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For IRAM use
Registration N°:
Date:

PROPOSAL FOR INTERFEROMETER

Deadline: 11 Sep 2003 Period: 15 Nov 2003 — 15 May 2004

TITLE

CO identification of submillimetre galaxies III.

CATEGORY: 1.3mm: ○ 3mm: ○ dual freq.: ● time filler: ○ special: ○

Scientific type: - Extragalactic: continuum ○ CO lines ● other ○
- Galactic: continuum ○ lines ○ circumstel. env. ○ young stel. obj. ○ cloud struct. ○ chem. ○ other ○
Observing type: mapping ○ detection ● size measure ○ snapshot ○ mosaic ○ other ○

ABSTRACT

We propose to continue our successful long-term program to determine the dynamical/molecular gas properties, via CO rotational line emission, of a sample of $\sim$ 30 SCUBA submillimetre galaxies with accurate radio positions and optical redshifts. From the 13 sources observed to date, we obtained solid CO line detections in 5, and tentative detections in 4 galaxies. More observations are scheduled in the current semester. This program provides a huge leap in our knowledge of the gas masses and properties of the luminous, obscured galaxies that produce at least half of the energy emitted in the early Universe. It enables statistically meaningful comparisons with other populations and galaxy formation models. It explores the feasibility of millimetre-based spectroscopic redshift measurements with current and future instrumentation, proves the reliability of radio identifications, and serves as a database for calibrating present and future photometric redshifts.

Is this a resubmission of a previous proposal ? no ● yes ○ – proposal number(s): ....
Is this a continuation of (a) previous proposal(s) ? no ○ yes ● – proposal number(s): N028,M05D,MD-7.....

LST range(s) per configuration	from: 6h	to: 16h	number of intervals: 12
	from: 12h	to: 20h	number of intervals: 12

Configurations: **A** ○ **B** ○ **C** ● **D** ● **Any** ○

Frequencies (exact) 3mm: see attachment 1.3mm:

Confidential information:

List of Objects (give most common names) with equatorial coordinates in J2000 (accurate to 2″) and LSR velocities

Source	α_{J2000}	δ_{J2000}	V_{LSR}
J123553	12 35 53.26	+62 13 37.7	z= 2.098
J123555	12 35 55.14	+62 09 01.7	z= 1.875
J123600	12 36 00.10	+62 02 53.5	z= 2.710
J123606	12 36 06.85	+62 10 21.4	z= 2.330
J123621	12 36 21.27	+62 17 08.4	z= 1.988
J163627	16 36 27.94	+40 58 11.2	z= 3.180
J163655	16 36 55.75	+40 59 10.0	z= 2.614
J221737	22 17 37.39	+00 10 25.1	z= 2.639

(continue on next page, if needed)

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who will reduce data: Neri et al.

join to this form: scientific aims ≤ 2 typed pages and ≤ 2 pages Figs., Tables and list of related publications

IRAM Plateau de Bure Interferometer: Proposal Technical Summary
Please fill one sheet per frequency setup

- **Program Title:**

CO identification of submillimetre galaxies III.

- **Source position and velocity:**

Source	RA (J2000.0)	DEC (J2000.0)	LSR Velocity (km/s)
J123553	12 35 53.26	+62 13 37.7	z= 2.098

- **Category and Project type:** dual-frequency lines detection
- **Size of largest structure in (arcseconds)** unresolved
- **Expected continuum flux:** 1–4 mJy at 1.3mm
- **Expected continuum source size:** unresolved
- **For pure continuum projects:**
  - *Preferred observing frequency:*
  - *Expected Line contamination at observing frequency:*
  - *Frequencies to avoid:*
- **For line projects:**
  - *Receiver configuration (fill in empty columns) :*

	line name	Freq. (GHz)	band	
LINE	12CO(3-2)	86-113	USB	/RECEIVER 1
LINE	12CO(6-5)	212-237	LSB	/RECEIVER 2

  - *Correlator configuration (fill in empty columns) :*

	width	freq.		Receiver		Mode
SPECTRAL 1	160	180	/RECEIVER	1	/BAND	SSB
SPECTRAL 2	160	320	/RECEIVER	1	/BAND	SSB
SPECTRAL 3	160	460	/RECEIVER	1	/BAND	SSB
SPECTRAL 4	160	600	/RECEIVER	1	/BAND	SSB
SPECTRAL 5	160	180	/RECEIVER	2	/BAND	DSB
SPECTRAL 6	160	320	/RECEIVER	2	/BAND	DSB
SPECTRAL 7	160	460	/RECEIVER	2	/BAND	DSB
SPECTRAL 8	160	600	/RECEIVER	2	/BAND	DSB

  - *Expected width of spectral line (to zero power) and narrowest feature:* $\sim$ 400 km/s
  - *Number of lines observed simultaneously (add sketch of frequency setup):* 1–2 (varies by source)
  - *Line frequencies:* varies by source
  - *Expected source size in each line:* unresolved
  - *Expected line strength:* 0.5–6 mJy
- **For mapping projects:**
  - *Configuration required (AB, BC, CD, D, other):* D
- **For detection projects:**
  - *Observing time required:* 20 hours for each object
- **For snapshot or size measurements:**
  - *Baseline range in meters:*
  - *Configuration list:* C,D
  - *Number of hour angles per baseline:*
  - *Observing time per hour angle:*
- **Phase Calibrators (2 or more):** varies by source
- **Amplitude Calibrator:** 3C345
- **Required accuracy of bandpass calibration:** good
- **Special requirements:** none

CO identification of submillimetre galaxies III.

Proposal history: Considering the fundamental importance of the dusty far-IR/submm population for the understanding of galaxy formation and evolution, recognizing the difficulties of reliable spectroscopic identifications of faint submillimetre (submm) galaxies, and realizing the strategic importance of such work for IRAM and for the scientific preparation of large future international programs such as Herschel and ALMA, in July 2002 we proposed to the IRAM Director CO detection observations on a new sample of distant submm sources with recently established spectroscopic redshifts. The program was started in the late summer 2002 semester with three targets. Our subsequent regular proposal M05D was accepted for the winter semester, with the option for a long-term status (> 4 semester, > 30 sources) if the program proves successful, and if a progress report is submitted each semester. Such a report was submitted for the summer 2003 semester, with a list of 8 new targets. Our program has so far been very successful in that probably the majority of the targets were detected. Below we give a brief update on the program status. For the new PC members we repeat the science motivation. The results of our initial observations are reported in an ApJ Letter (Neri et al., in press, astroph/0307310), and more details on three sources can be found in our accompanying proposal (Neri et al.).

Background

At least half of the cosmic extragalactic energy density (not counting the cosmic microwave background) emerges at far-infrared wavelengths (Fixsen et al. 1998; Hauser et al. 1998). During the last years, surveys with SCUBA at 850 μm and MAMBO at 1200 μm have resolved a significant fraction of this background into a population of faint (mJy) submm sources that may be luminous and ultraluminous infrared galaxies at redshifts $1 < z < 5$ (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Bertoldi et al. 2000, 2003). This population of luminous, dusty starburst galaxies contributes significantly to the cosmic star formation at high redshift and may trace the epoch of bulge/elliptical formation. While surveys at submillimetre and millimetre wavelengths have by now identified several hundred sources, spectroscopic redshift and CO detections have, until the summer of 2002, only been obtained for two sources at $z \sim 3$ (Ivison et al. 2001; Frayer et al. 1998; Genzel et al. 2003), mainly because of the faintness of their optical/near-IR counterparts and the lack of accurate positions.

Recently some of us have been able to substantially increase the number of accurate source positions from deep VLA radio maps (Ivison et al. 2002). Optical follow-up spectroscopy at Keck for these radio-detected submm sources was surprisingly successful, resulting in a reliable sample of now > 70 sources with optical redshifts (Chapman et al. 2003). Based on these, we have observed 13 sources with the IRAM Plateau de Bure interferometer since the summer of 2002, detecting CO emission lines in at least 5 of them, with 4 more tentative detections which are to be confirmed in ongoing observations.

These observations have demonstrated that the strategy adopted for our proposed long-term programme is successful. Searching for CO emission in ~ 30 SCUBA submm sources, for which both accurate positions and optically-determined redshifts are currently available, will enable us to show that the submm population indeed has a mean redshift of $z > 2.5$ and contributes about half of the high-z star formation activity. It will also provide the first sample of high redshift luminous infrared galaxies for which detailed studies of the intrinsic source properties are possible.

Scientific goals

The scientific goals of this long-term program are to:

- detect CO rotational line emission with moderate resolution (D-configuration) interferometric observations for a significant and representative sample of $\sim$ 30 submm galaxies, increasing the prior number of CO-confirmed redshifts by a factor of 10, at which point statistically meaningful comparisons to other populations and galaxy formation models can be made.

- explore the intrinsic source properties (gas mass and physical properties, dynamical mass, source size, relationship to emission at other wavelengths) by more detailed and spatially resolved 1–3 mm PdB interferometry of a sub-sample of the program sources (see accompanying proposal by Neri et al.). As has already been shown in two cases from our program (SMM J04431 and SMM J16368), such spatially resolved images deliver critical information in testing current hierarchical galaxy formation models, exploring how early and with what mass the luminous far-IR/submm galaxies were formed. We may also be able to constrain the CO-luminosity function at high redshifts (as Keres et al. (2003) did for a local sample), and thereby study its evolution, and constrain the total mass density of cold neutral gas in the early Universe.

- survey the local environment of SMM sources for companions, and for other CO or continuum sources, in order to clarify the importance of merging.
- test the reliability of radio and optical identifications of submm galaxies, and create a database for calibrating present and future photometric redshifts, which are degenerate in redshift and dust temperature.
- explore the general feasibility of millimetre-based spectroscopic redshifts with current instrumentation. The detection of CO will open the door for observations of other molecular and atomic lines (e.g. HCN and CI), which will allow to study the properties of the ISM in detail in a large sample of high$-z$ sources. Our CO survey has thereby the potential to act as a spearhead project for ALMA.

Observations to date

By now we have observed 13 sources (Table 2). CO line emission was definitely detected towards 5, likely detected towards 4, not detected towards 3, and one source is a tentative non-detection. Observations are on-going to confirm the tentative results, and one additional target will likely be scheduled this semester. Our observations show a wide variation in source properties. In two cases, the targeted object is not the CO and continuum source. In one case, there apprear two CO emission sources. The line shapes are often irregular and broad, indicative of dynamically perturbed or interacting systems. In several cases the source appears resolved, motivating higher resolution follow-up studies (see accompanying proposal by Neri et al.). The CO detections toward SCUBA submm sources

- provide an important confirmation of the optical/UV redshifts. It is interesting that their redshift range is close to the peak of the merging assembly history of galaxy formation. The formation of such massive systems at $z \sim 3$ is not easy to understand in current hierarchical models of galaxy formation (e.g., Genzel et al. 2003). If all SMM galaxies were similar to those we observed, their abundance would be inconsistent with current semi-analytic models of cold dark matter galaxy formation.
- locate the actual submm source. In most cases, the identity was ambiguous before our observations. In two cases, the optical redshift corresponded not to the submm/CO sources, indicating a strong clustering of galaxies in their proximity. The multiple nature of the submm background sources may in fact explain why we were able to detect strong UV emission lines in these gas- and dust-rich sources.
- allow to derive the dynamical masses associated with these luminous infrared galaxies, supporting the interpretation that this population consists of gas-rich and massive ($\sim 10^{11} M_\odot$) interacting starburst/AGN systems, of very massive galaxies with deep central potential wells.

A detailed analysis was completed for the first three targets we observed (Neri et al., in press). The current analysis of a larger sample will be part of the PhD thesis of T. Greve. To illustrate the wealth of information we can gain from these observations, we refer the program committee also to a more detailed discussion of three sources in our accompanying proposal (Neri et al.).

Future prospects

Based on these initial observations, it is clear that our program is demanding in observing time even with the superior sensitivity (a factor 5 relative to OVRO) of the PdBI, requiring 2–3 tracks per source for an initial detection, and more for follow-up at higher resolution. We anticipate that this cooperative program will require at least 2 years for execution. With this report we restate our request for a long-term allocation to determine the CO properties of a sample of $\sim$ 30 SCUBA submm galaxies, continuing this winter with another 8 objects. We have now observed 13 objects, and one other is currently scheduled.

In this program we like to observe a significant number of sources (>30) in order to be able to look for any redshift evolution in the FIR to CO luminosity, and to discern any differences between objects with and without AGN.

Using multi-object spectrographs at the Keck and Gemini telescopes our program to determine optical redshift for both millimetre (MAMBO) and submillimeter (SCUBA) selected galaxies continues now targeting mainly MAMBO sources. As a result, the number of potential excellent targets for PdBI observations is expected to increase further. The current number of sources with secure redshifts is close to 30 (Chapman et al. 2003).

Observing strategy

For the coming winter semester we propose to observe $\sim$ 8 objects for which optical redshifts were obtained with an accuracy of $\Delta z < 0.005$ (see attached source list). We concentrate on detecting the 3 mm CO line emission, though the 1 mm receivers are critical also to determine accurate continuum positions and fluxes, to observe an additional CO tracer, and to estimate source sizes and identify those sources which will be most suitable for higher-resolution follow-up.

The observed 850μm flux densities range from 6 to 12 mJy, resulting in expected 1.2 mm continuum flux densities of $\sim 1-4$ mJy (for the apparenty typical 850 μm/1.2 mm flux density ratio of 3–4).

Assuming parameters from Version 3.7-00 of the Bure manual and our previous experience, with 6 antennas and winter conditions we expect that a single transit (giving eight hours on-source) will yield 1σ sensitivities of 0.6 mJy per $\sim 100\,\mathrm{km\,s^{-1}}$ channel at 3 mm, and 0.6 mJy across the 1 mm continuum bandpass (averaging both sidebands). Requiring a $\geq 5\sigma$ detection and a cross-check of having at least two $\geq 3\sigma$ detections in independent datasets, we will need 2 tracks per source, or a total of 16 tracks for eight sources. To correct for the likely systematic blueshift of UV line features relative to CO emission, we will tune the 3 mm receivers slightly redward of the measured UV redshifts, except in cases where we have spectroscopic redshifts for nebular lines such as Balmer α. For the redshift uncertainty of $\Delta z = 0.005$, any source at $z \geq 1$ should then have the CO line peak fall within 0.5×580 MHz = 290 MHz of the 3 mm band center. In the event that no line emission is seen in a single track from a predicted strong source, we will consider re-observing the source with a different bandwidth setting, adjacent and red-shifted from the first one. Allowing additional tracks for such retunings we request on average 2.5 tracks per source, and thus **a total of 20 tracks**. The present proposal requests observing time mostly for the D configuration, which is well matched for detection experiments. Wemay consider observing the second or third track inC configuration if the source is well detected in D.Such datayields crucial information on the source size.

Because of our upcoming spectroscopic observations and ongoing analysis of recent data, we propose to retain the possibility of exchanging targets in the source list for better targets we might identify, and in particular for sources from the MAMBO deep fields (currently one in the new list, one was already observed). In each such case a written request for changing the source will be submitted to the IRAM director. A 'better' target would be one with a clearer optical/IR identification, a stronger (sub)mm flux, or a more accurate redshift.

References: • Barger et al. 1999, ApJ, 518, L5 • Bertoldi et al. 2000, A&A, 360, 92 • Chapman et al. 2003, Nature, 422, 695 • Fixsen, D.J. et 1998, ApJ, 508, 123 • Frayer et al. 1998, ApJ, 506, L7 • Genzel et al. 2003, ApJ, 584, 633 • Hauser, M.G. et al. 1998, ApJ, 508, 25 • Hughes et al. 1998, Nature, 394, 241 • Ivison et al. 2002, MNRAS, 337, 1 • Keres et al. 2003, ApJ, 582, 659 • Neri, Genzel, Ivison, Bertoldi, Blain, Chapman, Cox, Greve, Omont, Frayer 2003, ApJ Letter, in press, astroph/0307310 • Smail et al. 1997, ApJ, 490, L5 • Smail et al. 2002, MNRAS, 331, 495 • Webb et al. 2003, ApJ, 582, 6

Table 1. Proposed targets for PdBI observations.

Source (1)	$S_{850}\pm$ (2)	z (3)	Line (4)	$\nu_{\rm obs}$ (5)	Line (6)	$\nu_{\rm obs}$/B (7)
J123553.26+621337.7 (82)	8.8± 2.1	2.098	3-2	111.62	6-5	223.20
J123555.14+620901.7 (85)*	6.0± 1.9	1.875	2-1	80.19	6-5	240.51
J123600.10+620253.5 (92)	6.9± 2.0	2.710	3-2	93.21	7-6	217.43
J123606.85+621021.4 (105)	11.6± 3.5	2.330	3-2	103.84	6-5	207.65
J123621.27+621708.4 (140)*	7.8± 1.9	1.988	3-2	115.73	6-5	231.42
J163627.94+405811.2 (e.43)*	6.3± 1.9	3.180	3-2	82.73	7-6	220.53
J163655.75+405910.0 (m.20)	2.8± 0.7†	2.607	3-2	96.05	7-6	223.63
J221737.39+001025.1 (851)*	6.1± 1.9	2.639	3-2	95.03	7-6	221.67

(1) source name (coordinates are listed on the cover page)
(2) 850 μm flux density from SCUBA, in mJy, with 1σ uncertainty
(3) redshift, known to $\Delta z = \pm 0.005$ but represented here to $\Delta z = \pm 0.1$
(4) CO transition to be observed at the PdBI in the 3 mm window
(5) observed frequency for this line, in GHz
(6) – (7) same as columns (4) – (5) for the CO transition to be observed at the PdBI in the 1 mm window
† at 1.2 mm with MAMBO; $*$ optical spectra shown in Fig.2

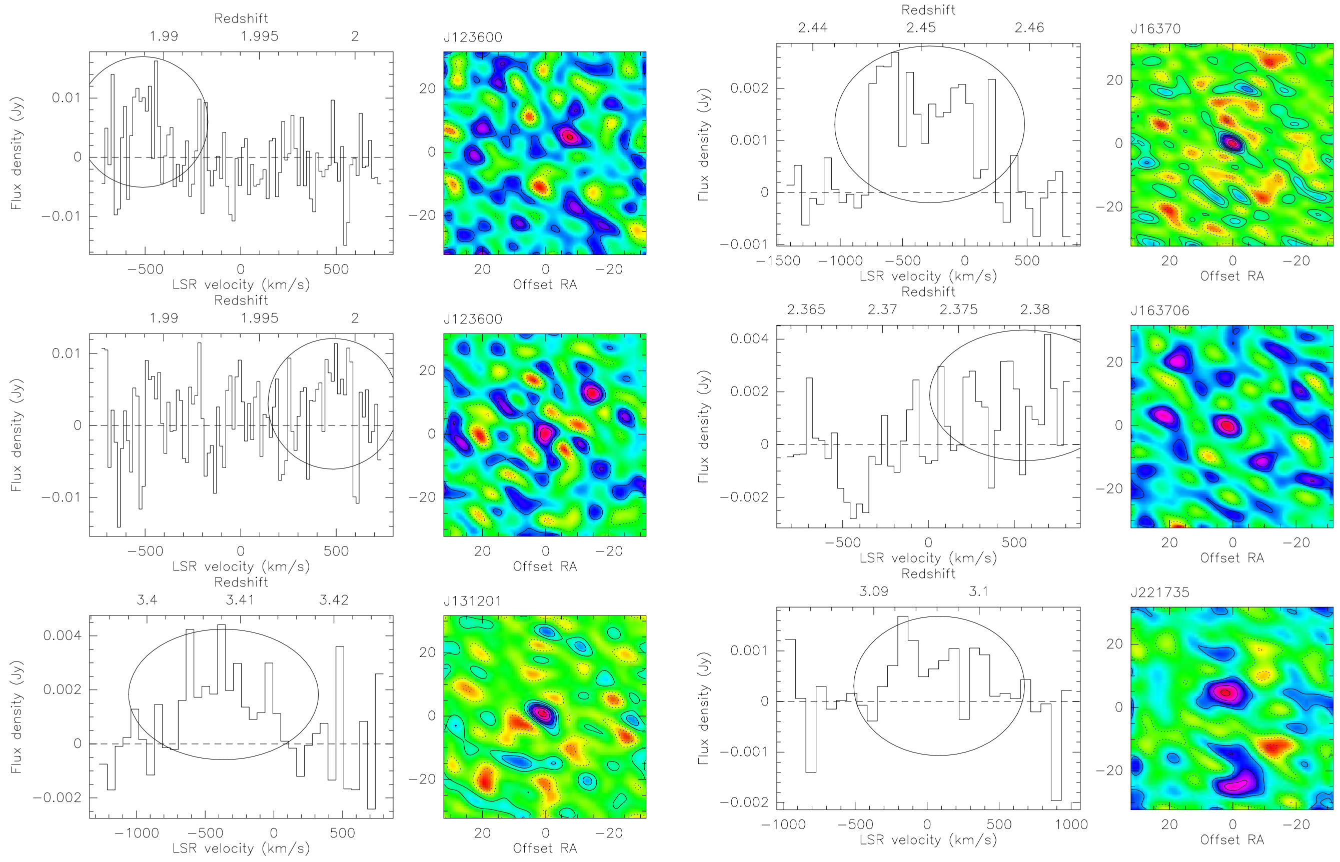

Figure 1. Recent detections of CO. The upper left two panels show the tentative detection of two CO emitters toward J123600.2+621047. The center right image shows a tentative detection toward J163706.5+405314.

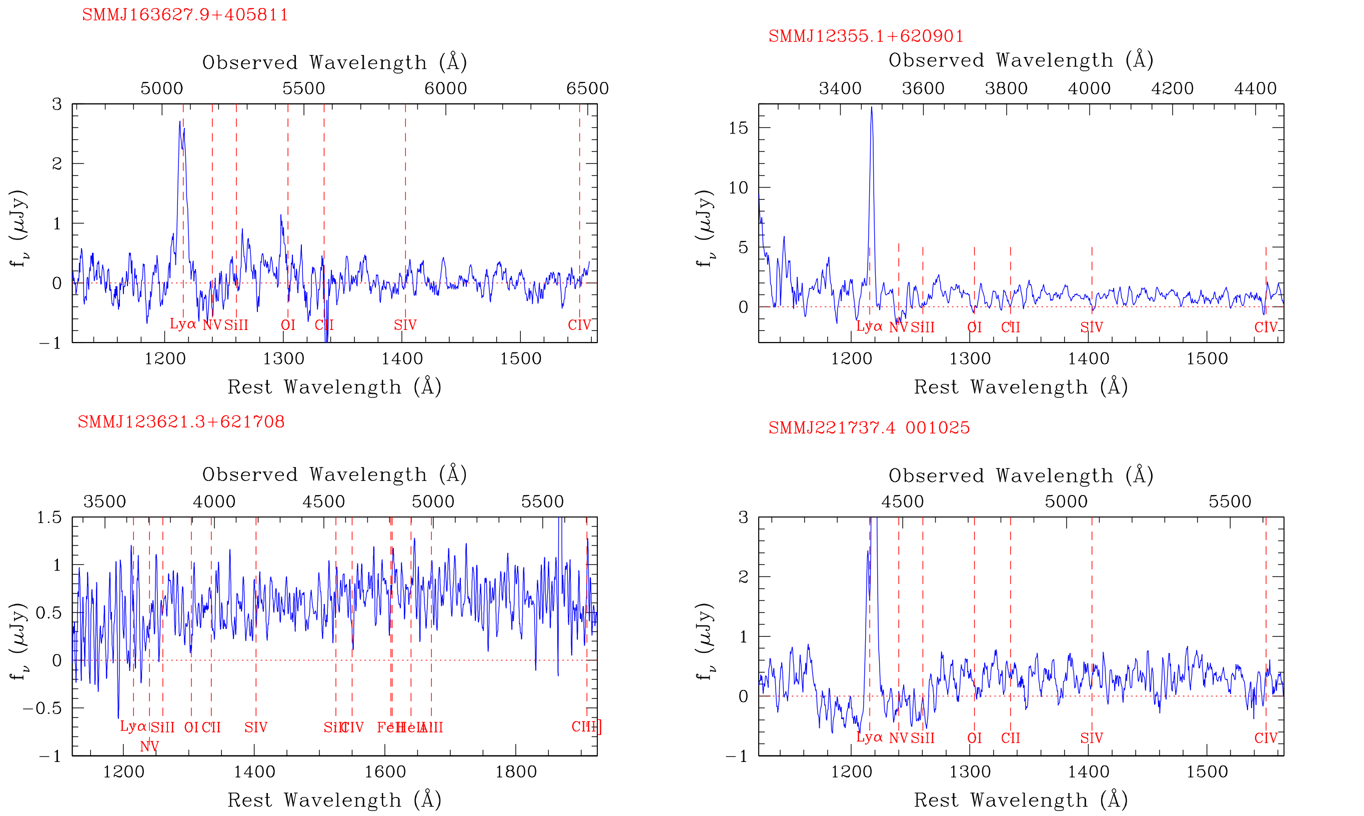

Figure 2. Optical spectra of four of the new SCUBA/MAMBO sources we propose to search for CO. All the optical redshifts have been confirmed to lie within 0.5” of the radio position.

Table 2. Status of the CO observations towards SCUBA SMM galaxies.

name	Pr	det	CO	S/N	pk	wid	I_CO		--offset--			z	S850	alias & comments	
					mJy	kms	Jy*km/s		"	"	km/s		mJy		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
J044307.3+021023	1	+	3-2	5.5	3.9	350	1.4	0.2	-1	-1	17	2.509	7.2	3" extended	#
J094303.7+470015	12	+	4-3	5.0	3.0	420	1.1	0.1	-4	-1	-207	3.346	10.5	H6, wrong opt.ID	#&
J105230.7+572210	2	-	3-2									2.6	11.0	LE850.6	
J105238.3+572436	2	-	3-2									3.0	10.9	LE850.2	
J123600.2+621047	3	(+)	3-2	3.5	6.0	200	1.2		0	0	500	1.999			
		(+)	3-2	4.5	7.7	200	1.5		-8	+5	-500	1.989		second source	
J131201.1+424208	3	+	4-3	9.1	2.2	500	1.1		1	1	-400	3.408	6.2	extended	
J131232.3+423950	3	-	3-2									2.32	5.9		
J163631.5+405547	2	-	3-2									2.28	6.3	N2850.13	
J163639.0+405636	2	(-)	2-1									1.49	9.0	N2850.7 more data	
J163650.4+405735	12	+	3-2	5.0	4.0	840	2.3	0.2			115	2.3853	8.2	N2850.4	#&
			7-6				1.1	0.2			-85	2.383			
J163658.2+410523	2	+	3-2	7.8	1.8	700	1.3		0	0	-300	2.45	10.7	N2850.2 ERO	&
J163706.5+405314	3	(+)	3-2	3.7	1.2	brd			0	0	+400	2.378	12	MAMBO source	
J221736.0+001554	3	(+)	3-2	4.1	.94	500	0.5				-400	3.097	6.3	(135)	

(1) SMM object name, i.e. coordinate
(2) From semester: 1=S02, 2=W02/03, 3=S03
(3) + detected, - not detected, ? unknown status, () uncertain
(4) CO transition
(5) signal to noise of line peak intensity
(6) peak line flux
(7) line FWHM, in km/s
(8)-(9) integrated line flux and uncertainty, sigma
(10)-(12) offset in position and velocity from optical target
(13) redshift of CO line, or (~) optical z
(14) 850 um = 350 GHz continuum flux density
(15) SMM source alt. name, comments
\# Neri et al. 2003, ApJ Letters, in press
& High resolution followup proposed, Neri et al.