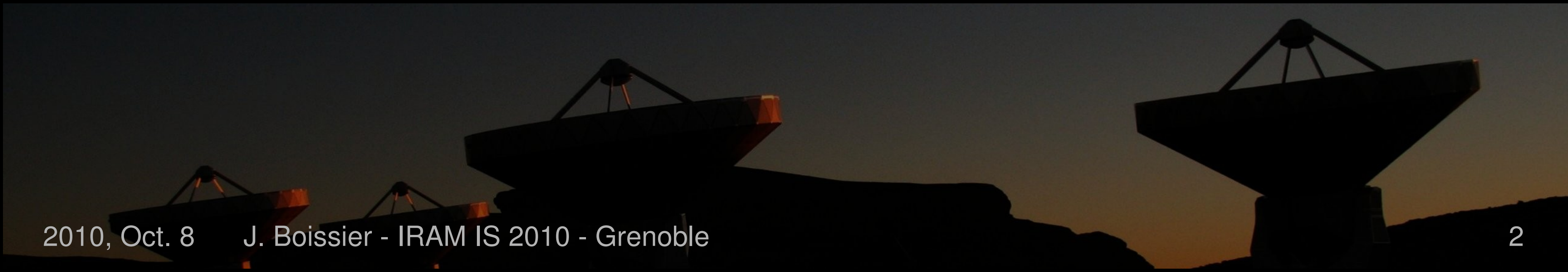
The study of comets in millimeter interferometry (with the IRAM Plateau de Bure Interferometer)

- Jérémie Boissier (ESO ALMA fellow at italian ARC, Bologna ; IRAM, France) *boissier@iram.fr*

- Dominique Bockelée-Morvan, Nicolas Biver, Jacques Crovisier, Emmanuel Lellouch, Raphael Moreno (LESIA - Obs. Paris, France)
- Olivier Groussin, Philippe Lamy, Laurent Jorda (LAM - Obs. Marseille, France)
- Jean-François Crifo (Service d'Aéronomie, Paris, France)
- A.V. Rodionov (TsNIIMASCh, Moscow, Russia)

Outline

- Few words about comets
- Study of comets with the IRAM interferometer
  - “Recent” Hale-Bopp results
    - Coma morphology
    - CO origin
  - 17P/Holmes outburst
  - 8P/Tuttle nucleus observations
- Conclusions, prospects



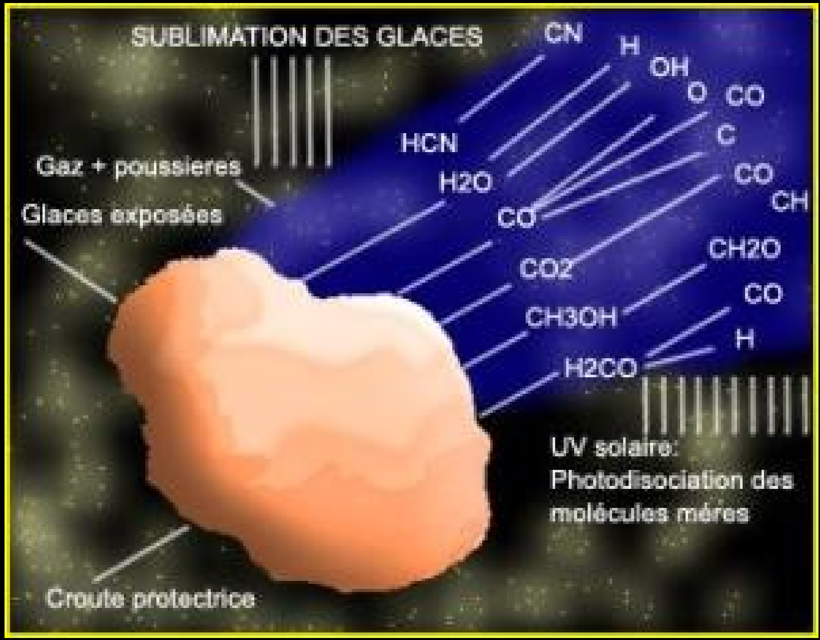
Generalities about comets

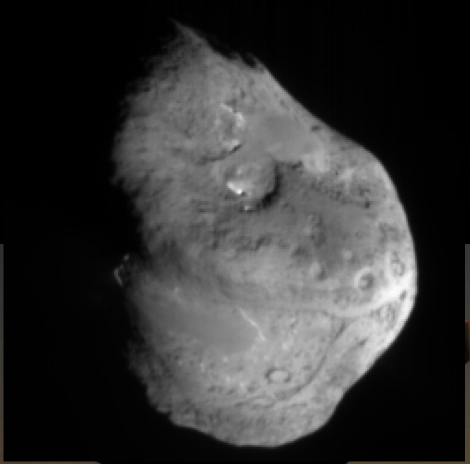
- Small icy bodies created during the Solar System formation then preserved far from the Sun

- Nucleus: Ice + refractory grains
- Coma: Sublimated volatiles and dust

- Why study them ?
  - Their composition and structure may provide constraints on the chemistry in the early Solar System
  - Assess their role in the planet evolution (cometary impacts)

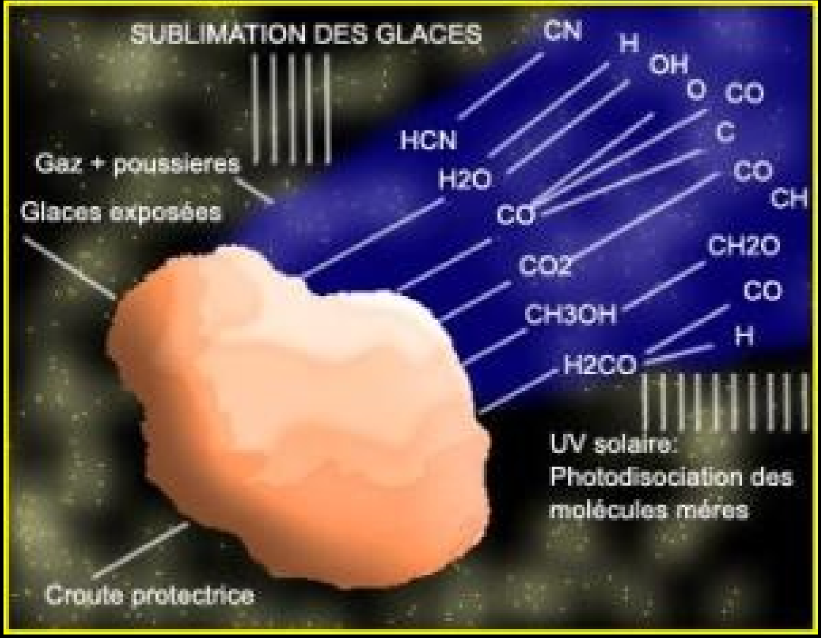
- How ?
  - Space probes to few objects
  - Ground based observations required
  - mm observations probe the inner coma




Tempel 1 as seen by the Deep Impact spacecraft

Radioastronomy of comets

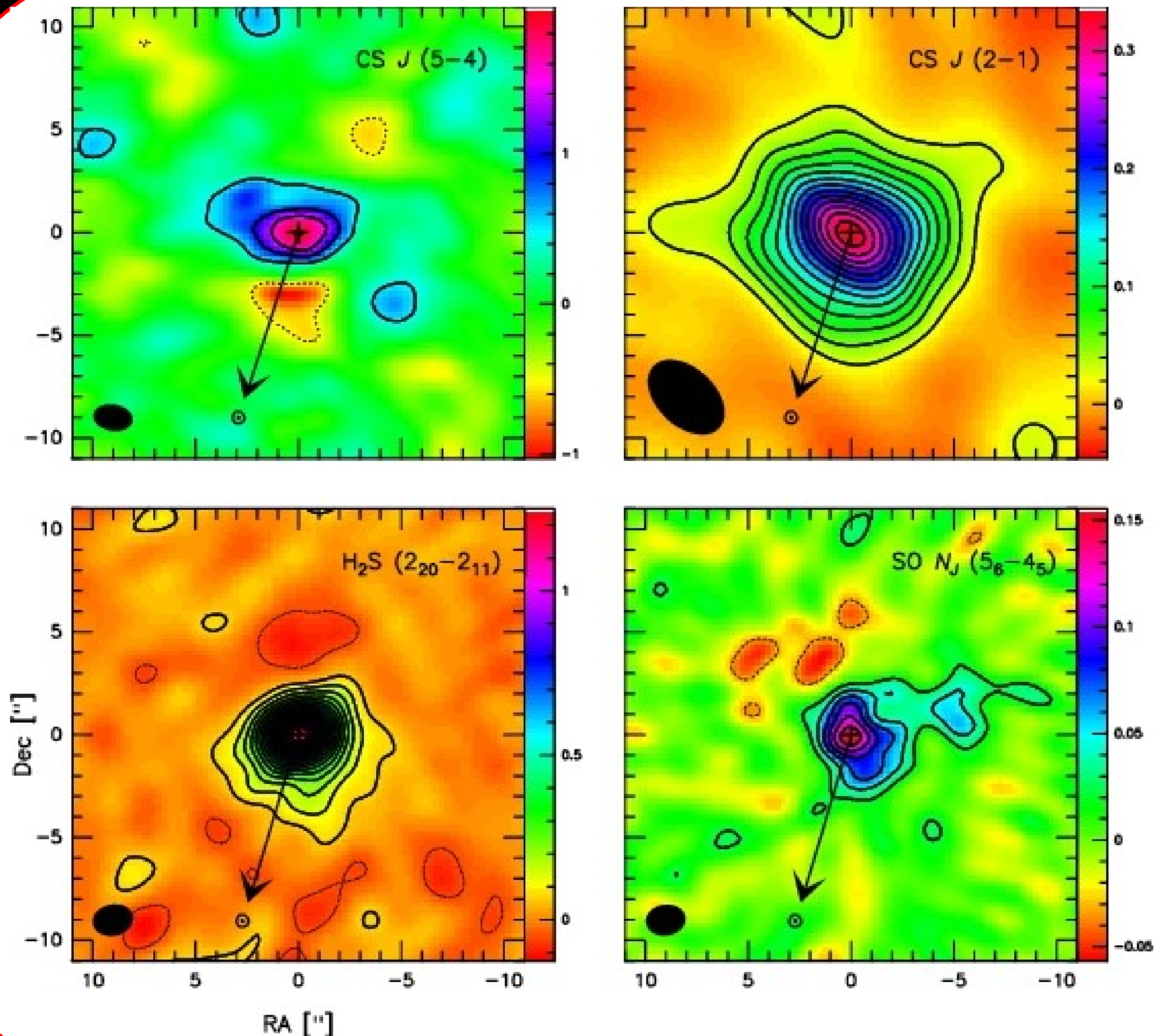
- Single dish spectroscopy (beams ~10-50")
  - Molecule abundances
  - Gas velocity
  - Gas temperature
  - *Average parameters of the coma*
  - 30 yrs of observations (30m, CSO, JCMT)
  - >35 comets observed: comparative studies of the comet compositions *(chemical diversity)*
- Bolometers
  - Large scales dust coma
- Interferometry (beams 1-10")
  - Structure of the inner coma
    - Gas radial extent
    - Jets, inhomogeneities
  - Nucleus thermal emission
  - We need strong (or near Earth) comets !



Radio interferometric observations of comets

1985: Halley (VLA)
1987: Wilson (VLA)
1992: 1991 A1 Shoemaker-Levy (VLA)
1996/1997: Hyakutake (VLA, PdBI)
1997: 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 (in october)

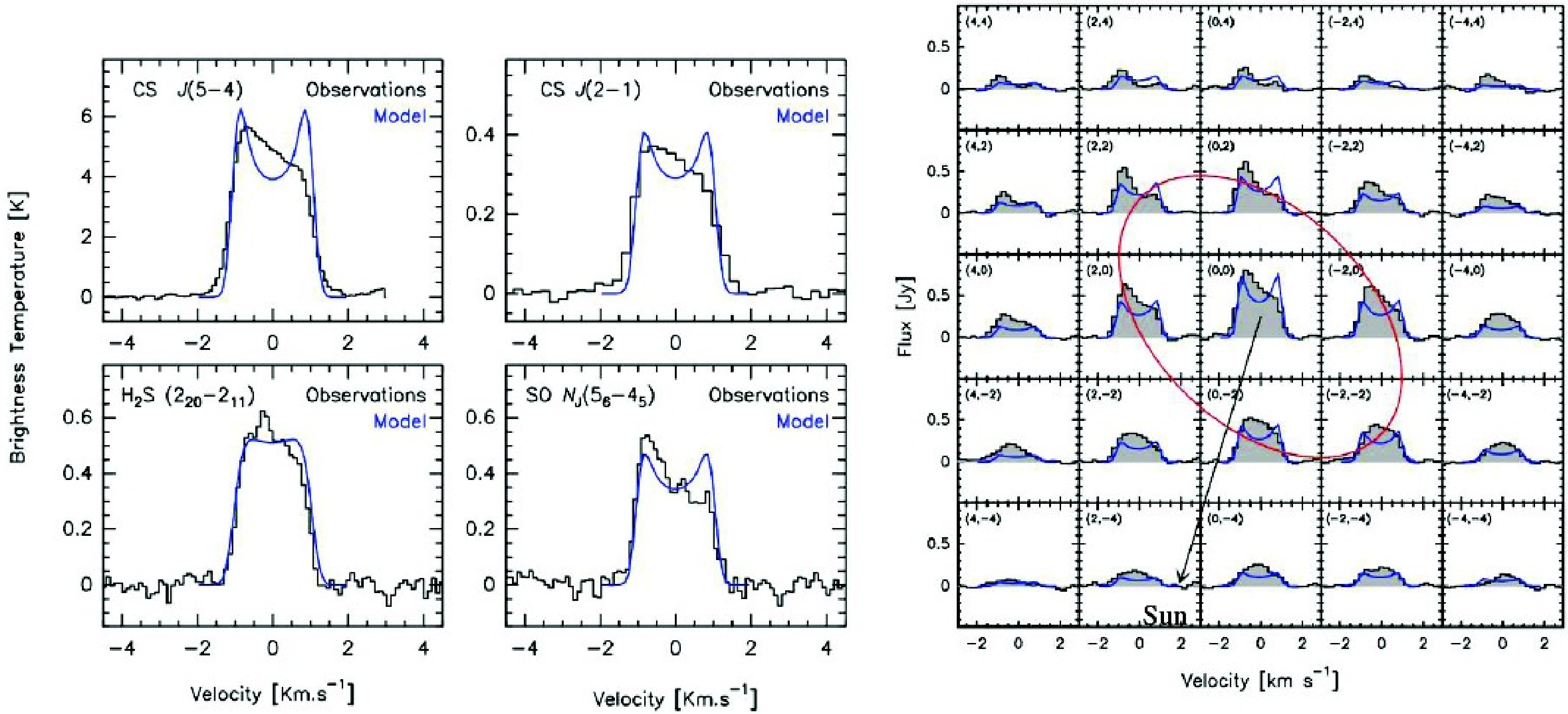
Observations of Hale-Bopp at the Plateau de Bure



Levels = 2σ - Boissier et al. 2007

Hale-Bopp gas coma: Morphology (1)

- Many evidences for spatial and spectral asymmetries

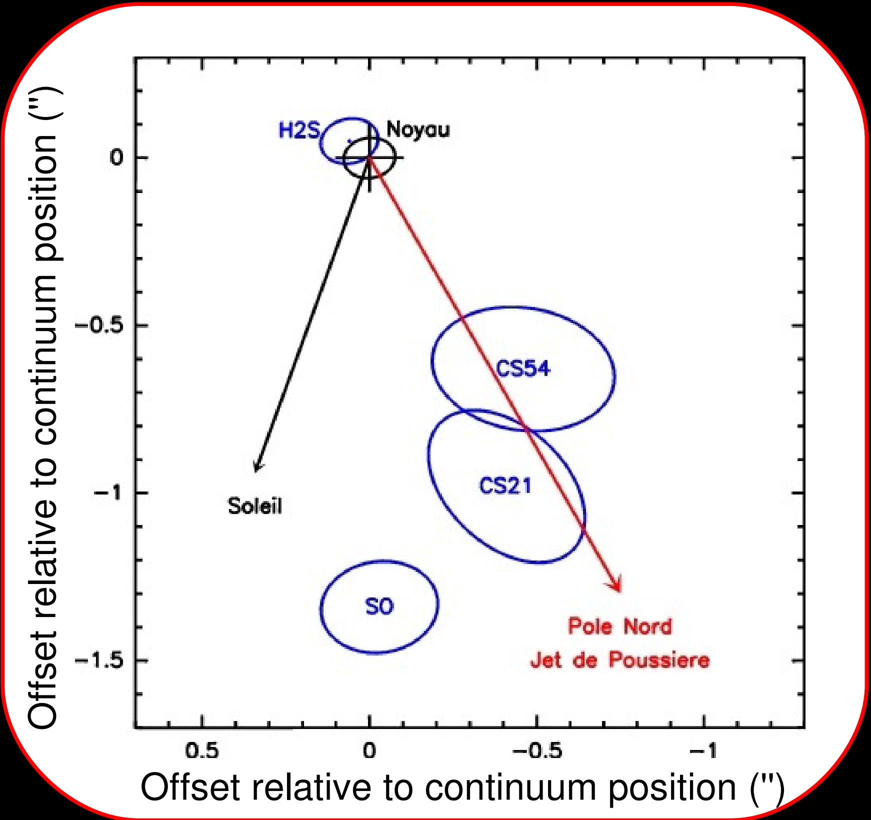


Overall autocorrelation spectra

CS *J* (2-1) spectral map

Hale-Bopp gas coma: Morphology (2)

- Astrometric considerations
  - ***Boissier et al. 2007***
  - Continuum positions (*Altenhoff et al. 1999*): true nucleus
  - Ephemeris biased by the dust jet in the visible
  - Jet gaseous counterpart: molecules with shifted apparent positions (HCN, H_2CO, CS, HNC, SO)
  - H_2S not present in the polar jet

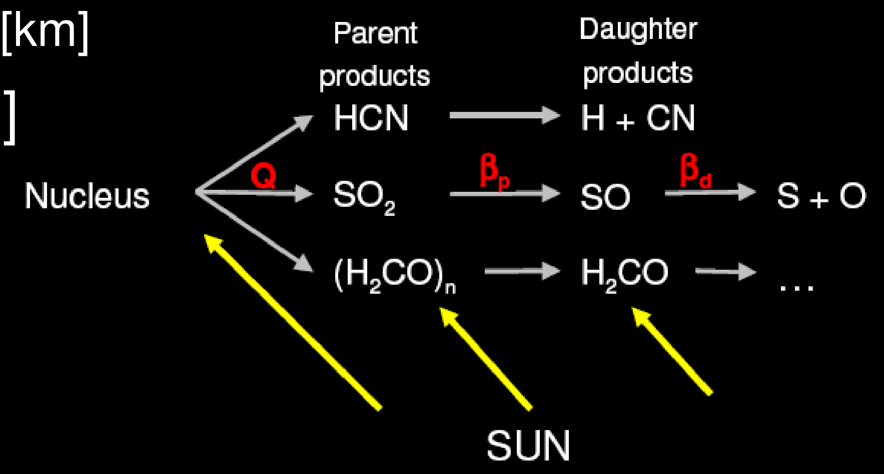


- Independant CO equatorial jet
  - ***Boissier et al. 2010***

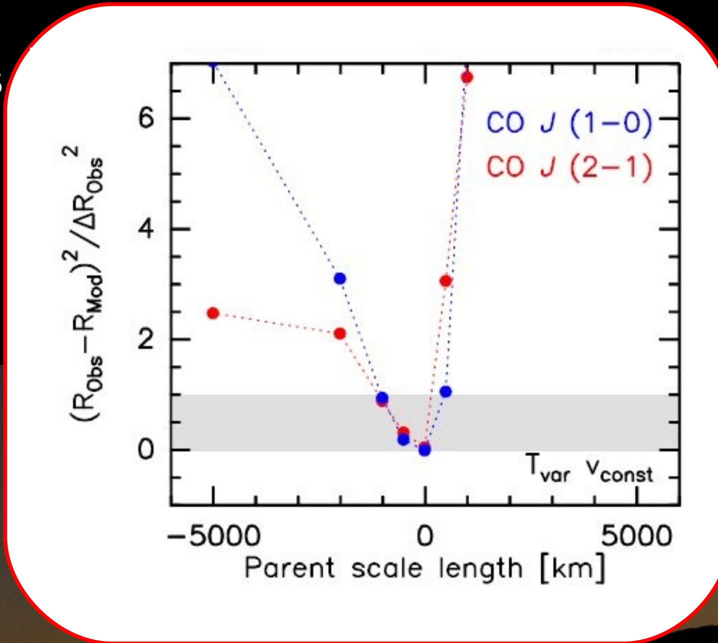
- *Different molecules have different outagassing patterns: heterogeneity of the nucleus*

Hale-Bopp gas coma: Gas radial extent (1)

- Determine the origin (nuclear or extended) of a molecule
  - Constrain parent scalelength $L_p = \beta_p x \, v$ [km]
- Measure its photodissociation rate β_d [s^{-1}]
  - Required to measure correct abundances
- Condition: Int Beam < L < SD beam



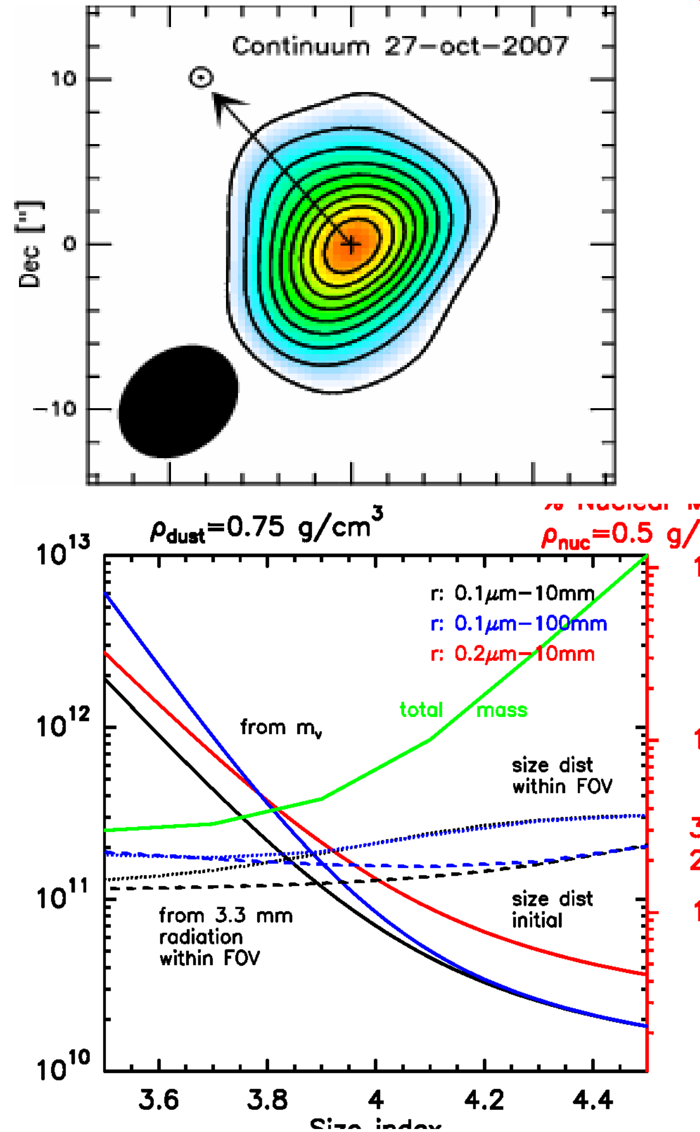
- The case of CO
  - Observed in many comets
    - Highly variable abundance
  - Drives the activity at large heliocentric distances
  - Debated Origin (role of organic grains ?)
  - IR studies of HB: extended source (5000 km)
  - PdB results: no need for extended source
  - Extended sources with Lp>1500km is excluded
  - ***Bockelée-Morvan et al. 2010***



17P/Holmes outburst: Dust observations

- Outburst on 24 Oct. 2007
  - PdBI on 27 and 28
- Imaging the big (mm) particles coma surrounding the nucleus
- Modelling flux radial extent (27 and 28)
  - Thermal emission model
    - Computing κ for different kinds of materials
  - Dust density distribution model
    - Isotropic outflow, Q=Q(t)
    - Slow decrease of the dust production rate
  - Grain fragmentation
- Estimate of the released dust mass
  - Few % the nucleus mass, gas to dust ratio 25%

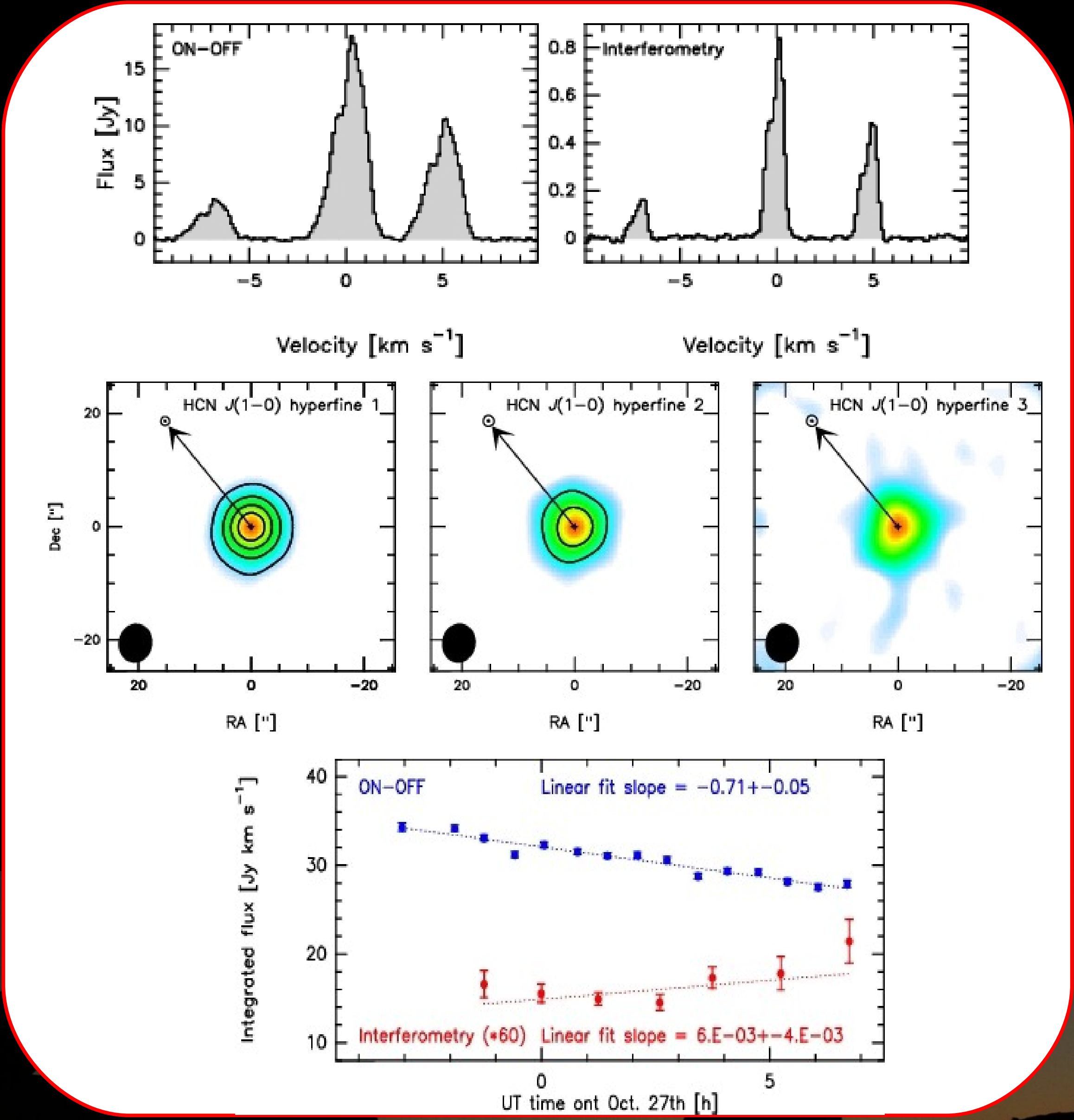
Boissier et al. 2009, EM&P



Holmes outburst: HCN observations

- Single dish and interferometry
  - HCN *J*(1-0) at 88.6 Ghz
  - 54'' and 7'' beams (1''=1200km)
- Line width = gas velocity
  - 0.5 kms^{-1} @ 10000 km
  - 1.0 kms^{-1} @ 60000 km
- Different time evolutions
- 2 sources of HCN in the coma
  - Outburst (fast HCN molecules emission filtered out in int. mode)
  - Slowly variable compact source of slow HCN molecules (Lp=750 km)

Boissier et al. 2009, EM&P

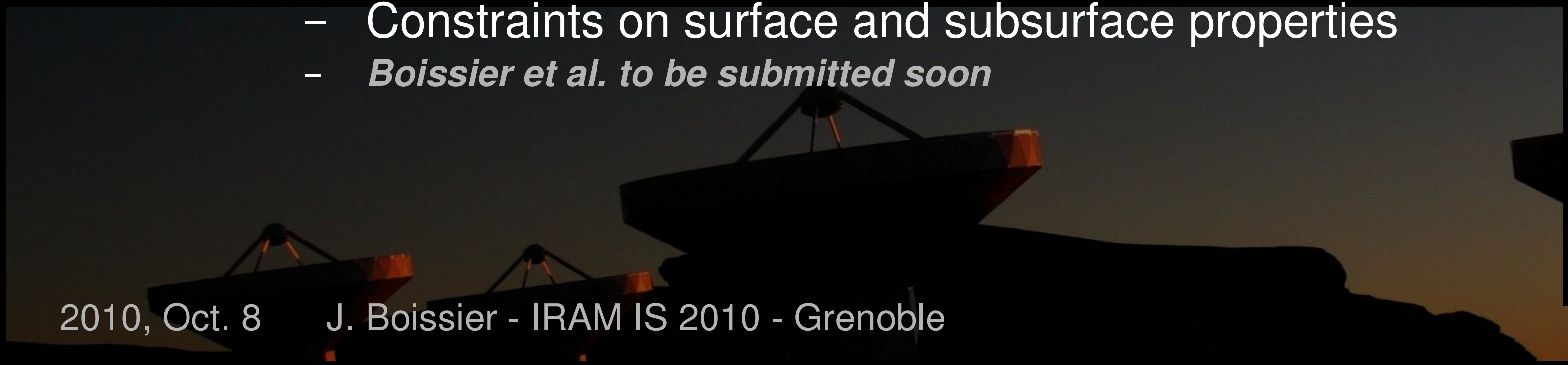


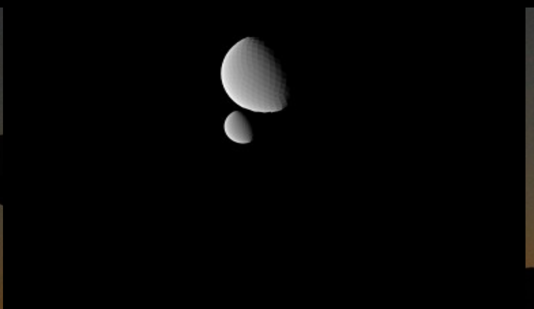
8P/Tuttle nucleus

- Close approach to the Earth in January 2008
  - Δ = 0.25 AU, low activity, large nucleus expected

  Good target for ground based observation of the nucleus thermal emission
- Plateau de Bure observations
  - Thermal flux at 240 GHz (1.25 mm)
  - 3.0 ± 0.5 mJy (± 20% uncertainty of the absolute flux calibration)
  - Nucleus size r_{mm} ~ 2 ± 0.4 km

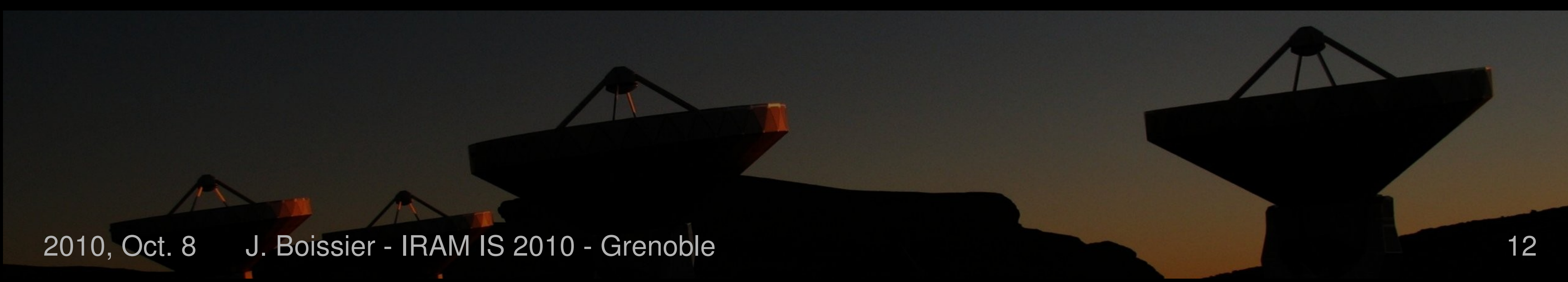
  Boissier et al. 2009
- Other observations
  - Arecibo radar experiment: bilobate shape, r_{radar} ~ 3.1 km (Harmon et al. 2010)
  - Spitzer IR observations: r_{IR} ~ 2.8 km (Groussin et al. 2008)
  - HST observations: bilobate shape (Lamy et al. 2010)
- Model of the nucleus emission using “known” size and shape
  - Constraints on emission properties @ mm wavelengths
  - Constraints on surface and subsurface properties
  - ***Boissier et al. to be submitted soon***





Summary, prospects

- mm interferometry is a powerful tool to study comets
  - Gas coma
    - Gas radial extent
    - Coma morphology
  - Dust coma
  - Nucleus
    - Astrometry
    - Size estimates
    - Nucleus properties
- Models and methods ready for further observations
  - 103P/Hartley at the PdBI in Oct.-Nov 2010
  - 1 comets every 2 years at PdBI (more if NOEMA is built)
    - NOEMA = PdB 12 antennas + new receivers and correlator
  - ALMA



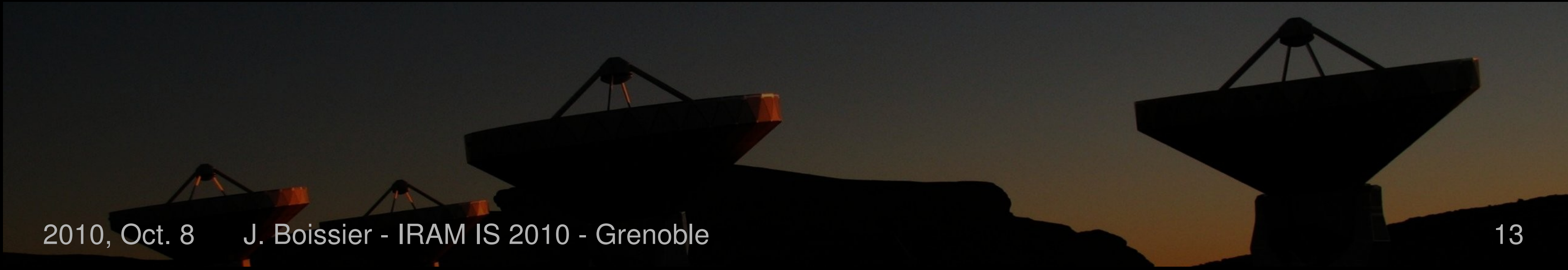
Cometary science with ALMA

- ALMA abilities and cometary science
  - Gain in sensitivity
    - Observe more comets (including Ecliptic comets)
    - Observe minor species (including new molecules)
    - Measure isotopic ratios
    - Monitor distant activity
    - Detect nuclei
    - Astrometric precision 0.2 mas if S/N>30
    - Measure emission light curves
  - Gain in angular resolution
    - Study extended sources (HNC, CO?, H_2CO)
    - Characterize the gas and dust coma morphology
    - Study gas sources at nucleus surface
    - Separate nucleus from dust coma
  - Good instantaneous uv-coverage
    - Coma kinematics
    - Time evolution

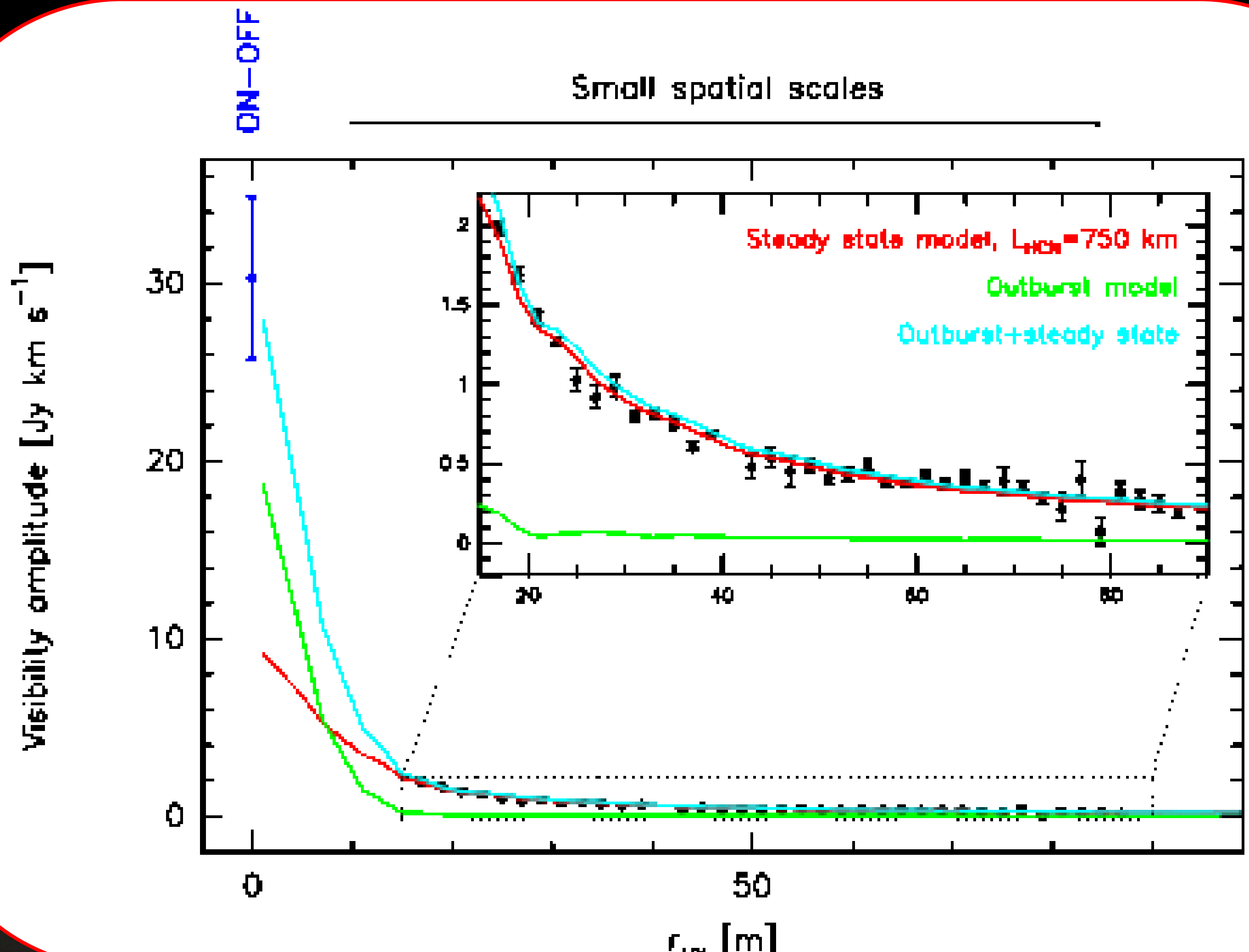
- *Detailed composition*
- *Relation between chemical properties and dynamical classes*

- *Nucleus-coma interface*
- *Nucleus homogeneity*
- *Gas-Dust interrelation*

- *Measure albedo independent sizes*
- *Constrain nucleus shapes*
- *Constrain thermal properties*
- *Improve orbit determinations*



Holmes: Visibilities



Hale-Bopp gas coma: Gas radial extent (2)

- H_2S 2_{20}-2_{11} line at 217 GHz
  - Measure: β_{H2S} ~ 1.5-3.0 10^{-4} s^{-1}
  - Theoretical value: 2.5 10^{-4} s^{-1}
    Crovisier et al. 1991
- Measuring β_{CS}

  CS *J*(2-1) and *J*(5-4) at 98 and 245 GHz
  - CS created from CS_2 L_{CS2} ~ 500 km
  - Our study: β_{CS} ~ 1-5 10^{-5} s^{-1}
  - Other results
    - 1 10^{-5} s^{-1} *Jackson et al. 1982* (UV)
    - 1 10^{-4} s^{-1} *Snyder et al. 2000* (BIMA)
    - 2 10^{-5} s^{-1} *Biver et al. 2003* (mm SD)
- Radial extent of SO
  - SO N_J (5_6-4_5) line at 220GHz
  - SO created from SO_2
  - Ill known value of β_{SO} (1.5, 3.2, 4.9, 6.2 10^{-4} s^{-1} ?)
  - Measure β < 1.5 10^{-4} s^{-1} : SO more extended than expected
  - SO_2 detected in Hale-Bopp. Q_{SO} = $2Q_{SO2}$: Additional, extended, source of SO ?

Boissier et al. 2007, A&A