THE COOL INTERSTELLAR MEDIUM IN ELLIPTICAL GALAXIES. II. GAS CONTENT IN THE VOLUME-LIMITED SAMPLE AND RESULTS FROM THE COMBINED ELLIPTICAL AND LENTICULAR SURVEYS

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ABSTRACT

We report new observations of atomic and molecular gas in a volume-limited sample of elliptical galaxies. Combining the elliptical sample with an earlier and similar lenticular one, we show that cool gas detection rates are very similar among low-luminosity E and S0 galaxies but are much higher among luminous S0s. Using the combined sample we revisit the correlation between cool gas mass and blue luminosity which emerged from our lenticular survey, finding strong support for previous claims that the molecular gas in ellipticals and lenticulars has different origins. Unexpectedly, however, and contrary to earlier claims, the same is not true for atomic gas. We speculate that both the active galactic nucleus feedback and merger paradigms might offer explanations for differences in detection rates, and might also point toward an understanding of why the two gas phases could follow different evolutionary paths in Es and S0s. Finally, we present a new and puzzling discovery concerning the global mix of atomic and molecular gas in early-type galaxies. Atomic gas comprises a greater fraction of the cool interstellar medium in more gas-rich galaxies, a trend which can be plausibly explained. The puzzle is that galaxies tend to cluster around molecular-to-atomic gas mass ratios near either 0.05 or 0.5.

Key words: galaxies: elliptical and lenticular, cD – galaxies: ISM

1. INTRODUCTION

With this paper, we conclude our surveys of atomic and molecular gas in volume-limited samples of elliptical and lenticular galaxies (S0s: Welch & Sage 2003; Sage & Welch 2006; Es: Sage et al. 2007, Paper I). The prime motivation for our work has been to address the long-standing mystery of why those kinds of galaxies typically have much less cool gas than their stars have returned over the last 10 Gyr. We have accepted the penalty of long integration times in order to finesse possibly serious biases in earlier studies—toward optically luminous galaxies and/or those already known or suspected to contain large amounts of gas—and also in order to probe for cool gas at mass limits far below those implied by our current understanding of stellar evolution.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Data from the GBT and IRAM 30 m Telescopes

The properties of the sample have been described in Paper I. The 22 H\textsc{i} spectra presented here were recorded at the NRAO Robert C. Byrd Green Bank Telescope (GBT)5 in 2007 April. At the frequency of the 21 cm hyperfine transition the GBT has FWHM = 8.7. Sensitivity limits were designed to provide 5σ detections, or upper limits, of 0.02\,M\odot, where M\odot is the mass of gas returned within a 10 Gyr old galaxy according to Faber & Gallagher (1976). Observations were conducted in seven 2–9 hr sessions between April 21 and 28. Each session included flux calibration on either 3C 48 or 3C 286 and a scan of a spiral galaxy with strong H\textsc{i} emission. Calibration observations were omitted during two sessions which immediately followed another program using the same backend setup. The observing unit was a standard on–off sequence in which 150 s each were spent on the source and nearby sky. Off positions were located either one-half degree east or west of the galaxy to avoid spurious emission from objects known from the NASA Extragalactic Database to be at a similar redshift. Data were reduced with GBTIDL following standard procedures. Occasional bad scans were deleted and noise spikes removed. The baseline on each summed, smoothed spectrum was defined by a window from 2000 to 4000 km s\textsuperscript{−1} wide, except 1000 km s\textsuperscript{−1} wide in the case of UGCA 298. The baseline window was centered on the galaxy optical velocity whenever possible, but was shifted to avoid Galactic foreground emission for low-redshift objects. The line window (Column 2 in Table 1) was chosen to include visible emission, otherwise it was centered on the systemic velocity and its width set equal to twice the measured stellar velocity dispersion. First- or second-order polynomial fits were generally found to be satisfactory, although fourth-order fits were made in the case of NGC 584, 636, 1172, and 4125. Spectra were binned to 5.12 km s\textsuperscript{−1} resolution.

In 2007 June, the IRAM 30 m Telescope on Pico Veleta, Spain was used to search 24 galaxies for CO emission in the J = 1–0 and J = 2–1 transitions. The telescope has FWHM = 21′′ and 11′′, respectively, at the frequencies of those transitions. Single pointed observations were made in all cases. Sensitivity requirements on the J = (1–0) transition were derived using the same criterion as for the GBT sessions, and the observing procedure followed the same pattern as in previous visits to the 30 m Telescope (Welch & Sage 2003). CLASS was used for data reduction, and standard procedures explained in our earlier papers were followed. A linear baseline was subtracted from each summed scan, and line windows were defined in the same way as for the H\textsc{i} data. Final spectra were binned to resolutions...
of 10.4 km s\(^{-1}\), except 13 km s\(^{-1}\) in the case of the CO(1–0) spectra of NGC 821 and NGC 4308.

Figure 1 shows the final, baseline-subtracted spectra. We have included a few CO spectra from Paper I in order to facilitate comparison with the new H\(_{\text{I}}\) observations. A summary of the measurements made from the new data is presented in Table 1.

### 2.2. The Impact of Differing Telescope Beam Sizes

The beam sizes of the H\(_{\text{I}}\) and CO observations are very different (9’ and 21'' for H\(_{\text{I}}\) and CO(J = 1–0), respectively). Naturally, then, these data are not appropriate for comparisons of local H\(_{\text{I}}\) and H\(_{2}\) surface densities. We believe, however, that they can be used to determine total gas masses with accuracies sufficient for the purposes of this investigation. H\(_{\text{I}}\) emission in local elliptical and lenticular galaxies has been mapped with the Very Large Array and Westerbork Synthesis Radio Telescope by Sage & Welch (2006), Morganti et al. (2006), and Oosterloo et al. (2007). H\(_{\text{I}}\) maps of four low-luminosity ellipticals have been published by Lake et al. (1987). The detected gas is usually several arcminutes (several tens of kiloparsecs) in diameter.

In the case of very gas rich systems or systems with close companion galaxies (our selection criteria generally exclude the latter) the atomic gas extends up to 10' in diameter. Inspecting maps published in the above works indicates that the GBT (median beam diameter \(\sim 50\) kpc for our E and S0 galaxies) would see most of the emission in most cases, especially in low-luminosity galaxies, although quantifying that impression is difficult. The Arecibo Telescope (median beam diameter \(\sim 15\) kpc for our samples) has been used by ourselves (Sage & Welch 2006) to measure \(M(H_1)\) in six galaxies, and by several previous workers whose results we have included. It is possible that Arecibo has missed appreciable emission in a few galaxies, but we lack interferometer observations to quantify the situation.

Turning to the molecular phase, the regions sampled by the 30 m Telescope have median diameters of 1.8 and 1.7 kpc for E and S0 galaxies, respectively. As part of our lenticular survey (Welch & Sage 2003) unpublished CO observations at several positions across five galaxies (NGC3607, NGC4150, NGC4310, NGC4460, and NGC5866) were made with the 30 m Telescope. It was found that the central pointing accounts for about half...
Figure 1. CO and H\textsc{i} spectra from the IRAM 30 m Telescope and the GBT, respectively. Arrows indicate the optical systemic velocity from NED, and horizontal lines show the velocity range over which the integrated line intensity was calculated in all spectra.
Figure 1. (Continued)
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(median value 57%) of the total emission seen at all positions. That result is consistent with comparisons by one of us (Young) of 30 m fluxes with interferometer maps (Young 2002, 2005; Young et al. 2008) of CO emission in a number of E and S0 galaxies. Consequently, we believe that the values of \( M(H_2) \) presented in the present work can be taken to represent the total molecular gas mass to within a factor of \( \leq 2 \).

Thus, even though the beam sizes for \( \text{H}_1 \) and CO are quite different, they are reasonably well suited to the goal of detecting all, or nearly all, of the atomic and molecular emission. The atomic gas is certainly present on much larger physical scales than the molecular gas, but this is compensated to some degree by corresponding differences in beam size. Current heterodyne arrays such as HARP on the James Clerk Maxwell Telescope and HERA on the IRAM 30 m Telescope could be used to improve our understanding of beam size effects by mapping the strongest sources in the CO(3–2) and CO(2–1) lines, respectively. At present, though, we have no evidence for a luminosity trend in the relative extent of atomic and molecular gas, and do not anticipate systematic biases introduced by the differences in beam size.

3. RESULTS

3.1. Status of Our Search for Cool Gas

The present survey, like our earlier one of lenticular galaxies, differs from previous work in two ways. First, the samples are volume limited, and are not biased toward objects already known or suspected to be gas rich. While Malmquist bias is almost certainly still present, we have reduced it as much as possible given the state of our knowledge of nearby early-type field galaxies embodied in the Nearby Galaxies Catalog (Tully 1988) and the Third Reference Catalogue of Bright Galaxies (RC3; de Vaucouleurs et al. 1991). Second, current understanding of stellar evolution is used to fix sensitivity limits, mandating long integration times for low-luminosity galaxies. Our goal in both surveys has been to collect in every case, either from the literature or from new telescope sessions, observations of molecular and atomic gas sufficiently sensitive to detect ~1% of the gas predicted to be returned by stars during the past 10 Gyr.

One galaxy, Haro 20, still lacks CO observations to our knowledge, while only NGC 4627 has apparently not been searched for atomic hydrogen. We have not attempted to derive an upper limit on the \( \text{H}_1 \) content of Maffei 1 from the early, insensitive observation of that galaxy (Spinrad et al. 1971). Because the selection criteria for the present work do not exclude nearby companions (unlike our earlier study of lenticulars) there are a few cases where the low spatial resolution of single-dish observations at 21 cm hinders the attribution of the detected atomic gas to individual galaxies—an important problem when attempting to understand the fate of internally recycled material. Cases of severe confusion include NGC 3226 (Huchtmeier 1994), where nearby NGC 3227 (type Sa) is also in the telescope beam. Likewise, an unknown fraction of the atomic gas found near NGC 7464 (Li & Seaquist 1994) must be attributed to neighboring NGC 7465. We therefore treat NGC 3226 and NGC 7464 as \( \text{H}_1 \) non-detections despite the fact that \( \text{H}_1 \) has been clearly seen toward both of them. We also exclude those two galaxies when making statistical comparisons with our lenticular galaxy sample. Finally, we note that NGC 7468, which was briefly discussed in Paper I, continues to stand out for its large quantity of atomic gas.

### Table 2

| Type | Atomic Hydrogen | Molecular Gas |
|------|-----------------|---------------|
|      | Present % | Knapp N/ % | Present % | Knapp N/ % |
| E    | 19        | 27          | 54        | 64          |
| E/S0 | 67        | 17          | 31        | 26          |
| S0   | 57        | 21          | 103       | 103         |

**Notes.** Columns list the morphological type from Sandage & Bedke (1994) when available, otherwise from de Vaucouleurs et al. (1991), and the percent of galaxies detected in our combined S0 and elliptical surveys or listed by Knapp (1999) out of a total of N galaxies. Columns 2–5 concern \( \text{H}_1 \) detections, while CO detections are summarized in Columns 7–10.

3.2. Comparisons with Previous Studies

We have located published \( \text{H}_1 \) and CO observations of 13 and 8 galaxies, respectively, in the present survey. The majority of the \( \text{H}_1 \) overlap comprises objects fainter than \( M(B) = −19 \), some with early, insensitive observations. The present \( \text{H}_1 \) measurements are consistent with published ones in all instances. Improvements in detector technology, and our observational practice of scaling the detection limits with luminosity whenever possible, has resulted in new detections or much lower limits on gas content in those cases.

The new CO data are consistent with literature values for the majority of galaxies previously observed; only two cases of disagreement deserve comment. Wiklind et al. (1995) report an IRAM 30 m Telescope detection of NGC 4125, finding \( l(1–0) = 2.5 \text{ K km s}^{-1} \) (without a stated uncertainty) over a 400 \text{ km s}^{-1} emission feature. We do not detect that galaxy, measuring \( l(1–0) = 0.74 \pm 0.44 \text{ K km s}^{-1} \) by integrating over a similar velocity range. The other case, NGC 4278, has been observed by Combes et al. (2007), who report detecting emission at both \( J = 1–0 \) and \( J = 2–1 \) at roughly 5\( \sigma \) using the same telescope but with more sensitive data than ours. We do not confidently detect NGC 4278 in either transition, although the two measurements of \( l(1–0) \) are consistent at the combined 1\( \sigma \) level. Very recently Crocker et al. (2010) reports that the Plateau de Bure Interferometer has failed to detect \( J = 1–0 \) emission from NGC 4278, setting an upper limit equivalent to 0.49 \text{ K km s}^{-1} at the 30 m Telescope, i.e., roughly 1.6\( \sigma \) below our weak detection. It does not appear, therefore, that the \( J = 1–0 \) transition in NGC 4278 has yet been reliably measured. Our upper limit on the \( J = 2–1 \) transition for NGC 4278 is approximately one-third of the 4\( \sigma \) measurement published by Combes et al.

3.3. Cool Gas Detection Rates

3.3.1. Global Detection Rates Among E and S0 Galaxies

From the volume limited lenticular and elliptical samples (i.e., Welch & Sage 2003; Sage et al. 2007 and the present work) we have distilled subsets classified as E (27 galaxies), E/S0 (7), S0 (21), S0/ Sa (8), or uncertain (10), using classifications from the Carnegie Atlas (Sandage & Bedke 1994) when available, otherwise from the RC3. To reduce the effects of different selection criteria we omit the two elliptical sample members with companions (see above); all types listed as uncertain are likewise excluded. All further references to morphological type issues in this paper will be to the remaining subsets unless otherwise indicated. We emphasize that they encompass our
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Atomic Hydrogen. It is surprising that our surveys detect atomic hydrogen more frequently than previous ones, since Knapp (1999) finds that large IRAS fluxes correlate with increased H\(_1\) detection rates among early-type galaxies. That
may simply be due, however, to our efforts to achieve greater sensitivity among fainter galaxies. We find both H$\alpha$ and CO more frequently among lower luminosity galaxies (see below) whereas Table 2 lumps together all luminosities.

**Carbon Monoxide.** Given the bias of previous studies, the fact that we find a somewhat lower CO detection rate among ellipticals is consistent with the strong correlation between CO and FIR flux in early-type galaxies (Knapp 1999). Our detection rate of 26% is essentially the same as the those reported by Knapp & Rupen (1996) from elliptical samples having IRAS 100 $\mu$m fluxes of 1.5 Jy or less (their Table 5). We caution against ascribing much significance to that agreement, however, partly because of the luminosity dependence of detection rates. Also, although we omit “uncertain” classifications, the remaining uncertainties in Carnegie/RC3 types could significantly alter the rates in Table 2. Adding all six E/S0 galaxies to type E, for example, would increase H$\alpha$ and CO detection rates to 27% and 64%, respectively.

The present observations are consistent with the result in Paper I that the 30 m Telescope more frequently detects CO(2–1) among lenticulars than ellipticals, which was derived by comparing members of our original lenticular and elliptical samples. We focus now on types E, E/S0, and S0 as defined above, and on cases where either or both of the $J = 1–0$ and $J = 2–1$ transitions have been detected at 3$\sigma$ or higher, and thereby find 2–1 detection rates of 10/10 galaxies = 100% among S0s, 3/3 galaxies = 100% for type E/S0, and 3/5 galaxies = 60% among ellipticals. The statistics of small numbers suggests caution when extrapolating those results. Furthermore, selection effects are present at some level, because the 2–1 spectra from our elliptical survey are a bit noisier than spectra in the same transition from the lenticular study, thereby lowering detections among ellipticals—recall that our sensitivity requirements are translated into noise limits on $J = 1–0$ spectra.

We point out in Paper I that lower 2–1 detection rates could indicate that ellipticals contain cooler and/or less centrally concentrated molecular gas than S0s. That conclusion, though, is not supported by Figure 2, an update of Figure 2 in Welch & Sage (2003), which compares the intensities in the two transitions.

### 3.3.2. The Luminosity Dependence of Detection Rates

Ignoring possible luminosity differences, the results in Table 2 support the long-held opinion that cool gas is more difficult to find in elliptical galaxies than in lenticulars. Accounting for luminosity reveals the more nuanced perspective shown in Figure 3. Cool gas is indeed much more likely to be found in lenticulars than in ellipticals, but only when comparing luminous galaxies. In contrast, low-luminosity objects are very likely to contain detectable amounts of cool gas, be they type E or S0, which is consistent with previous H$\alpha$ (Lake & Schommer 1984) and CO (Lees et al. 1991) surveys. The puzzles, then, are why low-luminosity objects are easier to detect, and why gas is found more frequently among luminous early-type galaxies with robust disks. We now consider possible explanations.

### 3.3.3. Explanations for Variations in Detection Rates

The trends shown in Figure 3 are unlikely to reflect environmental effects because our selection criteria exclude galaxies within clusters. Likewise our target sensitivities, which scale with absolute luminosity, cannot produce different detection frequencies for samples of similarly luminous galaxies. Early discussions of internal processes which might favor accumulation of cool gas in lower luminosity systems (Faber & Gallagher 1976; Lake & Schommer 1984) were based on the reasoning that red giant ejecta would, if well mixed, be heated to only modest temperatures because of the small stellar velocity dispersion. The cooling time of such material might therefore be short enough to allow most of it to form dense clouds which would be more difficult for the occasions supernova to push out of the galaxy. Efforts to follow the evolution of red giant outflows (Parriott & Bregman 2008) have focused on the net...
effects of energy transfer between the ejected gas and a hot ambient medium without incorporating supernova events. The growth of a central complex of cool gas and dust remains generally plausible. More significant for the question of luminosity effects, though, is that Parriott & Bregman do not find that ejecta from slower moving red giants (i.e., denizens of less massive galaxies) are able to cool more efficiently. Another possibility, that increased rotational support among low-luminosity systems could be linked to higher detection rates, is not supported by the work of Brighenti & Mathews (1997).

We have speculated in Paper I about the role of active galactic nucleus (AGN) feedback in the evolution of the cool interstellar medium (ISM). A variety of recent theoretical and observational work (e.g., Bower et al. 2006; Kauffmann et al. 2008; Cattaneo et al. 2009; Kormendy et al. 2009) has raised the possibility that the AGN feedback paradigm, which emerged from efforts to address the cooling flow problem in X-ray galaxy clusters, might be extended to individual galaxy scales. Although many details remain to be worked out, the emerging picture is that cooling at the center of a hot halo stimulates AGN activity. The resulting outflow reheat the halo, cutting off the supply of fuel to the active nucleus and presumably helping destroy clouds of atomic or molecular gas throughout the galaxy. The presence of a massive hot halo, then, decreases the likelihood of finding cool gas. An explanation for the luminosity trend in Figure 3 emerges naturally from such a picture because of the well-known scaling relation between the luminosities of X-ray halos and of the stars in the host galaxy (e.g., Canizares 1987; O’Sullivan et al. 2001). Without enough hot gas to promote AGN feedback, a low-luminosity E or S0 galaxy would be more likely to retain cool gas.

How might a disk component give rise to a higher detection rate? One possibility, that supernova explosions are less effective at removing cool gas in flatter galaxies, is not supported by the work of D’Ercole & Ciotti (1998). The AGN feedback paradigm may offer a promising line of attack, because S0 galaxies are significantly dimmer in X-rays than ellipticals of similar luminosity (Esquivel et al. 1995). Therefore, even bright lenticulars perhaps lack the massive hot halos needed to transfer energy to the cool ISM. Furthermore, and regardless of galaxy luminosity, gas returned within a high angular momentum disk environment might be more likely to settle into an extended, dense sheet able to survive heating by surrounding X-ray gas.

It is widely accepted that early-type galaxies have formed through a series of mergers. Does the merger paradigm identify what processes might reduce detection rates among more luminous galaxies? Objects resembling field ellipticals (e.g., Naab et al. 2006; Kang et al. 2007) aimed at identifying the cause of the well-known dichotomy of ellipticals, namely that luminous galaxies usually rotate slowly and have boxy isophotes whereas faint ones tend to be rapid rotators with disky isophotes. It seems that boxy galaxies are the common outcome of so-called dry (i.e., nearly gas-free, with $M_{\text{gas}}/M_{\text{stars}} \lesssim 0.1$) mergers, while (wet) mergers of gas-rich disks generate objects resembling elongated, rotationally supported ellipticals or lenticulars. AGN feedback does not play an important role in generating the dichotomy (Kang et al. 2007; Naab et al. 2007). Wet mergers probably spark bursts of star formation, yet since stars form very inefficiently the resulting galaxy would likely contain a significant amount of gas. In the merger paradigm, then, the luminosity trend in Figure 3 could arise because more mergers are needed to build luminous galaxies, but each merger reduces the gas content of the resulting object. In this picture, mergers between a few luminous gas rich disks could produce modern luminous lenticulars, which would then be expected to contain more gas than their elliptical counterparts. Interestingly, Bois et al. (2010) find that the outcomes of wet merger simulations are strongly resolution dependent, and such events might after all be able to produce slowly rotating elliptical galaxies. One might then ascribe low detection rates among luminous ellipticals to stellar feedback acting on the cool ISM.

In summary, we believe that both the currently developing paradigms of AGN feedback and the formation of early-type galaxies in mergers offer useful insights into the causes of the detection frequencies shown in Figure 3.

3.4. Observational Evidence on the Origin of the Cool Gas in Early-type Galaxies

3.4.1. Cool Gas Masses

One of the most striking results from our earlier lenticular survey (e.g., Figure 12 of Sage & Welch 2006) is a cutoff of the form $\log(M_{\text{obs}}) \sim 0.2 \times \log(L_B)$ in the total mass of cool gas present, in which $M_{\text{obs}} = 1.4 M_{\text{H I}} + M_{\text{H_2}}$ is the observed mass of atomic and molecular gas and $L_B$ is the total blue luminosity. Subsequent work has not clearly confirmed that feature. A similar cutoff was suggested in our preliminary report on the elliptical sample (Figure 2 of Paper I), but is not obvious when the full sample is considered (Figure 4(a)). On the other hand, an upper cutoff appears to be present in the combined sample (Figure 4(b)). That impression is greatly enhanced, however, by two galaxies at the low-luminosity end of the plot. The current situation, then, is that the cutoff is uncomfortably sample dependent. Sensitive observations of additional low-luminosity galaxies will help settle the question.

We now turn attention to the entire mass range covered by the data. Early work on the distributions of $M_{\text{H I}}$ (Knapp et al. 1985; Wardle & Knapp 1986) and, separately, of $M_{\text{H_2}}$ (Lees et al. 1991) in generally FIR-biased samples has uncovered significant differences between E and SO galaxies, which presumably arise because the two phases originate in different ways in these galaxy types. Does the picture change when comparing volume limited samples? In the spirit of previous investigators we seek to answer that question using the Kaplan–Meier cumulative distribution function (CDF), which is appropriate for samples containing upper limits (Feigelson & Nelson 1985). The value of CDF($x$) is the expected fraction of the sample in which the value of some parameter $x$ is less than $X$. We have carried out the calculations using two independent software packages: ASURV version 1.3 (Icose & Feigelson 1990) and R (R Development Core Team 2009), finding essentially the same results. Tests such as log-rank or Kolmogorov–Smirnov are used to compute the likelihood that two CDFs are drawn from the same parent population—the R package employs log-rank and the Peto-Prentice modification of the Wilcoxon test on two censored data sets (Feigelson & Nelson 1985 and references therein).

Figure 5 compares CDFs generated by R for E and SO galaxies. They are derived from mass estimates alone (left
panels) and from masses scaled by the predictions of stellar mass return \( M(\text{pre}) \), Ciotti et al. 1991, right panels); the scaling is equivalent to dividing by \( L_B \). In light of earlier work some results are unexpected, and independent of scaling. The CDFs of \( M(H_1) \) (middle two plots), which overlap in places, are likely to have been drawn from the same parent populations with probabilities of 15%–20%, depending on the method used to compare the two functions. Thus we do not rule out the proposition that E and S0 galaxies have the same cumulative mass distributions of atomic hydrogen. That result might in fact be reasonable if we are correct in speculating that much of the \( H_1 \) in both galaxy types has fallen in from a surrounding reservoir. One might then expect the mass of the reservoir and its central galaxy to be at least roughly proportional regardless of optical morphology.

On the other hand, the distributions of \( M(H_2) \) are clearly quite different, especially among higher masses. The probabilities that the two samples come from the same parent population are 2%–4%. We therefore support the work of Lees et al. (1991) which points toward different evolutionary histories for the molecular ISM components in E and S0 galaxies.

If only the total cool ISM is considered (bottom two panels in Figure 5) then the CDFs of E and S0 types are again rather similar, which probably reflects the fact that typically most of the cool ISM is atomic gas. We find probabilities of 8%–26% that the two cool gas distributions come from the same parent population.

3.4.2. Molecular to Atomic Gas Mass Ratios

We have previously (Sage & Welch 2006; Sage et al. 2007) reported tentative evidence that the mix of atomic and molecular phases in galaxies with increasing amounts of cool gas, be they ellipticals or lenticulars, tends to shift in favor of \( H_1 \). Adding more data makes the trend, shown in Figure 6, more convincing. Partly because of our decision to use Carnegie/RC3 morphological types, earlier indications of an offset between ellipticals and lenticulars has disappeared. The paucity of data continues to hinder attempts to compare the distributions of molecular to atomic gas mass ratios in Es and S0s. Lees et al. (1991) find no reliable difference between the two distributions, while an analysis similar to that described above returns probabilities of \( ~40% \) that our samples of \( M(H_2) / M(H_1) \) have been drawn from the same parent population. More detections are needed before any meaningful difference appears.

Perhaps the most striking aspect of Figure 6 is the presence of two clumps separated by roughly an order of magnitude along both axes. We refer to the clump centered near \( M(\text{obs}) / M(\text{pre}) = 0.1, M(H_2) / M(H_1) = 0.05 \) as gas rich, and to the one centered at roughly \( (0.005, 0.5) \) as gas poor. Overplotted curves of constant \( M(H_2) / L_B \) and \( M(H_1) / L_B \) reveal that the separation is mostly caused by differences in \( H_1 \) content. The outstandingly \( H_2 \)-rich outlier near the top of Figure 6 is NGC 3607 whose striking central dusty and CO-rich disk(s?) presents a fascinating challenge for ideas of cool ISM origins (Welch & Sage 2003; Lauer et al. 2005). The reader will note that the seven \( H_1 \) non-detections are contained in the gas-poor group while all three CO non-detections are members of the gas-rich clump. We do not believe that fact can be ascribed to significantly different \( H_1 \) and CO sensitivities because achieving similar sensitivities in the two phases has been a goal of our observing strategy (Section 2).

Low-luminosity galaxies are known to be relatively gas rich. We search for a possible luminosity difference between clump members by arbitrarily defining the clumps as containing the 17 galaxies toward the top left in Figure 6 (excluding NGC 3607) and the remaining 13 galaxies toward the bottom right, arriving at the memberships shown in Table 4. The two luminosity distributions are shown in Figure 7. Gas-rich clump members are indeed fainter by the equivalent of 0.7 mag in the mean. The difference, however, is significant at only 1.2 times the combined standard deviation of the means. The Kolmogorov–Smirnov test indicates a probability of 18% that the two samples are drawn from the same parent population, which we interpret as only weak support for the hypothesis that the two distributions differ.

3.4.3. Speculations on the Origin of the Gas

Differences in global kinematics and morphology motivated our suggestion (Sage & Welch 2006) that internal processes such as cooling flows produce most of the molecular gas we find,
Figure 5. Comparisons of the Kaplan–Meier cumulative distribution functions (CDFs) for the atomic, molecular, and total cool gas content of galaxies in the combined surveys, and classified E or S0 in the Carnegie Atlas or RC3. Dotted lines around each CDF trace the 95% pointwise confidence intervals. Insets give the probabilities that the two data sets have been drawn from the same parent population, and are derived using the log-rank and Peto-Prentice tests. Masses are in solar units.

while much of the H\textsubscript{i} has fallen in. Are the results described above at least consistent with those ideas?

An explanation for why ellipticals and lenticulars might share a common CDF for atomic gas but have different CDFs for molecular gas (Figure 5) can be found by returning to our speculation that AGN feedback might produce different detection rates among bright galaxies (Figure 3). We propose that the efficiency of whatever process couples AGN outflow energy to the cool ISM is linked to the galaxy type by angular momentum considerations, i.e., a greater tendency for returned (and therefore presumably H\textsubscript{2}-rich) gas in lenticular galaxies to settle into highly flattened disks. For example, simple geometry suggests that a highly collimated outflow might not often impact a thin sheet of gas. On the other hand, the morphology of the central galaxy might have little connection to the distribution of any infalling gas, which we postulate is mostly H\textsubscript{i}. In that case, the influence of AGN outflows on atomic gas would be similar in Es and S0s, but the outflows would be more effective at removing molecular gas from Es than from S0s.

Merger simulations have not yet attempted to incorporate the conversion of atomic gas into the molecular phase. The merger scenario, however, does offer a plausible explanation for why more gas-rich galaxies might also be richer in atomic gas. Suppose galaxies start life imbedded in reservoirs of atomic gas, and that various amounts of this material survives subsequent mergers and blowout due to star formation episodes. Perhaps, then, the gas poor clump comprises galaxies which for some reason have failed to draw down their reservoirs, or whose reservoirs have been removed during successive mergers. Capture of varying amounts of reservoir gas would shift such objects along paths of nearly constant $M(\text{H}_2)/L_B$ toward the lower right in Figure 6. Objects which have captured most nearby gas would join the gas-rich clump. It is not clear, though, why reservoir depletion would be the kind of all-or-nothing process needed to produce discrete clumps.

We have searched for other properties besides optical luminosity which might offer clues to the cause of the distribution in Figure 6; references are identified in Table 4. Relevant to the infall scenario, H\textsubscript{i} interferometer observations have been published for nine galaxies, and in eight cases the atomic gas shows evidence of external acquisition; the evidence is equivocal in the case of the ninth galaxy, NGC 7013. Because interferometry
requires high column densities it is perhaps not surprising that all but one galaxy (NGC 1052) occupy the gas-rich clump. More sensitive H i observations of the members of Table 4 are clearly needed.

Returning to optical frequencies, we find that all four galaxies for which published observations suggest previous interactions (e.g., shells, counterrotating stellar components) reside in the gas-poor clump. It seems unlikely that the small clump luminosity difference could lead to a selection effect, but we presently have no other explanation for that curious result.

In summary, published observations of Figure 6/Table 4 galaxies are consistent with the merger paradigm in which interactions among early-type galaxies are common, and with the notion that capturing various amounts of atomic hydrogen could produce the general trend seen in that figure. They do not appear, however, to point toward an explanation for its bimodal nature.

4. SUMMARY AND CONCLUSIONS

We present H i and CO observations of a volume-limited sample of elliptical galaxies, supplementing the earlier work of Sage et al. (2007) on the same sample (Paper I), and of Welch & Sage (2003) and Sage & Welch (2006) on an analogous group of lenticulars. The observations reported here have generally, but not always, strengthened the trends described in Paper I and in our earlier studies of S0s. We now summarize the most significant results from those three investigations and the present one.

1. We do not clearly confirm our earlier finding of an upper cutoff to the mass of cool gas in early-type galaxies (Figures 4(a) and (b)). Settling that question will require additional mass estimates for atomic and molecular gas in galaxies with $L_B \lesssim 10^7 L_\odot$ (Figure 4(b)).

2. Supporting earlier results derived from FIR-biased samples, we find significantly different cumulative mass distributions for molecular gas in E and S0 galaxies (Figure 5). Contrary to previous work, however, we do not rule out the hypothesis that the cumulative distributions of atomic gas are the same.

3. More gas-rich early-type galaxies have lesser proportions of molecular gas (Figure 6). The ratio of molecular to atomic gas mass $M(H_2)/M(H)$ varies by roughly two orders of magnitude, from $\sim 5$ for extremely gas-poor systems to $\sim 0.05$ for the most gas-rich ones. Surprisingly, the variation manifests itself as clumping around quite different...
combinations of gas content and molecular mass fraction. We are presently unable to identify a reason for this striking result.

4. We extend previous work which shows that cool gas is generally easier to find in S0s than ellipticals, by demonstrating that the effect appears primarily among luminous galaxies (Figure 3). Low-luminosity objects of either type are likely to contain detectable quantities of cool gas.

Our surveys of E and S0 galaxies provide a general picture of cool gas in early-type galaxies in low-density environments, which is largely free of the biases present in earlier work. We have explored for the first time the relationship between the two gas phases across a wide range of ISM mass, with results which challenge current ideas of ISM evolution. We speculate on how some of our findings might be explained, finding that both the AGN feedback and merger paradigms offer attractive possibilities. From an observational perspective the central and obvious obstacle to better understanding remains low sensitivity. Despite generous grants of telescope time we have still not glimpsed the cool gas within even most bright ellipticals. Many detections are weak, and the maps required to fully account for gas missed by single pointing observations are not yet available. Finding the gas, and charting its morphology and kinematics across a wide range of optical luminosity, will be the task of the next generation of radio telescopes. Only by taking on that task can we hope to answer the fundamental question of how internal processes compete with external ones to shape what we see. At present the greatest certainties remain the ones which motivated our surveys: Stars in E and S0 galaxies have returned much more gas missed by single pointing observations are not yet available.

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