The HI content of elliptical and lenticular galaxies with recent star formation

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ABSTRACT
As a first step toward constraining the efficiency of the star formation episodes that lead to elliptical (E) and lenticular (S0) K+A galaxies, a survey for HI within a sample of E and S0 K+A galaxies and their likely progenitors (i.e., actively star forming E and S0 galaxies) has been conducted with the NRAO Green Bank Telescope (GBT). The sample was taken from a larger parent sample drawn from the Sloan Digital Sky Survey (SDSS). Here, the GBT data and initial results are discussed. Over half (19 out of 30) of all observed galaxies have detectable 21-cm emission. It was found that both the K+A and star forming early-type (SFE) galaxies were on average more gas poor than disk galaxies at the same luminosity while being more gas rich than more typical E and S0 galaxies with detected 21-cm emission. The gas richness of K+A galaxies appears to be similar to that of SFE galaxies. The star formation rates and estimated star formation time scales of the SFE galaxies imply that they are capable of only marginally changing their atomic hydrogen content. Follow-up observations are required to explore these same issues in terms of molecular gas, which is more likely to actively participate in the star formation process. Kinematic data for the HI gas, the warm ionised gas, and the stars within the galaxies combined with the SDSS g and i band surface brightness profiles imply that the atomic hydrogen is most likely spatially coincident with the star forming regions within $\sim 1$ kpc of the galaxies’ centres.

Key words: galaxies: elliptical and lenticular, cD – galaxies: star-burst – galaxies: ISM

1 INTRODUCTION
Identifying and understanding the processes that drive morphological changes within galaxies is essential to a general understanding of galaxy evolution. Dissipation modulated mergers of similar sized disk galaxies have been shown to be capable of producing spheroidal galaxies similar to observed elliptical galaxies (e.g., Meza et al. 2003, Aceves & Velázquez 2005). Many have argued that as disk galaxies move into and through galaxy clusters, processes such as gas stripping can truncate the star formation activity within the galaxies’ disk components, leading to more bulge-dominated, earlier-type galaxies (e.g., Larson et al. 1981, Gunn & Gott 1972, Nulsen 1982, Abadi et al. 1999). In fact, there is observational evidence that, for instance, the fraction of lenticular galaxies within clusters decreases toward the clusters’ centres while the fraction of disk galaxies decreases (Dressler et al. 1997, van Dokkum et al. 1998). Pasano et al. 2000). The stripping of gas from some disk galaxies falling into clusters has been directly observed (Vogt et al. 2004). For field galaxies, however, processes or events which are capable of stripping gas in a similar manner are rare. If field galaxies evolve along the Hubble sequence to become more concentrated spheroidal galaxies, they most likely do so via some other mechanism.

It is within this context that so called “K+A” (or “E+A”) galaxies may be extremely useful. K+A galaxies are galaxies whose spectra have two dominant components; one that resembles that of a typical early-type galaxy or K giant star and one that resembles that of a main sequence A star. K+A galaxies by definition have extremely weak or no nebular emission lines, implying that they are not currently forming stars. However, the presence of an intermediate age stellar population, usually inferred from strong Balmer absorption lines, implies that these galaxies have formed stars within the last $\sim 1$ Gyr. The initial discovery of and follow-up searches for K+A galaxies identified them as belonging to a cluster population (Dressler & Gunn

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Couch & Sharples (1987), especially at intermediate 
(redshifts (Tran et al. 2004). However, relatively 
large samples of K+A galaxies culled from modern 
spectroscopic surveys such as the Sloan Digital Sky Survey 
(SDSS; York et al. 2000) have revealed that locally $(z<0.2)$, 
the fraction of K+A galaxies tends to be higher in lower 
density environments (Goto 2003; Quintero et al. 2004; 
Hogg et al. 2006; Helmboldt et al. 2007). Imaging data has 
also confirmed that these galaxies tend to be earlier-type 
galaxies with Sersic indexes $\sim$2-3 (Quintero et al. 2004). 
Follow-up imaging has also demonstrated that for the typi-
cal K+A galaxy, the most recent episode of star formation 
occurred within the centre of the galaxy (Yamauchi & Goto 
2003; Helmboldt & Walterbos 2007). These episodes of star 
formation are then capable of changing their host galaxies 
into more centrally concentrated galaxies not by reducing 
the prominence of disk components, as in the case of gas 
stripping, but by increasing the stellar masses/luminosities 
of their centres. Taking all of this information into account, 
it is clear that understanding the processes that trigger and 
halt the star formation that leads to K+A galaxies is an im-
portant step toward understanding how field galaxies may 
evolve along the Hubble sequence.

One integral part of understanding these processes is 
estimating the efficiency of the star formation episodes that 
lead to K+A galaxies. Among galaxies going through bursts 
of nuclear star formation, the most efficient star-bursts are 
capable of exhausting their supplies of gas in $\sim$100 Myr 
(Kennicutt 1998). The majority of these star-bursts are also 
associated with mergers or galaxy-galaxy interactions (e.g., 
Leech et al. 1993; Sanders & Mirabel 1996). Less efficient 
star-bursts are associated with mergers significantly less fre-
quently; the star formation that is found within galaxy disks, 
which is typically driven by internal processes, is even less 
efficient than these bursts (Kennicutt 1998). This implies 
that the enhanced star formation brought about by galaxy 
mergers is the most efficient mode of star formation found 
within galaxies. Estimating the efficiency of the star forma-
tion that leads to K+A galaxies is then crucial to constraining 
the processes that may be driving that star formation.

To obtain a statistical estimate of the star formation 
efficiency, one needs to measure the amount of cold gas 
contained within a sample of K+A galaxies and within a 
sample of their actively star forming progenitors. A sample 
of 335 star forming elliptical (E) and lenticular (S0) galaxies 
with $m_r<16$ taken from the fourth data release of the 
SDSS has been identified by Helmboldt et al. (2007) as 
most likely being a sample of the progenitors of morpho-
logically similar (i.e. E and S0) K+A galaxies. These star 
forming early-type galaxies, or SFE galaxies, were identi-
cified as actively forming stars by their emission line ratios 
using the emission line fluxes measured by Tremonti et al. 
(2004). They were also morphologically classified by visual 
inspection of their SDSS g-band images down to a limit-
ing r-band magnitude of 16. A sample of 253 E and S0 
K+A galaxies with $m_r<16$ were also selected from the 
SDSS. To maximise the K+A sample size, a less stringent 
definition was used than has been used by some authors 
(e.g., Zabludoff et al. 1996; Tran et al. 2004; Goto et al. 
2003), but which is similar to that used by Quintero et al. 
(2004). Formally, it was required that a K+A galaxy have 
$H_\delta_A > 2$ Å and log $W(H\alpha) < 0.11H_\delta_A + 0.15$, where 
$W(H\alpha)$ is the H\alpha emission line equivalent width in units 
of Å measured by Tremonti et al. (2004) and $H_\delta_A$ is the 
spectral index defined by Worthey & Ottaviani (1993) to 
measure the strength of the H\delta absorption line, also in units 
of Å. The values for $H_\delta_A$ were taken from Tremonti et al. 
(2004) and include their corrections for H\delta emission. 
This definition was empirically derived using the location of all 
avtively star forming galaxies and all quiescent early-type 
galaxies within the SDSS with $m_r<16$ (see Fig. I).

It was found that the distributions of masses as traced 
by stellar velocity dispersion were nearly identical for star 
forming E and S0 galaxies and E and S0 K+A galaxies. 
The fractions of these two types of galaxies among all SDSS 
galaxies with $m_r<16$ also depend on environment in nearly 
the same way. Modelling of the star formation histories of the 
star forming E and S0 galaxies implies that their proper-
ties are consistent with episodes of star formation that last 
about 200 Myr on average. This time scale is short enough 
for them to become K+A galaxies. The model prediction for 
the distribution of H\delta absorption line strengths for the star 
forming E and S0 galaxies as they become K+A galaxies is 
neatly identical to that observed for the actual E and S0 
K+A galaxies. Therefore, in addition to being morphologi-
cally similar, the star forming E and S0 galaxies and the E 
and S0 K+A galaxies appear to be linked in a clear evolu-
tionary sequence.

The star forming E and S0 galaxies and the E and S0 
K+A galaxies from the Helmboldt et al. (2007) sample 
provide the opportunity to explore the efficiency of the star 
formation episodes that likely lead to elliptical and lenticular 
K+A galaxies. This is unique to the Helmboldt et al. (2007) 
sample because (i) there is evidence that these two partic-
ular samples, which are relatively large, are evolutionarily 
linked (ii) there are few other known actively star forming 
elliptical galaxies at low redshift (Fukugita et al. 2004) and 
(iii) previous HI measurements for a few actively star form-
ing S0 galaxies are confined to only the most gas-rich objects 
(Pogge & Eskridge 1993). As a first step toward constraining 
the efficiency of the star formation episodes that lead 
to E and S0 K+A galaxies, a survey for neutral hydrogen 
has been conducted with the NRAO Green Bank Telescope 
(GBT) within a subset of star forming and K+A elliptical 
and lenticular galaxies. These observations will provide a 
first look at the cold gas content of these objects and will 
allow for a comparison of the gas richness of each of the two 
galaxy classes to each other and to other types of galaxies. 
This information will be used to select candidates for follow-
up observations aimed at detecting molecular gas which will 
provide a much better estimate of the amount of "fuel" for 
star formation that is available within both classes of galax-
ies. In this paper, the observations, data, and general HI 
properties are presented (§2 and §3) and future follow-up 
observations are discussed (§4).

2 SAMPLE SELECTION, OBSERVATIONS, 
AND DATA REDUCTION

As discussed above, all galaxy targets were selected from the 
Helmboldt et al. (2007) sample of elliptical and lenticular 
star forming and K+A galaxies. The sample was chosen to 
be large enough as to be representative of the parent sample
HI in early-type galaxies with recent star formation

Figure 1. From the fourth data release (DR4) of the SDSS and the measurements of Tremonti et al. (2004), the Hα emission line equivalent width, \( W(Hα) \) (emission is positive), versus the strength of the Hδ absorption line, \( Hδ_A \) (absorption is positive), for galaxies with \( \geq 3\sigma \) detections of Hα and \( m_r < 16 \) (upper). For galaxies with no significant detection of Hα, the upper limit for \( W(Hα) \) is plotted in the lower panel. Early-type galaxies are represented by \( x \)'s; star forming early-type (SFE) galaxies are represented by white circles for elliptical and lenticular galaxies and white triangles for early-type spiral galaxies. Similarly, elliptical and lenticular K+A galaxies are represented by black circles and spiral K+A galaxies are represented by black triangles. Galaxies that were observed with the GBT are highlighted as boxes. In both panels, the definition of K+A galaxies used by Helmboldt et al. (2007) is illustrated by the solid lines.

Data was obtained with the GBT for 30 of the remaining galaxies in August, 2006 (see Table I for a summary), with 7 targets being excluded due to time constraints and their proximity to the sun during the observing run. For all galaxies, the GBT spectrometer was used with a total bandwidth of 12.5 MHz, 16,384 channels, and a central frequency of \( 1420.405(1+z)^{-1} \) MHz where \( z \) is the redshift measured from the SDSS optical spectrum of each target. The expo-
Table 1. Observations

| Name            | UT Date          | Exp. Time (s) | Morph. Type | Spec. Type | \( V_\text{r} \) (km s\(^{-1}\)) | Alt. Name |
|-----------------|------------------|---------------|-------------|------------|----------------------------------|-----------|
| J003823.71+150222.56 | 2006-08-19       | 3438          | S0          | SFE        | 5384                             | UGC 00386 |
| J013214.68-090635.24 | 2006-08-19       | 3438          | E           | SFE        | 5311                             | ...       |
| J013730.83-085307.73 | 2006-08-19       | 1146          | S0          | K+A        | 1797                             | MCG -02-05-026 |
| J015432.72-004612.40 | 2006-08-16       | 4585          | E           | K+A        | 4819                             | ...       |
| J024032.84-080851.65 | 2006-08-16       | 1376          | S0          | K+A        | 1340                             | NGC 1047  |
| J031117.74-084448.04 | 2006-08-16       | 2293          | E           | SFE        | 4004                             | ...       |
| J031651.20+411520.87 | 2006-08-19/20    | 4586          | S0          | K+A        | 1665                             | ...       |
| J032234.54+402118.36 | 2006-08-19/20    | 5733          | S0          | K+A        | 2216                             | ...       |
| J080142.49+251245.08 | 2006-08-20       | 2294          | S0          | K+A        | 4685                             | CGCG 118-049 |
| J083228.05+523022.32 | 2006-08-19       | 2294          | E           | SFE        | 5094                             | MKR 0091  |
| J090244.63+311526.04 | 2006-08-20       | 2294          | E           | SFE        | 4145                             | CGCG 150-062 |
| J102757.13+003002.77 | 2006-08-19       | 2294          | E           | K+A        | 1298                             | MCG +10-15-083 |
| J103901.68+641559.00 | 2006-08-19       | 2294          | E           | SFE        | 1700                             | UGC 05776 |
| J110059.99+525917.88 | 2006-08-19       | 2294          | E           | K+A        | 810                              | ...       |
| J113744.40+542044.52 | 2006-08-19       | 2294          | E           | K+A        | 907                              | ...       |
| J11543.20+590509.59 | 2006-08-19/20    | 4587          | E           | K+A        | 3495                             | SBS 1149+601 |
| J121024.49+131014.16 | 2006-08-19       | 2294          | E           | K+A        | 1691                             | KUG 1207+134 |
| J121548.09+525639.84 | 2006-08-19/20    | 4587          | E           | SFE        | 5441                             | CGCG 269-046 |
| J130658.07+521526.64 | 2006-08-19       | 2294          | E           | K+A        | 4753                             | MCG +09-22-012 |
| J133253.05-011531.14 | 2006-08-19       | 764           | E           | K+A        | 3592                             | CGCG 017-019 |
| J140058.32+553405.16 | 2006-08-19       | 2294          | S0          | K+A        | 1852                             | ...       |
| J140123.99+364000.35 | 2006-08-19       | 2294          | S0          | SFE        | 2706                             | MRK 0465  |
| J140820.65+505240.44 | 2006-08-19       | 2293          | E           | K+A        | 2401                             | ...       |
| J142054.96+400715.59 | 2006-08-19       | 4588          | E           | SFE        | 5273                             | CGCG 219-071 |
| J144425.44+415140.69 | 2006-08-19/20    | 5735          | E           | SFE        | 5300                             | CGCG 219-071 |
| J150747.75+011731.38 | 2006-08-19       | 2293          | E           | K+A        | 2909                             | CGCG 021-011 |
| J160723.27+414232.04 | 2006-08-19/20    | 8029          | E           | SFE        | 5453                             | CGCG 223-041 |
| J210729.75+092113.82 | 2006-08-16       | 2292          | S0          | K+A        | 4136                             | ...       |
| J222730.71-093953.97 | 2006-08-14       | 153           | S0          | SFE        | 1700                             | ...       |
| J225304.56+010839.95 | 2006-08-16       | 2292          | E           | K+A        | 4655                             | NGC 7402  |

sure time used was adjusted for each target by monitoring the rms noise of its spectrum in real time as the galaxy was observed in position switching mode in intervals of 10 minutes on and off the source with the goal of reaching a 3σ detection limit of 10^8 M☉ assuming H⊙ = 70 km s\(^{-1}\) Mpc\(^{-1}\) for a velocity width of 200 km s\(^{-1}\), the median Hα velocity width for the SFE galaxies. In position switching mode, an exposure is taken while pointing at the object immediately followed by another exposure, usually of equal duration, of a blank part of the sky. For these observations, the "blank" sky exposure was obtained by slewing to a position 1° away from the target in both right ascension and declination. For exposures on and off the source that are of equal length, the antenna temperature is given by

\[
T_{\nu,A} = T_{\text{sys}} \frac{S_{\text{on}} - S_{\text{off}}}{S_{\text{off}}} \tag{1}
\]

where observations of bright radio sources of known flux density at 1400 MHz were used to convert the system temperature, \( T_{\text{sys}} \), into units of flux density. These computations were done at the telescope with the software packageGBTIDL. After combining all on and off target exposures for each source, the final calibration of the spectra was done within IRAF using customised scripts. After calibrating them, the spectra were smoothed with a 100 channel wide boxcar to yield an effective channel width of approximately 16.7 km s\(^{-1}\). The final step in the data reduction involved fitting a cubic spline function to the continuum of each spectrum within IRAF while interactively adjusting the location and size of the fitting window(s) and the number of spline segments used (typically between 10 and 15). The final calibrated, continuum subtracted spectra are displayed in Fig. 2-4 along with the SDSS g-band images.

For each galaxy, the peak flux density was measured within ±500 km s\(^{-1}\) of the SDSS-measured radial velocity from the continuum subtracted spectrum and was compared to the rms flux density measured outside this 1,000 km s\(^{-1}\) window. For those sources where the peak flux density was more than five times the rms, the integrated flux of the emission line, \( S_{\text{int}} \), was computed and the velocity width was roughly estimated to be \( W_{50} \approx \frac{S_{\text{peak}}}{\sigma} \). The error in the integrated flux was then computed using the rms measured outside the 21-cm emission line window and assuming the emission line spans 2\( W_{50} / \Delta \nu \) channels where \( \Delta \nu \) is the width of a single channel in units of km s\(^{-1}\). For these galaxies, the median value of the estimate of \( W_{50} \) is approximately 75 km s\(^{-1}\). Using this fact, a 3σ upper limit for the integrated flux was computed for the remaining sources assuming \( W_{50} = 75 \) km s\(^{-1}\). These upper limits were compared to the integrated fluxes measured from the continuum subtracted spectra within ±500 km s\(^{-1}\) of the expected line centre. Those galaxies whose integrated fluxes were larger than this upper limit were considered detections and the errors in the integrated fluxes were computed as above. For each galaxy with an HI detection, the HI mass was computed using the integrated flux and assuming H⊙ = 70 km s\(^{-1}\) Mpc\(^{-1}\).

To measure the location of the centre of the HI line,
HI in early-type galaxies with recent star formation

Figure 2. The continuum subtracted GBT spectra for the first 10 galaxies in Table 1 in units of mJy. Each spectrum is accompanied by its galaxy’s SDSS g-band image. For each galaxy spectrum, the measured rms value for the continuum is marked above and below $F_v = 0$ with dashed lines. For galaxies with detected 21-cm flux density (see §2), a Voigt profile fit to the emission line is plotted as a red dotted line. The line centres and velocity widths derived from these fits are given in Table 2.

as well as to obtain a better measurement of the full width at half power, $W_{50}$, a Voigt profile was fit to each HI emission line. Rather than being motivated by physical reasons, the choice of the Voigt profile was made to provide a more flexible function than a simpler profile (e.g., a Gaussian) because of the somewhat irregular shapes of some of the emission lines. The fitting of Voigt profiles also allows for reliable measurements of the centres and velocity widths of the emission lines for those galaxies with relatively weak detections (e.g., J090244.63+311626.04). For all but one galaxy, J140820.65+505240.44, the radial velocity of the HI lines estimated in this manner agreed with the radial velocities measured from the SDSS spectra within $\pm W_{50}/2$. For J140820.65+505240.44, the HI radial velocity is about 250 km s$^{-1}$ smaller than the SDSS-measured radial velocity and there are no obvious optical companions within the
area of the GBT beam. This velocity discrepancy may be the result of a significant amount of HI gas that is currently being deposited within this galaxy. Follow-up radio frequency spectral imaging is required to adequately address this issue. A second galaxy, J225304.56+010839.95, has a companion galaxy that is nearby both in position on the sky and in radial velocity. This companion, NGC 7401, is at a radial velocity of about 370 km s\(^{-1}\) larger than that of J225304.56+010839.95 according to NED and was also detected in 21-cm emission. As can be seen from the spectrum plotted in Fig. 4, the emission lines from these two galaxies are somewhat blended. Separate Voigt profiles were fit simultaneously to effectively de-blend the two line profiles so that the line centres and velocity widths could be estimated for J225304.56+010839.95 and NGC 7401 separately. For the measurement of the HI mass of J225304.56+010839.95, the emission line window was adjusted by eye to isolate its emission from that of NGC 7401.

All derived parameters discussed above are listed in Table 2. Galaxies whose integrated fluxes were less than their
estimated $3\sigma$ upper limits were considered non-detections; only the HI mass upper limits and rms values are listed in Table 2 for these galaxies. Overall, 19 of the 30 targets had detected 21-cm emission; nearly all (9 out of 12) SFE galaxies had detectable HI; a little more than half (10 out of 18) K+A galaxies had detected emission from HI. Among all 30 galaxies, roughly equal fractions of elliptical (13 out of 20) and lenticular (5 out of 8) galaxies had detected 21-cm emission.

For one galaxy, J121024.49+131014.16, the GBT observations were taken when the object was relatively close to the sun. As a result, the true shape of the continuum was not recovered using the on/off technique given by equation (1), and the resulting irregular continuum could not be adequately subtracted as evidenced by the spectrum plotted in Fig. 3. The upper limit for the HI mass of this galaxy should therefore be taken only as a rough estimate.

Figure 4. The same as Fig. 2 but for the last 10 galaxies in Table 1.
3 RESULTS AND DISCUSSION

3.1 Gas richness

With HI detections for nearly two thirds of the observed SFE and K+A galaxies and relatively stringent upper limits on the HI mass for the remaining galaxies, a comparison of the gas richness of these galaxies to that of other galaxies can be made. To this end, the samples of Helmboldt et al. (2004) and Lake & Schommer (1984) were chosen as comparison samples. The sample of Helmboldt et al. (2004) consists of 69 galaxies drawn from the HI Parkes All Sky Survey (HIPASS; Barnes et al. 2001) that were imaged using B, R, and narrow-band Hα filters and are predominantly spiral and irregular galaxies. The sample of Lake & Schommer (1984) consists of 28 faint $M_B > -20$ for $H_S = 50$ km s$^{-1}$ Mpc$^{-1}$ E and S0 galaxies observed with the 305-m telescope of the Arecibo Observatory, 12 of which were detected in 21-cm emission. For the sample of Helmboldt et al. (2004), the so-called gas-to-light ratio, or $M(HI)/L_B$ was computed in the B and R bands using the integrated 21-cm flux from the HIPASS spectra. Since only B-band optical magnitudes were available for the majority of the galaxies of Lake & Schommer (1984), only $M(HI)/L_B$ was computed for these galaxies using the published values for $L_B$ and $M(HI)$. For the SFE and K+A galaxies, the SDSS $g$ and $r$ band Petrosian magnitudes were used with the conversions given by Smith et al. (2002) along with the GBT data to compute values or upper limits for $M(HI)/L_B$ and $M(HI)/L_R$. The gas-to-light ratio is plotted as a function of luminosity in both bands in the panels of Fig. 3 with linear fits to the data. From these plots, it is evident that both SFE and K+A galaxies are on average more gas poor than typical disk galaxies at the same luminosity. About 75% of both SFE and K+A galaxies lie below the lines fit to the data with the upper limits for all galaxies with no detected 21-cm emission lying below these lines. In contrast, for those galaxies with detected 21-cm emission, the SFE and K+A galaxies appear to be more gas rich than the E and S0 galaxies of Lake & Schommer (1984). These results imply that the HI content of the SFE and K+A galaxies is on average somewhere in between what is typical for disk galaxies and the average value for E and S0 galaxies and are consistent with what was found by Buyle et al. (2005). The same was found to be true for the distributions of stellar mass and velocity dispersion for the parent SFE and K+A samples by Helmboldt et al. (2007).

The results summarised above imply that the gas richness of the SFE galaxies is on average relatively similar to that of the K+A galaxies. Does this then imply that the star formation that leads to K+A galaxies is very inefficient? This is not necessarily true. It is more likely that the relative amount of molecular and not atomic hydrogen within these galaxies will provide a true estimate of the average star formation efficiency since it is more likely that molecular gas will more actively participate in the star formation process.
The gas-to-light ratio of each galaxy is reduced according to within a 3 arcsec aperture. This was done assuming that the gas-to-light ratio versus luminosity in the B (upper) and R (lower) bands for the SFE (circles) and K+A (squares) galaxies determined using the SDSS $g$ and $r$ band Petrosian magnitudes and the conversions given in Smith et al. (2002). For both types of galaxies, upper limits are represented by open points with arrows for galaxies with no detected 21-cm emission. In both panels, the red lines indicate the path each SFE galaxies will traverse after 200 Myr of star formation assuming that only HI is consumed by the star formation and stellar mass-to-light ratios of 2.27 and 1.56 in the B and R bands respectively (see §3.1). Also plotted is the data from Helmboldt et al. (2004) (represented by x’s); the solid lines are linear fits to these data. The triangles represent the data for E and S0 galaxies taken from Lake & Schommer (1984).

However, the fact that the gas-to-light ratios for the SFE and K+A galaxies are quite similar at the same luminosity might imply that they are not evolutionarily linked as was concluded by Helmboldt et al. (2007) since one would naively expect the K+A galaxies to be more gas poor on average. Yet, even if the atomic hydrogen was the primary fuel of 2.27 and 1.52 in the B and R bands respectively and were assumed to be 200 Myr; Helmboldt et al. (2007) would cause their gas content to change by a relatively small amount. This is illustrated in Fig. 5 where we have recomputed the gas-to-light ratios for the SFE galaxies using the SFR per unit B and R band luminosities, $\Psi_B$ and $\Psi_R$, computed using the Hα emission line flux and the SDSS $g$ and i band “fibre” magnitudes (i.e., the magnitudes measure within a 3 arcsec aperture). This was done assuming that the gas-to-light ratio of each galaxy is reduced according to

$$\frac{M(HI)}{L} = \frac{M(HI)_0 - L_0 \Psi_{i\alpha}}{L_0(1 + \Psi_{\text{co}} \Upsilon^*_{\alpha} \Upsilon^*)}$$

where $M(HI)_0$ and $L_0$ are the initial HI mass and luminosity, $t_{\text{co}}$ is the star formation “cut-off” time which was assumed to be 200 Myr, and $\Upsilon^*$ is the stellar mass-to-light ratio. Using the stellar masses measured by Kauffmann et al. (2003), the median values for $\Upsilon^*$ for the SFE galaxies of Helmboldt et al. (2007) were determined to be 2.27 and 1.52 in the B and R bands respectively and were assumed for all SFE galaxies for this computation. Using the recomputed values of $M(HI)/L_B$ and $M(HI)/L_R$, the path each SFE galaxy would take is plotted as a red line in Fig. 6 and show that while the gas-to-light ratios of the most gas poor SFE galaxies will change significantly, the overall gas richness of the SFE galaxy sub-sample was changed relatively little. Therefore, it appears that the similarity between the gas-to-light ratios for SFE and K+A galaxies does not rule out the scenario in which SFE galaxies evolve into K+A galaxies. Future follow-up observations in the millimetre regime aimed at detecting emission lines from CO to measure the relative amounts of molecular gas within SFE and K+A galaxies are required to both test the validity of this proposed scenario and to estimate the typical star formation efficiency (or, amount of molecular gas consumption) for these systems.

### 3.2 The location of the HI

The results discussed above imply that the SFE galaxies are capable of only using up a relatively small fraction of their neutral hydrogen via star formation. Since the single-dish GBT observations provide no spatial information, one may

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**Figure 5.** The gas-to-light ratio versus luminosity in the B (upper) and R (lower) bands for the SFE (circles) and K+A (squares) galaxies determined using the SDSS $g$ and $r$ band Petrosian magnitudes and the conversions given in Smith et al. (2002). For both types of galaxies, upper limits are represented by open points with arrows for galaxies with no detected 21-cm emission. In both panels, the red lines indicate the path each SFE galaxies will traverse after 200 Myr of star formation assuming that only HI is consumed by the star formation and stellar mass-to-light ratios of 2.27 and 1.56 in the B and R bands respectively (see §3.1). Also plotted is the data from Helmboldt et al. (2004) (represented by x’s); the solid lines are linear fits to these data. The triangles represent the data for E and S0 galaxies taken from Lake & Schommer (1984).

**Figure 6.** The full width at half power of the stellar velocity distribution, $W_{50}(\text{stars})$ (upper), and the Hα emission line, $W_{50}\text{H(\alpha)}$ (lower), measured from the SDSS spectra versus the 21-cm line velocity width, $W_0$, measured from the GBT spectra. Only the SFE galaxies are included in the lower panel since any Hα emission detected within the K+A galaxies in not likely linked to current star formation. In both panels, black points represent SFE galaxies and grey boxes represent K+A galaxies. Points representing elliptical galaxies are flagged with x’s. The dashed lines represent the case where the SDSS-measured velocity widths match the values of $W_0$; the dotted lines represent the median ratio of stellar/ionised gas velocity width to the HI velocity width for SFE galaxies only, which is equal to 4.35 for the stellar velocity and 1.52 for the ionised gas velocity.
then question whether the majority of the HI is spatially coincident with the regions of star formation, or if it typically extends substantially beyond these regions. The kinematic information available from both the SDSS and GBT spectra can provide some insight into this issue. Using the IDL program \textit{edispfit} written by D. Schlegel, the line-of-sight (LOS) stellar velocity dispersion was measured for each galaxy using its SDSS spectrum. The \textit{edispfit} routine determines the best-fitting velocity dispersion and the 1σ error in that dispersion by cross-correlating each spectrum with several template spectra that have been broadened by various Gaussian velocity distributions while masking regions of the spectrum that may contain emission lines. Velocity widths in which the Hα emission line for all galaxies with \( > 5\sigma \) detections of that line were also obtained from [Tremonti et al. (2004)] in Fig. 6 the full width at half power of the LOS stellar velocity distribution, \( W_{50}(\text{stars}) \), and of the Hα emission line, \( W_{50}(\text{Hα}) \), are plotted as functions of \( W_{50} \), the velocity width of the HI emission line. For the Hα velocity widths, only the SFE galaxies are included because even though the K+A definition of [Helmholdt et al. (2007)] allows for a low level of Hα emission, any detected Hα emission is most likely not the result of ongoing star formation. All of the SFE galaxies with detected HI have stellar velocities significantly greater than \( W_{50} \); the median ratio of \( W_{50}(\text{stars}) \) to \( W_{50} \) for these galaxies is about 4.4 (see Fig. 5). All but a few (3-4) K+A galaxies are consistent with the same value for this ratio. In contrast, the median ratio of \( W_{50}(\text{Hα}) \) to \( W_{50} \) is about 1.5 for the SFE galaxies with three of them having values of \( W_{50}(\text{Hα}) \) and \( W_{50} \) that are essentially the same. These results imply that it is much more likely that the HI gas is located within the same regions as the star formation rather than throughout the galaxies. The fact that the HI emission line velocity width tends to be larger than that of the Hα emission line may indicate that the neutral hydrogen extends to somewhat larger radii (i.e., where the circular velocity is likely higher) than the emission line gas, or that it extends beyond the area covered by the 3 arcsec aperture used by the SDSS spectrograph.

But, where are the star forming regions located within these galaxies? To partially answer this question, the \( g - i \) surface brightness profiles measured by the SDSS photometric pipeline (see [Stoughton et al. 2002]) within concentric circular apertures for all 30 galaxies are plotted in Fig. 7. The majority of the galaxies either have negative \( g - i \) gradients within the inner parts of their profiles indicative of increasingly younger stellar populations, or have a \( "\text{dip}" \) in their profiles most likely due to both a decrease in mean stellar age and an increase in internal dust extinction towards the galaxy centres. In fact, the \( z \)-band dust extinction estimates made by [Kauffmann et al. 2003] using model fits to the stellar continua of the SDSS spectra of the galaxies presented here indicate similar levels of dust extinction for the SFE and K+A galaxies. The \( z \)-band extinction for both types of galaxies ranges from 0 to \( \sim 1 \) mag with mean values for both classes of about 0.35 mag, corresponding to a colour excess of \( E(g - i) \sim 0.4 \) [Schlegel et al. 1998]. Both the negative gradients and the dip features in the surface brightness profiles indicate that for the majority of the galaxies, the star formation is occurring preferentially in the galaxies’ centres. This is similar to what has been found previously for both K+A [Yamauchi & Goto 2003] and SFE [Helmholdt & Walterbos 2007] galaxies. For most of these galaxies, the changes in the \( g - i \) profile shapes indicative of star formation occur within the inner kiloparsec, as indicated by the vertical dashed lines in the profiles displayed in Fig. 7. When taken into account with the kinematic data plotted in Fig. 6, one would also expect to find the majority of the neutral atomic hydrogen within \( \sim 1 \) kpc from the centres of these galaxies. Interferometric data obtain with an instrument such as the NRAO Very Long Array is required to produce synthesis images of 21-cm emission with high enough spatial resolution to adequately and properly address this issue.

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Figure 7. The observed $g - i$ profiles taken from the SDSS photometric pipeline (Stoughton et al. 2002) for all 30 galaxies observed with the GBT. Galaxies with HI detections are represented by stars; those without detections are represented by open points. In each panel, the angular size corresponding to 1 kpc for $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ is marked with a vertical dashed line.

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