The study of comets in interferometry at millimeter wavelengths: Recent results and future prospects

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Outline

• Introduction
  − Generalities about comets
  − Comets at millimeter wavelengths

• Recent results (Plateau de Bure observations)
  − Volatiles in cometary atmospheres
  − Cometary nuclei
  − Dust in cometary atmospheres

• Prospects
  − Comets with ALMA and NOEMA
Introduction: Generalities about comets (1)

- Remnants of the planet formation era
  - Nucleus composition and structure provide us with insights into the conditions in the early Solar System
  - Comet impacts on young planets may have played a role in their evolution

- Comets:
  - Nucleus: ice and refractories
  - Atmosphere (coma): gas and dust

- 2 dynamic classes
  - Ecliptic comets (short period)
  - Oort cloud comets (long period)

- Diversity among comets
  - Chemistry
  - Geology
Introduction: Generalities about comets (2)

- Direct studies of the nucleus are difficult
  - Small objects (~10km)
  - Presence of the atmosphere
- Ground based observations:
  - Size, shape, rotation
- Spacecrafts:
  - Composition, structure
  - But only a handful of objects

**Analysis of the coma to derive information about the nucleus**
- Continuum: dust
  + Vis: reflected Sun light
  + IR, mm: thermal emission
- Spectroscopy: volatiles
  + Vis: daughter products
  + IR, mm: parent products

Tempel 1 as seen by the Deep Impact spacecraft (Jul. 2005)
Hartley 2 as seen by the Deep Impact spacecraft (Nov. 2010)
Introduction: Comets at mm wavelengths (1)

- Single Dish (Beam $\sim \lambda/D \sim 10''$ for $D = 30m, \lambda = 1mm$)
  - Spectroscopy of molecules in the inner coma ($10^4 km$)
    - Rotational emission lines
      - CO, SO, HCN, H$_2$S, CH$_3$OH, HCOOH, HOCH$_2$CH$_2$OH,...
      - Isotopologues
    - Global parameters of the coma
      - Abundances, outflow velocity, temperature
    - Systematic observations to study comet taxonomy and diversity

Ecliptic comets - Oort Cloud comets - Crovisier et al. 2009, EM&P
Introduction: Comets at mm wavelengths (2)

- **Single Dish** (Beam \( \sim \lambda/D \sim 10'' \) for \( D = 30m, \lambda = 1mm \))
  - Spectroscopy of molecules in the inner coma (10^4 km)
  - Bolometer observations of the dust

**OR**

- **Interferometry** (Beam \( \sim \lambda/B \sim 1'' \) for \( B = 250m \))
  - Distribution of the molecules in the coma (10^3 km)
  - Dust coma (extended source)
    - Thermal emission of mm grains
    - Production rates, size distribution,...
  - Nucleus properties (point source)
    - Thermal emission of the nucleus
    - Size, surface thermal properties

**Radio interferometric observations of comets**

1985: Halley (VLA)
1987: Wilson (VLA)
1997: C/1995 O1 Hale-Bopp (VLA, BIMA, OVRO, PdBI)
2004: C/2002 T7 Linear (BIMA)
2004: C/2001 Q4 NEAT (BIMA)

2006: 73P/SW3 (SMA)
2007: 17P/Holmes (PdBI, SMA)
2008: 8P/Tuttle (PdBI)
2010: 103P/Hartley 2 (PdBI)
2012: C/2009 P1 Garradd (PdBI)
2013: C/2011 L4 PanSTARRs
Recent results: 103P/Hartley 2

- **103P/Hartley 2**
  - Ecliptic comet (period=6yrs, perigee=0.12AU in Oct. 2010)
  - Epoxi mission target (flyby in Nov. 2010, A’Hearn et al. 2011)
  - Herschel observations (dust and water)
    + D/H = value in the oceans on Earth (Hartogh et al. 2011)
  - Worldwide support observations
    + 51 ground- and 3 orbit-based observatories

- **Plateau de Bure campaign**
  - 4 nights at the Plateau de Bure
    + 23 Oct. 2010: HCN J(1-0) @ 89 GHz (perigee)
    + 28 Oct. 2010: CH$_3$OH @ 157GHz (perihelion)
      - Simultaneous 30m observations
    + 04 Nov. 2010: HCN J(1-0) @ 89 GHz (6h before Epoxi flyby)
    + 05 Nov. 2010: HCN J(3-2) @ 266GHz (10h after Epoxi flyby)
  - Interferometry (1-6" – 100-500km)
  - Single Dish (position switch, 18-53" – 2000-5000km)
Hartley 2: Temperature in the coma (1)

- Methanol observations
  - 6 lines detected in 3 different beams
Hartley 2: Temperature in the coma (2)

- Temperature profile in the coma
  - Rotation diagrams
    + Linear relation $\ln(A/T_dv) = B - E_u/kT$
  - Temperature increase
    + No LTE or Photolytic heating
  - IR: higher T at 50-100km from the nucleus
    + Time variations or adiabatic cooling?

\[
\ln \left( \frac{8\pi \nu^2 k \int T_b dv}{hc^3 A_{uv}g_u} \right) = \ln \left( \frac{\langle N \rangle}{Z(T_{rot})} \right) - \frac{E_u}{kT_{rot}}
\]
Hartley 2: Morphology of the coma (1)

- HCN observations
Hartley 2: Morphology of the coma (2)

- Astrometry: gas peaks always to the south wrt nucleus
  - Time variations
  - Orientation deduced from Epoxi flyby
- *Outgassing mainly from the small lobe of the nucleus*

![Graphs showing time variations in Hartley 2 coma morphology](image-url)
Hartley 2: Morphology of the coma (2)

- Astrometry: gas peaks always to the south wrt nucleus
  - Time variations
  - Orientation deduced from Epoxi flyby

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Hartley 2: Morphology of the coma (2)

- Astrometry: gas peaks always to the south wrt nucleus
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  + Orientation deduced from Epoxi flyby
- Outgassing mainly from the small lobe of the nucleus
Hartley 2: Thermal emission (1)

- **Fluxes:**
  - 23 Oct. $0.65 \pm 0.03 \text{ mJy} @ 89 \text{ GHz}$
  - 28 Oct. $1.23 \pm 0.09 \text{ mJy} @ 157 \text{ GHz}$
  - 04 Nov. $0.25 \pm 0.04 \text{ mJy} @ 89 \text{ GHz}$
  - 05 Nov. $1.69 \pm 0.48 \text{ mJy} @ 266 \text{ GHz}$

- **Combined contributions:**
  - Dust coma (mm grains)
  - Nucleus
    - Size, shape measured by Epoxi
    - Thermal model
    - $\rightarrow \text{Synthetic emission light curve}$
Hartley 2: Thermal emission (2)

- **Thermal model of the nucleus**
  - Emission light curves
  - Nucleus rotation drives the time variations in the PdB data

- **Dust contribution**
  - \( F_{\text{dust}} = F_{\text{tot}} - F_{\text{nuc}} \)
  - Grain thermal model
  - Size and velocity distribution
  - \( Q_{\text{dust}} \sim 1000 \text{ kg s}^{-1} \) (dust-to-gas ratio >>2)
Nucleus thermal emission

- **8P/Tuttle**
  - Size and shape measured in radar/IR/visible
    + Contact binary
    + Radius 3 km
  - Detection at PdB at 1 mm (Jan. 2008)
    + Negligible dust contribution
  - **Thermal Inertia < 10 SI, low mm emissivity**
    + Boissier et al. 2011

- **C/2009 P1 (Garradd)**
  - Oort cloud comet, unknown size
    + Only 13 reliable size measurements for OC comets
  - Tentative detection (4.8σ) at 2mm with the PdBI
    + Negligible dust contribution
    + **Nucleus radius: 7.8 km**
  - Offset between expected and observed positions
    + Asymmetric coma (sunwards jet) affects obs in the visible
    + Noise peak? Upper limit on the radius 5.6 km
Dust thermal emission (1)

- **17P/Holmes observations in 2007**
  - Outburst on 24 Oct. 2007
    + $10^6$ brightness increase
    + Similar to outbursts in 1892 and 1893
  - PdBI (3.4 mm) on 27 and 28 Oct. 2007
    + Image of the large grains (mm) in the coma

- **Modeling the emission radial extension**
  - Dynamic model of the coma
    + Isotropic outflow with decreasing $Q_{\text{dust}}$ after outburst
    + Grain size and velocity distributions
      - $n(a) \propto a^q$, at the injection in the coma ($a_{\text{min}}, a_{\text{max}}$)
      - $V(a) = V_0 \left(\frac{a}{a_0}\right)^\delta$, $V_0$ velocity of grains with size $a_0$, $\delta=0.5$
  - Grain thermal model
    + Opacity computed for a wide range of parameters
      - Organics, silicates, ice, porosity
      - Mie theory
      - *Opacities in the ALMA bands, Boissier et al. 2012*
    - Simple outflow does not fit the observations
Dust thermal emission (2)

- **2 components are needed**
  - Expanding shell of fast grains
    + Extended emission, short baselines
  - Stable core of slow grains
    + Point source emission
    + Same level on 27 and 28 Oct.

- **Comparison to visible**
  - Constraints on size distributions
    + Different size index for the core and the shell
  - Mass estimates
    + 3-9% of the nucleus was ejected
    + 1 km sized cube (nucleus radius ~2 km)
    + Massive disruption of a part of the nucleus
    + Origin remains unknown
Summary

• **Study of comets in mm interferometry:**
  - Volatiles in the coma
    + Temperature, coma morphology, origin of molecules (nucleus vscoma chemistry)
  - Dust in the coma
    + Production rates, dust properties
  - Nucleus
    + Size, thermal properties

• **Observations limited by the sensitivity**
  + Strongest molecular lines (CH$_3$OH, HCN)
  + Comets very active (Hale-Bopp, Holmes)
  + Comets very close to the Earth (103P, Tuttle)
  + Large nucleus (Garradd)
  - Sensitive search for faint molecular lines had to be made in single dish
    + Very important to constrain the conditions in the early Solar System

• **ALMA and NOEMA will change this**
Comets with ALMA and NOEMA

- **Gain in sensitivity**
  + More comets (both dynamic classes)
  + More lines (minor species, isotopes, new molecules)
  + Monitor distant activity
  + Detect nuclei (emission light curve)
  + Astrometry (precision ~mas)

- **Gain in angular resolution**
  + Extended sources (HNC, CO, H$_2$CO,...)
  + Coma morphology (gas and dust)
  + Gas sources on the surface
  + Separate nucleus from dust contribution

- **Gain in instantaneous uv-coverage**
  + Coma kinematics

- **The chemistry of comets**
  + Detailed composition
  + Taxonomy
  + Composition vs dynamic class
  + Origin of cometary material

- **Cometary atmosphere**
  + Nucleus-coma interface
  + Gas jets
  + Nucleus homogeneity

- **Cometary nuclei**
  + Measure albedo independent sizes
  + Constrain nucleus shape
  + Constrain thermal properties
  + Improve orbit determination
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The origin of cometary matter: nitriles and isotopes in comet C/2011 L4 (PanStarrs)
ALMA in March 2013
(2012.1.00411.S - PI N. Biver)

- **Cometary nuclei**
  + Measure albedo independent sizes
  + Constrain nucleus shape
  + Constrain thermal properties

Physical properties of the nucleus of comet C/2011 L4 (PanStarrs)
ALMA in January March 2013
(2012.1.00143.S - PI O. Groussin)
(+PdBI in April 2013)
• Thanks !
Comets at mm wavelengths

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