Interferometric imaging of carbon monoxide in comet C/1995 O1 (Hale-Bopp): evidence of a strong rotating jet

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ABSTRACT

Context. Observations of the CO $J(1-0)$ 115 GHz and $J(2-1)$ 230 GHz lines in comet C/1995 O1 (Hale-Bopp) were performed with the IRAM Plateau de Bure interferometer on 11 March, 1997. The observations were conducted in both single-dish (ON-OFF) and interferometric modes with 0.13 km s^{-1} spectral resolution. Images of CO emission of between 1.7 and $3''$ angular resolution were obtained.

Aims. The ON-OFF and interferometric spectra show a velocity shift with sinusoidal time variations related to the Hale-Bopp nucleus rotation of 11.35 h. The peak position of the CO images moves perpendicularly to the spin axis direction in the plane of the sky. This suggests that a CO jet is present, is active night and day with about the same extent, and is spiralling according to the nucleus rotation. The high quality of the data allows us to constrain the characteristics of this CO jet.

Methods. We developed a 3D model to interpret the temporal evolution of CO spectra and maps. The CO coma is represented as the combination of an isotropic distribution and a spiralling gas jet, both of nucleus origin.

Results. The analysis of the spectra and visibilities obtained from the interferometric data shows that the CO jet contains $\sim 40\%$ of the total CO production and is located close to the nucleus equator at a latitude $\sim 20^\circ$ north. Our inability to reproduce all observational characteristics shows that the true structure of the CO coma is more complex than assumed, especially within the first thousand kilometres from the nucleus. The presence of another moving CO structure, faint but compact and possibly created by an outburst, is identified.

Key words. comets: individual: C/1995 O1 – radio lines: solar system – techniques: interferometric

1. Introduction

Millimetre spectroscopy has provided many insights into the composition and physical properties of cometary atmospheres. Many cometary parent molecules originating in the nucleus were identified with this technique. The high spectral resolution capabilities, and the possibility to observe several rotational lines belonging to the same molecule, has allowed us to retrieve unique information about the velocity and temperature of the expanding coma, and the anisotropy of gas production at the nucleus surface. Because of the low, diffraction-limited spatial resolution provided by radio dishes at millimetre wavelengths, at best typically $10''$, studies concerning the spatial distribution of parent molecules in the coma have been rare.

The exceptional brightness of comet C/1995 O1 (Hale-Bopp) close to its perihelion on 1 April, 1997, motivated a wealth of innovative cometary observations. Among them, interferometric imaging of rotational transitions of parent molecules was successfully attempted. The Berkeley-Illinois-Maryland Association (BIMA) array mapped comet Hale-Bopp in HCN $J(1-0)$ and CS $J(2-1)$ with $9''$ angular resolution. Spatial asymmetries, implying the presence of gas jets, were detected (Veal et al. 2000; Wright et al. 1998; Woodney et al. 2002).

Constraints on the photodissociative scalelengths of HCN and CS were obtained from the radial extent of their radio emissions (Snyder et al. 2001). Using the Owens Valley Radio Observatory (OVRO) millimetre array, Blake et al. (1999) obtained maps of HCN, DCN, HNC, and HDO at spatial resolutions of $2-4''$ over $2-3 \text{ h}$ integration time. The presence of arc-like structures offset from the nucleus is reported for all species apart from HCN, and interpreted in terms of jets of icy particles releasing unaltered gas in contrast to that outgassed from the nucleus.

Interferometric observations of rotational lines in comet Hale-Bopp were also made with the Plateau de Bure interferometer (PdBI) of the Institut de Radio Astronomie Millimétrique (IRAM) at a resolution of $1-3''$. A short and preliminary account of these observations was given in Wink et al. (1999), Despois (1999), and Henry et al. (2002). Millimetre lines of CO, HCN, CS, HNC, CH_3OH , H_2S , SO, and H_2CO were mapped (Wink et al. 1999; Boissier et al. 2007). At the same time, continuum maps of the dust and nucleus thermal emissions were obtained (Altenhoff et al. 1999). The PdBI was also used in single-dish mode to detect new cometary molecules (Bockelée-Morvan et al. 2000; Crovisier et al. 2004a,b).

We present observations of the CO $J(1-0)$ (115 GHz) and $J(2-1)$ (230 GHz) lines, performed on 11 March 1997, at the Plateau de Bure interferometer. Among the ~ 20 molecules

* Deceased.

identified in comet Hale-Bopp, and in general in cometary atmospheres, carbon monoxide CO is of particular interest for the following reasons:

1. This species is the main agent of distant cometary activity, as first demonstrated for comet 29P/Schwassmann-Wachmann 1 (Senay & Jewitt 1994; Crovisier et al. 1995). This was later confirmed for comet Hale-Bopp from its long-term monitoring, which showed the change from a CO-dominated to an H₂O-dominated activity at heliocentric distances $r_h \sim 3\text{--}4$ AU (Biver et al. 1997, 1999a).
2. In comets within 3 AU from the Sun, CO is, most often, the second major gaseous component of the coma after water. CO production rates relative to water are highly variable from comet to comet, ranging from less than 1% to ~20% (Irvine et al. 2000; Bockelée-Morvan et al. 2004, for a review). The value obtained in comet Hale-Bopp near perihelion is among the highest ever observed in comets: ~20% (e.g., Bockelée-Morvan et al. 2000; DiSanti et al. 2001).
3. There continues to be much debate about CO production mechanisms. Because CO has a low sublimation temperature, the nucleus surface certainly contains a small amount of CO ice. Therefore, CO should outgas at some depth inside the nucleus, possibly from pure CO ice sublimation and/or from amorphous water ice when crystallizing and releasing trapped molecules (e.g., Enzian et al. 1998; Capria et al. 2000, 2002), if indeed pre-cometary ices condensed in amorphous form, something that is somewhat debated (Mousis et al. 2000). Another mechanism proposed to explain the CO production of comet Hale-Bopp near perihelion is the release of CO trapped in crystalline water ice during water ice sublimation (Capria et al. 2000, 2002). Comparing the CO jet morphology, as the nucleus rotates, to those of less volatile species or dust might provide clues to the origin of CO.
4. There are several pieces of observational evidence that a significant part of the CO observed in cometary atmospheres could be produced by a distributed source. From in situ measurements of the local CO density in 1P/Halley with Giotto, Eberhardt et al. (1987) concluded that only about 1/3 of the CO originated in the nucleus. The spatial distribution of CO molecules deduced from infrared long-slit observations of comet Hale-Bopp led DiSanti et al. (1999, 2001) to suggest that one-half of the CO was released by a distributed source when comet Hale-Bopp was within 1.5 AU from the Sun. The spatial resolution of the CO maps obtained at PdBI, which corresponded approximately 1000 km to 1700 km radius on the comet depending on the line observed, is below the estimated radial extension of the CO distributed source of $\sim 5 \times 10^3$ km (DiSanti et al. 2001; Brooke et al. 2003). Therefore, an important aspect of the study of the CO PdBI interferometric data is that independent information about the existence of a CO distributed source in Hale-Bopp coma can possibly be obtained. The study of the radial distribution of the CO molecules is presented in a separate paper (Bockelée-Morvan & Boissier 2009). The brightness distribution of both 115 GHz and 230 GHz lines can be fully explained by pure nuclear CO production, provided that opacity effects and temperature variations in the coma are taken into account (Bockelée-Morvan et al. 2005; Bockelée-Morvan & Boissier 2009).

The observations of the CO $J(1-0)$ and $J(2-1)$ lines, performed both in single-dish and interferometric modes, are presented in Sect. 2. They show evidence of a rotating CO jet. A model that simulates a CO spiralling jet as the nucleus rotates is presented in

Fig. 1. The Plateau de Bure Interferometer in C1 configuration

Sect. 3. This model allowed us to compute synthetic spectra, visibilities, and interferometric maps as a function of time, which were compared to the observations. Observations are analysed in Sect. 4, where we infer the model free parameters. A discussion is given in Sect. 5.

2. Observations

2.1. Description

Comet C/1995 O1 (Hale-Bopp) was observed from 6 March to 22 March, 1997 with the Plateau de Bure interferometer of IRAM, located in the French Alps. The observations of the $J(2-1)$ (230.538 GHz) and $J(1-0)$ (115.271 GHz) CO rotational transitions were carried out on 11 March, from 4h to 15h UT. On this day, comet Hale-Bopp was at the geocentric distance $\Delta = 1.368$ AU and heliocentric distance $r_h = 0.989$ AU. The weather conditions were good to excellent and the atmospheric seeing was $\sim 0.4''$ for both 1.3 and 3 mm receivers.

The comet was tracked using orbital elements provided by Yeomans (JPL, solution 55). The ephemeris was computed by Rocher (IMCCE, Observatoire de Paris) with a program that takes into account planetary perturbations. The first interferometric maps obtained on 9 March (HCN $J(1-0)$ line) inferred that both continuum and molecular peak intensities were offset by about $5\text{--}6''$ North in declination (Dec) from the nucleus position provided by the ephemeris. Observations on March 11 were performed with the ephemeris corrected by $6''$ North in Dec.

The PdBI was used in the compact configuration C1 (see Fig. 1) with five 15-m antennas providing 10 baselines (the spacing between two antennas) ranging from ~ 20 to ~ 150 m. In 1997, the PdBI comprised a flexible spectral correlator made of six independent units, providing correlated spectra with 64 to 256 channels spaced by between 0.039 MHz and 2.5 MHz. We used 256 channels of 78 kHz separation for the observations of the 230 GHz line, and 256 channels of 39 kHz separation for those of the 115 GHz line. The four other units were used for the continuum observations presented in Altenhoff et al. (1999). The effective spectral resolution is a factor of 1.3 broader than the channel spacing, and corresponds to ~ 0.13 km s⁻¹ for both lines.

The observing cycle was : pointing, focusing, 4 min of cross-correlation on the calibrators (2200+420 BL Lac, MWC349 and 3C373), 2 min of autocorrelation, and 51 one min scans of cross-correlation on the comet interlaced with scans on the phase calibrator (2200+420 BL Lac) observed every 20 min. The cycle was completed by another 2 min of autocorrelation on Hale-Bopp. For the autocorrelation observations (in this mode, the five antennas behave as five independent single-dish telescopes), we used position-switching (ON–OFF) with a 5' offset to remove the sky background. The spectra of the five antennas were then coadded. Hereafter, these autocorrelation observations are referred to as ON–OFF observations.

The amplitude and phase calibrator was 2200+420. MWC349 was used to determine the flux density of 2200+420. Bandpass calibration was made on 3C273. Because of the lower accuracy of the phase calibration after 12.5 h UT, only interferometric data acquired before 12.5 h UT were considered. Calibration was done with the IRAM CLIC software, and the data hence derived were stored in uv -tables. Reduction and cleaning of the maps were performed with the MAPPING/GILDAS software¹.

Concerning ON–OFF spectra, antenna temperatures T_A^* were converted into main beam brightness temperatures T_{mB} by means of $T_{mB} = T_A^* F_{\text{eff}} / B_{\text{eff}}$ with beam efficiencies B_{eff} of 0.83 and 0.58, at 115 GHz and 230 GHz, respectively, and forward efficiencies F_{eff} of 0.93 and 0.89, at 115 GHz and 230 GHz, respectively. Flux density per beam (S in Jy) is then related to antenna temperature by means of $S/T_A^* = (2k\Omega_{mB}/\lambda^2) F_{\text{eff}} / B_{\text{eff}} = 19.61 F_{\text{eff}} / B_{\text{eff}}$, where Ω_{mB} is the main beam solid angle. For both ON–OFF and interferometric data, the uncertainties in flux calibration are at most 10% and 15% for the $J(1-0)$ and $J(2-1)$ lines, respectively. The rms in phase noise ranges from 10 to 27° at 230 GHz and from 4.6 to 20° at 115 GHz, depending on the baseline.

For each spectral channel, the cross-correlated spectra produce interferometric maps with spatial resolutions determined by the uv -coverage (Fig. 2). When all cross-correlation data are considered, the full width at half maximum (FWHM) of the synthesized beam is $2.00'' \times 1.38''$ with major axis at position angle $pa = 99.56^\circ$ at 230 GHz, and $3.58'' \times 2.57''$ with $pa = 86.00^\circ$ at 115 GHz. The FWHM of the primary beam of the antennas is $20.9''$ at 230 GHz, and $41.8''$ at 115 GHz.

2.2. ON–OFF spectra

ON–OFF spectra of the CO $J(2-1)$ line are shown in Fig. 3a. The integration time is 2 min (on+off) for each spectrum. They show a feature moving from positive to negative velocities, and back to positive velocities again, with respect to the nucleus velocity frame. In other words, a jet-like CO gas feature, with a velocity vector that has rotated with respect to Earth during the course of the observations, is observed. This CO gas feature contributes to as much as 28% of the total line area.

The synodic rotation period of comet Hale-Bopp in February–April 1997 was deduced from studies of the dust shells (Sarmecanic et al. 1997; Farnham et al. 1999; Ortiz & Rodríguez 1999). The most accurate value $P = 11.31 \pm 0.01$ h measured by Farnham et al. (1999) agrees with a slightly longer sidereal rotation period of $P = 11.34 \pm 0.02$ h (Licandro et al. 1998; Jorda et al. 1999). Figure 4 plots the evolution in the line velocity shift (the spectrum first order momentum) with time. The points follow a sinusoidal curve of period corresponding to the comet's

Fig. 2. uv -coverage at the PdBI on 11 March, 1997 with the C1 configuration. For each arc of ellipse, the white circle represents the uv -point at the beginning of the observations. The time evolution of the uv -points loci is counterclockwise.

nucleus rotation (taken to equal 11.35 h throughout this paper). The sinusoid determined from a least squares fit of fixed period $P = 11.35$ h has a mean level of $v_0 = -0.05 \pm 0.01$ km s⁻¹ and its amplitude is $\mathcal{A} = 0.29 \pm 0.03$ km s⁻¹ (Fig. 4). The line area does not show significant variation with time, and has a mean value of 4.22 ± 0.03 K km s⁻¹ in main beam brightness temperature scale T_{mB} (i.e., 82.8 Jy km s⁻¹ in flux density scale). Fluctuations of $\sim 10\%$ at most are observed (with a standard deviation of 5%), which are not correlated with the velocity shift variations. The velocity shift curve obtained for the $J(1-0)$ line is much more noisy (errorbars ~ 0.2 km s⁻¹ in individual spectra), but is similar to the $J(2-1)$ velocity shift curve: a least squares sinusoid fit with P fixed to 11.35 h leads to $\mathcal{A} = 0.39 \pm 0.16$ km s⁻¹, $v_0 = -0.05 \pm 0.05$ km s⁻¹ (Henry 2003). Adding all spectra, the mean velocity shift of the $J(1-0)$ line is -0.09 ± 0.05 km s⁻¹, in agreement with that of the $J(2-1)$ line (-0.083 ± 0.007 km s⁻¹). The line area of the $J(1-0)$ line is 0.552 ± 0.022 K km s⁻¹ in the T_{mB} scale (i.e., 10.8 Jy km s⁻¹).

From the spin axis orientation and the equatorial coordinates of the comet, it is possible to derive the angle θ_ω (aspect angle) between the spin axis and the line of sight, and the North pole position angle pa_ω , defined from North to East. The different spin orientations published in the literature are listed in Table 1.

Adopting the spin orientation derived by Jorda et al. (1999) and Schleicher et al. (2004), the comet spin axis was then only 20° from the plane of the sky. In this geometrical configuration, a polar CO jet would lead to an almost constant velocity shift. A jet close to the equator can explain a velocity shift following a sinusoid centred around $v_0 \sim 0$ km s⁻¹. Both this sinusoidal curve and the constant CO line area indicate that the amount of CO gas released in this jet did not vary during nucleus rotation. Given the Sun direction (phase angle of 46°, $pa = 160^\circ$), this near-equatorial CO jet was active day and night with about the same extent.

¹ <http://www.iram.fr/IRAMFR/GILDAS/>

Fig. 3. CO $J(2-1)$ spectra obtained in ON-OFF and interferometric modes as a function of time, given in UT hours on 11 March, 1997. The velocity scale is with respect to the comet rest velocity. Spectra have been shifted vertically according to observation time, but are scaled identically. **a)** ON-OFF spectra: the integration time is 2 min (on+off); **b–d)** interferometric spectra (visibility amplitude as a function of spectral channel): averages of 25 to 27 scans of 1 min. Only data for the 3 shortest baselines are shown.

From the line areas of the $J(1-0)$ and $J(2-1)$ ON-OFF profiles, we derive a CO production rate $Q_{\text{CO}} = 2.1 \times 10^{30} \text{ s}^{-1}$. Here, we assumed a Haser parent molecule distribution for CO, and run our excitation model (Sect. 3) with a kinetic temperature T of 120 K which agrees with temperature determinations pertaining to the 10 000–20 000 km (radius) coma region sampled by the primary beam of PdBI (Biver et al. 1999a; DiSanti et al. 2001). Using an extended production for CO consistent with the IR observations does not significantly affect the inferred Q_{CO} . DiSanti et al. (2001) inferred a total CO production rate (nuclear+distributed) fully consistent with our value. In the following sections, we assume $T = 120 \text{ K}$ and a total Q_{CO} of $2 \times 10^{30} \text{ s}^{-1}$.

2.3. Interferometric data

We present in Fig. 5 the line integrated maps of CO $J(2-1)$ and $J(1-0)$. Eight hours of observations were averaged (from 4.5 h UT to 12.5 h UT) and 25 velocity channels (12 on both sides of the central channel corresponding to the nucleus

velocity) were coadded. An asymmetrical shape, which is not aligned with the elliptical clean beam (the synthesized interferometer beam), is observed and related to the anisotropy of the gas emission.

In the line integrated interferometric map of CO $J(2-1)$ (Fig. 5), the position of the peak brightness (C_m) is at $\text{RA} = 22^{\text{h}}30^{\text{m}}38.02^{\text{s}}$ and $\text{Dec} = 40^{\circ}46'3.1''$ (with an astrometric precision of $0.07''$) in apparent geocentric coordinates given for 7.00 h UT. The peak position of the CO $J(1-0)$ brightness ($\text{RA} = 22^{\text{h}}29^{\text{m}}38.46^{\text{s}}$ and $\text{Dec} = 40^{\circ}41'10.1''$ at 4.00 h UT) is consistent with that of $J(2-1)$, taking into account the comet motion from 4 to 7 h UT (see Boissier et al. 2007). The peak position of the continuum emission at 230 GHz observed simultaneously also almost coincides ($0.2''$ offset) with the CO $J(2-1)$ peak (Altenhoff et al. 1999; Boissier et al. 2007). Using orbital elements based on optical astrometric positions from April 1996 to August 2005 (JPL solution 220), the offset between the CO peak and the ephemeris is $+2.9''$ in Dec and $+0.4''$ in RA. Therefore, positions of the CO and radio continuum brightness peaks differ by typically $+3''$ in Dec from optical astrometric

Fig. 4. Time evolution of the velocity shift of CO $J(2-1)$ ON-OFF spectra shown in Fig. 3a. The plotted curve is the least squares sinusoid fit to the data. It has a fixed period of 11.35 h, an amplitude of 0.29 ± 0.03 km s $^{-1}$, and a velocity centre $v_0 = -0.05 \pm 0.01$ km s $^{-1}$ (dotted line).

Table 1. Spin axis orientation.

α_ω	δ_ω	pa_ω	θ_ω	Epoch	Ref. ^a
30°	45°	66°	143°	May–Nov. 1996	[1]
170°	−40°	272°	9°	May–Nov. 1996	[2]
240°	−56°	224°	53°	May–Nov. 1996	[2]
275°	−50°	217°	74°	Mar.–Nov. 1996	[3]
320°	−60°	189°	78°	Sep. 1995–Jan. 1998	[4]
290°	−40°	215°	88°	Sep. 1996–May 1997	[5]
290°	−60°	203°	72°	Feb. 18, 1997	[6]
255°	−60°	216°	59°	Feb. 1997	[2]
275°	−57°	211°	68°	Feb.–Mar. 1997	[7]
276°	−54°	213°	71°	Apr. 1996–May 1997	[8]

Columns 1 and 2 are the equatorial coordinates found in the literature. Columns 3 and 4 are the corresponding position angle (pa_ω) and aspect angle (θ_ω) on 11 March, 1997. ^a [1] : Sekanina et al. (1997); [2] : Sekanina & Boehnhardt (1999); [3] : Licandro et al. (1999); [4] : Biver et al. (1998); [5] : Metchev & Luu (1998), [6] : Vasundhara & Chakraborty (1999); [7] : Jorda et al. (1999); [8] : Schleicher et al. (2004).

positions. A bright dusty jet was identified southward in the optical images of comet Hale-Bopp near perihelion (e.g., Jorda et al. 1999). As shown by Boissier et al. (2007), the optical astrometric positions were not affected by dusty jets than the radio positions. Boissier et al. (2007) showed that the astrometric positions provided by the IRAM continuum radio maps inferred an orbit that does not require the existence of non-gravitational forces acting on the Hale-Bopp nucleus, in contrast to those derived from only optical positions, thereby solving a contentious issue. In conclusion, there is no substantial offset between the nucleus position and the mean photometric centre of CO emission.

The $J(1-0)$ and $J(2-1)$ spectral channel maps (Fig. 6) were obtained with the same procedure. The peak brightness in the blue channels is stronger than that in the red ones. This indicates that there is more emission toward the Earth, which is consistent with the ON-OFF spectra. The interferometric observations indeed covered only 2/3 of the nucleus rotation period, when the jet was, most of the time, facing the Earth (Fig. 4). The spectral maps show that the CO coma structure is complex. The interpretation of the brightness distribution on these maps

Fig. 5. CO $J(1-0)$ (top) and $J(2-1)$ (bottom) line integrated maps observed on 11 March, 1997 (all data). Twenty-five spectral channels have been averaged. The synthesized beam is in the lower left. The dashed square on the $J(1-0)$ map corresponds to the size of the $J(2-1)$ map. For the CO $J(1-0)$ line, contours are 0.037 Jy/beam, and the rms is 0.018 Jy/beam. For the $J(2-1)$ line, contours are 0.186 Jy/beam and the rms is 0.066 Jy/beam. Iso-contours are successive multiples of 10% of the maximum intensity, at 10 to 100% of the maximum intensity. The solar direction is indicated. The original images have been shifted so that the maximum brightness peaks at the centre of the maps. In units of line area, the intensities at maximum brightness are 0.93 ± 0.04 and 4.65 ± 0.15 Jy km s $^{-1}$ for the $J(1-0)$ and $J(2-1)$ lines, respectively.

is not straightforward, since the signal is here averaged over the entire period of observation and the CO coma is rotating. The most central channels are sensitive to molecules expanding

Fig. 6. CO maps as a function of spectral channel on 11 March, 1997 (all data averaged). RA and Dec positions are with respect to the mean photometric centre C_m determined from the entire data set. The velocity (with respect to the comet rest velocity) of the spectral channels is indicated in the *top left* corner of the maps. The synthesized beam is in the *lower left*, and is coloured according to the velocity value. $J(1-0)$ line (*top*): contour interval is 0.053 Jy/beam and the rms is 0.046 Jy/beam. $J(2-1)$ line (*bottom*): contour interval is 0.283 Jy/beam and the rms is 0.15 Jy/beam. Contours correspond to multiples of 10% the peak flux density measured on channels at Doppler velocities of -0.71 and -0.81 km s^{-1} .

Fig. 7. Individual maps of CO $J(2-1)$ for data subsets of 1 h. Isocontours are successive multiples of 10% of the maximum intensity, at 10 to 100% of the maximum intensity. For each map labelled (*i*) on the *top left corners*, a cross identifies the mean photometric centre C_m determined from the entire data set. The arrow represents the direction of the individual photometric centre C_i with respect to C_m , and C_i is evaluated by fitting a 2D Gaussian of adjustable width. The beam shape is shown in the *bottom right-hand corner*.

along directions close to the plane of the sky. They exhibit coma structures towards north-west and south-east quadrants (roughly along a direction perpendicular to the projected rotation axis; see the 230 GHz maps in Fig. 6). These structures may trace the jet at the time that it was near the plane of the sky. Channels at high negative velocities (-0.6 to -0.9 km s $^{-1}$) show a much brighter and strongly peaked intensity distribution because the jet is here facing the Earth.

To investigate whether there is temporal evidence for the rotating jet in the images of the CO emission, we combined five separate subdivisions of about 1 h each. Resulting maps are presented in Fig. 7. Because of Earth's rotation, the beam shape rotates with time from map to map and changes dimension (see next paragraph). This prevents a detailed study of the rotating jets directly from the maps and, as explained later, another approach will be used. However, an interesting feature is observed. From the observations averaged over the entire day, we derived the mean photometric centre of CO emission, C_m . For each map *i*, we can also derive the photometric centre, C_i , and the vector $\mathbf{J}_i = \overrightarrow{C_m C_i}$, as shown in Fig. 7. The time evolution of $\mathbf{J}_i$ is presented in Fig. 8. We observe that it moves counterclockwise (disregarding C_5) along an ellipse, whose long axis is perpendicular to the spin axis direction. This displacement is that expected in presence of a CO rotating jet. Provided C_m coincides with the nucleus position, $\mathbf{J}_i$ reflects the jet direction on map *i*. For a spherical nucleus and constant jet activity, the C_i 's locus should then be an ellipse, whose long axis position angle is perpendicular to the spin axis, the other characteristics of the ellipse (axis lengths, centroid) being related to the amount of CO gas inside the jet, as well as to its latitude on the nucleus surface. A least squares fit of the photometric centres leads to an ellipse (Fig. 8) that corresponds to a spin axis with position angle $pa_\omega = 211^\circ$ and aspect angle $\theta_\omega = 79^\circ$, in good agreement with most of the published values (Table 1). The ellipse dimensions and position inferred from the fit do not provide direct quantitative information about the jet relative strength and latitude because the nucleus position may be off by a fraction of an arcsec with respect to C_m . However, the significant displacement of the photometric centre during nucleus rotation excludes a high-latitude jet, in agreement with the conclusion obtained from the ON-OFF spectra. The small offset between C_m and the nucleus position (as determined from the peak of the continuum emission) is also consistent with a low-latitude jet.

For a deeper study of the interferometric data, we decided to work on complex visibilities in the uv -plane. For the benefit of readers unfamiliar with interferometry, we explain briefly

Fig. 8. Time evolution of the photometric centres. Photometric centres C_i , with *i* referring to the maps shown in Fig. 7, are given with their errorbars. The ellipse drawn is a least squares fit to the data. It corresponds to a parallel of latitude 10° North of a sphere, with spin axis aspect angle = 80° and position angle = 211° .

what this means and how maps are obtained. An interferometer measures the Fourier transform (FT) of the source brightness distribution on the sky. The complex visibilities $\mathcal{V}(u, v)$ sample the FT at points (u, v) in the Fourier plane, also called the uv -plane. These points are the projections of the baselines onto the plane of the sky and define the uv -coverage of the observations (Fig. 2). As the Earth rotates, the locus of the points (u, v) produced by one baseline is an arc of ellipse. Therefore, the uv -radius $\sigma = \sqrt{u^2 + v^2}$ changes with time (except if the source observed is circumpolar, because the locus is then a circle). The longer we observe, the longer are these arcs, the larger is the uv -plane coverage (see Thompson et al. 1991, Chap. 4, Sect. 4.2). The uv -coverage produced by a pair of antennas comprises two arcs of ellipse that are symmetrical with respect to the centre $(u, v) = (0, 0)$; this is because the source brightness distribution is a real function, so its FT verifies $\mathcal{V}(u, v) = \mathcal{V}(-u, -v)$.

To compile a map, one has first to compute the inverse Fourier transform of the sampled signal. This *dirty map* should be then deconvolved from the *dirty beam*, which is the FT of the uv -coverage. Because the uv -plane is not regularly covered, interpolations have to be made when performing the FT. When the uv -coverage is highly anisotropic, the dirty beam also exhibits intense sidelobes, which might not be properly accounted for in the deconvolution step. This might result in the apparition of artefacts. The anisotropic uv -coverage also results in an elliptical clean beam.

Since the individual baselines have different directions and lengths, they probe different scales and regions of the coma, and visibilities have to be studied independently for each baseline. In Fig. 9, we plot the time evolution of the visibility amplitude $\bar{V}$ of the CO $J(2-1)$ line with respect to the uv -radius σ . The visibilities were integrated over velocity and have units of line area. If we assume that the line is optically thin and its excitation does not vary within the field of view, for an isotropic coma described by a parent molecule distribution, the visibility curve would follow $\bar{V}(\sigma) \propto \sigma^{-1}$, provided that the photodissociation scalelength is large compared to the field of view, which is the case here (Bockelée-Morvan & Boissier 2009). We can observe in Fig. 9 some modulations with respect to the mean evolution (in $\sigma^{-1.18}$) that are not caused by noise. They cannot be due to variations in the activity of the comet, since the area of the line, observed in ON-OFF mode, is roughly constant with time. Furthermore, modulations do not exhibit the same behaviour from one baseline to another.

In Fig. 3b–d, we presented spectra acquired for the three shortest baselines of the interferometer. As for the ON-OFF spectra (Fig. 3a), we can see spectral features moving from red to blue velocities. Figure 10 presents the time evolution of the interferometric velocity shifts. At least for the five shortest baselines, they can be fitted by sinusoids of period equal to the nucleus rotation period. We observe that these curves are not in phase. As the baselines have neither the same length, nor the same orientation, this phase difference may suggest that the CO jet is spiralling and detected at different times with the various baselines. A straight jet would produce velocity shift curves in phase.

The next section presents a model with a rotating gas jet developed to interpret these data.

3. Model

We present a static 3-dimensional model of a spiralling gas jet. It computes uv -tables (i.e., visibilities) corresponding to the observational conditions of the data, i.e., of the same uv -coverage. The time evolution of the coma is simulated by computing a series of successive static uv -tables.

The CO coma is modelled as a combination of an isotropic outgassing and a gas jet defined by:

- its half-width Ψ ;
- its latitude ℓ on the nucleus, assumed to be spherical;
- the fraction f_{co} of the CO released within the jet.

The model parameters are summarized in Table 2.

The coordinate frame ($Oxyz$) used in the calculations has its origin at the comet nucleus with the z -axis along the line of sight opposite to the Earth, and the x and y -axes pointing East and North in the plane of the sky. r_0 is the nucleus radius. The jet direction at the nucleus surface $\mathbf{J}_0$ is $(\theta_0, \phi_0)_t$ in the ($Oxyz$) frame at time t (usual spherical coordinates) and moves with time according to the nucleus rotation. We define

$\mathbf{R}_\omega$ to be the rotation matrix for a time lapse Δt , so that we have $(\theta_0, \phi_0)_{t+\Delta t} = \mathbf{R}_\omega \cdot (\theta_0, \phi_0)_t$. The jet direction at distance $r = r_0 + v_{\text{exp}} \Delta t$ in the coma is $\mathbf{J}_r = \mathbf{R}_\omega^{-1} \cdot \mathbf{J}_0$, where v_{exp} is the gas expansion velocity.

We assume a Haser-like parent molecule distribution for CO. As we remarked upon in Sect. 1, although infrared observations suggest that part of the CO in Hale-Bopp coma originated in a distributed source (DiSanti et al. 2001; Brooke et al. 2003), the present observations do not require CO to be extended (Bockelée-Morvan & Boissier 2009). The local density at (r, θ, ϕ) direction is then given by

$$n_{\text{CO}}(r, \theta, \phi) = \frac{Q(r, \theta, \phi)}{4\pi r^2 v_{\text{exp}}} \exp\left(-\frac{(r - r_0)}{L_{\text{CO}}}\right), \quad (1)$$

where

$$Q(r, \theta, \phi) = Q_{\text{iso}} + 4\pi Q_{\text{jet}} \mathcal{G}(r, \theta, \phi), \quad (2)$$

and Q_{iso} and Q_{jet} are the total CO production rates of the isotropic contribution and within the jet, respectively. For the sake of simplicity, the total CO production rate $Q_{\text{CO}} = Q_{\text{iso}} + Q_{\text{jet}}$ is fixed, and assumed to equal $2 \times 10^{30} \text{ s}^{-1}$ (Biver et al. 1999a, see Sect. 2.2). We define $f_{\text{co}} = \frac{Q_{\text{jet}}}{Q_{\text{CO}}}$ as a free parameter. The function $\mathcal{G}(r, \theta, \phi)$ describes the jet pattern and is a normalized Gaussian ($\int \mathcal{G}(\Omega) d\Omega = 1$) of half width Ψ centred on $\mathbf{J}_r$. The photodissociative scalelength is $L_{\text{CO}} = v_{\text{exp}}/\beta_{\text{CO}}$, where β_{CO} is the CO photodissociation rate.

The code uses $N = 47$ (Oxy) grids, each of which sample one channel of the spectrum centred on $v_i = \left(\frac{N+1}{2} - i\right) \delta v$, in the nucleus velocity frame, with $\delta v = 0.10 \text{ km s}^{-1}$. The (Oxy) grids are $100'' \times 100''$ long². They are divided into 256×256 cells, whose dimensions are $(\delta x, \delta y)$ ($\delta x = \delta y = 0.39''$).

In the optically thin case, the brightness distribution in the plane of the sky [$\text{W m}^{-2} \text{ sr}^{-1}$], when selecting only molecules contributing to channel i , is given by

$$F_i(x, y) = \frac{N_i(x, y)}{\delta x \delta y} h\nu A_{ul} \frac{1}{4\pi \Delta^2}, \quad (3)$$

where ν is the line frequency, A_{ul} is the Einstein coefficient for spontaneous emission, δx and δy have units of radians, and Δ is the geocentric distance.

We define $N_i(x, y)$ to be the number of CO molecules in the upper state of the transition sampled by the cells with Doppler velocities contributing to channel i

$$N_i(x, y) = \int_{x-\frac{\delta x}{2}}^{x+\frac{\delta x}{2}} \int_{y-\frac{\delta y}{2}}^{y+\frac{\delta y}{2}} \int_{-10 L_{\text{CO}}}^{10 L_{\text{CO}}} n_{\text{CO}} p_u H_i dx dy dz, \quad (4)$$

where p_u is the relative population of the upper level of the transition, which depends on the radial distance to nucleus, n_{CO} is evaluated by Eq. (1), and H_i is the function used to select velocities, defined by

$$H_i(x, y, z) = \begin{cases} 1 & \text{if } v_z(x, y, z) \in \left[v_i - \frac{\delta v}{2}; v_i + \frac{\delta v}{2}\right] \\ 0 & \text{elsewhere} \end{cases} \quad (5)$$

where $v_z(x, y, z)$ is the gas velocity projected onto the line of sight. The gas velocity is radial, and its amplitude is represented by a Gaussian centred on v_{exp} , of width $2 \sqrt{\ln(2)kT/m}$, to account

² This is much larger than the primary beam of the antennas, but was necessary in order to maintain a good resolution in the Fourier plane.

Fig. 9. Time evolution of the visibility amplitudes with respect to the uv -radius σ . Different symbols are used for the different baselines. For some baselines, the arrow shows the direction of time evolution of the uv -radius. The uncertainties in the data points due to thermal and phase noise range from 0.29 to 0.65 Jy km s⁻¹. Phase noise affects the uncertainties by in between 2% (short baselines) and 10% (long baselines). The mean error bar (± 0.40 Jy km s⁻¹) is quoted on the figure. The dashed curve is a least squares fit of a power law to the data.

for thermal broadening, where k is the Boltzman constant, T is the kinetic temperature, and m is the CO molecular mass.

Because the CO production rate is high in comet Hale-Bopp and a dense CO jet is present, optical depth effects need to be considered when calculating the CO $J(2-1)$ brightness distribution (i.e., $F_i(x, y)$). They are not expected to affect the ON-OFF spectra significantly, but could be significant in the case of the interferometric signals. The results presented in this paper were performed by solving the full radiative transfer equation, as explained in Boissier et al. (2007), assuming the local velocity dispersion to be thermal.

A synthetic 47-channels ON-OFF spectrum is obtained by the convolution of F_i with the antennas primary beam. For each channel i , the visibilities are defined by (see e.g., Thompson et al. 1991, Chap. 4, Sect. 4.1):

$$\mathcal{V}_i(\sigma) = \frac{c}{v\delta v} \int_{4\pi} A(s) F_i(s) \exp\left(-\frac{2i\pi v}{c} \sigma \cdot s\right) d\Omega, \quad (6)$$

where σ is the baseline vector for two antennas, with coordinates (u, v) in the uv -plane, s is a vector in the sky plane with coordinates (x, y) in radian units, A is the power pattern of the antennas, $d\Omega$ is an element of solid angle on the sky, and $\mathcal{V}_i(\sigma)$ is in units of [W m⁻² Hz⁻¹] or janskys. Equation (6) can be approximated to be

$$\mathcal{V}_i(u, v) = \frac{c}{v\delta v} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} A(x, y) F_i(x, y) \times \exp\left(-\frac{2i\pi v}{c} (ux + vy)\right) dx dy. \quad (7)$$

Visibilities are computed with a Fast Fourier Transform (FFT) algorithm.

The population of the rotational levels (p_u) is derived from an excitation model that takes into account collisions with H₂O and IR radiative pumping of the $v(1-0)$ CO vibrational band (Crovisier & Le Boulot 1983; Crovisier 1987). This model describes populations p_u as a function of radial distance r , given a H₂O density law with r . For simplicity, we assumed an isotropic H₂O coma, and a p_u that only depends upon r . The collisional CO-H₂O cross-section is taken to be equal to $\sigma_c = 2 \times 10^{-14}$ cm² (Biver et al. 1999b), and the H₂O production rate is $Q_{\text{H}_2\text{O}} = 10^{31}$ s⁻¹ (Colom et al. 1999). In the simulations presented in Sect. 4, a kinetic temperature $T = 120$ K is used (see Sect. 2.2 for further discussion). The evolution of the population of the CO $J = 2$ and $J = 1$ levels is shown in Fig. 11. The beam size of 20.9'' for CO $J(2-1)$ corresponds to $r \sim 10\,000$ km in the coma. Most CO molecules within the field of view are in local thermal equilibrium.

Given the evolving coma, a full simulation of the observations would require to compute for each one minute scan the visibilities corresponding to the current state of the coma and their uv -coverage. To limit the computer time, we modelled an entire nucleus revolution ($P = 11.35$ h) with 12 snapshots (see Fig. 12). We tested the validity of the approach by verifying that calculations of higher time sampling (namely 36 snapshots) provide similar results. Between 2 snapshots i and $i + 1$, the jet direction changed according to $(\theta_0, \phi_0)_{i+1} = \mathbf{R}_\omega(\theta_0, \phi_0)_i$, where $\mathbf{R}_\omega$ is the rotation matrix for a time span of $P/12$. Provided that the initial

Fig. 10. Time evolution of the CO $J(2-1)$ velocity shifts and fitted sinusoids. Baselines are indicated in the *top left* corners. Observations are shown with empty circles with errorbars, and dashed curves for the sinusoids. Model results (plain squares and plain curves) are for parameter set (3) of Table 3 with $pa_\omega = 210^\circ$ ($\theta_\omega = 80^\circ$, $\Psi = 18.3^\circ$, $\ell = 20^\circ$ and $f_{\text{CO}} = 35.5\%$).

jet longitude at time t corresponding to snapshot $i = 1$ is fixed, a composite uv -table can be computed with the uv -coverage of the observations. The numerical code computes twelve composite uv -tables, each of them corresponding to different initial jet longitudes at intervals of $360^\circ/12$. The longitude origin is chosen so that the sub-terrestrial point on the nucleus surface is at a longitude of 0° . For illustration, Fig. 12 shows the twelve jet positions for a jet at a longitude of 0° at the time of the first snapshot. The model also computes synthetic ON-OFF spectra for each snapshot.

4. Jet morphology analysis

The ON-OFF and interferometric velocity shift curves observed for CO $J(2-1)$ (Figs. 4 and 10), and the time evolution of the visibilities (Fig. 9) are now analysed with the model presented in the previous Section to constrain its free parameters. Because of the limited signal-to-noise ratio of the data, a similar analysis was impossible for $J(1-0)$ observations. For the spin axis orientation defined by its aspect angle θ_ω and position angle pa_ω ,

Table 2. Model parameters.

Fixed parameters		
heliocentric distance	r_h	0.989 AU
geocentric distance	Δ	1.368 AU
gas expansion velocity ^(a)	v_{exp}	1.05 km s ⁻¹
total CO production rate ^(a)	Q_{CO}	2.0×10^{30} s ⁻¹
CO photodissociation rate ^(b)	β_{CO}	7.50×10^{-7} r _h ⁻²
nucleus rotation period	P	11.35 h
Free parameters		
fraction of CO in the coma outgassed in the jet	f_{CO}	
jet latitude	ℓ	
jet half-width	Ψ	
rotation axis aspect angle	θ_ω	
rotation axis position angle	pa_ω	

^(a) Biver et al. (1999a); ^(b) Huebner et al. (1992).

Fig. 11. Relative populations of the CO rotational levels $J = 1$ and $J = 2$, as function of distance from the nucleus. A kinetic temperature of 120 K is assumed.

we restricted our study to the mean values found in the literature (see Table 1): $\theta_\omega = 60$ to 90° , and $pa_\omega = 200$ to 230° . The jet width Ψ was tested from 1° to 90° , the jet latitude ℓ from 0° to 90° North, and f_{CO} from 10% to 80%.

4.1. ON-OFF velocity shift curve

As discussed in Sect. 2.2, data shown in Fig. 4 are well fitted by a sinusoid with a period $P = 11.35$ h, an amplitude $\mathcal{A} = 0.29$ km s⁻¹, and centred on $v_0 = -0.05$ km s⁻¹. We can also define a phase $t_0 = 11.75 \pm 0.12$ UT, which corresponds to the time when the velocity shift is equal to v_0 on the increasing side of the curve. We used these three parameters ($\mathcal{A}$, v_0 , t_0) as criteria when selecting the models that could explain the observations. We note that the position angle pa_ω of the spin axis has no influence on the velocity shift.

The phase t_0 is controlled only by the initial longitude of the jet. From t_0 derived from the observations, we infer the initial longitude to be 300° at 3 h 47 UT.

To first order, $\mathcal{A}$ is governed by f_{CO} and Ψ : it increases when either f_{CO} increases or Ψ decreases. This behaviour can be easily explained. If f_{CO} increases – all other parameters remaining unchanged – more signal from the jet falls into the same number of spectral channels. The velocity shift and the amplitude of the velocity shift curve then increase. In a similar way, when Ψ decreases – keeping f_{CO} constant – an equal amount of signal coming from the jet covers a larger number of spectral channels. This results in reducing both the velocity shift and $\mathcal{A}$. This is

Fig. 12. Schematic view of comet Hale-Bopp nucleus on 11 March, 1997, as seen from the Earth assuming $pa_\omega = 210^\circ$ and $\theta_\omega = 80^\circ$ for the spin orientation. East is on the left. The latitudes are shown by steps of 10° and the arrow shows the rotation direction. The symbols represent the series of jet positions used to make a composite uv -table for an equatorial jet. Plain (respectively dotted) symbols mean that the jet is on the visible (respectively hidden) side of the nucleus.

Fig. 13. Evolution of the amplitude of the velocity shift curve $\mathcal{A}$ with θ_ω and Ψ , for $f_{co} = 66\%$ and $\ell = 0^\circ$. The cross indicates the value of Ψ required to fit the observations ($\mathcal{A} = 0.29 \pm 0.03 \text{ km s}^{-1}$) for $\theta_\omega = 70\text{--}90^\circ$ and $f_{co} = 66\%$.

illustrated in Figs. 13 and 14, which show the evolution in $\mathcal{A}$ with f_{co} and Ψ . Moreover, $\mathcal{A}$ is insensitive to the aspect angle θ_ω , except for small Ψ 's, as observed in Figs. 13 and 14. Furthermore, we note that the jet latitude ℓ has little influence on the amplitude, within the limits that we tested ($|\ell| < 45^\circ$) (Fig. 15). To conclude, the observed amplitude of 0.29 km s^{-1} can be fitted by many (f_{co}, Ψ, ℓ) combinations.

The mean velocity v_0 of the simulated curves depends mainly on the jet latitude ℓ . An equatorial jet always produces a curve centred on 0 km s^{-1} , regardless θ_ω . For $\theta_\omega < 90^\circ$, a jet with a northern (respectively southern) latitude produces a curve centred on a negative (respectively positive) velocity. This behaviour is again understandable. With $\theta_\omega < 90^\circ$, the North pole

Fig. 14. Evolution of the amplitude of the velocity shift curve $\mathcal{A}$ with θ_ω and f_{co} , for $\Psi = 20^\circ$ and $\ell = 0^\circ$. The cross indicates the value of f_{co} required to fit the observations ($\mathcal{A} = 0.29 \pm 0.03 \text{ km s}^{-1}$) for $\theta_\omega = 70\text{--}90^\circ$ and $\Psi = 20^\circ$.

Fig. 15. Evolution of $\mathcal{A}$ (top) and v_0 (bottom) with Ψ for several f_{co} and ℓ . Simulations have been done with $\theta_\omega = 80^\circ$ and $pa_\omega = 210^\circ$. Observed values are $\mathcal{A} = 0.29 \pm 0.03 \text{ km s}^{-1}$ and $v_0 = -0.05 \pm 0.01 \text{ km s}^{-1}$.

is pointing towards the Earth (see Fig. 12). As a result, a northern jet is directed towards the Earth for a longer time than a southern one. The opposite effects are obtained for $\theta_\omega > 90^\circ$, while $\theta_\omega = 90^\circ$ (rotation axis in the plane of the sky) always produces a curve centred on 0 km s^{-1} , irrespective of the sign of the latitude. The greater the rotation axis is from the plane of the sky, the greater the shift in the velocity shift curve. Furthermore, the velocity shift curve is shifted all the more because Ψ is small and f_{co} is large (Fig. 15). This study leads us to the conclusion that, here again, many combinations (f_{co}, Ψ, ℓ) are able to reproduce the observed v_0 . However, it shows that only a northern jet can describe the observations.

For a given $(\theta_\omega, \ell, f_{co})$ parameter set, it is possible to find the jet width Ψ that is able to reproduce the amplitude

Fig. 16. The pairs of parameters (f_{co}, Ψ) that reproduce the amplitude $\mathcal{A} = 0.29 \pm 0.03 \text{ km s}^{-1}$ (dotted curves) and the mean velocity $v_0 = -0.05 \pm 0.01 \text{ km s}^{-1}$ (dashed curves) for several pairs of (θ_ω, ℓ) . The intersections of the curves give, for each (θ_ω, ℓ) combination, the only pair (f_{co}, Ψ) that reproduces $\mathcal{A}$ and v_0 .

Table 3. Selected sets of parameters θ_ω , ℓ , Ψ and f_{co} reproducing the velocity shift curve of the ON–OFF observations.

Set	θ_ω	ℓ	Ψ	f_{co}
(1)	70°	10°	19.9°	35.7%
(2)	80°	10°	11.9°	33.6%
(3)	80°	20°	18.3°	35.5%
(4)	80°	30°	33.0°	47.8%

$\mathcal{A} = 0.29 \text{ km s}^{-1}$. Figure 16 shows in dotted curves the locus of the pairs (f_{co}, Ψ) that reproduce the correct amplitude $\mathcal{A}$ for several fixed (θ_ω, ℓ) values. The same method is employed to determine the pairs of variables (f_{co}, Ψ) that reproduce the correct velocity centre $v_0 = -0.05 \text{ km s}^{-1}$ (dashed curves in Fig. 16). For each set (θ_ω, ℓ) , the intersection of the dotted and the dashed curves infers the only pair (f_{co}, Ψ) that reproduces $\mathcal{A}$ and v_0 . We completed these computations for latitudes of between 0° and 45°, and for $\theta_\omega = 70^\circ$ and 80° . Computations for $\theta_\omega = 90^\circ$ were useless because they infer that $v_0 = 0 \text{ km s}^{-1}$.

The combinations $(\theta_\omega, f_{\text{co}}, \Psi, \ell)$ selected by this study are summarized in Table 3. We note that the jet strength f_{co} is typically between 35% and 50%. The jet is located on the northern hemisphere at a latitude of between 0° and 45° (both excluded) for $\theta_\omega = 80^\circ$, and between 0° and 20° (both excluded) for $\theta_\omega = 70^\circ$.

The velocity shift curve obtained for parameter set (3) is shown in Fig. 10, together with the observed curve. We note the almost perfect match between model and observations. The corresponding synthetic line profiles are shown in Fig. 17. At any time, the jet contributes to both blue and red channels, their relative contributions varying because of its spiral shape.

4.2. Interferometric velocity shift curves

We now study the velocity shift curves observed for the individual baselines. Figure 10 shows model results for the parameter set (3) in Table 3 (i.e., $\theta_\omega = 80^\circ$, $pa_\omega = 210^\circ$, $\Psi = 18.3^\circ$, $\ell = 20^\circ$ and $f_{\text{co}} = 35.5\%$). Other parameter sets in Table 3 produce similar curves. Modelled curves are periodic functions, with a period equal to P . They mimic sinusoidal curves, although significant deviations from a sinusoid are observed. This is because line shifts measured in $\mathcal{V}(u, v)$ spectra are (u, v) dependent: stronger

jet contrast appears in specific regions because of spatial filtering. Then, because of the combination of Earth and jet rotation, regions with more or less jet contrast are sampled by the individual baselines. Simulations indicate that these curves evolve toward a true sinusoid when the jet width Ψ is increasing (f_{co} kept constant), due to smaller jet contrast. These curves change when varying the jet parameters in the same way as for the ON–OFF curve. Changing the spin axis parameters by $\pm 10^\circ$ does not significantly affect the curves.

The modelled velocity shift curves for the different baselines are not in phase, t_0 (defining the phase, see Sect 4.1) increasing with decreasing baseline length (Fig. 18). We expect a phase offset because of the spiral shape of the jet. With respect to long baselines, short baselines probe molecules in more distant regions of the spiral. Hence, they sample molecules released on average at earlier times. In addition, baselines of different length (even if they are parallel) detect the maximum amount of signal from the jet at different times due to the curvature of the jet. This can be understood from Fig. 19, which plots the amplitude of the visibility as a function of both the orientation and length of the baselines for a simple geometry (rotation axis along the line of sight and equatorial jet) and at a given time. The combination of both effects introduces a phase offset in the velocity shift curves. The delay between two baselines in the velocity shift curves represents the elapsed time between the jet detection by one baseline and its detection by the following one. We note that, given the large curvature of the spiral (molecules travel $r \sim 10^4 \text{ km}$, when the nucleus rotates by 90°), only its innermost part contributes significantly to the detected signal. The dashed curve in Fig. 18 shows the evolution of t_0 with uv -radius, assuming that t_0 varies linearly with σ/v_{exp} , which agrees approximately with the t_0 curve computed by the model (plain curve).

The comparison between modelled and observed phases t_0 and amplitudes $\mathcal{A}$ shows that there is relatively good agreement for some baselines and strong discrepancies for others (Fig. 18). Good agreement for both t_0 and $\mathcal{A}$ is obtained for baselines 3–4 and 2–4. Phase t_0 is well reproduced for baseline 1–3 (but not amplitude). A strong discrepancy (of 3 h for t_0 , and a factor of almost 2 for $\mathcal{A}$) is observed for baselines 1–4, 1–5, and possibly 4–5 (errorbars are large for this baseline). It is remarkable that good agreement is obtained for baselines of field of view aligned along the spin vector, while discrepancies are observed for baselines of field of view perpendicular to the spin vector.

Fig. 17. Synthetic CO 230 GHz ON-OFF line profile as a function of UT time on 11 March for parameter set (3) of Table 3 ($\theta_\omega = 80^\circ$, $pa_\omega = 210^\circ$, $\Psi = 18.3^\circ$, $\ell = 20^\circ$ and $f_{co} = 35.5\%$). The total spectrum (jet+isotropic contribution) is shown by thick lines. The grey spectrum shows the contribution of the CO jet.

Clearly our model is too simple to reproduce all observational characteristics. We were unable to identify any simple explanation of these discrepancies. Velocity acceleration inside the jet would change the t_0 evolution with baseline in an opposite way: it would produce a flatter increase with decreasing baseline length than obtained with a constant velocity. The presence of other CO evolving structures in the coma of Hale-Bopp is, however, the most likely explanation (Sect. 4.5).

4.3. Visibilities

Figure 9 shows the time evolution in the visibilities $\bar{V}$ plotted as a function of the uv -radius σ (as defined in Sect. 2.3, $\bar{V}$ refers to the amplitude of the visibilities integrated over

Fig. 18. Phase t_0 (bottom) and amplitude $\mathcal{A}$ (top) of the velocity shift curves as a function of uv -radius. Dots with errorbars are the data. The range of uv radius spanned by the baselines is shown with horizontal lines in the bottom figure. The plain curve shows model calculations with $\theta_\omega = 80^\circ$, $pa_\omega = 210^\circ$, $\Psi = 18.3^\circ$, $\ell = 20^\circ$ and $f_{co} = 35.5\%$. The dotted curve in the bottom figure assumes that the elapsed time between jet detection by baseline at uv -radius σ_1 and jet detection by baseline at σ_2 (or in ON-OFF spectrum at $\sigma_2 = 15$ m) is equal to $(\sigma_2 - \sigma_1)/2v_{exp}$, with $v_{exp} = 1.05$ km s $^{-1}$. The reference time is t_0 measured on the ON-OFF velocity shift curve. The orientation of the baselines fringes during the course of the observations is shown at the bottom, together with the spin axis direction in the (RA, Dec) plane: e.g., the field of view of baseline 3-4 has its long dimension (reflecting the primary beam of the antenna) along the spin vector of the comet, and its short dimension (related to the baseline length) perpendicular to it. The Sun direction in the (RA, Dec) plane is also indicated.

velocity). A least squares fit to these data implies that $\bar{V}(\sigma) \propto \sigma^{-1.18 \pm 0.02}$, which should be compared with the σ^{-1} variation expected for a parent molecule distribution and an optically thin line (Bockelée-Morvan & Boissier 2009). This trend can be explained by optical depth effects being more important for long baselines probing the inner coma.

Modulations are observed about this fit: they trace variations in the brightness distribution sampled by the individual baselines as the baselines and jet rotate. These modulations are characterized by both their shape and amplitude. Their shape depends on the rotation-axis position angle pa_ω and the jet latitude ℓ . For example, a high-latitude jet would result in strong modulations for baselines 3-4, 2-4, and 2-3, and no modulations for baselines 1-3 and 1-4, which scan regions along the equator (Fig. 20). The reverse is expected for a high-latitude jet

Fig. 19. Visibilities of the CO 230 GHz line (central channel) as a function of baseline orientation in the uv plane and baseline length (σ from 5 to 100 m by step of 5 m) at a given time. The rotation axis ($P = 11.35$ h) is along the line of sight ($\theta_\omega = 0^\circ$). The jet is equatorial, has an aperture $\Psi = 30^\circ$, and its direction at the nucleus surface is at a position angle of 60° in the plane of the sky (i.e., $\theta_0 = 30^\circ$). Other parameters are $Q_{\text{CO}} = 1 \times 10^{30} \text{ s}^{-1}$, $f_{\text{CO}} = 1$, with assumed optically thin conditions.

Fig. 20. CO 230 GHz modelled visibilities for a high-latitude jet.

and a pa_ω of 90° from the nominal pa_ω of the Hale-Bopp rotation axis. Qualitatively, the observed modulations exclude both a high-latitude jet and a rotation-axis position angle that differs much from the pa_ω derived from visible observations. This confirms the conclusion obtained from the time evolution of the photometric centres (Sect. 2.3), which is sensitive to both the amplitude and phase of the visibilities.

We compared the observed visibilities to those computed by the model with the sets of jet parameters (2), (3), and (4) given in Table 3 (those with $\theta_\omega = 80^\circ$ and $pa_\omega = 210^\circ$). The lowest χ^2 (reduced $\chi^2_{N-n} = 5.1$ for $N = 150$ data points and $n = 5$ free parameters) was obtained for the set of parameters (3) with $\Psi = 18.3^\circ$, $\ell = 20^\circ$, and $f_{\text{CO}} = 35.5\%$. Simulations with the parameter set (2) (respectively (4)) show larger (respectively lower) modulations than observed, and χ^2 values 60% (respectively 22%) larger than

Fig. 21. CO 230 GHz modelled visibilities for the jet and rotation axis parameters which reproduce at best the observations (set (3) with $pa_\omega = 210^\circ$).

Fig. 22. CO 230 GHz modelled visibilities for set (3) with $pa_\omega = 210^\circ$ assuming an optically thin line.

with parameters (3). Using the jet parameter set (3), we also compiled simulations with $\theta_\omega = 60$ and 70° , and $pa_\omega = 200, 220$, and 230° . The χ^2 was minimized for $pa_\omega = 220^\circ$ ($\chi^2_{N-n} = 3.8$), while θ_ω has no significant influence on the visibilities. However, $pa_\omega = 210^\circ$ provides a solution that explains the visibilities of the 3–4 baseline more accurately. Figure 21 shows the modelled visibilities with parameters (3) and $pa_\omega = 210^\circ$. Looking at the shape of the modulations, there is overall agreement between model and observations, although the agreement is not perfect. A plot of observed versus modelled visibilities shows that the closest agreement is for baselines 3–4, 1–5, 1–4, 1–3, and 4–5. The largest discrepancies are for baselines 2–4, 1–2, and 2–5. For most baselines, jet detection (traced by amplitude increase) occurs ~ 1 h earlier in the simulation than in the observations. In contrast, in the velocity shift curves, the simulated jet is late with respect to the observed jet for most baselines. This again shows that our model is too simple to explain the data satisfactorily.

The visibilities obtained when optical depth effects are neglected, exhibit the same temporal behaviour (Fig. 22). However, as expected, the modulations are more prominent in the optically thin case.

The visibilities obtained with jet parameter set (3) vary according to $\bar{V}(\sigma) \propto \sigma^{-1.24}$, which is consistent, to first order, with the observed variation ($\propto \sigma^{-1.18 \pm 0.02}$).

Fig. 23. CO 230 GHz Hale-Bopp maps as a function of time. *Left column:* observations; *central column:* simulations with the jet and rotation axis parameters that reproduce most effectively the observations (set (3): $\theta_\omega = 80^\circ$, $pa_\omega = 210^\circ$, $\Psi = 18.3^\circ$, $\ell = 20^\circ$ and $f_{co} = 35.5\%$); *right column:* simulations for an isotropic coma.

4.4. Maps

Simulated maps as a function of time are compared with observed maps in Fig. 23. The shape of the observed CO coma is relatively well reproduced by the model. Some differences may be caused by the presence of other CO coma features, as suggested by noticeable discrepancies at 8h50–9h5 UT. The time evolution of the photometric centre measured in the simulated data (jet parameters (3) with $pa_\omega = 210^\circ$) is shown in Fig. 24. When the position of the photometric centre is defined with respect to the mean photometric centre for the observing period, and can therefore be directly compared to the measurements, there is good agreement in the overall evolution. As expected, the relative (modelled–observed) positions generally differ, with discrepancies reaching $\sim 0.3''$ for 4h30–5h30 and 7h20–8h20 data (maps 1 and 3). However, the good overall agreement confirms a posteriori that the observed time evolution of the CO 230 GHz peak brightness position is related to the CO rotating coma.

We compiled synthetic 230 GHz spectral maps that are directly comparable to the observations (Fig. 6). Some observed basic features are well reproduced, such as the very peaked and strong emission in the blue channels at high velocity and the elongated coma in the East-West direction for the blue channels at velocities close to zero. However, the asymmetry in the

Fig. 24. Time evolution of the photometric centre, determined by fitting data in the uv -plane. Measurements for Hale-Bopp CO 230 GHz observations are shown by black dots with errorbars. Those from simulations with jet parameter set (3) ($pa_\omega = 210^\circ$) are plotted with red stars: empty squares show absolute positions and filled squares show photometric centres with respect to the mean photometric center over the period, which can be directly compared to the real data. The accuracy of the photometric centre position measured in the simulated data is also shown.

spatial distribution observed in the red channels is not reproduced by the model. As a matter of fact, the model, whose parameters were constrained by the large-scale ON–OFF observations, predicts that the inner parts of the jet probed during the course of the interferometric observations were most of the time projecting Earthward (i.e., with negative Doppler velocities). The discrepancies between modelled and observed spectral visibilities discussed previously are observed directly on the spectral maps.

4.5. Evidence of a second moving structure

The inability of our one-jet model to reproduce satisfactorily the interferometric data is due to the presence of a second moving CO structure, possibly produced during an outburst.

This moving structure is that seen North-West from the nucleus at positive velocities in the time-averaged channel maps (Fig. 6). This structure, which is moving away from the observer, is oriented along the fringes of baselines 1–4, 1–5, 3–5, and 4–5, i.e., along those for which a strong discrepancy in the time variation of the velocity shift is observed. This structure is clearly detected by these baselines: hence, the velocity shift measured for these baselines is smaller than expected (Fig. 10).

To study the time evolution of this structure, the spectral data were smoothed to a spectral resolution of 0.5 km s^{-1} , for velocity channels centred on -1.0 , -0.5 , 0 , $+0.5$, $+1.0 \text{ km s}^{-1}$ with respect to the comet rest velocity. Five consecutive time intervals (#1, #2, #4, #5, #6) of between ~ 50 min and 1h30 long, were considered. The time intervals correspond to characteristic line shapes in the spectrum recorded by baseline 3–4 (Fig. 3):

Fig. 25. Time evolution of the CO 230 GHz photometric centre for individual velocity channels at $v = -1.0, -0.5, 0, +0.5, +1.0 \text{ km s}^{-1}$. The spectral data were smoothed to a spectral resolution of 0.5 km s^{-1} . The time intervals labelled 1 to 6 are given in Sect. 4.5. Note that they do not correspond to those used for Figs. 23 and 24. The *top figure* shows the measurements, while the model (set of parameters (3) in Table 3) is shown in the *bottom figure*. To illustrate how the photometric centres are affected by the main jet, we have connected points (coloured in blue) indicative of the motion of the CO main jet. The so-called “red jet” is shown by red symbols.

#1 (4h30–5h48 UT) symmetric shape ; #2 (5h48–7h07 UT) and #4 (7h07–9h08 UT) asymmetric shape with strong blueshift ; #5 (9h08–10h00 UT) symmetric shape; and #6 (10h00 UT–11h28) asymmetric shape with high redshift. A sixth period, labelled #3, merging intervals #2 and #4, was also considered.

The 5×6 extracted data sets were analysed in the Fourier plane by assuming that the brightness distribution is a 2D Gaussian, and that its intensity, width and offset with respect to the line-integrated, time-averaged centre C_m were free parameters. Figure 25 shows the observed time evolution of the offset (RA(t), Dec(t)) for each channel. The same plot is shown using model parameter set (3) as input.

For a non-rotating nucleus, the motion of a cloud of gas released during a short time interval from a nuclear source should follow a straight line in the (RA, Dec) quadrant and the velocity channel where its velocity vector is projected. For a rotating nucleus, a permanent nuclear source near the equator will produce an expanding jet that will appear successively in the different channels as the nucleus rotates. In the case of comet Hale-Bopp, if the equatorial jet projects North-West in (RA, Dec) at positive velocity channels (V_+) at a given time, then it will project North-West in negative velocity channels (V_-), South-East/ V_- , South-East/ V_+ . As shown in Fig. 25, there is satisfactory agreement between model and observations for channels centred on $-1.0, -0.5$ and 0 km s^{-1} . We tentatively connected the points corresponding to the motion of the CO main jet. At time #1, the jet is moving westward in the $v = 0$ channel; at time #4, it is moving eastward in the $v = -0.5 \text{ km s}^{-1}$ channel; at time #5, eastward in the $v = 0$ channel; and at time #6, eastward in the $v = +0.5 \text{ km s}^{-1}$ channel.

The motion of the red structure is clearly apparent in the channels at $v = +0.5$ and $+1 \text{ km s}^{-1}$. The direction of the motion suggests that it originates in a low latitude region at the nucleus surface. The longitude of this source is estimated to be within $90\text{--}150^\circ$ westward from the source of the main jet. The weak contribution of the red structure to some baselines can be explained by spatial filtering, implying that a compact structure is present. The CO 230 GHz flux density in channels $v = +0.5$ and $+1 \text{ km s}^{-1}$ is four times lower than in channel $v = -0.5 \text{ km s}^{-1}$, at the time that the CO main jet is contributing. This may explain why the red source does not contribute much to the ON-OFF spectra.

5. Discussion

5.1. Model assumptions

The observations presented in this paper have been interpreted with a simple geometric model of a CO rotating coma. Apart from the assumed conical shape of the jet at ejection (see the discussion below), several other simplifying assumptions were made to limit the number of free model parameters. The outflow velocity was fixed and taken to be constant throughout the coma, whereas some acceleration is expected by gas dynamical models (Combi et al. 1999). Day-to-night asymmetries in velocity for the CO background gas were not taken into account, although they are clearly present. The velocity cutoff and width of the blue wing of the CO velocity profiles are indeed 10% higher than the corresponding values for the red wings (Fig. 3), which suggests higher velocities towards the sunlit side of the nucleus given the Earth-comet-Sun geometry. In addition, we assumed that CO

molecules inside the jet expand at the same velocity as those in the background. We believe that including slight variations in the flow velocity field would not change the main conclusions of this paper, although the characteristics of the jet could somewhat differ. For example, including the day-to-night asymmetry in velocity would shift the jet towards lower latitudes. Higher velocities inside the jet would require a proportionally higher jet contribution to the total CO production f_{co} to fit the ON-OFF data. We also did not consider the temperature variations in the coma that can have direct effects on CO excitation. A kinetic temperature that is higher in the jet than in the background gas would have resulted in a higher inferred f_{co} . However, a 10 K difference in temperature would change f_{co} by less than 10%.

5.2. CO jet

Our observations, interpreted with the help of a simple model, suggest the presence of a spiralling “jet” of CO, originating in the nucleus. The rotation of this jet is consistent with the rotation period and axis direction derived from most optical studies. The jet originates in a low-latitude ($\approx 20^\circ$) region of the nucleus, and is responsible for a significant amount of the total CO production ($\sim 40\%$) in a ~ 20 – 30° wide aperture. This is the first evidence of a CO spiralling coma around a comet nucleus. The CO ro-vibrational line emission observed in comet Hale-Bopp from January to May 1997 exhibits strong East/West asymmetries, the position of the maximum brightness moving with time from up to $\sim 2''$ West to $\sim 2''$ East of the continuum peak (DiSanti et al. 2001; Brooke et al. 2003). This is probably caused by the rotating CO structure observed in the radio (Brooke et al. 2003) and shows that this CO structure is not a transient phenomenon related to some outburst.

Our model, which includes a single jet, appears to be too simple to interpret all the observational characteristics. Other “jets” are present, in particular another moving structure has been identified at positive velocities in the interferometric data. Its full characterization is difficult on the basis of our data and beyond the scope of this paper. The CO main jet is certainly more complex than a simple conical spiralling structure. Gas structures created by inhomogeneities in gas production at the nucleus surface will unescapably be modified during their outflow by the surrounding collisional environment (the collisional sphere in Hale-bopp coma exceeded 10^5 km near perihelion, Combi et al. 1999).

Gas dynamical models investigating the behavior of expanding dusty gas jets have been developed (see the review of Crifo et al. 2005). One or several active sources releasing water were considered, the remainder of the nucleus being assumed to be weakly active. They show that, because of lateral expansion driven by pressure gradients, jets broaden with increasing distance to nucleus, and interact with each other, to become eventually almost indiscernible in the outer coma. In addition, if there is solar modulation of the surface gas flux, the jet morphology will change its appearance as the nucleus rotates. These calculations may not however be relevant to the CO jet seen in comet Hale-Bopp. First of all, it is very likely that CO diffuses from subsurface layers. Our observations suggest that, to first order, there is no significant day-to-night asymmetry in the amount of CO gas released by the active source. Secondly, if the active source responsible for the CO jet does not produce similarly strong enhancement in water production, pressure smoothing will not be very effective and jet broadening may be produced instead by molecular diffusion. In this case, it is possible that a nearly invariant CO density pattern corotates with the nu-

cleus and remains relatively well preserved on large scales in the coma. However, it can be anticipated that the jet development will still be influenced by the surrounding environment.

A good illustration is the following. Rodionov & Crifo (2006) performed time-dependent 3D gas dynamical calculations by simulating rotationally-induced gas coma structures. They used an arbitrarily Halley-like aspherical nucleus, scaled to the Hale-Bopp nucleus size and homogeneous in composition. Carbon monoxide was assumed to diffuse uniformly from below the surface, and H₂O sublimates according to solar illumination. The computed CO coma was asymmetric. The model output has faint H₂O and CO spiralling structures resulting from weak shocks induced by the surface topography. In other words, the CO outflow is largely influenced by the general and detailed properties of the flow. The analysis of the CO Plateau de Bure observations using time-dependent (multi-fluid) gas dynamics calculations was performed by Boissier et al. (2005, 2009). They show that the observed time variations cannot be explained by the above mentioned shock structures, and are instead caused by a strong inhomogeneity in CO production from the nucleus surface or subsurface. Many hypotheses can explain this CO overproduction. It can traduce inhomogeneities in CO content inside the nucleus but also local variations in mantle thickness, or in some properties of the nucleus material (e.g., dust/ice matrix structure, thermal conductivity). We leave this discussion to experts and encourage them to perform numerical simulations (see the review of Prialnik et al. 2005).

5.3. Comparison with other studies

There are two open questions about our study:

- 1) is the CO jet that we observed related (correlated) to jets observed for other molecules?
- 2) is the CO jet that we observed related (correlated) to observed dust jets?

In their interferometric observations of several molecular species (HCN, HNC, DCN, HDO) with the OVRO array, Blake et al. (1999) observed that the molecular emissions reach their maxima at positions offset by a few arcsec from the continuum emission of the comet, and attributed these offsets to the presence of molecular jets. We do not observe such large offsets for CO when averaging the data over 70% of the rotation period. However, offsets of close to 1–1.5'' were observed for other molecules observed at the PdBI, which were interpreted to be the gaseous signatures of the high latitude dust jet observed in the visible (Boissier et al. 2007). The strong CO jet has no strong H₂S, CS, SO and HCN counterparts, although weak rotational modulations in the line shapes of their radio emission are observed for some of them (Boissier et al. 2007).

Lederer & Campins (2002) and Lederer et al. (2009) observed spiralling jets of OH, CN and C₂. Several (up to five) active areas were necessary to reproduce their observations from their Monte Carlo simulation. The strongest jets originate in low-latitude regions (-22° to $+20^\circ$). One of them could thus be associated with our CO jet. One low-latitude southern area is responsible for one-half of the OH coming from jet-source, but has a large opening angle (120°), so is unlikely to be related to the CO jet. Spatial profiles of H₂O obtained from long-slit observations of infrared water lines only show small East-West asymmetries (Dello Russo et al. 2000). In summary, there is no strong evidence of a strong H₂O jet associated with the CO jet.

Woodney et al. (2002) mapped HCN in comet Hale-Bopp with the BIMA array. Their observations, which spanned over

Fig. 26. Drawings of the inner coma of comet Hale-Bopp on 11 and 12 March, 1997 (N. Biver, 25.6 cm Newtonian telescope).

several days, were binned and averaged according to the phase of the comet rotation, to avoid smearing due to rotation. They found a jet morphology, possibly correlated with CN imaged in the visible. However, there is apparently no correlation of the HCN with dust jets. The presence of a high-latitude HCN jet is however inferred by the PdBI data (Boissier et al. 2007).

Dust jets also appear to be uncorrelated with our CO jet. From visible imaging at the time of the PdBI observations, Jorda et al. (1999) observed a high latitude (64°) dust jet. In the analysis of Vasundhara & Chakraborty (1999), strong dust jets are present from latitudes $+65^\circ$ and -65° , in addition to weaker jets from low latitudes (see also Schleicher et al. 2004). In February–May 1997, the high-latitude northern jet produced repetitive sunward shells instead of a full spiral (Fig. 26), indicating that the source of this dust jet stopped during the night, in contrast to the CO jet.

In addition to the CO main jet, we have identified a second moving structure in red channels that we believe originates in a low latitude source. Interestingly, on 1997 March 12.14 UT the dust coma presented a well defined shell at $\sim 40''$ in a direction opposite to the repetitive sunward shells produced by the high-latitude sources (Fig. 26). This shell was not present on March 11.16 UT, nor on March 14.80 UT, and can be attributed to an outburst initiated on March 11.20 UT, i.e., at the time when the

red structure began its expansion. The red structure is possibly related to this outburst.

5.4. Plans for further studies

ON–OFF and interferometric data were obtained at the Plateau de Bure interferometer for HCN, HNC, CS, H_2S , SO, H_2CO , and CH_3OH (Wink et al. 1999; Boissier et al. 2007). Some lines (e.g., lines of HCN and CS) do exhibit rotation-induced variations in their velocity shifts. Our analysis of the Plateau de Bure observations continues and will be presented in forthcoming papers.

The present study has showed that radio observations can provide valuable information about the distribution of parent molecules in inner cometary atmospheres and its temporal evolution. In contrast with standard imaging techniques, radio observations are sensitive to radial velocities, i.e., they are sensitive to the gas distribution along the line of sight, whereas the other techniques are rather sensitive to the distribution on the plane of the sky. They also probe different gas species. Radio observations and other techniques therefore provide complementary information.

Radio interferometric imaging is a powerful tool for astrometry. Our observations show that rotating comas can be also detected from the motion of the centroid of molecular maps. This opens new perspectives because possibly useful constraints on the rotation properties of cometary nuclei will be obtained from these measurements.

The analysis of our interferometric data was hampered by the limited instantaneous uv -coverage of the Plateau de Bure interferometer. The Atacama Large Millimeter and submillimeter Array (ALMA), with its 50 antennas, will be able to obtain images of molecular and continuum emissions with a short sampling time, high sensitivity, and high angular resolution. It will provide a 3D dynamical picture of inner cometary gaseous atmospheres, simultaneous images of the dust coma, and spatial information about the gas temperature (Biver 2005; Bockelée-Morvan 2008). Important breakthroughs in terms of nucleus and coma processes can be expected.

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