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Letter to the Editor

The spatial sodium distribution in the coma of comet Hale-Bopp (C/1995 O1)*

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Abstract. Long-slit spectra of sodium D-line emission in the coma of comet Hale-Bopp (C/1995 O1) have been obtained on 14 March and 16 April 1997 from the Observatoire de Haute-Provence, France, and the William Herschel Telescope on La Palma, Spain. The spectra show Na spatial profiles within $\approx 2.5\ 10^5$ km from the nucleus along and perpendicular to the sun-comet line. In both observing periods secondary maxima are present, indicating spatial structures in the coma sodium distribution. A comparison with the structures seen in the cometary dust continuum is made. A Na production rate of $\approx 3\ 10^{24}$ - $5\ 10^{25}$ s^{-1} could be derived on March 14, 1997, corresponding to less than 0.3% of the normal cosmic abundance ratio Na/O.

Key words: comets – Comet Hale-Bopp (C/1995 O1)

1. Introduction

Sodium D-emission in comets is the only tracer of a non-volatile cometary constituent accessible in ground-based observations, except in sungrazing comets, where other metallic lines are seen. It has been observed in several comets in the past (e.g.: Greenstein and Arpigny 1962; Rahe et al. 1976; Oppenheimer 1980; Hicks and Fink 1997). However, the recent intensive observing campaigns of the perihelion passage of comet Hale-Bopp (C/1995 O1) have resulted in a unique coverage of several aspects of Na emission in one comet. The most striking observation was the discovery of a several degrees long sodium tail in wide field images (Cremonese et al. 1997a). In addition, high-resolution measurements of the Doppler shift of cometary Na atoms provide information on their kinematic in the coma region (Arpigny et al. 1998) and in the tail (Cremonese et al. 1997b).

Observations of the inner coma sodium distribution in comets suggest the existence of an extended source for Na atoms, in addition to a nucleus source (Huebner 1970; Oppenheimer 1980; Arpigny et al. 1998). Release from dust particles or neutral parent molecules has been discussed. Recently, the existence of an ionic parent molecule has been suggested and the effect of collisions of sodium with heavy neutrals was evaluated (Combi et al. 1997). The spatial sodium profiles presented here provide further constraints on the nature of the sodium source.

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* Based on observations obtained at the William-Herschel-Telescope, La Palma, and the Obs. de Haute-Provence, France

Table 1. The heliocentric distance, r_h, and velocity, v_{hel}, the geocentric distance, Δ, and velocity v_{geo}, and the phase angle, β, are given.

date	time UT	air mass	r_h [AU]	Δ [AU]	v_{hel} [km/s]	v_{geo} [km/s]	β [°]
14.3.97	03:51	3.243	0.968	1.343	-10.1	-11.7	47.6
	04:56	2.255	0.968	1.343	-10.1	-11.7	47.6
16.4.97	20:22	2.286	0.956	1.536	9.0	26.3	39.5
	21:19	3.966	0.956	1.536	9.0	26.3	39.5

2. Observations and data reduction

Comet Hale-Bopp was observed on 14 March, 1997, at the Observatoire de Haute-Provence, France, using the CARELEC spectrograph (slit length 5.5 arcmin, 1.1 arcsec/pixel, dispersion: 1.8 Å/pixel) at the 1.93m telescope. On 16 April 1997, spectra of comet Hale-Bopp were taken using the ISIS double beam spectrograph (slit length: 4 arcmin, 0.36 arcsec/pixel) at the 4.2m William-Herschel-Telescope (WHT) of the Isaac-Newton-Group telescopes at La Palma, Spain, with a dispersion of 0.4 Å/pixel (see Table 1).

Sodium emission is caused by resonant scattering of the incoming solar light. Therefore, the line intensity and acceleration of sodium atoms by solar radiation pressure depend strongly on the Doppler shift of Na emission with respect to the solar Fraunhofer absorption lines. In both observing periods the effective solar flux was relatively similar, resulting in accelerations for Na atoms of 24 cm s^{-2} and 22 cm s^{-2} on 16 April and on 14 March, 1997, respectively. However, as the Na atoms accelerate in the coma, they experience a decreasing acceleration in March and an increasing acceleration post-perihelion, caused by the shift of cometary sodium D-emission towards or away from the center of the solar Fraunhofer absorption lines. Therefore, the excitation and dynamics of sodium in the coma of Hale-Bopp can differ somewhat in March and April.

The spectra were bias subtracted, flatfielded and wavelength calibrated. Because of the unfavourable observing conditions for Hale-Bopp at perihelion, the comet could only be observed close to twilight. Determining the sky contribution was therefore difficult. The variable water content of the atmosphere results in contamination of the Na emission lines by telluric water absorptions, which cannot be completely removed. However, because of the different spectral regions and depending on the Doppler shifts, each Na line is affected differently. Therefore, we consider as real all structures which appear always in both emission lines. In March, an absolute flux calibration could be obtained, but in April, non-photometric conditions did not allow us to derive absolute fluxes. To measure Na emission, the underlying continuum by reflected solar light on cometary dust particles was subtracted. For the spectra obtained in March the solar spectrum was taken from a solar atlas (Kurucz et al., 1984), smoothed by convolution with a Gaussian profile to the resolution of the measured spectra. In April, the reflected solar light from the moon was measured.

3. Spatial distribution

Sodium emission is observed up to distances $>2\ 10^5$ km sunward in both observing periods (Figs. 1 and 2). In all spectra taken around the nucleus position, the sodium distribution is very asymmetric. In profiles along the sun-comet line the emission is always stronger towards the sunward direction. To compare Na and the dust continuum, both spatial profiles have been normalized to the same maximum intensity in Figs. 1a and 2a.

Sodium emission falls off less steeply than the dust emission and shows a sudden drop in intensity at about $5\ 10^4$ km and $7\ 10^4$ km in March and April, respectively (Figs. 1c and 2c). However, Na and dust show a similar general sunward/tailward asymmetry. The asymmetric continuum is indicative of preferred sunward outgassing of volatiles from the nucleus. The asymmetry in sodium reflects asymmetric outgassing from the nucleus itself and/or release from a non-isotropic parent distribution. Asymmetries are also found in spectra taken at the nucleus position with the slit along the direction perpendicular to the sun-comet line (Fig. 3). For both, sodium and continuum emission a simple distribution for outgassing of a parent species from the nucleus (following a $1/\rho$ distribution, ρ: nucleocentric distance) cannot be applied.

Secondary maxima of the sodium intensity distribution are found sunward. Such maxima are also present when the slit is aligned perpendicular to the sun-comet line (Fig. 3), but not when offset by 2 arcmin tailward (Fig. 4). NH_2 emissions present in our spectra do not show secondary maxima and only a relatively weak sunward/tailward asymmetry. However, similar secondary maxima are present in the continuum (Figs. 1b and 2b) where the slit cuts through dust jets and shells, which can be seen in optical images of Hale-Bopp's dust distribution.

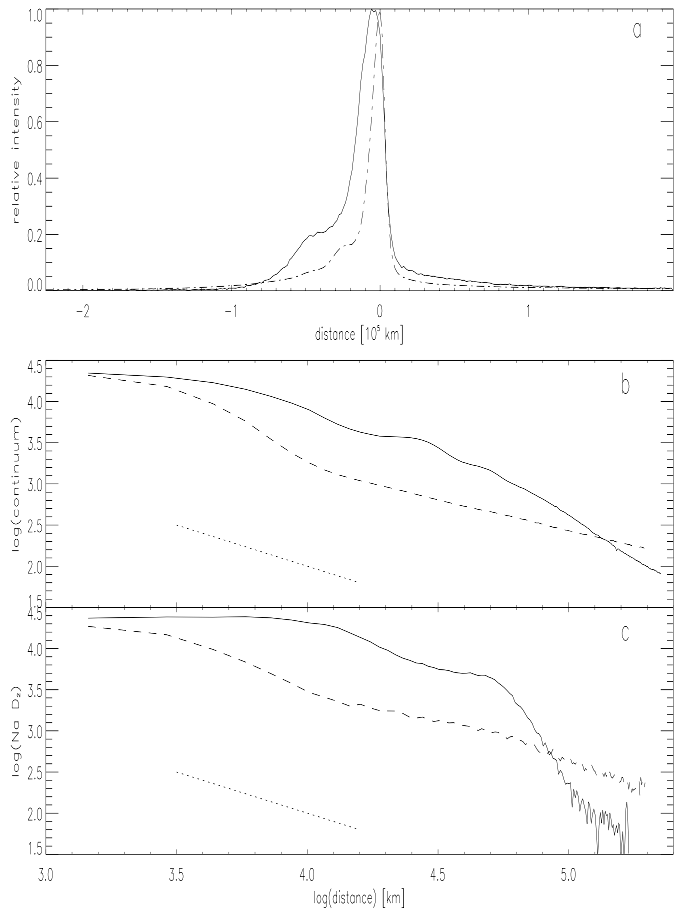

Fig. 1a–c Spatial sodium and continuum distribution on 14 March 1997 (3:51 UT, exposure time: 60 s) along the radial direction. **a:** Na D_2 line intensity (solid line) and continuum distribution (dashed-dotted line) over nucleocentric distance along the sun-comet line. Intensities are normalized to one at maximum intensity. The Sun direction is to the left. **b**, **c**: Continuum **b** and Na D_2 **c** distribution over nucleocentric distance on logarithmic scales. Solid line: sunward, dashed line: tailward direction. A distribution corresponding to an inverse distance law is shown for comparison (dotted line).

Comparing sodium and dust intensities, it is important to note that the maxima present in the dust are weaker and their position and number does not correspond to the sodium emission.

4. Sodium production rate

On 14 March, 1997, we derived the sodium production rate from the spectrum taken with the slit placed across the tail at 2 arcmin offset to the antisolar direction (Fig. 4). We integrate the column density, N, across the slit and multiply by the average velocity, $\bar{v}$, of Na atoms at the observed distance from the nucleus: $Q_{\rm Na} = \bar{v} \int N dx$. The derived column densities are inversely proportional to the excitation rate, which also depends on the velocity of sodium atoms and the resulting Doppler shift relative to the solar spectrum. From high-resolution Doppler-shift mesurements of the Na velocity in the coma (Arpigny et al. 1998) we

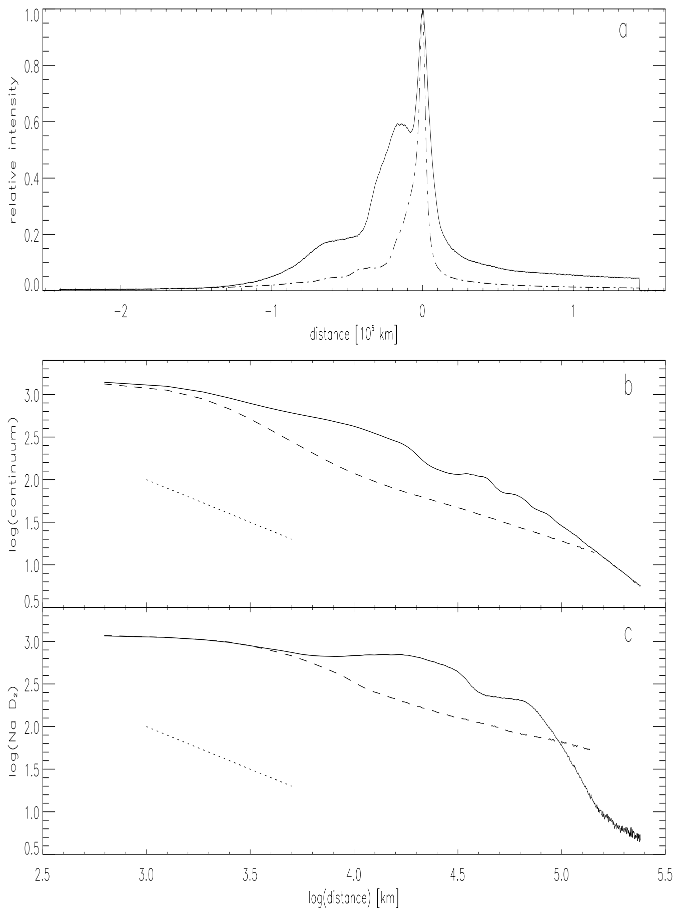

Fig. 2a–c Spatial sodium and continuum distribution on 16 April 1997 (20:22 UT, exposure time: 120s) along the radial direction. **a**: Na D_2 line intensity (solid line) and continuum distribution (dashed-dotted line) over nucleocentric distance along the sun-comet line. The intensities are normalized to one at maximum intensity. The Sun direction is to the left. **b**, **c**: Continuum **b** and Na **c** distribution over nucleocentric distance along the sun-comet line on logarithmic scales. solid line: sunward, dashed line: tailward direction. A distribution corresponding to an inverse distance law is shown for comparison (dotted line).

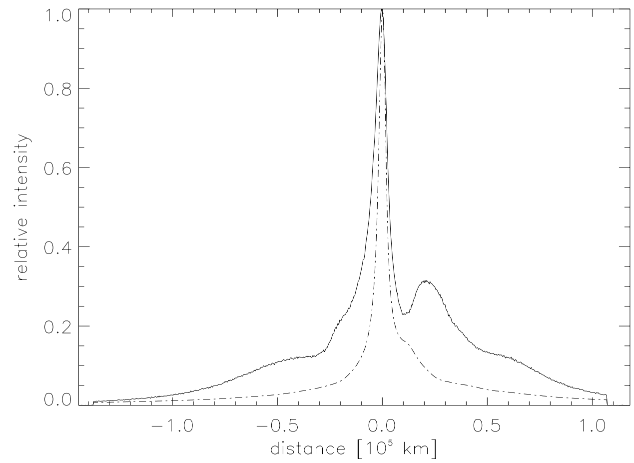

Fig. 3. Normalized sodium (solid line) and continuum (dashed-dotted line) distribution on 16 April 1997 (21:19 UT, exposure time: 120s) perpendicular to the radial direction, over nucleocentric distance in the sky plane.

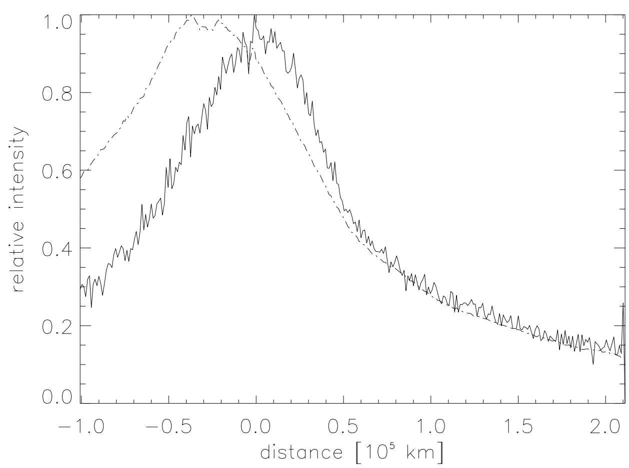

Fig. 4. Normalized sodium (solid line) and continuum (dashed-dotted line) distribution on 14 March 1997 (4:58 UT, exposure time: 120s) perpendicular to the radial direction and offset by 1.6 10^5 km tailward, over distance in the sky plane. The difference of the position of sodium and dust illustrates the efficient radiative acceleration of the sodium atoms along the antisolar direction in comparison to the more slowly moving dust particles, resulting finally in two seperate tails.

estimate the mean velocity along the tail to $\bar{v} = 1 - 6$ km s^{-1}, resulting in a production rate $Q_{\rm Na} \approx 3\,10^{24}$ s^{-1} up to $5\,10^{25}$ s^{-1}. Because part of the Na tail is not covered by our 5.5 arcmin long slit (see Fig. 4), total sodium production rates will be slightly higher than the derived value. The water production rate was about 0.5-1 10^{31} s^{-1} during mid-March (Crovisier, personal communication). If we assume a normal cosmic abundance of Na/O = 2.4 10^{-3} (Anders and Grevesse 1989) in comet Hale-Bopp, only a small fraction of $< 0.3\%$ of sodium is released in the coma. Observations of the distant sodium tail in wide field images taken in April 1997 (Cremonese et al. 1997c) also resulted in low abundances of sodium. Our observations support that most of the sodium is confined in the cometary dust and only a small fraction is released in the coma and nucleus.

5. Discussion

The overall extended sodium distribution in the inner coma of comet Hale-Bopp is clearly not in agreement with a pure nuclear source combined with free radial outflow and tailward acceleration by solar resonance fluorescence. In this case an extent of only a few 10^3 km sunward would be expected. An extended Na cloud can be caused by the existence of an extended source, in addition to a nucleus source, or by hindering the effective tailward acceleration on the Na atoms.

A possible external source for Na could be a molecular parent (sublimated either directly from the nucleus, or from dust particles), or release of Na directly from dust grains (e.g. Huebner 1970; Oppenheimer 1980), for example by sputtering. This would be in agreement with the implication of low velocities for the Na parent from high-resolution Doppler shift measurements (Arpigny et al. 1998). The sudden decrease in Na intensity on the sunward coma side could then give an indication for the destruction scale length of the Na parent. Observations of Na originating from dust particles in the large-scale dust tail (Cremonese et al., 1997b; Fitzsimmons et al. 1997) support the link of sodium to the dust. In addition, the general sunward/antisunward asymmetry in the coma found for Na and dust, but not for NH_2, would be also in agreement with release of sodium from dust particles.

A comparison of tailward features in Na and H_2O^+ in comet Halley has led to suggest an ionic parent for sodium (Combi et al. 1997). In the innermost coma of comet Hale-Bopp strong continuum intensities do not allow us to measure the weak ion emissions in our spectra. A comparison of the H_2O^+ distribution in the cross-tail spectrum on 14 March does not show any similarities to sodium and does not suggest a link between sodium and ionic species.

However, care must be taken when comparing sodium intensities to possible parent molecules, because a strict correlation with spatial structures of its parent is not to be expected. Strong radiation pressure forces act on Na because of its high fluorescence efficiency, but not as efficiently on its parents. The sodium distribution is therefore expected to differ from the neutral and ionic coma. The situation would be further complicated if sodium is a granddaughter product. A release similar to CN could be possible for which sublimation of a parent from small dust particles has been proposed (e.g.: A'Hearn et al., 1986).

The need for an extended source must be compared to other mechanisms which could result in an increase of the sodium cloud. Collisional coupling of Na to water molecules can increase the size of the sodium coma (Combi et al., 1997). However, an estimate of the resulting coupling region in Hale-Bopp (Arpigny et al., 1998) shows that this effect alone is insufficient to explain the total extent of the sodium coma in Hale-Bopp. The spectral irradiance within the sodium line profiles can reach intensity levels comparable to that of the Sun inside the coma, and internal radiative pressure could become important. When taking collisional coupling and internal radiative pressure effects into account, a central source of Na could play a larger role.

The combined effect of a nuclear source with an extended coma source is consistent with the observed spatial sodium distribution. The formation of the observed structures in the long-slit intensity profiles needs to be further investigated through detailed modeling of the sources and dynamics in the coma. This will yield useful information related to the nature of the sources themselves.

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