Millimeter Detection of Dust and CO
from high redshift QSOs

Alain Omont (IAP)
OUTLINE

• DUST MM DETECTION IN HIGH Z QSOs (z = 2 – 6.5)

• Background: high z SCUBA/MAMBO ULIRGs
  black hole / spheroid correlation

• IRAM-30m/MAMBO 1.2 mm Observations of bright QSOs

• Results: 55 detections. Statistics \( \Rightarrow \) \( z \) & \( L_{bol} \) dependence

• Properties and Origin of Dust Emission

• CO EMISSION IN HIGH z QSOs

• CO detection in high z QSOs with the IRAM interferometer

• FUTURE: ALMA Capabilities
COLLABORATION

General  P. Cox , A. Beelen  IAS, Orsay  
       F. Bertoldi (+ E. Kreysa)  MPIfR, Bonn
       C. Carilli  NRAO

QSO samples
   SDSS z > 6 : X.Fan, M. Strauss
   PSS : G. Djorgovski

SCUBA 850µm
   R. McMahon, K. Isaak, R. Priddey  Cambridge

CSO 350µm  D. Benford, T. Phillips  Caltech

Radio VLA  C. Carilli, A. Petric, F. Walter  NRAO

CO
Radiogalaxies  C. de Breuck  ESO-IAP

PARALLEL WORKS
Radioquiet QSOs SCUBA  Isaak, Priddey, Mc Mahon et al. ; Willot et al., etc.
Radioloud QSOs  SCUBA  Willott et al.
Radiogalaxies : SCUBA  Archibald et al., Ivison et al., etc.
Etc
⇒ X AGN
Highlights

• AGN (10^{13} - 10^{14} Lo) + ULIRG (10^{12} - 10^{13} Lo)

• Massive star formation at less than 1 Gyr
  (where SCUBA/MAMBO galaxies not yet identified at z>4)

• Large mass of dust $\rightarrow$ Heavy elements enrichment + dust formation

• Coeval Bulge/Black-Hole evolution $\rightarrow$ Massive Ellipticals

• Dust heating combines starburst + AGN

• CO detection $\rightarrow$ starburst $\rightarrow$ $\Delta V$ $\rightarrow$ Virial mass

• $\rightarrow$ ALMA :
  - starbursts in ULIRGs & LIRGs at all redshifts
  - mapping + V structure of gas $\rightarrow$ virial mass

Redshifts of studied QSOs

Haas et al

Redshift distribution of SCUBA ULIRGs
What is the Reionization Era?
A Schematic Outline of the Cosmic History

- The Big Bang
  The Universe filled with ionized gas
- The Universe becomes neutral and opaque
  The Dark Ages start

- Reionization
  PopIII stars + 1st galaxies
  - Formation of 1st galaxies
  - First AGN

- z ~ 4–7:
  - Current frontier
    - Galaxies and QSOs detection
    - End of reionization

- z ~ 1.5–4:
  - Peak of star formation
    - submm sources + LBGs
    - Peak of QSO activity
    - Proto-cluster formation

- z ~ 0.5–1.5:
  - Final phase of active star formation
    - ISOCAM sources
    - Weak X-ray AGN
    - Cluster formation

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<th>z</th>
<th>D$_{\text{phot}}$ (Gpc)</th>
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<tr>
<td>~ 300 thousand</td>
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<tr>
<td>~ 500 million</td>
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<td>~ 3.5 billion</td>
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The high z mm-submm window

Very steep submm SED of ULIRGs

→ Sensitivity at ~1mm independent of z for $0.5 < z < 10$!
**SCUBA(-MAMBO) census of high-z ULIRGs**

- Take advantage of steep submm spectrum
- Account for the whole submm background
- \( z \) at Keck for radio ones (~50%) (weak AGN ?)
  - History of star formation up to \( z \sim 3-4 \)
- Small but uncertain number at \( z > 4 \)
  - CO detected at IRAM-PdB in 6-8  
    (Neri et al 2003)

**SCUBA(-radio) redshift distribution**  
Chapman, Blain, Ivison, Smail 2003

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**SCUBA (+MAMBO) submm counts**  
How many? ... Cumulative number counts:

**Star-formation rate**
Black Hole / Spheroid Correlation

- Supermassive black holes (SMBH) in almost all local massive galaxies
- \( M_{\text{BH}} \sim 0.001 - 0.006 \ M_{\text{bulge}} \)
- Tight correlation \( M_{\text{BH}} \)-bulge velocity dispersion : \( M_{\text{BH}} \sim \sigma^{3.8-4.8} \)
- Possible correlation \( M_{\text{BH}} \)-dark halo mass : \( M_{\text{BH}} \sim M_{\text{DM}}^{1.27-1.82} \)
- Despite lack of understanding the precise physical origin, there is a strong link between formation process of SMBHs and host galaxies (bulges) → AGN-starburst connection
IRAM-30m/MAMBO 1.2 mm observations of bright high-z QSOs

1. Aims

• Correlations between major starbursts and black-holes at high z

  → black-hole/spheroid mass correlation

• Easiest way to find (biased) cases of ULIRGs at very high z

  Redshifts of SCUBA/MAMBO sources are difficult to determine and practically unknown at z > 4

  Better to search similar sources around known objects: (bright) QSOs or radiogalaxies (Archibald et al. 2001)
IRAM-30m/MAMBO 1.2 mm Observations of bright high-z QSOs

2. Sample

(Bright) QSOs ($L_{bol} \sim 10^{13} - 10^{14} L_o$) with $z \sim 2$-6, from optical surveys: PSS, SDSS, etc.

Range of redshifts: large sample at $z > 4$; comparison at $z \sim 2$; largest redshifts identified $\rightarrow z = 6.4$

Range of luminosities: $M_B \sim -24$ -28

$\rightarrow$

Omont et al. 1996 (+McMahon et al. 1994) small sample (20) APM etc.
Carilli et al. 2001 deep SDSS sample (41) at $z > 4$
Omont et al. 2001 bright PSS sample (62) at $z > 4$
Omont et al. 2003 bright sample (35) at $z \sim 2$
Bertoldi et al. 2003 (+ Bertoldi & Cox 2002, Petric et al. 2003) (6) highest $z \rightarrow 6.4$
Beelen et al. 2004 extension to fainter luminosities (40) at $z \sim 2$ & $z > 4$

Total $\sim 200$ observed sources

(Parallel studies with SCUBA: series of papers by Priddey, Isaak, McMahon et al.)
IRAM-30m/MAMBO  1.2 mm  Observations of high-z bright QSOs

3. Observations

IRAM  30m Telescope
Pico Veleta (Granada, Spain)
11” beam
Reasonably good pointing accuracy ~2”
Wobbling secondary mirror

MAMBO bolometer cameras
Built at MPIfR Bonn (E. Kreysa group)
37 → 117 channels
Pointed observations on central channel
Good sky substraction with other channels
(MOPSI software Zylka, Bertoldi, etc.)

rms ~ 30 mJy in 1 sec.
Average rms ~0.6-0.7 mJy → 2h per source
Several hundreds of hours of observation
IRAM-30m/MAMBO  1.2 mm  Observations of bright QSOs

4. Summary of results

High rate of detection :  ~55 sources detected\(\Rightarrow\)  ~ 25\%

Strong propensity to the presence of interstellar matter (dust) around active massive black holes \(\Rightarrow\) fuel of QSO activity, black-hole/bulge coeval growth

\(\Rightarrow\ \Rightarrow\ \Rightarrow\)

• No significant dependence on \(z\)
• Small dependence on \(L_{\text{opt}}\)
• Evidence for DUST emission
• Starburst or AGN dust heating ?
• Arguments for substantial contribution from starburst

\(\Rightarrow\ 1.3\ \text{mm dust detection at IRAM interferometer in more than 10 high } z\ \text{QSOs } \Rightarrow\ \text{high angular resolution}\)

\(\Rightarrow\ \Rightarrow\ \Rightarrow\)

Prominent sources: BR 1202-725 \(z=4.7\), PSS 2322 \(z=4.1\), SDSS J1148 \(z=6.4\), etc.
No significant dependence on redshift
The redshift behavior of $L_{\text{FIR}}$ is very different from radiogalaxies where a strong increase with $z$ is observed by Archibald et al. 2001.
FIR is weakly correlated with rest-UV.
**Dust emission from the most distant quasars**  
* Bertoldi et al. 2003

\[ S_{250\text{GHz}} = 5.0 \text{ & } 3.0 \text{ mJy} \]
\[ \rightarrow L_{\text{FIR}} \sim 10^{13} L_\odot \quad \text{(uncorrected for possible moderate lensing)} \]
\[ \rightarrow M_{\text{dust}} \sim 10^8 M_\odot \text{ at } t \sim 0.8 \text{ Gyr} \quad \rightarrow \text{Rapid metal enrichment} \]
\[ \rightarrow \text{Dust formation in supernovae or Pop III stars} \]

+ CO detection (→ C. Carilli)

*SDSS Fan et al. 2003*
MAMBO imaging observation of J1148

1.2 mm map

Signal/Noise map

white contours: optical image

QSO 5.0+-0.6 mJy
ULIRG 5.8+-1.1 mJy

z=0.5 elliptical galaxy
CONFIRMATION OF DUST ORIGIN OF THE EMISSION

• Flux ratios 850 µm / 1.2 mm characteristic of dust

• Flux ratios FIR / radio comparable to local ULIRGs

• Many are confirmed as radio quiet from deep VLA observations
  Carilli et al. 2001, Petric et al. 2004, Beelen et al. 2004

• A few are found weakly radio loud, but dust emission confirmed
  Carilli et al. 2001

• Radio to mm Spectral Energy Distribution (SED) very comparable
to templates of starburst dust emission : M 82, etc.
  Cox et al. 2002
SED from radio to submm of bright QSO PSS2322 at z=4.1 is in good agreement with standard SED of the template local Luminous IR Galaxy M 82.

Proportionality of radio (synchrotron) and far-IR (dust) luminosities of star forming regions/galaxies on 4 orders of magnitude.
mm/submm emission dominated by cold dust at 30-50 K
(Benford et al. 1999, Priddey & McMahon 2001)

FIR-submm Spectral Energy Distribution of high-z AGN
*Benford et al. 1999*  $\rightarrow T_{\text{dust}} \sim 40-50$ K ($\rightarrow 100$ K)
Comparison of dust and cold dust

SED of QSOs and Radio Galaxies (local)

Haas et al. 2003
DUST TEMPERATURE & FAR-INFRARED LUMINOSITY

mm/submm emission dominated by cold dust at 30-50 K
(Benford et al. 1999, Priddey & McMahon 2001)

\[ L_{\text{FIR}} \sim 3-4 \times 10^{12} \left( S_{1.2\text{mm}} / \text{mJy} \right) L_\odot \rightarrow \sim 10^{13} \quad L_\odot \]

• Comparable to brightest SCUBA sources
• Typically ~ 0.1 \( L_{\text{opt}} \)

• Probably at a few 100 pc to ~1 kpc from the center
• (no direct relation with AGN obscuration by very close dust)

• (possibility of:
  - warmer closer dust component: seen in mid-IR Haas et al., Freudling et al., etc.
  - colder dust component, farther out)

MASS OF DUST

• Typically ~ \( 10^8 \) Mo
• But inversely proportional to uncertain dust emissivity
• \( \rightarrow M_{\text{H}_2} \sim \) a few \( 10^{10} \) Mo
WHICH HEATING FOR COLD DUST?
→ FAR-IR LUMINOSITY?

STARBURST OR AGN?

Both are viable:

- For AGN heating:
  (see e.g. Sanders et al. 1989, Andreani et al. 1999, Willott et al. 2002, Haas et al. 2003, Freudling et al. 2003, etc.)

- $L_{\text{FIR}}$ is only a tiny fraction of $L_{\text{bol}}$ ($\sim 0.1$)

- Possible to imagine adequate geometry/ UV radiative transfer

- Higher T ($\sim 100$ K) dust detected in far/mid-IR must be heated by the AGN
Models of AGN strong dust emission by Haas et al. 2003
- **Starburst powering of dust heating**

- Is known to dominate in most local and high z ULIRG’s (where $L_{\text{FIR}} \sim 10^{12} \, L_\odot$):
  - ISO spectroscopy (Genzel et al., etc.)
  - Correlation of $L_{\text{FIR}}$ with CO and with radio
  - No X-Ray detection of most SCUBA sources

- Extension to $L_{\text{FIR}} \sim 10^{13} \, L_\odot$ is possible in exceptional objects: central collapse or major merging in massive ellipticals?

- Arguments for a **substantial starburst contribution** to heating of cold dust in millimeter detected high z QSOs:
  - Correlation with CO in strong sources above CO detection limit
  - Correlation with radio intensity seems rather general
  - Large starbursts are needed to quickly synthesize stars and metals
WHICH HEATING FOR COLD DUST? → FAR-IR LUMINOSITY?

STARBURST OR AGN?

Conclusions

- Both are viable

- Probably a combination of both in various proportions

- Proportions may depend on redshift, with more starburst at \( z > 4 \) than at \( z \sim 2 \) as for radio-quasars/radiogalaxies (Willott et al. 2002)

- But some starburst probably always present in 1.2mm detected sources
CO detection in high z QSOs

As for dust, the detection of CO at high z is also made easier by the larger CO luminosity (higher J line) in rest frame, for a fixed detection band (3 mm)

--> Little decrease in sensitivity from z~1 up to z~5

~25 CO detections at high z
with IRAM (& Caltech) Interferometers
CO lines

Continuum submm radiation

F. Combes, Maoli, Omont 1999
Information from high angular resolution 1.3 mm dust observation

Plateau de Bure IRAM interferometer
CO detection in high z QSOs

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~25 CO detections at high z with IRAM (& Caltech) Interferometers

LUMINOUS OBJECTS:

• Bright QSOs (brightest 10% of those where dust is detected)
• Radiogalaxies (Papadopoulos et al, De Breuck et al.)
• Strong lenses (Case studies: Cloverleaf, FIRAS10214, APM0835)
• About 10 SCUBA galaxies (Neri, Genzel, Ivison, Bertoldi, Greve, et al.)

NEED ACCURATE REDSHIFT for neutral gas, from optical / near-IR
Early detection of CO in **BR1202-0725** at $z=4.69$

(Ohta et al. 1996, Omont et al. 1996,)

• Two peak emission both in 1mm continuum and 3mm CO(5-4)
• Origin still unclear: premerging two monsters or intricated lensing
• Peculiar unique case
SDSS J1148  
CO 3-2 (VLA), 6-5, 7-6 (PdBI)  
z = 6.42

Walter, Bertoldi, Carilli et al. 2003, Nature
Bertoldi, Cox, Neri et al. 2003, A&A Let
PdBI observations of (sub)mm galaxies (from SCUBA)

Bertoldi, Blain, Chapman, Cox, Genzel, Greve, Ivison, Neri, Omont, Smail

\[ \langle \sigma \rangle = 255 \text{ km/s} \rightarrow M_{\text{dyn}} > 10^{11} \text{ } M_{\odot} \text{ within 4 kpc} \]

\[ M_{\text{gas}} \approx 2 \times 10^{10} \text{ } M_{\odot} \]
OUTCOME OF CO DETECTION

- Confirmation of Strong Starburst
- Approximate mass of molecular gas
- Excitation temperature if multi CO lines detection
- Velocity Range
  - --> Total Virial Mass (if extension determined or guessed)
- Spatial Distribution (if resolved)
  - Pre-merging
  - Lensing
- Good correlation CO/FIR intensities
- However in most cases the information still remains sketchy
**J1148 dense gas**

Density \( \sim 10^6 \text{ cm}^{-3} \)

temperature \( \sim 100 \text{ K} \)

size \( R \sim 400 - 1400 \text{ pc} \)

gas mass \( (1-2) \times 10^9 M_{\odot} \)

dyn. mass \( M_{\text{dyn}} \sin^2 i \sim (2-6) \times 10^9 M_{\odot} \)

Most mass in molecular gas!

\( M_{\text{dyn}} / M_{\text{BH}} \) much smaller than today
FUTURE

New Facilities:
• Ground: SMA, CARMA, APEX, LMT...
• Balloon/Space: BLAST, SIRTF, ASTRO-F, HERSCHEL ...

DOMINATED BY ALMA

• 64 movable 12-meter antennas + compact array
• Sensitivity gain ~ 50 / existing equipment
• >~1000 in imaging speed

- Higher frequency $\rightarrow T_{\text{DUST}}$
- CO + Dust detection in ALL QSOs & radiogalaxies $\rightarrow$ highest $z$
- $C^+$, CI and other molecules
- Spatially resolved / Velocity
- Companions, proto-clusters
- Lensing
ALMA at Chajnantor
(Courtesy NAOJ)
ALMA and the high z Universe: capabilities and main goals

By far the most sensitive instrument both for dust and CO detection

No confusion limitation

However, not a very efficient wide field survey instrument

../..
ALMA high z capabilities:

1. Sensitivity

- Dust detection at 850μm ~50 times more sensitive than SCUBA
- Survey speed close to 1000 times faster
- e.g. a 4'x4' field at sensitivity of 0.1 mJy in two weeks
  (20 times lower than current SCUBA field surveys)
  → detection of ~100-300 high-z galaxies,
- CO detection in many of them.
- Detection of LIRGs with $L_{\text{FIR}} \sim 10^{11}$ Lo up to z~10-20, if any,
  i.e. the first starbursts in the Universe
ALMA and the high z Universe: capabilities and main goals

By far the most sensitive instrument both for dust and CO detection

However, not a very efficient wide field survey instrument

No confusion limitation

High angular resolution: 1 kpc for z~1-10

Full velocity information of heterodyne technics
ALMA high z capabilities: 2. High angular & spectral resolution

High angular resolution $\rightarrow$ 0.1” $\rightarrow$ ~1 kpc for $z > 1$

Full velocity information of heterodyne technics

$\rightarrow$ Dynamical masses

$\rightarrow$ Full mapping and information on molecular gas and starbursts in whole early phases of galaxy building up

$\rightarrow$ Special cases and details of strongly lensed objects
**ALMA and the high z Universe: capabilities and main goals**

By far the most sensitive instrument both for dust and CO detection

However, not a very efficient wide field survey instrument

No confusion limitation

High angular resolution: 1 kpc for z~1-10

Full velocity information of heterodyne technics

Submm capability $\rightarrow$ full SED of cold dust $\rightarrow$ $L_{\text{FIR}} + T_{\text{dust}}$ (+ redshifted 157$\mu$m C$^+$ line)

Very large bandwidth: 2x8GHz $\rightarrow$ easily covering the whole 3mm window $\rightarrow$ blind redshift search of emission and absorption molecular lines

Polarisation capability

Study of high z patchy ionization on a few arcsec scale?