IRAM 300, rue de la Piscine
38406 ST. MARTIN d'HERES (France)
Fax: (33/0) 476 51 59 38

For IRAM use
Registration N°:
Date:

PROPOSAL FOR INTERFEROMETER

Deadline: 03 March 2003 Period: 15 May — 15 Nov. 2003

TITLE

CO identification of submillimetre galaxies II.

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 (4 semester) 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. We already detected CO emission in 3 of these galaxies, while the 5 remaining sources are scheduled in the current semester. This program promises an order of magnitude 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 will increase the number of CO detections and enable statistically meaningful comparisons with other populations and galaxy formation models. It will explore the feasibility of millimetre-based spectroscopic redshift measurements with current and future instrumentation, prove the reliability of radio identifications, and serve 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): MD-7..................

LST range(s) per configuration	from: 8h	to: 24h	number of intervals: 6
	from: 10h	to: 02h	number of intervals: 6

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

Frequencies (exact) 3mm: see attached sheet 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}
J105224	10:51:24.6	57:21:19	z=2.4
J123635	12:36:35.6	62:14:24	z=2.0
J131201	13:12:01.1	42:42:08	z=3.4
J131232	13:12:32.3	42:39:50	z=2.3
J163651	16:36:51.4	41:05:06	z=3.1
J221804	22:18:04.4	00:21:54	z=2.3
J221735	22:17:35.1	00:15:33	z=2.4
J221733	22:17:33.2	00:09:07	z=2.7

(continue on next page, if needed)

Principal Investigator:
name, institution, address, fax, e-mail:

Co-PI: R. Genzel (genzel@mpe.mpg.de)
Max-Planck-Institut für extraterrestrische Physik
Giessenbachstr. 1, D-85741 Garching, FRG
phone = 49–89–30000–3281; fax = 49–89–30000–3601

Co-PI: R. Ivison (rji@roe.ac.uk)
Astronomy Technology Centre, Royal Observatory
Blackford Hill, Edinburgh EH9 3HJ, UK
phone = 44–131–668–8361; fax = 44–131–668–8407

Other Investigators (name, institution,fax):
F. Bertoldi. MPIfR, D
R. Neri, IRAM, F
P. Cox, IAS, F
A. Omont, IAP, F
T. Greve, Edinburgh, UK
S. Chapman, A. Blain, Caltech, USA
I. Smail, Durham, UK

who will reduce data: Neri, Greve, Genzel

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 II.

- **Source position and velocity:**

Source	RA	DEC	LSR Velocity
see cover page			

- **Category and Project type:** 3-mm 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:* 3 transits = 24h per object
- **For snapshot or size measurements:**
  - *Baseline range in meters:*
  - *Configuration list:* 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 II.

Proposal history: Considering the fundamental importance of the faint, dusty far-IR/submm population for the understanding of galaxy formation and evolution, recognizing the difficulties and slow progress being made in the spectroscopic identification of large samples 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 IRAM CO detection observations on a new sample of distant submm sources with recently established spectroscopic redshifts. The program was started in the late summer semester and in the early winter with three targets. Our proposal M05D to the IRAM PC was accepted for the winter semester, with the option for a long-term status if the program proves successful, and if a progress report is submitted each semester. The initial results of this program are most encouraging in that CO emission was detected from all three sources we observed. Below we give a brief report on the preliminary analysis of these observations, and a brief science motivation replacing the longer version of the previous proposal. Since five more sources are scheduled for the beginning of the D-configuration period starting in mid March, we shall provide another update for the PC meeting should further results be obtained by then.

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 $850\,\mu$m and MAMBO at $1200\,\mu$m 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 contribute more than 50% of 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 only been obtained for 3 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. The CO results indicate very massive systems with $\sim 10^{11}\mathrm{M}_{\odot}$, whose formation at $z \sim 3$ are not easy to understand in current hierarchical models of galaxy formation (e.g., Genzel et al. 2003).

Recently a group based in the USA and UK has been able to substantially increase the number of accurate source positions from ultra-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 ~ 30 sources with precise redshifts (Chapman et al. 2003). Based on these results, three of these sources were observed with the IRAM Plateau de Bure interferometer during the fall/winter of 2002, and *all* were detected in the CO($3 \rightarrow 2$) or ($4 \rightarrow 3$) transitions (Neri et al. in preparation). The CO detections provide a solid confirmation of the optical/UV redshifts and allow us to derive the dynamical masses associated with these luminous infrared galaxies.

The above observations have doubled the number of millimetre-confirmed redshifts, and thereby demonstrated that the strategy adopted for our proposed long-term programme is solid and potentially successful. Searching for CO emission in all the ~ 30 SCUBA submm sources for which both accurate positions and optically-determined redshifts are currently available will enable us to prove 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 will be achievable.

Scientific goals

The scientific goals of this long-term program (4 semesters) are to:

- detect CO rotational line emission with moderate resolution (D-configuration) interferometric observations for a significant and representative sample of ~ 30 submm galaxies, increasing the known number of 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. 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 – see also previous results by Ivison et al. (2001) and Genzel et al. (2003). 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.

- 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

In the following, we detail the results obtained so far on three submm SCUBA sources observed in CO emission. In the 3 sources, CO has been clearly detected (see Figure 1), and in the cases of SMM J09431 and SMM J04431 the CO emission appears to be resolved.

- **SMM J09431:** The PdBI CO(4-3) map is centered on H6 (which appears to be a NLSy1), however, the dust/CO source matches up with the ERO H7 4$''$ west, for which we have no optical redshift. Since the CO source is at the redshift deduced from the Ly-α and UV data on the H6 radio source ($z = 3.3$) but at the position of the H7 companion radio source, this appears to be another interesting case of interaction or clustering.
- **SMM J16368 (ELAIS N2 850.4):** 1.3 mm continuum emission as well as CO(3-2) and CO(7-6) emission, is detected at the expected redshift of $z = 2.38$, unresolved within 1 arcsec. The line appears to show multiple components, which have spatial offsets of about 0.5$''$. Interpreting these velocity offsets as motions in a gravitational potential, the implied dynamical mass is $> 8 \times 10^{10}$ M$_\odot$. The UV/optical source is spatially extended, and the optical/UV spectra suggest a merger geometry with a dusty starburst/AGN (the submm source) interacting with a nearby ($\sim 1''$) UV bright star forming galaxy.
- **SMM J04431 (ms0440/N4):** at $z = 2.51$ extended CO emission was detected with a half-diameter of about 1.4", possibly due to a $\sim$ 3 kpc size disk, which is magnified by a foreground cluster. The velocity gradient –if due to rotation– implies a dynamical mass $> 4 \times 10^{10} M_\odot$ within 3 kpc. The CO emission is at about the same redshift as the extremely red object N4 for which Keck has established the redshift.

SMM J16368 and SMM J04431 thus show dynamical masses similar to those implied for SMM J02399 (Genzel et al. 2003), indicating that the SMM backgound galaxies belong to a population of very massive galaxies with deep central potential wells. 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. Thus even the first detections of our on-going program already place interesting constraints on the models of structure formation.

Our observations also show the importance of interferometric observations to properly identify the optical or radio counterparts. In all three cases, the identity was ambiguous before our observations. In the case of SMM J09431, the optical redshift even corresponded to the wrong object, which luckily happens to have the same redshift as the SCUBA source.

Table 1: Properties of the SMM Sources observed

SMM	z	$S_{\rm CO(3-2)}$ [mJy]	$S_{\rm CO(4-3)}$ [mJy]	$S_{\rm CO(7-6)}$ [mJy]	S_{230} [mJy]	S_{350} [mJy]	FWHM [km/s]	config.
J04431	2.51	4.0			1.3	7.2	350	DCB
J09431	3.36		2.0		2.1	10.5	400	D
J16368	2.38	2.8		12	2.6	8.2	700	DCB

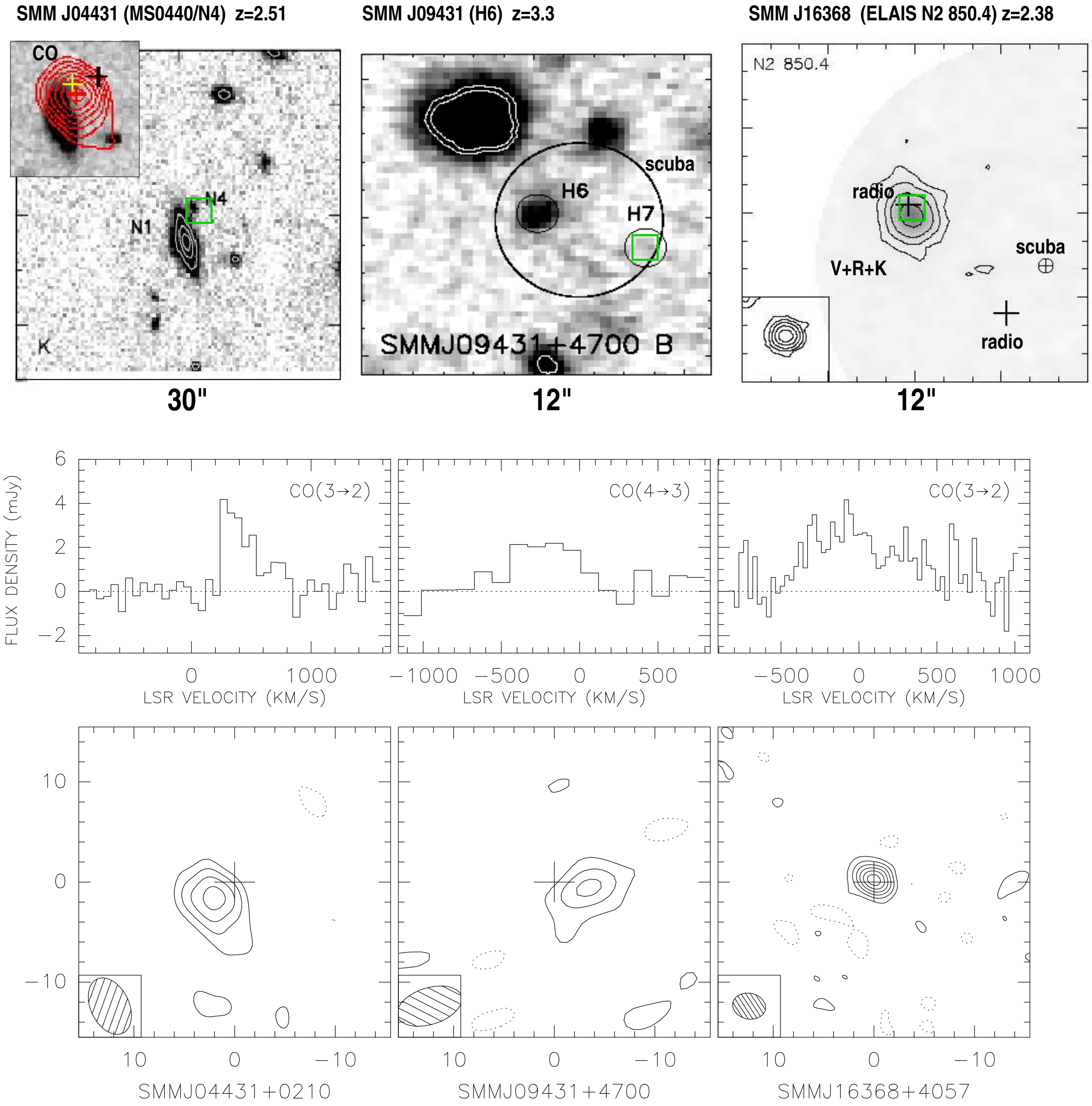

Figure 1. *The top row* shows optical or near-IR images of the three SCUBA sources we observed so far. A light square indicates the position of the CO centroid. The *middle and lower rows* show the spectra and images of the CO emission observed with the PdBI (contours are in steps of 2σ). Note that the intial target J09431 H6 is not the CO source, which coincides with H7. For J04431 the phase tracking center is indicated in the upper left insert by a black cross, the ERO N4, which seems to be the CO source, by a white cross. For J16368, the PdBI pointed at the radio position coincident with the extended optical galaxy.

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 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 summer with another 8 objects. We have now observed 3 objects, and another 5 are scheduled for the upcoming D-configuration period.

Our program to determine optical redshift for millimetre and submillimeter-selected galaxies continues vigorously. Using multi-object spectrographs at the Keck and Gemini telescopes we continue to observe sources that overlap in ultra-deep radio images and SCUBA and MAMBO surveys. Five dark nights are currently scheduled at Keck in March and May 2003, 30 hours are scheduled in March or April at Gemini North, and additional time at Gemini South. The current number of sources with secure redshifts is close to 30 (Chapman et al. 2003), with a further 10 expected each clear night at Keck. We plan to continue our campaign with a comparable request for Keck and Gemini time in semester 2003B. As a result, the number of potential excellent targets for PdBI observations is expected to increase further.

Observing strategy

For the coming summer semester we propose to observe ~ 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 could be used to determine accurate continuum positions and fluxes, to estimate source sizes and to observe an additional CO tracer.

The observed 850μm flux densities range from 5 to 13 mJy, resulting in expected 1 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 5 antennas and summer conditions we expect that a single transit (giving eight hours on-source) will yield 1σ sensitivities of 0.8 mJy per $\sim 100\,\mathrm{km\,s^{-1}}$ channel at 3 mm, and 0.8 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 2–3 tracks per source, or a total of 16–24 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 3 tracks per source, and thus **a total of 24 tracks**. The present proposal requests observing time mostly for the D configuration, which is well matched for detection experiments and is adapted for the summer conditions. Wemay consider observing the second or third track inC configuration if the source is well detected in D.Such datayields crucial information on source size.

Because of our upcoming spectroscopic observations, we propose to retain the possibility of exchanging a few targets in the source list for better targets we might identify. In each such case a written request will be submitted to the IRAM director. A 'better' target would be one with a clearer optical/IR identification, a stronger submm 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, submitted • 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 • Smail et al. 1997, ApJ, 490, L5 • Smail et al. 2002, MNRAS, 331, 495 • Webb et al. 2003, ApJ, 582, 6

Table 2. Proposed targets for PdBI observations.

Source Name (1)	S_{850} (2)	z (3)	Line/A (4)	$\nu_{\rm obs}$/A (5)
SMM J105224	11.7	2.4	CO(3–2)	101.71
SMM J123635	6.8	2.0	CO(3–2)	115.27
SMM J131201	6.2	3.4	CO(4–3)	104.79
SMM J131232	5.9	2.3	CO(3–2)	104.79
SMM J163651	5.7	3.1	CO(3–2)	84.34
SMM J221804	9.0	2.3	CO(3–2)	104.79
SMM J221735	6.3	2.4	CO(3–2)	101.71
SMM J221733	9.0	2.7	CO(3–2)	93.46

(2) 850 μm flux density from SCUBA, in mJy
(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