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Three tails of comet Hale-Bopp

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Abstract. We report on the imaging detection of the sodium tail of comet Hale-Bopp using large field-of-view, multi-wavelength observations from the McDonald Observatory in March 1997. We subtract off-band images from sodium-filter images to obtain the atomic sodium tail, and we find it to be more extended in width than either the dust or ion tails. The cross-tail integrated brightness of the sodium tail increases with distance from the nucleus for at least 8 million km. The direction of the sodium tail in our data is different from the ion tail, the dust tail, and the sodium tails imaged at different times by other observers. To account for these characteristics, there must be an extended source of sodium atoms tailward of the comet nucleus. We propose that the sodium tail in March 1997 was produced by the release of sodium atoms from grains in the dust tail.

Introduction

The apparition of comet Hale-Bopp in early 1997 brought considerable attention to the origin, evolution and loss of atmospheric material from the surfaces of primitive bodies. The transient atmosphere associated with a comet's passage through the inner solar system is similar, in many ways, to those associated with Mercury, our Moon, and Jupiter's moon Io. Production of gas by sputtered and/or evaporated surface material, loss by ionizing radiation, and transport by flowing magnetized plasma and/or photon pressure all influence the brief time histories of these atmospheres. Imaging observations of sodium (Na) emission have proven to be a valuable diagnostic of neutral gas and plasma processes in such systems.

Spectral detections of Na in comets, starting with comets 1882 I and 1882 II [*Levin*, 1964], have lead to postulations of several source mechanisms (a good review is given by *Combi et al.* [1997]). Possible sources include dust grain evaporation for sun-grazing comets [*Huebner*, 1970], and the release of Na-bearing molecules from sublimating ices on the nucleus [*Oppenheimer*, 1980]. More recently, analysis of spatially resolved spectra led *Combi et al.* [1997] to postulate the dissociation of molecular ions in the plasma tail as a source.

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The bright comet Hale-Bopp provided the first opportunity for two-dimensional imaging of a comet's sodium tail. After the first report on Na emission from Hale-Bopp by *Kawabata et al.* [1997] on February 26, the European Hale-Bopp Team [*Cremonese et al.*, 1997a] obtained images of a Na tail on April 16, showing a different morphology from the comet's plasma and dust tails. In this letter, we report on observations taken between these two times, showing that the Na tail changed significantly between March and April of 1997.

Observations

We made our observations on March 17 and 20, 1997, from Boston University Station at the McDonald Observatory in Fort Davis, Texas. The telescope and detector systems have been described in several previous works that dealt with imaging the extended Na atmospheres of Io (Jupiter) [*Mendillo et al.*, 1990; *Flynn et al.*, 1992] and the Moon [*Mendillo et al.*, 1991, 1993; *Mendillo and Baumgardner*, 1995]. It is a 0.1 meter refractor with a six-degree field of view, optimized for very low level imaging using either an image-intensified or a bare CCD camera system [*Baumgardner et al.*, 1993]. A filter wheel provides images at a choice of four narrow band (~±7 Å) wavelengths. The optical system is a coronagraph with a choice of masks to occult the bright disks of Jupiter or the Moon. The images of Hale-Bopp have the comet to one side of the center of the field of view in order to avoid the central mask. We made observations at three wavelengths: 5893 Å (to detect Na at 5890 and 5896 Å), 6199 Å (an emission line of H_2O^+), and 6050 Å (an off-band wavelength used to subtract continuum light sources). Table 1 summarizes the multi-wavelength set of images used in this study.

Data Reduction

We first bias subtract, flat-field, and normalize the images to a single exposure time. We then subtract background scattered light from the sky, including a gradient introduced by evening twilight and scattered moonlight. Finally, we correct the images for atmospheric extinction by measuring the changes in the brightnesses of several field stars in each series of images.

We next subtract the 6050 Å images from Na and H_2O^+ images to remove the dust tail. To obtain an estimate of the relative brightnesses of the dust tail as seen in the different wavelength bands, we assume that

Table 1. Hale-Bopp Imaging Data, March 1997

Date	U.T.	Filter (Å)	Exposure (s)
March 17	2:02	5893	60
	2:04	6050	60
	2:11	5893	120
	2:16	6050	240
March 20	1:57	6050	90
	2:02	6050	90
	2:04	6050	90
	2:12	6199	90
	2:19	6199	180
	2:23	6050	180
	2:30	6199	180

the Moon and dust tail are spectrally similar, and take images of the Moon seen though translucent white glass with each filter. (These lunar images are also corrected for atmospheric extinction.) This technique measures the relative instrumental brightness of the lunar (i.e., solar) spectrum at the different wavelengths. We then subtract the offband image, scaled by the correct factor, from the Na and H_2O^+ images to effectively remove emission from the dust tail. We note that the scattered light from comet dust is typically reddened with respect to the solar spectrum by at most 10% per 1000 Å (Lien, 1991), and that our off-band filter is displaced by at most 160 Å from the two on-band filters.

The final reduction steps calibrate the images in brightness units of Rayleighs (R). Through each filter, we image a standard source which is a disk coated with a phosphor containing carbon-14. The C_{14} decays and causes the phosphor to glow. Finally, we adjust the image brightnesses to account for the filter transmissions at the relevant emission line wavelengths. The Na emission from the Earth's atmosphere was approximately 200 R on March 17, and this is removed from the final Na images.

The complete set of original images and the final Na and H_2O^+ images are shown in Figure 1(a-f). Our subtraction method completely removes the dust tail from the 6199 Å image, without any significant oversubtraction from the ion tail or background. This gives us confidence that the dust-tail subtraction from the Na image is similarly accurate. The Na tail in March 1997 was broader than the dust tail as seen from the Earth. It was also narrower near the nucleus and broader further away. The narrow Na tail observed by *Cremonese et al.* [1997a,b] in mid April is not evident in our data.

Discussion

To portray more clearly the spatial relationships between the three comet tails, we plot the Na brightness contours on an image of the dust and ion tails in Figure 1(g). Although a portion of the Na tail overlaps the ion tail, the brightest portion of the Na tail does not coincide with the ion tail; we thus rule out Na released by recombination of Na^+ or dissociation of Na-bearing molecular ions along the plasma tail as sources for most of the tail. This contrasts with a result from *Combi et al.* [1997] who measured a bifurcated cross-tail Na emission profile in comet Halley which closely resembled the ion tail structure.

Surprisingly, the total cross-tail integrated brightness of the Na tail increases with distance from the nucleus. In Figure 1(h) we plot the tail brightnesses, integrated perpendicular to the comet-sun axis, versus distance from the comet nucleus. The Na tail increases in brightness out to at least 8 million km, while the H_2O^+ and dust tail profiles decrease over the same distance.

The peculiar brightness distribution of the Na tail indicates that most of the Na could not have traveled in atomic form from the nucleus. *Combi et al.* [1997] observed "flat" Na brightness profiles out to 120,000 km along the tails of comets Halley, Bennett, and Kohoutek, and attempted to model the distribution with a nuclear gas source of Na. They found that such a source results in a tailward brightness which decreases with distance, despite the effects of changing g-factor and radiation acceleration as the atoms move away from the nucleus. They concluded that extended Na sources operate down the tails of these comets, and the same conclusion applies to Hale-Bopp's diffuse Na tail.

The morphology of the diffuse Na tail is most consistent with a source from dust. Most significantly, the brightest portion of the Na tail lies within the dust tail, near the anti-solar edge (the edge closest to the ion tail). This side of the dust tail contains dust particles with the highest value of β, which is the ratio of radiation pressure acceleration to gravitational acceleration [*Finson and Probstein*, 1968].

There are several possible mechanisms for liberating Na from dust grains. Dust grain evaporation has been proposed as a source for sun-grazing comets [e.g., *Huebner*, 1970]. Presumably, the same processes proposed for the regoliths of the Moon and Mercury are applicable, including thermal desorption, solar photodesorption, and solar wind sputtering [e.g., *Sprague et al.*, 1992; *Potter and Morgan*, 1997]. Another possibility is the electrostatic disruption of dust, caused by charging of the grains in the plasma of the solar wind [*Mendis and Horanyi*, 1991].

Certain characteristics of comet Hale-Bopp may have been amenable to a high production rate of Na from dust. Hale-Bopp was producing dust at a rate of $\sim 3 \times 10^5$ kg/s [*Senay et al.*, 1997], one of the highest of any comet in decades [*Schleicher et al.*, 1997]. In addition, Hale-Bopp's dust had a smaller mean grain size than most comets, giving the dust a higher than average temperature for a given distance from the sun [*Hanner*, 1997]. Combined, these properties may have enhanced the production of Na from dust grain evaporation relative to other comets at the same heliocentric distance (.95 AU).

We estimate that the Na gas production rate in Hale-Bopp on March 17 was among the largest in the solar system. In order to derive a lower limit to the Na production rate, we assume that the D-line resonance wavelengths of the atoms are Doppler shifted entirely outside of the Fraunhofer D-line features, meaning that the emission rate per atom is maximized. This means that the column abundance of Na (in cm^{-2}) is given by (6×10^4) times the emission rate in Rayleighs [adapted from *Brown and Yung*, 1976]. From the computed column abundances, and by summing over the entire Na image, we derive a total Na abundance in the tail of $\sim6\times10^{30}$ atoms. Using the theoretical 47 hour photoionization lifetime at 1 A.U. [*Huebner*, 1992; also see *Combi et al.*, 1997; *Cremonese et al.* 1997b], and assuming sources and sinks are balanced in the Na tail, we derive a total production rate of at least 3.5×10^{25} Na atoms s^{-1}, or about 1 kg s^{-1}. If the radial velocities are lower than we have assumed, or the photoionization lifetime is shorter, then a higher production rate of Na atoms is required to explain the observed emission rates. (Also, our images do not capture all of the Na because the tail extends to the edge of our field of view.) For comparison, Jupiter's moon Io (the largest known source of Na atoms) typically ejects ~few $\times10^{26}$ Na atoms s^{-1}.

Perhaps the most interesting aspect of Hale-Bopp's Na tail was the dramatic appearance in April 1997 of a bright, narrow tail component [*Cremonese et al.* 1997a]. Unlike the diffuse tail, the narrow tail decreased in brightness with distance from the nucleus. The brightness and morphology of the narrow tail was consistent with a nuclear source of $\sim5\times10^{25}$ Na atoms s^{-1} [*Cremonese et al.* 1997b], comparable to the diffuse Na tail production rate. Since no narrow tail is obvious in our data, this nuclear source must have commenced (or increased) between March 17 and April 16, 1997.

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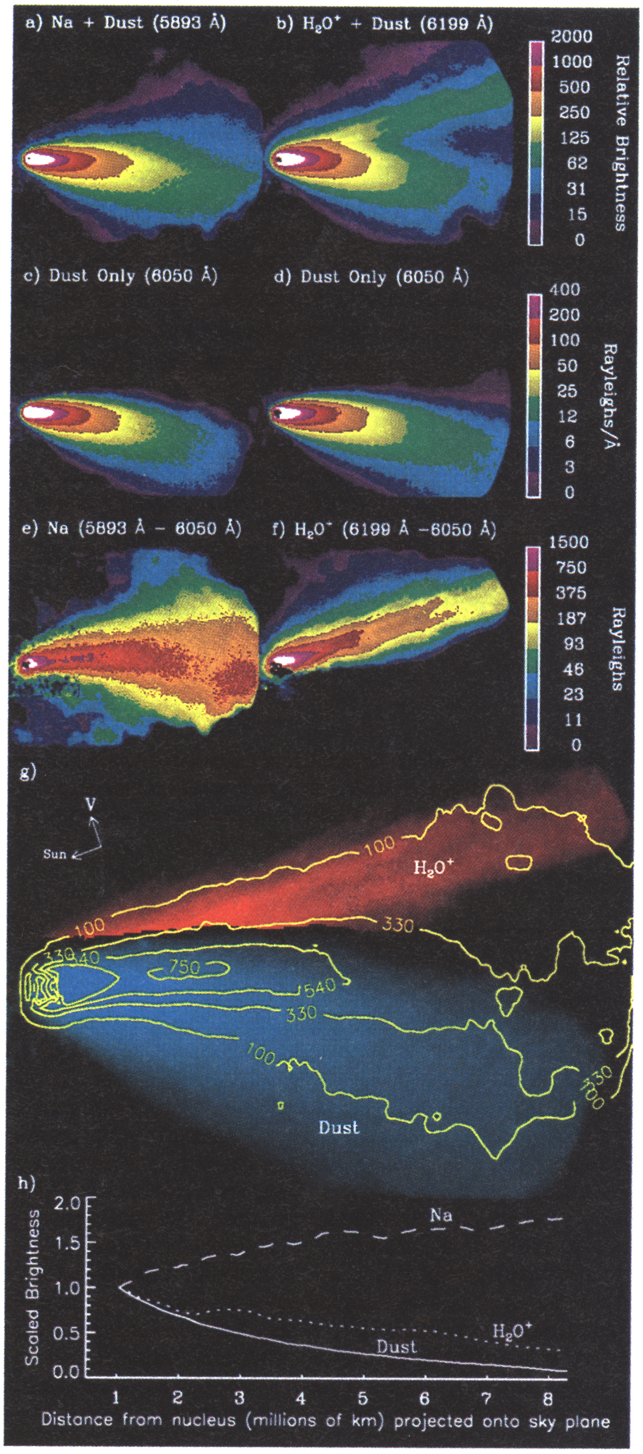

Figure 1. Comparisons of Hale-Bopp's tails. a) Average of two images at 5893 Å, March 17, showing both dust and sodium atoms. b) Average of three images at 6199 Å, March 20, showing dust and the ion tail (H_2O^+). c,d) Images at 6050 Å (off-band) on March 17 and 20, respectively, showing dust only. e) Image of the sodium tail; difference of 5893 Å and off-band images. f) Image of the H_2O^+ tail; difference of 6199 Å and off-band images. g) Superposition of the H_2O^+, Na, and dust tails. The dust tail has been placed "on top" of the ion tail to show its full extent. Contours are the brightness of the sodium tail in Rayleighs. h) Cross-tail integrated brightness profiles of the three tails. The tail brightnesses are integrated perpendicular to the radial vector from the nucleus, and plotted versus distance from the nucleus. Unlike the dust and ion tails, the sodium tail increases in brightness with distance from the nucleus.

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