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The neutral ISM in Luminous Compact Blue Galaxies

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Abstract. Luminous Compact Blue Galaxies are a class of rapidly evolving galaxies that are common at $z \sim 1$ but rare at $z \sim 0$. Through HI and CO observations of a locally defined sample, we have determined dynamical masses and gas depletion timescales and constrained evolutionary scenarios. We find that $\sim 80\%$ are likely to fade into dwarf ellipticals but the remaining 20% may be the precursors to low mass spirals or Magellanic irregulars. Star formation rates scale with the $1.4^{\rm th}$ power of total gas column density and follows the Schmidt law prescription of Kennicutt (1998). The star formation rate is also proportional to the molecular-to-atomic mass ratio. CO line ratios indicate abundant warm, dense gas and is consistent with the entire molecular ISM actively forming stars.

1. Introduction

Deep optical images of the night sky reveal the presence of a large excess of faint blue galaxies, $B - K < 5$, an order of magnitude more numerous than the predictions of a non-evolving galaxy population (Ellis 1997). A subset of these faint blue galaxies are termed "Luminous Compact Blue Galaxies" (LCBGs); vigorously star forming galaxies with similar luminosities to grand-design spirals.

LCBGs appear to have evolved more than any other galaxy class in the last ~ 8 Gyr (Lilly et al. 1998). At $z \sim 1$, LCBGs are numerous with a total star formation rate density equal to that of grand design spirals at that time. At $z \sim 0$, however, the number density of LCBGs has decreased by a factor of ten and they contribute negligibly to the local star formation rate density of the Universe (Marzke et al. 1998). It is not known what drives their rapid evolution nor what is their final state.

Morphologically, LCBGs resemble a wide range of nearby galaxy types, from spiral to irregular galaxies (Phillips et al. 1997) and therefore need not all follow the same evolutionary path. There are two main evolutionary scenarios currently being discussed in the literature. Koo et al (1994) and subsequent authors have suggested that some subset of the most compact LCBGs at intermediate redshifts may be the progenitors of local low-mass elliptical galaxies such as NGC 205. This scenario relies on the assumption that we are witnessing the last major episode of star formation in these galaxies, after which there may not be much gas left to fuel future starbursts, and the galaxies will fade to reach the low luminosities characteristic of low-mass ellipticals. Alternatively, Hammer et al. (2001) have proposed that some LCBGs may have large reservoirs of gas that allow for continued star formation, albeit at a lower rate than the current burst, and become today's population of small spiral or irregular galaxies.

Observations of the ISM from which the stars form provide a clear means to differentiate between the two evolutionary scenarios. The gas mass divided by the star formation rate gives a lower limit to the gas depletion timescale, and thence the evolutionary timescale. The dynamical mass can be determined from the gas linewidth and extent. Mass, not luminosity, is the fundamental quantity that allows identification of similar galaxies in various stages of evolution, since it is independent of the age of their stellar populations.

Based on optical linewidth measurements, LCBGs have low mass-to-light ratios, $\sim 0.1M_*/L_*$ (Guzmán 2001). Their relatively low mass likely explains the lack of detection of molecular gas in these objects at intermediate redshifts (Wilson & Combes 1998). To study the properties of the ISM in LCBGs, we must find local counterparts. This is a challenging task given their rapid evolution and consequent rarity in the nearby Universe. We use the same color ($B - V < 0.6$), surface brightness (SBe < 21 mag/arc sec^2) and magnitude ($M_B < -18.5$) criteria that Jangren et al. (2003) used to define the LCBG population at intermediate redshifts and applied a distance cutoff of 70 Mpc ($v < 4900$ km s^{-1} for $H_0 = 70$ km s^{-1} Mpc^{-1}). Under these constraints, we found 4 nearby LCBGs in the literature and an additional 16 from the first release of the Sloan Digital Sky Survey. The distance cutoff corresponds, approximately, to a mass sensitivity, $M_{\mathrm{H_2}} \sim 10^7\ M_\odot$, for hour long integrations on millimeter wavelength telescopes.

In this paper we present observations of HI and CO of this local LCBG sample. The singledish data provide a global picture of the neutral ISM in LCBGs and allows us to draw some preliminary conclusions about the fates of this class of galaxies at higher redshifts. In addition, the uniformity both of the sample and the observations allow us to investigate how the star formation rate varies with the gas density and molecular mass fraction in this class of galaxies. Finally, we show recently obtained interferometric observations of one object that shows the details of the molecular gas in relation to its star forming sites.

2. Observations

HI observations were carried out with the 100 m Green Bank Telescope (GBT) in winter 2002. The main beam half power width is $9\farcm2$ at 21 cm. The three lowest transitions of CO were observed from 2002-2003 with a variety of telescopes so as to ensure a matching beam sample, $\theta_{\mathrm{FWHM}} = 21''$; the J =1–0 line at the IRAM 30 m, 2–1 at the JCMT 15 m, and 3–2 at both the CSO and HHT 10 m.

All 20 galaxies have been observed by the GBT (Figure 1) and JCMT (Figure 2). The detection rate was 100% in HI and 65% in the CO(2–1) line. Those galaxies with CO detections have also been observed with either the CSO or HHT in the 3–2 line. We recently completed a CO(1–0) survey of all the galaxies using the IRAM 30 m and analysis is underway; the larger collecting area of this telescope has increased the detection rate of molecular gas. In addition, follow-up interferometric observations are in the process of being made for the brighter members of our sample (§4).

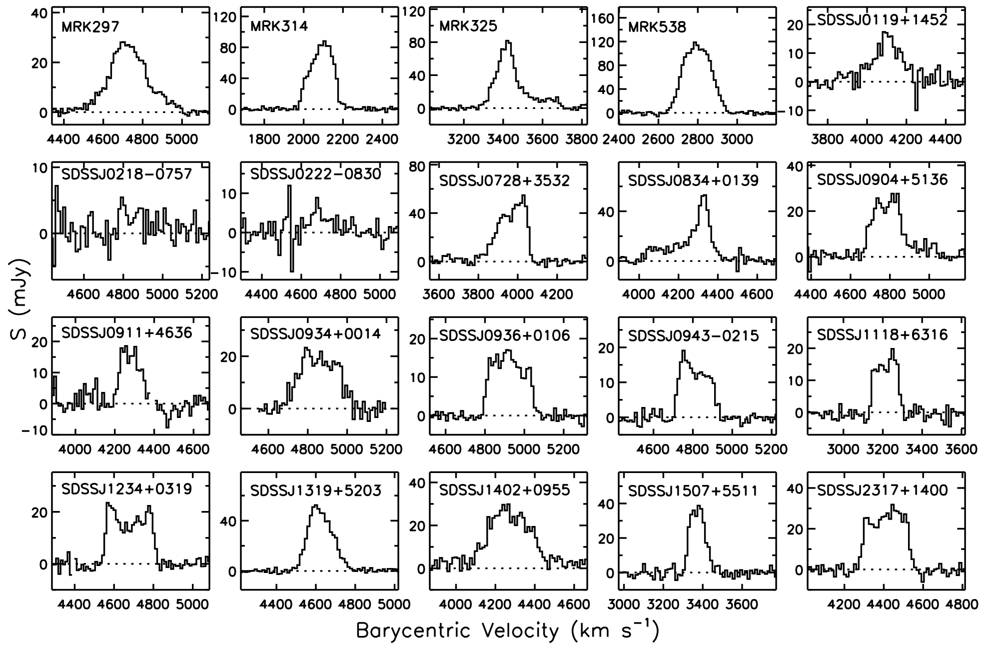

Figure 1: GBT HI spectra of the 20 galaxies in our local LCBG sample. The velocity axis spans 800 km s^{-1} for each spectrum so that linewidths and spectral shapes can be directly compared.

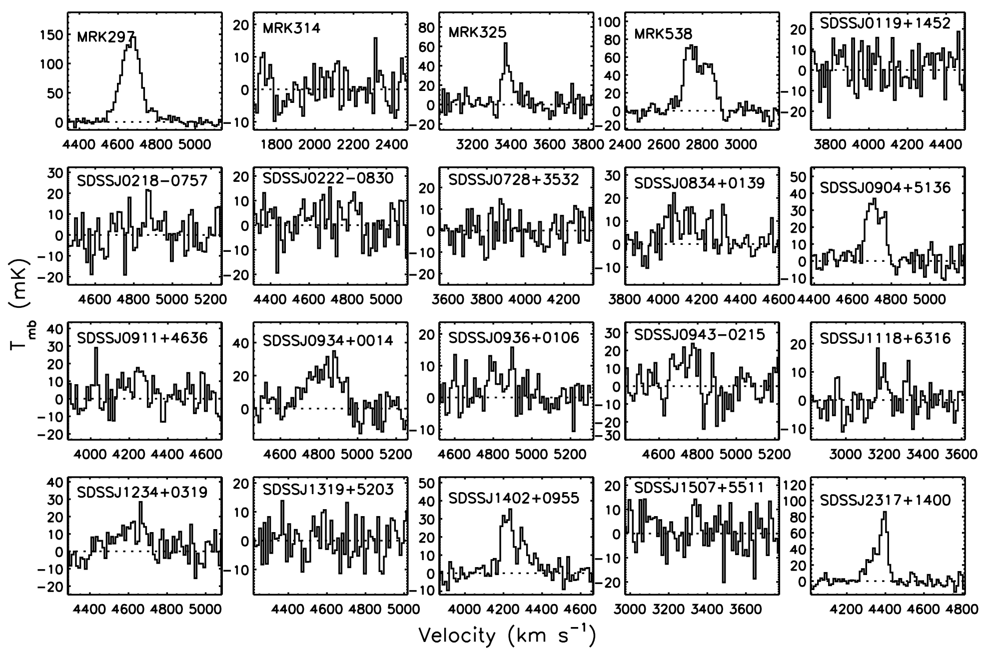

Figure 2: JCMT CO(2–1) spectra of the local LCBG sample. The source order and velocity axes are the same as in Figure 1.

3. Analysis

3.1. Dynamical masses

In the absence of mergers, mass is an evolutionary invariant. The GBT does not resolve the galaxies so their size is unknown. However, HI linewidths in our local sample, $\Delta v_{\rm FWHM} = 100 - 300$ km s^{-1}, are similar to Hα linewidths measured for LCBGs at intermediate redshifts by Phillips et al. (1997). Therefore the dynamical masses do not appear to be greatly underestimated by the optical measurements.

If we scale the HI size from the measured optical sizes, we infer dynamical masses, $M_{\rm dyn} = 4 \times 10^9 - 1 \times 10^{11}\ M_\odot$, for our sample. Future VLA observations will refine these mass estimates by measuring an HI size. However, we can conclude that most LCBGs are *not* the bulges of massive disks. Further details are in Garland et al. (2003).

3.2. Gas depletion timescales

The gas mass divided by the star formation rate is a measure of the timescale for the gas to be used up, assuming that stars continue to form at the current observed rate and that there is no recycling of material. Star formation rates for our sample were calculated from IRAS fluxes following the prescription in Kewley et al. (2002), atomic masses are directly determined from the integrated HI intensity, and molecular masses were estimated from the JCMT CO(2–1) integrated intensities assuming a 2–1/1–0 ratio of unity and a Galactic CO-to-H_2 conversion factor of 1.8×10^{20} cm^{-2} K^{-1} km s^{-1}.

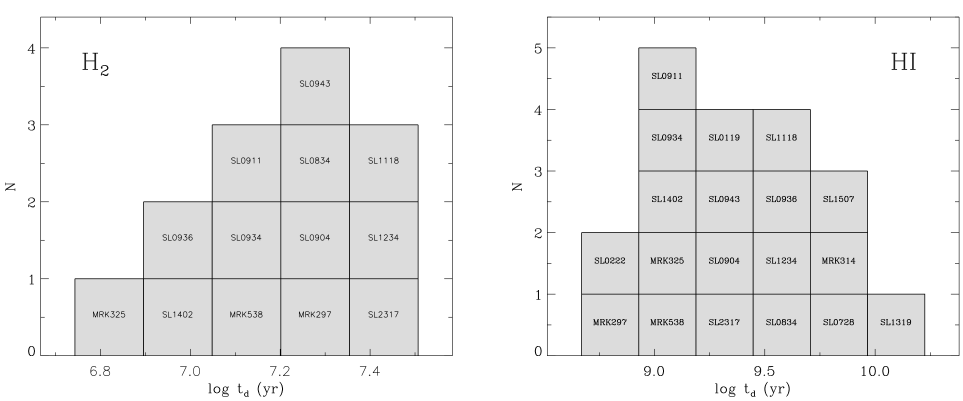

Figure 3: Histogram of gas depletion timescales, $t_{\rm dep} = M_{\rm gas}/{\rm SFR}$, for molecular gas (left panel) and atomic gas (right panel).

Histograms of the depletion time for molecular and atomic gas are shown in Figure 3. Molecular gas will deplete in a few tens of million years, comparable to GMC lifetimes estimated in the Milky Way (e.g. Williams & McKee 1997), but most have a large reservoir of atomic gas that, if converted to star forming material, could sustain star formation at the current rate for $1-10$ Gyr. If this is typical of LCBGs at $z \sim 1$, then most will run out of material to form stars and fade into dwarf ellipticals by $z = 0$. However, $\sim 20\%$ are capable of sustained star formation to the present epoch and may be the precursors to Magellanic irregulars or perhaps low mass spirals.

There are numerous caveats to this simple calculation including (1) star formation may not be constant but may proceed in short-lived bursts; (2) substantial quantities of gas may be lost from these low mass systems in coordinated supernova events (Fragile et al. 2003); (3) the rate and efficiency for the conversion of atomic to molecular gas is unknown. To address the last issue, we have begun to analyze our survey to study the properties of and relationships between the atomic and molecular gas and the star formation rate. This is the subject of the next three sections.

3.3. Global star formation properties

The uniformity in sample selection and observations provide an excellent dataset for the examination of global star formation properties. Scaling from optical radii, we find that the star formation rate density scales as the total gas column density – the Schmidt law – along the same relation as Kennicutt (1998) found (left panel of Figure 4). Interestingly, the density and star formation rate lie intermediate in the range between normal galaxies and starbursts, appropriate to values typical of the *centers* of normal disks. However, as noted in §3.1, the dynamical masses appear to be too low for most LCBGs to evolve into spirals.

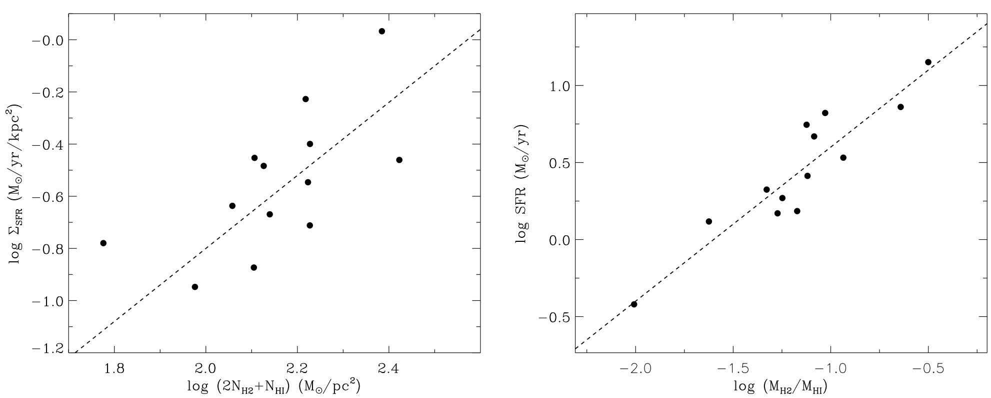

Figure 4: Global star formation correlations in our local LCBG sample. The left panel plots the star formation rate density against total gas column density. The dotted line is the Schmidt law relationship, $\Sigma_{\rm SFR} = 2.5 \times 10^{-4} \Sigma_{\rm gas}^{1.4}$, (in the units of the plot) from Kennicutt (1998). The right panel plots the star formation rate versus the molecular to atomic mass fraction. The dotted line is the relationship, ${\rm SFR} = 40(M_{\rm H_2}/M_{\rm HI})\ M_\odot\ {\rm yr}^{-1}$.

The data also revealed an unexpected correlation between the rate at which stars form and the molecular to atomic mass ratio (right panel of Figure 4). This suggests that the more efficiently a galaxy creates molecular clouds, the higher the star forming rate. Surprisingly, this result appears to be independent of the total molecular mass but the limited dynamic range of the latter may obscure any such trend.

3.4. Multi-transition CO analysis

The short depletion timescales and high luminosities show that LCBGs are efficiently forming stars. To examine the conditions of the molecular gas in these environments, we have observed the three lowest CO transitions at the same 21″ resolution ($\simeq 5$ kpc at $d = 50$ Mpc) for many of the galaxies in our sample.

The analysis of the multi-transition CO data is just underway. An LVG analysis on one object is shown in Figure 5. This result, plus a preliminary inspection of the sample shows that, in general, the $3-2/1-0$ line ratio is typically rather high ~ 0.5. This suggests the conditions of the *entire* molecular ISM in these galaxies is similar to localized star forming regions such as the center of Orion in our Galaxy and is consistent with the high efficiency of star formation in these systems.

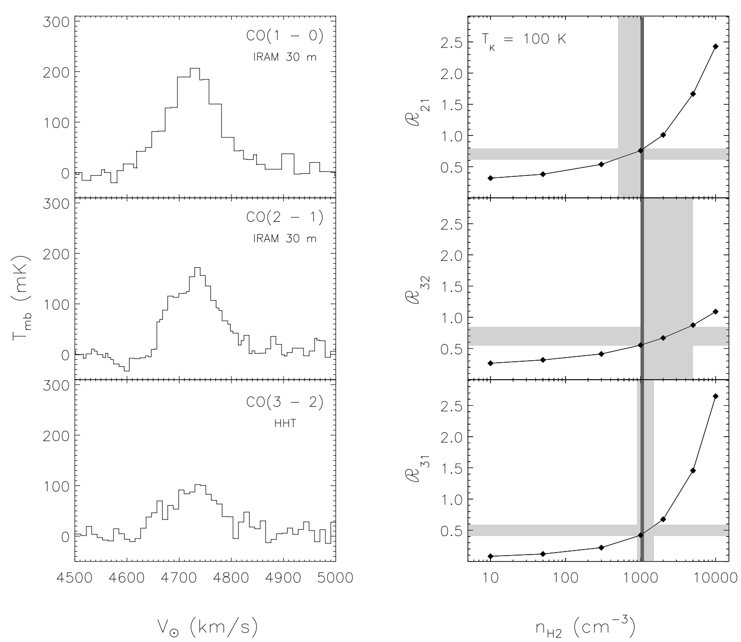

Figure 5: CO spectra and LVG model results of MRK 297. The left panel shows the data, the right panel shows ratios of integrated intensity, e.g. $R_{21} = I_{\rm CO2-1}/I_{\rm CO1-0}$, versus the molecular hydrogen volume density, $n_{\rm H_2}$. The connected dots show the results of LVG modeling for a kinetic temperature $T_{\rm K} = 100$ K and observed total column density, $N_{\rm CO} = 4.4 \times 10^{17}$ cm^{-2}. The horizontal light grey area show the 3σ observed values of the $I_{\rm CO}$ ratios, the vertical grey area shows the allowed $n_{\rm H_2}$ for each column density ratio. The results imply relatively warm and dense gas, $T_{\rm K} = 100$ K, $n_{\rm H_2} = 10^3$ cm^{-3}.

4. A high resolution study of MRK 325

A natural follow-up to the aforementioned singledish observations of the global properties of the ISM in LCBGs is to study the brightest members of our sample at higher resolution with interferometers. Our goal is to examine the relationship between the atomic and molecular gas surface density and kinematics with star formation sites to learn about how the gas is converted from atomic to molecular form and thence to stars in these low mass, but efficient star forming factories (e.g. Pisano, Wilcots, & Elmegreen 2000).

We have begun these follow-up observations with VLA and OVRO observations of MRK 325 (Figure 6). Optical observations show a disturbed, possibly nearly face on, disk with multiple bright HII regions (Pisano et al. 2001). The molecular gas is strongest toward the brightest star forming region but also faintly follows the continuum emission. There is no clear velocity gradient in the CO emission. We will measure the star forming efficiency in the two main HII regions here and also, by resolving self-gravitating giant molecular associations, estimate the CO-to-H_2 ratio.

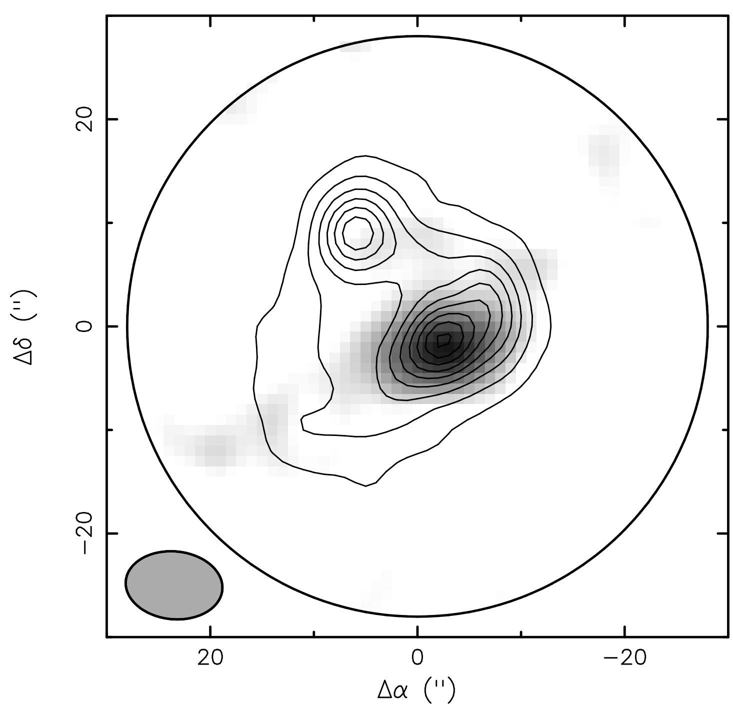

Figure 6: OVRO map of CO(1–0) in MRK 325 (greyscale) compared to a VLA 21 cm continuum map (contours). The continuum traces ionized gas, likely from HII regions, and shows extended emission and two prominent peaks. The molecular gas is strongest toward the brightest continuum source but also faintly follows the continuum to the southeast and the secondary peak in the northeast. The $9''.4 \times 6''.5$ CO beamsize is indicated in the lower left corner.

5. Summary

The identification and study of LCBGs as a rapidly evolving class of galaxies was originally made at optical and infrared wavelengths at intermediate redshifts. Their systematic study at radio wavelengths has only recently been made possible by large scale surveys such as Sloan, through which we can identify rare nearby examples. We have observed 20 LCBGs within 70 Mpc in HI and the three lowest transitions of CO in order to estimate dynamical masses and basic properties of the ISM such as mass, temperature, density, and how they relate to star formation rates.

Our primary finding is that most LCBGs have too low a mass to evolve into grand design spirals and that $\sim 80\%$ will deplete their (atomic + molecular) gas within a few Gyr and fade into gas poor dwarf ellipticals. The remaining 20% can sustain star formation over much longer timescales and may be the precursors to low mass spirals or Magellanic irregulars.

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