Molecular gas in massive galaxies at z>1

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Abstract

We have conducted SMA observations of four massive galaxies at z = 1 – 1.4, the epoch when massive galaxies are thought to assemble their mass. Our sample is unique in that it is selected to be very massive galaxies with log(M)>11 and with IR luminosity higher than log(L)>12.6 which obtained from the DEEP2/POWIR survey overlap. We were expecting to use CO(4-3) transition line measurements to derive the gas mass properties. After calibration of our data only two of our four targets satisfy our quality requirement, and for the two remaining objects, we did not identify any notable detection. Although we cannot derive the flux from any emission line, we still can use the background level to estimate an upper limit of the intensity line flux of our source, and then derive an upper limit of gas mass. Our results implies that, in the case our targets are "disk" galaxies, the ratio $\mathcal{M}_{gas}/\mathcal{M}_{tot}$ of our targets are bellow 10%, much more lower than derived for less massive studies at lower redshift as stated by previous studies. However, additional dataset are required, to identify if our target galaxies are really "disk" galaxies or starburst galaxies.

I Introduction

a/ SFR & Gas mass

The relation between star formation rate (SFR) and gas content of galaxies is crucial to understand galaxies formation and evolution. Schmidt (1959) first suggested the existence of a power law relation between surface densities of SFR and gas masses. Kennicutt (1998) fit the local populations of spiral galaxies and IR-luminous galaxies (Luminous InfraRed Galaxies/Ultra-Luminous Infrared Galaxies (LIRGs/ULIRGs)), with the gas mass including both neutral (HI) and molecular (H_2) hydrogen for spirals, and molecular gas only for ULIRGs (as their HI is likely negligible). The molecular gas component is routinely estimated using its most luminous tracer, carbon monoxide (CO) that is generally optically thick.

From fig.1, these can be implied that there have two major star formation mode: a *long-lasting mode* appropriate for both local spirals and distant BzK galaxies, and a *rapid starburst mode* appropriate for ULIRGs.

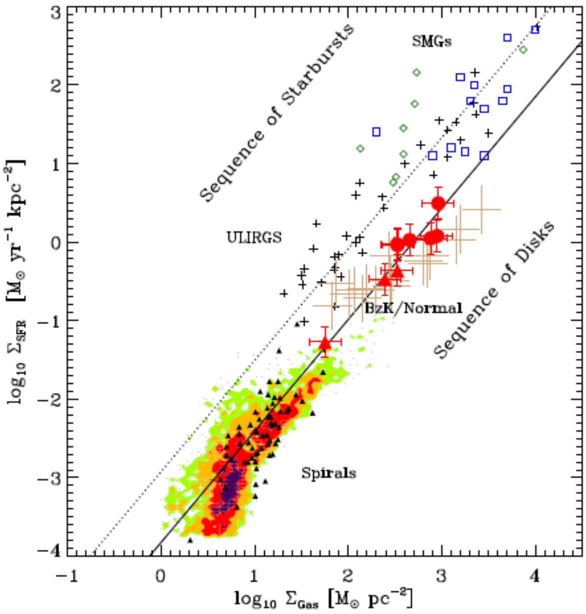

Figure 1. The SFR density as a function of the gas (atomic and molecular) surface density. The solid line is a fit to local spirals and z = 1.5 BzK galaxies, and the dotted line is the same relation shifted up by 0.9 dex to fit local ULIRGs and SMGs. (Daddi et al 2010b)

b/ Goal of the project

The goal of our project is to study the molecular gas of the most massive star-forming galaxies selected at 1<z<1.4. We would like to know if these objects follow the same sequence in the SFR versus M_{gas} diagram than less massive galaxies at similar redshift (fig 1.). Such objects may also follow a different pattern, for instance if their molecular gas reservoir is already exhausted.

Given the redshift of our targets, we expect detecting the CO(4-3) line using our SMA observations at 230GHz.

II Data

a/ Objects selection (DEEP2/POWIR)

Based on Keck spectra and deep Palomar NIR imaging combined with deep Spitzer 24μm imaging we have obtained the largest spectroscopically confirmed sample of massive galaxies with secure redshifts, total infrared luminosities and star formation rates, located within the Extended Groth Strip field. Our sample is unique in that it is selected to be very massive galaxies with $M_* > 10^{11} M_\odot$, with large total IR luminosities of $L_{IR} > 10^{12.6} L_\odot$.

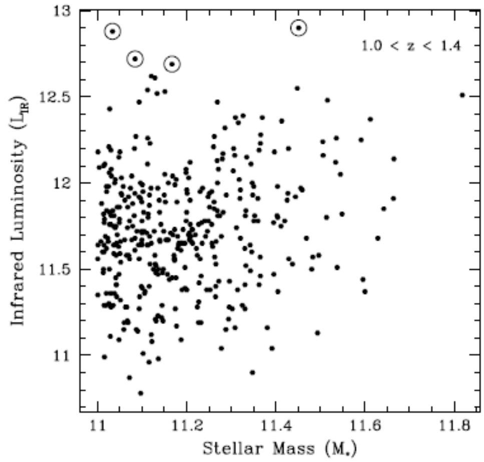

Figure 2. Shown here are all galaxies at 1.0 < z < 1.4 within the DEEP2/POWIR survey. The four galaxies in our SMA data (shown as circles) are those with a high stellar mass and IR luminosity.

Information about these four objects:

Target	RA	Dec	z	Log(M_{tot})	Log(LIR)
141951+524656	214.962799	52.782265	1.24	11.17	12.69
141633+521001	214.138901	52.166939	1.336	11.03	12.88
141635+521235	214.147263	52.209801	1.018	11.08	12.72
142341+532825	215.920944	53.473537	1.081	11.45	12.9

b/ SMA data

The Submillimeter Array (SMA) is an 8-element radio interferometer located atop Mauna Kea in Hawaii. Operating at frequencies from 180 GHz to 700 GHz, the 6m dishes may be arranged into configurations with baselines as long as 509m, producing a synthesized beam of sub-arcsecond width. Each element can observe with two receivers simultaneously, with 2 GHz bandwidth each. The digital correlator backend allows flexible allocation of thousands of spectral channels to each receiver.

Our SMA data.

- Observation date : 28 March / 12, 13 & 20 April, 2011
- Observation time : 8hr per object (one track)
- Array configuration : compact
- Receiver tuning : around 230Ghz

Observe date (2011)	Target	Bandpass Calibrator	Flux Calibrator	Pointing Calibrator	Gain Calibrator
28 Mar	142341+532825	3C279	Titan	Neptune	1419+543 & 1635+381
12 Apr	141635+521235	3C84	Titan	3C279	1419+543 & 1635+381
13 Apr	141951+524656	3C84	Titan	3C279	1419+543 & 1635+381
20 Apr	141633+521001	3C84	Titan	3C279	1153+495 & 1419+543

Quality of data

The opacity on 225GHz, ambient temperature, humidity and wind speed can present the quality of our data (Fig.3). The lower value of opacity describes the fewer absorption and scattering of radiation in atmosphere. The lower value ambient temperature, humidity and wind speed will make the antenna become more stable.

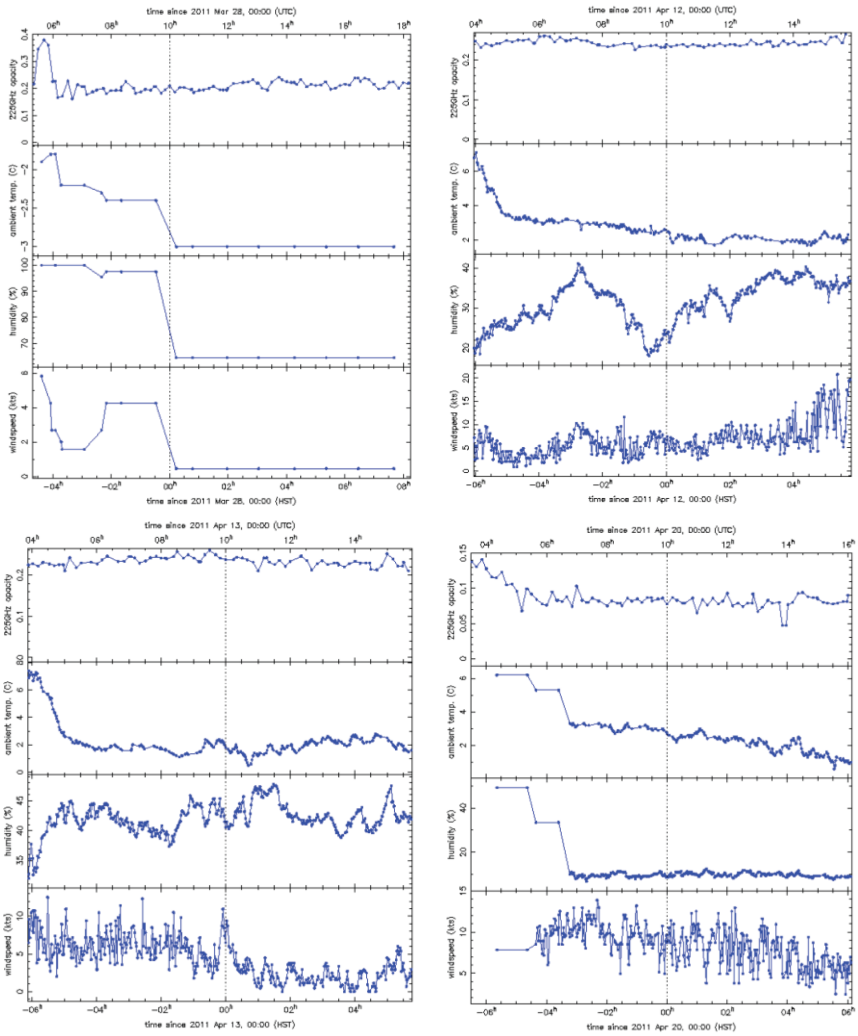

Figure 3. The Y-axis presents (i) the opacity on 225GHz (ii) ambient temperature (iii) humidity (iv) wind speed. More lower value of them describe more better data we get. The X-axis presents the hour angle.

Raw data

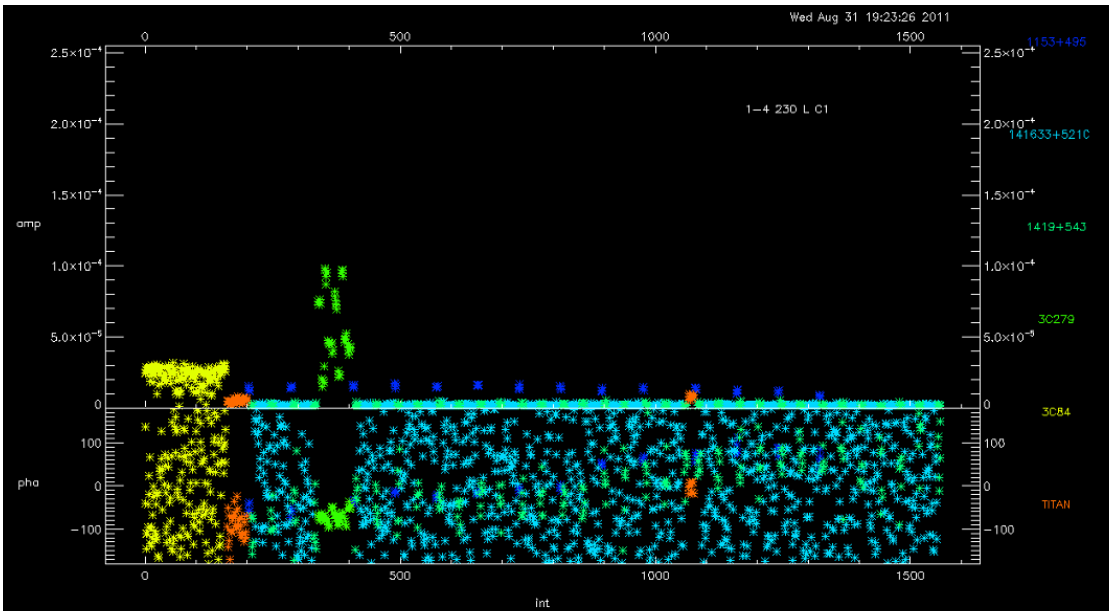

Figure 4. This diagram shows one sample of the raw data from our SMA observations.
The X-axis is integrate time and the Y-axis are amplitude and phase.

In fig.4, our target source is 141633+5210 (light blue). 3C84 (yellow) is bandpass calibrator, 3C279 (dark green) is pointing calibrator, Titan (orange) is flux calibrator, and we have two gain calibrators which are 1153+495 (dark blue) and 1419+543 (light green). The phase can be equated to position. In fig.4, besides the pass band calibrator, the brighten sources always have more accurate phase. Since our target source is faint, the phase of target source distribute in every degree. Those calibrators are use to calibrate our target.

III Data Reduction

I use the IDL software package – MIR[1] to read and reduce our SMA data. The following command assumes that I am in the IDL environment and also I use the date of 20 April 2011 observation as my sample to describe my data reduction.

Step1-Read data

I use the following command to read our SMA data.

IDL> readdata

Step2-Data selection

After reading the data, I will do the data selection and plot them into continuum.

IDL> select, /p, /re

[1] https://www.cfa.harvard.edu/~cqi/mircook.html

/p = for good data with positive weights; */re* = reset, for all the cases to reset the filter

IDL> plot_continuum, x=int

This command will let IDL to plot the diagram like figure 4. IDL will plot all diagrams in each baseline. Because of our SMA observation have 8 antenna (sometime the amounts of antenna will less than 8), so the total amounts of the diagrams is (8*7)/2 = 28.

I also can select individual source to plot their continuum with the following command.

IDL>select, /p ,/re ,source=' titan'
IDL> plot_continuum, x=int

Step3-Data flagging
Because of some point is weird, I can *flag* them in the diagram. *Flag* is setting the weights to negative. When the next time we select the positive weighting source, the flag point will disappear.

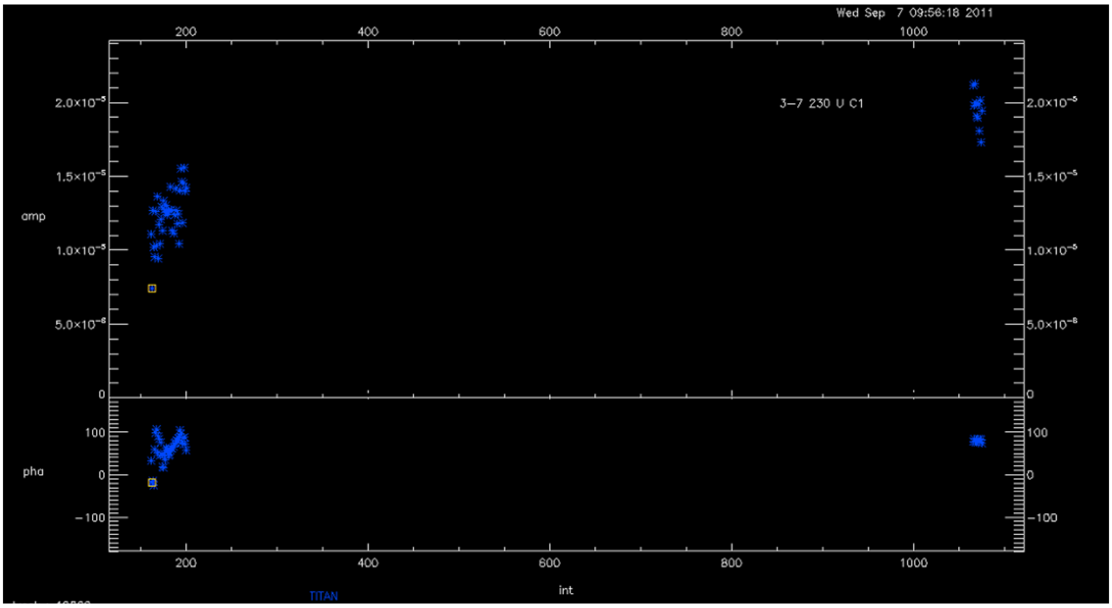

Figure 5. This diagram shows only Titan source and the yellow box is flag point.

Step4-Regenerating continuum
The following command will generate the continuum band by averaging all the bands with channel numbers from 2 to 63 for each band.

IDL>select, /p ,/re
IDL>uti_avgband, chstart=2,chend=63

uti_avgband can check each chunk for bad data, reports them to the screen and automatically flags them out.

Step5-System temperature correction

IDL>select, /p, /re
IDL>apply_tsys

apply_tsys will usually result in an improvement in the signal-to-noise ratio of longer tracks that were taken over a range of elevation angles. Some improvement may be obtained in cases of marginal weather.

Step6-Bandpass calibration
I do bandpass calibration with smoothing over 3 channels.

IDL>select, /p, /re
IDL>pass_cal, smoothing=3, cal_type='phase', ntrim=5,
3c84 yes

IDL>select, /p, /re
IDL>pass_cal, smoothing=3, cal_type='amplitude', ntrim=5
3c84 yes

smoothing = number of channels to smooth
ntrim = number of channels that from the start and the end which not including in the smoothing.

Step7-Gain calibration (phase)
I do an antenna-based phase calibration with box smoothing over 0.6 hours and my reference antenna on 6. In this case, I only apply the bright calibrator (1153+495) when doing my gain calibration.

IDL>select, /p, /re
IDL>gain_cal, cal_type='phase', tel_bsl='telescope', refant=6, x='hours',$
IDL>/preavg, smooth=0.6
1153+495 yes 1.0

Step8-Measure flux
Before I measure the flux, I will plot the Elevation vs Hour angle diagram (fig. 6). Since that is better for measure flux that flux calibrator can cover in the same hour angle.

IDL>select, /p, /re
IDL>plot_var, x='ha', y='el'

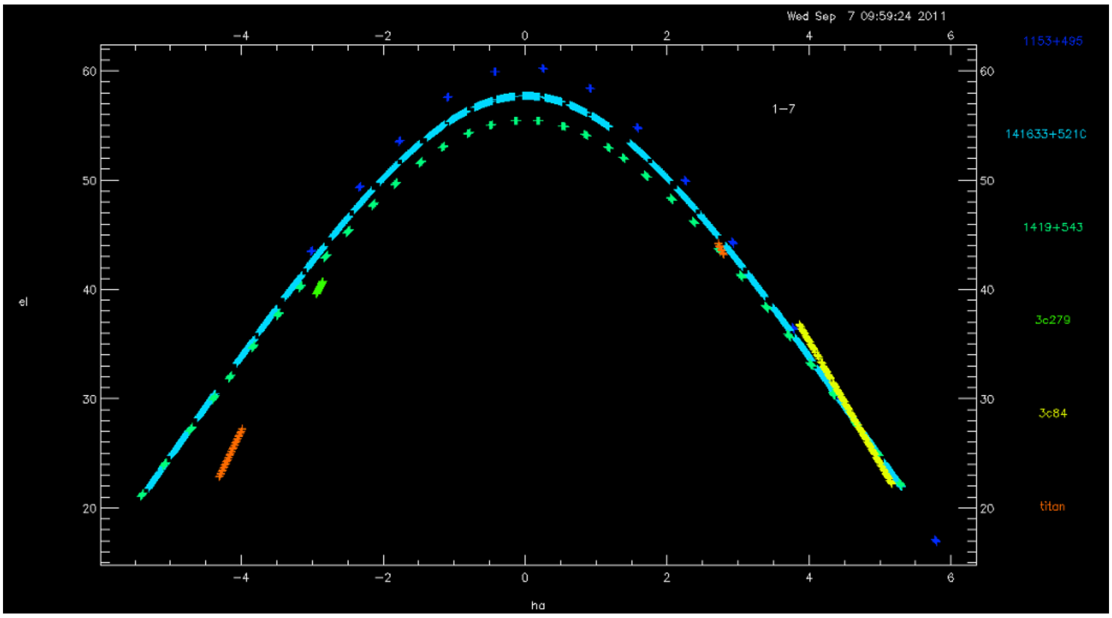

Figure 6. Elevation vs Hour angle

I select the hour angle between "-5" and "4" to do flux measure.

IDL>select, /p, /re
IDL>result=dat_filter(s_f,'"ha" gt "-5" and "ha" lt "4"')
IDL>flux_measure
Result:
Scalar average:

# Source	Flags	Nscans	Flux(Jy)	SNR	meantime	REAL	IMAG
titan	1	40	0.9780	188	5.20	0.8518	-0.1274
3c84		17	5.5383	127	3.78	3.0968	0.6371
titan		11	1.0565	108	12.08	0.6096	-0.2771
1153+495	g	44	1.8689	230	8.73	1.8628	0.0008
1419+543		163	0.2816	277	10.32	0.2404	0.0168
141633+521		777	0.1190	379	10.35	0.0009	0.0005

Vector average:

# Source	Flags	Nscans	Flux(Jy)	SNR	meantime	REAL	IMAG
titan	1	40	0.8612	121	5.20	0.8518	-0.1274
3c84		17	3.1616	31	3.78	3.0968	0.6371
titan		11	0.6697	32	12.08	0.6096	-0.2771
1153+495	g	44	1.8628	228	8.73	1.8628	0.0008
1419+543		163	0.2410	205	10.32	0.2404	0.0168
141633+521		777	0.0010	2	10.35	0.0009	0.0005
3c279		60	6.8272	97	6.55	6.7547	-0.9919

Step9-Flux calibration

I apply the scalar average flux into flux calibrator (Titan). It is because the values of the scalar average flux are more near the values which show at the website of SMA observer centre[2]. In this case, because of Titan have two values, so I average their values as 1.01725.

IDL>select, /p, /re

[2] http://sma1.sma.hawaii.edu/smaoc.html

IDL>sma_flux_cal

titan 1.01725 Yes

Step10-Gain calibration (amplitude)

I do an antenna-based amplitude calibration with box smoothing over 0.6 hours and my reference antenna on 6. I apply only bright gain calibrator (1153+495) in this case and the flux value is 1.8689 which measured by scalar average flux.

IDL>select, /p, /re
IDL>gain_cal ,cal_type='amplitude', tel_bsl='telescope', refant=6, x='hours',$
IDL>/preavg, smooth=0.6
1153+495 yes 1.8689

Step11-Check my calibration

After doing my calibration, I use the following command to plot them into continuum. (Fig. 7)

IDL> select, /p, /re
IDL> plot_continuum, x=int

In fig. 6, the phase of weak gain calibrator (1419+543, colored in light green) is slightly going up when the integrate time is larger than 1350. It is because the integrate time from 1350 without the source of bright gain calibrator (1153+495, colored in dark blue).

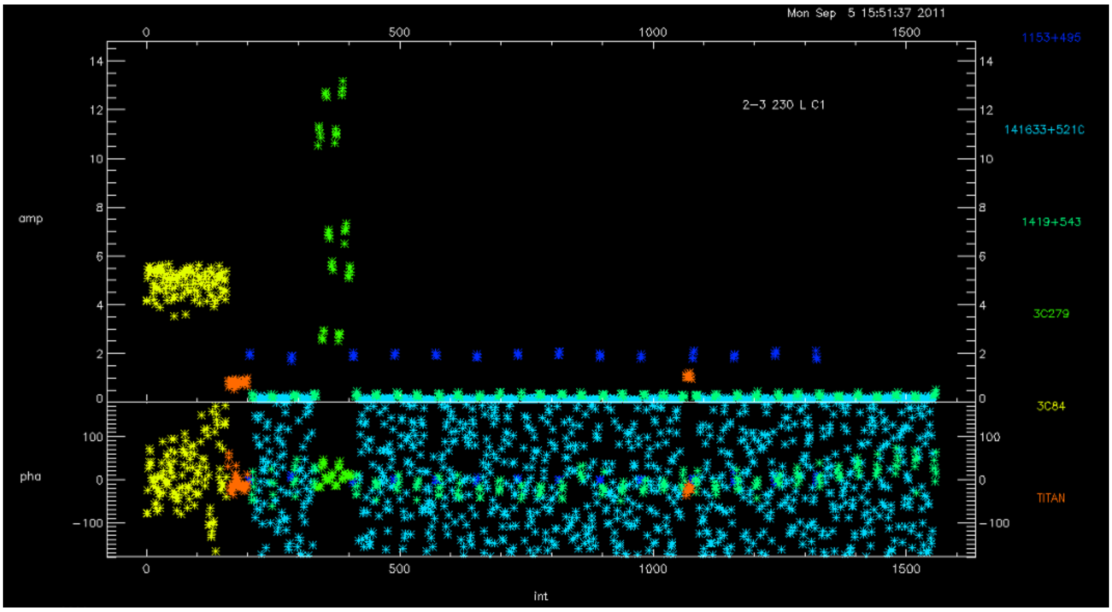

Figure 7. Amplitude and Phase vs Integrate time after doing calibration.

I use the following command to flag both weak gain calibrator and target source which integrate time is larger than 1350.(Fig 8.)

IDL>select, /p, /re, source=['1419+543','141633+521001']
IDL>result = dat_filter (s_f, ' "int" gt "1350" ')
IDL>flag, /flag

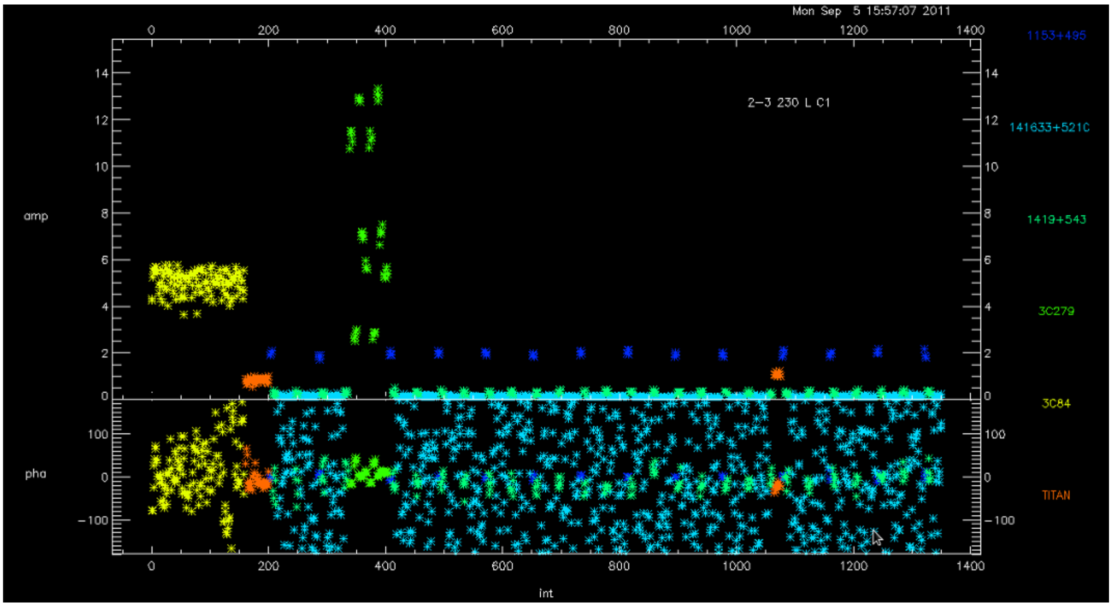

Figure 8. Amplitude and Phase vs Integrate time after flagging the Integrate time which larger than 1350.

Step12-Saving the file into MIRIAD format

Before mapping, I need to translate my file into *.vis* file.

idl2miriad, source='1153+495', sideband='u', dir='1153+495-1.vis'
idl2miriad, source='1419+543', sideband='u', dir='1419+543-1.vis'
idl2miriad, source='141633+521001', sideband='u', dir='141633+521-1.vis'

Test of the calibration

The calibration is tested by doing gain calibrators mapping. All the gain calibrators are quasars (point source). For a good calibration, gain calibrators should be looks like point source. (Fig. 9)

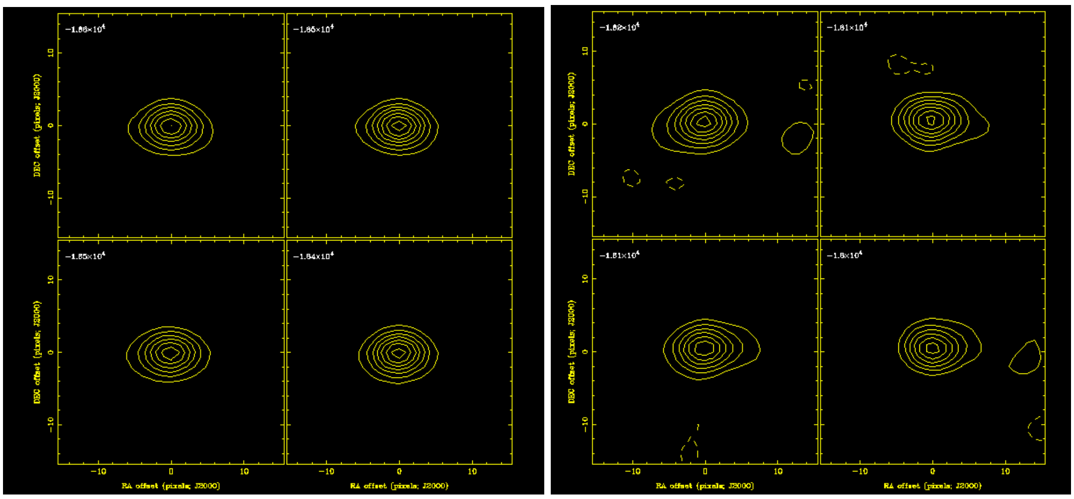

Figure 9. Left panel shows the clean map of bright calibrator(1153+495). Right panel shows clean map of weak calibrator(1419+543). Both of them are mapping in different channel.

IV Results and Analysis

After testing the calibration, only two of our four targets satisfy our quality requirement. From the clean map, we found that our target sources do not have a notable detection (Fig. 10). Most of our detections are lower than 3σ. Although few of our detections are potentially above 3σ, they are all far away from the expected position of our sources (> 5 arcsec) or the detections is not present in different continuous channels. We conclude that our target source do not have any detection.

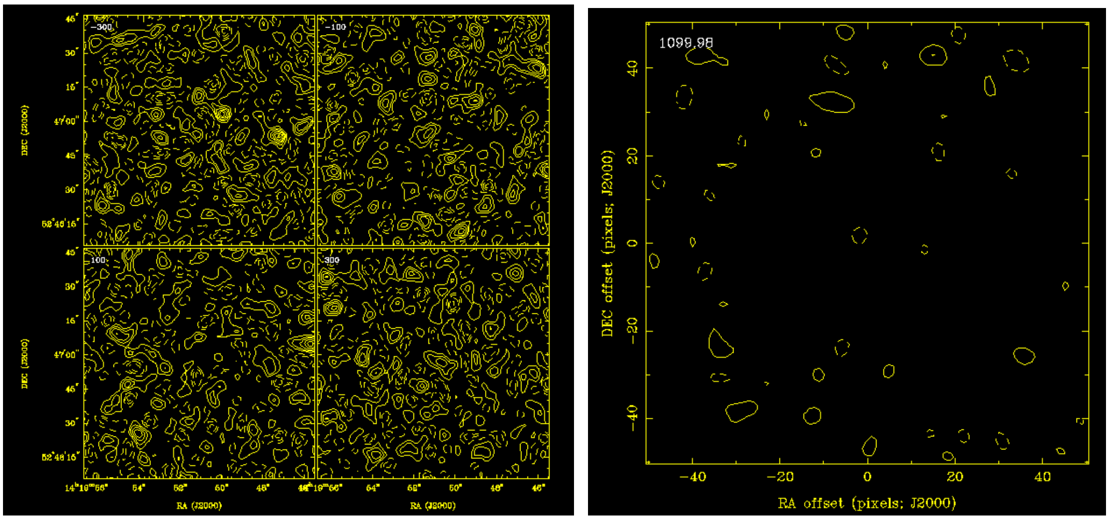

Figure 10. Left panel : clean map of target source 141951+524656(13 April) in different channels.
Right panel : clean map of target source 141633+521001(20 April), only in one channel.

Although our results do not have any notable detection, we still can bring some constrain on the gas properties of our target galaxies.

Luminosities: Basic Relations

The line luminosity (L'_{co}) can be expressed for a source of any size in terms of the total line flux (S_{co}). $\Delta\upsilon$ is the velocity of the line width, V_{obs} is frequency at which the emission line is expected, D_L is luminosity distance and z is redshifts of our target galaxies.

$$L'_{co}=3.25\times10^{7} S_{co}\Delta\upsilon V_{obs}^{-2} D_L^{2} (1+z)^{-3}$$

(Solomoon & vanden Bout 2005)

We use IDL to measure the background level and estimate an upper limit of the intensity line flux of our sources (S_{co}).

From CO Luminosity to Molecular Mass

For a single cloud or an ensemble of no overlapping clouds, the gas mass determined from the virial theorem, M_{gas} , and the CO line luminosity, L'_{co}, are related by

$$M_{gas} / L'_{co} = \alpha_{CO} \sim 4.6$$

(Solomoon & vanden Bout 2005)

Usage of the Milky Way value for the molecular gas mass to CO luminosity ratio,

α_{CO}= 4.6M$_\odot$ (Kkms^{-1} pc^2)$^{-1}$, overestimates the gas mass in ULIRGs and probably in EMGs (the Early universe Molecular emission line GalaxieS). For these starbursts, we require an empirical derivation of the conversion factor to derive molecular gas masses from CO luminosities (α_{CO} = M_{gas} / L_{CO} = 0.8 for local ULIRGs and distant SMGs/QSOs – Downes & Solomon 1998; Greve et al. 2005).

Assuming that our galaxies are "disk-like" galaxies, similar to lower-mass BzK galaxies observed at similar redshifts (Dannerbauer et al. 2009; Daddi et al. 2010a – i.e. α_{CO}= 4.6), we can estimate an upper limit of gas mass.

	141951+524656	**141633+521001**
S_{co} **(Jy)**	0.0047	0.0021
$\Delta\upsilon$ **(kms-^{1})**	200	200
V_{obs} **(GHz)**	205.841	197.382
z	1.24	1.336
L'_{co} **(Kkms^{-1} pc^2)**	4.77×10^9	2.46×10^9
M_{gas} **(M$_\odot$)**	2.19×10^{10}	1.13×10^{10}
M_{tot}	1.48×10^{11}	1.07×10^{11}
L_{IR}	4.9×10^{12}	7.6×10^{12}
M_{gas}/M_{tot}	0.15	0.11

The ratio of M_{gas}/M_{tot} is much lower than our expectation. If our target are BzK galaxies, the value of M_{gas}/M_{tot} should be around 0.4 - 0.8 (Daddi et al. 2010a).

In galaxies like Milky Way and local star-forming spiral galaxies, the molecular gas has relatively low excitation and is rather diffusely distributed (low density and temperature), resulting in a highly subthermalization gas. In contrast, dusty starburst systems like ULIRGs in the local universe and SMGs and QSOs in the distant universe have very dense and warm gas with a CO spectral energy distribution showing almost thermalized emission up to at least the rotational transition J = 3.
In fact starbursts (ULIRGs and SMGs) display just slightly (> 50%) sub-thermalized CO (4-3) transition lines (Ivison et al. 2011), while the CO(4-3) to CO(1-0) subthermalization factor of about five times lower in typical spirals (Dannerbauer, et al. 2009).

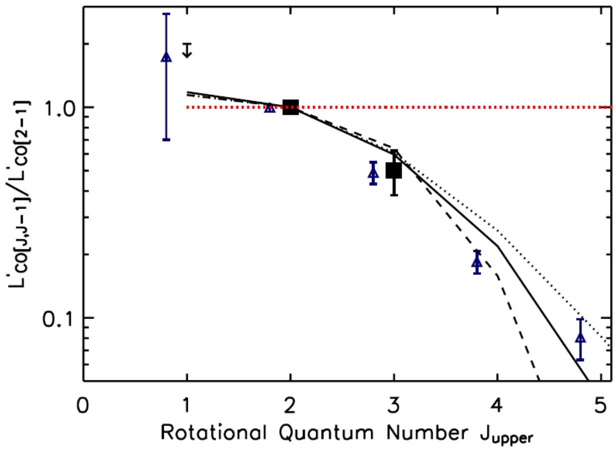

Figure 11. CO line luminosity of the BzK − 21000 at z = 1.522 obtained from PdBI and VLA observations, normalized to the CO(2-1). The black solid, dotted, and dashed lines show the LVG model. The red line is in the case of ULIRGS or SMGs which thermalized emission up to at least J=3. (Dannerbauer, et al. 2009).

Assume that our target galaxies are ULIGRs/SMGs which molecular gases are almost fully thermalized, the thermalized emissions of CO are approximately the same at all quantum number. (Fig. 11) We realize that the $\mathcal{L}'_{co}$ of our targets is much lower than our expectation. (Fig .12)

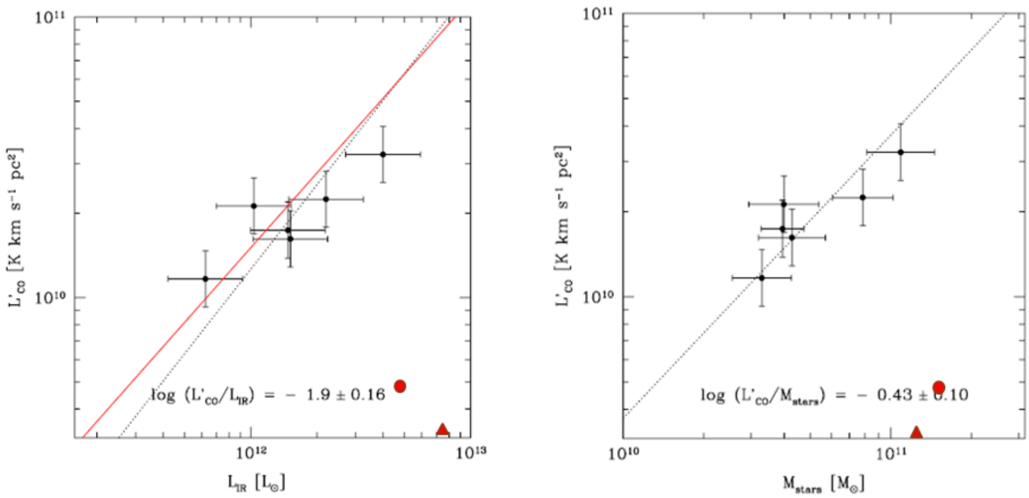

Figure 12. The red points are our targets, 141951+524656(13 April) is circled and 141633+521001(20 April) is triangle. CO luminosities ($\mathcal{L}'_{co}$) vs. the bolometric IR luminosities (L_{IR}, left panel) and vs. the stellar masses (right panel). The dotted line in each panel is the best linear fit. (Daddi et al. 2010a)

In case that our targets are similar to Bzk galaxies or Milky Way, CO(4-3) transitions line are 5 times weaker than CO(1-0).(Fig. 10) We can derive another $\mathcal{L}'_{co}$ which applied the factor of 5. We realize that we are pretty much in the range like indicated in Daddi et al. 2010a. (Fig. 13)

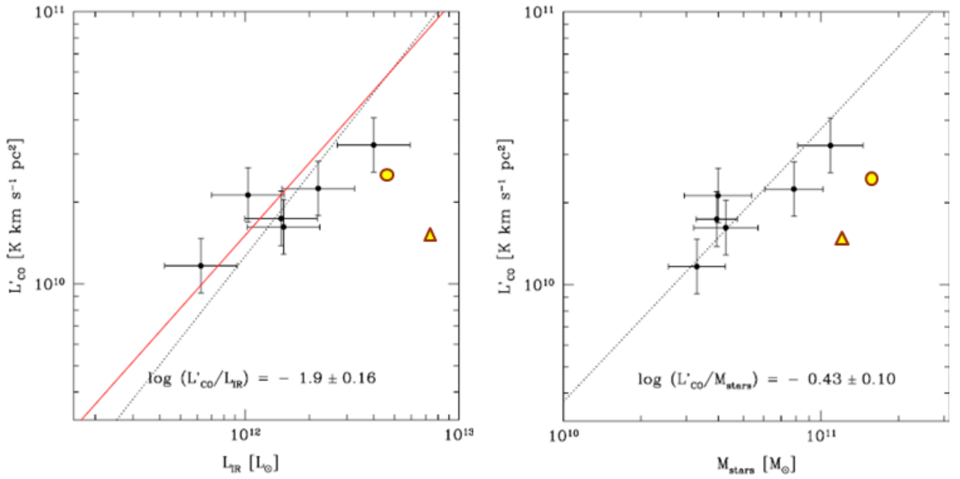

Figure 13. Same as Fig. 11, the yellow points are our targets, 141951+524656(13 April) is circled and 141633+521001(20 April) is triangle. (Daddi et al. 2010a)

However, from our inferred M_{gas} and L_{IR}, our objects may be more consistent with ULIRG/SMG in the L_{IR}/M_{H2} diagram. (Fig. 14)

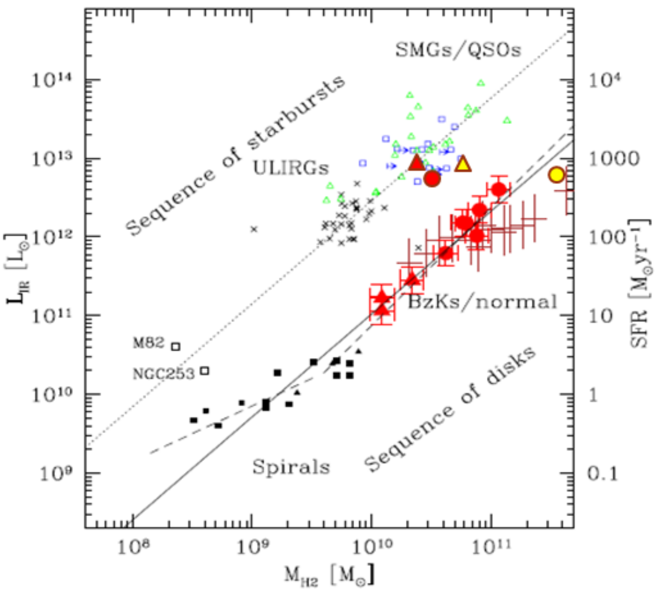

Figure 14. Shown here are diagram of L_{IR} vs M_{H2} . (Daddi et al. 2010b)
The red points presented our target are ULIGRs/SMGs which molecular gases are fully thermalized.
The yellow points are the position corrected by sub-thermalization.

V Conclusions

Using our unique SMA observations of four star-forming massive galaxies at $1<z<1.4$, we derived an upper limit of CO luminosities for two of our galaxies. Assuming a given CO to H2 conversation factor we could derive their gaseous mass, although we do not know whether our target galaxies are more similar like ULIGRs/SMGs or spirals/BzK galaxies. We found that their gaseous masses are much lower than for previous studies at similar redshifts in any case. We suggest there have two explanations: (a) Both of our target galaxies have almost exhausted their gas. (b) their gas more sub-thermalized than previous studies involve and the intensity of the CO (4-3) transitions are much more lower than expected, so we cannot detect the emission lines. We need additional observation data to constrain the temperature of the CO gas for our target galaxies. PdB IRAM or ALMA data to observe CO (2-1) transitions emission lines is required to conclude fully.

References:

Daddi et al. 2010a, ApJ, 713, 686
Daddi et al. 2010b, arXiv:1003.3889
Downes D., & Solomon P. M., 1998, ApJ, 507, 615
Greve, T., et al., 2005, MNRAS, 359, 1165G
Ivison, R., et al., 2011, MNRAS, 412, 1913I
Dannerbauer, H., et al. 2009, ApJ, 698, L178
Solomon, P, M., & van den Bout, P. A. 2005, ARA&A, 43,677