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: Sept. 12th, 2002 – Period: Nov. 15th - May 15th, 2003

TITLE

CO identification of submillimetre galaxies

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 begin a long-term program to determine the dynamical/molecular gas properties, via CO rotational line emission, of a large new sample of submm galaxies with radio positions and accurate Keck redshifts. This program will represent 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 vastly increase the number of CO detections and enable statistically meaningful comparisons with other populations and galaxy formation models. This work will explore the feasibility of mm-based spectroscopic redshift measurements with current and future instrumentation, test the reliability of radio identification and serve as a database for calibrating present and future photometric redshifts. We propose to observe a sample of 25–50 galaxies, beginning in the 2002/3 winter with 8 sources (2–3 tracks each).

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: 6h	to: 14h	number of intervals: 12
	from: 12h	to: 20h	number of intervals: 12

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

Frequencies (exact) 3mm: see attached sheet 1.3mm:

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

Source	α_{J2000}	δ_{J2000}	$V_{\rm LSR}$
SMM J09431	09 43 04.1	+47 00 16	z=3.3
SMM J10519	10 51 55.5	+57 23 13	z=3.7
SMM J10525	10 52 30.7	+57 22 10	z=2.6
SMM J10526	10 52 38.3	+57 24 36	z=3.0
SMM J16365	16 36 31.5	+40 55 47	z=2.2
SMM J16366	16 36 39.0	+40 56 36	z=2.1
SMM J16368	16 36 50.4	+40 57 35	z=2.4
SMM J16370	16 36 58.2	+41 05 24	z=2.4

(continue on next page, if needed)

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

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

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

Other Investigators (name, institution,fax):
F. Bertoldi. MPIfR, D
R. Neri, IRAM, F
A. Omont, IAP, F
P. Cox, IAS, 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 + 1 page 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

- **Source position and velocity:**

Source	RA (J2000.0)	DEC (J2000.0)	LSR Velocity (km/s)

- **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:* 16h 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

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 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. Utilising gaps in the PdBI schedule during the current D configuration, the program was started in August on one source. Based on the existing experience with sources previously observed, it is clear that such a program will be 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. It is anticipated that this cooperative program will require 2 years for execution. We request a long-term allocation to determine the CO properties of a sample of 25–50 submm galaxies, starting in the 2002/3 winter with 8 submm galaxies.

Background: The detection of dust-obscured starburst galaxies at high redshifts using SCUBA and MAMBO (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Bertoldi et al. 2000) has been a key breakthrough in recent observational cosmology. These galaxies contribute at least 50% of the total star and energy production rate in the early Universe. Detailed studies of their abundance, mass, clustering, chemical/physical properties, etc., are crucial if we are to understand the formation of stars, galaxies and structure in the young Universe.

About two hundred (sub)mm sources have now been detected. As of early 2002, however, spectroscopic redshifts and CO detections had only been obtained for 3 sources (e.g. Ivison et al. 1998, 2000, 2001; Frayer et al. 1998, 1999; Genzel et al. 2002; Kneib et al. in prep). Most (sub)mm galaxies could not be accurately localized to allow a unique identification with an optical/IR host galaxy (Barger et al. 1999; Smail et al. 2002) and many are too faint for spectroscopic follow-up (e.g. Downes et al. 1999; Dunlop et al. 2002; Dannerbauer et al. 2002), although some continuum-faint objects may well have strong Lyman$-\alpha$ emission lines, as we recently noticed. These far-IR-dominated galaxies have therefore become notoriously difficult to study in the optical/near-IR.

Other methods of determining redshifts are plagued by large uncertainties. Radio-to-mm flux ratios have been used for rough redshift estimates (e.g., Carilli & Yun 2000) but the redshift and dust temperature are degenerate (Blain 1999) leading to large uncertainties in the redshifts (and consequently the implied FIR luminosities, star-formation rates and energy and metal production rates). Large uncertainties are also found in photometric redshift estimates from the far-IR spectral slopes, obtained through observations at 0.85 mm and 1.2 mm (Eales, Bertoldi et al. in prep).

The lack of redshifts has stalled progress for 5 years. CO detections of (sub)mm galaxies, impossible without accurate redshifts, have been the ultimate goal of the intensive follow-up efforts that began with the discovery of the first submm galaxies in 1997. There are discussions at IRAM and elsewhere to build broad-band mm-spectrometers to target such sources without prior redshift measurements, but the realisation of such instruments for the IRAM 30m, LMT or GBT will take years.

Recent advances: Fortunately, several important breakthroughs have been made in 2002: first, extremely deep VLA radio observations are now available for the largest MAMBO and SCUBA fields and $\sim$50% of the (sub)mm sources have statistically reliable radio counterparts (Ivison et al. 2002). Next, armed with radio positions accurate to 0.3–0.8$''$ it now appears that many (sub)mm sources in those fields *do* have optical hosts, or ERO hosts, or combinations of the two ('blue/red composites'), although a significant fraction of optically faint SCUBA/MAMBO sources remains. For the submm sources with hosts bright enough to attempt optical or IR spectroscopy with 10-m class telescopes an intensive spectroscopic survey has begun at Keck.

Our sample of submm-bright galaxies with Keck redshifts is drawn from six fields: the HDF, SSA22, Westphal-Groth and SSA13 (Chapman et al. 2001), ELAIS N2 and the Lockman Hole (Scott et al. 2002), with masks in preparation for A 851 and A 2125 (Cowie et al. 2002; Bertoldi et al., in prep) and the CUDSS 03hr field (Webb et al. 2002). The sample consists of sources with radio detections, usually brighter than 30 μJy at 1.4 GHz, and with typical 850-μm flux densities of $\sim$8 mJy (Ivison et al. 2002). Spectroscopic targets were chosen from within this sample at random and prioritised equally, without regard for their optical brightness ($I =$ 22.2–26.5). An initial night with Keck/ESI yielded 5 sources with strong emission lines, often despite extremely faint continuum magnitudes. In 2002 March, we exploited the multiplexing advantage of Keck/LRIS to target a further 26 (sub)mm galaxies. Of the 31 (sub)mm galaxies observed during 3 nights with Keck/ESI/LRIS, redshifts were obtained with confidence for 25, spanning z=1.0–4.5 (Chapman et al. 2002). Identifications are mostly based on Ly α, which varies tremendously in both line flux (1–60 μJy) and equivalent width. Weaker stellar and interstellar features, and continuum breaks are detectable in most sources, strengthening the redshift identifications. Our targets generally have faint UV continua, and so there is some bias towards identifying redshifts for galaxies with strong emission lines. The small proportion of unidentified sources could in principle be absorbed Ly α galaxies at similar redshifts. Our optical and near-IR spectra reveal a multitude of features associated with starburst activity, including P-Cygni wind absorption profiles and an array of interstellar absorption lines (see Figure). We have 4 further Keck/LRIS nights (Sep–Jan) and we expect 10–15 more in Feb–Jul 2003, probably yielding a sample of $\sim$100 galaxies.

We note that our sample of submm sources with spectroscopic redshifts may be biased in several ways. About half of all the (sub)mm sources either do not have radio counterparts or have optical hosts too faint for spectroscopy. As the detected sources appear to be star-forming galaxies, often coupled with weak AGN, they are expected to follow the radio/far-IR relation (Condon 1992), so that a cm-radio selection of our targets may set a threshold in the maximum redshift at which the galaxy can lie (barring AGN contributions to the radio flux). Furthermore, some galaxies may fall into the spectroscopic desert at $z = 1.3$–1.8: at these redshifts the optical passband covered in our spectroscopy samples the rest-frame near UV where there are few strong spectral features, making redshift identification difficult. Despite these limitations, our sample provides the very first opportunity to systematically study the molecular gas in (sub)mm galaxies.

Of course, the scientific method dictates that many will question whether our radio/optical identifications are correct. The only unambiguous and *definitive* proof of a correct identification and redshift is via detection of CO line emission (Frayer et al. 1998, 1999), because vast amounts of molecular gas and strong continuum emission are unlikely to be a chance spatial coincidence. Furthermore, CO measurements reveal crucial information about the source structure, the molecular gas properties and the dynamical mass of the galaxies.

Scientific goals: We propose here the first semester observations of a longer term program ($\geq$4 semesters) with the following goals:

- detect CO rotational line emission with moderate resolution (D-configuration) interferometric observations for a significant and representative sample of 25–50 (sub)mm 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.
- test the reliability of radio and optical identifications of (sub)mm 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 mm-based spectroscopic redshifts with current instrumentation. In view of plans at IRAM to develop a wide-band spectrometer for the 30m telescope as a dedicated redshift machine, it is crucial to establish the typical line-to-continuum ratio in a significant and representative sample of distant submm sources.
- 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 where such follow-up exists, such spatially resolved work delivers critical information in testing current hierarchical galaxy formation models, exploring how early and with what mass the luminous far-IR/submm galaxies were formed (Ivison et al. 2001; Genzel et al. 2002).

Observing strategy: For the coming winter we propose to begin with a sample of $\sim$ 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, but will use the 1 mm receivers to determine accurate continuum positions and fluxes, to estimate source sizes and to observe an additional CO tracer. The 1 mm observations will be critical for identifying those sources which will be most suitable for higher-resolution line and continuum PdBI follow-up. 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 a typical 850 μm/1.2 mm flux density ratio of 3–4). From 16 detections of CO line emission from $z \geq 1$ QSOs, radio galaxies, and starbursts, the 3 mm CO line/1 mm continuum flux density ratio was found to be typically in the range 1 to 2 (Cox et al. 2002). For the three (sub)mm-selected sources with observed CO emission (SMM J14011, SMM J02399, and HR 10), this ratio is closer to 0.5. Allowing for a range of 0.5–1.5 for the 3 mm line/1 mm continuum ratio, we predict 3 mm line fluxes of approximately 0.5–6 mJy. Assuming parameters from Version 3.7-00 of the Bure manual and our previous experience, we expect that a single transit (giving eight hours on-source) will yield 1σ sensitivities of 0.6 mJy per $\sim$ 100 km s^{-1} channel at 3 mm, and 0.6 mJy across the entire 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, e.g. N2 850.4). 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 at a second bandwidth setting. Allowing another four tracks (over all eight sources) for such retunings implies a total request of 20–28 tracks. Should we fail to detect line emission from our first five candidates, including the two objects being observed this fall via DDT, we shall suspend the project and discuss with IRAM possible alternative strategies.

Since these observations are not likely to begin before March 2003, we propose to retain the possibility of exchanging a few targets in the source list below for better targets we might identify during the 4 Keck nights scheduled for Sep–Jan (plus our unknown Keck allocation for Feb–Jul 2003, plus 10 hr of optimally-flexed Gemini/GMOS time). 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. 2000, AJ, 119, 2092; • Bertoldi et al. 2000, A&A, 360, 92; • Blain 1999, MNRAS, 309, 955; • Blain et al. 2002, Physics Reports, in press (astro-ph/0202228); • Carilli, Yun, 2000, ApJ, 530, 618; • Chapman et al. 2001, ApJ, 548, L147; • Chapman et al. 2002, Nature, submitted; • Condon 1992, ARAA, 30, 575; • Cowie et al. 2002, AJ, 123, 2197; • Cox et al. 2002, in The Cold Universe, in press.; • Dannerbauer et al. 2002, ApJ, 573, 473; • Downes et al. 1999, A&A, 347, 809; • Dunlop et al. 2002, MNRAS, submitted (astro-ph/0205480); • Frayer et al. 1998, ApJ, 506, L7; • Frayer et al. 1999, ApJ, 514, L13; • Frayer et al. 2000, AJ, 120, 1668; • Genzel et al. 2002, ApJ, submitted; • Hughes et al. 1998, Nature, 394, 241; • Ivison et al. 1998, MNRAS, 298, 583; • Ivison et al. 2000, MNRAS, 315, 209; • Ivison et al. 2001, ApJ, 561, L45; • Ivison et al. 2002, MNRAS, in press (astro-ph/0206432); • Scott et al. 2002, MNRAS, 331, 817; • Smail et al. 1997, ApJ, 490, L5; • Smail et al. 2002, ApJ in press (astro-ph/0112100); • Webb et al. 2002, ApJ, in press (astro-ph/0201180)

Table 1. Proposed targets for PdBI observations.

Source (1)	S_{850} (2)	z (3)	Line/A (4)	$\nu_{\rm obs}$/A (5)	$\Delta\nu$/A (6)	Signal/A (7)	Line/B (8)	$\nu_{\rm obs}$/B (9)	$\Delta\nu$/B (10)
SMM J09431 (H6)	10.5	3.3	CO(4–3)	106	35	∼ 2.9	CO(8–7)	212	71
SMM J10519 (LE 850.18)	4.5	3.7	CO(4–3)	98	33	∼ 1.3	—	—	—
SMM J10525 (LE 850.6)	11.0	2.6	CO(3–2)	96	32	∼ 3.1	CO(7–6)	224	75
SMM J10526 (LE 850.2)	10.9	3.0	CO(3–2)	86	28	∼ 3.1	—	—	—
SMM J16365 (N2 850.13)	6.3	2.1	CO(3–2)	110	37	∼ 1.8	CO(6–5)	220	73
SMM J16366 (N2 850.7)	9.0	2.1	CO(3–2)	113	38	∼ 2.5	CO(6–5)	227	76
SMM J16368 (N2 850.4)	8.2	2.4†	CO(3–2)	102	34	∼ 2.3	CO(7–6)	237	79
SMM J16370 (N2 850.2)	10.7	2.4	CO(3–2)	101	34	∼ 3.0	CO(7–6)	235	78

Columns are
(1) source name (coordinates are listed on the cover page)
(2) 850 μm flux density from SCUBA, in mJy
(3) redshift, known to $\Delta z = \pm 0.005$ but represented here to $\Delta z = \pm 0.1$; † additional near-IR z available
(4) CO transition to be observed at the PdBI in the 3 mm window
(5) observed frequency for this line, in GHz
(6) channel width corresponding to 100 km s^{-1} for this line in the source rest frame, in MHz
(7) predicted strength per 100 km s^{-1} channel of this line in mJy, calculated as described in the text
(8) – (10) same as columns (4) – (6) for the CO transition to be observed at the PdBI in the 1 mm window

Figure. The left-hand panel in each row shows the Keck/LRIS spectrum of the submm galaxies in their rest frame (Chapman et al. 2002), with features identified; most show surprisingly strong UV emission lines, which provide reliable measures of their redshifts. The right-hand panels display views of a $20'' \times 20''$ field surrounding the source in the optical, the near-IR and radio (from left to right — Ivison et al. 2002). In each case we circle the submm source in red and show the 68% error circle for the submm position in blue. The optical image of N2 850.4 is shown as a true colour VRI image; the two sources from the Lockman Hole sample are I-band. The near-IR images are deep K-band exposures and these are overlaid by contour plots representing 850-μm emission. Finally, the deep radio maps identify the radio counterparts to the submm sources, whose spectra are shown on the left. For ELAIS-N2 850.4 we highlight the presence of several strong emission lines which exhibit P-Cygni features indicating that the star formation in this galaxy is driving a strong wind from the galaxy (Smail et al., in prep). For L 18 (or LE 850.18) we show two spectra, the lower spectrum is for the source which is ringed faintly on the I-band image, which turns out to be an optically-brighter companion to the submm source at a very similar redshift (one of the many blue/red composites identified by Ivison et al. 2002). The close proximity of this galaxy to the submm source strengthens the redshift identification for the fainter galaxy.