The ATLAS$^{3D}$ Project – XI. Dense molecular gas properties of CO-luminous early-type galaxies

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ABSTRACT
Surveying eighteen $^{12}\text{CO}$-bright galaxies from the ATLAS$^{3D}$ early-type galaxy sample with the Institut de Radio Astronomie Millimétrique (IRAM) 30m telescope, we detect $^{13}\text{CO}(1-0)$ and $^{13}\text{CO}(2-1)$ in all eighteen galaxies, HCN(1-0) in 12/18 and HCO$^+$(1-0) in 10/18. We find that the line ratios $^{12}\text{CO}(1-0)/^{13}\text{CO}(1-0)$ and $^{12}\text{CO}(1-0)/\text{HCN(1-0)}$ are clearly correlated with several galaxy properties: total stellar mass, luminosity-weighted mean stellar age, molecular to atomic gas ratio, dust temperature and dust morphology. We suggest that these correlations are primarily governed by the optical depth in the $^{12}\text{CO}$ lines; interacting, accreting and/or starbursting early-type galaxies have more optically thin molecular gas while those with settled dust and gas discs host optically thick molecular gas. The ranges of the integrated line intensity ratios generally overlap with those of spirals, although we note some outliers in the $^{12}\text{CO}(1-0)/^{13}\text{CO}(1-0)$, $^{12}\text{CO}(2-1)/^{13}\text{CO}(2-1)$ and HCN/HCO$^+$ (1-0) ratios. In particular, three galaxies are found to have very low $^{12}\text{CO}(1-0)/^{13}\text{CO}(1-0)$ and $^{12}\text{CO}(2-1)/^{13}\text{CO}(2-1)$ ratios. Such low ratios may signal particularly stable molecular gas which creates stars less efficiently than 'normal' (i.e. below Schmidt-Kennicutt prediction), consistent with the low dust temperatures seen in these galaxies.

Key words: galaxies: elliptical and lenticular, cD – galaxies: ISM – galaxies: stellar content – galaxies: evolution – galaxies: kinematics and dynamics

1 INTRODUCTION
Molecular gas is an essential ingredient for star formation found in many, but not all, galaxies. Early-type galaxies (ellipticals and lenticulars) were classically thought to completely lack molecular gas and to be passively-evolving ‘red and dead’ galaxies. However, we have long known that not all early-types are empty of cold gas; molecular gas was first detected in early-type galaxies by Wiklind & Rydbeck (1988) and Phillips et al. (1987).

Shortly after these first detections, surveys detected 10-20 galaxies, but were biased towards early-types with particular properties, such as those bright in the far infra-red (Wiklind & Henkel 1989; Sage & Wrobel 1989) or with optically obscuring dust (Wang et al. 1992). These selection effects made it easy to dismiss any early-type galaxies with molecular gas as peculiar systems. The next generation of surveys increased numbers (30-50 galaxies) and were less biased, if still not complete (Welch & Sage 2003; Sage et al. 2007; Combes et al. 2007). In Young et al. (2011; hereafter Paper IV), we have recently completed an extensive (259 galaxies) molecular gas detection campaign for the volume-limited ATLAS$^{3D}$ sample of early-type galaxies (Cappellari et al. 2011a; hereafter Paper I). We find a 22% detection rate, down to a typical detection threshold of $6 \times 10^{-17} \text{M}_\odot \text{Hz}^{-1}$, robustly establishing that many early-type galaxies host a substantial amount of molecular gas.

The majority of early-type galaxies with molecular gas are obviously star-forming, based on ultraviolet (UV), optical or infrared data. Indeed, the detection rate for star formation seen in UV nearly matches the molecular detection rate ($\approx 30\%$, Kaviraj et al. 2007). According to the current observations, the star formation efficiencies of early-type galaxies broadly follow the Kennicutt-Schmidt law (Shapiro et al. 2010; Crocker et al. 2011). A subset shows no obvious sign of ongoing star formation (Crocker et al. 2008, 2011), although these determinations are difficult due to their very low specific star formation rates. Recently, Saintonge et al. (2011) have determined that star formation efficiencies are reduced for more massive, more concentrated and higher stellar surface density galaxies, all properties that positively correlate with early-type morphology.

In a spiral galaxy, the presence of a stellar disc renders the gas disc more locally unstable to axisymmetric perturbations, likely boosting its star formation efficiency (e.g. Jog & Solomon 1984). In Krajnović et al. (2011, hereafter Paper II) and Emsellem et al. (2011, hereafter Paper III), we found that the vast majority of early-type galaxies (the fast rotators) are consistent with being a family of disc-like systems resembling spiral galaxies with the gas and dust removed (Cappellari et al. 2011b, hereafter Paper VII). However, the fast rotators are generally characterized by larger spheroids than spiral galaxies. This increase in the depth of the potential well is expected to make their gas discs more stable against fragmentation (Kawata et al. 2007).

Indeed, simulations with a centrally-concentrated stellar mass distribution (as found in spheroids) and no stellar disc show that the cool gas is more stable than in spiral galaxies (Martiz et al. 2009). This stability (termed ‘morphological quenching’) should lower the efficiency of star formation and produce a cool interstellar medium (ISM) with properties (velocity dispersion, density distribution, etc.) different from those of galaxies with stellar discs. In this paper, we present the first major attempt at constraining the empirical properties of the molecular gas in early-type galaxies, especially looking for any divergence from the properties found for spiral galaxies.

The surveys mentioned above have used the bright $^{12}\text{CO}(1-0)$ emission line to measure the total molecular content of early-type galaxies, but little work has been done to constrain the molecular gas properties using other species and transitions. Several other molecular species are bright enough to measure, including $^{13}\text{CO}$, HCN and HCO$^+$. These species have been widely observed in starburst and Seyfert galaxies and also in some local spiral galaxies.

The observed $^{12}\text{CO}/^{13}\text{CO}$ ratio is widely used to indicate the average optical depth of the molecular gas, although it may also be influenced by chemical processes. The $^{12}\text{CO}$ isotope is far more...
abundant and becomes optically thick at lower H$_2$ column densities. Its use as a measure of the total molecular hydrogen content (via one of the $^{12}$CO-H$_2$ conversion factors $X_{CO}$ or $\alpha_{CO}$) relies on the assumption that it is optically thick, and essentially counts the number of virialized molecular clouds of a similar temperature and density (e.g. Young & Scoville 1991). The less abundant $^{13}$CO isotope is optically thin until higher column densities and thus the $^{12}$CO/$^{13}$CO ratio (often denoted $\Psi$) should reflect differences in average optical depth in $^{12}$CO, either within the molecular clouds themselves or because of the additional contribution of a diffuse molecular component. Variations in the $^{12}$C to $^{13}$C abundance ratio and $^{12}$CO-$^{13}$CO fractionation (due to charge-ion reactions or selective photodissociation) must also be considered, although they do not seem to drive this ratio in spiral galaxies (Papadopoulos et al. 2001).

The HCN(1-0) and HCO$^+$(1-0) lines have higher critical densities (approximately $10^5$ and $10^6$ cm$^{-3}$, respectively) than CO(1-0) ($n_{crit} \approx 10^4$ cm$^{-3}$). The critical density is simply the density at which collisions are more frequent than radiative decays, not a strict limit with no emission at lower densities. Thus depending on the density distribution of the molecular gas, the typical gas density probed by the HCN(1-0) and HCO$^+$(1-0) transitions will vary from system to system, although in all cases it will be higher than the densities probed by CO(1-0).

Higher HCN/$^{12}$CO and HCO$^+$/$^{12}$CO ratios in luminous infrared galaxies (LIRGs) and ultra-luminous infrared galaxies (ULIRGs) are thus taken to indicate higher dense gas fractions in these galaxies (Gao & Solomon 2004; Graciá-Carpio et al. 2006). The more moderate increase of HCO$^+$/$^{12}$CO compared to HCN/$^{12}$CO in these systems may be explained by the order of magnitude difference in the critical densities of HCN(1-0) and HCO$^+$(1-0) (Juneau et al. 2003). In both the Milky Way and M31, the HCN/$^{12}$CO ratio declines with radius, signaling the decline of the dense gas content (Helfer & Blitz 1997; Brouillet et al. 2003). Indeed, Helfer & Blitz (1997) find that the HCN(1-0)/$^{13}$CO(1-0) ratio correlates with the hydrostatic pressure in the disc: HCN(1-0)/$^{13}$CO(1-0) $\propto P_{\lambda}/10^{15}$

Molecular chemistry can also influence the HCN and HCO$^+$ emission seen in galaxies. X-ray dominated regions (XDRs) around active galactic nuclei (AGN) may enhance the HCN abundance relative to CO (e.g. Lrrp & Dalgarno 1996). This effect has been observed in Seyfert galaxies and led to the recommendation to prefer HCN as a dense gas tracer (Graciá-Carpio et al. 2006; Krips et al. 2007). However, Papadopoulos (2007) warn about possible effects of free electrons in cosmic-ray dominated regions (CRDRs) and XDRs, or highly turbulent molecular clouds destroying HCO$^+$. Nevertheless, most of these chemical effects rely on the conditions found in starbursts or AGN, and hence HCN and HCO$^+$ are likely to remain good tracers of dense gas in more quiescent regimes.

Until recently, the only early-type galaxy to be studied in molecular species other than $^{12}$CO was Centaurus A (Cen A), with its striking lane of dust and gas. The $\approx 5 \times 10^8$ M$_\odot$ of molecular gas in its disc extends to about 2.6 kpc (Phillips et al. 1987; Eckart et al. 1990), while $4 \times 10^8$ M$_\odot$ of atomic gas is seen in a warped disc out to about 6 kpc (van Gorkom et al. 1990; Struve et al. 2010). While often considered a galaxy completely in its own class, its molecular and atomic gas content is not very different to that of some of our sample galaxies. In terms of molecular emission line studies, Wild et al. (1997) found a $^{12}$CO(1-0)/$^{13}$CO(1-0) ratio of 14 towards the center of Cen A and 11 towards two positions in its disc, similar values as found in spirals. As for HCN, Wild & Eckart (2000) find a higher ratio of HCN(1-0)/$^{12}$CO(1-0) in the center (0.067) than in offset positions along the disc (0.02-0.04).

In Krips et al. (2010), the $^{13}$CO(1-0), $^{12}$CO(2-1), HCN(1-0) and HCO$^+$(1-0) emission lines of four early-type galaxies were measured as a pilot project for this work. Two of these galaxies have particularly low $^{12}$CO(1-0)/$^{13}$CO(1-0) ratios of around 3 and two have more typical ratios of around 10. The HCN(1-0)/HCO$^+$(1-0) and HCN(1-0)/$^{12}$CO(1-0) ratios are in the range observed for spiral and Seyfert galaxies, but lower than for starbursts. Most curiously, none were detected in HCO$^+$(1-0), despite 3/4 being detected in HCN(1-0), which usually has a similar integrated intensity. In one case, the HCN(1-0)/HCO$^+$(1-0) ratio is constrained to be larger than 2, indicating some significant difference in the chemical or physical properties of this galaxy’s molecular gas compared to those of spiral, Seyfert and starburst galaxies.

In this paper, we extend the original sample of 4 early-type galaxies from Krips et al. (2010) to a sample of 18 galaxies from the ATLAS$^{3D}$ sample. Section 2 describes the sample selection and Section 3 describes our observations and data reduction. We compare the profiles of the different molecular lines within each galaxy and discuss the derived line ratios in Section 4. In Section 4, we also investigate the variations of the molecular line ratios with other galaxy properties. Our conclusions are presented in Section 5.
2 SAMPLE

We draw our sample from the \(^{12}\text{CO}(1-0)\) detections of Paper IV which presents \(^{12}\text{CO}(1-0)\) data on 259 of the 260 early-type galaxies in the ATLAS\(^{3D}\) sample. The ATLAS\(^{3D}\) sample is volume-limited and complete to a distance \(D < 42\) Mpc, with a cut-off absolute magnitude of \(M_K = -21.5\). It includes only early-type galaxies, defined according to classical galaxy morphology [Hubble 1936; Sandage 1961] by the absence of spiral arms (for non-edge on galaxies) or by the lack of galaxy-scale dust lanes (for edge on galaxies). Further details on the sample can be found in Paper I.

Paper IV detects \(^{12}\text{CO}\) in 56/259 of the ATLAS\(^{3D}\) sample galaxies, based on centrally-pointed observations using the Institut de Radio Astronomie Millimétrique (IRAM) 30m telescope. A rms noise of around 3.0 mK (\(T_A^*\)) in \(^{12}\text{CO}(1-0)\) was achieved for every galaxy. With a conversion factor \(X_\text{CO} = 3.0 \times 10^{20}\) cm\(^{-2}\) (K km s\(^{-1}\))^\(-1\), this results in a molecular gas mass detection limit of \(1 \times 10^7\) M\(_\odot\) for the nearest sample galaxies (11 Mpc) and \(1 \times 10^8\) M\(_\odot\) for the furthest sample galaxies (40 Mpc). Due to the expected lower intensity of the \(^{13}\text{CO}(1-0), \, ^{12}\text{CO}(2-1), \, \text{HCN}(1-0), \, \text{HCO}^+(1-0)\) lines, we selected the 18 strongest \(^{13}\text{CO}(1-0)\) detections for follow-up at these frequencies. Both peak brightness temperature and line width were used to determine the ‘strength’ of the \(^{13}\text{CO}(1-0)\) detections. Out of these 18 galaxies, four were previously observed and reported in the Krips et al. (2010) pilot study. Details of the sample galaxies are provided in Table II, including the \(H_\odot\) mass derived in Paper IV.

The necessity of choosing the brightest \(^{12}\text{CO}(1-0)\) detections biases our sample towards galaxies with large molecular gas masses and large molecular gas mass fractions, as can be seen in the top panel of Fig. I. However, using Kolmogorov-Smirnov tests, the 18 galaxies selected are consistent with being a randomly drawn subsample of both the remainder of the CO-detected galaxies and the non-CO detected ATLAS\(^{3D}\) galaxies, with respect to the distribution of their absolute \(K\)-band magnitude, \(\Sigma_K\) (a measure of local environment density; see Paper VII) and \(\lambda_K\) (a measure of the stellar specific angular momentum used to classify galaxies as fast or slow rotators; see Paper III). The distributions of these three parameters are plotted in the bottom panel of Fig. I. The selected subsample is slightly biased with respect to dust temperature (indicated by the \(f_{\text{obs}}/f_{\text{100}}\) ratio) when compared to the other CO detections (top panel of Fig. I). The probability that the two distributions are drawn from the same parent population is only 1.1%, the CO-rich subsample being biased toward higher dust temperatures, but also possibly being more narrowly spread than the other CO detections.

3 IRAM 30M OBSERVATIONS AND DATA REDUCTION

We used the IRAM 30m telescope at Pico Veleta, Spain, to observe the \(^{13}\text{CO}(1-0), \, ^{12}\text{CO}(2-1), \, \text{HCN}(1-0)\) and \(^{12}\text{CO}^+(1-0)\) transitions in July 2009 and April 2010. The Eight Mixer Receiver (EMIR) was used, tuned to either the \(^{13}\text{CO}(1-0)\) or HCN(1-0) redshifted frequency at 3mm and simultaneously to \(^{12}\text{CO}(2-1)\) at 1mm for both 3mm setups. The rest frequencies and beam sizes for each of the lines are specified in Table I. We observed in wobbler-switching mode with reference position offsets of \(\pm 120^\prime\). The Wideband Line Multiple Autocorrelator (WILMA) backend provided a bandwidth of 8 GHz at 2 MHz channel resolution (2 MHz corresponds to 6.7, 5.5 and 2.7 km s\(^{-1}\) at \(^{12}\text{CO}(1-0), \, \text{HCN}(1-0)\) and \(^{12}\text{CO}(2-1), \, \text{respectively}\). This bandwidth is sufficient to observe \(^{12}\text{CO}^+(1-0)\) and HCN(1-0) simultaneously.

System temperatures ranged from 90 to 200 K at 3mm and 250 to 600 K at 1mm. The pointing was checked approximately every 2-3 hours or more frequently during periods of high wind. Focusing was performed at the beginning of the night, after sunrise or sunset, and/or after about 5-6 hours of observing.

Observations for four sample galaxies (NGC 3032, NGC 4150, NGC 4459 and NGC 4526) were taken in August 2008 and published in Krips et al. (2010). We note that these observations used the old SIS receiver and thus a different observing setup than the other 14 galaxies. Observing details are described in Krips et al. (2010).

Conversions from antenna temperature (\(T_A^*\)) to main beam temperature were calculated by dividing by the ratio of the beam and forward efficiencies, \(\eta \equiv B_{\text{eff}}/F_{\text{eff}}\). We used values appropriate for when the observations were taken. For the new observations, values tabulated in the EMIR Commissioning Report were used. To obtain \(B_{\text{eff}}\) and \(F_{\text{eff}}\) values at frequencies not specified in these tables, we linearly interpolated between the two nearest values. The conversion ratios used for the new observations are: \(\eta(\text{HCN})=\eta(\text{HCO}^+) =0.85, \, \eta(\text{HCN}(1-0))=0.75, \, \eta(\text{HCN}(1-0))=0.85, \, \eta(\text{HCN}(2-1))=0.66). \) For the older observations, we base our conversions on the measurements performed in August 2007 and June 2008. For the 1mm values, linear interpolation is again used. However, noting the discrepant values found for the C150 receiver, we follow the approach of Paper IV for the 3mm values. The 3mm \(B_{\text{eff}}\) values are based on the aperture efficiency plot on p. 15 of the IRAM 2007 Annual Report \(B_{\text{eff}} =1.21\lambda_{\text{eff}}, \) where \(\lambda_{\text{eff}}\) is the aperture efficiency. This results in: \(\eta(\text{HCN})=\eta(\text{HCO}^+) =0.75, \, \eta(\text{HCN}(1-0))=0.78, \, \eta(\text{HCN}(1-0))=0.78, \, \eta(\text{HCN}(2-1))=0.65 and \eta(\text{HCO}^+(2-1))=0.63\).

Linear baselines were fit to frequencies outside of the expected line region for each scan, then the scans were averaged together weighted by their system temperature. The spectra for four sample galaxies are shown in Fig. II in the \(T_{\text{mb}}\) scale, with the rest in Appendix I. The figures include \(^{12}\text{CO}(1-0)\) and \(^{12}\text{CO}(2-1)\) spectra from Paper IV and Welch & Sage (2003) for comparison.

As all of the galaxies have previous well measured molecular linewidths from the \(^{12}\text{CO}(1-0)\) data, we use this prior knowledge to help ascertain detections and measure integrated intensities. In order for a galaxy to be detected, we require the integrated intensity over its \(^{12}\text{CO}(1-0)\)-detected velocity range to be three times greater than the uncertainty expected over such a velocity width. As in Sage et al. (2007) and Paper IV, the statistical uncertainty of a signal in a sum over \(N_\ell\) channels of width \(\delta v\) and rms noise level \(\sigma\) is \(\sigma_l^2 = (\delta v)^2 \sigma^2 N_\ell (1 + N_0/N_\ell), \) where \(N_0\) is the number of baseline channels used (and thus the \(N_0/N_\ell\) term contributes the uncertainty from estimating the baseline level). The rms noise is measured outside of the range where line emission is expected. If a galaxy is not detected, we give three times the measured uncertainty as an up-
per limit. Integrated intensities with errors are tabulated in Table 5 along with the velocity range integrated over. We note that only the measurement errors are tabulated, systematic uncertainties are also important at around 10%.

4 RESULTS

4.1 Consistency of line profiles

Assuming that the intrinsic velocity dispersion of the molecular gas is low (< 30 km s\(^{-1}\); the channel width), the spectral profile of each molecular line is governed by the velocity field of the galaxy coupled with the spatial distribution of the gas emitting in that line. Changes in spectral shape from line to line can indicate different molecular gas properties at different locations within a galaxy. We thus compare the line profiles of each galaxy, testing for consistency as documented in Appendix B. Briefly, we first determine whether a Gaussian or a double-peaked profile is the best fit to the \(^{12}\)CO(1-0) line. Then, using this best fit functional form, we determine whether the shape parameters (leaving amplitude free) for all other lines are consistent with those derived for the \(^{12}\)CO(1-0) line.

Three galaxies, NGC 1266, NGC 3607 and NGC 4526, have line profiles inconsistent with \(^{12}\)CO(1-0) for all or almost all of their other lines. For NGC 1266 (best fit by a Gaussian), the FWHM is significantly greater in its \(^{12}\)CO(2-1), HCN(1-0) and HCO\(^+\)(1-0) lines and is significantly narrower in all \(^{13}\)CO lines (further discussed in Section 4.1). Alatalo et al. (2011) find that NGC 1266’s \(^{12}\)CO(1-0) and \(^{13}\)CO(2-1) line profiles are best fit by two nested Gaussians (with a shared centre). We thus perform such a nested two-Gaussian fit for the other molecular lines of NGC 1266, but find that the two-Gaussian fit does not result in a significantly lower \(\chi^2\) value in these other lines. For NGC 3607 and NGC 4526, the distinct changes in shape are consistent with pointing offsets which preferentially miss one of their double-peak profiles.

Out of all the galaxies, NGC 5866 has the most interesting diversity of line profiles. Despite an asymmetry likely due to pointing in both \(^{12}\)CO lines, it is clearly double-peaked in both \(^{12}\)CO lines, HCN(1-0) and HCO\(^+\)(1-0), while both \(^{13}\)CO lines show a clear single central peak. In this galaxy, the molecular gas must have different properties in the centre and disc.

The line most frequently found to be inconsistent with \(^{12}\)CO(1-0) is the \(^{13}\)CO(2-1) line. These two lines have the highest signal-to-noise ratio and thus their parameters are best constrained, making it harder for them to be formally consistent. The different beam sizes (factor 2) means a smaller region is traced in \(^{12}\)CO(2-1) providing one reason for potential line-profile differences along with gas property variations and, additionally, the \(^{13}\)CO(2-1) is very sensitive to pointing offsets, as clearly seen in NGC 3607, NGC 3665, NGC 4526 and NGC 8566.

At some level, we expect the intrinsic line profiles in the various lines to all be different, due to different local conditions in the molecular gas. Higher signal-to-noise data should show such varying profiles and allow variations in the physical properties of the molecular gas to be studied. However, the relatively low signal-to-noise ratio of our observations does not allow for such detailed work and we thus only consider integrated intensity ratios for the remainder of this paper.

4.2 Line ratio diagnostics

Molecular line ratios are a first step to diagnose the state of the molecular gas within galaxies. Here we compare the line ratios of our early-type galaxies with those of spirals, Seyfert nuclei and starbursts. We also test if the molecular line ratios correlate with other ISM and stellar properties of the galaxies.

We compute the integrated line ratios after using interferometric \(^{12}\)CO(1-0) data (Alatalo et al., in prep.) to estimate beam correction factors for each galaxy. Appendix B tabulates these values and describes the process. This step is necessary, as the transitions we compare are at different frequencies, thus measured over different beam sizes. Corrections from HCN or HCO\(^+\) to \(^{12}\)CO(1-0) are up to 60% in the case of the most centrally-concentrated sources, but the corrections for most sources range between 30-50%. All corrections are under 10% between the \(^{12}\)CO and \(^{13}\)CO lines and no
Table 3. \(^{12}\)CO(1-0), \(^{13}\)CO(1-0), \(^{12}\)CO(2-1), \(^{13}\)CO(2-1), HCN(1-0) and HCO\(^{+}\)(1-0) integrated intensities.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Vel. range (km s(^{-1}))</th>
<th>(^{12})CO(1-0) (K km s(^{-1}))</th>
<th>(^{12})CO(2-1) (K km s(^{-1}))</th>
<th>(^{13})CO(1-0) (K km s(^{-1}))</th>
<th>(^{13})CO(2-1) (K km s(^{-1}))</th>
<th>HCN(1-0) (K km s(^{-1}))</th>
<th>HCO(^{+})(1-0) (K km s(^{-1}))</th>
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<tbody>
<tr>
<td>IC066</td>
<td>1310–1516</td>
<td>11.46 ± 0.29</td>
<td>16.78 ± 0.32</td>
<td>1.35 ± 0.11</td>
<td>1.37 ± 0.13</td>
<td>0.27 ± 0.06</td>
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<tr>
<td>IC1024</td>
<td>1359–1619</td>
<td>11.41 ± 0.38</td>
<td>15.74 ± 0.36</td>
<td>0.72 ± 0.08</td>
<td>1.90 ± 0.10</td>
<td>&lt; 0.27</td>
<td>&lt; 0.28</td>
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<tr>
<td>NGC1222</td>
<td>2253–2603</td>
<td>17.32 ± 0.45</td>
<td>28.95 ± 0.49</td>
<td>0.78 ± 0.10</td>
<td>1.42 ± 0.10</td>
<td>&lt; 0.36</td>
<td>0.37 ± 0.12</td>
</tr>
<tr>
<td>NGC1266</td>
<td>1750–2500</td>
<td>34.76 ± 0.99</td>
<td>105.22 ± 0.88</td>
<td>1.04 ± 0.09</td>
<td>4.04 ± 0.11</td>
<td>2.83 ± 0.15</td>
<td>1.97 ± 0.15</td>
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<tr>
<td>NGC2764</td>
<td>2514–2944</td>
<td>16.17 ± 0.48</td>
<td>24.54 ± 0.71</td>
<td>1.41 ± 0.11</td>
<td>2.01 ± 0.14</td>
<td>0.28 ± 0.08</td>
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<td>NGC3032(^1)</td>
<td>1475–1630</td>
<td>8.32 ± 0.23</td>
<td>6.61 ± 0.27</td>
<td>0.84 ± 0.07</td>
<td>1.23 ± 0.09</td>
<td>0.27 ± 0.04</td>
<td>&lt; 0.33</td>
</tr>
<tr>
<td>NGC3607</td>
<td>670–1227</td>
<td>10.44 ± 0.29</td>
<td>19.54 ± 2.20</td>
<td>1.66 ± 0.17</td>
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<td>1737–2432</td>
<td>11.97 ± 0.64</td>
<td>14.35 ± 0.83</td>
<td>3.71 ± 0.19</td>
<td>5.64 ± 0.19</td>
<td>0.49 ± 0.08</td>
<td>&lt; 0.23</td>
</tr>
<tr>
<td>NGC4150(^1)</td>
<td>75–350</td>
<td>6.04 ± 0.47</td>
<td>10.99 ± 0.49</td>
<td>0.42 ± 0.07</td>
<td>0.87 ± 0.11</td>
<td>&lt; 0.24</td>
<td>&lt; 0.25</td>
</tr>
<tr>
<td>NGC4459(^1)</td>
<td>980–1385</td>
<td>10.03 ± 0.56</td>
<td>11.52 ± 0.51</td>
<td>2.99 ± 0.13</td>
<td>4.03 ± 0.21</td>
<td>0.59 ± 0.12</td>
<td>&lt; 0.62</td>
</tr>
<tr>
<td>NGC4526(^1)</td>
<td>280–980</td>
<td>21.63 ± 1.00</td>
<td>32.26 ± 0.89</td>
<td>5.95 ± 0.28</td>
<td>6.76 ± 0.34</td>
<td>1.75 ± 0.12</td>
<td>&lt; 0.63</td>
</tr>
<tr>
<td>NGC4694</td>
<td>1083–1264</td>
<td>6.14 ± 0.35</td>
<td>6.60 ± 0.28</td>
<td>0.35 ± 0.08</td>
<td>0.65 ± 0.14</td>
<td>&lt; 0.20</td>
<td>&lt; 0.20</td>
</tr>
<tr>
<td>NGC4710</td>
<td>896–1368</td>
<td>31.65 ± 0.74</td>
<td>40.42 ± 0.62</td>
<td>4.77 ± 0.15</td>
<td>6.13 ± 0.20</td>
<td>1.41 ± 0.10</td>
<td>0.89 ± 0.10</td>
</tr>
<tr>
<td>NGC5866</td>
<td>432–1051</td>
<td>21.57 ± 0.38</td>
<td>17.35 ± 0.68</td>
<td>3.27 ± 0.16</td>
<td>3.80 ± 0.18</td>
<td>0.84 ± 0.09</td>
<td>0.57 ± 0.09</td>
</tr>
<tr>
<td>NGC6014</td>
<td>2266–2570</td>
<td>7.48 ± 0.38</td>
<td>10.81 ± 0.37</td>
<td>0.78 ± 0.13</td>
<td>1.54 ± 0.10</td>
<td>0.20 ± 0.05</td>
<td>&lt; 0.14</td>
</tr>
<tr>
<td>NGC7465</td>
<td>1827–2117</td>
<td>11.89 ± 0.39</td>
<td>21.48 ± 0.43</td>
<td>0.63 ± 0.14</td>
<td>1.15 ± 0.06</td>
<td>0.13 ± 0.03</td>
<td>0.29 ± 0.03</td>
</tr>
<tr>
<td>PGC058114</td>
<td>1383–1768</td>
<td>11.37 ± 0.38</td>
<td>21.65 ± 0.27</td>
<td>0.56 ± 0.09</td>
<td>1.45 ± 0.20</td>
<td>&lt; 0.33</td>
<td>0.38 ± 0.11</td>
</tr>
<tr>
<td>UGC09519</td>
<td>1501–1818</td>
<td>12.64 ± 0.38</td>
<td>13.96 ± 0.29</td>
<td>0.45 ± 0.10</td>
<td>0.88 ± 0.18</td>
<td>&lt; 0.21</td>
<td>0.29 ± 0.07</td>
</tr>
</tbody>
</table>

\(^1\) Pilot sample galaxies from [Krips et al. 2018].

Figure 2. Example molecular line spectra from the IRAM 30m telescope; spectra of the remaining 14 galaxies are shown in Appendix A. The spectra have been binned to a channel width of 30 km s\(^{-1}\) and the scale is in main beam temperature (mK). The blue line shows the best-fit Gaussian or double-peak function (fits are only performed on detected lines). The vertical dashed lines indicate the velocity range integrated over to obtain integrated intensities. Top to bottom: \(^{12}\)CO(1-0), \(^{12}\)CO(2-1), \(^{13}\)CO(1-0), \(^{13}\)CO(2-1), HCN(1-0) and HCO\(^{+}\)(1-0). The \(^{12}\)CO(1-0) and \(^{13}\)CO(2-1) data are from Paper IV.
correction is required between HCN(1-0) and HCO\(^+\)(1-0) as they are very close in frequency. Errors on the integrated intensity ratios are calculated using a very simple Monte Carlo simulation of errors through division. We include the measurement errors of Table 3, and for ratios of lines not measured simultaneously (i.e. all except HCN/HCO\(^+\)), a 10% systematic error contribution. This simulation is necessary because the non-linear operation of division produces a strongly biased (non-Gaussian) error distribution, which is not well approximated by the standard error propagation formula. The bias is particularly noticeable here because our measurements are small compared to the measurement errors. The dust morphology has been studied in several other works (e.g. Schinnerer et al. 2010; Tan et al. 2011). In general, high PAH ratios seem to signal more active star formation by tracing the diffuse gas created by feedback processes. The majority of early-type galaxies have PAH ratios similar to those of dusty spiral galaxies (5-20), with the low-end ratios ranging from 2 to 10%.

### 4.2.1 \(^{12}\)CO\(^{13}\)CO

The sample galaxies vary by a factor of 10 in both \(^{12}\)CO(1-0)/\(^{13}\)CO(1-0) (hereafter IR\(_{10}\)) and \(^{12}\)CO(2-1)/\(^{13}\)CO(2-1) (hereafter IR\(_{21}\); see Table 3). However, about half the sample galaxies have significantly larger IR\(_{10}\) than IR\(_{21}\) ratios, as can be seen comparing the galaxies to the solid 1:1 line in Fig. 4A (error bars do not intersect the line). The galaxy area probed by the (1-0) transition is not in diameter to that of the (2-1) transition, so the higher IR\(_{10}\) ratios may indicate that the more extended gas traced by the (1-0) transition is even more optically thin in some early-type galaxies. However, the difference in the (1-0) and (2-1) ratios may instead be dominated by the local temperature and density of the molecular gas. Spatially-resolved studies will have to determine what drives the higher IR\(_{10}\) compared to IR\(_{21}\) ratios.

The highest IR\(_{10}\) and IR\(_{21}\) ratios for the early-type sample are similar to those of the most extreme starbursts, while the low-end ratios have never before been seen in integrated galaxy measures, matching the very lowest values measured in galaxies (Tan et al. 2011). As mentioned above, spirals have radial gradients in IR\(_{10}\), the value generally decreasing with radius in the disc (Paglione et al. 2003; Tan et al. 2011), although it can have local maxima within spiral arms or intense star-forming regions (Schinnerer et al. 2010; Tan et al. 2011). In general, high IR\(_{10}\) ratios seem to signal more active star formation by tracing the diffuse gas created by feedback processes. The majority of early-type galaxies have IR\(_{10}\) ratios similar to those of spirals (5-20), with NGC 1222, NGC 1266 and UCG09519 being exceptions at the high end and NGC 4526, NGC 4459 and NGC 3665 being exceptions at the low end.

Figures 4A and 5A show how the IR\(_{10}\) ratio varies with several galaxy properties. Figure 4A, focusing on ISM properties and environment and Figure 5A focusing on stellar properties. The galaxy with a significant molecular outflow, NGC 1266, is identified in each plot with a circle and will be discussed separately. At the top of each plot, the Spearman rank correlation coefficient and the probability that the null hypothesis (no correlation) is true are given. Low probabilities for the null hypothesis (we take ‘low’ to be less than 0.03) suggest the data are correlated. The dust morphology has two discrete categories (disc and filament), so the null hypothesis is that the sample means are the same. We evaluate this probability by Welch’s t-test (similar to the Student t-test but not assuming that the sample variances are the same).

By the above measures, IR\(_{10}\) is correlated with the molecular-to-atomic gas ratio (atomic gas measured by H I emission), the dust temperature, M\(_K\) and the single stellar population (SSP) derived age. The IR\(_{10}\) ratios of the galaxies with dust discs are also signifi-
A is represented by yellow squares without error bars. A sample galaxy with a molecular outflow, is identified by blue circles. Cen ratio along one axis is not yet well constrained by literature data. NGC 1266, (Brouillet et al. 2005) in the bottom plot. The band reflects the fact that the ratios from Gao & Solomon (2004a) in the middle plot, and GMCs in M31, blue triangles, respectively (Krips et al. 2010). The grey band highlights the bursts and Seyfert nuclei are portrayed by purple circles, green stars and by yellow squares with error bars or upper or lower limits. Spirals, starbursts, Early-types, Duct et al. 2011, hereafter Paper IX) or in tails of atomic gas (Serra et al., in prep.). However, unlike the direct relation between \( R_{10} \) and \( f_{\text{HII}}/f_{100} \) seen in Young & Sanders (1984) and Aalto et al. (1993), a number of the early-type galaxies with high \( R_{10} \) do not have particularly warm dust (IC 1024, NGC 4694, NGC 7465 and UGC 09519). These galaxies are interacting or accreting, but do not (currently) have starburst or nuclear activity substantially heating their dust. For these galaxies, the low optical depth in \(^{12}\)CO(1-0) must be attributed to unsettled gas as opposed to feedback from intense star formation. Indeed, interacting galaxies have been observed to have increased gas velocity dispersions (Irwin 1994; Elmegreen et al. 1995), which would allow for a decreased optical depth in \(^{12}\)CO(1-0).

Thus, the \( R_{10} \) ratio seems driven to higher values by gas-rich interactions (major mergers, minor mergers, or tidal gas capture) and/or feedback from starburst activity. The gas-rich interactions tend to have large amounts of atomic gas involved, thus explaining the correlation with the molecular-to-atomic gas ratio. Dust temperatures of these galaxies are middle to high, never very low. The strong apparent correlation with \( K \)-band luminosity may be due to our sample selection, since we have no high mass, high gas-fraction (generally interacting) galaxies or low mass, low gas-fraction (generally settled) galaxies. Similarly, the strong trend with SSP age may be tied to the biased gas fraction because SSP age is very sensitive to the fraction of young to old stars (which is presumably higher in high gas fraction galaxies). As mentioned above, including low mass, low gas-fraction galaxies in future work will allow us to see if either galaxy mass or SSP age affect the \( R_{10} \) line ratio.

In the fourth panel of Fig. 4a, the eye is drawn to a correlation

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**Figure 3.** Molecular line ratio diagrams. Early-type galaxies are represented by yellow squares with error bars or upper or lower limits. Spirals, starbursts and Seyfert nuclei are portrayed by purple circles, green stars and blue triangles, respectively (Krips et al. 2010). The grey band highlights the region occupied by spirals from Paolone et al. (2008) in the top plot, spirals from Gao & Solomon (2004a) in the middle plot, and GMCs in M31 (Brouillet et al. 2005) in the bottom plot. The band reflects the fact that the ratio along one axis is not yet well constrained by literature data. NGC 1266, a sample galaxy with a molecular outflow, is identified by blue circles. Cen A is represented by yellow squares without error bars.
between [O III]/Hβ, although the Spearman correlation coefficient reveals this is not particularly likely. Indeed, it is hard to state a connection: high HCN/12CO10 values shiv away from the lowest values of [O III]/Hβ while low HCN/10 values galaxies have middle valued-ratios. Coupled with another optical emission line ratio such as [N II]/Hα or [S II]/Hα, [O III]/Hβ is frequently used to distinguish HI-region photoionisation from shock ionisation or from a power-law continuum source such as an AGN. Unfortunately, without the second line ratio, the values observed for our galaxies are degenerate. Thus the lack of a clear correlation may be due to various ionisation sources which are differently (or not) related to molecular gas properties.

Some relation also looks possible for HCN/12CO10 and Σ3, mostly driven by galaxies at high local environmental densities having low HCN/10 values. These are all galaxies that are in the Virgo cluster or the centre of their group. It is possible that in these galaxies, the molecular gas is additionally pressure confined by the hot intra-cluster or intra-cluster medium and so has such high optical depth. But more galaxies are needed to rule in such a scenario.

We have suggested that either stellar feedback and/or ongoing accretion of cold gas leads to more optically thin molecular gas and higher HCN/10 ratios. However, chemical effects may also be able to explain such relations. 13C is a secondary product of nucleosynthesis and should build up in abundance relative to 12C as a stellar population ages and returns material to the interstellar medium. Interactions may bring less enriched material into galaxies, with presumably less 13C, explaining the higher HCN/10 ratio seen in these systems. Chemical fractionation due to isotopic ion exchange towards 13CO and away from 12CO may also cause the trend with fiso/f1000 at lower temperatures the lower-energy 13CO will be more strongly preferred. If the majority of molecular gas is at low temperatures in the more settled galaxies, then this option could also be responsible for the observed trends. Ratios involving HCN and HCO+ help disentangle these options in the next sections.

We note that three of the early-type galaxies have extremely low HCN/10 and HCN/12 ratios, at the limit seen in spiral galaxy discs: NGC 5665, NGC 4459 and NGC 4526. A HCN/10 minimum value of 3.3 was reported in [Tan et al. (2010), but spiral discs generally have HCN/10 values above 5 (Young & Sanders 1986; Paglione et al. 2001; Schinnerer et al. 2010). The values observed here indicate that the gas in these three galaxies is either less affected by star formation feedback (remaining very optically thick and/or fractionated towards 12CO) or is more enriched with 13C.

### 4.2.2 HCN

For HCN, we consider ratios with both 12CO(1-0) and 13CO(1-0) (see Table 4). HCN/13CO(1-0) varies by a factor of about 7, from 0.015 to 0.108, while HCN/12CO(1-0) varies by only a factor ≈3 from 0.18 to 0.58, if NGC 1266 is excluded (because of its unique properties associated with its molecular outflow). Our early-type galaxies mostly lie within the HCN/12CO(1-0) range of normal spirals indicated by the grey band in Fig. 4 Based on the galaxies of Gao & Solomon (2004b) with far-infrared luminosity L10 < 1011 L⊙ (thus below the LIRG luminosity threshold). The three galaxies above the grey band are NGC 3607, NGC 4459 and NGC 4526. These are three galaxies that were also low in HCN/10 and HCN/12, signaling that it may be their weakness in 13CO that is the shared trait between the two ratios. NGC 7465 lies below the grey band; it is a galaxy with high HCN/10 and HCN/12. Few spirals have measured HCN/13CO(1-0) ratios, but the early-types definitely have HCN/13CO(1-0) ratios lower than starbursts (even those with high starburst-like HCN/10 ratios), while they overlap with approximately half of the Seyfert nuclei.

We plot the inverse of these ratios (thus 12CO(1-0)/HCN and 13CO(1-0)/HCN) against the same galactic properties as before to make plots with the same orientation as for HCN/10 (Figs. 4b,c and 5b,c). Again ignoring NGC 1266, very similar trends to those of HCN/10 are seen with 13CO(1-0)/HCN, although the lower number of galaxies (only 12 detected in HCN) makes it easier for the null hypothesis of no correlation to be accepted. Correlations with the molecular-to-atomic gas ratio, dust temperature, SSP age and M_K are still significant. A correlation with stellar metallicity is also shown to be likely, but would probably not be if the one lower limit at high Z were included. For the 13CO(1-0)/HCN ratio, no correlation is seen with any galaxy parameter.

In the 12CO(1-0)/HCN ratio, there is no difference in the carbon isotope, so the continued presence of most of the trends observed with HCN/10 rules out enhanced 13C abundance as their cause. If ion-exchange reactions leading to fractionation were responsible for the trends with 12CO(1-0)/HCN, inverse relations would be expected for 13CO(1-0)/HCN. As this is not seen, fractionation is also unlikely to explain the observed trends. With both abundance variations and ion-exchange reactions unable to drive the observed trends, a varied average optical depth of 12CO/CO(1-0) is left as the most likely cause.

HCN/12CO(1-0) is frequently used as a dense gas tracer in star-forming galaxies. Gao & Solomon (2004b) find an increased HCN/12CO(1-0) ratio for LIRG and ULIRG galaxies and suggest that gas traced by HCN is more closely tied to star formation than that traced by 12CO. In Fig. 6 we place our early-type galaxies on a HCN/12CO(1-0) versus L10 plot along with the late-type galaxies from Gao & Solomon (2004b). The early-type galaxies at high L10 do not behave as nicely as the late-types, instead they exhibit a wide range of HCN/12CO(1-0) ratios. However, much of this may be due to the optical depth effects in 12CO(1-0) described above. We colour-code the early-type galaxies by their HCN/10 ratio, and as expected if the optical depth of 12CO(1-0) plays a role, galaxies with low HCN/10 ratios are seen at high HCN/12CO(1-0) and vice versa (a blue colour indicates high HCN/12CO(1-0)). Thus HCN/12CO(1-0) is not a good tracer of dense gas fraction in early-type galaxies. HCN/13CO(1-0) should be better. Additionally, we see that NGC 1266 has a high HCN/13CO(1-0) ratio despite its high HCN/10 ratio. It thus exhibits a dense gas ratio like a LIRG or ULIRG regardless of optical depth considerations. Thus high dense gas fractions are not limited to galaxies that are extremely bright in the FIR.

If we instead use HCN/13CO(1-0) as a dense gas tracer, we find that there is only about a factor 3 variation in this ratio (ignoring NCG 1266) among the early-type galaxies. Unfortunately, few spiral galaxies have both HCN and 13CO(1-0) measured; only a comparison with a larger spiral sample will really tell whether the early-type galaxies as a population have different dense gas fractions.

### 4.2.3 HCO+

HCO+(1-0) is detected in 10 of the 18 sample galaxies, including 3 cases where HCN is not detected (NGC 1222, PGC 058114 and UGC 09519). The HCN/HCO+ ratios for the detected early-type galaxies range from 0.44 (and possibly less) to > 2.77. Ratios of 0.66 to 1.7 are seen in M31 giant molecular clouds (GMCS) (Brouillet et al. 2003), this region is shaded in grey in the bottom panel of Fig. 5. Most early-type galaxies are also found within...
Figure 4. Molecular line ratios against ISM properties and environment (from left to right): (1) molecular-to-atomic gas ratio, (2) $f_{\text{60}}/f_{\text{100}}$ ratio of IRAS fluxes (a dust temperature proxy), (3) dust morphology (disc or filamentary; from Paper II), (4) median $[\text{O III}]/\text{H}\beta$ emission line ratio (a measure of the ionised gas excitation; from Sarzi et al., in prep.), and (5) $\rho_{\text{10}}$ (a measure of the local galaxy density; from Paper VII). From top to bottom, the molecular ratios are (a) $R_{10}$, (b) $^{12}\text{CO}(1-0)/\text{HCN}$ and (c) $^{13}\text{CO}(1-0)/\text{HCN}$. NGC 1266 is highlighted with a circle. The Spearman rank correlation coefficient (‘$r$’) and the probability that the null hypothesis (‘$P_0$’, no correlation) is true are given at the top of each plot.
Figure 5. Molecular line ratios against stellar properties (from left to right): (1) absolute K-band magnitude, SSP best-fit (2) age, (3) metallicity, (4) alpha-element abundance (McDermid et al., in prep.) and (5) specific stellar angular momentum normalized by ellipticity (Paper II). From top to bottom, the molecular ratios are (a) $^{12}$CO(1-0)/HCN and (b) $^{13}$CO(1-0)/HCN. NGC 1266 is highlighted with a circle. The Spearman rank correlation coefficient ($r'$) and the probability that the null hypothesis ($P_0'$, no correlation) is true are given at the top of each plot.

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this range, as are most starbursts and Seyferts, although Seyfert nuclei appear biased towards higher and spiral galaxies toward lower HCN/HCO\(^+\) ratios (e.g., Kyrgts et al. 2008). As for the \(^{13}\)CO(1-0)/HCO\(^+\) ratio, the early-type galaxies have larger ratios than the starbursts (and many of the Seyferts), analogous to the smaller HCN/\(^{13}\)CO(1-0) ratios observed. Thus both ratios agree that early-type galaxies have lower dense gas fractions than starburst (and many Seyfert) galaxies, at least if the latter systems are not dominated by chemical enhancement of the HCN and HCO\(^+\).

Curiously, two of our galaxies (NGC 3665 and NGC 4526) have quite high HCN/HCO\(^+\)(1-0) ratios, 2 or higher based on our HCO\(^+\) non-detections. These are two of the three galaxies with extremely low \(R_{10}\) values. The third very low \(R_{10}\) galaxy (NGC 4459) is also a non-detection in HCO\(^+\); its HCN/HCO\(^+\) must be above 1.4. None of these three galaxies has a clear Seyfert nucleus based on optical emission line ratio classification (Ho et al. 1997) or a powerful X-ray nucleus, although one (NGC 3665) has conspicuous radio jets that may signal an X-ray bright AGN hidden within. Still, an AGN driving XDR chemistry cannot be the common link between these three galaxies. Instead, the possible low efficiency of star formation in these galaxies may support a lower ionisation fraction and thus a smaller abundance of HCO\(^+\) relative to HCN. Information from other molecular gas tracers, such as HNC, will help diagnose if this is the case.

### 4.3 Molecular gas classes

As mentioned above, early-type galaxies exhibit a variety of molecular line ratios. Here we draw attention to two basic classes: galaxies with settled dust and gas discs and those with unsettled dust and gas.

Galaxies with settled discs include NGC 3032, NGC 3607, NGC 3665, NGC 4459, NGC 4526, NGC 4710, NGC 5866 and NGC 6014. Most also have clearly double-peaked spectra, indicating that the molecular gas distribution extends beyond the turnover of the galaxy’s rotation curve (Paper V), and all have more molecular than atomic gas. These galaxies have low \(R_{10}\) and \(R_{21}\) values, in three cases strikingly low (below 3). They also have high HCN/\(^{12}\)CO(1-0) ratios, consistent with the idea that they are very optically thick in \(^{12}\)CO(1-0). Many also have high (> 1.4) HCN/HCO\(^+\)(1-0) ratios.

Within this set of settled gas discs, we find that those with the greatest \(K\)-band luminosities have the lowest \(R_{10}\), \(R_{21}\) and HCN/\(^{12}\)CO(1-0)/HCN ratios. If these galaxies also have the least efficient star formation (as predicted by morphological quenching for galaxies with high bulge to disk ratios) then the very optically thick molecular gas in these galaxies might result from reduced mechanical and/or radiative feedback accompanying the less efficient star formation. Another option is that they are generally found in environments where hot gas may confine their molecular gas to a thin (and thus more optically thick) layer.

The second class of galaxies we draw attention to are those with unsettled dust (Paper II), signaling either ongoing gas accretion or a merger: IC 676, IC 1024, NGC 1222, NGC 2764, NGC 4694, NGC 7465 and UGC 09519. Recent work suggests that minor mergers are likely to supply the cold gas to many of the currently star-forming early-type galaxies (Kaviraj et al. 2009), so such signs of accretion are not unexpected. These galaxies generally have more atomic than molecular gas and the atomic gas distributions frequently, although not always, show signs of interaction (Serra et al. 2011). PGC 058114 does not have optical photometry for dust classification, but generally seems to fit in this class. These galaxies all have high \(R_{10}\) ratios and low HCN/\(^{12}\)CO(1-0) ratios (see Fig. 4). Increased turbulence from the interaction, diffuse molecular gas within the significant atomic phase and/or significant radiative or mechanical feedback from a related starburst creates a lower optical depth in these galaxies. This group has a wide spread in dust temperatures.

NGC 4150 may bridge the two classes; recent HST WFC3 imaging reveals a dust disc with spiral structure and stellar population analysis suggests a recent (\(\approx\) 1 Gyr) minor merger (Crockett et al. 2011). H I observations show a low-column density cloud of atomic hydrogen, possibly leftover from this minor merger (Morganti et al. 2006). However the overall molecular-to-atomic gas fraction is quite high, making NGC 4150 more similar to members of the settled disc group. Its molecular line ratios lie in the middle of the ranges we observe. In general, there is likely to be a continuum from highly disordered to settled ISM. Many of the interacting galaxies may have or may be developing a disc, and some of the galaxies with discs may not be entirely settled yet.

As mentioned previously, NGC 1266 stands apart in many ways from the other galaxies. It has a massive molecular outflow, discovered during the IRAM 30m survey of the ATLAS3D galaxies (Alatalo et al. 2011). Here we note its extremely high HCN/\(^{12}\)CO(1-0) ratio of 2.7, higher than most starbursts and Seyfert nuclei found in the literature. The interpretation of this ratio as an extremely high dense gas fraction fits with the very high surface density implied by the interferometric \(^{12}\)CO observations. But an increased ionisation rate due to X-rays, cosmic rays, or very intense FUV emission could also boost the HCN abundance. The clear line profile mismatches suggest spatial variations in the molecular properties or multiple molecular components. The \(^{12}\)CO(2-1), HCN(1-0) and HCO\(^+\)(1-0) lines were all fit with wider Gaussians (FWHM = 154\(\pm\)14, 152\(\pm\)15 and 176\(\pm\)21 km s\(^{-1}\), respectively) than the \(^{12}\)CO(1-0) line (FWHM = 132\(\pm\)18 km s\(^{-1}\), suggesting that they are more prevalent with respect to \(^{12}\)CO(1-0) in the molecular outflow (which reaches higher velocities). On the other hand, the narrow profiles of both the \(^{13}\)CO(1-0) (FWHM = 94\(\pm\)9 km s\(^{-1}\)) and \(^{13}\)CO(2-1) (FWHM = 106\(\pm\)9 km s\(^{-1}\)) lines indicate reduced emission from the \(^{13}\)CO lines in the outflow. The outflow must therefore have an even higher \(R_{10}\) ratio and is likely very optically thin.
consistent with the large velocity gradient modeling performed in [Alatalo et al. (2011)] using the $^{12}\text{CO}(1-0), ^{12}\text{CO}(2-1)$ and $^{12}\text{CO}(3-2)$ transitions. The lack of strong $^{13}\text{CO}$ wings confirms a typical $X_{\text{CO}}$ factor should not be used for the molecular outflow.

5 CONCLUSIONS

Using the IRAM 30m telescope, we have surveyed the $^{13}\text{CO}$, HCN and HCO$^+$ emission of the 18 galaxies with the strongest $^{12}\text{CO}$ emission in the ATLAS$^{3D}$ sample of nearby early-type galaxies. We detect all 18 galaxies in both $^{12}\text{CO}(1-0)$ and $^{13}\text{CO}(2-1)$ transitions, 12/18 in HCN$(1-0)$ and 10/18 in HCO$^+$(1-0).

Fitting the $^{12}\text{CO}(1-0)$ lines with a double-peak or Gaussian profile and evaluating the reduced $\chi^2$ value, we find that one third of the galaxies are best fit by a Gaussian, one third with a clear double-peak profile and the remaining one-third with a very flat-topped ‘double-peak’ profile. Two galaxies (NGC 1266 and NGC 5866) have clearly different profiles in the various molecular lines, indicating spatial variations of the molecular gas conditions within the galaxies. Discrepant profiles in a few other galaxies are consistent with pointing offsets. We hypothesize that at higher signal-to-noise ratio, we have clearly different profiles in the various molecular lines, indicating spatially inconsistent due to changing molecular gas conditions. Higher signal-to-noise single-dish data or interferometric maps in the various lines will allow us to determine if this is indeed the case.

The molecular gas line ratios of early-type galaxies are generally consistent with the ranges observed in spiral galaxies, although we also identify some outliers. In terms of the HCN/$^{12}\text{CO}(1-0)$ ratio, often used as a dense gas tracer, we extend the work of [Gao & Solomon (2004b)] to lower FIR luminosities and find an increased scatter in the ratio, compared to late-type galaxies of similar FIR-luminosities. Because of the important effects of the optical depth of $^{12}\text{CO}(1-0)$ seen in the $R_{10}$ ratio, we suggest that optical depth may be undermining the use of HCN/$^{12}\text{CO}(1-0)$ as a dense gas tracer and instead recommend the use of HCN/$^{13}\text{CO}(1-0)$. Unfortunately, few spirals have literature HCN/$^{13}\text{CO}(1-0)$ ratios. Determining whether the early-types have significantly different dense gas fractions thus requires a larger sample of spirals to be observed in both HCN$(1-0)$ and $^{13}\text{CO}(1-0)$.

We compare the molecular gas ratios $R_{10}$, $^{12}\text{CO}(1-0)$/HCN and $^{12}\text{CO}(1-0)$/HCO$^+$ to several ISM and stellar galaxy properties. $R_{10}$ is found to correlate with the molecular-to-atomic gas ratio, dust temperature, dust morphology, absolute $K$-band magnitude and SSP age. $^{12}\text{CO}(1-0)$/HCN similarly correlates with the molecular-to-atomic gas ratio, dust temperature, absolute $K$-band magnitude and SSP age. The persistence of most $R_{10}$ correlations with $^{12}\text{CO}(1-0)$/HCN rules out abundance variations of $^{13}\text{CO}$ as the driving factor of the relations. No correlation with any of these properties is seen in the $^{13}\text{CO}(1-0)$/HCN ratio, further ruling out a dominant contribution from ion-exchange fractionation towards $^{13}\text{CO}$ at low temperatures.

With these options removed, a change in optical depth of the $^{12}\text{CO}(1-0)$ line is the best explanation for the correlations we see. Based on the lower molecular-to-atomic gas ratios, unsettled dust and occasionally high dust temperatures, we find that high $R_{10}$ and $^{12}\text{CO}(1-0)$/HCO$^+$ ratios in early-type galaxies are linked to recent or ongoing interactions and/or starbursts. Both of these processes can naturally account for optically thinner $^{12}\text{CO}(1-0)$ line emission, as interactions are known to be more turbulent and star formation feedback can also produce more turbulence or heat up the molecular gas. Early-type galaxies with settled gas and dust discs tend to have less optically thin molecular gas, along with lower dust temperatures and higher molecular to atomic gas mass ratios. The correlations with $K$-band luminosity and SSP age can plausibly be explained by sample selection effects, further work including less massive early-type galaxies with settled gas and dust discs is required before conclusions are reached.

A set of outliers with low $R_{10}$ and $R_{12}$, high HCN/$^{12}\text{CO}(1-0)$ and only upper limits to their HCN/HCO$^+$ ratios are identified. These galaxies may have particularly stable molecular gas which remains very optically thick in $^{12}\text{CO}$ or have their molecular gas confined to a thin layer by hot gas pressure. NGC 1266, a galaxy with a molecular outflow, also stands apart from both spirals and the rest of the early-type sample. Its HCN/$^{13}\text{CO}(1-0)$ and $^{13}\text{CO}(1-0)$/HCO$^+$ ratios suggest that it has a very high dense gas fraction, but its high $R_{10}$ and $R_{12}$ values simultaneously suggest that much of its $^{12}\text{CO}$ emission is optically thin. This combination of ratios is seen in some other extremely active starburst or Seyfert galaxies.

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The spectra of the remaining 14 galaxies not shown in Fig. 1 are shown here in Fig. A1.

APPENDIX B: TEST OF LINE PROFILE CONSISTENCY

Here we document how we test for line profile consistency. As the $^{12}$CO(1-0) spectra generally have the highest signal-to-noise ratio, we first fit a single Gaussian and a double-peaked profile to these lines. Our double-peak function is a parabola cut off symmetrically by a steeply declining exponential on either end:

$$f(v) = \begin{cases} T_{mb,0} e^{-(v - v_0 - w)/15 \text{ km s}^{-1}} & v < v_0 - w \\ T_{mb,0} + a(v - v_0)^2 & v_0 - w \leq v \leq v_0 + w \\ T_{mb,0} e^{-(v - v_0 + w)/15 \text{ km s}^{-1}} & v > v_0 + w \end{cases}$$

The parabola is a function of the velocity, $v$, and is centered at $v_0$, with a cutoff at $v_0 \pm w$ on either side. $T_{mb,0}$ gives $T_{mb}$ at the central velocity, $v_0$, and the parameter ‘a’ describes the steepness of the parabola ($a > 0$ in order to guarantee a double-peak or flat-topped shape). $T_{mb,0} + T_{mb,0} \times a \times w^2$ is the peak height. Instead of a sharp cutoff from the peaks to zero, which leads to fitting problems, a steep exponential decay with a decay constant of 15 km s$^{-1}$ is specified on both sides.

The fits were performed with the Interactive Data Language (IDL) package MPFIT (Markwardt 2009). The reduced $\chi^2$ values for the Gaussian and double-peak fits to the $^{12}$CO(1-0) spectra are listed for each galaxy in Table B1. 7/18 galaxies are best fit by a Gaussian, 6/18 by a double-peak profile and 5/18 by a flat-topped profile ($a = 0$). For most galaxies, this fit-based classification agrees with the by-eye classification in Davis et al. (2011, hereafter Paper V).

For all the other transitions of each galaxy, we constrain the type of fit to that which provides the lower $\chi^2$ value in the $^{12}$CO(1-0) line. Uncertainties in the fit parameters are then determined by Monte Carlo simulations, adding Gaussian noise to the observed spectra and refitting 1000 times. The distributions of the resulting parameters are not necessarily Gaussian, so we use the equivalent to a 2$\sigma$ range, containing 95% of the probability. The measured line profiles are consistent with each other when the uncertainties on all their parameters ($v_0$, $\sigma$ for the Gaussian, $v_0$, $a$, $w$ and $a$ for the double-peak profile) overlap. We use the $^{12}$CO(1-0) profile as a base and compare the other lines to it.

Table B1 lists whether the line profile of each of the other five lines is consistent with that of $^{12}$CO(1-0) (1 indicates consistency, 0 inconsistency). We note that consistency here is not that the intrinsic line profiles agree to within a certain measure, but instead that the observed line profiles do not rule out such agreement (i.e. are often too low signal-to-noise).

APPENDIX C: DERIVATION OF BEAM CORRECTION FACTORS

A single-dish telescope measures an average surface brightness (usually expressed as a temperature) that results from the convolution of its main beam pattern with the sky brightness. The pattern of the main beam is roughly a Gaussian, with a half-power beam width (HPBW) that depends inversely on frequency. Thus, for a given telescope, a lower frequency line is measured over a larger sky region than a higher frequency line. For non-uniform sources, different intensities will be measured over differently sized beams, an effect that is often called ‘beam dilution’ for central point sources or centrally concentrated sources.

Our data consist of the integrated intensities (i.e. brightness temperatures integrated over specific frequency or velocity ranges) of lines at different frequencies, therefore measured over different beam areas. For HCN(1-0) and HCO$^+$ (1-0), the frequencies are so close that the difference in area is small ($\approx 1\%$) and their ratio can be computed without any correction. However, the difference is significant for all other line ratios. In the worst case, we compare the integrated intensity of HCN(1-0) and HCO$^+$ (1-0) in a 27.7 arcsec beam to the integrated intensity of $^{12}$CO(1-0) in a 21.3 arcsec beam (a factor 1.7 in area).

To predict and thus correct the effect of different beam sizes, the structure of the source must be known in the tracer used. Interferometric $^{12}$CO(1-0) maps obtained for all sources as part of the ATLAS$^{3D}$ project (Altalalou et al., in prep.) reveal the distribution of this line. Unfortunately, the other lines do not yet have interferometric data. Still, we can perform a first-order correction assuming that the distributions of the other lines are identical to that of $^{12}$CO(1-0), within a scaling factor.

For each galaxy and for each transition, we first perform the weighted integration of the interferometric $^{12}$CO(1-0) map using a Gaussian with appropriate HPBW as the weighting function. The HPBWs we use are determined by the formula: HPBW = $2460\nu/\nu_0$ [arcsec]. This results in HPBWs of 27.7, 27.7, 22.3, 21.3, 11.2 and 10.7 arcsec for the HCN(1-0), HCO$^+$ (1-0), $^{12}$CO(1-0), $^{13}$CO(1-0), $^{12}$CO(2-1) and $^{13}$CO(2-1) lines, respectively. Then we divide this spatially integrated flux by the beam area, obtaining an estimate of the integrated intensity of $^{12}$CO(1-0) in each differently-sized beam. This derived intensity is written as $I_{27.7\nu}^{\text{int}}(^{12}\text{CO}(1-0))$, where the ‘int’ denotes the interferometric origin and the HPBW is specified in arcseconds. With the assumption that other lines have spatial distributions identical to that of $^{12}$CO(1-0) to within a scaling factor, we can then estimate their integrated intensities over different beam sizes. For example, to compute the estimated HCN(1-0) integrated intensity measured over the smaller $^{12}$CO(1-0) beam:

$$I_{21.3\nu}^{\text{int}}(\text{HCN}) = \frac{I_{27.7\nu}^{\text{int}}(^{12}\text{CO}(1-0))}{I_{27.7\nu}^{\text{int}}(^{12}\text{CO}(1-0))} I_{27.7\nu}^{\text{int}}(\text{HCN}),$$

where the prime indicates that this is an estimated, and not directly measured, integrated intensity.

We list the correction factors required for the line ratios we study in Table C1. These have been applied to the ratios listed in Table B4.

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Figure A1. Molecular line spectra from the IRAM 30m telescope; spectra of the first 4 galaxies are shown in Fig. 2. The spectra have been binned to a channel width of 30 km s$^{-1}$ and the scale is in main beam temperature (mK). The blue line shows the best-fit Gaussian or double-peak function (fits are only performed on detected lines). The vertical dashed lines indicate the velocity range integrated over to obtain integrated intensities.
Figure A1 – continued
Table B1. Line profile fits and consistency.

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Notes: The three types of fits denoted in the “Fit” column are a single Gaussian (G), a double-peaked profile (D) or a flat-topped profile (F). The final five columns indicate whether the line specified in the column heading has a profile consistent with the $^{12}$CO(1-0) profile (1) or not (0).

Table C1. Integrated intensity correction factors.

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