SODIUM IN COMETS

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Abstract. A great deal of attention has been given to the production and spatial distribution of sodium in comets after the discovery of the sodium tail, by Cremonese et al. (1997a), on Hale–Bopp. The sodium has been observed in several comets in the past, but the Hale–Bopp represent the first time where it will be deeply analyzed considering the several data and scientists working on that. The sodium tail stimulated different studies trying to explain the mechanism source and provided the new lifetime for photoionization of the neutral sodium atom. We took into account other sodium observations performed in this century and we focalized our attention to comet Hale–Bopp to understand the main sources responsible for the sodium features observed.

We analyzed the sodium tail observations performed by Cremonese et al. (1997b) and Wilson et al. (1998) finding that the Hale–Bopp had four different tails. The wide field images and the high resolution spectroscopy performed along the sodium tail provided very important clues to distinguish the two sodium tails observed and their possible sources. Considering most of the data reported in several papers has been possible to draw a real sketch on what has occurred to the comet during March and April 1997. We are going to demonstrate that the sodium tail observed by Wilson et al. (1998) was not the same reported by Cremonese et al. (1997a) and in the images taken by the European Hale–Bopp Team there were two distinct sodium tails. The observations allowed us to define "narrow sodium tail" the tail reported by Cremonese et al. (1997a), and "diffuse sodium tail" the tail overimposed to the dust tail. We suggest that the narrow sodium tail was due to a molecular process instead of the diffuse one due to the release of sodium atoms by the dust particles. Such a conclusion is supported by the spatial distribution of sodium on the nucleus and in the coma as reported from other authors.

1. Introduction

The sodium atom provides a significant probe of the composition of the comet because it has the strongest spectrum of any nonvolatile atomic component of these objects. It is characterized by one of the most high efficiency in resonant scattering of the solar radiation and it can be observed with a lower column density than for other elements. The sodium is present in other Solar System bodies as for instance Mercury, Io and the Moon where it is used as a tracer of the main processes working on their atmospheres. An understanding of the nature of the sodium fraction in the comet would provide important clues to the relationship between volatile and non-volatile components of the nucleus and the nuclear formation processes which led

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to their fractionation. In particular, the question of whether the sodium originates in dust grains or in molecules embedded in the volatile nuclear matrix provides constraints on thermal models of the formation of comet dust grains and of the nucleus as a whole. It could be a further element to relate to the interstellar medium where it has been observed as neutral atom and in some molecules, providing a relation to the composition of interstellar grains and the size of the sodium depletion in the interstellar medium. Moreover it could allow us to understand the distribution of the sodium in the Solar System considering the not negligible number of objects where it is present. Sodium D-line emissions from comets has been observed several times during this century and one of the first evidence has been reported from Newall observing comet 1910a in January 1910 at the Cambridge Observatory (Newall, 1910). He used a direct-vision prism inserted between the eye and the eyepiece of the telescope, sometimes the 63 cm equatorial was used, sometimes the 16 cm finder attached to it. At the beginning of his observations it appeared that the main part of the luminosity of the envelope, in front of the nucleus, and the side trains, behind the nucleus were due to sodium. The extension of the sodium emission was measured till 8 arcmins from the nucleus, in the tailward direction. After four days the sodium was visible only close to the nucleus and after 6 days it was confined to the nucleus. 47 years later another interesting observation of sodium on comets was reported by Nguyen–Huu–Doan (1960) on comet Mrkos, in the range of $r = 0.57–0.82$, in this case he observed a long sodium tail on a plate obtained with a prism objective in front of the small telescope utilized. Looking at the picture reported by Nguyen–Huu–Doan (1960) is very difficult to measure the length of the sodium tail as after 2 or 3 degrees from the nuclear region is overimposed with the dust tail, but most likely it was the first time that an extended sodium feature has been observed.

In the following years the sodium was observed in other bright comets as Ikeya-Seki, Seki-Lines, Bennett, Kohoutek, West and Halley (Spinrad and Miner, 1968; Oppenheimer, 1980; Rahe et al., 1976; Combi et al., 1997), but the field of view was few hundreds thousand of km not allowing to detect a sodium tail. Such observations stimulated our concern on searching for sodium in comet Hale–Bopp considering its high activity already at larger heliocentric distances. On February 1997 two japanese astronomers (Kawabata and Ayani, 1997) reported to have seen the sodium emissions on a spectrum obtained on the nucleus of this comet and we thought to take some wide field images in the sodium light. The same instrument mounted to observe the dust and ion tails has been used, with a further interferential filter to isolate the sodium D-lines.

The discovery of the sodium tail, occurred on April 16 (Cremonese et al., 1997a), raised the interest of several observers on the production and the spatial distribution of sodium on comet Hale–Bopp (Arpigny et al., 1998; Brown et al., 1998; Rauer et al., 1998; Wilson et al., 1998). For instance some data taken by the ICE spacecraft on comet Giacobini–Zinner (Ogilivie et al., 1998) have been re-interpreted suggesting the presence of sodium even in that short period comet.

Then further observations of the sodium tail have been reported by Kupperman et al. (1998) looking at some images of the NASA spacecraft Polar, taken in the same period of the European Hale–Bopp Team, and by Wilson et al. (1998) during their run on the lunar sodium atmosphere, one month before the discovery.

In this work we will focalize our attention mainly on the sodium observations performed on comet Hale–Bopp and in particular using the data obtained on the sodium tail. As we think that the processes and the possible sources working on Hale–Bopp can be present even in other comets and because it is the first time that the sodium emissions have been so well observed and analyzed in these objects.

2. Observations

The sodium tail has been discovered using the CoCam wide-field imaging instrument on La Palma plus a narrow band sodium filter ($\lambda_c = 5892$ Å, FWHM = 15 Å). CoCam is of a 35 mm camera zoom lens working at f/3.5 and imaging onto a 2220 $\times$ 1180 pixel EEV CCD chip, whose pixel size of 22.5 μm square corresponds to 26 arcsec, thereby achieving on the sky a total field of 17 $\times$ 9 degrees. Images were also obtained with a continuum filter to subtract the dust contribution ($\lambda_c = 6250$ Å, FWHM = 25 Å). This instrument was mounted only to study the large scale phenomena of comet Hale–Bopp.

Furthermore high resolution spectroscopy was performed at several points along the sodium tail, perpendicular to the tail axis, and in the nuclear region on April 19.9 UT, 20.9 UT and 23.9 UT, using the 4.2 m William Hershel Telescope (WHT) with the Utrecht Echelle Spectrograph and 1024 $\times$ 1024 pixel TEK CCD chip, providing a dispersion of 0.053 Å pixel^{-1} and a resolution of 0.1 Å with a slit width of 1.1 arcsec. Some spectra were obtained even on the dust tail at different positions and with the slit perpendicular to the syndyne, that is an ideal line connecting all the particles sensitive to the same solar radiation pressure force.

The first CoCam sodium image showed a third well distinct tail, not overimposed to the dust and ion tails, much narrower and long more than 30 $\times$ 10^6 km (7 degrees).

Then removing the dust contribution from the sodium images we realized there were two distinct sodium tails. The second sodium tail was almost overimposed to the dust tail, very broad and diffuse, and it appeared very similar to the large sodium feature observed by Wilson et al. (1998).

3. Analysis and Discussion

The analysis of the sodium tail discovered the 16th of April has been carried out adopting two different models applied at some wide field images and at the high resolution spectra obtained along the same tail. The first model has been applied to the high resolution spectra providing the surface brightness and the velocity of the neutral atoms along the tail, as a function of the distance from the nucleus. It was soon evident that the sodium neutral atoms underwent an acceleration in the anti-sunward direction due to simple radiation pressure, through photon scattering (fluorescence) in the resonant D-line transitions. A numerical code has been written in order to integrate the equation of the motion of the sodium atom and to obtain the g-factor, the velocity, the beta and the brightness variation, as a function of the distance from the nucleus along the tail. The model assumed that emission out the D_1 and D_2 lines is negligible and the acceleration is only due to the solar radiation pressure interacting with the sodium atoms by the resonant fluorescence mechanism. The g-factor has been calculated using the high resolution full disk solar spectrum, providing 10 s^{-1} at the D_2 wavelength (5890Å), and it allowed us to compute the ratio between the radiation pressure force and the gravitational force, β. Figure 1 shows the output of the model and the good fit of the observed velocities. The calculation of the intensity assumed a constant production rate.

The most interesting result of the model is the photoionization lifetime of the sodium atom, two different values have been considered to fit the brightness variation along the tail. First of all the experimental value has been used, according to several papers reporting the study of planetary atmospheres where the sodium is present, but it didn't fit the observed intensities. Then we realized it was necessary to adopt an higher value, as it was suggested by Huebner et al. (1992) according to the theoretical calculation of the cross section by Chang and Kelly (1975). In so doing it has been demonstrated that the theoretical value, 1.69×10^5 s, must be the new adopted lifetime.

The very large sodium feature observed on Hale–Bopp offered an interesting chance to apply an approach similar to that used for the dust tails. Such an approach assumed that the interaction with the radiation pressure, due to the resonant fluorescence in the D-lines for the sodium atoms, was the main process responsible for the existence of the tail, as it occurs for the dust particles. If the particles with the same β were ejected with the velocity v_0 from the inner coma, then the resulting sodium tail had to be a syndynamic tube of width $2v_0t$, where t represents the mean travel time of the sodium atoms from the nucleus to a given tail distance. The axis of the syndynamic tube is the syndyne defined by β(Na), which is computed by means of Keplerian mechanics (Finson and Probstein, 1968; Fulle, 1992), and is equal to:

$$\beta(\mathrm{Na}) = \frac{hg(L)(1\,\mathrm{AU})^2}{\lambda G M_\odot m}, \tag{1}$$

where g is the gravitational constant, h is Planck's constant, $M_\odot$ is the Sun's mass, $g(L)$ is the g-factor at the heliocentric distance of 1 AU and m is the mass of the atom or molecule composing the syndyne. Applying the syndynamic model to the CoCam images, taken on April 21.9 UT, the best β value was found fitting the Position Angles of the sodium tail at different distances from the nucleus. Furthermore

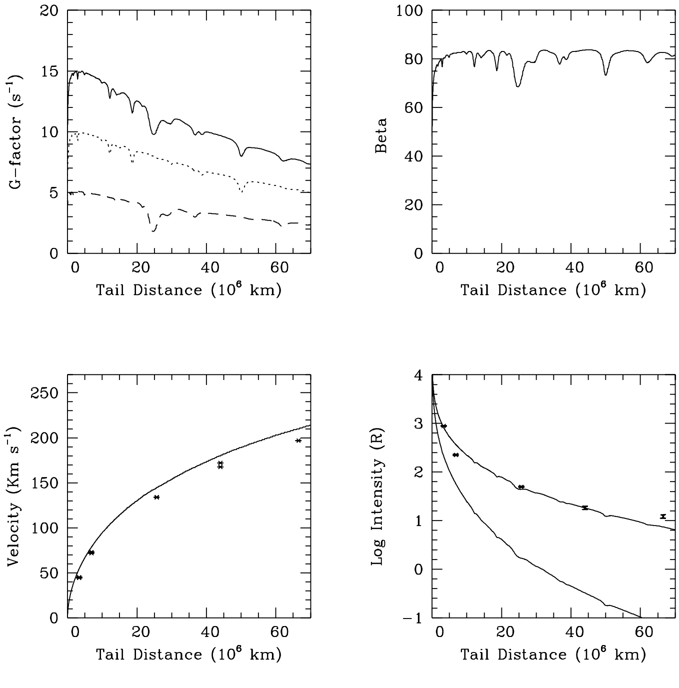

Figure 1. Results of the model referred to April 21.9. (a) Theoretical g factors for the D_1 line (bottom), D_2 line (middle), and both combined (top) as a function of the tail distance deprojected along the antisolar direction. (b) β(Na) values in function of the Tail Distance deprojected along the antisolar direction. (c) Measured velocities (*), deprojected along the antisolar direction, compared to the computed velocity (curve). (d) Observed brightness distribution in the tail as measured from the high-resolution spectra versus model predictions for two photoionization lifetimes: (1) (lower) assuming a Na lifetime at 1 AU of $\tau = 14$ hours (the experimental photoionization cross section) and (2) (upper) assuming $\tau = 47$ hours (theoretical photoionization cross section).

the same model was applied to calculate the velocities of the sodium atoms along the tail and the comparison with the observed values was very good assuming the same best fitting $\beta = 82 \pm 3$ (Table I). This high value of β implied that only atoms can satisfy the fit and not molecules or dust grains, for which the largest value reported in literature is $\beta \simeq 2$. Following the model it was possible to get the mass of the particles composing the tail as it provided the ratio between the g-factor and the mass m. Assuming a $g(L)$(1 AU) = 15.6 s^{-1}, for both the D-lines, it turned out $m = 22 \pm 1$ amu yielding that the observed tail was composed by only neutral sodium atoms. Such a result confirmed the spectroscopic observations performed along the sodium tail showing only the sodium D-line emissions (Cremonese et al., 1997a).

TABLE I

Observed and modelled velocities in the sodium tail on April 23.9 UT. L is the sky-projected distance from the nucleus, v_{ro} is the measured radial velocity corrected for the relative velocity between comet nucleus and Earth, v_{rc} is the computed radial velocity of the Na atoms along the line of sight in the comet nucleus reference frame (to be compared directly with v_{ro}) for the best fitting syndyne of $\beta = 82 \pm 3$

L deg	L 10^6 km	v_{ro} km s^{-1}	v_{rc} km s^{-1}	t days
0.89	3.83	62 ± 1	63 ± 2	2.0 ± 0.1
3.13	13.49	117 ± 1	118 ± 2	3.7 ± 0.1
5.07	21.89	149 ± 1	151 ± 3	5.0 ± 0.1
7.17	31.03	178 ± 1	176 ± 3	6.1 ± 0.1

The models described above have been used to look for the main mechanism responsible for the narrow distinct tail observed in the wide field images, but they didn't provide any information on the source of the sodium atoms. We can only say that the source have to be located in the nuclear region to explain the high velocity of the neutral atoms and the morphology of the tail. A further problem raised looking at the images pubblished by Wilson et al. (1998), taken one month before the discovery, was the different morphology of the sodium tail and its position with respect to the ion and dust tails. At the same time a deeper analysis of the CoCam images, after the subtraction of the dust contribution to the sodium data, yielded that there were two different large structures due to the sodium emission. The sodium tail present on the images of both teams was much more diffuse and almost overimposed to the dust tail. The first hypothesis raised by Wilson et al. (1998) pointed out a completely different sodium tail and its morphology is most consistent with a source from dust. This suggestion confirms the detection of slow sodium atoms even on the dust tail (Fitzsimmons et al., 1997), some millions of km far from the nucleus.

An interesting point on the two sodium tails and their possible sources is provided by the high resolution spectra obtained along the narrow sodium tail. Figure 2 shows the four syndynes where we obtained the high resolution spectra. The syndyne corresponding to β = 82 is the narrow sodium tail, while the syndynes with the β values 0.6, 0.06 and 0.006 are related to the dust size particles of 2 μm, 20 μm and 200 μm respectively. The syndynes with $\beta \leq 1$ point at the position of the diffuse sodium tail.

The spectrum obtained on the narrow sodium tail at 0.4 degrees from the nucleus, corresponding to 1.6×10^6 km, showed the sodium emissions at the two

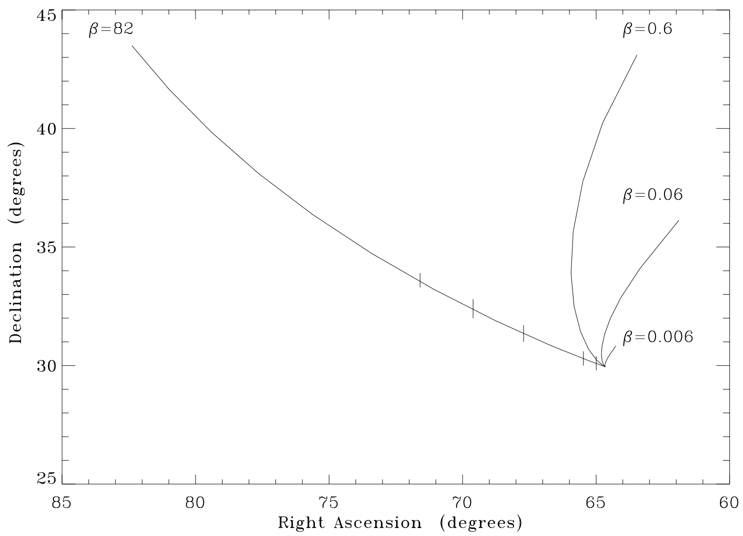

Figure 2. Plot of the syndynes referred to April 23.9 UT, along the β = 82 syndyne the positions of the slit have been indicated, at 0.4, 0.89, 3.13, 5.07, 7.17 degrees from the nucleus.

edges of the slit with a very different profile. In the slit edge, farther from the anti-sunward direction and the narrow sodium tail, the emission lines had a clear double component (Figure 3). The faster component (F in the Figures 3 and 4) had a radial velocity of 37.7 km/s, corrected for the comet geocentric velocity, and it is well fitted by the first model applied by Cremonese et al. (1997b). The slower component (S in the Figures 3 and 4) had a velocity of 6 km/s pointing at sodium atoms released locally. At this large distances from the nucleus we think only dust particles can be the source of sodium. Approaching the narrow sodium tail axis, on the other edge of the slit, and going away from the dust tail the double component is much less clear. The two emission profiles shown in Figures 3 and 4 have been taken on the same spectrum separated by 135.000 km. At larger distances from the nucleus the double peak is no longer present and the emissions are much sharper.

It means we could have two different sources, each one responsible for one sodium tail. The diffuse tail observed overimposed on the dust tail is due to the release of sodium atoms by dust particles, not yet accelerated at higher velocity, for instance through an evaporation process (Huebner, 1970). Presumably, even the processes proposed for the regolith of Moon and Mercury, and their sodium atmospheres, can be applicable, including thermal desorption, solar photodesorption and solar wind sputtering (e.g., Sprague et al., 1992). The narrow sodium tail is due to a source located in the nuclear region not yet identified.

Several processes can be taken into account in the nuclear region, but an important point is to understand if there was an extended source. Arpigny et al. (1998) and Rauer et al. (1998), using spectroscopic observations performed in the coma, found that in April the sodium atoms had up to 4 km/s anti-sunward velocity at 1.4 $\times$ 10^5 km sunward, very high compared to the motion of other neutrals (typically 1 km/s at 1 AU). They assumed that, near 1 AU after perihelion, the sunward extent could have been $\sim$6 to 9 $\times$ 10^4 km, still appreciably less than the distances at which sodium was observed on that side of the nucleus on 17 April. They concluded that the overall extended sodium distribution in the inner coma of Hale–Bopp is clearly not in agreement with a pure nuclear source combined with free radial outflow and tailward acceleration by solar resonance fluorescence. There could be an external source, as a molecular parent (sublimated either directly from the nucleus, or from dust particles) or release of sodium directly from dust grains, in addition to the nucleus source. An interesting model, by Brown et al. (1998), suggested a 55% nucleus source and 45% extended source to explain the narrow sodium tail observed in April.

Ip and Jorda (1998) suggested, as extended source, the very small dust grains, 10–100 Å. They would be picked up by the cometary plasma flow and be brought to collisional interact with the dust population in the coma, in this way the micron dust particles would be constantly bombarded by the tiny grains at a relative speed of tens of km/s. Impact vapour containing sodium atoms would be generated as a result.

A further hypothesis is based on a comparison of tailward features in Na and H_2O^+ in comet Halley that has led to suggest a ionic parent for the narrow sodium tail (Combi et al., 1997), but a simple model used by Brown et al. (1998) showed that the sodium velocities due to a plasma source are much higher than those measured. Moreover the H_2O^+ distribution in a cross-tail spectrum, on Hale–Bopp, reported by Rauer et al. (1998), does not show any similarities to sodium and does not suggest a link between sodium and ionic species. However, we have to pay attention when comparing sodium distribution to possible parent molecules, as its high fluorescence efficiency is not so strong on its parents.

Some hypothesis have been proposed to explain the narrow sodium tail, but probably some authors still have to realize the difference between the wide field images taken by the European Hale–Bopp Team and Wilson et al. (1998), as in the second case it was not present. The disappearence of this large feature one month before the discovery could provide important insights on its source. Kawakita and Fujii (1998) wrote a model to study the brightness distribution of the sodium atoms along the narrow tail based on a Monte Carlo simulation. It can deal with the dependence of the g-factor and the radiation pressure for the sodium atoms on their heliocentric velocity, then the collisions between the neutral atoms and the water molecules are included. They showed as the narrow tail was present even in the images of Wilson et al. (1998), but it was much shorter and fainter, so it was not possible to distinguish it from the sodium released by the dust particles. The idea is interesting, but the model applied is very rough, as it takes into account a starting velocity of the sodium atoms relative to the nucleus equal to 0 km/s and it doesn’t provide the width of the tail to be compared with the data available. As it

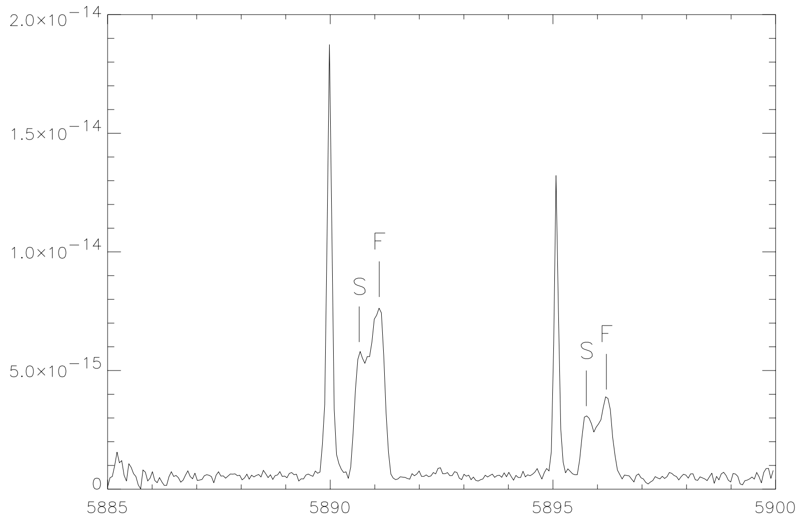

Figure 3. Profile of the sodium *D*-lines toward the dust tail at 0.4 degrees from the nucleus, the highest peaks are due to the terrestrial emissions. The spectrum has not been corrected by the comet velocity and the *y*-axis shows the absolute flux in erg cm^{-2} s^{-1}.

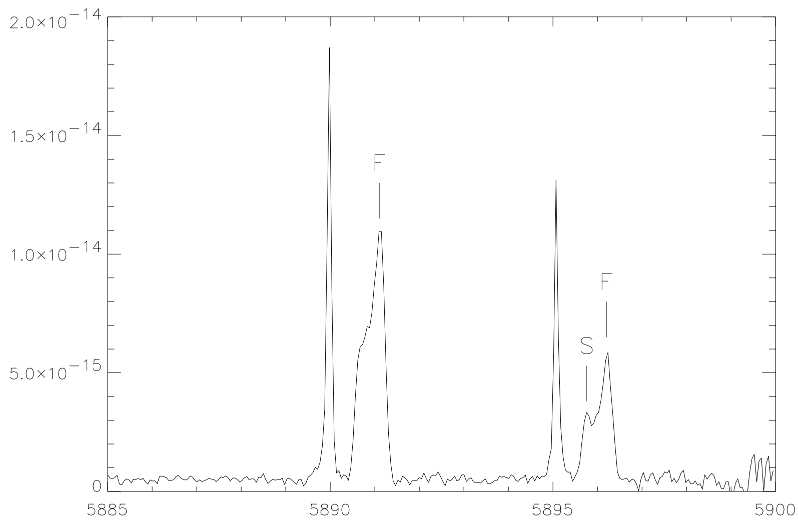

Figure 4. Profile of the sodium D-lines toward the fast sodium tail axis, on the same spectrum of the previous figure, but at the opposite slit edge.

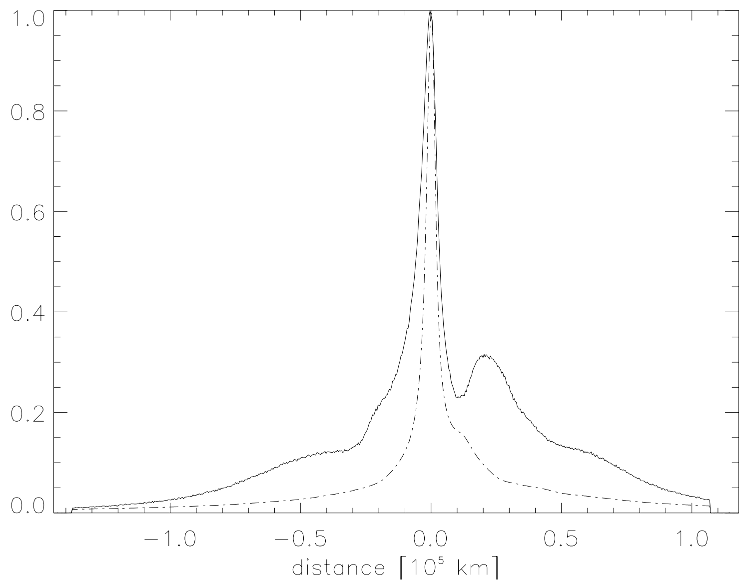

Figure 5. Normalized sodium (solid line) and continuum (dashed-dotted line) distribution on 16 April 1997, perpendicular to the radial direction, over nucleocentric distance in the sky plane.

has been showed by Cremonese et al. (1997b) and Brown et al. (1998) the narrow tail width is dependent from the starting velocity of the sodium atoms and working on this parameter is possible to get important information on the nuclear source and the location of the release region.

Mendillo et al. (1998) applied a similar model to the narrow tail and the sodium tail discovered on comet Hyakutake finding that the starting velocity of the sodium atoms was higher than 1 km/s, and only with these values it is possible to fit well the tail width at different distances from the nucleus. Running the model for the dates of the European Hale–Bopp Team and Wilson et al. images it turns out that the narrow sodium tail was present on both period, but in March the tail was not narrow and much more spread and short with the result that it was not possible to distinguish it from the sodium coma due to the dust particles. The reason why there was this difference is related to the Swing effect, that for the sodium atom can be very strong. The acceleration of sodium, due to the fluorescence mechanism, can change up to a factor 20 depending from the heliocentric velocity of the comet.

4. Conclusion

Several efforts have been paid to understand the processes related to the sodium coma and possible sources of the sodium tails, but there is not yet a clear idea. It has been recognized the dust particle as one source of sodium atoms, but we don't know in which way it works. Do we have to invoke a molecule released by the grain and then dissociated leaving sodium atoms?

Another source seems to be identified and it is the dissociation of a molecule bearing sodium, working in the inner coma and responsible of the narrow sodium tail. Biver et al. (1997) reported the upper limit of NaOH and NaCl from their radio observations and the values are similar or a little bit lower than the measured production rate of sodium along the narrow tail. It means we have to look for a different molecule.

The spatial distribution of the sodium atoms in the nuclear region and in the coma can provide an important issue on the characteristics of this extended source. The spectroscopic observations performed on the nucleus showed a general sunward/tailward asymmetry and a secondary maxima (Rauer et al., 1998). The same behaviour has been observed even for the dust continuum, but with maxima not in phase with sodium emission and much weaker (Figure 5). The asymmetry in sodium reflects asymmetric outgassing from the nucleus itself and/or release from a non-isotropic parent distribution. Then the sodium and continuum emissions are clearly anisotropic and a simple distribution for outgassing of a parent species from the nucleus cannot be applied, as reported by Rauer et al. (1998). The conclusion in their work suggests the existence of an extended source in addition to a possible nucleus source, as reported also by Combi et al. (1997) and Brown et al. (1998). In other words we could identify three different sources, the dissociation of a parent molecule, the release directly from the nucleus and from the dust grains, working all together at the same time.

The comet Hale–Bopp gave us one more present represented by four distinct tails due to four different sources. The two new sodium tails stimulated the interest on the sodium that could be an element more common than predicted in comets. Then it can really be used as a tracer of other more important processes, utilizing its much higher efficiency in interacting with the solar radiation.

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