HI in four star–forming low-luminosity E/S0 and S0 galaxies

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ABSTRACT

We present HI data cubes of four low–luminosity early–type (E/S0 and S0) galaxies which are currently forming stars. These galaxies have absolute magnitudes in the range $M_B = -17.9$ to $-19.9$ ($H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$). Their HI masses range between a few times $10^8$ and a few times $10^9$ $M_\odot$ and the corresponding values for $M_{HI}/L_B$ are between 0.07 and 0.42, so these systems are HI rich for their morphological type. In all four galaxies, the HI is strongly centrally concentrated with high central HI surface densities, in contrast to what is typically observed in more luminous early–type galaxies. Star formation is occurring only in the central regions.
In two galaxies (NGC 802 and ESO 118–G34), the kinematics of the H I suggests that the gas is in a strongly warped disk, which we take as evidence for recent accretion of H I. In the other two galaxies (NGC 2328 and ESO 027–G21) the H I must have been part of the systems for a considerable time. The H I properties of low-luminosity early-type galaxies appear to be systematically different from those of many more luminous early-type galaxies, and we suggest that these differences are due to a different evolution of the two classes.

The star formation history of these galaxies remains unclear. Their $UBV$ colours and Hα emission-line strengths are consistent with having formed stars at a slowly-declining rate for most of the past $10^{10}$ years. If so, their star formation history would be intermediate between late-type spiral disks and giant ellipticals. However, the current data do not rule out a small burst of recent star formation overlaid on an older stellar population.

Three of the galaxies have weak radio continuum emission, and the ratio of the far-infrared (FIR) to radio-continuum emission is very similar to that of spirals of similar FIR- or radio luminosity. We find that, except in the largest galaxy observed, the radio-continuum emission can be accounted for solely by thermal (free–free) emission from H II regions, with no non–thermal (synchrotron) disk component. Thus, although these galaxies have gaseous disks, a disk magnetic field may be very weak or absent.

Subject headings: galaxies: kinematics and dynamics – radio emission lines

1. Introduction

Disentangling the star–formation history of early–type galaxies is not straightforward. Such galaxies have traditionally been regarded as old, gas–poor stellar systems, yet we now know that they have a complex, multi–phase interstellar medium (e.g. Knapp 1999) and often contain detectable (and occasionally large) amounts of neutral hydrogen (Knapp et al. 1985). The standard view is that such galaxies are dominated by an old stellar population which probably formed quite rapidly. This appears to be true for the most luminous galaxies, but not necessarily for those of lower luminosity for which the star formation histories could be different (e.g. Faber et al. 1995; Worthey 1996). Differences in star–formation histories are indicated by, for example, different abundance ratios as function of luminosity (e.g. Worthey et al. 1992, Matteucci 1994). Such differences may point to longer periods of star formation in smaller early–type galaxies, with corresponding differences in the way the ISM is enriched. Such more extended star formation could be related to the disks that become more important towards lower luminosities (e.g. de Jong & Davies 1997).

1Based on observations with the Australia Telescope Compact Array (ATCA), which is operated by the CSIRO Australia Telescope National Facility
Many low-luminosity early-type galaxies show direct evidence for ongoing star formation in their central regions in the form of H II-region emission-line spectra (Phillips et al. 1986).

Differences in the star-formation history of large and small early-type galaxies are mirrored by other differences between the two groups. In general, low-luminosity galaxies are less well studied than their giant counterparts (probably because they are under-represented in magnitude-limited galaxy samples); but several global properties of early-type galaxies appear to change at an absolute magnitude of $M_B \sim -19$ to $-20$. Luminous ellipticals often have boxy isophotes and anisotropic velocity dispersions, while smaller ellipticals tend to be rotationally flattened (e.g., Kormendy & Bender 1996) and at large radii they contain disks very similar to S0 galaxies (Rix, Carollo & Freeman, 1999). The two groups also have different radio and X-ray properties, with luminous galaxies being more likely to have X-ray coronae (Canizares et al. 1987) and active nuclei (Sadler et al. 1989). In the last few years, HST observations have shown that a relation exists between the central structure and global galaxy properties like rotation (e.g. Lauer et al. 1995).

Many of these differences can be understood in terms of the different amounts of gas present during a galaxy’s formation and evolution. In many models for galaxy formation (e.g. Kauffmann 1998, Baugh et al. 1998), the gas supply is a key factor in determining the characteristics of early-type galaxies. It is therefore important to know the properties of the gas in elliptical and S0 galaxies over a wide range of luminosities, and to study how these properties relate to other characteristics of these galaxies.

To study in more detail the relation between gas content and other structural parameters, we are undertaking a program to study the HI properties in a large number of early-type galaxies (Morganti et al. 1997a, 1997b, Oosterloo et al. 1999a, 1999b, Morganti et al. 1999). In this paper, we present HI observations of four gas-rich, low-luminosity early-type galaxies that were listed by Phillips et al. (1986) as having H II region-like optical spectra.

Throughout this paper, we use $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ unless otherwise stated.

2. Four low-luminosity early-type galaxies with H II-region spectra

Phillips et al. (1986) listed seven low-luminosity E/S0 and S0 galaxies with optical spectra characteristic of H II regions. We have used the Australia Telescope Compact Array (ATCA) to image four of these galaxies (NGC 802, NGC 2328, ESO 118–G34 and ESO 027–G21) in the HI line. A fifth galaxy, NGC 1705, has already been observed in HI by Meurer et al. (1992, 1998). We briefly describe the four galaxies we observed, and summarize their properties in Table 1.

NGC 802. This is an isolated E/S0 galaxy of absolute magnitude $M_B = -18.0$ which has been very little studied. A spiral galaxy to the north-east, ESO 052–G14, is at higher redshift and not associated (Sadler & Sharp 1984). NGC 802 is listed as a UV–bright galaxy by Coziol et al. (1997).

ESO 118–G34. This galaxy is classified as an S0 galaxy that lies in a small group of galaxies
which includes the spirals NGC 1672 and NGC 1688 (Garcia 1993). Its absolute magnitude is $M_B = -17.9$. It has been imaged in Hα/[N II] by Buson et al. (1993). The galaxy appears to be actively forming stars, with several bright H II-region complexes in the central $\sim 20$ arcsec.

NGC 2328. This is an isolated E/S0 galaxy of $M_B = -18.7$. It has been detected in CO by Lees et al. (1991) and Wiklind et al. (1995). A narrow–band image in Hα/[N II] (Sadler 1987) shows extended emission–line gas in the central 9 arcsec, distributed in a clumpy, ring–like structure.

ESO 027–G21. This is an S0 galaxy ($M_B = -19.9$) which lies in a small group of galaxies, and has not previously been studied in detail. Optical images suggest that the galaxy may have a weak spiral arm extending to the south–east.

3. Radio observations

3.1. Single–dish H I observations at Parkes

Three of our four galaxies were observed in 1988 with the Parkes telescope by Sadler and J.B. Whiteoak. The Parkes 64-m telescope has a beam of 14.7 arcmin at 1.415 GHz. The 1988 observations used two cryogenically cooled FET receivers connected to horizontal and vertical polarized ports of the feed, with noise temperatures of $\sim 60$ K. NGC 2328 was observed with a bandwidth of 5 MHz; and NGC 802 and ESO 027–G21 with a 10 MHz bandwidth. The 1024-channel autocorrelator was used in $2 \times 512$ channel mode, giving a velocity scale of 2.1 km s$^{-1}$ per channel for NGC 2328 and 4.2 km s$^{-1}$ per channel for the other two galaxies. The final resolution (after smoothing) is roughly 4 and 8 km s$^{-1}$ respectively.

Table 2 summarizes the results and the derived H I masses, while Figure 1 shows the Parkes single–dish profiles.

3.2. ATCA Observations

We used several different configurations of the Australia Telescope Compact Array (ATCA) to image the four galaxies in H I. Table 3 summarizes the observations. Except for one observation (NGC 802 with the 375-m array), we used a narrow (8 MHz) band with 512 velocity channels. The band was centered on the optical velocity of each galaxy, and the final velocity resolution (obtained after hanning smoothing the data) is $\sim 6$ km s$^{-1}$. We generally chose compact configurations of the ATCA (375-m and 750-m arrays) to allow us to investigate the full extent of the H I emission. As a result, the spatial resolution of our H I images is typically $\sim 50$ arcsec. Two of the galaxies were also observed with 1.5-km arrays to improve the spatial resolution in the centre.

We used the second IF for simultaneous continuum observations with a bandwidth of 128 MHz and 33 channels. The observed continuum frequencies are given in parentheses in Table 3. For
ESO 118–G34, two continuum frequencies (13 and 20 cm) were measured.

We observed each galaxy for about 12 hours in each run, with calibrators observed every hour to monitor the gain changes. The flux density scale was set by observations of PKS 1934–638, for which we adopted a flux density of 14.9 Jy at 1400 MHz. This source was also used as the bandpass calibrator.

### 3.2.1. Neutral Hydrogen Data

The spectral data were calibrated with the MIRIAD package (Sault et al. 1995), which has several features particularly suited for ATCA data. The continuum subtraction was also done in MIRIAD, by using a linear fit through the line–free channels of each visibility record and subtracting this fit from all the frequency channels (i.e. UVLIN). We already knew that none of the four galaxies contained a strong continuum source (Sadler 1984; see also below), so continuum subtraction did not cause any complications for the line data. An interference spike generated by the ATCA data acquisition system is present at 1408 MHz, but since this frequency is outside the velocity range of interest, it does not affect our data.

For NGC 802 and ESO 118–G34, which were observed with more than one ATCA configuration, we combined the data from different runs after calibration and continuum subtraction. The final reduction (i.e. CLEAN and moment analysis of the data cube) was done using GIPSY (van der Hulst et al., 1992). The final cubes were made with both natural and uniform (or robust) weight. Table 4 lists the corresponding rms noise and size of the restoring beams.

As expected from the Parkes observations, we detect H I in all four galaxies and Table 2 gives the H I fluxes. The total intensity and intensity–weighted mean–velocity fields of the H I emission were derived from a data cube by smoothing the original data cube spatially to a resolution about twice as low as the original. The smoothed cube was used as mask for the original cube: pixels with signal below $3\sigma$ in the smoothed cube were set to zero in the original cube (van Gorkom & Ekers 1989).

The total H I fluxes measured at the ATCA are typically 10–30% lower than those measured at Parkes, which may imply that some very extended low–level H I has been resolved out with the ATCA or removed by the $3\sigma$ clipping. It is also possible that the single–dish fluxes could be slightly too high because of miscalibration in the 1988 data. Data from the Parkes HI multibeam survey (Barnes et al., in preparation), due for release in 2000, will provide an independent check of the single–dish data.
3.2.2. Continuum Data

The continuum data from the ATCA were also reduced using MIRIAD, and Table 5 summarizes the results. Data from the second IF were used (see Table 3), except for the 1.5-km array observation of ESO 118–G34, where the second IF was set to 2.4 GHz and a 1.3 GHz flux density was measured from emission–free channels in the line data (first IF).

For each galaxy in Table 5, we give two continuum measurements. The first uses all the available data, except baselines to the 6-km ATCA antenna. This gives a typical beam of 20–40 arcsec diameter, and hence a good estimate of the total flux density since all the sources are likely to be unresolved at this resolution. To get the highest possible spatial resolution (about 8 arcsec), we made a second set of images by including the baselines to the 6-km ATCA antenna as well. This gives a very patchy \( uv \) coverage because of the big gap between the long and short baselines, and the emission may not be imaged very well, but a comparison of the fluxes derived from the low- and high-resolution images gives us some information on the likely spatial extent of the continuum emission.

Three of the four galaxies were detected as continuum sources, but the continuum emission was weak and either unresolved (ESO 027–G21) or barely resolved (NGC 2328 and ESO 118–G34) in the higher–resolution images. In all three detected galaxies, the radio continuum source is centered on the galaxy’s nucleus and almost all the continuum emission arises from within the central 5–10 arcsec.

For ESO 118–G34, we have continuum data at both 1.3 and 2.4 GHz, and measure a spectral index of \(-0.6\). NGC 2328 was detected at 5 GHz with a flux density of 2.5 mJy by Sadler et al. (1989) using the VLA B/C array. This implies a steep spectral index of \(-0.9\), but the true spectral index may be flatter than this since it is possible that some extended 5 GHz emission was resolved out by the VLA. For the remaining galaxies, the only other continuum measurements available are upper limits at 11 cm (Sadler 1984).

4. Results

Figures 2 and 3 show the \( \text{H} \text{I} \) distribution and velocity field, obtained using natural weighting, for each of the four galaxies observed. Figure 4 shows the \( \text{H} \text{I} \) total–intensity distributions and velocity fields obtained by using uniform (or robust) weighting, with slightly higher spatial resolution (see Table 4 for the beam sizes). The low resolution total \( \text{H} \text{I} \) images can give an indication of the overall extent of the \( \text{H} \text{I} \) emission compared to the optical object, while the higher resolution data gives more information about the kinematics of the \( \text{H} \text{I} \). Table 6 summarizes the main \( \text{H} \text{I} \) properties derived from the ATCA images.

In Figure 5 we show the position–velocity plots along the kinematical major axis of the \( \text{H} \text{I} \) of the four galaxies. For NGC 802 the plot obtained from the high resolution data cube is also
shown. In the following section, we briefly summarize the characteristics of the H I emission for each object.

4.1. Notes on individual galaxies

4.1.1. NGC 802

The most striking characteristic of the H I in NGC 802 is its kinematics: the velocity field shows that the rotation axis of the bulk of the H I appears to be quite mis-aligned with the optical minor axis. However, the position–velocity diagrams of this galaxy show that the H I in this galaxy may not be in a single, flat disk–like structure and that the velocity field, given the broad H I profiles and the relatively low spatial resolution, does not give a complete description of the kinematics of the H I. The high–resolution version of the position–velocity diagram, taken along the kinematical major axis, shows that the brightest H I rotates roughly about the optical major axis, but there is also fainter H I at higher projected velocities which appears to lie closer to the center of the galaxy (the ridge of H I seems to curve back to the center at velocities away from systemic). This is suggestive of a warped H I structure like that observed, for example, in the luminous dust–lane elliptical NGC 5266 (Morganti et al. 1997a). The ionized gas also shows very little rotation along the optical major axis. Figure 6 shows the ionized gas velocities measured from an optical spectrum (see §5.1) taken along PA 145\degree, roughly aligned with the optical major axis. A very shallow velocity gradient is observed. It is possible that NGC 802 is forming a minor–axis dust lane or a polar ring. NGC 802 shares this characteristic with the small elliptical galaxy NGC 855 (Walsh et al. 1990) and possibly also with ESO118–G34 (see below). This strongly suggests that a significant fraction of the H I in NGC 802 has been accreted relatively recently. The kinematic timescale \((V/R)\) in NGC 802 is of the order of a few times 10\(^8\) years. Given that the H I distribution is not very chaotic, the accretion event probably occurred of the order of \(\sim 5 \times 10^8\) years ago.

The radial surface–density profile of the H I in NGC 802 (Figure 7) is quite peaked towards the center, with the central density being about 4.5 \(M_\odot\)pc\(^{-2}\). Given the limited spatial resolution of the H I data, the true central surface density is likely to be even higher. This value is much higher than typically found in more luminous early–type galaxies (that usually have values in the range 0–2 \(M_\odot\)pc\(^{-2}\) e.g. Oosterloo et al. 1999a, 1999b), and is consistent with the fact that star formation is occurring in the center of NGC 802.

4.1.2. ESO 118–G34

The position–velocity diagram of the H I in ESO 118–G34, taken along PA 160\degree, is qualitatively similar to that of the H I in NGC 802. Also here, very broad profiles are observed and the overall shape of the H I in this diagram is also S-shaped. Given the round shape of the optical isophotes, it
is not possible to determine the orientation of the rotation axis relative to that of the optical galaxy. Although there is an overall rotation pattern in the H I, the velocity field shows deviations from that what expected for a flat disk, and also the H I distribution also has some irregular features. In the inner parts, the kinematical major axis seems to be along PA $160^\circ$, while at larger radii it seems to be more like $45^\circ$. It appears that also in ESO 118–G34 the H I is likely to be in a strongly warped structure. The range of velocities observed suggests that we are viewing the H I from close to face–on. Hence, small changes in the orientation of the H I disk lead to relatively large signatures in the velocity field. The H I distribution in ESO 118–G34 is quite extended, but strongly peaks in the center, with central surface densities very similar to those observed in NGC 802.

4.1.3. NGC 2328

Of the four galaxies we observed, NGC 2328 has perhaps the most regular H I distribution. The H I is in a regularly rotating disk, aligned with the optical image of the galaxy. As in the other galaxies, the H I distribution peaks quite markedly in the center, although it seems that the central H I density could be somewhat lower than in NGC 802 and ESO 118–G34.

Although the spatial resolution is quite low, the position–velocity diagram suggests that the rotation velocity does not decrease in the outer part of the H I disk. This would indicate the presence of a dark matter halo. We can make a very rough estimate of the mass–to–light ratio in this galaxy. The projected rotation velocity at 1.5 arcmin radius is about 50 km s$^{-1}$. Assuming circular orbits and a spherical mass distribution, this implies $M/L_B \sim 1.1/\sin^2 i$ at this radius. Although we are limited by the resolution of our data, we estimate that the H I disk has an inclination of about $30^\circ$. The optical axis ratio gives a lower limit to the inclination of about $25^\circ$, so the H I disk in NGC 2328 is observed relatively face–on and as a result the mass estimate is quite uncertain. If we adopt $30^\circ$ for the inclination of the H I disk, we find $M/L_B \sim 4.6$ at about $5R_e$ (i.e. 6 kpc from the center). Higher resolution observations, complemented with optical data, would be needed to make a proper study of the mass distribution in this galaxy.

4.1.4. ESO 027–G21

In ESO 027–G21, as in NGC 2328, the H I appears to be in a regularly rotating disk aligned with the optical major axis of the galaxy. The velocity field shows that the kinematical position angle changes with radius, indicative of a warped H I disk. Also the faint extensions of the H I distribution to higher projected velocities at large radii in the position–velocity map shows this.

Also in this galaxy, the surface density profile peaks at the center with a relatively high surface density of almost $6 M_\odot$pc$^{-2}$. The value derived from the natural weighted cube is basically the same as that derived from the cube made with robust weighting, indicating that this value is probably not much affected by the low spatial resolution. An optical spectrum taken along the major axis
(Figure 6, see also §5.1) shows that the rotation velocities rise quite steeply in the center, and that the level of rotation of the inner H I disk of 65 km s\(^{-1}\) is already reached at a radius of a few arcseconds (Figure 6). The position–velocity map (Figure 5) shows, contrary to the other three galaxies observed, a minimum in the center. Given that the radial H I density profile (in space) peaks in the center, this implies that the rotation curve in this galaxy rises more quickly than in the other galaxies, as is observed in the optical spectrum.

As for NGC 2328, the H I data for this galaxy allow us to estimate the mass–to–light ratio. With the same assumptions, taking a projected rotation velocity of the outermost H I at 1.5 arcmin radius of about 100 km s\(^{-1}\), we find \(M/L_B \sim 3.3/\sin^2 i\) at a radius of about \(5R_e\) in ESO 027–G21. Taking the optical axis ratio to make an estimate of the inclination, we find \(i = 40^\circ\) and hence \(M/L_B \sim 8\).

4.2. Distribution and Kinematics of the H I

The kinematics and distribution of the H I in the four galaxies can be summarized as follows:

- All four galaxies have an extended H I distribution, typically extending to \(5R_e\).
- The H I surface density is strongly peaked at the center, with central surface densities of at least \(4 M_\odot/pc^2\). These high surface densities are related to the central star formation regions observed in all four galaxies.
- The H I lies in a rotating, disk–like structure, although the exact H I structure varies from galaxy to galaxy. In two of the galaxies (NGC 802 and ESO 118–G34) the H I is likely to be strongly warped, and in NGC 802 the kinematical major axis of the H I is even perpendicular to the optical major axis. This suggests that in these two galaxies a significant fraction of the H I has been accreted relatively recently (of the order of \(5 \times 10^8\) yr ago). In the two other galaxies (NGC 2328 and ESO 027–G21) the H I appears to have a more regular distribution and kinematics, although in ESO 027–G21 the outer H I disk also shows a mild warp.

Most of these results are in good agreement with the findings of Lake et al. (1987) for the four low–luminosity ellipticals they studied. Lake et al. also find the H I distributed in relatively regularly rotating disks extending well beyond the optical galaxy, with some indications that at least some of the H I has been accreted relatively recently, or is in fact accreting. They also find that the H I in low–luminosity early–type galaxies is more centrally concentrated than in more luminous early–type galaxies.

In two galaxies (NGC 2328 and ESO 027–G21) we can make a very rough estimate of the mass–to–light ratio, and we find values of \(5 - 8 M_\odot/L_\odot\) in the \(B\) band, at \(\sim 5 R_e\). Although these values are quite uncertain, it does appear that they are significantly lower (by a factor 2–4) than...
what has been found for more luminous early–type galaxies (e.g. Morganti et al. 1999), where typical values of \(20 \, M_\odot / L_\odot\) are found at \(\sim 5 \, R_e\). In general, lower values for \(M/L\) are found for low–luminosity early–type galaxies (see e.g. Jørgensen, Franx and Kjærgaard 1996). Given the star formation we observe in the four galaxies, this difference is likely to be due to the different stellar populations in the two groups of galaxies rather than a difference in dark matter content. In fact, in the \(V\) band the differences in \(M/L\) are smaller (by roughly a factor 1.6), given that our low–luminosity galaxies have bluer colours than the more luminous galaxies (assuming that ESO 027–G21 has similar colours to the other three galaxies). Hence the low values for \(M/L_B\) probably arise from the very blue colors of these galaxies, as can be seen from Table 1.

In these two galaxies, the fastest rotating H I is observed at the largest radii, which would indicate the presence of dark haloes, but higher resolution data are needed to determine to what extent this is due to warping of the outer H I disk, as seems to be the case in ESO 027–G21. The rotation curve of ESO 027–G21 appears to be flat from a radius of a few arcseconds to about 1 arcminute where the disk appears to become more edge on. Given that the effective radius of this galaxy is 19 arcseconds, this is suggestive for the presence of dark matter.

### 4.3. H I emission from other galaxies in the field

In two cases we detected H I from another galaxy in the fields of our program galaxies. Figure 8 shows H I total–intensity images for these two objects.

In the NGC 802 field, we detected H I emission from AM 0155–675 (J2000.0 position \(\alpha = 01^h 57^m 04^s, \delta = -67^\circ 42' 54''\)), which lies \(\sim 15\) arcmin NW of NGC 802. This object is classified as a pair of galaxies by Arp& Madore (1987). We measure an H I systemic velocity of 1385 \(\text{km s}^{-1}\) \(\pm 10\) \(\text{km s}^{-1}\), though it is not clear whether the H I is associated with both members of the pair, or only one. No optical velocity is catalogued.

An anonymous galaxy is also detected 5 arcmin south of ESO 027–G21. The H I systemic velocity of this galaxy is 2455 \(\text{km s}^{-1}\) \(\pm 10\) \(\text{km s}^{-1}\), i.e. very close to that of ESO 027–G21. Corwin et al. (1985) suggest that this galaxy may be interacting with ESO 027–G21, but the H I data do not show any indications for such an interaction.

### 5. The interstellar medium and star formation in the four galaxies

Table 6 summarizes the known properties of the interstellar medium (ISM) in the four galaxies. In general, early–type galaxies have a complex, multi–phase ISM (e.g. Knapp 1999) which can include cold (CO, H\(_2\)), cool (H I), warm (H III) and hot (X–ray) components.

Although there is no information about the X–ray properties of the four galaxies studied here, such low–luminosity galaxies would not be expected to contain detectable amounts of hot X–ray...
gas (e.g. Fabbiano 1989) and it seems reasonable to assume that cooler gas dominates the ISM.

There is also very little known about the molecular gas content of these galaxies. CO has been detected in NGC 2328 by Lees et al. (1991) and Wiklind et al. (1995). The observations by Lees et al. used the 10.4 m telescope of the Caltech Submillimeter Observatory on Mauna Kea to observe the $^{12}$CO(2–1) line at 230.5 GHz. The telescope half–power beamwidth at this frequency was 32 arcsec, and they derived a molecular hydrogen mass of $6.6(\pm1.0) \times 10^7 M_\odot$ for NGC 2328 (converted to $H_\odot = 50$ km s$^{-1}$ Mpc$^{-1}$), based on the generally–adopted conversion relation between CO and H$_2$. Wiklind et al. used the 15 m SEST telescope in Chile to observe NGC 2328 in the $J=1–0$ CO line at 115 GHz, where the SEST half–power beam was 44 arcsec. They derived an H$_2$ mass of $2.9 \times 10^8 M_\odot$ for NGC 2328, i.e. about four times larger than that measured by Lees et al. Since their measurements used a slightly larger beam this may mean that the CO is spatially extended over at least the central 2–3 kpc, or may simply reflect uncertainties introduced by the assumption of a H$_2$/CO conversion ratio. The H I mass in the central 30–40 arcsec of NGC 2328, based on the radial profile shown in Figure 7, is around $3 \times 10^7 M_\odot$, so that molecular hydrogen appears to dominate the ISM of NGC 2328 in the central 2 kpc where star formation is taking place.

Because the CO measurements are made with single dishes, little is known about the kinematics of the molecular gas. Lees et al. measure FWHM = 112 km s$^{-1}$ from their CO profile, i.e. almost identical to the FWHM of 111 km s$^{-1}$ measured from the Parkes H I profile in Figure 1. Wiklind et al. measure a much larger FWHM of 280 km s$^{-1}$ from the SEST data, and the reason for this is unclear.

In summary, it is clear that molecular gas is an important constituent of the ISM in these galaxies, and further CO data would be very valuable.

In the four galaxies in Table 6, the H I mass to blue luminosity ratio ($M_{HI}/L_B$) has values around 0.1 to 0.4, which are more typical for spiral galaxies than for early–type galaxies (Bregman et al. 1992).

All four galaxies were detected by IRAS at 60 and 100 $\mu$m (Knapp et al. 1989) and we can use the far–infrared flux densities to estimate the mass of dust which is present (Roberts et al. 1991). The dust masses inferred in this way are quite low (typically a few times $10^5 M_\odot$), and the ratios $M_{HI}/M_{dust}$ range from 1500 to over 6000. A ratio of about 1000 is often observed in early–type galaxies (Henkel & Wiklind, 1997), although some galaxies do have much higher ratios. These high ratios might mean that the abundances in the ISM are low because much of the H I is accreted recently and is primordial. It is also quite possible that much more dust is present but that it is too cool to emit in the IRAS bands (e.g. Young et al. 1989).
5.1. Location of the star–forming regions

Two of the galaxies studied (ESO 118–G34 and NGC 2328) show distinct, clumpy HII regions in CCD frames (Buson et al. 1993; Sadler 1987). In both these galaxies, the Hα emission is confined to the central 1–2 kpc.

In ESO 118–G34, narrow–band CCD images show that the line–emitting region has a diameter of about 1.3 kpc, or 17 arcsec (Buson et al. 1993), and the mass of ionized gas is estimated as \(5.1 \times 10^4 M_\odot\). In NGC 2328 the emitting region is somewhat smaller, with a diameter of 0.6 kpc or 8 arcsec (Sadler 1987), but the mass of ionized gas is similar at \(6.8 \times 10^4 M_\odot\). In both cases the star–forming region is very small compared to the HI disk.

For the other two galaxies (NGC 802 and ESO 027–G21), no narrow–band CCD images are available. As a result, little is known about the structure of the star–forming regions, except that they are centrally concentrated (because the Phillips et al. (1986) spectra show emission lines from the nucleus). This is confirmed by optical spectra taken by us in July 1997 at the ANU 2.3-m telescope at Siding Spring, and shown in Figures 6a and 6b. For each of these two galaxies, a single spectrum was taken with the slit aligned along the optical major axis. In both galaxies, strong emission lines were detected, with emission–line ratios typical of star–forming regions. This is in contrast with more luminous galaxies, where, if ionized gas is detected, the spectrum is usually LINER–like and the emission is not associated with star formation (e.g. Phillips et al. 1986, Goudfrooij 1999). In NGC 802 the gas extends to about 6 arcsec from the nucleus (though, as noted earlier, the misalignment between the kinematic axes of stars and gas in this galaxy means that the spectrograph slit was probably not aligned with along the major axis of the gas disk). In ESO 027–G21, the gas extends somewhat further from the nucleus (10–12 arcsec) but is still centrally concentrated.

Hence, we confirm that star formation is occurring in all galaxies and that the brightest star–forming regions are confined to the innermost regions of the central stellar bulge. The fact that the star formation is occurring in the center is consistent with the strong central peaks we observe in the HI distributions.

5.2. Star formation rates

We can use the Hα emission–line fluxes observed by Phillips et al. (1986) to estimate the current star formation rate in each of our four galaxies. Although the Phillips et al. measurements are from slit spectra, the Hα fluxes derived in this way give a reasonable estimate of the total value because the emission region is so centrally concentrated. Buson et al. (1993) discuss this further, and compare slit and CCD total fluxes for several galaxies.

We use the relations between Hα luminosity and star formation rate given by Kennicutt (1983) to derive the star formation rate in solar masses per year for (a) stars more massive than \(10 M_\odot\)
and (b) all stars. Kennicutt assumes an initial mass function of the form:

\[ \phi(m) \propto m^{-1.4} \quad (0.1 \leq m \leq 1 M_\odot) , \text{ and} \]
\[ \phi(m) \propto m^{-2.5} \quad (1 \leq m \leq 100 M_\odot). \]

Table 7 shows the results. The derived star formation rates are relatively low in absolute terms. We find values lower than 0.5 \( M_\odot \) per year, compared to \( \sim 4 M_\odot \) per year for spirals like our own Galaxy and up to 50 \( M_\odot \) per year for extreme starburst galaxies. These are clearly not ‘starburst’ galaxies, but relatively quiescent systems.

However, the galaxies in Table 7 are only about one–tenth as luminous as the bright spiral galaxies studied by Kennicutt (which typically have \( M_B \sim -21.3 \) for Sab galaxies and \( -20.9 \) for Scs). If we were to scale down the star formation rate of a typical spiral by a factor of ten, we would have a SFR of \( \sim 0.4 M_\odot/\text{year} \). Hence, scaling by optical luminosity, two of our galaxies (ESO 118–G34 and NGC 2328) are forming stars at about the same rate per unit blue luminosity as a typical spiral galaxy, while the other two have a significantly lower SFR.

### 5.3. Star formation history and the gas depletion time

Most late–type disk galaxies have current star formation rates (SFR) which are similar to the past rates averaged over the age of the disk (Kennicutt 1983). In other word, these galaxies have evolved at a nearly constant rate. Conversely, the star formation rates in luminous ellipticals were much higher in the past than that they are now. What can we say about the four galaxies we have studied here?

To estimate the past star formation rate, we need to know both the total mass and the mean age of the stellar population. We have very little information on the underlying stellar population other than the broad–band \( UBV \) colours listed in Table 1, but we can nevertheless set some limits on the minimum likely star formation rate in the past and get some indication of possible star formation histories.

To make a rough estimate of the total stellar mass for each galaxy, we simply use the value of \( L_B \) in Table 1 and assume \( M/L_B = 3.0 \). We first assume that all four galaxies began forming stars roughly \( 10^{10} \) years ago (e.g. Searle et al. 1973). Dividing the total stellar mass by \( 10^{10} \) years implies a mean past SFR in the range \( \langle R \rangle = 0.6-4 \, M_\odot/\text{yr} \) for the four galaxies. In all four cases, this is significantly higher than the current rates of \( 0.02 - 0.3 \, M_\odot/\text{yr} \). The ratio of present to past rates, \( \text{SFR}/\langle R \rangle \) (Table 8) lies between 0.02 and 0.5. Thus these galaxies appear to have had a different star–formation history from the late–type disks studied by Kennicutt (1983).

Searle et al. (1973) present model broad–band colours for galaxies which are \( 10^{10} \) years old and have an exponentially–declining SFR (\( \propto e^{-\beta t} \)). The broad–band colours in Table 1 are consistent
with their models for a Salpeter IMF and $\beta \sim 1$ if $t$ is in units of $10^{10}$ yr. This is a very slow decline in SFR compared to the giant ellipticals, whose colours are consistent with $\beta > 10$.

The $UBV$ colours of the galaxies studied here, along with the current star–formation rate estimated from $H\alpha$ emission lines, are consistent with these low–luminosity star–forming E/S0 and S0 galaxies having a star formation history intermediate between late–type spiral disks (which have a roughly constant SFR) and giant ellipticals (which have had little or no recent star formation). However, it is also important to point out that within our small sample we see considerable variation in the current SFR. The two most ‘active’ star formers, NGC 2328 and ESO 118–G34 have a SFR 5–15 times higher than NGC 802 and ESO 027–G21, even though all four galaxies have a similar $H\ I$ content.

Column 7 of Table 8 gives the gas depletion time for the four galaxies, i.e. the time after which the total supply of $H\ I$ will be exhausted if star formation continues at the present rate. For the two galaxies with lower SFRs, the gas depletion time is very long, whereas in NGC 2328 and ESO 118–G34 it is of order $10^{9}$ years (i.e. comparable to the value in many spiral disks; Kennicutt 1983). Note, however, that these estimates assume that there is no recycling of the ISM through stellar mass loss. Kennicutt, Tamblyn & Congdon (1994) show that including a proper time–dependent treatment of the gas return from stars extends the gas lifetimes of disks by factors of between 1.5 and 4. This would imply gas depletion times of several Gyr even for NGC 2328 and ESO 118–G34.

The discussion above assumes that the $H\ I$ disks in these galaxies are long–lived so that star formation can continue over a Hubble time. However, as discussed earlier, the $H\ I$ in two of our galaxies (NGC 802 and ESO 118–G34) may have been accreted within the past $5 \times 10^{8}$ years or so. The current optical data do not rule out a small burst of recent star formation overlaid on a much older stellar population, and a more detailed study of the stellar population, measuring radial and line-strength and colour gradients, would be useful to pin down the star formation history of these galaxies more precisely.

6. The FIR–radio correlation

Since our four galaxies appear to be forming stars at a reasonable rate, it is interesting to see how they behave with respect to the well–known correlation between the far-infrared (FIR) emission and the radio continuum emission (the so-called FIR–radio correlation) observed for spiral galaxies (e.g. Helou et al. 1985; Wunderlich et al. 1987, see Condon 1992 for a review).

The slope of the FIR–radio correlation is somewhat steeper than 1, especially if low-luminosity galaxies are included in the samples studied (Fitt et al. 1988, Cox et al. 1988, Devereux & Eales 1989). The properties of the four galaxies we studied are also consistent with a steeper slope. This can be quantified by calculating the FIR/radio ratio $q$ at 1.4 GHz following Helou et al. (1985):

$$q = \log[(S_{\text{FIR}} / 3.75 \times 10^{12} \text{ Hz})/S_{1.4}]$$
where \( S_{\text{FIR}} = 1.26 \times 10^{-14} [2.58 \cdot S_{60} + S_{100}] \), with \( S_{60} \) and \( S_{100} \) the IRAS flux densities in Jy at 60 and 100 \( \mu \)m respectively and \( S_{1.4} \) is the continuum flux density at 1.4 GHz in W m\(^{-2}\) Hz\(^{-1}\) (1 Jy = \( 10^{-26}\) W m\(^{-2}\) Hz\(^{-1}\)). The calculated values of \( q \) are given in Table 7. The median value of \( q \) for our galaxies is 2.60. The values of \( q \) are significantly higher than the mean value of 2.14 ± 0.14 measured for a sample of 38 more luminous spiral galaxies by Helou et al. (1985). This means that they lie below a FIR–radio correlation with slope 1, as used by Helou et al.

Our galaxies do follow the steeper correlation found by e.g. Devereux and Eales (1989). As shown in Figure 9, all the galaxies (except NGC 1705, as noted by Meurer et al. 1998) turn out to have a radio luminosity very close to that predicted from their FIR luminosity (represented by the solid line). Thus the galaxies studied here are similar to spiral galaxies with a similarly low FIR luminosity. In principle it is possible that we could have underestimated the radio continuum flux densities by a factor of 2–3 by resolving out very extended emission. However, this would require most of the radio continuum emission to be much more extended than the optical galaxy and probably more extended than the H I disk as well, which seems very unlikely.

One explanation for the steeper slope of the FIR–radio correlation is that the FIR emission consists of two components. One component is directly related to the on-going star formation, while the other is a ‘cirrus’ component more related to the H I emission of the disk (e.g. Devereux and Eales 1989). In galaxies of low luminosity the contribution of the second component could be higher than in more luminous galaxies, so that low–luminosity galaxies would appear over–luminous in the FIR compared to their radio flux. An alternative explanation is that the radio luminosity might be deficient in low–luminosity galaxies because the cosmic rays are more likely to escape by diffusion (Chi and Wolfendale 1990).

In the four galaxies studied here, there is direct evidence for massive star formation since H II regions are seen. We also know that the dust content of these galaxies is relatively low (at least compared to their neutral gas content – see §5 and Table 6) and the FIR dust temperature (35–40 K; see Table 7) similar to that seen in typical S0s and spirals. Thus the most plausible explanation for the observed high values of \( q \) appears to be a deficit of radio continuum emission rather than an FIR excess.

The radio continuum emission from spiral galaxies has three main components (e.g. Condon 1992):

1. Thermal (free–free) emission from H II regions
2. Non–thermal synchrotron emission from supernova remnants (SNRs)
3. Large–scale non–thermal emission associated with the galaxy’s disk.

In spiral galaxies, radio emission from SNRs contributes no more than 3–10% of the total emission (e.g. Helou et al. 1985), and non–thermal disk emission is always the dominant component (though its relative contribution may vary with frequency). Figure 10 plots \( L_{\text{H}\alpha} \) luminosity \( L_{\text{H}\alpha} \) versus 1.4 GHz radio power \( P_{1.4} \). For three of the four galaxies (the exception is ESO 027–G21), the entire radio continuum output can be accounted for by thermal (free–free) radio emission from
the HII regions which produce the Hα photons. It therefore appears that these three galaxies have no significant non–thermal disk emission in the radio continuum, probably due to the absence of the magnetic field necessary to generate synchrotron emission.

The remaining galaxy, ESO 027–G21 (which is also the brightest of the four), has radio continuum emission well in excess of that expected from the thermal emission of its HII regions. This galaxy nevertheless has a high q, so it may be that non–thermal disk emission is present but at a lower level than would be expected for a spiral galaxy.

7. Discussion and Conclusions

7.1. H I characteristics

The observations presented in this paper confirm that if H I is present in a low–luminosity early-type galaxy, it usually lies in a disk–like structure. These H I structures show, in varying degrees, regular rotation while their density profiles are centrally concentrated. The central H I densities are high enough for star formation to occur. Our observations bring the number of low–luminosity early–type galaxies for which imaging H I data are available to about 10. In almost all of these galaxies the H I lies in disks or disk–like structures with high central densities. In agreement with the findings of e.g. Lake et al. (1987), our data suggest that in some galaxies a significant fraction of the H I has been accreted relatively recently. In other galaxies the distribution and kinematics of the H I do not show signs of any recent accretion event and the gas must have been present in the galaxy, and in a disk, for a significant time.

These characteristics differ from what is observed in more luminous early–type galaxies. One main difference appears to be that central densities similar to those observed in low–luminosity early–type galaxies (and the associated star formation) are seldom found in more luminous early–type galaxies, even if they have a regular H I disk (e.g. Oosterloo et al. 1999a, 1999b). The peak H I surface densities in luminous early–type galaxies are generally below \(2 \, M_\odot \, pc^{-2} \) and the locations of the maximum surface densities are usually at large radius and not near the center. In fact, the H I distribution in such galaxies often shows a central hole (e.g. Lake et al. 1987). In contrast, the central surface densities in low–luminosity early–type galaxies appear to be more similar to those in late–type spirals. The H I surface densities at larger radii do seem to be similar in low–luminosity and in luminous early–type galaxies.

Another difference appears to be that the range in morphology and kinematics of the H I in such galaxies is larger than in low–luminosity galaxies. More or less regular H I structures have been observed in some luminous early–type galaxies (e.g. NGC 807 Dressel 1987, NGC 2974 Kim et al. 1988, NGC 3108 Morganti et al. 1999), but in many luminous early–type galaxies the H I has quite an irregular morphology, where the H I usually consists of filaments at large radii (e.g. NGC 2865 Schiminovich et al. 1995; IC 1459 Oosterloo et al. 1999a). Counterparts of such cases do not
appear to exist at lower luminosity, or are at least much less common.

In general, the H I content of luminous early–type galaxies depends on (at least) three factors (e.g. Knapp et al. 1985, Roberts et al. 1991, van Gorkom and Schiminovich 1997). Since the H I content correlates with the presence of optical peculiarities, the H I must have an external origin in many early-type galaxies and is the remnant of an accretion/merger event. However, the H I content is also an indicator of how ‘disky’ an early–type galaxy is because it also correlates with the presence of a (usually faint) disk component. It is still conceivable that in galaxies of this latter group the H I also is accreted, but this then must have happened a very long time ago allowing the gas to settle in a disk. Alternatively, the H I may have been accreted in a number of small accretion events over a long period that would not disrupt the galaxy and would allow a disk to form. A third factor is that the H I content depends on environment.

Although, as in luminous early–type galaxies, evidence is observed that both accretion and the presence of a disk play a role in low–luminosity early–type galaxies, it appears that low–luminosity galaxies mostly belong to the second class of objects. This indicates that the evolution of these systems is in general somewhat different than that of many luminous early–type galaxies. The fact that in those low–luminosity early–type galaxies where the H I properties indicate that a significant fraction of the H I is accreted, the H I structures are still relatively regular, suggests that the H I has been accreted through less violent events than in early–type galaxies of higher luminosity.

The different H I properties parallel the structural differences that are observed at other wavelengths between low–luminosity and luminous early–type galaxies, and that also point to a different evolutionary path for low-luminosity galaxies. For example, in low–luminosity early–type galaxies the stellar rotation is in general more important than in more luminous early–type galaxies (e.g. Kormendy & Bender 1996). It has recently been suggested that this argues against major mergers as the dominant mechanism in the final shaping of low–luminosity early–type galaxies and favors instead the dissipative formation of a disk (Rix, Carollo and Freeman, 1999). The lack of chaotic H I structures in low–luminosity early–type galaxies would be consistent with this, as would perhaps the high central H I densities.

Studying a sample of merging galaxies where the progenitors are of roughly equal mass, Hibbard and van Gorkom (1997) found that although large amounts of H I are often present in these systems, by the final stages there is little if any H I within the remnant body. They suggest that in such mergers the atomic gas is efficiently converted into other forms within the main body of the merger remnants. The H I still present in these systems is likely to settle at large radii. The high H I concentrations in low–luminosity early-type galaxies would then suggest that no major merging event has occurred in these galaxies. Alternatively (or additionally), it is also conceivable that the centers of luminous early–type galaxies are too hostile for H I to exist.

Optical emission lines of ionized gas have been observed in many luminous early–type galaxies (e.g. Phillips et al. 1986). The emission–line spectra are usually of the LINER class and are not H II region–like spectra. This indicates that gas is present, but that some mechanism prevents this gas
from being neutral. Mechanisms that have been suggested for this are photoionization by old hot stars and mechanical energy from electron conduction by hot, X-ray emitting gas (e.g. Goudfrooij 1999). It is possible, especially if hot X-ray gas plays a role, that this ionization mechanism does not work in low-luminosity galaxies, so that central concentrations of H I can still build up over time.

7.2. Star formation

Consistent with the high central H I surface densities in the galaxies studied here, star formation is occurring in their central regions. A comparison of past and present star formation rates suggests that these galaxies could have been forming stars steadily, at a slowly declining rate, for the past $10^{10}$ years. The question of whether these galaxies contain a component of primordial H I gas therefore remains open. A slowly declining star formation rate would imply that these galaxies have contained significant amounts of H I during most of their existence, but in some galaxies there are also indications that H I has recently been accreted. A more detailed study of the stellar population would be interesting if it could date the star formation history more accurately. The four galaxies show considerable variation in their current SFR. The two most ‘active’ star formers, NGC 2328 and ESO 118–G34 have a SFR 5–15 times higher than NGC 802 and ESO 027–G21, even though all four galaxies have a similar gas content.

Star formation appears to be limited to the central regions of the galaxies. Our observations are not detailed enough to allow the derivation of the rotation curves of these galaxies. Hence, we cannot do an analysis of the stability of the disks to see whether the star formation is occurring only where it is expected to be. However, we can make an analogy with the starburst dwarf galaxy NGC 1705, which shows many similarities with the galaxies studied here (e.g. star formation only in the central regions). Analysing the stability of the disk of this galaxy, Meurer et al. (1998) found that star formation takes place where the disk is least stable. In NGC 1705 this is only near the center due to the central concentration of the gas. Outside the central region, the surface densities are much lower and the disk becomes stable. It is quite likely that in our four galaxies a similar explanation applies.

Low–luminosity early–type galaxies appear to have similar ratios between the FIR and radio fluxes as spirals of comparable FIR luminosity. Many luminous early–type galaxies deviate from this because their radio emission is dominated by the contribution of an AGN (e.g. Wrobel & Heeschen 1991, Bregman et al. 1992). However such AGN are not present in the galaxies studied here, which are expected to follow the FIR–radio correlation. We suggest that the galaxies observed here are underluminous in the radio continuum compared to more luminous spirals, rather than overluminous in the FIR. The observed radio continuum, except in ESO 027–G21, can be accounted for by thermal emission alone. This suggests that the non–thermal emission, normally the strongest component, is suppressed, and might indicate that cosmic rays are more likely to escape the galaxy by diffusion, possibly due to a weaker magnetic field.
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Fig. 1.— Single–dish H I profiles measured at Parkes.

Fig. 2.— Total H I images (contours) obtained with natural weighting superimposed to optical images from the Digital Sky Survey (DSS) for NGC 802, ESO 118–G34, NGC 2328 and ESO 027–G21. Contour levels for NGC 802 from $2.9 \times 10^{19}$ atoms cm$^{-2}$ to $5.8 \times 10^{20}$ atoms cm$^{-2}$ in steps of $4.3 \times 10^{19}$ atoms cm$^{-2}$. Contour levels for ESO 118-G34 from $3.1 \times 10^{19}$ atoms cm$^{-2}$ to $3.1 \times 10^{20}$ atoms cm$^{-2}$ in steps of $2.4 \times 10^{19}$ atoms cm$^{-2}$. Contour levels for NGC 2328 from $1.0 \times 10^{19}$ atoms cm$^{-2}$ to $2.0 \times 10^{20}$ atoms cm$^{-2}$ in steps of $2.0 \times 10^{19}$ atoms cm$^{-2}$. Contour levels for ESO 027-G21 from $2.4 \times 10^{19}$ atoms cm$^{-2}$ to $8.1 \times 10^{20}$ atoms cm$^{-2}$ in steps of $8.1 \times 10^{19}$ atoms cm$^{-2}$. The linear scale (for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$) is as follows: 1 arcmin = 5.5 kpc for ESO 802; 1 arcmin = 5.2 kpc for NGC 2328; 1 arcmin = 13.5 kpc for ESO 027–G21.

Fig. 3.— H I velocity fields (contours) obtained with natural weighting superimposed to optical images from the Digital Sky Survey (DSS). The velocity contours are in steps of 5 km s$^{-1}$ for NGC 802 ESO 118–G34 and NGC 2328 and in steps of 10 km s$^{-1}$ for ESO 027–G21.

Fig. 4.— Total H I and velocity fields (contours) obtained from the high resolution data (see Table 4) superimposed to optical images from the Digital Sky Survey (DSS) for NGC 802, ESO 118–G34, NGC 2328 and ESO 027–G21 (velocity contours as in Fig.3). Contour levels for NGC 802 from $1.13 \times 10^{20}$ atoms cm$^{-2}$ to $1.13 \times 10^{21}$ atoms cm$^{-2}$ in steps of $1.13 \times 10^{20}$ atoms cm$^{-2}$. Contour levels for ESO 118-G34 from $6.1 \times 10^{19}$ atoms cm$^{-2}$ to $6.1 \times 10^{20}$ atoms cm$^{-2}$ in steps of $6.1 \times 10^{19}$ atoms cm$^{-2}$. Contour levels for NGC 2328 from $2.5 \times 10^{19}$ atoms cm$^{-2}$ to $2.5 \times 10^{20}$ atoms cm$^{-2}$ in steps of $2.5 \times 10^{19}$ atoms cm$^{-2}$. Contour levels for ESO 027-G21 from $6.0 \times 10^{19}$ atoms cm$^{-2}$ to $6.0 \times 10^{20}$ atoms cm$^{-2}$ in steps of $6.0 \times 10^{19}$ atoms cm$^{-2}$.

Fig. 5.— Position-velocity plots for (top) NGC 802 low and high resolution in p.a. 90$^\circ$; (middle) ESO 118–G34 in p.a. 160$^\circ$ and NGC 2328 in p.a. 110$^\circ$; (low) ESO 027–G21 in p.a. 80$^\circ$. Contour levels for NGC 802 low resolution from 2 to 23 mJy beam$^{-1}$ in step of 2mJy beam$^{-1}$ and from 2.5 to 13 mJy beam$^{-1}$ in step of 1.5mJy beam$^{-1}$ for the high resolution. Contour levels for ESO 118-G34 from 2.5 to 15 mJy beam$^{-1}$ in step of 1mJy beam$^{-1}$. Contour levels for NGC 2328 from 2.0 to 11 mJy beam$^{-1}$ in step of 1mJy beam$^{-1}$. Contour levels for ESO 027-G21 from 3.0 to 30 mJy beam$^{-1}$ in step of 2.5mJy beam$^{-1}$.

Fig. 6.— Optical spectra and rotation curves for (a) NGC 802 and (b) ESO 027–G21.

Fig. 7.— Radial H I surface density profiles for the four galaxies. For all four galaxies, crosses show the profiles measured from natural–weighting maps. For NGC 802 and ESO 118–G34, the open circles show the profiles derived from higher–resolution observations. For NGC 2328 and ESO 027–G21, open circles show profiles measured from maps made with natural rather than uniform weighting. The vertical dashed lines show the outer limit of star–forming regions in each galaxy.
Fig. 8.— Total H I of images for two companion galaxies: Top: AM 0155–675 in the field of NGC 802. Contour levels from $1.13 \times 10^{20}$ atoms cm$^{-2}$ to $4.52 \times 10^{20}$ atoms cm$^{-2}$ in steps of $1.13 \times 10^{20}$ atoms cm$^{-2}$. Bottom: anonymous galaxy in the field of ESO 027–G21. Contour levels from $2.2 \times 10^{19}$ atoms cm$^{-2}$ to $8.0 \times 10^{20}$ atoms cm$^{-2}$ in steps of $6.0 \times 10^{19}$ atoms cm$^{-2}$.

Fig. 9.— The FIR–radio correlation for four galaxies observed here, together with the four small H I–rich ellipticals observed by Lake et al. (1987) (NGC 3265, NGC 5666, UGC 7354 and A1230+09) and the blue compact galaxy NGC 1705 (Meurer et al. 1998). The solid line shows the relation derived for spirals by Devereux and Eales (1989), which has a slope of 1.28.

Fig. 10.— Comparison of H$\alpha$ emission–line luminosity and radio continuum flux density for the four galaxies (the radio continuum point for NGC 802 is an upper limit). The solid line shows the relation expected for H II regions (Terzian 1965).
Table 1: Optical properties of the four galaxies

|                | NGC 802 | ESO 118–G34 | NGC 2328 | ESO 027–G21 |
|----------------|---------|-------------|----------|-------------|
| RA (J2000.0)   | 01 59 07.1 | 04 40 17.2 | 07 02 36.7 | 23 04 19.6 |
| Dec            | −67 52 11 | −58 44 47 | −42 04 09 | −79 28 01 |
| Type           | E/S0    | S0          | E/S0     | S0          |
| \(B_T^0\)     | 14.12   | 13.49       | 12.54    | 13.38       |
| \((B - V)_T^0\) | 0.43    | 0.45        | 0.49     | –           |
| \((U - B)_T^0\) | −0.15   | −0.36       | 0.09     | –           |
| \(r_e\) (arcsec,kpc) | 16.5(2.1) | 13.1(1.2) | 17.3(1.5) | 19.0(4.3) |
| \(v_{hel}\) (km s\(^{-1}\)) | 1505 | 1171 | 1159 | 2504 |
| \(v_{hel}\) (km s\(^{-1}\)) | 1475 ± 5 | 1150 ± 5 | 1168 ± 5 | 2480 ± 5 |
| \(v_0\) (km s\(^{-1}\)) | 1321 | 941 | 884 | 2316 |
| Distance (Mpc) | 26.4 | 18.8 | 17.7 | 46.3 |
| \(M_B\) (mag) | −18.0 | −17.9 | −18.7 | −19.9 |
| \(L_B\) (\(L_\odot\)) | \(2.2 \times 10^9\) | \(2.1 \times 10^9\) | \(4.4 \times 10^9\) | \(1.4 \times 10^{10}\) |

Note. — References: a) revised RC3 b) ESO/Uppsala cat. c) Sadler (1984) d) this paper
Table 2: Single-dish H I observations at Parkes

| Galaxy      | $V_{\text{central}}$ (km s$^{-1}$) | Range (km s$^{-1}$) | On-source time (min) | Total H I flux (Jy km s$^{-1}$) | FWHM (km s$^{-1}$) | H I mass (M$_{\odot}$) |
|-------------|------------------------------------|---------------------|----------------------|---------------------------------|-------------------|-------------------|
| NGC 802     | 1475                               | 500–2650            | 20                   | 5.9                             | 73                | $9.7 \times 10^8$  |
| NGC 2328    | 1167                               | 695–1760            | 30                   | 4.4                             | 111               | $3.3 \times 10^8$  |
| ESO 027-G21 | 2480                               | 1530–3650           | 40                   | 10.8                            | 154               | $5.5 \times 10^9$  |
Table 3: Log of ATCA Observations

| Galaxy     | Date  | Configuration | Baseline range (m) | Frequency (MHz) | Time |
|------------|-------|---------------|--------------------|-----------------|------|
| NGC 802    | Jan95 | 375           | 31–459             | 1413 (1380)     | 12h  |
| NGC 802    | Feb96 | 1.5C          | 77–1485            | 1413 (1346)     | 12h  |
| ESO 118–G34 | Dec96 | 375           | 31–337             | 1415 (1344)     | 12h  |
| ESO 118–G34 | Mar97 | 1.5D          | 214–1439           | 1415 (2396)     | 12h  |
| NGC 2328   | Nov96 | 750A          | 77–735             | 1415 (1344)     | 12h  |
| ESO 027-G21 | Nov96 | 750A          | 77–735             | 1409 (1344)     | 12h  |
Table 4: Instrumental Parameters of the ATCA observations

|                  | NGC 802 | ESO 118–G24 | NGC 2328 | ESO 027–G21 |
|------------------|---------|-------------|----------|-------------|
| RA (J2000.0)     | 01 59 07 | 04 40 08    | 07 02 36 | 23 04 19    |
| Dec              | −67 52 40 | −58 45 59   | −42 04 09 | −79 30 01   |
| Synthesized beam (natural weighting) | 68.1'' × 54.6'' | 60.9'' × 58.0'' | 79.7'' × 56.4'' | 64.8'' × 49.2'' |
| Beam p.a.        | −11°    | 0°          | 6°       | −45°        |
| Synthesized beam (weighting) | 37.0'' × 25.0'' | 25.0'' × 23.0'' | 56.0'' × 41.0'' | 54.3'' × 40.4'' |
| Beam p.a.        | 0°      | −2°         | 0°       | −40°        |
| Number of channels | 512     | 512         | 512      | 512         |
| Central velocity (km s$^{-1}$) | 1580 | 1150 | 1150 | 2420 |
| Velocity resolution (after Hanning) (km s$^{-1}$) | 6.0 | 6.0 | 6.6 | 6.6 |
| rms noise in channel maps (nat. weight, mJy beam$^{-1}$) | 1.1 | 1.5 | 1.2 | 1.5 |
Table 5: Radio continuum observations of the four galaxies.

| Galaxy          | Array       | Freq. | Beam, PA             | Flux density (mJy) | rms (mJy) | Notes      |
|-----------------|-------------|-------|----------------------|-------------------|-----------|------------|
|                 | (GHz)       |       | (arcsec)             | Peak              | Total     |            |
| NGC 802         | 375+1.5     | 1.3   | 24.1 × 20.6 (24)     | <1.9              | –         | 0.37       |
|                 | 1.5C        | 1.3   | 7.5 × 5.4 (-75)      | <1.0              | –         | 0.19       |
| ESO 118–G34     | 375+1.5     | 1.3   | 20.3 × 18.5 (-2)     | 4.0               | 7.0       | 0.21       |
|                 | 1.5D        | 1.3   | 8.9 × 8.3 (-7)       | 2.8               | 6.5:      | 0.36       |
| NGC 2328        | 750A        | 1.3   | 55.9 × 41.6 (6)      | 8.1               | 9.4       | 0.13       |
|                 | 750A        | 1.3   | 8.3 × 6.2 (5)        | 3.1               | 8.3       | 0.11       |
| ESO 027–G21     | 750A        | 1.3   | 42.0 × 39.8 (42)     | 4.8               | 4.7       | 0.20       |
|                 | 750A        | 1.3   | 6.2 × 5.9 (-41)      | 1.5               | 3.7       | 0.10       |
| ESO 118–G34     | 375+1.5     | 2.5   | 17.5 × 14.9 (-8)     | 3.1               | 4.8       | 0.05       |
|                 | 1.5D        | 2.4   | 10.1 × 8.8 (-1)      | 1.9               | 4.4       | 0.07       |

Notes:
- Not detected
- 6 km ant.
Table 6: Components of the ISM in the four galaxies.

|       | NGC 802 | ESO 118–G34 | NGC 2328 | ESO 027–G21 |
|-------|---------|-------------|----------|------------|
| $M_{\text{HI}}$ ($M_\odot$) | 9.7 x 10^8 | – | 3.3 x 10^8 | 5.5 x 10^9 | a |
| $M_{\text{HI}}$ ($M_\odot$) | 7.6 x 10^8 | 2.5 x 10^8 | 2.0 x 10^8 | 4.7 x 10^9 | b |
| $M_{\text{HI}}/L_B$ | 0.42 | 0.12 | 0.07 | 0.40 |
| $M_{\text{H}_2}$ ($M_\odot$) | – | 2.9 x 10^8 | – | – | c |
| $M_{\text{H}_2}/M_{\text{HI}}$ | – | 0.87 | – | – |
| $L_{\text{H}_\alpha}$ (W) | 2.3 x 10^{32} | 3.2 x 10^{33} | 3.6 x 10^{33} | 7.8 x 10^{32} |
| $M_{\text{HII}}$ ($M_\odot$) | 5.5 x 10^3 | 7.3 x 10^4 | 8.3 x 10^4 | 1.8 x 10^4 |
| $S_{\text{60\mu m}}$ (mJy) | 380 | 2090 | 2770 | 780 | d |
| $S_{\text{100\mu m}}$ (mJy) | 830 | 3190 | 3770 | 1800 | d |
| $L_{\text{FIR}}$ ($L_\odot$) | 4.6 x 10^8 | 1.1 x 10^9 | 1.3 x 10^9 | 3.0 x 10^9 |
| $M_{\text{dust}}$ ($M_\odot$) | 1.5 x 10^5 | 1.7 x 10^5 | 1.5 x 10^5 | 1.1 x 10^6 |
| $M_{\text{HI}}/M_{\text{dust}}$ | 6415 | 1456 | 2144 | 4944 |

Note. — (a) From single–dish data, (b) from ATCA data, (c) Wiklind et al. (1995) (d) Knapp et al. (1989).
Table 7: Star formation properties of the four galaxies.

|                         | NGC 802 | ESO 118–G34 | NGC 2328 | ESO 027–G21 |
|-------------------------|---------|-------------|----------|-------------|
| SFR (> 10 $M_\odot$) ($M_\odot$/yr) | 0.003   | 0.046       | 0.051    | 0.011       |
| SFR (total) ($M_\odot$/yr)       | 0.021   | 0.29        | 0.32     | 0.070       |
| SFR (rel. to NGC 802)        | 1.0     | 13.8        | 15.2     | 3.3         |
| log $P_{1.4}$(total) (W/Hz)   | <19.93  | 20.47       | 20.55    | 21.09       |
| FIR/radio ratio $q$          | >2.78   | 2.61        | 2.59     | 2.43        |
| $L_{FIR}/L_B$                | 0.20    | 0.53        | 0.28     | 0.22        |
| $T_{60/100\mu m}$            | 36 K    | 41 K        | 43 K     | 35 K        |
Table 8: Timescales for star formation.

| Galaxy   | SFR  \((M_\odot/\text{yr})\) | \(T_{\text{dust}}\) (K) | \(M_{\text{HI}}/L_B\) | Est. \(M_{\text{stars}}\) \((M_\odot)\) | SFR  \(\langle R \rangle\) \((M_\odot)\) | \(T(\text{H I depletion})\) (yr) |
|----------|-------------------------------|--------------------------|----------------------|---------------------------------|---------------------------------|---------------------------------|
| NGC 802  | 0.021                         | 36                       | 0.42                 | 6.6\times10^9                   | 0.032                           | 7 \times 10^{10}               |
| ESO 027–G21 | 0.070                        | 35                       | 0.40                 | 4.2\times10^{10}               | 0.017                           | 8\times10^{10}                |
| ESO 118–G34 | 0.29                         | 41                       | 0.12                 | 6.3\times10^9                   | 0.46                             | 8\times10^{8}                 |
| NGC 2328  | 0.32                          | 43                       | 0.07                 | 1.3\times10^{10}               | 0.25                             | 2\times10^{9}                 |
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