A CO(3–2) survey of a merging sequence of luminous infrared galaxies

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ABSTRACT

Luminous infrared galaxies (L_IR > 10^{11} \, L_\odot) are often associated with interacting galactic systems and are thought to be powered by merger-induced starbursts and/or dust-enshrouded active galactic nucleus. In such systems, the evolution of the dense, star-forming molecular gas as a function of merger separation is of particular interest. Here, we present observations of the CO(3–2) emission from a sample of luminous infrared galaxy mergers that span a range of galaxy–galaxy separations. The excitation of the molecular gas is studied by examining the CO(3–2)/CO(1–0) line ratio, as a function of merger extent. We find the line ratios, to be consistent with kinetic temperatures of T_K = (30–50) K and gas densities of n_H2 = 10^3 \, cm^{-3}. We also find weak correlations between r_{31} and both merger progression and star formation efficiency [L_{IR}/M_{CO(1–0)}]. These correlations show a tendency for gas excitation to increase as the merger progresses and the star formation efficiency rises. To conclude, we calculate the contributions of the CO(3–2) line to the 850-\mu m fluxes measured with SCUBA (Submillimetre Common-User Bolometer Array), which are seen to be significant (~22 per cent).

Key words: ISM: molecules – galaxies: interactions – galaxies: ISM – galaxies: starburst – infrared: galaxies.

1 INTRODUCTION

Luminous infrared galaxies (LIGs) (L_IR > 10^{11} \, L_\odot) and ultraluminous infrared galaxies (ULIGs) (L_IR > 10^{12} \, L_\odot) are the dominant population for galaxies with bolometric luminosities greater than 10^{11} \, L_\odot in the local Universe (z \lesssim 0.3) (Soifer et al. 1986). Observations have shown that most are associated with merging/interacting galaxies which are rich in molecular gas (see Sanders & Mirabel 1996 for an extensive review). Analysis of the original Infrared Astronomical Satellite (IRAS) data showed that LIGs are quite rare in the local Universe but increase significantly with increasing redshift (Hacking, Houck & Condon 1987; Chapman et al. 2005). Studies of local LIGs have, therefore, become essential for a wider understanding of the role of mergers and starbursts both in the local Universe and at higher redshifts, where such objects are more commonly found.

Optical studies of local LIGs have shown that many are associated with interacting or merging galactic systems (Armus, Heckman & Miley 1987; Scoville et al. 1998; Arribas, Colina & Borne 2000; Veilleux, Kim & Sanders 2002). It is now thought that as a galactic merger progresses, gas and dust from the parent galaxies dissipate energy through shocks, giving rise to an in-fall of gas and dust towards the centre of gravity of the interacting system (Barnes & Hernquist 1996; Mihos & Hernquist 1996; Cox et al. 2006). The concentration of cold, dense material then acts to fuel starburst activity, or possibly an active galactic nucleus (AGN), or both (Kim, Veilleux & Sanders 1998). The energy produced by the starburst or AGN in the optical and ultraviolet is absorbed and then re-radiated by dust, leading to an intense infrared luminosity.

The effect of a galactic merger upon star formation, as well as its effect upon the total mass and properties of the molecular and atomic gas within the interacting system, has been the subject of several observational studies. Gao & Solomon (1999) used the CO(1–0) spectral line strength as an indicator of total molecular gas mass, M_{H2}, and plotted this quantity against the projected distance of the merging galactic nuclei at optical wavelengths, the projected component separation, in a merging sample of LIGs. The authors found a positive correlation between these two quantities. The authors also found an anti-correlation between the ratio of infrared luminosity to molecular gas mass, L_IR/M_{H2}, a measure of star formation efficiency, and the component galaxy separation for their sample. Both observations are consistent with a depletion of gas as a huge increase in star formation (to around ~100 \, M_\odot \, yr^{-1}) occurs. In a survey of literature data, Georgakakis, Forbes & Norris (2000) found strong evidence for gas depletion and increased star formation.
formation efficiency in a merging galaxy sample which included pre-merger and post-merger candidates. The authors also found an increase in the central molecular hydrogen surface density, as traced by CO(1–0), and a decrease in the fraction of cold gas mass as the galactic mergers progressed. This result is consistent with large molecular gas inflows, as predicted by numerical simulations, the conversion of neutral hydrogen to molecular hydrogen, stars and hot gas and molecular hydrogen depletion due to ongoing star formation.

Merging and starburst activity also affects the atomic component of the interstellar medium (ISM). Mirabel & Sanders (1989) have found that the ratio of molecular hydrogen to atomic hydrogen gas mass, \( M_{\text{H}_2} / M_{\text{H}_1} \), increases with \( L_{\text{IR}} \). It is currently unclear whether this increase is chiefly due to a depletion of HI via ejection from the interacting system, depletion of HI due to photoionization caused by the formation of young stars or enhanced formation of molecular clouds in merger induced shocks. Further observations of \( M_{\text{H}_1} \) have been attempted to investigate whether this depletion of atomic gas is also seen across a merging sequence of LIGs (van Driel, Gao & Monnier-Ragaigne 2001), but no conclusive answer has yet been derived.

The evolution of molecular hydrogen gas, which is associated with star formation, within merging LIGs is of particular interest. Observations of the CO(1–0) rotational transition are often used to trace the total molecular hydrogen gas mass e.g. Young & Scoville (1991). After \( H_2 \), CO is the most abundant molecule in the ISM ([CO/H_2] \( \sim 10^{-4} \)), and the CO(1–0) transition is typically thermalized in molecular clouds, making it a very convenient transition to observe. The low excitation energy, \( E_J/k_B = 5.5 \text{ K} \), and the low critical density \( n_\text{H}_2,\text{crit} \sim 410 \text{ cm}^{-3} \) of the CO(1–0) transition make it ideal for tracing the bulk metal-enriched \( H_2 \) in galaxies. These same properties, however, make CO(1–0) insensitive to the physical conditions of the molecular gas. If we require constraints on the density and kinetic temperature, we can observe the higher-J CO lines, (i.e. CO\( \geq 2 \)) (Zhu, Seagist & Kuno 2003). These transitions will only become thermalized and luminous for the denser and warmer gas components, and it is these dense components which are a direct indication of the star formation potential of the interacting systems.

The higher order CO(3–2) transition, in particular, is commonly used to trace the warmer, denser components of the ISM associated with star formation (Mauersberger et al. 1999; Bayet et al. 2006; Wilson et al. 2009) and constrain the kinetic temperature and density of the molecular gas. It is likely that there will be multiple density components of molecular gas within the ISM of LIGs, and the critical density of CO(3–2) \( n_{\text{H}_2,\text{crit}} > 8.4 \times 10^4 \text{ cm}^{-3} \), Jansen (1995) is well matched to the density of the star-forming component. The relative ratios of the higher-order CO-line intensities depend on both the density and the kinetic temperature of the molecular gas (Goldreich & Kwan 1974; Scoville & Solomon 1974). By measuring a range of CO-line ratios, one can therefore begin to constrain the likely conditions of the molecular ISM. Observing the CO(3–2) transition is convenient as it traces mostly the star-forming molecular gas and has relatively large luminosities compared to other commonly used tracers, such as HCN \( n_{\text{H}_2,\text{crit}} > 10^4 \text{ cm}^{-3} \), which have higher dipole moments, but lower abundances in the ISM. Measuring the CO(3–2) emission is also important since this emission can contaminate 850-\( \mu \text{m} \) continuum observations of the dust component on the ISM for these galaxies (Papadopoulos & Allen 2000). Correcting this 850-\( \mu \text{m} \) flux for CO emission is important when using this flux to determine the dust mass and kinetic temperature (Seagist et al. 2004).

In this paper, we present observations of the CO(3–2) rotational transition to investigate the evolution of the dense \( n_{\text{H}_2,\text{crit}} > 8.4 \times 10^4 \text{ cm}^{-3} \) molecular gas component as a function of merger extent in a sample of LIG mergers. Our aim is to study the evolution of merging LIGs by observing a LIG sample at differing stages of interaction, and thus obtain a detailed understanding of how the starburst evolves as the interaction proceeds. Such observations are key to obtaining a temporal understanding of the evolution of the molecular gas reservoir and how it relates to star formation activity as the merging component galaxies become increasingly tidally disrupted. Our study builds on work reported by Gao & Solomon (1999), in which a sample of luminous galaxies was chosen to represent a merging sequence with a range of nuclear separations of the merging components. We observe the CO(3–2) transition in a subset of this merging sample of 49 LIGs to trace the evolution of the warmer, denser molecular gas component as a function of merger separation. In particular, we investigate how the excitation of the molecular gas changes by examining the evolution of the CO(3–2)/CO(1–0) line ratio, \( f_{31} \), as merging progresses. \( f_{31} \) will be larger for warmer, denser gas and one might expect its value to increase with decreasing nuclear separation, as an increasing fraction of the total molecular gas becomes concentrated in star-forming regions. We then examine how the line ratio varies with merging extent, far-infrared (FIR) luminosity \( L_{\text{FIR}} \), defined in Section 2) and star formation efficiency \( [L_{\text{FIR}}/L_{\text{CO(1–0)}}] \), and compare our sample with two samples with smaller infrared luminosities. Finally we determine contamination arising from the CO(3–2) line flux upon the 850-\( \mu \text{m} \) continuum observations of the dust component of the ISM for these galaxies. Section 2 outlines the observations that were made, including the sample selection criterion, the choice of pointings and calibration of the data. The data reduction and results of the observations are presented in Section 3, and their interpretation and correlations with other data for the sample are discussed in Section 4. Section 5 outlines the conclusions which may be drawn from this study.

2 SAMPLE SELECTION AND OBSERVATIONS

2.1 The sample

Our sample of merging galaxies is a subset of a sample of merging galaxies defined by Gao & Solomon (1999), chosen such that the sources are observable by the James Clerk Maxwell Telescope (JCMT). Gao & Solomon (1999) chose a parent sample of 49 objects to include all LIGs with (a) available CO(1–0) and R-band CCD data (b) \( L_{\text{IR}} \geq 2 \times 10^{11} \text{L}_\odot \), and (c) having nuclear separations \( S_{\text{sep}} \) greater than 2 arcsec and less than half the sum of the galactic optical disc sizes. The constraint on nuclear separations was set to ensure that all genuinely interacting systems were included in the sample, whilst excluding difficult to measure, late mergers with separations of \( S_{\text{sep}} < 2 \) arcsec, as they are indistinguishable.
from merged single-nucleus galaxies with the usual seeing limit for optical observations.\(^3\)

The sample chosen for this study, hereafter referred to as the CO(3–2) sample, comprises of 33 objects from the Gao & Solomon sample, chosen to meet the following selection criteria.

(i) A declination such as to be observable from the JCMT (\(\delta > -40^\circ\)).

(ii) A distance such that the redshifted CO(3–2) emission line falls within the 315–373 GHz tuning range of the 345 GHz receiver, and at least 2 GHz either side of the strong 325 GHz atmospheric water vapour absorption feature (i.e. 0 < \(cz < 17230\) km s\(^{-1}\) and 21160 < \(cz < 29310\) km s\(^{-1}\)).

Shown in Fig. 1 is the statistical spread of nuclear separation, infrared luminosity and FIR luminosity, for the Gao & Solomon sample and the CO(3–2) sample defined here.

### 2.2 Choice of pointings

The beam width (full width at half-maximum, FWHM) for Receiver B3 on the JCMT is 14 arcsec and the nuclear separations for our sample lie between 2.5 and 40.6 arcsec, which made it necessary to choose suitable pointings carefully, so as to capture all of the CO(3–2) emission. The choices of pointing centre were made based on nuclear separation, which in turn were derived from either images taken at \(R\)-band from Sanders (1992), 645-nm (band 103aE) images from the Space Telescope Science Institute (STScI) Digitized Sky Survey (DSS) (Kent 1994) or with Wide Field Planetary Camera 2 (WFPC2) images taken with the Hubble Space Telescope. Where available, high-resolution CO(1–0) interferometry maps were also used to confirm the choice of pointings (Lo, Gao & Gruendl 1997; Casoli et al. 1999a; Wang et al. 2001). Three different categories of pointings/observations were identified.

(i) Objects with a projected nuclear separation of \(< 7\) arcsec (less than half of beam size): single pointing sufficient to capture all of the CO(3–2) emission. 16 objects of our sample were observed with a single pointing.

(ii) Objects with a projected nuclear separation of \(\sim 14\) arcsec (of order of the beam size): two pointings used, centred on the nuclei of the merging galaxies. Seven objects of our sample were observed with a dual pointing.

(iii) Objects with a projected nuclear separation > 14 arcsec: multiple pointings, separated by 1/2 beam (7 arcsec) were used to realize a fully sampled strip along the axis joining the two component nuclei. Five objects of our sample were observed with multiple pointings (see Fig. C1).

### 2.3 CO(3–2) observations

Observations of the CO(3–2) line (\(v_{rot} = 345.796\) GHz) were made using the dual-channel (orthogonal polarization), 345 GHz receiver (RxB3) on the JCMT. The Digital Autocorrelation Spectrometer (DAS) backend was used in one of two bandwidth modes, depending on the expected width of the CO(3–2) spectral line given the CO(1–0) linewidths. The single-channel, wideband mode, in which the two 900-MHz sub-bands are concatenated to realize a useable contiguous bandwidth of 1800 MHz (\(\Delta v \sim 1560\) km s\(^{-1}\)), was used for expected linewidths of \(\Delta v_{\text{FWHM}} > 500\) km s\(^{-1}\); the more sensitive dual-channel standard mode, with a single sub-band of 900 MHz (\(\Delta v \sim 780\) km s\(^{-1}\)), was used where lines of \(\Delta v_{\text{FWHM}} < 500\) km s\(^{-1}\) were anticipated. The wideband mode was only used where the velocity covered by standard mode was not sufficient to provide line-free regions for baseline removal.

Rapid beam switching at a secondary mirror chop frequency of 1–2 Hz and beam throws of 60–90 arcsec in azimuth were used to ensure good atmospheric cancellation. Hot/cold load calibrations were performed every 20 to 30 min to achieve consistent calibration to the \(T_A^*\) antenna temperature scale. The telescope pointing was checked every 2–3 h using local spectral line pointing sources, and any offset corrections applied to the telescope pointing model, resulting in an rms pointing accuracy of 1–2 arcsec. The science data taken for each pointing consisted of spectra from each RxB3 polarization channel, usually integrated for a period of around 10 min. Integration times of longer than 10 min were achieved by co-adding several \(~10\)-min spectra while checking the data for instrumental drifts and baseline problems.

Spectral line standards such as OMC1 were observed to check amplitude calibration and quantify calibration uncertainties, as well as to monitor the overall performance of the telescope. Mars and Uranus, when observable, were observed to establish main-beam efficiencies.

A total of 28 of the 33 sources in the CO(3–2) sample were observed over the period between 2000 October and 2003 July. The atmospheric opacity at 225 GHz measured at the Caltech
Submillimeter Observatory, was typically $\tau_{225\text{GHz}} \sim 0.1$ giving system temperatures of around 600 K in the receiver tuning range used for the observations. Of our 28 observed sources, 16/7/5 were observed with single/two/multiple pointings. Fig. 1 shows a comparison of the statistical spread of nuclear separations, infrared luminosities and FIR luminosities for the objects actually observed.

3 DATA REDUCTION AND RESULTS

All data were reduced using the JCMT spectral line reduction package MATE (Padman 1993). Individual spectra were inspected, with any scans showing significant baseline structure/ripple rejected ($\sim 5$ per cent of total). The spectra were then co-added, linear baselines fitted and removed and then the spectra were binned to 26 km s$^{-1}$ (30 MHz). The $I_{\text{CO}(3-2)}$ values were determined by directly integrating under the extent of the spectral line.

Planetary observations of Mars and Uranus were used to estimate $\eta_{\text{mb}}$ and calibrate the data directly from the sky-corrected antenna temperature, $T_A^*$ to the main-beam brightness temperature $T_{\text{mb}}$ via

$$
\eta_{\text{mb}} \equiv B_{\text{eff}} / F_{\text{eff}} = T_A^* / T_{\text{mb}}.
$$

Here, $B_{\text{eff}}$ and $F_{\text{eff}}$, the beam efficiency and forward efficiency follow the definitions given in Downes (1988). Values of $\eta_{\text{mb}} \sim 0.55$ were typically measured using this technique. Where no planetary observations were available, a canonical value for RXB3 on the JCMT of $\eta_{\text{mb}} = 0.55$ was adopted, which reflects the mean value obtained and published on the JCMT web pages for the observing period. The observed spread for $\eta_{\text{mb}}$ over the period of observing was $\sim 20$ per cent, consistent with that typically seen for RXB3 on the JCMT.

The uncertainty in $\eta_{\text{mb}}$ introduces a systematic calibration uncertainty of $\pm 20$ per cent. In addition, there are random noise contributions arising from (a) noise across each spectral channel, (b) determining the integrated spectral line and (c) fitting the overall subtracted baseline level. These errors can be combined, following Gao (1996) (see Appendix A), to give an overall error, $\sigma I_{\text{CO}(3-2)}$, in the velocity-integrated main-beam brightness temperature (the integrated line intensity), $I_{\text{CO}(3-2)}$.

The efficiency-corrected spectra together with the pointing centres superimposed on a Digital Sky Survey optical image, are shown in Fig. C1 at the end of the paper. The properties of the spectra for each pointing, together with the random errors $\sigma I$, are summarized in Table 1. Where no line was detected, an upper limit for $I_{\text{CO}(3-2)}$ of $2 \sigma$ is given, assuming the detected line would have had a full width to zero intensity of $\Delta W = 400$ km s$^{-1}$. The observed spectra shown in Fig. C1 show a wide range of effective linewidths (from 74 to 639 km s$^{-1}$) and often show double peaked velocity profiles. These profiles can arise when a single telescope beam picks up CO(3–2) emission from each of the interacting nuclear components or when there is rotation of the molecular gas around one of the nuclear components within the beam.

3.1 Luminosities and line ratios

Having determined $I_{\text{CO}(3-2)}$ for each pointing for each object, we proceeded to calculate the total CO(3–2) line luminosity and the CO(3–2)/CO(1–0) line luminosity ratio for each object as follows. For galaxies with a projected nuclear separation of $\lesssim 7$ arcsec, it was assumed that the angular size of the CO(3–2) emitting region was small compared to the 14-arcsec beam size when determining the overall CO(3–2) luminosity. Following Gao & Solomon (1999), the CO(3–2) line luminosities, $L_{\text{CO}(3-2)}$, were calculated by following the definition of CO(1–0) luminosity given by Solomon et al. (1997).

$$
L_{\text{CO}(3-2)} = T_B \Delta V \Omega_b D_L^2 \equiv 23.5 \Omega_{\text{mb}} D_L^2 I_{\text{CO}(3-2)}(1 + z)^{-3} \text{[K km s}^{-1}\text{ pc}^2].
$$

where $T_B$ is the peak line brightness temperature, $\Delta V$ is the effective linewidth, $I_{\text{CO}(3-2)} \equiv \int T_{\text{mb}} dV$. $T_{\text{mb}}$ is the main-beam brightness temperature, $D_L$ is the luminosity distance and $\Omega_{\text{mb}}$ is the solid angle (arcsec$^2$) of the source convolved with the beam. A value of $\Omega_{\text{mb}} = \Omega_b = 1.133 \theta_{\text{FWHM}}^2 = 222$ arcsec$^2$ was used for objects observed with a single pointing, following the above assumption that the CO(3–2) emitting region was small compared to the beam. For objects observed with multiple pointings, the same value was used after combining the individual fluxes from each pointing, $I_{\text{CO}(3-2)}$, to calculate a total flux, $I_{\text{CO}(3-2,\text{Total})}$.

Upon examining Submillimetre Common-User Bolometer Array (SCUBA) 850-μm continuum maps for Mrk 1027 after we made our CO(3–2) observations, we found that the dust emission from the source appeared extended ($6 \times 12$ arcsec$^2$) and that centre of this emission was offset by 3.5 arcsec relative to our CO(3–2) (0,0) pointing. We thus took $I_{\text{CO}(3-2,\text{Total})} = 1.6 \times 1.4I(0,0)$, with the first factor correcting for beam dilution and the second factor correcting for the pointing offset. For IRAS 10039–3338, the flux was inadvertently measured at 3.5 arcsec from centre of optical/IR emission, so we corrected this mispointing by using $I_{\text{CO}(3-2,\text{Total})} = 1.4I(0,0)$, which assumes the emission is small compared to the beam.

For galaxies observed by more than one pointing, it was necessary to combine the fluxes to determine the total line luminosity. For galaxies with a projected nuclear separation $\sim 14$ arcsec observed with two pointings, the fluxes were combined as a weighted sum using the method presented in Appendix B. For objects with nuclear separation greater than 14 arcsec, the fluxes from each pointing were combined by assuming a plausible underlying brightness distribution based on the object morphology. For IRAS 01077–1707, the emission appeared consistent with a single compact source at (14, 0), so we estimated the total flux via $I_{\text{CO}(3-2,\text{Total})} = I(14, 0)$. For Arp 236, the emission of the source appeared to be consistent with a source equal to the beam size, so we took $I_{\text{CO}(3-2,\text{Total})} = \sqrt{2}I(37)$. For Arp 299, we combined the fluxes via $I_{\text{CO}(3-2,\text{Total})} = [I(0, 0) + I(9, 4) + I(7, 1) + I(14, 2)]/2$, consistent with an interferometric CO(1–0) map appearing in Casoli et al. (1999b). For Arp 302, we assumed a uniform underlying distribution across the pointings at (0,0), (0,8) and (−1, −7) and combined these separately with the flux at (−4, −37), $I_{\text{CO}(3-2,\text{Total})} = I(0, 0) + I(8, 8) + I(−1, −7))/2 + I(−4, −37)$. For NGC 6670, the emission appeared to be strongest at pointings (0,0), (−21, −6) and (−35, −11), so we estimated the total flux via $I_{\text{CO}(3-2,\text{Total})} = I(0, 0) + I(−21, −6) + I(−35, −11)$, i.e. assuming that most of the emission is concentrated in these directions.

The derived values for the total CO(3–2) luminosity $L_{\text{CO}(3-2)}$ and the CO(3–2)/CO(1–0) line luminosity ratios, $r_{31}$ are presented in Table 2.

The full physical implications of line ratio measurements for molecular gas conditions require non-local thermodynamic equilibrium photon transport models. These can be solved numerically, accounting for the excitation between several energy levels of the molecular species present. A popular approach is the large
Table 1. Observational parameters for the LIGs observed in this study.

| Object       | RA (h:m:s) | Dec. (°:′:″) | \(cz^a\) (km s\(^{-1}\)) | \(\sigma_{\text{ICO}}(3-2)^b\) | \(\sigma_{\text{IC0}}(3-2)^b\) | Effective linewidth (km s\(^{-1}\)) |
|--------------|------------|--------------|-----------------|-----------------|-----------------|-----------------------------------|
| 00057+4021   | 00:08:21.0 | +40:37:56    | 13,516          | (0.0)           | 9.5             | 0.5                               | 221 |
| Arp 236      | 01:07:47.0 | −17:30:24    | 6016            | (6.2)           | 98.5            | 2.1                               | 301 |
| 01077−1707   | 01:10:08.2 | −16:51:11    | 10,540          | (0.0)           | <3.8            | 1.9                               | −   |
| 00057+4021   | 01:08:21.0 | +40:37:56    | 13,516          | (0.0)           | 107.8           | 2.1                               | 295 |
| Mrk 1027     | 02:14:05.6 | +05:10:27.7  | 8913            | (0.0)           | 51.8            | 2.1                               | 312 |
| 02483+4302   | 02:51:36   | +43:15:11    | 15,419          | (0.0)           | 5.74            | 0.7                               | 163 |
| UGC 2369     | 02:54:01.8 | +14:58:14    | 9354            | (0.0)           | 20.5            | 2.3                               | 302 |
| 03359+1523   | 03:38:46.9 | +15:32:55    | 10,600          | (0.0)           | 12.3            | 2.5                               | 181 |
| Mrk 1027     | 02:14:05.6 | +05:10:27.7  | 8913            | (0.0)           | 28.5            | 1.2                               | 283 |
| 02483+4302   | 02:51:36   | +43:15:11    | 15,419          | (0.0)           | 5.74            | 0.7                               | 163 |
| UGC 2369     | 02:54:01.8 | +14:58:14    | 9354            | (0.0)           | 20.5            | 2.3                               | 302 |
| 03359+1523   | 03:38:46.9 | +15:32:55    | 10,600          | (0.0)           | 12.3            | 2.5                               | 181 |
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| UGC 2369     | 02:54:01.8 | +14:58:14    | 9354            | (0.0)           | 20.5            | 2.3                               | 302 |
| 03359+1523   | 03:38:46.9 | +15:32:55    | 10,600          | (0.0)           | 12.3            | 2.5                               | 181 |

\(^a\) Optical redshift definition, values obtained from NASA/IPAC Extragalactic Data base (NED) http://nedwww.ipac.caltech.edu/

\(^b\) Effective linewidth \(\equiv T_{\text{mb,peak}}/I_{\text{IC0}}(3-2)\), where \(T_{\text{mb,peak}}\) is the peak main–beam brightness temperature of the line.
velocity gradient (LVG) method (Goldreich & Kwan 1974; Scoville & Solomon 1974) which assumes that large-scale systematic velocity gradients, rather than thermal motions, dominate the observed linewidths. This assumption simplifies the photon transport problem, since there is essentially no overlap in line emission between distant parts of the cloud. For the mean value of $R_{LVG} = 0.47$ for the LIGs in our sample, we performed an LVG fit assuming a $^{12}$CO(1–0)/$^{13}$CO(1–0) line ratio, $R_{CO}$, of $R_{CO} = 15–20$ measured typically for such galaxies (e.g. Casoli, Dupraz & Combes 1992; Papadopoulos & Seaquist 1998). This LVG fit yielded typical conditions of kinetic temperature $T_K = (30–50)$ K and a H$_2$ number density of $n = 10^3$ cm$^{-3}$ with a CO abundance per velocity gradient $\Lambda = [CO/H_2]_L/(dV/dL)$ of $10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$, though good solutions exist also for a much warmer ($T_K \sim 80–110$ K) and diffuse ($n \sim 3 \times 10^2$ cm$^{-3}$) gas phase. This degeneracy reflects both the lack of constraints that could be set by observing a larger number of molecular lines (especially high-J CO transitions, $^{13}$CO lines and high-density tracers such as HCN transitions), and the presence of a diffuse and warm gas phase along with a denser and cooler one that usually exists in such systems (e.g. Aalto et al. 1995). The hereby observed CO(3–2) line is the highest-J CO transition to have significant contributions from the former while tracing mostly the later phase (Papadopoulos, Isaak & van der Werf 2007). We intend to combine our CO(3–2) data with HCN observations for the same galaxy sample to further constrain the molecular gas conditions. We also intend to conduct a more detailed analysis of several of the LIGs in our sample, as part of a multi-J CO and HCN line survey of such systems (Papadopoulos et al. 2007).

### Table 2. Component separations, infrared and CO luminosities and line ratios for our LIG sample.

| Object         | Separation (kpc) | $L_{IR}$ 10$^{11}$ $L_\odot$ | $L_{FIR}$ 10$^{11}$ $L_\odot$ | $L_{CO}(3-2)$ (K km s$^{-1}$, Total) | $\sigma L_{CO}(3-2)$ (K km s$^{-1}$) | $L_{CO}(3-2)$ (10$^9L_\odot$) | $L_{CO}(1-0)$ (10$^9L_\odot$) | $r_{35}$ |
|----------------|-----------------|-------------------------------|-------------------------------|----------------------------------|--------------------------------|-----------------------------|-------------------------------|---------|
| 00057+4021     | 2.1             | 4.3                           | 3.31                          | 9.5                              | 0.5                           | 1.65                        | 3.8                           | 0.43    |
| Arp 236        | 6.1             | 4.71                          | 3.19                          | 152                              | 3.0                           | 5.21                        | 10.67                          | 0.49    |
| 01077–1707     | 22.4            | 4.33                          | 2.79                          | 24.6                             | 2.4                           | 2.49                        | 8.5                           | 0.29    |
| III Zw 35      | 4.1             | 4.15                          | 3.58                          | 18.5                             | 2.2                           | 1.21                        | 2.09                          | 0.58    |
| Mrk 1027       | 5               | 2.49                          | 1.69                          | 63.8                             | 2.6                           | 4.79                        | 5.35                          | 0.89    |
| 02483+4302     | 3.6             | 6.21                          | 4.54                          | 5.74                             | 0.7                           | 1.30                        | 2.88                          | 0.45    |
| UGC 2269       | 13.1            | 3.95                          | 2.66                          | 20.5                             | 2.3                           | 1.69                        | 7.25                          | 0.23    |
| 03359+1523     | 6.5             | 3.34                          | 2.42                          | 12.3                             | 2.5                           | 1.30                        | 6.9                           | 0.19    |
| 04232+1436     | 6.3             | 11.15                         | 7.49                          | 20.0                             | 2.4                           | 10.3                        | 9.0                           | 1.15    |
| Arp 55         | 10.7            | 4.66                          | 3.39                          | 45.1                             | 3.8                           | 5.74                        | 12.07                         | 0.48    |
| 10035–3338     | 3.1             | 4.54                          | 3.94                          | 15.3                              | 0.6                           | 1.46                        | 2.93                          | 0.50    |
| 10190+1322     | 6.6             | 11.34                         | 7.13                          | 10.3                              | 1.1                           | 4.86                        | 8.2                           | 0.59    |
| 10565+2448     | 6.2             | 9.58                          | 7.59                          | 28.4                              | 0.9                           | 4.31                        | 5.76                          | 0.75    |
| Arp 299        | 4.5             | 6.36                          | 4.74                          | 183                              | 2.8                           | 1.64                        | 3.0                           | 0.55    |
| 13001–2339     | 2.6             | 2.45                          | 2.0                           | 43.8                              | 1.5                           | 1.67                        | 2.55                          | 0.66    |
| Arp 238        | 12.1            | 5.17                          | 3.8                           | 16.3                              | 2.7                           | 1.34                        | 4.24                          | 0.32    |
| NGC 5256       | 4.8             | 3.05                          | 2.02                          | 39.6                              | 4.2                           | 2.46                        | 5.66                          | 0.43    |
| Mrk 673        | 4.0             | 2.2                           | 1.51                          | 18.9                              | 2.8                           | 2.04                        | 4.0                           | 0.51    |
| 14348–1447     | 5.7             | 20.43                         | 16.28                         | 19.4                              | 2.0                           | 10.55                       | 14.0                          | 0.75    |
| Arp 302        | 25.8            | 41.6                          | 4.1                           | 59.0                              | 2.4                           | 5.59                        | 19.7                          | 0.28    |
| Mrk 848        | 4.8             | 7.16                          | 5.29                          | 19.9                              | 1.1                           | 2.62                        | 7.03                          | 0.37    |
| NGC 6090       | 3.5             | 2.98                          | 1.94                          | 56.4                              | 2.2                           | 3.96                        | 5.0                           | 0.79    |
| 17132+3313     | 6.4             | 7.67                          | 5.73                          | 12.5                              | 2.5                           | 2.64                        | 7.24                          | 0.37    |
| NGC 6670       | 14.6            | 3.84                          | 2.73                          | 44.6                              | 3.4                           | 3.26                        | 11.6                          | 0.28    |
| 19297–0406     | 11.5            | 24.59                         | 19.28                         | <1.8                              | 1.1                           | <1.3                        | 9.43                          | <0.11   |
| 20010–2352     | 8.1             | 4.69                          | 3.16                          | 16.4                              | 1.4                           | 3.47                        | 6.38                          | 0.54    |
| II Zw 96       | 7.4             | 7.57                          | 6.36                          | 27.2                              | 1.7                           | 3.08                        | 6.04                          | 0.51    |
| NGC 7592       | 5.3             | 2.43                          | 1.68                          | <0.2                              | 3.1                           | <0.31                       | 4.55                          | <0.07   |
| **Mean**       | **7.15**        | **11.5**                      | **5.2**                       | **4.03**                          | **<0.6**                      | **3.1**                     | **<0.31**                     | **4.55** | **<0.07** |

$^a$ Calculated using equation (2), $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$, $L_d = K$ km s$^{-1}$ pc$^2$.

![Figure 2. A comparison of the $L_{FIR}$ for the SLUGS sample (open rectangles), our sample (narrow cross-hatch) and the Mauersberger sample (wide cross-hatch).](https://example.com/figure2.png)

### 3.2 Statistical properties of the sample

It is instructive to compare the CO(3–2) observations of the LIG sample here with the CO(3–2) observations of a sample of 29 local galaxies reported by Mauersberger et al. (1999) (Figs 2 and 3). The authors selected galaxies which exhibit strong $L_{CO}(1-0)$ and...
I$_{\text{CO}}$(2-1) intensities, though mostly due to their proximity rather than high intrinsic CO(1–0) or CO(2–1) luminosity. Their sample contained 27 non-infrared luminous galaxies with $0.9 \times 10^9 L_\odot < L_{\text{IR}} < 96 \times 10^9 L_\odot$ and two LIGs, NGC 2146 ($L_{\text{IR}} = 1.1 \times 10^{11} L_\odot$) and Arp 220 ($L_{\text{IR}} = 1.3 \times 10^{12} L_\odot$). The majority (26) of the galaxies were isolated spirals of type SAB, SA or SB. The CO(3–2)/CO(1–0) line ratio for most of the galaxies was between 0.2 and 0.7 with only four objects exhibiting line ratios greater than unity. Thus, most of our high infrared luminosity sample have a similar range of CO(3–2)/CO(1–0) line ratios to the Mauersberger sample i.e. a selection of nearby galaxies with moderate infrared luminosity.

We can also compare our CO(3–2) observations with those of a subsample of the SCUBA Local Universe Galaxy Survey (SLUGS) presented by Yao et al. (2003). The 60 galaxies chosen were a near-complete, flux-limited subsample $S_{60\mu m} > 5.24$ Jy sample with $L_{\text{FIR}}$ predominantly less than $10^{11} L_\odot$. Their subsample is therefore on average considerably less IR-luminous than our sample CO(3–2) (Fig. 2), yet we see from Fig. 3 that a similar spread of line ratios is observed with the majority exhibiting $r_{31} < 1$.

4 DISCUSSION

4.1 Evolution across the merging sequence

Since our sample represents a merging sequence of galaxies, we can now examine how the dense molecular gas component, traced by the CO(3–2) transition, evolves as merging progresses. In particular, we will determine the correlation between the CO(3–2)/CO(1–0) line ratio, $r_{31}$, and nuclear component separation, $L_{\text{FIR}}$ and $L_{\text{FIR}}/L_{\text{CO}(1–0)}$, a commonly used measure of star formation efficiency.

**Trend with nuclear separation**

Shown in Fig. 4 is a plot of log($r_{31}$) versus the logarithm of the nuclear separation [log(sep, kpc)], for which we see a weak anticorrelation ($r = -0.52$). We observe no correlation between log($L_{\text{FIR}}$) and the logarithm of the nuclear separation (Fig. 5). This lack of correlation is unsurprising, given that log($L_{\text{FIR}}$) is expected to depend on a number of different factors (e.g. the total extent of the star-forming regions, dynamical mass of overall merger), which in turn are not simply, if at all, related to the progression of the merger. In contrast, by looking at the CO(3–2)/CO(1–0) line ratio we are in effect independent of the overall mass of the merger system. If we assume therefore that $r_{31}$ is a measure of the extent of excitation of the molecular gas present in the merging galaxies, then the weak anticorrelation ($r = -0.52$) is consistent with the gas excitation increasing as the merger progresses.

**Correlations between line ratio, $L_{\text{FIR}}$ and star formation efficiency**

A common quantity used to determine the star formation efficiency of a galaxy or galactic region is log($L_{\text{FIR}}/L_{\text{CO}(1–0)}$), where we assume the FIR luminosity is a result of emission from dust heated by UV-photons emitted from star formation rather than AGN. Shown
in Fig. 6 is a plot of log($r_{31}$) versus log [$L_{\text{FIR}}/L_{\text{CO(1–0)}}$]. A weak correlation ($r = 0.38$) is seen, suggesting that there is an increase in gas excitation in galaxies that show an increased star formation efficiency. This is not surprising, as one might expect to observe higher gas excitation in regions where star formation is proceeding vigorously. No significant correlation is seen between log($r_{31}$) and log($L_{\text{FIR}}$) (Fig. 7, $r = 0.21$).

Our observations and analysis hint at an increase in excitation, as traced by CO(3–2), with the temporal progression of the merger. The uncertainties within our current data along with the relatively small number of sources per unit change in $L_{\text{FIR}}$ and nuclear separation make it difficult to state this with a sufficient degree of confidence, however. For the objects larger than a beamwidth, wide-angle jiggle-mapping with the newly commissioned HARP focal-plane array (Smith et al. 2003) will enable the full extent of the CO(3–2) line emission to be captured more accurately, enabling a more accurate line ratio to be determined.

4.2 Contribution to the 850-μm continuum flux

An 850-μm/450-μm continuum emission survey has recently been completed (Mortier & Isaak, in preparation) for the galaxies in the Gao and Solomon sample in order to map the distribution of the dust emission and determine dust masses and temperatures. This has been made with SCUBA, a bolometer array receiver on the JCMT (Holland et al. 1999). The SCUBA 850-μm camera has a total bandwidth of ~30 GHz set by a bandpass filter with a centre frequency of 347 GHz. If the redshift of an object is such that the CO(3–2) line falls within the bandpass of this filter, the CO(3–2) line emission will contaminate the continuum emission from the dust (Papadopoulos & Allen 2000). The CO(3–2) observations made here are thus very useful in determining the contribution of the CO(3–2) line emission to the 850-μm flux continuum flux measured using SCUBA.

The CO(3–2) contribution to the measured SCUBA 850-μm flux can be calculated using

$$S(V) = \frac{2kT_{mb}}{c^2} \Omega_b g(V) \int g(V)dV I_{\text{CO(3–2)}} [\text{Wm}^{-2} \text{Hz}^{-1} \text{beam}^{-1}],$$

(Seaquist et al. 2004) where $V_L$ is the line frequency, $\Omega_b$ is the main-beam solid angle and $I_{\text{CO(3–2)}} = \frac{1}{V_{\text{mb}}} dV$ is the velocity integrated main-beam brightness temperature in K km s$^{-1}$. For $g(V)$, the bandpass profile of the filter expressed as a function of the recession velocity $V = c \zeta$, we have adopted the same dual Gaussian form used by the SLUGS survey in Seaquist et al. (2004).

Table 3 shows the CO(3–2) contribution to the measured SCUBA 850-μm flux for the observed objects in the sample. As the SCUBA

| Object   | CO(3–2) contribution (mJy) (Filter corrected) |
|----------|-----------------------------------------------|
| 00057+4021 | 2.7                                           |
| Arp 236  | 91.4                                         |
| 01077−1707 | 14.9                                         |
| III Zw 35 | 12.6                                         |
| Mk 1027   | 43.7                                         |
| 02483+4302 | 0.6                                          |
| UGC 2369  | 13.8                                         |
| 03359+1523 | 7.4                                          |
| 04232+1436 | 0.0                                          |
| Arp 55    | 21.8                                         |
| 10039−3338 | 9.6                                          |
| 10190+1322 | 0.0                                          |
| 10565+2448 | 9.9                                          |
| Arp 299   | 103.1                                        |
| 13001−2339 | 27.2                                         |
| Arp 238   | 11.0                                         |
| NGC 5256  | 27.1                                         |
| 14348−1447 | 0.0                                          |
| Arp 302   | 37.4                                         |
| Mk 848    | 9.0                                          |
| Mk 673    | 10.7                                         |
| NGC 6090  | 38.7                                         |
| 17132+5313 | 1.6                                          |
| NGC 6670  | 30.6                                         |
| 19297−0406 | 0.0                                          |
| 20010−2352 | 2.2                                          |
| II Zw 96  | 15.6                                         |
| NGC 7592  | <4.1                                         |
80-μm fluxes are measured for the sample, these data will enable the correction for the CO(3–2) contamination of the dust emission to be made. These corrected 80-μm fluxes will be published in a forthcoming paper – preliminary results show that the mean CO(3–2) contribution for the sample is 22 per cent and the median contribution is 17 per cent (Mortier 2009, private communication). An 80-μm map of Arp 236 has been made (Frayer et al. 1999) and the total flux at 80 μm is reported at 273 mJy. The CO(3–2) contribution to this flux will be around 91.4 mJy (33 per cent). These results demonstrate the importance of determining the correction both when fitting dust emission models to observed fluxes to determine dust temperatures, and particularly when determining total dust masses, which are usually taken to be proportional to the 80-μm flux (Dunne et al. 2000).

5 CONCLUSIONS AND FURTHER WORK

We have observed the CO(3–2) emission from a sample of IR-selected merging galaxies using the single-pixel 350-GHz receiver at the JCMT. We have found that the CO(3–2) to CO(1–0) line ratio, \(r_{31}\), is less than unity for all but one object in our merging sample with a sample average of \(r_{31} = 0.47\). LVG modelling indicates that this is consistent with \(T_k = (30–50)\) K, \(n = 10^5\) cm\(^{-3}\) and \(\Delta = [\text{CO}/\text{H}_2]/(dV/dr) = 10^{-5}\) (km s\(^{-1}\) pc\(^{-1}\))\(^{-1}\), although warmer (\(T_k \sim 80–110\) K) and more diffuse (\(n \sim 3 \times 10^5\) cm\(^{-3}\)) conditions for the gas phase are not ruled out. We have calculated the CO(3–2) contribution to the 850-μm continuum flux for the galaxies in our sample. We have found that this contribution can be a large fraction of the 850-μm flux underlying the importance of making CO(3–2)-based flux corrections when deriving spectral energy distribution fits or dust masses from 850-μm fluxes. Our correction will be presented in a forthcoming paper presenting the 850-μm SCUBA data for this galaxy set.

The spread of line ratios observed in our merging sample was broadly similar to that measured in both an IR-selected subsample of the SLUGS (Yao et al. 2003), and a sample of normal galaxies (Mauersberger et al. 1999). We observe a weak anticorrelation between \(\log(r_{31})\) and \(\log(\text{sep}; \text{kpc})\) in our sample, a result consistent with gas excitation increasing as the merger progresses. A plot of line ratio versus star formation efficiency \(\{\log(r_{31})\} \text{versus } \log[L_{\text{FIR}}/L_{\text{CO}(1–0)}]\) also shows a weak correlation, as gas excitation increases with increased star formation efficiencies. These correlations are suggestive of an increase in the excitation of the molecular gas, as measured by the CO(3–2)/CO(1–0) line ratio, with the progression of galactic mergers. However, studies of line ratios of these kind are often unavoidably affected by uncertainties in line luminosities arising both from random errors and systematic errors in the absolute flux calibration, which can be as high as 20 per cent. Uncertainties also arise from assumptions that often must be made about the angular size and shape of the CO(3–2) emission regions relative to the telescope’s beam. These latter uncertainties will hopefully be reduced as more small sources (\(D_A < 10\) arcsec) are mapped interferometrically, and as more extended sources (\(D_A \geq 10\) arcsec) are mapped with the next generation of multi-element focal-plane heterodyne arrays, such as HARP-B on the JCMT.

Our future work includes an LVG analysis in which we will combine our CO(3–2) data with HCN line measurements for the same galaxy set to systematically probe the gas properties across the merging sequence. We also intend to improve our total luminosity estimates for our more extended sources by mapping them with the newly commissioned HARP-B focal-plane array.

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APPENDIX A: SYSTEMATICS AND ERROR ANALYSIS

As well as the systematic calibration errors of around ±20 per cent, there are random errors arising from noise across each spectral channel. This noise leads to errors in determining the integrated spectral line and in determining the overall subtracted baseline level. Following Gao (1996), these random errors were combined using

$$\sigma I = \sqrt{\sigma I_{\text{line}}^2 + \sigma I_{\text{base}}^2} = \sigma T_{\text{rms}} \sqrt{\Delta V \Delta W / \sqrt{1 - \Delta W / W}},$$

(A1)

where $\sigma T_{\text{rms}}$ is the rms noise on a single velocity channel of width $\Delta V$, $\Delta W$ is the full width to zero intensity of the line and $W$ is the total velocity coverage of the observation. These random errors in the velocity integrated main-beam brightness temperature, $\sigma I$, are presented separately from any overall calibration errors.

APPENDIX B: DERIVING THE GLOBAL CO(3–2) LUMINOSITIES FROM MULTIPLE POINTINGS

For galaxies with a projected nuclear separation $\sim$14 arcsec, the procedure followed for combining the two measured intensities was similar to that used by Zhu et al. (1999). Each galaxy was modelled as a Gaussian brightness distribution of diameter $D_0$ and inclination $i$ with a position angle PA. This procedure allowed the intrinsic intensities for each pointing $I_{01}$ and $I_{02}$ to be derived from the measured intensity for each pointing $I_1$ and $I_2$. For II Zw 96, NGC 5256 and Arp 55, detections were observed in both pointings and the parameters used in the source models are shown in Table B1. Objects where only a line was detected in one of two pointings were treated identically to the objects for which a single pointing was made, with the assumption that the CO(3–2) emitting region is small.

The optical images of Arp 55, NGC 5256 and II Zw 96 [Fig. C1 (w),(q) and (t)] suggest collisions between two face-on galaxies, and the optical brightness distributions are near circular so values of $\alpha = 0$ and PA = 0 were chosen for both components.

For each object, the intrinsic CO(3–2) intensities $I_{01}, I_{02}$ were calculated for two cases: (i) assuming that the half power width of the CO(3–2) emitting regions were both small compared to the 14-arcsec beam ($D_0 = 1$ arcsec) and (ii) assuming the half power width of the CO(3–2) emitting regions were around one half of a beam size ($D_0 = 7$ arcsec). This gave an assessment of the sensitivity of the model to the unknown beam filling factors. The results for the two differing source sizes are shown in Table B1. For calculating the final combined CO(3–2) intensity, the first model (i) corresponding to two small emitting regions was chosen in keeping with the assumptions made for the objects observed with a single pointing. Note that for Arp 55, it was found that the galaxy was inadvertently observed with a map centre of 09:15:54.9 + 44:19:54.4 (J2000) rather than the required coordinate of 09:15:54.7 + 44:19:51 [see Fig. C1(w)]. We thus incorporated this additional offset of (+1.9 arcsec,+3.4 arcsec) in each of the two pointings into our model, leading to an estimated total flux of 45.1 K km s$^{-1}$ [see the ‘Arp 55 (corrected)’ row in Table B1 above].

APPENDIX C: CO(3–2) SPECTRA AND POINTINGS

The main-beam efficiency-corrected spectra together with the pointing centres superimposed on a Digital Sky Survey optical image, are shown in Fig. C1.

Table B1. Details of the combination of the observations for the galaxies observed with two pointings. For each galaxy, the model with a small emitting region (1 arcsec) was chosen, and the value of $I_{\text{TOTAL}}$, marked with an asterisk used in calculating the final CO(3–2) luminosity.

| Object          | Pointing 1 | $D_0,1$ | PA$_1$ | Pointing 2 | $D_0,2$ | PA$_2$ | $I_1$ | $I_2$ | $I_{01}$ | $I_{02}$ | $I_{\text{TOTAL}}$ |
|-----------------|------------|--------|--------|------------|--------|--------|------|------|--------|--------|-------------------|
| Arp 55          | (0,0)      | 0      | 1      | 0          | +10,7  | 0      | 1    | 0    | 28.1   | 18.3   | 26.0              |
| Arp 55 (corrected) | (0,0)     | 0      | 7      | 0          | +10,7  | 0      | 7    | 0    | 28.1   | 18.3   | 30.8              |
| NGC 5256       | (0,0)      | 0      | 1      | 0          | +10,7  | 0      | 1    | 0    | 28.1   | 18.3   | 24.4              |
| NGC 5256       | (0,0)      | 0      | 7      | 0          | +10,7  | 0      | 7    | 0    | 18.4   | 29.0   | 13.1              |
| II Zw 96       | (0,0)      | 0      | 1      | 0          | +10,7  | 0      | 1    | 0    | 13.7   | 17.9   | 11.0              |
| II Zw 96       | (0,0)      | 0      | 7      | 0          | +10,7  | 0      | 7    | 0    | 13.7   | 17.9   | 12.3              |

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Figure C1. CO(3–2) spectra and optical images (with pointings and beam size). The optical image wavelength is 645 nm (band 103aE) (taken from the STScI DSS) (Kent 1994), http://archive.stsci.edu/cgi-bin/dss_form). Where the object was observed with both narrow (900 MHz) and wide (1800 MHz) spectrometer bandwidths, both spectra are show, with the wideband spectrum shown as a dotted line.
Figure C1 – continued
Figure C1 — continued
Figure C1 – continued
Figure C1 – continued

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