Observations of rotating jets of carbon monoxide in comet Hale-Bopp with the IRAM interferometer

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Abstract.
CO was observed on March 11, 1997 in comet Hale-Bopp with the IRAM Plateau de Bure interferometer. The maps show evidence for asymmetrical patterns, due to the existence of CO jets. Analysis of the spectra and their velocity shifts shows that there is a spiral CO jet rotating in a plane almost perpendicular to the sky plane. This is the first time that rotating jets are observed for parent molecules. We have developed a 3-D model simulating rotating spiral jets of CO gas. We present here the comparison between the observations and our models.

Keywords: comet C/1995 O1 (Hale-Bopp), comets, interferometry, molecules, radio lines

Comet Hale-Bopp was observed at the IRAM Plateau de Bure Interferometer (PdBI) between March 6 and March 22, 1997, while it was near its perihelion. The CO $J(2-1)$ and $J(1-0)$ lines were observed on March 11, from 4 to 15h UT. During the observations, the five 15-m antennas were in a compact configuration, providing baselines[1] from 20 to 150 m. Observations were performed either in the interferometric mode (for each couple of antennas, the signal received by one antenna is correlated with the other one) or in the single-dish mode, also called the *on-off* mode (for each antenna, the signal received is correlated with itself). $60'' \times 60''$ maps of the CO J(2-1) line were obtained with $2'' \times 1.4''$ spatial resolution ($\sim$ 1500 km in the coma) and 0.11 $\mathrm{km\,s^{-1}}$ spectral resolution.

Fig. 1.a. presents all the individual J(2-1) spectra obtained with the on-off mode of the interferometer. The velocity shift (the first order moment of the spectrum) is moving from positive to negative velocities. This is indicative of a jet which direction is moving from anti-Earthward to Earthward. The time evolution of the line velocity shift is plotted in Fig. 1.b. This curve is well fitted by a sinusoid with a period equal to the nucleus rotation period ($P = 11.35$ h from Jorda et al., 1999) and centred on $v_0 = -0.05$ $\mathrm{km\,s^{-1}}$. The spectrum velocity

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[1] A baseline is the vector between 2 antennas

shift represents the projection of the jet mean velocity on the line of sight. As the jet rotates with the nucleus, the velocity shift follows a sinusoid which amplitude and mean value v_0 depend both on the rotation axis coordinates and on the jet latitude, in addition to the jet strengh. Since the comet rotation axis was close to the sky plane (Jorda et al., 1999), the small negative value $v_0 = -0.05$ km s^{-1} that is observed is indicative of a northern jet located slightly above the equator.

The average CO $J(2-1)$ map, computed from the whole interferometric data set (Fig. 2), presents anisotropic features that cannot be due to the beam shape. We split this data set into several subsets of 1 h each, and we obtained the maps presented in Fig. 3.a. The direct interpretation of these maps is hampered by highly elliptical instrumental beams. Nevertheless, an interesting feature is to be noted. We have computed the mean photometric centre from the peak intensity on the map derived from the whole data set (last frame in Fig. 2). Similarly, we computed the individual centres for each map of Fig. 3.a. These centres follow a counterclockwise trajectory around the mean photometric centre (Fig. 3.b). Given the finite angular resolution of the observations, any anisotropic feature will offset the brightness distribution maximum toward its direction. Then, the displacement of the photometric centre reflects the evolution of the CO coma morphology, due to the rotation, as seen on the sky plane. In the case of a single rotating jet, this displacement should follow an ellipse which short axis has the position angle *P.A.* of the spin axis. The observed trajectory can be superimposed on an ellipse which short axis has $P.A. = 213^\circ$, corresponding to the rotation axis parameters of Jorda et al. (1999). This excludes those proposed by Farnham et al., (presented at IAU coll. 186 in Tenerife, Jan. 2002) providing $P.A. = 322^\circ$ at the time of the observations.

In order to go further in the analysis of the data, we studied directly the visibilities, which represent the Fourier transform of the brightness distribution on the sky. The observed visibilities show strong deviations from those expected for an isotropic distribution of CO. We developed a 3-D model of the coma consisting of an isotropic contribution plus a conical spiralling jet. Our goal was to understand and fit the velocity shifts curves (both on-off and interferometric) and the time evolution of the visibilities. The model results are in good agreement with the observations for a jet located at a latitude of $15^\circ \pm 5^\circ$ North, with an opening angle of $30^\circ \pm 10^\circ$. Furthermore, the jet outgassed $40 \pm 10\%$ of the CO in the coma. These results are in good agreement with the wide dust jet located at $10^\circ \pm 10^\circ$ North proposed by Samarasinha (2000, and personnal communication), in order to explain the coma morphology observed in the visible near the comet perihelion. The real structure of the jet may be more complicated than assumed, especially within the first thousand of kilometres from the nucleus. The question of its physical origin remains open. Here, we observed that nearly half of the CO was released in a small opening angle. It is then hard to explain how a highly volatile molecule can expand is such a way from a porous nucleus, as expected for comet Hale-Bopp. More details about the model and its results will be published in Astronomy & Astrophysics.

References

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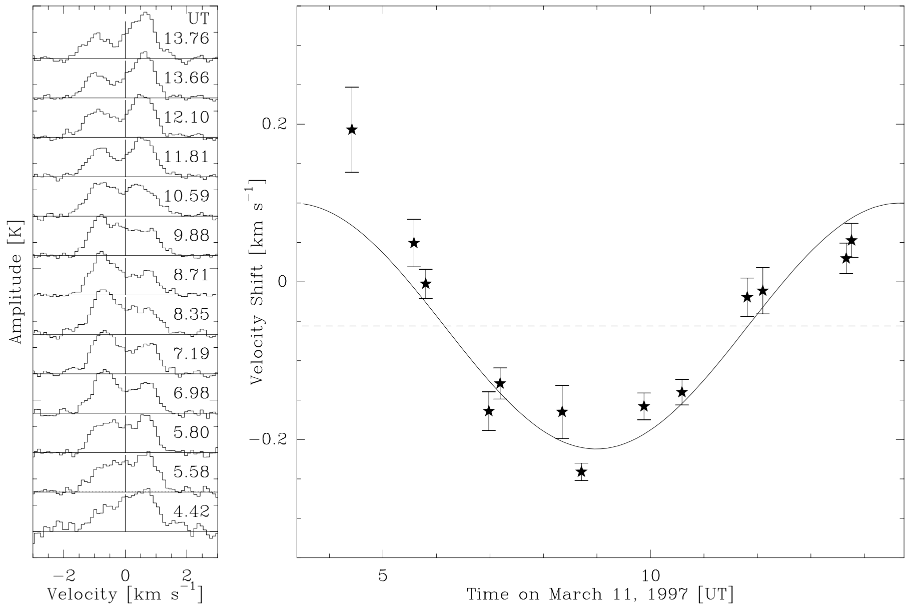


a. b.

Figure 1. **a : CO J(2-1) on-off spectra.** The integration time is 5 min for each spectrum. These spectra have been occasionally taken between the runs made in interferometric mode. **b : Time evolution of the velocity shifts of the indivisual spectra.** A sinusoid of period 11.35 h and centred on $v = -0.05\,\mathrm{km\,s^{-1}}$ (dashed line) is drawn

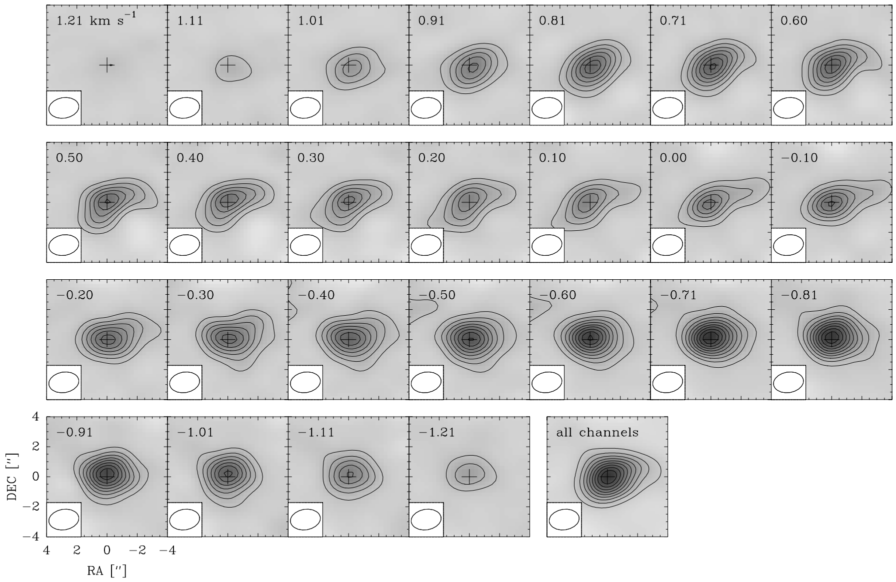
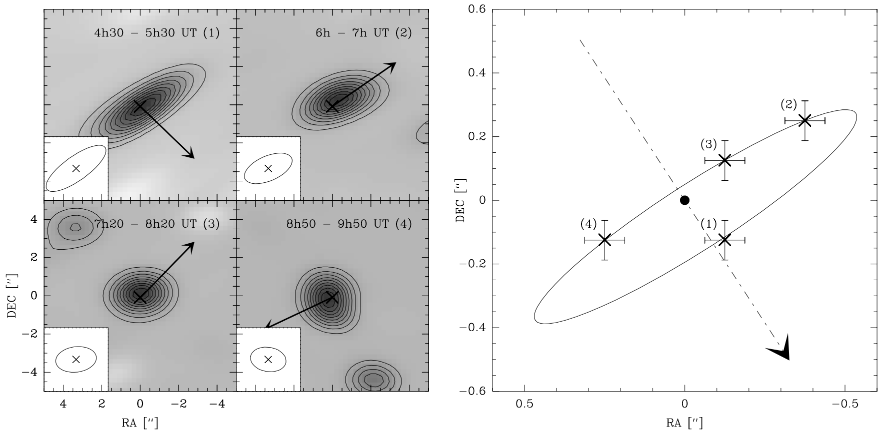


Figure 2. **CO J(2-1) spectral maps.** Each map corresponds to a velocity (in the nucleus frame). The beam shape is shown in the bottom left corner. The last frame is the result of co-adding all the individual spectral maps.



a. b.

Figure 3. **a : Individual maps for data subsets of 1 h.** Crosses locate the mean photometric centre (MPC) determined from the whole data set (last frame in Fig 2). For each map, the arrow represents the direction of the individual photometric centre. The beam shape is shown in the bottom left corner. **b : Time evolution of the photometric centres.** Crosses represent the photometric centres, the black disk locates the MPC, the dash-dotted arrow is the nucleus spin vector, and the ellipse drawn is the projection of a parallel of latitude 6 ° North of a sphere centred on the MPC, with aspect angle = 80 ° and position angle = 213 ° .