$ and $N_{H_1} = 7.1 \pm 2.3 \times 10^{20}$ cm$^{-2}$, respectively. If both components represent real absorption the total column density is $N_{H_1_{tot}} = (1.6 \pm 0.3) \times 10^{21}$ cm$^{-2}$. Alternatively, if the absorption is in reality contained in just one channel the optical depth is $0.053 \pm 0.010$, and the H\textsc{i} column density is $(2.2 \pm 0.7) \times 10^{20}$ cm$^{-2}$ or $1.8 \pm 0.6 M_{\odot}$ pc$^{-2}$. The true H\textsc{i} column density probably falls somewhere between these three estimates. If the H\textsc{i} is smoothly distributed inside one beam ($\sim 42.7$ kpc$^2$), the total H\textsc{i} mass and H$_2$/H\textsc{i} ratios range from 0.8–5.5 $\times 10^9 M_{\odot}$ and 9–60, respectively. Both estimates of the H\textsc{i} mass and surface densities assume an H\textsc{i} harmonic mean spin temperature, ($T_s$), of $\sim 100$ K (Dickey & Lockman 1990) and are not corrected for the presence of helium.

Figure 4. NGC 4459: H\textsc{i} spectrum for the central pixel (15$''$ on a side) centered on the optical center of NGC 4459. The CO in this galaxy fits inside the central pixel of the H\textsc{i} map. The red line is a Gaussian fit to the entire usable spectrum. The fit is centered on 1307 km s$^{-1}$, has an amplitude of 1.04 mJy, and a full width at half-maximum, FWHM/2.355 = 60.7 km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 5. NGC 2320: H\textsc{i} spectrum extracted from one pixel across the entire usable velocity range (1197 km s$^{-1}$) centered on NGC 2320. The red line is a two component Gaussian fit to the entire usable spectrum. The narrow component is centered on 5964 km s$^{-1}$, has an amplitude of $-0.77$ mJy beam$^{-1}$, and a full width at half-maximum, FWHM/2.355 = 101 km s$^{-1}$. The second component is centered on 5755 km s$^{-1}$, has an amplitude of $-0.38$ mJy beam$^{-1}$, and a full width at half-maximum, FWHM/2.355 = 168 km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 6. NGC 4150: as in Figure 1 but using box sizes of (a) 14$''$ on a side and (b) 2.9$''$ on a side, centered on the optical center of NGC 4150. Integrated intensities quoted in the text are obtained from panel (a). The red line in panel (a) is a Gaussian fit to the entire usable spectrum. The fit is centered on 229 km s$^{-1}$, has an amplitude of 1.8 mJy beam$^{-1}$, and a full width at half-maximum, FWHM/2.355 = 85.4 km s$^{-1}$.

(A color version of this figure is available in the online journal.)

4.3.2. H\textsc{i} Emission

For the galaxies with detected H\textsc{i} emission, Figure 6 shows the H\textsc{i} spectra for NGC 4150 and Figures 7–18 show images of the integrated H\textsc{i} intensity, spectra, velocity fields, and...
The spectrum was constructed by first using the integrated image (moment 0) to define a rectangular mask region within which the emission is located. The intensity was then integrated over the same spatial region for every channel, so that the noise in the line-free channels is indicative of the noise on the line as well. Bottom right: velocity field. The H\textsc{i} intensity-weighted mean velocity (moment 1) is shown in RGB color scale and in white contours from 4900 to 5200 km s\(^{-1}\) in steps of 30 km s\(^{-1}\). The black ellipse shows H\textsc{i} the beam size. The CO resolution is 7\arcsec.1 × 6\arcsec.3.

(A color version of this figure is available in the online journal.)

Figure 7. Top: UGC 1503. Solid black (positive) and gray (negative) contours show the H\textsc{i} integrated intensity in units of −10%, −20%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the peak (0.16 Jy beam\(^{-1}\) km s\(^{-1}\) = 9.9 × 10\(^{20}\) cm\(^{-2}\)). White contours show the CO integrated intensity in units of 10%, 20%, 30%, 50%, 70%, and 90% of the peak (6.3 Jy beam\(^{-1}\) km s\(^{-1}\) = 3.9 × 10\(^{21}\) cm\(^{-2}\)). The gray-scale image is an SDSS2 \(R\)-band image. Bottom left: H\textsc{i} spectrum. A comparison of the new H\textsc{i} interferometric data with that of previous single-dish observations yield the following: Our H\textsc{i} flux for NGC 807 is 10.3 Jy km s\(^{-1}\) and is within 10% of the H\textsc{i} flux measured by Huchtmeier et al. (1995), hereafter HSH95, using the Effelsberg 100 m telescope (9\arcsec.3 beam). Our H\textsc{i} flux for NGC 3032 is 0.64 Jy km s\(^{-1}\), which is smaller than 0.9 Jy km s\(^{-1}\) measured with the Arecibo telescope and 0.96 Jy km s\(^{-1}\) measured with the Westerbork at 45\arcsec resolution (Duprie & Schneider 1996; Serra et al. 2012). The Arecibo observations of NGC 3032 are three times less sensitive than our VLA C observations whereas the Westerbork observations are three times more sensitive. If the much lower sensitivity Arecibo observations and the lower resolution but higher sensitivity Westerbork observations both detected all of the flux, then the
Figure 8. UGC 1503. Individual channel maps showing H\textsubscript{i} emission. Contour levels are $-3, -2, 2, 3, 4, 5, 7, 9, 10$, and 11 times 0.3 mJy beam$^{-1} \sim 1\sigma$. The velocity of each channel (in km s$^{-1}$) is indicated at the top of each panel and the beam size in the first panel in the bottom left corner.

Table 4

Detections: H\textsubscript{i} Fluxes, Gas Masses, and Ratios

| Galaxy  | $S_{\text{HI}}$ (Jy km s$^{-1}$) | $N_{\text{HI}}$ (10$^{20}$ cm$^{-2}$) | $R_{\text{HI}}$ (arcsec) | $M_{\text{HI}}$ (10$^6$ M$_{\odot}$) | $\log[M_{\text{HI}}/L_K]$ | $M_{\text{H}_2}$ (10$^8$ M$_{\odot}$) | $(M_{\text{H}_2}/M_{\text{HI}})$ | Class$^a$ | Ref |
|---------|---------------------------------|-------------------------------------|--------------------------|-------------------------------|-----------------------------|---------------------------------|-----------------------------|----------|-----|
| U1503   | 1.8(0.2)                        | 9.9                                 | 47                        | 16(1)                         | −1.47                       | 19(3)                           | 1                           | D        | 1   |
| N807$^b$| 10.3(0.9)                       | 7.7                                 | 223                      | 42(3)                         | −1.17                       | 14(3)                           | 0.1                         | u/D      | 1   |
| N2320$^c$| ...                              | 2.2–16.0                           | ...                      | 1.2–7.4                       | −2.75                       | 47(9)                           | 6–40                        | d        | 2   |
| N3032   | 0.64(0.06)                      | 13                                  | 24                        | 2.5(0.3)                      | 0.68(0.13)                  | −2.27                           | 4.9(1.1)                   | 7        | d   |
| N3656   | 5.4(0.5)                        | 72                                  | 41                        | 8.0(0.2)                      | 20(3)                       | −1.51                           | 38(5)                      | 2        | u   |
| N4150   | 0.036(0.007)                    | 0.49                                | ...                      | ...                           | 0.016(0.004)                | −3.79                           | 0.58(1.1)                 | 36       | d   |
| N4150$^d$| 0.032(0.010)                    | 0.29                                | 45                        | 3.0(0.3)                      | 0.014(0.003)                | −3.85                           | 0.58(1.1)                 | 41       | d   |
| N5666   | 6.3(0.6)                        | 9.1                                 | 96                        | 14(1)                         | −1.08                       | 4.4(0.6)                        | 0.31                      | D        | 1   |

Notes. The value quoted in the third column is the observed peak H\textsubscript{i} column density. No correction is made for the presence of helium in either the H\textsubscript{i} or the H\textsubscript{2} masses.

$^a$ Morphological H\textsubscript{i} classifications as defined by the ATLAS$^{3D}$ classification scheme (Serra et al. 2012).

$^b$ The H\textsubscript{i} radius quoted for the disk of NGC 807 is measured from the galaxy center out to the edge or the tidal arms.

$^c$ The H\textsubscript{i} flux and mass come from the WSRT observations. The quoted H\textsubscript{i} flux accounts for only the H\textsubscript{i} associated with the optical galaxy and excludes a patch of H\textsubscript{i} emission outside and ~1′ to the south of NGC 4150 (see Section 4.3).

References. (1) Young 2002; (2) Young 2005; (3) Young et al. 2008; (4) Balcells et al. 2001; (5) Morganti et al. 2006.
VLA C array observations must be resolving out \(~30\%\) of the total H\textsc{i} flux. This is surprising in that the detected H\textsc{i} emission is so compact (i.e., there are probably no H\textsc{i} structures much larger than the primary beam). At about 10\arcmin to the northeast of NGC 3032 there are three distinct H\textsc{i} sources. A detailed presentation of the VLA H\textsc{i} observations for these three sources can be found in the Appendix. HSH95 also detect a larger H\textsc{i} flux from UGC 1503, 3.3 Jy km s\textsuperscript{-1}, than is found for the VLA C array image (1.8 Jy km s\textsuperscript{-1}), but an earlier H\textsc{i} detection (1.7 Jy km s\textsuperscript{-1}) by Haynes & Giovanelli (1984) with the Arecibo telescope is consistent with the new observations. It is unclear whether H\textsc{i} emission from UGC 1503 has been missed by the VLA C array. The diameter of the H\textsc{i} emission in UGC 1503 is \(~1.5\) so it is very unlikely that any emission could have been missed by the Arecibo observations. In the case of NGC 5666 the VLA C array observations recover a factor of two less flux than the VLA AD array (3.8 mJy km s\textsuperscript{-1} versus 6.2 mJy km s\textsuperscript{-1}). These two data sets have similar rms noises (\(~0.5\) mJy beam\textsuperscript{-1}) and so it is likely that the C array observations have resolved out a significant amount of flux. The HSH95 Effelsberg 100 m single-dish observations for NGC 5666 detect a smaller H\textsc{i} flux from NGC 5666, 4.5 Jy km s\textsuperscript{-1}, than is found for the combined VLA AD and C array image (6.3 Jy km s\textsuperscript{-1}). The rms noise of the HSH95 data, \(~1\)–\(~2\) mJy beam\textsuperscript{-1}, is about 2–4 times higher than the new observations. This is the most likely explanation for the smaller flux.

We find weak and poorly resolved H\textsc{i} emission in the data cube for NGC 4150 and spectra extracted from the central pixel appear to show low-level H\textsc{i} emission (Figure 6). Fitting a one-dimensional Gaussian to the spectrum in Figure 6(a) gives an FWHM of 201 \pm 41 km s\textsuperscript{-1} centered on 229 \pm 17 km s\textsuperscript{-1} and an amplitude of 1.8 \pm 0.3 mJy beam\textsuperscript{-1}. The center velocity of the emission is in close agreement with both the systemic velocity of CO (239 \pm 20 km s\textsuperscript{-1}; Young 2005) and measurements of the optical velocity (226 \pm 22 km s\textsuperscript{-1}; Fisher et al. 1995). If the H\textsc{i} emission is unresolved the total flux is then 36 \pm 6 mJy km s\textsuperscript{-1}, which gives a total mass of (1.6 \pm 0.3) \times 10\textsuperscript{7} M\textsubscript{\odot}. Similar WSRT observations yield an H\textsc{i} flux of 56 mJy km s\textsuperscript{-1} (Morganti et al. 2006). The WSRT observations have an angular resolution of 42\arcsec 29 \times 26\arcsec 00. A total of four 12 hr tracks produced an rms noise of 0.3 mJy beam\textsuperscript{-1}, three times more sensitive than the VLA observations. The WSRT observations show that the H\textsc{i} in NGC 4150 is actually resolved (Morganti et al. 2006).

Recent single-dish Arecibo H\textsc{i} observations of NGC 4150 by Sage & Welch (2006) produce spectra with similar line widths, but those authors quote an H\textsc{i} mass of 1.56 \times 10\textsuperscript{8} M\textsubscript{\odot}, which is more than an order of magnitude larger than those derived from the interferometric data. One possible reason for the larger H\textsc{i} flux include is confusion with a nearby source. An analysis of the moment zero map (Figure 15) provided by Raffaella Morganti shows that roughly half of the detected H\textsc{i} is located inside the galaxy (\(~1.4 \times 10\textsuperscript{8} M\textsubscript{\odot}\) while the other half is located outside of the galaxy (\(~1.6 \times 10\textsuperscript{8} M\textsubscript{\odot}\) about 1\arcmin to the south at a position of R.A. 12\textsuperscript{h}10m29\textsuperscript{s}79 and decl. 30\textdegree 22\textarcmin 45\textsec 96. The emission to the south does not appear to have any visible optical counterpart. In fact, there are no visible counterparts (in projection or velocity of \(~\pm 500\) km s\textsuperscript{-1}) within 40\arcmin of NGC 4150 listed in the NASA Extragalactic database (NED). Therefore, it is unlikely that confusion with any additional field sources is occurring. A second possibility is confusion with high-velocity galactic H\textsc{i}. This possibility can be ruled out since the high-velocity clouds along the line of sight toward the position of NGC 4150 have negative velocities (Kalberla et al. 2005). A third possibility is that a significant amount of H\textsc{i} is in smooth, low-density complexes that are only detected by the lower resolution instrument. This is the most plausible explanation since H\textsc{i} disks around early-types often extend significantly outside of their optical components (Sadler et al. 2000; Morganti et al. 2006; Grossi et al. 2009).

4.4. H\textsc{i} Column Densities and the M\textsubscript{H2}/M\textsubscript{H1} Mass Ratio

Our HI-detected sample galaxies have H\textsubscript{2}/H\textsubscript{i} mass ratios ranging from 0.1 to 41 (see Table 4). This is a similar range in H\textsubscript{2}/H\textsubscript{i} mass ratios found in both the single-dish and interferometric volume-limited surveys. The single-dish survey of
Sage & Welch (2006) find $\text{H}_2/\text{H}_1$ mass ratios in the range of 0.01–5. The interferometric ATLAS$^3$D survey find $\text{H}_2/\text{H}_1$ mass ratios in the range of 0.01–36 (Serra et al. 2012). The lower end of the range in our mass ratio is an order of magnitude larger than that of the volume-limited samples. This is probably due to the fact that our early-type sample is biased toward the most CO-rich objects. All of our sample galaxies with $\text{H}_2/\text{H}_1$ mass ratios greater than 10 reside in group or cluster environments. This is also consistent with what is found by the recent volume-limited surveys. We discuss the role of environment on the $\text{H}_1$ content of our sample galaxies in Section 7.1.

The interferometric observations for NGC 4150 give an $M_{\text{H}_2}/M_{\text{H}_1} = 41$. However, this mass ratio may be too high since it is possible that the WSRT observations may have missed a significant amount of flux (see discussion in Section 4.3.2). If the $\text{H}_1$ mass is instead derived from the Arecibo flux (Sage & Welch 2006) and the distance in Table 1, the mass ratio is much lower, $M_{\text{H}_2}/M_{\text{H}_1} \sim 2$.

5. $\text{H}_1$ VERSUS CO MORPHOLOGY

The top panels of Figures 7, 10, 12, 14, 15, and 17 show integrated $\text{H}_1$ maps overlaid with each galaxy’s respective molecular
gas map. A wide-field image of the H\textsc{i} emission for NGC 807 is depicted in the top panel of Figure 9. Figures 8, 11, 13, and 18 show the individual channel maps. A detailed discussion of the H\textsc{i} morphology as compared to that of the CO is given for each galaxy below. Table 4 gives morphological classifications of the H\textsc{i} according to the ATLAS\textsuperscript{3D} classification scheme (Serra et al. 2012).

**UGC 1503.** This is an isolated early-type galaxy. The H\textsc{i} emission in this galaxy is detected over 288 ± 10 km s\textsuperscript{-1} centered on a systemic velocity of 5086 ± 10 km s\textsuperscript{-1}. The H\textsc{i} systemic velocity is in good agreement with stellar absorption line velocity measurements of 5062 ± 43 km s\textsuperscript{-1} from Falco et al. (1999) and 5098 ± 25 km s\textsuperscript{-1} from Wegner et al. (2003). The H\textsc{i} systemic velocity is also in good agreement with the CO systemic velocity, 5080 ± 15 km s\textsuperscript{-1}, after correction from the radio to the optical definition (Young 2002). The diameter of the H\textsc{i} emission is approximately 1.6. Like the CO emission, the H\textsc{i} in this galaxy is centrally peaked (0.16 Jy beam\textsuperscript{-1} km s\textsuperscript{-1} = 9.9 × 10\textsuperscript{20} cm\textsuperscript{-2}) and centered on the optical center of the galaxy. An inspection of the integrated intensity map shows that H\textsc{i} is distributed into two concentric symmetric ring-like structures (Figure 7). The central ring appears to be bisected by a bright bar-like feature along the minor axis. Circular depressions or holes are observed symmetrically oriented inside the inner ring and about the central bar-like feature. The highest surface densities are found in the bisecting bar-like structure. The inner ring-like structure lies at a radius of 12′′ and has a fairly constant surface density of ∼85 mJy beam\textsuperscript{-1} km s\textsuperscript{-1} = 5.2 × 10\textsuperscript{20} cm\textsuperscript{-2}. The outer ring-like structure is located at a radius of 24′′ and has a steadily declining surface density out to its edge. Both ring-like structures are about one beam width in diameter and so are unresolved. It is interesting to note that the molecular gas does not appear to extend outside the inner edge of the inner ring.

**NGC 807.** The H\textsc{i} in this galaxy is detected over 468 km s\textsuperscript{-1} centered on a systemic velocity of 4750 ± 21 km s\textsuperscript{-1}. The H\textsc{i} systemic velocity is in good agreement with stellar absorption line velocity measurements of 4747 ± 41 km s\textsuperscript{-1} from Falco et al. (1999) and 4721 ± 30 km s\textsuperscript{-1} from Wegner et al. (2003). The H\textsc{i} systemic velocity is also in good agreement with the CO systemic velocity, 4728 ± 25 km s\textsuperscript{-1}, after correction from the radio to the optical definition (Young 2002). The lower resolution map made from the combined AD and C array data gives the appearance of a smooth central H\textsc{i} disk with two tidal arms extending to the northwest and southeast along the major axis. The higher resolution C array data shows that the H\textsc{i} distribution is actually very clumpy and complicated (see the top panel of Figure 9). The H\textsc{i} in this galaxy is distributed about equally between the inner disk and the outer tidal arms with ∼5.5 × 10\textsuperscript{7} M\odot in each component. The diameter of the H\textsc{i} emission out to the edge of the tidal arms is approximately 7′/4. The inner disk has a radius of ∼2:7 and appears to be distributed asymmetrically with about 60% of the H\textsc{i} located to the northwest. The opposite is true of the tidal arms.
The bulk of the H I in the tidal arms, \( \sim 70\% \), is located in the arm to the southeast. The H I intensity is centrally peaked (0.72 Jy beam\(^{-1}\) km s\(^{-1}\) = \( 7.7 \times 10^{20} \) cm\(^{-2}\)) and is roughly coincident with the CO intensity peak. However, the intensity peaks are slightly offset (\(~5''-9''\) from the optical center of the galaxy. Interestingly, the CO distribution is also asymmetric, but the bulk of the CO emission (\(~70\%\)) is actually located to the southeast.

**NGC 2320.** NGC 2320 is a member of the A569 cluster of galaxies. The H I in this galaxy is detected only in absorption. The absorption may be due to a small disk of H I, which may not be large enough to be seen in emission due to the presence of the 17 mJy continuum source. There is a small extension of CO emission southwest of the galaxy center, which also has roughly the same velocity as the H I absorption peak (6032–6282 km s\(^{-1}\); see Figure 12 of Young 2005). This indicates that the absorbing H I and the CO extension could be part of the same gas complex that is actively falling in toward the center of the galaxy.

**NGC 3032.** NGC 3032 is a low-luminosity field lenticular with a small counterrotating stellar disk of radius of \(~2''\) at its center (McDermid et al. 2006). The H I in this galaxy is detected over 146 km s\(^{-1}\) centered on a systemic velocity of 1550 \( \pm 5 \) km s\(^{-1}\), so the H I systemic velocity is in good agreement with the CO systemic velocity (Young et al. 2009) as well as with stellar absorption line velocity measurements of 1555 \( \pm 41 \) km s\(^{-1}\) from Falco et al. (1999) and 1559 \( \pm 10 \) km s\(^{-1}\) from Emsellem et al. (2004). The CO and H I line widths also match well. The C array data give the appearance of a smooth H I disk. It is apparent from the individual channel maps that the H I structures are not well resolved. The diameter of the H I emission is approximately 1' thus it is only slightly more extended than the CO emission. There is an extension
of the H\textsc{i} gas ($\sim 6.8 \times 10^6$ $M_\odot$, roughly 10% of the total mass) outside the main disk to the south. This small amount of H\textsc{i} is oriented in roughly the same direction as a similar extension of the CO. The H\textsc{i} intensity is centrally peaked (0.38 Jy beam$^{-1}$ km s$^{-1}$ = 1.3 $\times$ 10$^{21}$ cm$^{-2}$) and roughly coincident with the optical and CO emission peaks.

NGC 3656. The H\textsc{i} data published by Balcells et al. (2001) show that the H\textsc{i} in NGC 3656 is located in a nearly edge-on, warped minor-axis gaseous disk 7 kpc in diameter. The rest is situated outside the galaxy in what appear to be two tidal tails or perhaps a disrupted outer H\textsc{i} disk or ring. Balcells et al. (2001) note that the velocity structure of the H\textsc{i} distribution is asymmetric, indicating non-circular motions, and they suggest that this is due to recent or ongoing accretion. Their derived position angle of the inner H\textsc{i} disk is 170$^\circ$ and closely matches the position angle derived from the Young’s (2002) CO data. Balcells et al. (2001) H\textsc{i} systemic velocity of 2850 $\pm$ 11 km s$^{-1}$ is in good agreement with the CO systemic velocity of 2840 $\pm$ 15 km s$^{-1}$ (Young 2002) as well as with a stellar absorption line velocity measurement of 2890 $\pm$ 11 km s$^{-1}$ from Rothberg & Joseph (2006). The CO and H\textsc{i} line widths also match well. The H\textsc{i} intensity is centrally peaked (0.32 Jy beam$^{-1}$ km s$^{-1}$ = 6.6 $\times$ 10$^{21}$ cm$^{-2}$) and roughly coincident with the optical and CO emission peaks.

NGC 4150. NGC 4150 is a small nearby lenticular galaxy located on the outskirts of the Virgo Cluster at a projected distance of 18 deg from M87 (Karachentsev et al. 2003). Morganti et al. (2006) quote a WSRT H\textsc{i} mass of 2.5 $\times$ 10$^6$ $M_\odot$, and describe the morphology of the H\textsc{i} inside the galaxy as that of a rotating disk with a diameter of about 1$'$, 1$''$. A close inspection of the integrated intensity map reveals that the H\textsc{i} distribution in the disk is highly asymmetric. The bulk of the H\textsc{i} ($\sim 60\%$) is located in the northwest portion of the stellar disk. The H\textsc{i} peaks at the center (30.4 mJy beam$^{-1}$ km s$^{-1}$ = 3.04 $\times$ 10$^{19}$ cm$^{-2}$) and again at a radius of 17$''$ along the major axis to the northwest. There is a small unresolved clump of H\textsc{i} at the center of the disk that appears to be spatially coincident with the CO disk. The H\textsc{i} gas in the southern part of the disk has column

Figure 13. NGC 3032. Individual channel maps showing H\textsc{i} emission. Contour levels are $-3$, $-2$, 2, 3, 4, 5, 6, 7, 8, and 8.5 times 0.6 mJy beam$^{-1}$ $\sim 1\sigma$. The velocity of each channel (in km s$^{-1}$) is indicated at the top of each panel and the beam size in the first panel in the bottom left corner.
densities up to five times lower than those in the northern and central components. The low surface density of the gas and the asymmetric distribution of the H I imply that the gas is currently being accreted from an outside source. Single-dish observations show that the H I and CO have matching line width (Welch & Sage 2003).

NGC 5666. This is an isolated, low-luminosity field early-type galaxy. The H I emission in this galaxy is detected over 210 ± 11 km s$^{-1}$ centered on a systemic velocity of 2219 ± 10 km s$^{-1}$. The H I systemic velocity is in good agreement with stellar absorption line velocity measurements of 2222 ± 40 km s$^{-1}$ from Falco et al. (1999) and 2224 ± 8 km s$^{-1}$ from Wegner et al. (2003) and the CO systemic velocity of 2225 ± 15 km s$^{-1}$ (Young 2002). The CO and H I line widths also match well. The lower resolution map made from the combined AD and C array data gives the appearance of a smooth H I disk. The diameter of the H I emission is approximately 3.2. There is a slight asymmetry in the H I distribution in that the spatial extent of the H I is larger on the eastern side of the galaxy (i.e., the contours of the integrated intensity are farther apart in the east). Like the CO emission, the H I in this galaxy is centrally peaked (0.94 Jy beam$^{-1}$ km s$^{-1}$ = 9.1 $\times$ 10$^{20}$ cm$^{-2}$) and centered on the optical center of the galaxy. An inspection of the higher resolution C array data shows that the H I distribution is actually clumpy, with the overall appearance of a ring with a bright clump/disk of H I at its center. The H I ring begins at a radius of ~ 45$^{\prime}$. The H I-detected sample galaxies fit well into the ATLAS$^{3D}$ H I morphological classification scheme. The H I-detected sample galaxies can be divided up into three categories: (D) very extended regularly rotating H I disks (UGC 1503 and NGC 5666), (d) small regularly rotating H I disks that do not extend outside the optical body of the galaxy (NGC 2320, NGC 3032, and NGC 4150), and (u) unsettled H I morphologies (NGC 807 and NGC 3656). In the case of NGC 2320 we do not actually know the true extent of the H I emission, but we think it likely to be distributed like the CO, in a compact disk within the optical body of the galaxy. We prefer to classify NGC 807 as an intermediate between the D and u ATLAS$^{3D}$ subclasses, because the kinematics of the H I are surprisingly regular despite obvious tidal features. We have no galaxies in our sample where the H I is found to be in small scattered external clouds. This could be due to the fact that the galaxies are biased toward the most CO rich objects.

None of the H I-detected galaxies exhibit central H I holes. In all cases except for NGC 807 the H I and CO emission is centrally peaked. In the case of NGC 807 the H I and CO emission peaks are offset from the optical center but still coincide with each other. All of our sample H I-detected galaxies have peak H I column densities at or above 10$^{21}$ cm$^{-2}$ except for NGC 4150, which peaks at 2.9 $\times$ 10$^{19}$ cm$^{-2}$. This is consistent with the peak H I column densities derived from the recent single-dish surveys. Serra et al. (2012) note that the early-type galaxies in their sample with H I column densities of 10$^{21}$ cm$^{-2}$ all have the largest amounts of molecular gas, complex and prominent dust distributions, and strong evidence of star formation. The same is true for our H I-detected sample galaxies except for NGC 2320, where there is no evidence of star formation (Young et al. 2008; Crocker et al. 2011). Serra et al. (2012) find that 50% of the very extended H I disks (class D) differ in orientation and kinematics from their stellar components, whereas the small H I disks (class d) are tightly coupled to their host galaxy. Our sample only exhibits the later trend. We see no misalignments between the H I major axis and the stellar isophotal major axis in any of our sample D galaxies. This could be an additional result of selection bias toward the CO richest objects or simply to the small sample size.

Figure 14. NGC 3656. H I and CO overlaid on an SDSS$^{2}$ R band image. Solid black contours show the H I integrated intensity in units of 2%, 6%, 15%, 30%, 50%, 70%, and 90% of the peak (0.32 Jy beam$^{-1}$ km s$^{-1}$ = 7.2 $\times$ 10$^{21}$ cm$^{-2}$). The H I map is constructed from B, C, and D array VLA data (Balcells et al. 2001). The circular ellipse shows the H I beam size. Solid white contours show the CO integrated intensity in units 2%, 5%, 10%, 20%, 30%, 50%, 70%, and 90% of the peak (81.1 Jy beam$^{-1}$ km s$^{-1}$ = 4.7 $\times$ 10$^{22}$ cm$^{-2}$). The CO resolution is 7.8 $\times$ 6.2. The H I spectra and velocity field are published in Balcells et al. (2001).
6. H\textsubscript{i} VERSUS CO KINEMATICS

Global kinematic position angles, inclinations, and systemic velocities are derived by fitting exponentially rising model rotation curves to the H\textsubscript{i} velocity fields depicted in the bottom right of Figures 7, 10, 12, 15, and 17 using the National Radio Astronomy Observatory’s AIPS task GAL. In the case of NGC 3656 we produced an H\textsubscript{i} velocity field by obtaining and re-reducing the VLA B and C array data using similar techniques as in Balcells et al. (2001); the data are mapped with a Briggs robust parameter of 1.0 giving a beam size of 11.6 $\times$ 10.2 and an rms noise level 0.18 mJy beam$^{-1}$ in a 21 km s$^{-1}$ channel. In the case of NGC 3032 the spatial resolution is sufficiently poor that the exponential fits are not robust. A solid body fit to their velocity fields proved more stable for NGC 3032. Estimates of the position angle of the kinematic major axis, inclination angle, and systemic velocities derived from these fits are consistent with values derived from the dust and CO maps of these five galaxies (Young et al. 2008, 2009).

The GAL fits are weighted by the integrated intensity, so the fitted position angle is actually the kinematic axis at small radii. In order to get a good idea of how the position angle changes with radius, constant velocity rotation profiles were fitted to the velocity fields using concentric annuli. Annuli of 30$''$ are used for NGC 807 and annuli 10$''$ are used for the galaxies with smaller H\textsubscript{i} diameters. The constant velocity method also produces fitted position angles that agree with those derived from the CO to within a few degrees. The H\textsubscript{i} position angles of the major axis for all the galaxies discussed in this section are constant with increasing radii (within the margin of error), and never vary more than $\sim$5–10 deg. There is a hint of a possible warp suggested by the slight presence of an integral sign shape in the zero velocity curve of the H\textsubscript{i} velocity field for NGC 3032 (bottom left panel of Figure 12). This integral sign feature may
also be present in the CO velocity field of NGC 3032 (Young et al. 2008). However, the spatial and velocity resolution are poor for both H\textsubscript{i} and CO data sets.

In the case of NGC 4150 not only is the spatial resolution poor, but the distribution of the velocities is also highly non-uniform (see Figure 15(c)). The AIPS task GAL assumes a circularly rotating disk and so may not give correct results for the H\textsubscript{i} in NGC 4150. For this galaxy we employed the kinemetry techniques of Krajnovi\v{c} et al. (2006) to measure the position angle as a function of radius. The measured position angles for NGC 4150 derived from this technique inside 12′′ are consistent with the stellar morphological and kinematic positions angles as well as the kinematic position angle derived from CO measurements.

Position–velocity plots for UGC 1503, NGC 807, NGC 3656, NGC 4150, and NGC 5666 are constructed using the kinematic centers and position angles derived from the model fits described above (see Figure 19). Both the H\textsubscript{i} (black contours) and CO (red contours) data cubes are sliced through the galaxy nucleus at the kinematic position angle listed in Table 5. The position–velocity diagrams for UGC 1503, NGC 807, and NGC 3032 show steeply rising, approximately solid body rotation regions in their centers followed by a flattening at the edges of the H\textsubscript{i} distribution. In the case of NGC 5666 the position–velocity plot represents the superposition of two separate components, an inner H\textsubscript{i} disk (radius of <25′′) and an outer H\textsubscript{i} ring (radius of >25′′). The H\textsubscript{i} in the inner ring does not appear to extend past the region of solid body rotation while the material in the outer ring has only a flat constant velocity component. It is interesting to note that the material in the ring appears to be rotating 20 km s\textsuperscript{-1} or 15% slower than the material at the edge of the inner H\textsubscript{i} disk. The appearance of slower rotation of the ring could be due to a central mass concentration as is observed for the Milky Way or perhaps a change in the orientation of the velocity field.

However, the GAL constant velocity fits for NGC 5666 show that the position angle in the vicinity of the ring does not change more than a few degrees from that of the disk component. Thus, it is not clear whether these two components are kinematically distinct.

In the case of NGC 3656, we use two position angles to construct the position–velocity plots in Figure 19. The angle of 191 deg is derived from the CO map, weighted toward the inner part of the CO, and there is some evidence of a warp as the outer regions tend toward position angles less than 180 deg. Balcells et al. (2001) use 170 deg and that position angle also cuts through a prominent H\textsubscript{i} shell in the southern part of the galaxy. The resulting position–velocity overlays produce obvious signatures of non-circular gas motions in the outer
portions of the H\textsubscript{i} disk. As in the other cases the CO does not appear to extend past the solid body portion of the rotation curve and appears to be for the most part kinematically settled. The H\textsubscript{i} also appears to be kinematically settled within the CO radius.

The position–velocity overlays show that the kinematics of the CO and the H\textsubscript{i} match for UGC 1503, NGC 807, NGC 3032, NGC 3656, and NGC 5666, which strongly suggests a common origin for the two gas phases in these five galaxies. The position–velocity plot of NGC 4150 shows that the H\textsubscript{i} and
CO share the same sense of rotation, but have very different line widths. This is likely due to the fact that much of the H\textsc{i} in this galaxy is currently unsettled due to a recent interaction (Section 5). We do not have an H\textsc{i} velocity map for NGC 2320, however its gas morphology as discussed in Section 5 also implies a common origin between both gas phases.

The dynamical mass interior to the H\textsc{i} disk’s outer edge can be calculated using the observed gas velocities:

\[ M_{\text{dyn}} = (2.33 \times 10^5 M_\odot) V^2 R, \]

where \( R \) is the radius of the outer edge in kpc and \( V \) is the observed velocity in km s\(^{-1}\), corrected for inclination. This assumes that the gas disks are intrinsically circular, and that the gas itself moves along circular orbits. The implied dynamical masses (Table 5) range from a few \( \times 10^9 M_\odot \) to a few \( \times 10^{11} M_\odot \) interior to the edge of the H\textsc{i} disk, and the observed masses of atomic gas are a few percent of these dynamical masses. Table 5 also gives the orbital time for gas at the edges of the H\textsc{i} disks.

7. DISCUSSION

7.1. The Effect of Environment on the H\textsc{i} content

As in other recent H\textsc{i} early-type surveys, we find that the most H\textsc{i}-deficient galaxies either reside in cluster/group environments, show indications of recent interactions or both. The most H\textsc{i} rich galaxies reside in the field, but several of these galaxies also show indications of recent interactions.

The deficiency of atomic gas in clusters galaxies is thought to be due to mechanisms such as (1) tidal interactions, (2) ram pressure (Gunn & Gott 1972), (3) turbulent/viscous stripping (Nulsen 1982), and (4) fast evaporation of the atomic gas due to the presence of a hot intracluster medium (ICM; Grossi et al. 2009). Grossi et al. (2009) suggest that these mechanisms would also aid in limiting the number of H\textsc{i} rich dwarfs in clusters, thus limiting the available reservoirs of gas from which other larger galaxies can feed. In the three H\textsc{i}-undetected lenticulars (NGC 4459, NGC 4476, NGC 4526), there is no indication in the CO or optical data of a recent tidal interaction (Young 2002; Young et al. 2008). Therefore, we conclude that the H\textsc{i} in these...
Figure 19. Position–velocity curves. CO (red contours) and H\textsubscript{i} (black contours). The data cubes are sliced through the galaxy nucleus at the kinematic position angles derived from the GAL fits to the H\textsubscript{i} velocity maps (see Table 5 and Section 6). The derived H\textsubscript{i} kinematic position angles are within a couple of degrees of those derived from the CO data. The H\textsubscript{i} contour levels are all \((−2, 2, 4, 6, \ldots)\) times the rms noise from Table 2. The CO contour levels are all \((−2, 2, 4, 6, \ldots)\) times the rms noise in Tables 2, 3, and 3 of Young (2002), Young (2005), and Young et al. (2008), respectively. In the case of NGC 3656 the contours are multiplied by an additional factor of 1.3.

(A color version of this figure is available in the online journal.)

galaxies has most likely been removed by one or a combination of the last three mechanisms mentioned above. Additionally, current photodissociation models imply that a sudden increase in pressure will increase the gas surface density such that large portions of a galaxy could spontaneously become molecular without converting the diffuse gas to self-gravitating clouds (e.g., Elmegreen 1993). This is perhaps a plausible explanation for why no H\textsubscript{i} is detected over the entirety of the CO disks of these three galaxies. We will explore this possibility in more depth in Paper II (D. M. Lucero & L. M. Young 2013, in preparation).

NGC 4150 is detected in H\textsubscript{i} despite being a Coma group member. The presence of H\textsubscript{i} in this galaxy can be explained by the fact that it resides near the edge of the cluster where the ICM densities are probably lower (i.e., ram pressure and evaporation are much less effective), and the population of H\textsubscript{i}-rich dwarfs is probably higher. Indeed, it appears likely that NGC 4150 is accreting gas from a nearby low surface brightness dwarf galaxy. The H\textsubscript{i} surface densities of both NGC 4150 and the unknown H\textsubscript{i} source peak at \(\sim 0.2 \, M_\odot \, \text{pc}^2\) (corrected for helium and inclination) which is more than 25 times smaller than the lowest peak surface density of the
H$_{\text{i}}$-detected field galaxies. This implies that the stripping/evaporation mechanisms are either still affecting the gas content at a reduced efficiency or only existed for a shorter period of time compared with those cases where the H$_{\text{i}}$ has been completely stripped.

Many of the same mechanisms discussed above could also be at work in group environments, and could also explain the H$_{\text{i}}$ deficiency in NGC 83 and NGC 2320. Both galaxies are located relatively nearby to strong sources of X-ray emission. NGC 83 is a member of the NGC 83 Group. This group is very near (in velocity and spatially) to the galaxy cluster PCC S49-147. A GIS X-ray mosaic image shows that the NGC 83 group could be embedded in the diffuse X-ray ICM associated with PCC S49-147 (Nakazawa et al. 2007a). NGC 2320 is about 2$^\circ$ or 2.9 Mpc in projection from NGC 2329, which lies at the center of the A569 cluster. The A569 cluster was recently observed with the Einstein satellite (Burns et al. 1994). The X-ray emission in this cluster is relatively compact, is quite bright, and is centered on NGC 2329.

NGC 83 and NGC 2320 are the most luminous galaxies in the present sample. Grossi et al. (2009) suggest that the presence of a hot X-ray interstellar medium (ISM) in luminous early-type galaxies may prevent an atomic phase from forming altogether or cause the H$_{\text{i}}$ (whether it originates from mass loss or accretion) to evaporate. Unfortunately, neither NGC 2320 and NGC 83 have been searched deeply for hot gas, and no evidence of a hot ISM has been reported for either galaxy in the literature outside of what has been discussed above. The blue luminosities of NGC 83 and NGC 2320 are well in the range in which O’ Sullivan et al. (2001) find copious amounts of hot gas. The lower luminosity sample galaxies live in the lower range where the X-ray luminosity is dominated by emission from X-ray binary systems rather than hot gas (see Figure 9 of O’Sullivan et al. 2001).

Interestingly, the CO properties of the H$_{\text{i}}$-deficient galaxies do not differ that much from their field counterparts. The only difference worth mentioning is that the cluster/group galaxies have larger peak H$_2$ surface densities than both the group and field galaxies. One might expect the density of the molecular gas in the center of cluster/group galaxies to be increased due to ICM/ram pressures (Nakanishi et al. 2006). We will explore the effects of external pressures on the gas surface density in depth in Paper II (D. M. Lucero & L. M. Young 2013, in preparation). Of course, the larger peak H$_2$ surface densities could be a resolution...
effect, as all of the cluster galaxies are 2–5 times nearer than the other galaxies in the sample.

7.2. The Origin of the Cold Gas in Early-type Galaxies

We find an overwhelming amount of evidence that suggests that both the neutral hydrogen and molecular gas in our early-type galaxy sample share a common origin be it external or internal. The kinematics of the H\textsc{i} and CO gas phases in the sample galaxies are remarkably similar. The H\textsc{i} and CO line widths, intensity peaks, and kinematic position angles match in all cases. We find that if the H\textsc{i} is in a relaxed disk, so is its CO. Alternatively, if the H\textsc{i} appears disturbed, so does its CO. Thus, our results are consistent with the ATLAS\textsuperscript{3D} volume-limited survey, which also find that the two gas phases always exhibit the same kinematics. Other early-type galaxies with differing CO and H\textsc{i} line widths (e.g., Welch \\& Sage 2003; Sage \\& Welch 2006; Sage et al. 2007; Welch et al. 2010) are probably cases in which the H\textsc{i} is either still falling in or being affected by tidal or ram pressure stripping. The existing interferometric data show that the H\textsc{i} is often extended over tens of kiloparsecs while the CO is confined to the inner 1–4 kpc. The kinematics of the H\textsc{i} and CO always match where the two phases overlap. Outside the CO radius the H\textsc{i} often exhibits a range of other morphologies and kinematics.

As in the previous H\textsc{i} surveys, the total gas content (H\textsc{i}+H\textsubscript{2}), H\textsc{i} content, and H\textsubscript{2} content only weakly correlate with galaxy luminosity. This is an indication that the cold gas may have an external origin. Indeed, a large number (45\%) of the sample galaxies show evidence that their cold gas has been obtained or is currently being accreted from outside sources. These include NGC 2320, NGC 3032, NGC 3656, NGC 4150, and NGC 4476. The most obvious cases are NGC 3032 and NGC 4476. The cold gas systems (H\textsc{i} and CO) in these two galaxies are counterrotating with the bulk of the stars, and therefore an internal origin can be ruled out (Young et al. 2008; Crocker et al. 2010). Additionally, small extensions of H\textsc{i} and CO in NGC 3032 and NGC 4150 oriented in roughly the same direction imply that this gas is actively falling onto these galaxies. NGC 2320 contains an absorbing H\textsc{i} complex and an extension of CO emission that have similar velocities redshifted with respect to the systemic velocity, indicating that gas is actively falling in toward the galaxy. The radio continuum emission in NGC 2320 is thought to be powered by an AGN. Perhaps the cold gas in NGC 2320 is helping to fuel the central AGN activity (Young 2005). Tidal features (optical and H\textsc{i}) and the non-circular motions implied by the velocity structure of the H\textsc{i} in NGC 3656 also suggest that the cold gas in this galaxy has been acquired during a recent interaction (Balcells et al. 2001).
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Figure 22. Top: solid black (positive) and solid gray (negative) contours show the H\textsubscript{i} integrated intensity in units of $-20\%$, $-10\%$, $-1\%$, $1\%$, $10\%$, $20\%$, $30\%$, $40\%$, $50\%$, $60\%$, $70\%$, $80\%$, and $90\%$ of the peak ($0.33$ Jy beam$^{-1}$ km s$^{-1} = 1.1 \times 10^{21}$ cm$^{-2}$). The gray-scale image is an SDSS2 red band image. Bottom left: H\textsubscript{i} spectrum. Constructed in a similar manner to UGC 1503. Bottom right: velocity field. The H\textsubscript{i} intensity-weighted mean velocity (moment 1) is shown in RGB color scale and in white contours from 6150 to 6450 km s$^{-1}$ in steps of 21 km s$^{-1}$. The black ellipse shows the beam size.

The origin of the cold gas in NGC 83, UGC 1503, NGC 807, NGC 4459, NGC 4526, and NGC 5666 is less clear. The kinematics of the H\textsubscript{i} and or CO disks in the field early-types UGC 1503 and NGC 5666 suggest that the gas/dust disks in these systems are well settled into dynamic equilibrium. The orbital timescales at the edge of the H\textsubscript{i} disks in UGC 1503 and NGC 5666 are 0.5 Gyr and 0.4 Gyr, respectively. If the cold gas in these two galaxies was acquired from an external source, it must have occurred several orbital timescales ago. There is no overwhelming evidence for an outside origin of the molecular gas for the cluster/group galaxies NGC 83, NGC 4459, and NGC 4526 except perhaps slight asymmetries in the CO distributions of NGC 4459 and NGC 4526 (Young et al. 2008). The generally symmetric appearance of the optical images of these three galaxies also suggests that it has been well over a Gyr since any mergers, if any, have occurred. One then might conclude that their cold gas originated solely from mass loss. However, Davis et al. (2011) suggest that the tell tale signatures of an external origin for the cold gas may get erased by environmental processes such as ram pressure or by galaxy wide processes in the most massive objects such as NGC 83. If true, prograde gas cannot completely rule out an external origin of the cold gas in these particular galaxies. The H\textsubscript{i} in NGC 807 appears to be in a relaxed disk out to a radius of 1.4, and then outside this radius the H\textsubscript{i} appears to be tidally disrupted. A deep optical image taken by the WIYN telescope also shows the presence of faint stellar tidal arms oriented in a similar manner to that of the H\textsubscript{i} tidal features (bottom panel of Figure 9). The kinematics of the H\textsubscript{i} and CO in NGC 807 are surprisingly regular. The uniformity of the kinematics probably mean that the cold gas was already distributed in a relaxed regular rotating structure like those observed in NGC 5666 and UGC 1503 before the interaction occurred. This of course does not rule out the possibility that the cold gas in NGC 807 was acquired a few orbital timescales before the most recent interaction. A better way to distinguish between external and internal gas origins would be to look for significant differences in angular momentum between the cold gas and the stars. Unfortunately, we lack the necessary stellar kinematic information to carry out this type of analysis for these particular galaxies.
8. CONCLUSIONS

In this paper, we present an analysis of new VLA and archive HI observations of 11 CO rich early-type galaxies as well as a preliminary comparison between the HI and CO morphologies and kinematics. The new HI observations have 2–16 times better resolution than that of the recent volume-limited HI surveys of early-type galaxies.

In summary, 6 of the 11 sample galaxies (UGC 1503, NGC 807, NGC 2320, NGC 3032, NGC 3656, and NGC 4150) are detected in HI; the other five are not, even though they have strong CO detections. The HI-detected galaxies have a wide range of HI masses \((1.4 \times 10^8 \text{ to } 1.1 \times 10^{10} \, M_\odot)\). There does not appear to be any correlation between the HI mass or morphology (E versus S0).

HI absorption is detected for NGC 2320. The peak of this absorption is red shifted with respect to the optical systemic velocity by 60 km s\(^{-1}\) and may be associated with a small extension of CO emission that is at a similar offset velocity as the HI. We suggest that the absorbing HI and the CO extension are probably part of the same gas structure that is actively falling toward the center of the galaxy.

The HI in UGC 1503, NGC 3032, NGC 4150, and NGC 5666 is distributed in disk-like structures in regular rotation with diameters of a few to 16 kpc. The HI emission for these galaxies peaks at the disk center \((5\sim9 \times 10^{20} \, \text{cm}^{-2})\). There are no kpc sized HI holes like those observed in early-type spiral galaxies. NGC 807 and NGC 3656 have a significant amount of HI located in tidal arms far from the main disk. The cold gas kinematics of NGC 807 are surprisingly regular despite the fact that the gas has recently been disturbed.

The relatively high resolution of the HI maps presented in this work enable more detailed comparisons of CO and HI kinematics than have previously been possible for early-type galaxies. In the regions where both phases are detected, they show identical kinematics within our measurement errors.

Figure 23. [KUG] 950+295: individual channel maps showing HI emission. Contour levels are \(-5, -3, 3, 12, \) and 15 times \(0.6 \, \text{mJy beam}^{-1} \sim 1\sigma\). Negative contours are gray. The velocity of each channel (in km s\(^{-1}\)) is indicated at the top of each panel and the beam size in the first panel in the bottom left corner.
In the three cases where HI traces a clear turnover in the circular rotation speed, the molecular disks extend out to the turnover (so they would be useful in a Tully–Fisher analysis) but not far beyond that point (so the molecular gas is strongly concentrated in the solid-body part of the rotation curve).

A little over half of the early-type sample galaxies show evidence that their cold gas has been obtained or is currently being accreted from outside sources. We find no evidence in the present early-type galaxy sample to support the suggestion that the HI and CO have different origins. There is also no indication that the origin of the cold gas is dependent on galaxy morphology (E versus S0), stellar luminosity, or environment.

As in the recent volume-limited surveys of early-type galaxies, there is a clear correlation with environment and HI. All of the HI-nondetected galaxies reside in group or cluster environments. The galaxy with the smallest detected HI mass (NGC 4150) resides at the edge of the Virgo Cluster where ICM densities are expected to be low.

Overall, the results of these observations are consistent with the recent HI surveys, which also find a mix of HI morphologies and masses, low HI peak surface densities, and a paucity of HI in early-type galaxies which reside in high-density environments.

The fact that all of the isolated field galaxies are detected in HI is consistent with the assumption that once an early-type has obtained some cold gas, it is much easier to hold on to it in low-density environments. The very regular kinematics and highly extended HI disks in UGC 1503 and NGC 5666 imply that their gas systems are relatively old, at least a few orbital timescales (on the order of a few Gyr). NGC 807, NGC 3032, and NGC 3656 show indications that their cold gas has recently been acquired or disturbed. This is good evidence to support the proposition that there is still a significant amount of cold gas in field environments on which early-type galaxies can feed.

The conclusions presented in this work are based on a relatively small sample of galaxies biased toward early-type galaxies known to contain substantial amounts of molecular gas. Clearly, we must extend our analysis to a much larger and more homogenous sample of early-type galaxies.
Figure 25. 0949+2935: individual channel maps showing H\textsc{i} emission. Contour levels are −5, −3, 3, 5, 6.5, 6.8, 7.2, and 7.4 times 0.6 mJy beam$^{-1}$~$\sim$~1σ. Negative contours are gray. The velocity of each channel (in km s$^{-1}$) is indicated at the top of each panel and the beam size in the first panel in the bottom left corner.

We thank the reviewer for his/her thorough review and highly appreciate the comments and suggestions, which significantly contributed to improving the quality of the publication. We are grateful to Jacqueline van Gorkom for providing the H\textsc{i} map and of NGC 3656 as well as Raffaella Morganti and Tom Oosterloo for providing the WSRT H\textsc{i} map and image cube for NGC 4150. This work is based on observations collected with the Very Large Array operated by the National Radio Astronomy Observatory. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has also made use of the NASA/IPAC Extragalactic database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This work is partially supported by NSF grants AST-0507432 and AST-1109803.

Facility: VLA

APPENDIX

H\textsc{i} DETECTION OF SOURCES IN THE VICINITY OF NGC 2320 AND NGC 3032

In this section, we report new VLA observations of several H\textsc{i} sources detected in the fields of NGC 2320 and NGC 3032. H\textsc{i} images, spectra, velocity fields, and individual channel maps can be found in Figures 20–26. The properties of the H\textsc{i} detections for these sources can be found in Table 6. A description of the data reduction can be found in Section 3. All of these field
sources are outside the field of view the BIMA CO observations of Young (2002, 2005) and Young et al. (2008).

A.1. NGC 2321

NGC 2321 is classified as a barred spiral galaxy in the RC3 catalog. NGC 2321 is also a likely member of the A596 cluster as its systemic velocity (6318 km s\(^{-1}\)) is well within the velocity dispersion of that cluster (∼300 km s\(^{-1}\)). NGC 2321 is about 10′ from NGC 2320 and about 8′ from the cluster center in projection.

Figures 20 and 21 show the integrated intensity, the \(\text{H} \text{l}\) spectrum, velocity map, and the individual channel maps. The total \(\text{H} \text{l}\) flux is \(2.6 \pm 0.3\) Jy km s\(^{-1}\), which translates to an \(\text{H} \text{l}\) mass of \(4.1 \times 10^9\) \(M_\odot\). The \(\text{H} \text{l}\) emission is detected over \(301 \pm 11\) km s\(^{-1}\) centered on a systemic velocity of \(6316 \pm 11\) km s\(^{-1}\), which gives a circular velocity of \(V_{\text{circ}} \sin i = 151\) km s\(^{-1}\). This flux is consistent with single-dish \(\text{H} \text{l}\) observations made with the meridian transit Nancay radiotelescope (Theureau et al. 1998) which quote an \(\text{H} \text{l}\) flux of \(2.3 \pm 1.0\) Jy km s\(^{-1}\).

The channels maps show the characteristic butterfly pattern, and so the \(\text{H} \text{l}\) is probably distributed in a disk in
semi-regular rotation. The H\textsc{i} is not centrally peaked, but peaks inside the disk. In the northeastern part of the disk there is a marginally resolved region of what appears to be H\textsc{i} in absorption (peak $-68$ Jy beam$^{-1}$ km s$^{-1}$ at R.A. $7^h55^m59^s.0$, decl. $50^\circ45^\prime22^\prime.3$). However, there is no evidence of any continuum source at the position of the absorption. There is a 2.9 mJy source listed in the NVSS about 1.4' to the northeast (Condon et al. 1998), which is clearly visible in a radio continuum map made from the new VLA data, but cannot be associated with the absorption. An inspection of the channel maps shows that there is significant negative emission in only two channels, and these channels are quite far apart in velocity space. We conclude that the negative emission is a 5σ artifact due to problems with imaging a source that is located significantly far from the pointing center and continuum subtraction (similar to those of NGC 4459, see Section 3). We attempted to use various other continuum subtraction techniques, but are unable to produce a data cube without the artifact. It is surprising that all of the flux is recovered, despite the artifact.

A.2. KUG 0950+295 and DS96 0949+2935

We detect three distinct sources of H\textsc{i} emission about 12' to the northeast of NGC 3032 in projection. These include the following.

KUG 0950+295. Classified as an irregular galaxy in the RC3 catalog, it is located 13' to the northeast of NGC 3032 in projection. The total H\textsc{i} flux is 0.94 ± 0.10 Jy km s$^{-1}$, and it is detected over 100 ± 11 km s$^{-1}$ centered on a systemic velocity of $1650$ ± $11$ km s$^{-1}$, which gives a circular velocity of $V_{\text{circ}} \sin i = 50$ km s$^{-1}$. This flux is consistent with single-dish H\textsc{i} observations made with the 100 m radio telescope at Effelsberg, which quote an H\textsc{i} flux of $1.2$ Jy km s$^{-1}$ detected over 90 km s$^{-1}$ centered on a systemic velocity of $1638$ ± $8$ km s$^{-1}$ (Huchtmeier et al. 2000). We derive a distance of 22 Mpc using the systemic velocity derived from the 100 m observations and $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$. Using this distance and our flux we calculate an H\textsc{i} mass of $1.1 \times 10^8 M_\odot$. The H\textsc{i} in this galaxy is centrally peaked. As in NGC 3032 the H\textsc{i} distribution is only a few beams across and so is not well resolved. An inspection of the H\textsc{i} velocity field shows that the emission exhibits solid body rotation with only a slight suggestion of becoming flat near the outer parts of the H\textsc{i} distribution.

DS96 0949+2935. The H\textsc{i} emission associated with DS96 0949+2935 has a double horned H\textsc{i} profile indicative of a rotating disk galaxy, but only a few faint features are visible in the POSS2 images. We detect three distinct sources of H\textsc{i} emission located 13' to the northeast of NGC 3032. We attempted to use various other continuum subtraction techniques, but are unable to produce a data cube without theartifact. It is surprising that all of the flux is recovered, despite the artifact.

Table 6

| Galaxy     | Morph | R.A. (J2000) | Decl. (J2000) | $V_{\text{helix}}$ (km s$^{-1}$) | $D$ (Mpc) | $S_\text{H}$,H (Jy km s$^{-1}$) | $M$(H\textsc{i}) ($\times 10^8 M_\odot$) |
|------------|-------|-------------|--------------|---------------------------------|-----------|-------------------------------|----------------------------------|
| NGC 2321   | SBa   | 07h55m59s.0 | 50$^\circ$45$^\prime$22$^\prime$.3 | 6318(13) | 87 | 2.3(0.2) | 41 |
| KUG 0950+295 | Irr   | 09h52$^m$57.3 | 29$^\circ$18$^\prime$38$^\prime$.4 | 1628(42) | 22 | 0.94(0.10) | 1.1 |
| DS96 0949+2935 | dwarf | 09h52$^m$43.8 | 29$^\circ$20$^\prime$53$^\prime$.9 | 1456(16) | 20 | 1.20(1.1) | 1.1 |
| Unknownb   | ?     | 09h52m52.2   | 29h21m08s.3   | 1602(10) | 22 | 0.20(0.02) | 0.23 |

Notes. Morphological types, positions, and systemic velocities are taken from NED if available. The distance is calculated from the systemic velocity and $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$. No correction is made for the presence of helium or inclination effects in the H\textsc{i} masses.

b Position and systemic velocity measured from the H\textsc{i} line from the VLA C array observations presented in this paper.

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