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Letter to the Editor

Production and kinematics of sodium atoms in the coma of comet Hale-Bopp*

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Abstract. High-resolution spectra of sodium D line emission in comet Hale-Bopp (C/1995 O1) were obtained at the Observatoire de Haute-Provence, France, on 25–27 March and on 15–17 April, 1997. The observations have been used to measure the velocity of sodium atoms in the coma within 2 10^5 km from the nucleus. A comparison between the March and April data provides an illustration of the influence of the heliocentric radial velocity on the strength of the fluorescence (Swings effect), and on the velocity of Na atoms achieved by solar radiation pressure acceleration. Evidence for the presence of a distributed source in the coma is found from the relatively high tailward velocities on the sunward side of the coma, in addition to the sunward extent of sodium emission up to 1.4 10^5 km in April.

Key words: comets: general – Comet: C/1995 O1 (Hale-Bopp) – atomic processes – line: profiles

1. Introduction

The recent discovery of a sodium tail in comet C/1995 O1 (Hale-Bopp) extending to several 10^7 km (Cremonese et al. 1997) has raised a number of questions related to the production, motion, and lifetime of these Na atoms under the action of solar radiation near 1 AU. Analysis of wide field images (Cremonese et al. 1997) shows that the extended sodium tail is created by solar radiation pressure acceleration of Na atoms released from a nucleus or near-nucleus source.

Although the nucleus might provide the major source for Na, release from an additional distributed source in the coma cannot be excluded. Observations of sodium in past comets led to several suggestions on the existence of an extended coma source, caused by neutral or ionic parent molecules, or sublimation of cometary dust particle (e.g. Spinrad & Miner 1968; Huebner 1970; Oppenheimer 1980; Combi et al. 1997). However, whether and to which extent such possible parents do play a role for the release of sodium is still unclear, and the nature of a possible distributed source for Na needs further investigation.

High-resolution spectroscopic observations covering the Na D-lines were performed in March and April 1997 within 2 10^5 km from the nucleus. Analysis of the intensity and velocity profiles of the sodium emissions with nucleocentric distance suggests the influence of an extended source in the coma.

2. Observations and data reduction

Comet Hale-Bopp was observed in March and April 1997 at the Observatoire de Haute-Provence (OHP), using the ELODIE echelle spectrometer (Baranne et al. 1996) at the 1.93 m telescope (Table 1). With this spectrometer (resolution ≈ 43000, corresponding to $\approx 7\,\mathrm{km\,s^{-1}}$ at the wavelength of Na D emission) two spectra are obtained simultaneously via two optical fibers of $2''$ aperture separated by $1\farcm8$.

On 25–27 March, 1997, spectra were obtained with the pair of fibers aligned with and perpendicular to the sun-comet line. On 15–17 April 1997, 13 pairs of spectra were secured with the fibers along the radial vector in almost all cases.

Line profiles of the Na D_1 and D_2 emission have been derived after subtracting the underlying dust-scattered solar spectrum, corrected for telluric absorptions. Since the conditions were not really photometric, no accurate absolute calibration of the Na emission could be made. To obtain a general overview of the trend of brightness with nucleocentric distance, we attempted to put all measured line intensities in April on a uniform scale by normalizing to the same exposure time and correcting for extinction (see below, Fig. 2).

3. Results and discussion

Cometary sodium emission is caused by resonance with the incoming solar flux. The line intensity therefore depends strongly on the Doppler shift of the cometary lines with respect to the solar Na Fraunhofer absorption lines (Swings effect). Using the heliocentric velocities in Table 1, the solar flux at the excitation

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* Based on observations secured at OHP (France)

Table 1. Observing circumstances. r and Δ denote the heliocentric and geocentric distances, $\dot{r}$ and $\dot{\Delta}$ the corresponding velocities, respectively. β is the phase angle.

date	r [AU]	Δ [AU]	$\dot{r}$ [km/s]	$\dot{\Delta}$ [km/s]	β [°]
25.03.1997	0.921	1.319	−3.9	4.7	49.0
26.03.1997	0.919	1.322	−3.3	6.1	48.9
27.03.1997	0.918	1.326	−2.7	7.4	48.8
15.04.1997	0.951	1.521	8.5	25.7	40.2
16.04.1997	0.956	1.536	9.0	26.3	39.5
17.04.1997	0.961	1.551	9.5	26.7	38.9

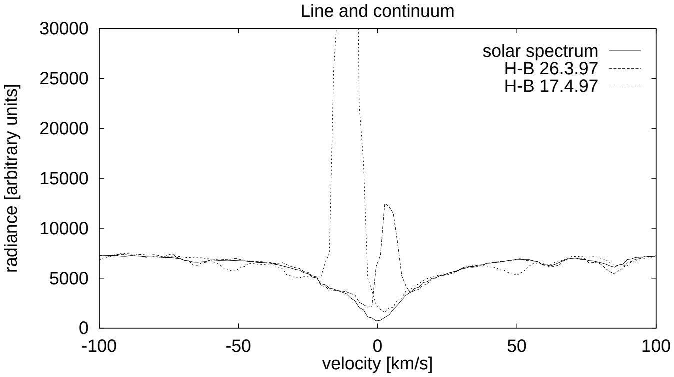

Fig. 1. Comparison of Na emission from spectra taken at the nucleus position in March and April. The underlying continua for the two observing periods have been superimposed; since, as observed on earth, the cometary continuum is Doppler-shifted by $\dot{r} + \dot{\Delta}$, this sum of radial velocities has been subtracted. The solar spectrum, representing the cometary continuum, is also drawn as a reference with the Na D_2 Fraunhofer line at zero velocity. With respect to the latter, the emission lines are displaced by $\dot{\Delta} - (\dot{r} + \dot{\Delta}) = -\dot{r}$.

wavelength of the cometary sodium lines on 17 April is found to be a factor of 6 higher than on 26 March and the resulting intensities of the Na lines (Fig. 1) differ substantially.

Sodium emission can be observed at the extreme sunward positions of the fibers, i.e., 1. and 1.4 10^5 km, respectively, in March and April (Fig. 2). Moreover, the spatial distribution seems to be rather similar at both epochs, showing a sharp peak at the nucleus position.

3.1. *Kinematics*

The spectral resolution of the ELODIE spectrometer allows us to investigate the kinematics of sodium atoms in the coma. The emission lines are significantly Doppler-shifted with respect to the cometary nucleus. During April, they show, in addition, variations in line shape with increasing distance (Fig. 3). The emission lines measured at the nucleus position represent the instrumental profile, with a FWHM of 7 km s^{-1}. Emission lines from offset positions are Doppler-shifted and are broader and asymmetric with a wing towards higher velocities.

Sodium velocities corresponding to the peak intensity of the Na D_2 line are shown in Fig. 4. The line-of-sight velocities were converted to velocities along the sun-comet line by a factor $1/\cos\beta$ and a factor of $1/\sin\beta$ was used to convert distances to the radial direction. The scatter in velocity of the points near zero velocity at the position of the nucleus gives an upper limit to the error on the velocity determination.

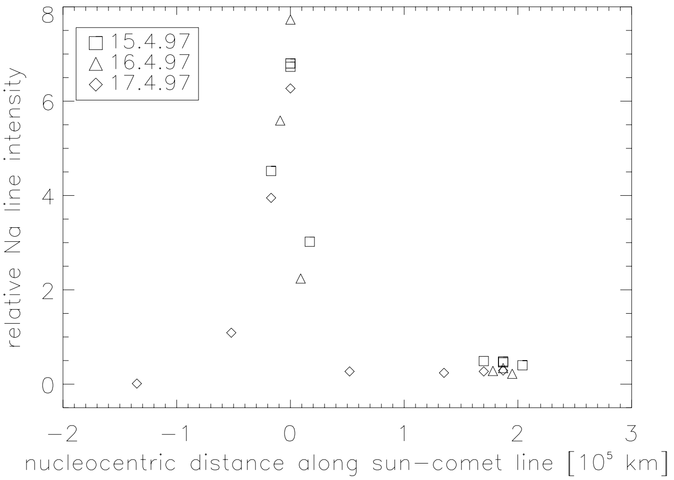

Fig. 2. Na D_2 line intensity in relative units versus nucleocentric distance along the sun-comet line in April.

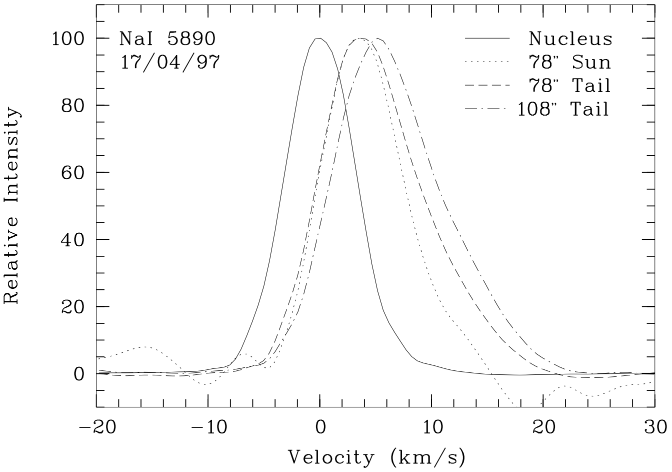

Fig. 3. Normalized Na D_2 line profiles observed on 17 April 1997 at the nucleus, 78 ″ (1.4 10^5 km along the sun-comet line) offset on each side, and 108 ″ away in the tailward direction. The velocity scale here refers to a frame at rest with respect to the comet's nucleus.

In April, up to 4 km s^{-1} anti-sunward velocity is reached at 1.4 10^5 km sunward and up to 6 km s^{-1} at 2.0 10^5 km tailward. These velocities are high compared to the motion of other neutrals (typically 1 km s^{-1} at 1 AU). In March, the observed Doppler shifts correspond to less than 1 km s^{-1} (Fig. 4) and the lines do not show any significant asymmetry or broadening. The lower velocities result from the smaller acceleration in March caused by the reduced incoming solar flux, and provide an illustration of the influence of the comet's heliocentric velocity on the motion of Na atoms.

Because the sodium lines offset from the nucleus are not Gaussian shaped, we quantify the full width of the line profile

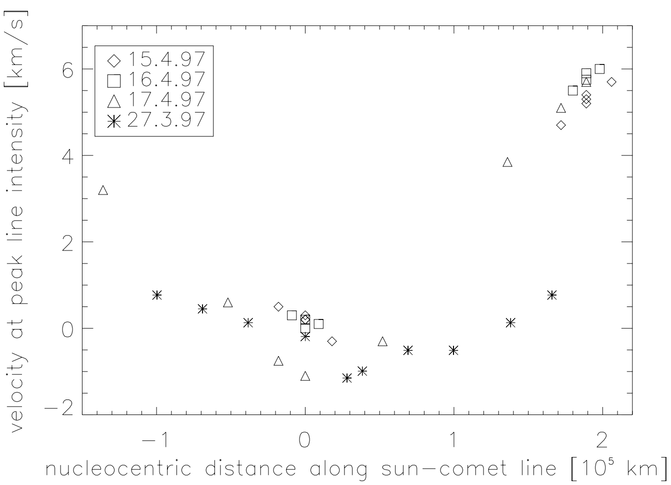

Fig. 4. Cometocentric velocity along the sun-comet direction corresponding to the peak intensity value of the Na D_2 line on 15–17 April and 27 March 1997.

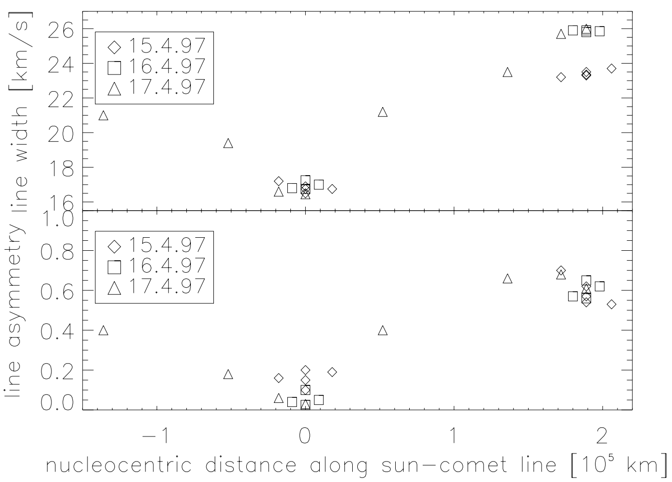

Fig. 5. Total Na D_2 line width (top) and asymmetry (bottom) measured at an intensity level of 10% of the peak line intensity (see text).

at the 10% level of the maximum line intensity. The resulting widths increase with increasing distance from the nucleus (Fig. 5, top). The full width of the instrumental profile is 16.6 km s^{-1}, in agreement with the widths found around the nucleus position. The increase in width is accompanied by an increase in line asymmetry due to a growing high velocity line wing (Fig. 5, bottom). We characterize the line asymmetry by using the parameter $a = 1 - \frac{\Delta v^+}{\Delta v^-}$, where $\Delta v^\pm$ is the difference between the velocity at 10% of the peak line intensity on the shortward (v^-) and longward (v^+) side of the line profile and v_p (the velocity at peak intensity), i.e. $\Delta v^\pm = |v_\mathrm{p} - v^\pm|$.

3.2. Implications for possible sources of Na

In the interpretation of the kinematics, one should pay attention to the dependence of Na excitation on the cometocentric velocity which could modify the line profiles (Greenstein effect). However, the Na lines are intrinsically rather narrow and little affected by this effect, except possibly in the high-velocity wings for the far offset positions. A further complication could result from telluric lines modifying the line profiles. It is nevertheless possible already to discuss some implications.

A pure nucleus source is unable to explain the sunward extent of sodium emission, unless Na atoms are somehow transported much farther to the sunward direction than expected in view of the strong tailward radiation pressure. If working alone, the latter would result in a sunward extent of only a few 10^3 km.

Collisional effects in the coma and the consequent entrainment of the sodium atoms coupled to the expanding H_2O dominated gas, as envisaged by Combi et al. (1997), will lead to an inflated Na cloud on the sunward side in a comet with a copious gas release such as Hale-Bopp. However, comparison with examples considered by these authors indicates that, near 1 AU after perihelion, the sunward extent could have been $\sim$ 6 to 9 10^4 km, still appreciably less than the distances at which Na was observed on that side of the nucleus in Hale-Bopp on 17 April. These estimates were derived by considering the balance between the outward collisional forces and the repulsive solar radiation force, and using a simple $1/R^2$ distribution law for $n(H_2O)$ (R = nucleocentric distance): the distance where decoupling between Na atoms and water molecules occurs, R_d, and correlatively the sunward outer boundary of the Na coma, are easily shown to vary as $(Qr^2/g_1(\dot{r}))^{1/2}$, Q being the H_2O (or OH) production rate and g_1 the radiation pressure acceleration at r = 1 AU. In this way, one can explain the values of R_d found for comets Kohoutek and P/Halley from the Na radial profiles analysed by Combi et al. (1997). For comet Hale-Bopp, we made use of results for Q(OH) published recently (Colom et al. 1998, Schleicher et al. 1998), allowing for an uncertainty factor of 2–3, to obtain the range quoted above for the predicted sunward extent of sodium. While the collisional effects invoked by Combi et al. should indeed be included in future detailed investigations, it should be pointed out that the Na coma model proposed by these authors relies upon exceptionally large cross-sections for elastic water-sodium collisions (1-2 10^{-14} cm^2), for which no experimental evidence exists so far.

Since Q is larger and g appreciably smaller around perihelion than near mid-April, the collisional coupling model predicts a significantly larger sunward extent of the Na cloud (by a factor 2–3). Comparison of the March and April observations does not support such prediction. This is corroborated by unpublished long-slit spectra we obtained close to perihelion, which in fact indicate a shrinking of the Na cloud. Furthermore, the peculiar velocity profiles of Na compared to other species do not favour a strong dynamical coupling except in the central parts of the coma.

The relatively high velocities and high-velocity line wings on the sunward side of the coma suggest that the sodium observed at distant positions is released at even larger sunward distances and subsequently accelerated by solar radiation pressure to the observed velocities. Such an extended source would then be efficient only at large distances from the nucleus.

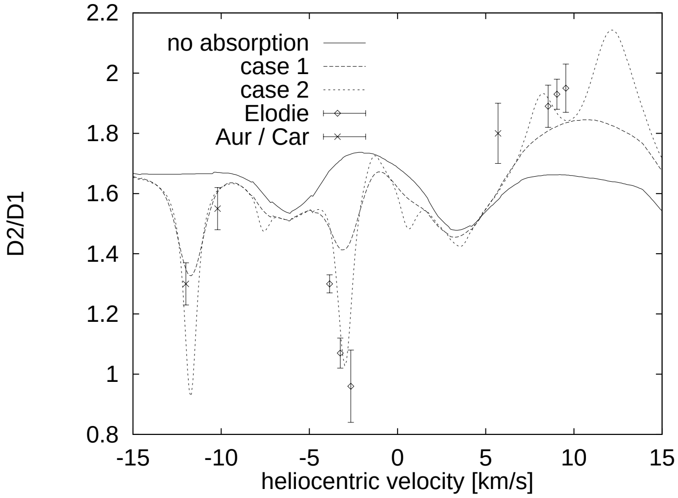

Fig. 6. Na D_2/D_1 line ratio derived from near-nucleus spectra. Diamonds: data obtained with the ELODIE spectrometer on 25–27.3.1997 and 15–17.4.1997; crosses: additional data obtained using lower resolution specrographs (AURELIE and CARELEC) at OHP on 10/14 March and April 4; solid line: ratio derived from the solar Fraunhofer lines (Kurucz et al. 1984). For other models see text.

On the other hand, since the observations do not provide the tangential component of the velocity field, nor the line-of-sight distribution of Na, it is not possible to totally exclude a purely central, anisotropic, source.

The velocities recorded on the tailward side of the nucleus provide another argument in favour of the existence of an extended source and/or the action of some collisional braking. Indeed, in a solar radiation field at 0.96 AU (April observations), the velocity acquired by Na atoms issued from the nuclear region should be greater than 10 km s^{-1} at a distance of 2 10^5 km along the radius vector. This is to be compared with $\approx 6\,\mathrm{km\,s^{-1}}$ characterizing the bulk of the observed profile at that distance. Given the known acceleration due to radiation pressure (24 cm s^{-2} for April), such velocity should have been reached already over a little less than 10^5 km.

In summary, our observations of sodium in the coma are consistent with the combination of a central source, probably with collisional entrainment limited to the densest regions of the coma, and (an) extended source(s).

The nature of the distributed source of Na remains unclear. Sodium atoms could be released by destruction of a neutral or ionic parent molecule, or by release from dust particles. The low anti-sunward velocity of sodium in March on the tailward side of the coma implies a low-velocity parent. For ions, this can be achieved when observing inside the ionopause or by a heavy ionic molecule, because otherwise the interplanetary magnetic field would accelerate the ions quickly. For example, measurements of the H_2O^+-ion velocity on the tailward side of the coma in March give velocities higher by 2 km s^{-1} than the observed v_{Na}. The parent of Na therefore must be a heavier ionic molecule, or neutral. On the other hand, measurements of Na emission in the dust tail of comet Hale-Bopp (Fitzsimmons et al. 1997) imply that dust grains in the distant tail are a major source of sodium in Hale-Bopp. Although the mechanism of sodium release from dust particles is unclear, dust grains could also serve as a source for Na atoms in the inner coma. They would be in agreement with a low velocity parent for Na. Clearly, detailed modeling based on various possible modes of production, including a central source and (a) distributed source(s), and incorporating all relevant physical processes (collisional as well as radiative) is required. The Na velocities presented will provide a further constraint to such models, in addition to the spatial sodium distribution in the coma.

3.3. *The Na D_2/D_1 line ratio*

The Na D_2/D_1 line ratio expected for single resonance scattering is shown in Fig. 6 (solid line). The disagreement with the measured ratios (diamonds and crosses) in near-nucleus spectra in March and April can be explained, partly or totally, by the modulation of the sodium emission lines by the many telluric (mainly H_2O) lines present in the Na region.

The combination of (i) a varying topocentric velocity, (ii) a variable atmospheric water distribution and (iii) a Na profile varying with position in the coma, creates a time- (and space-) dependent differential effect on the D_2 and D_1 lines. A first analysis indicates that the departures from the theoretical ratio caused by telluric lines occur with the right orders of magnitude. The predicted D_2/D_1 ratios for two typical sets of conditions are superimposed to the pure fluorescence ratio in Fig. 6. Case 1 includes an average water content for OHP. This corresponds to an equivalent width of 60 mÅ for the 5891.65 Å H_2O line. The FWHM of Na, assumed to be Gaussian, is 70 mÅ. Case 2 has one third more water (the highest values we observed with ELODIE) and the FWHM of Na is only 12 mÅ. A Lorentz profile with a FWHM of 40 mÅ was adopted for the water lines. Most of the observed D_2/D_1 line ratios could likely be reproduced with more sophisticated models. A detailed analysis will show if other processes (multiple scattering, optical depth effects) are required to explain possible small remaining deviations.

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