EVIDENCE FOR CHEMICAL HETEROGENEITY IN THE NUCLEUS OF C/1995 O1 (HALE–BOPP)

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Abstract. We present an analysis of OH, CN, and C_2 jets observed in the coma of Comet Hale–Bopp on UT April 22, 23, and 25, 1997. Monte Carlo models designed to simulate the gas jets were employed to analyze the nuclear active areas responsible for the observed coma gas jets. Our results indicate that four active areas are necessary to reproduce the CN and C_2 jets while five active areas are required to simulate the OH jets. The additional OH active area must produce significant levels of OH, but cannot emit measurable quantities of either carbon radical. This difference suggests that the nucleus of Comet Hale–Bopp is chemically heterogeneous.

Keywords: C/1995 O1 (Hale–Bopp), comets, gas jets

1. Introduction

Understanding the composition, structure, and homo- or heterogeneity of cometary nuclei is of utmost importance if we are to gain insights into these building blocks of planetary formation. The direct study of cometary nuclei, however, is difficult. When the comet is near the Sun, the nucleus is obscured by the coma. When little or no coma is present, the comet is far from the Sun and faint. Instead, many of the chemical and physical properties of the nucleus and its active areas are inferred by analyzing the coma gas and dust jets, which originate in the nucleus. The apparition of Comet Hale–Bopp in 1997 provided us with an excellent opportunity to study the morphology of different species in the coma, including tracking the evolution of gas and dust jets over many days, and sometimes months (Lederer et al., 1999).

Gas jets in Comet Hale–Bopp were observed in five species. Laffont et al. (1999) reported sunward dust and C_2 jets. As observed in Comet Halley (A'Hearn et al., 1986a, b), CN jets were also detected in Comet Hale–Bopp (Larson et al., 1999, Mueller et al., 1999). In these observations, Comet Hale–Bopp's dust jets coincided with the CN jets in the sunward direction, but not in the anti-sunward direction. Lederer et al. (1999) extended the list of observed gas jets in Comet Hale–Bopp to include not only C_2 and CN, but also OH, NH, and C_3 jets. Again, the gas jets were evident in the anti-sunward direction where no dust jets could be

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TABLE I
Comet Hale–Bopp observing details

Dates	April 22, 23, 25, and 26, 1997–	
r_H (AU)		0.987–1.016
Δ (AU)		1.62–1.69
Phase angle		36.0–33.3
PA_s		240°–247°
Species	Dust, OH, CN, C_2	

detected. Further analysis of these gas images demonstrated that although dust jets have some overlap with the gas jets in the sunward direction, the morphology of the gas jets was significantly different from that of the dust jets.

These morphological and spatial differences help us characterize the gas and dust jets separately, and yield clues about the origin of the gas jets. Previous observational evidence for chemical inhomogeneities in other cometary nuclei (e.g., Comets Encke and Halley) has been reported by several authors (A'Hearn et al., 1983; Mumma et al., 1990). Until now, we did not know whether Comet Hale–Bopp's gas jets originated from a homogeneous or heterogeneous nucleus. Through Monte Carlo models presented here, the observed morphology of gas jets is used to constrain the location and composition of the nuclear active areas in Comet Hale–Bopp. Our results indicate that the nucleus of this comet is chemically heterogenous.

2. Observations and Data Reduction

Data were obtained at Lowell Observatory with the 42″ (1.1 m) Hall Telescope and the 2048 × 2048 SITe charge-coupled device (CCD) camera (2 × 2 binned). The scale of the resultant images is 1.14″/pixel. The Comet Hale–Bopp filter set was employed for all observations. Each filter isolates either the light that fluoresces from a particular gas species (OH at 3090 Å, CN at 3870 Å, and C_2 at 5141 Å), or the light scattered by dust for the continuum filters centered at 3448 Å, 4450 Å, 5260 Å, and 7128 Å (see Farnham et al., 2000 for further details). Table I summarizes the observing details, including the dates on which the observations were made, the heliocentric (r_H) and geocentric (Δ) distances of the comet, the phase angle (Sun–comet–Earth), the position angle of the Sun (PA_s), and the species that were observed. The plate scale for these observations was roughly 1390 km/pixel.

Standard data reduction procedures were applied to obtain an absolute calibration of the observations. Images were corrected for atmospheric extinction and flux calibrated using the standard stars and calibration method outlined in Farnham et al. (2000). The underlying continuum due to the scattered light from dust in the comet's coma was computed and subtracted from each gas image; the amount of gas contamination in relevant filters was computed and eliminated. The resulting gas images contain signal created by fluorescence of the target gas species. A Minimum Azimuthal Subtraction (MAS) routine was applied to enhance the jets. Here, a template representative of the average radial brightness profile is subtracted from the data to yield an image representative of the non-isotropic component. Further details of the data reduction and enhancement routine can be found in Lederer (2000).

3. Modeling Results

Monte Carlo modeling can be used to investigate the chemical and physical properties responsible for the gas jets we observe. Our modeling effort was simplified because the Sun was located at a high cometocentric latitude in April, 1997, which dictates that any active area that resides entirely below roughly 20°S latitude is never exposed to the Sun. This limits the number of active areas that must be included in the model, and the uniqueness of the model is better constrained.

Here, we present the results of models designed to characterize the active areas on the cometary nucleus and simulate the behavior of gases as they evolve from the nuclear active areas into the observed coma gas jets. The modeling was performed using the 3-D time-dependent Monte Carlo cometary coma model described by Lederer (2000). The final model is a 2-D image of the coma projected onto the plane of the sky as dictated by the geometry describing the observations (Table I). Figure 1 demonstrates the fit of the models to the data. On the left are the images of the data taken on April 26, 1997 (approximately one month following perihelion). The images on the right are the best-fit Monte Carlo models. All three gas species are presented in this figure (OH top, CN middle, C_2 bottom).

This Monte Carlo model includes: (i) Collisions of the observed radicals (OH, CN, C_2) with other gases in the coma (primarily water and OH because these are the most abundant coma gases), (ii) gas acceleration in the coma, (iii) radiation pressure from the Sun, and (iv) ejection of the precursors (parents) of the observed gases from discrete active areas on the nucleus that result in coma jets. The observed daughter radicals are produced when a parent decays. The parent's behavior has been modeled through a distribution representative of either an exponential decay or a triangular distribution. The former distribution represents the photodissociation of a parent gas (e.g., H_2O or HCN) while the latter represents production from an extended source (e.g., sub-micron organic grains). For all gas species, observations are best described by models that include radicals produced partially by parent gases and partially by an extended source (see Lederer, 2000 for further discussion).

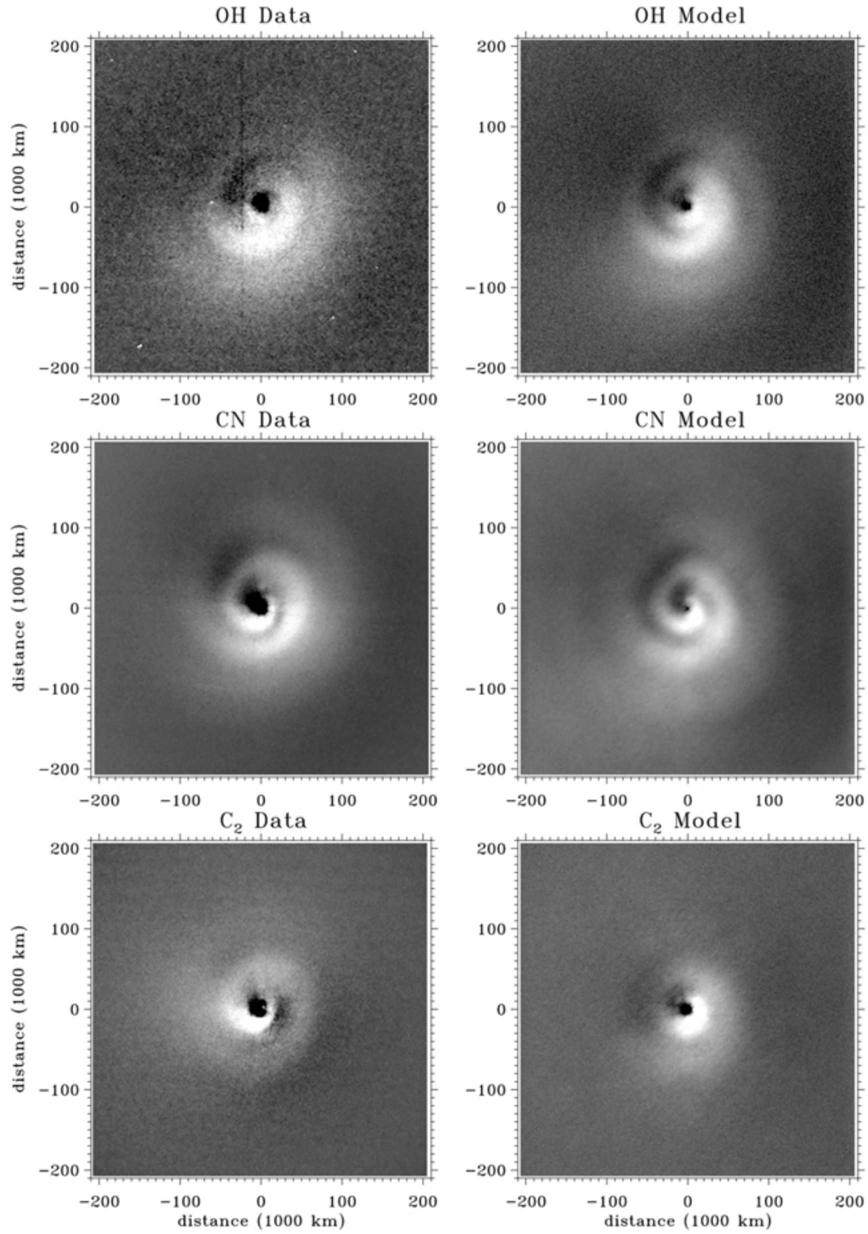

Figure 1. Data and models (April 26, 1997). The images on the left are OH, CN, and C_2 data. The images on the right are the Monte Carlo models that best reproduce the observations for each species. Greyscale translates to intensity. The jets originate from a triangular (grain) extended source. A diffuse (isotropic) gas source model must be combined with the jet model to reproduce the morphology. North is up and east is left. The position angle of the sun is 247°.

TABLE II
Parameters describing the model active areas

Species	lat (°) (± 5)	long (°) (± 10)	Open. Ang. (°) (± 10)	Strength (± 20%)	Q_g (%) (± 5%)
OH (AA 1)	60	175	20	1.0	9
OH (AA 2)	20	240	40	3.0	22
OH (AA 3)	15	120	60	1.2	8
OH (AA 4)	−22	225	60	5.3	17
OH (AA 5)	−12	120	120	10.0	44
CN (AA 1)	60	175	40	1.0	16
CN (AA 2)	13	240	40	4.0	43
CN (AA 3)	15	120	60	1.3	16
CN (AA 4)	−22	225	40	4.0	25
C_2 (AA 1)	60	175	50	1.0	16
C_2 (AA 2)	13	240	60	4.0	43
C_2 (AA 3)	15	120	90	1.3	16
C_2 (AA 4)	−22	225	90	4.0	25

Table II lists the free parameters in our model that describe the discrete nuclear active areas responsible for the coma jets, including: (a) The cometocentric latitude and longitude of the center of the active area (AA), (b) the opening angle (*Open. Ang.*) of the active area, (c) the relative strength of the active area (*Strength*), and (d) the contribution (%) that each individual active region makes to the total production rate of radicals by grains (Q_g). The relative strength denotes the number of particles of a given species that one active area would produce, compared with the other areas producing that species if all active areas were equally illuminated.

Our results indicate that three to four active areas, producing the same OH:CN:C_2 mixture, are necessary to reproduce the coma jets in all three gas species. Three of these active areas are located in the northern hemisphere ([60°N, 175°], Active Area 1; [20°N, 240°] for OH or [13°N, 240°] for CN and C_2, Active Area 2; and [15°N, 120°], Active Area 3). The third of these is necessary to reproduce the CN, but not the OH or C_2 (see Discussion). The fourth, Active Area 4, is located at [22°S, 225°]. A fifth region, Active Area 5([12°S, 120°]), must be included in the OH models to recreate the OH jet morphology, but *cannot* be included in the CN or C_2 models. This region is responsible for about half of the jet-source OH.

4. Discussion

The number of active areas required by our models depends on the species of interest. Our models best reproduce the coma morphology when three to four areas for CN and C_2, or four to five areas for OH are active on the comet's surface. The model parameters required to fit the CN and OH data are more restrictive than those needed to fit the C_2 data. Therefore, the models more rigorously constrain the locations of the active areas producing OH and CN jets than the C_2 jets. We base our conclusions primarily on our OH and CN analyses, and include the C_2 study as it does offer additional information.

In all species, care should be taken when directly comparing the observation's inner coma with the model's inner coma. The processing applied to (a) emphasize the jet morphology (applied to both the observation and the model) and (b) subtract the underlying continuum (applied only to the observation), can affect the morphology. The combination affects the intensities (brightness) within 10–20,000 km of the central condensation, so we did not place great emphasis on morphology fits within $\approx$ 20,000 km. The continuum subtraction can create residual effects within 40–70,000 km, especially in the SW (lower right) quadrant where the dust jets are the most visible. The underlying continuum contributes 10–20% of the signal in the OH data, 20–30% in CN, and 60–70% in C_2. The continuum subtraction, then, will most notably affect the C_2 data, as can be seen in the C_2 data image presented here. We believe that these effects are largely responsible for the intensity differences between the C_2 data and model (e.g., the innermost C_2 jet appears strongest in the south (data) versus the southeast (model), and a dark trough is visible in the southeast portion of the data, but not in the model).

In addition, our models only produce C_2 as a daughter product, not as a granddaughter or great-granddaughter. Studies by Lederer (2000) suggest that changing the parent and daughter lifetimes (as would be necessary to include these processes) would most strongly affect how the intensity of the jets changes with distance from the nucleus, but should not affect the locations of the coma jets. This may partially explain the discrepancies between the morphology of the C_2 data and model. A full analysis of how each input parameter affects the models can be found in Lederer (2000). Based on this analysis, we can say with confidence that although the C_2 fit is not as good, it does not alter our conclusions.

Vasundhara and Chakraborty (1999; hereafter VC99) report that three active areas are required to model the dust jets in their April 10 and May 2, 1997 images. However, incorporating the exact locations of the active areas employed by VC99 produced significant discrepancies between our model's coma gas jet locations and widths when compared with our observations. Hundreds of combinations of active area parameters were subsequently tested. Fortunately, the data are remarkably limiting and only the combination of jet parameters presented here results in a model that fits the observations to within the errors listed (Table II).

Although there are some differences in the exact locations of the active areas between the models in this study and those in VC99, there are also significant similarities. Both models require one active area at a high latitude (Active Area 1) and at least two active areas located near the comet's equator (Active Areas 2 and 4). The region located at the high northern latitude (60°N; Active Area 1) is likely physically much smaller than the near equatorial active areas. Unlike VC99, our gas models require an additional active area at a very low latitude (22°S; Active Area 4). The gas production from this region, which is always exposed to near-twilight conditions, may not be strong enough to lift relatively large (optically scattering) dust particles from the surface, but could lift sub-micron grains in the gas flow, which may be the extended source that produces the gas jets. This would explain why VC99, whose data detects only the larger, optically scattering dust particles, did not invoke a source at this latitude to reproduce their dust jets.

Comparison of the strengths and locations of Active Areas 1, 2, and 4 shows that they are emitting roughly the same relative mixture of OH:CN:C_2. An ambiguity in the total number of active areas arises here because Active Area 3 is emitting only a relatively minor amount of gas, but is required to simply increase the amount of CN in the sunward trough closest to the central condensation. In contrast, the OH and C_2 images display jet peaks that coincide with the location of this CN trough. Although Active Area 3 is not required to reproduce the morphology (shape or brightness levels) of the OH and C_2 jets, it is included in the OH and C_2 models to verify that the same mixture of OH:CN:C_2 *can* be emitted from all four active areas required to reproduce the CN morphology. Alternatively, if some of the CN is a granddaughter product as opposed to a daughter product (an effect not currently included in our models), the effect might also result in filling in this trough. Hence, we do not consider the presence of Active Area 3 to be as well constrained as the other active areas.

If only these active areas existed (1–4), then one could reasonably assume that Comet Hale–Bopp was homogeneous because the same OH:C_2:CN mixture can be emitted from each nuclear region. However, important evidence suggests otherwise: the cometocentric locations of two active areas producing the OH jets do not coincide with those that recreate the CN and C_2 jets. Although one varies only slightly in latitude (Active Area 2), the other requires an entire additional region (Active Area 5). In contrast, the dissimilarities in the CN and C_2 morphologies are created by the differences in the opening angles, daughter velocities, and daughter lifetimes of these two species, not by any variations in active area locations.

Our models indicate that the latitude of Active Area 2, which produces a relatively small portion of the gas jets, is somewhat higher for OH compared with the carbon species. It is unclear whether this difference is real because (i) it resides at the same longitude for all three species (240°), and (ii) it differs only slightly in latitude (20° for OH; 13° for CN and C_2). Attempts were made to resolve the difference in latitude by shifting either the OH-producing region to a more southerly location consistent with the carbon-species, or the reverse. Shifting either source by only ∼5° caused a noticeable (detrimental) change in the morphology, suggesting that the difference in locations is real. Alternatively, an additional (unknown) effect not included in our model may be responsible for this difference.

The existence of Active Area 5, producing only OH, is of particular interest because it implies that the nucleus of Comet Hale–Bopp is not homogeneous. This active region produces roughly half of the OH that originates from the extended source. However, no appreciable amount of CN or C_2 can be emitted from this region without negatively altering the morphology of the carbon species jets. This additional active area creates the bulk of the morphology differences between OH and the carbon species (e.g., variations in coma jet width, anti-sunward OH peaks coinciding with troughs observed in the carbon species). These results suggest that the composition of the nucleus is heterogeneous.

5. Conclusions

Our models suggest that Comet Hale–Bopp's coma gas jets, observed in April, 1997, originated from a heterogeneous nucleus. Four to five active areas on the surface of Comet Hale–Bopp are necessary to recreate the gas jet morphology evident in our observations of OH, CN and C_2. Three of the active areas can be modeled as having been produced by the same mixture of these gas species; the mixture of an additional active area is indeterminate, but may be the same. Significantly, the fifth active area produces almost half of the jet-source OH, but cannot produce measurable amounts of CN or C_2. This active area is responsible for the variations observed between the morphology of the OH coma jets and that of the carbon species. The extreme enhancement of OH originating from this active area suggests that the coma is not produced by a completely homogeneous nucleus.

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