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Present and Future Cometary Science with the IRAM Plateau de Bure Interferometer

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Abstract Interferometric observations are essential to probe the molecular emission in the inner cometary atmospheres and study the outgassing from the nucleus. Mapping the continuum emission can provide information about the dust and/or nucleus properties. We present here a summary of the observations of the dust and gas coma of comet 17P/Holmes and nuclear observations of 8P/Tuttle, both carried out with the IRAM interferometer at Plateau de Bure (PdBI) in 2007–2008. The observations of these two comets demonstrate the ability of the PdBI in terms of cometary science. In the near future, several improvements will be made (new receivers at 0.8 mm, a new wide-band correlator) allowing more frequent and more detailed studies of comets. On the long term, NOEMA, an expansion project, may add up to six antennas to the Plateau de Bure Interferometer, and increase the baseline lengths. Such an instrument would offer a complement to ALMA to track comets of the northern hemisphere with about half the sensitivity of ALMA for continuum studies.

Keywords Comets · Radio lines and continuum: Solar System · Techniques: interferometry

1 Introduction

Spectroscopic observations of comets at millimeter wavelengths allow the determination of the coma composition in a large number of molecules. Single dish data provide a limited spatial resolution, allowing the determination of only large-scale averages of the coma temperature and velocity fields, from which little information about the coma structure and the nucleus outgassing pattern can be obtained. With interferometric techniques, it

Based on observations carried out with the IRAM Plateau de Bure Interferometer.

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becomes possible to image the emission of molecules present in the inner coma with a much better spatial resolution. Such observations, however, require bright enough sources, thus are not frequent.

The Plateau de Bure is currently one of the most sensitive interferometers available in the millimetre range. Since the last cometary observations (Hale-Bopp in 1997, Bockelée-Morvan et al. 2000; Henry et al. 2002; Boissier et al. 2007) several technical improvements have been performed and the sensitivity has been significantly increased. The current state and performance level of the instrument are summarized in Sect. 2. In Sect. 3 we present the preliminary results of two recent observing campaigns targeting comets: the observations of 17P/Holmes a few days after its outburst in October 2007 and those of the nucleus of 8P/Tuttle in December 2007–January 2008. Section 4 describes the future of the Plateau de Bure on a time scale ranging from months (ongoing development) to years (extension project currently under a feasibility study).

2 The Plateau de Bure interferometer

The IRAM Interferometer is located on the Plateau de Bure (2,552 m) in the French Alps. This array is made of six 15 m-antenna that can be moved to form four different configurations from compact (maximum baseline $\sim$100 m, resolution $\sim$ 5” at 100 GHz) to extended (maximum baseline $\sim$760 m, resolution $\sim$ 0.7” at 100 GHz).

The antennas are equipped with receivers allowing observations in dual-polarization in three wavelength ranges. The maximum bandwidth usable for continuum measurements is 2 GHz (with a channel spacing of 2.5 MHz), the best spectral resolution available is 0.038 MHz, which corresponds to 0.04–0.15 km s^{-1}, depending on the frequency. The receiver characteristics are described in Table 1.

3 Observations of Comets in 2007–2008

3.1 Comet 17P/Holmes

17P/Holmes underwent an outburst on 24 October 2007 and was observed with the Plateau de Bure Interferometer as a target of opportunity project on October 27 and 28. We imaged the rotational line emissions of HCN J(1–0) and HNC J(1–0) at 88.6 and 90.6 GHz respectively, as well as the thermal dust emission in the coma. The spatial resolution of the data is about 7”, corresponding to 8,000 km given the distance of the comet. Single dish (ON–OFF) spectra were taken all along the observations, to monitor the emission of HCN and HNC in a much larger beam of 54” (65,000 km).

Table 1 Characteristics of the three observing bands of the Plateau de Bure interferometer

Band	Frequency range (GHz)	λ (mm)	Continuum sensitivity[a] (mJy)	Line sensitivity[b] (mJy)
1	80–120	2.5–3.7	0.07 at 90 GHz	7 at 90 GHz
2	130–175	1.7–2.3	0.14 at 150 GHz	14 at 150 GHz
3	200–267	1.1–1.5	0.24 at 230 GHz	24 at 230 GHz

[a] Continuum sensitivity after 6 h of integration on source, with a bandwidth of 2 GHz

[b] Line sensitivity after 6 h of integration on source, with 100 kHz channels in each polarization

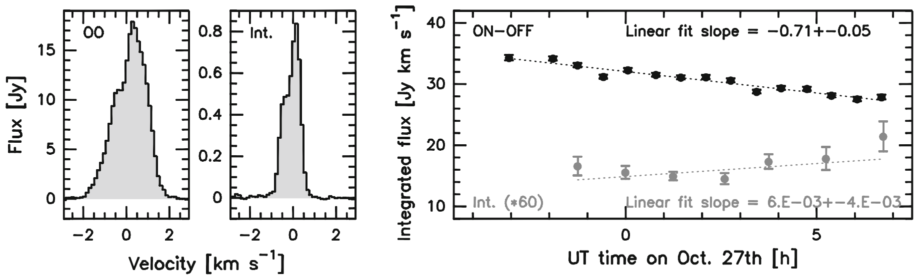

Fig. 1 PdBI observations of 17P/Holmes on October 27, 3 days after its outburst. *Left* ON–OFF and interferometric spectra of the HCN $J(1–0)$ line. *Right* Time evolution of the ON–OFF and interferometric fluxes of the HCN $J(1–0)$ line

The HCN ON–OFF flux (F_{OO}) is reproduced by simple (1D, steady-state) coma models assuming a HCN production rate of 6.2×10^{27} molecules s^{-1} on October 27. The line width appears to be much larger on ON–OFF than on interferometric spectra (Fig. 1). This indicates that the two observing modes probed molecules at different velocities from 0.5 km s^{-1} at $r \sim$5,000 km from the nucleus (interferometric beam) to 1 km s^{-1} at r $\sim$30,000 km (ON–OFF beam). These molecules were produced at different times when the quantity of grains and gas produced in the inner part of the coma after the outburst was rapidly fading (Biver et al. 2008). Therefore, this difference of velocity between the inner and outer coma can trace both a time variation of the velocity acquired by the molecules in the coma soon after their release, and an acceleration during their expansion. Biver et al. (2008) measured a decrease of the gas expansion velocity from a radio monitoring performed with beam sizes of typically 10–20”.

While F_{OO} decreases by more than 20% during the 8 h of observations (Fig. 1), the interferometric flux F_{Int} remains constant. This suggests that we are observing the emission of molecules which are not in the same regime. Given the radial extent of the emission measured in interferometric data, it seems that the molecules located close to the nucleus are released by a slowly variable, slightly extended source ($\sim$750 km) which could be the sublimation of icy grains created by the outburst.

Though the ON–OFF detection of HNC J (1–0) is good, we have only a 3σ detection in interferometric mode. The F_{OO}/F_{Int} ratio is much higher for HNC than HCN, which suggests an extended origin of HNC (Lis et al. 2008).

The analysis of the continuum emission provides constraints on the coma dust characteristics. We tried to reproduce the radial extent of the dust emission measured on October 27 and 28 using a model of thermal emission based on the Mie theory for spherical grains made of ice and silicates released in the coma by an outburst. The small difference in flux between the 2 days indicates that the coma is refilled with mm sized particles, very likely created by the fragmentation of bigger chunks. The measured fluxes can be reproduced assuming that 1–4% of the nucleus mass has been released during the outburst.

3.2 Comet 8P/Tuttle

The thermal emission of the nucleus is observable in millimetre interferometry only for comets with a big nucleus and/or a low dust production. Comet 8P/Tuttle was a good candidate since its nucleus size was estimated to be up to 16 km (Licandro et al. 2000) and the active fraction of the surface only 1.6%. We estimated that the sensitivity of the IRAM interferometer would ensure an easy detection (Flux ∼47 mJy at 1 mm at a geocentric distance of 0.25 AU). The comet was observed twice at frequencies around 240 GHz in December 2007 and January 2008. Despite our expectations the nucleus was barely detected: the fit of the visibilities with a point source model provides a flux of the order of 3 mJy with an accuracy of about 0.5 mJy. This indicates that the nucleus mean diameter is about 3.5 km, well below the estimation above.

Other studies attempted to detect the nucleus at different wavelengths and different results were found concerning its size. Radar observations with Arecibo (Harmon et al. 2008) are in agreement with the previous value of (Licandro et al. 2000) while optical and infrared observations (with Hubble and Spitzer space telescopes and the VLT (Groussin et al. 2008; Lamy et al. 2008) yield size measurements very similar to ours.

4 The future of the Plateau de Bure

4.1 Short term improvements

In 2009, two major improvements will be performed at the Plateau de Bure:

1. The installation of a new wide band correlator (WIDEX) that will be able to handle a bandwidth of 4 GHz in two polarizations. This will represent a gain of a factor 2 in terms of continuum sensitivity. This will make much easier the detection of cometary nuclei. Table 2 summarizes the expected performances as a function of the geocentric distance of the comet. This is not optimum for the study of narrow lines such as those of molecules in cometary atmosphere for which the use of the current correlator will be still possible.
2. The opening of the 0.8 mm band (277–371 GHz). This window is very insteresting for cometary science since some of the most intense emission lines are located in this range (HCN $J(4–3)$, CS $J(7–6)$, CH_3OH). It contains as well some strong lines of HCN isotopes that will be observable for the most active comets.

4.2 The NOEMA project

IRAM's long term plans include an ambitious extension project for the Plateau de Bure Interferometer to create the NOrthern Extended Millimetre Array (NOEMA). The project's feasibility study considers adding six new antennas, extending the baseline to 1.6 km and developing a correlator working with a 16 GHz bandwidth in two polarizations. NOEMA would provide a gain in sensitivity of a factor up to 5 in continuum and up to 3 for line observations. In addition the higher number of antennas will improve the image quality

Table 2 Possible studies of the thermal emission of cometary nuclei with WIDEX working at the PdBI (1 mm observations with 2 × 4 GHz bandwidth)

Geocentric distance (AU)	0.25	0.5	1
Required size (km) for detection[a]	<2	3.5	7
Required size (km) for lightcurves[b]	2.5	5	10

[a] 10σ detection of the nucleus after an integration time of 8 h

[b] 10σ detection of the nucleus after an integration time of 2 h

thanks to a better sampling of the Fourier plane. If approved this project will create in the next decade an instrument in the northern hemisphere with a continuum sensitivity close to half the ALMA sensitivity while current interferometers will stay about one order of magnitude below.

5 Conclusion

The recent cometary observations carried out with the Plateau de Bure interferometer give rise to the interest of such observations: depending on the comet properties, it is possible to study the gas coma, the dust coma and/or the nucleus itself. The recent and forthcoming amelioration of this instrument should make it possible to observe comets on a regular basis (about one every 2 years in addition to the apparition of new comets, usually very active). In the long term, the NOEMA project could bring an extraordinary gain in sensitivity and imaging quality, thereby enabling more frequent and more detailed studies of comets in the northern hemisphere.

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