The Astrophysical Journal Letters, 771:L1 (4pp), 2013 ???
doi:10.1088/2041-8205/771/1/L1

POTASSIUM DETECTION AND LITHIUM DEPLETION IN COMETS C/2011 L4 (PANSTARRS) AND C/1965 S1 (IKEYA-SEKI)

M. Fulle[1], P. Molaro[1], L. Buzzi[2], and P. Valisa[2]
[1] INAF-Osservatorio Astronomico, Via Tiepolo 11, I-34143 Trieste, Italy; fulle@oats.inaf.it
[2] Società Astronomica Schiaparelli, Via Beato Angelico 1, Varese, Italy

Received 2013 May 10; accepted 2013 June 4; published 2013 ???

ABSTRACT

On 2013 March 21 high-resolution slit spectrographs of the comet C/2011 L4 (Panstarrs), at a heliocentric distance $r = 0.46$ AU, were obtained at the Osservatorio Astronomico Campo dei Fiori, Italy. Emission lines of sodium were the strongest in the spectrum as is common in comets, but potassium lines were also detected. These have rarely been observed in comets since the apparition of the brightest comet C/1965 S1 (Ikeya-Seki). Lithium was not detected and stringent upper limits of its abundance compared to other alkali were derived. We obtain the abundance ratios $\mathrm{Na/K} = 54 \pm 14$ and $\mathrm{Na/Li} \geqslant 810^3$. In addition to Mercury's exosphere (Leblanc & Doressoundiram), we show that photoionization at the beginning of the alkali tails may increase the solar ratio $\mathrm{Na/K} = 15.5$ (Asplund et al.) by a factor three, close to that required to match the observed value. In the same tail position, the Na/Li ratio increases only by a factor two, very far from the factor $\geqslant 8$ required to match an original meteoritic ratio. We apply the same model to similar alkali data (Preston) of the comet C/1965 S1 (Ikeya-Seki) and obtain consistent results. An original solar Na/K ratio fits the observed value at the beginning of the alkali tails within the slit size, whereas Li is depleted by a factor $\geqslant 8$.

Key words: atomic data – comets: general – comets: individual (C/2011 L4 (Panstarrs))

Online-only material: color figures

1. INTRODUCTION

Comets provide unique information on the cosmic abundances of the solar nebula which collapsed to form the solar system. Besides sodium, which is already detected in many comets, very few data are available regarding the alkali content of comet nuclei. In particular, potassium was remotely detected (Preston 1967) in spectra of the comet C/1965 S1 (Ikeya-Seki), where the Na/K ratio was as high as that observed in Mercury (Killen et al. 2010). A detection of the potassium line at 7698.9645 Å in the comet C/1995 O1 (Hale-Bopp) was reported by Fitzsimmons & Cremonese (1997), but no Na/K ratio has yet been extracted from this spectrum. Laboratory analyses of samples collected from the comet 81P/Wild 2 showed that most potassium is in the form of eifelite and K-feldspar grains (Zolensky et al. 2006). Detections of the potassium and lithium lines were also reported from the impacts of the comet D/1993 F2 (Shoemaker-Levy 9) on Jupiter (Roos-Serote et al. 1995). The Na/Li ratio extracted from spectra of the plume in Jupiter's atmosphere was consistent with a meteoritic ratio (Costa et al. 1997), although these transient emissions, unlike resonant fluorescence, could not be readily converted into atomic abundances and were probably contaminated by the alkali of Jupiter's deep atmosphere. In this Letter, we discuss the remote detection of potassium in the comet C/2011 L4 (Panstarrs), which allows us to discuss the Na/K abundance in this comet. In addition to models of Mercury's exosphere (Leblanc & Doressoundiram 2011), we will discuss the transfer of alkali atoms from the parent bodies (mainly the dust grains in the sunward coma) to the beginning of alkali tails (Fulle et al. 2007) where they have been observed. This will allow us to use actual estimates of lithium abundances in comets. The physical process relating alkali line intensities to atomic abundance is very simple, namely, resonance fluorescence (Swing 1941). The absorption of solar radiation in the resonance transitions populates atomic upper levels, which, trickling down, give rise to the emission lines. The population in the upper level depends on the energy available at the considered wavelength, i.e., upon whether or not a Fraunhofer line comes in the way of absorption. These Fraunhofer lines as seen from the comet have different Doppler shifts depending on the radial heliocentric velocity v (the so-called Swing effect).

2. THE OBSERVATIONS OF COMET C/2011 L4 (PANSTARRS)

High-resolution ($\lambda/\Delta\lambda \approx 10^4$ in the spectral range 424–864 nm) Echelle spectra (Figure 1) of the comet C/2011 L4 (Panstarrs) were obtained on 21.8 UT 2013 March (mid-exposure time) with the Multi-Mode Spectrograph mounted on the 0.6 m telescope at the Osservatorio Astronomico Schiaparelli located in Campo dei Fiori, Varese, Italy (Ashish et al. 2012). The multi-order Echelle spectra were absolutely flux calibrated against spectra of the standard star HR 464 located on the sky nearby, observed immediately after the comet, and then merged into a one-dimensional continuous spectra. The slit was east–west (E–W) oriented and guided on the brightest coma by means of a monitor of a guiding CCD camera covering 3×4 arcmin^2 on the sky. The slit width projected on the sky was set to 4″, and the slit length to 17″. The total exposure time was 40 minutes. At the observations, the Sun–comet distance was $r = 0.46$ AU; the Earth–comet distance $\Delta = 1.19$ AU; the comet was receding from the Sun at a speed of 36 km s^{-1}, and from Earth at a speed of 14 km s^{-1}. The Sun–comet–Earth phase angle was 54°. Images of the same dust coma showed that the apex distance (i.e., the distance between the brightest inner coma and its sunward boundary) was about 100″, corresponding to 10^5 km projected along the Sun–comet vector.

The cometary spectrum shows a number of emission features with very prominent Na I, but also with the K I lines clearly

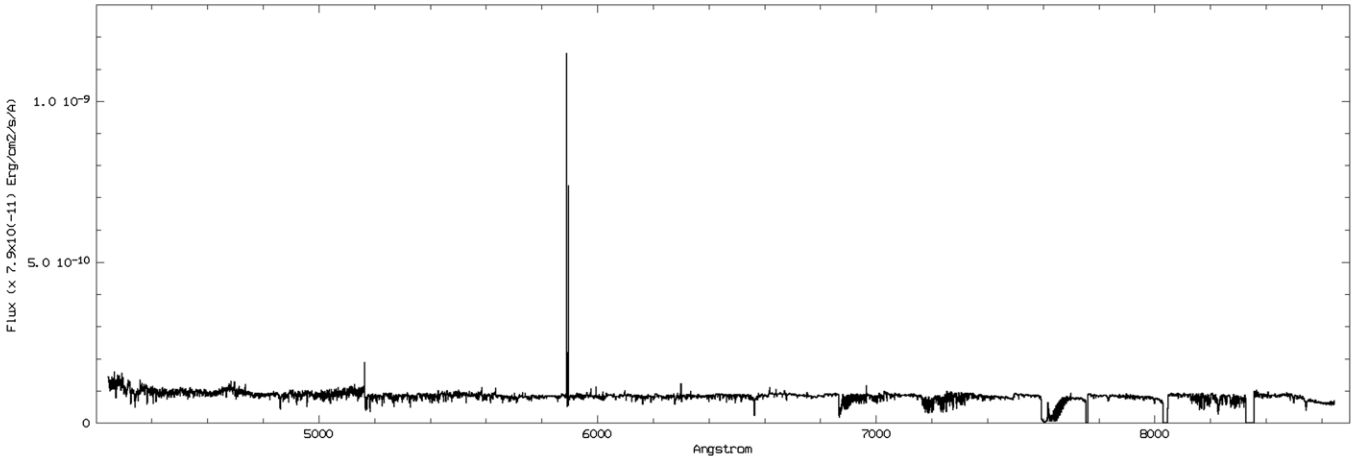

Figure 1. C/2011 L4 spectrum shown over the complete observed wavelength range. It is dominated by the sodium emission and by O_2 telluric absorption bands.

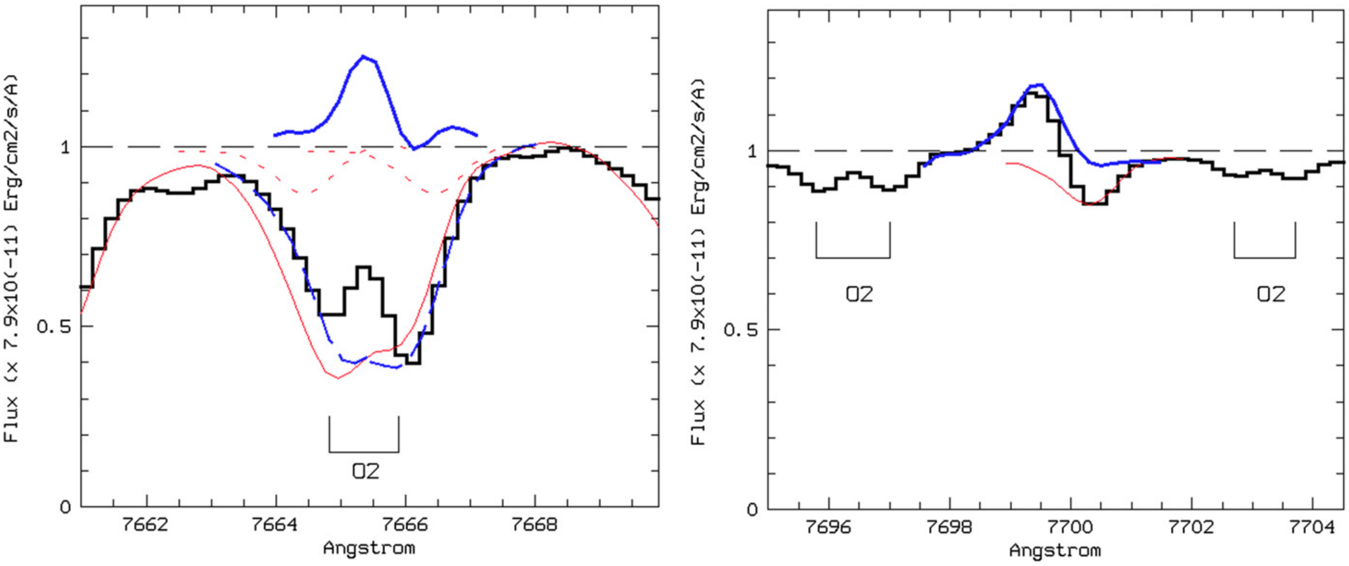

Figure 2. C/2011 L4 spectrum is shown in the region of the K I λλ7664.8991 Å (left panel) and in the region of the K I λλ7698.9645 Å (right panel). Binned thick black line: observed spectrum. Continuous blue line: reconstructed spectrum after the correction of telluric O_2 absorption bands and solar continuum reflected by cometary dust (see Section 2 for the details of the procedure).

(A color version of this figure is available in the online journal.)

detected. Other identified emissions include the C_2 Swan band $dv = 0$ and the satellite $dv = 1$e, $dv = -1$, NH2 (7–0) and NH2 (9–0), and the [O I] at λλ6300 and 6363 Å redshifted of 14 km s^{-1} (Figure 1). The alkali lines are shown in Figures 2 and 3, where the reconstructed profile is estimated after accounting for the contamination of the telluric O_2 absorption bands and of the solar spectrum reflected by the cometary dust. These corrections are computed by means of a twilight spectrum which was also recorded with the same spectrograph setup. The K I line at λλ7664.8991 Å (binned thick black line in the left panel of Figure 2) is blended with two telluric O_2 lines at 7664.73 and 7665.79 Å, and with the K I solar absorption produced by comet dust reflection of the solar light and redshifted by 50 km s^{-1}. In order to reconstruct the cometary K I emission, we used a twilight spectrum (continuous red line in the same panel) to which we subtracted the solar K I absorption at rest (left dashed red line in the same panel) and added the K I absorption redshifted by 50 km s^{-1} (right dashed red line in the same panel). The obtained local continuum (dashed blue line in the same panel) well reproduces the wings of the absorption. The resulting emission K I line (continuous blue line in the same panel) is the difference between the original spectrum (binned thick black line in the same panel) and the reconstructed local continuum (dashed blue line in the left panel of Figure 2). The other K I emission line at λλ7698.9645 Å (right panel of Figure 2) and the Na I lines at λλ5895.9242 and 5889.9510 Å (Figure 3) are not contaminated by telluric bands, but are partially eroded by the corresponding solar absorption line reflected by the comet dust. In these cases, the twilight feature (continuous red line) has been redshifted by 50 km s^{-1} to match the red wing and to reconstruct the true emission profile (continuous blue line in Figures 2 and 3). The intensities of the corrected alkali lines are reported in Table 1. No emission is detected at the position of the Li I λλ6707.78 Å line (Figure 4) and the 3σ upper limit for the Li I emission is shown in Table 1.

The abundance Na/x of sodium related to an atom x (Table 1) is extracted from the line intensity I (Table 1) by means of the relationship $\mathrm{Na}/x = (g_x/g_{\mathrm{Na}})(I_{\mathrm{Na}}/I_x)$, where the g factors g_x at 1 AU are computed (Table 1) as a function of the heliocentric radial velocity v (thus taking into account the Swing effect)

Table 1
Atomic Parameters of Alkali for Heliocentric Velocity $35 \leqslant v \leqslant 140$ km s^{-1}

Atom	λ^a	I^b	g^c	Na/x^d	Na/x^e	β_λ	a^f	a^g	τ^h	τ^i
Li	6707.78	$\leqslant$0.027	9.15 ± 0.15	$\geqslant 810^3$	$\geqslant 410^3$	440 ± 7	12.3 ± 0.2	133 ± 2	$4\ 10^3$	$4\ 10^{2\ j}$
Na	5889.95	85 ± 1	3.23 ± 0.34	1	1	47 ± 5	2.0 ± 0.2	22 ± 2	$4.0\ 10^{4\ k}$	$3.7\ 10^3$
Na	5895.92	49 ± 1	1.62 ± 0.17	...	...	24 ± 3	...	...	...	...
K	7664.90	2.1 ± 0.2	4.12 ± 0.21	54 ± 14	18 ± 5	35 ± 2	1.5 ± 0.1	16 ± 1	$9.1\ 10^{3\ l}$	$8.4\ 10^2$
K	7698.96	1.3 ± 0.1	2.16 ± 0.03	...	...	18 ± 0.2	...	...	...	...

Notes.
[a] Wavelength of the emission line (Å).
[b] Measured intensity of the emission line (10^{-11} erg s^{-1} cm^{-2} Å^{-1}).
[c] Computed g-factor (10^{-11} erg s^{-1}).
[d] Relative abundance at the source without photoionization.
[e] Relative abundance at the source with photoionization observed at 10^5 km from the source.
[f] Anti-sunward acceleration (m s^{-2}) at $r = 0.46$ AU.
[g] Anti-sunward acceleration (m s^{-2}) at $r = 0.14$ AU.
[h] Photoionization lifetime (s) at $r = 0.46$ AU.
[i] Photoionization lifetime (s) at $r = 0.14$ AU.
[j] Preston (1967).
[k] Fulle et al. (2007).
[l] Huebner et al. (1992).

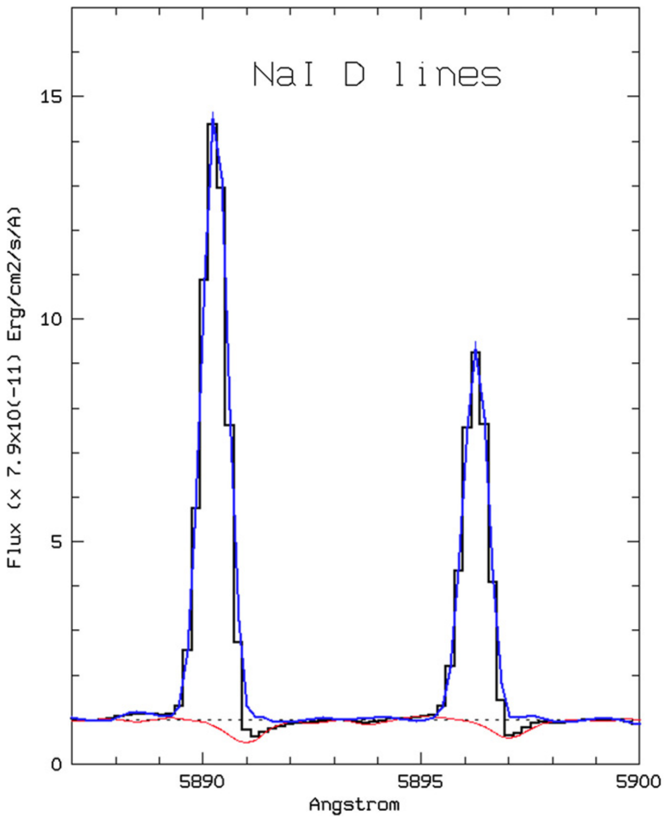

Figure 3. C/2011 L4 spectrum is shown in the region of the Na I D lines at λλ5895.9242 and 5889.9510 Å (binned thick black line). The red wing of cometary emissions are partially eroded by the corresponding solar Na I feature reflected by the comet dust. The twilight feature (red continuous line) has been redshifted by 50 km s^{-1} to match the red wing and to reconstruct the true emission profiles (continuous blue line).

(A color version of this figure is available in the online journal.)

using the high-resolution visible solar flux (Kurucz et al. 1984) and the oscillator strengths for the observed resonant lines (Morton 2003, 2004). Regarding g_K at $\lambda = 7664.8991$ Å, in the range $35 \leqslant v \leqslant 45$ km s^{-1} the solar spectrum is dominated by the strong absorption of telluric oxygen, so that we had to assume the same mean value obtained at smaller and larger v values. The intensity ratio between the two Na and K lines (1.7 ± 0.1 for Na and 1.6 ± 0.3 for K, respectively) matches the corresponding g-factor ratio (2.0 ± 0.4 for Na and 1.9 ± 0.1 for K, respectively), so that we can exclude significant optical thickness in the lines.

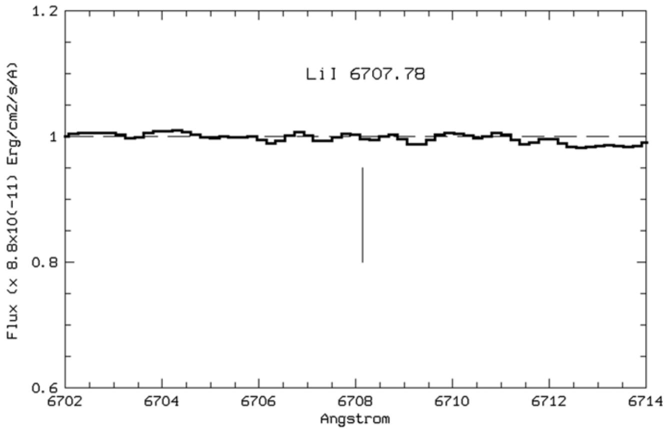

Figure 4. C/2011 L4 spectrum is shown in the region of the LiI line at λλ6707.78 Å (binned thick black line) after subtraction of the contamination of the solar spectrum. No emission was detected at the position of lithium line redshifted by 14 km s^{-1} (vertical line).

3. MODEL OF ALKALI TAILS OF COMET C/2011 L4 (PANSTARRS)

Five processes are expected to extract alkali atoms from the parent body, namely, (1) thermal desorption, (2) photon-stimulated desorption, (3) solar wind sputtering, (4) micrometeoroid vaporization, and (5) photodissociation of parent molecules. Given the atomic parameters of alkali and the results of laboratory experiments on cosmic analogues, it is expected that the cloud of atoms leaving the parent surface maintains its original (presumably solar) abundance (Leblanc & Doressoundiram 2011). Hereafter, when we refer to solar lithium abundance, we mean that measured in meteorites (Asplund et al. 2009). After the atom release, many phenomena must be taken into account to infer the Na/K ratio in Mercury's exosphere (Leblanc & Doressoundiram 2011), and the main one also occurring in comets is photoionization by solar UV radiation. All alkali atoms are pushed in the anti-sunward direction by solar radiation pressure, with accelerations $a = GM_{\odot}(\sum_{\lambda} \beta_{\lambda})r^{-2}$ in the comet reference frame. Here G is the gravitational constant, $M_{\odot}$ is the Sun mass, r is the Sun–comet distance, and β is the ratio between solar gravity and radiation pressure forces. From the g factors we compute (Table 1) $\beta_{\lambda} = g_{\lambda}(1\,\mathrm{AU})^2/(cmGM_{\odot})$, where c is the velocity of light and m is the mass of the atom (Fulle 2004). As it happens for the ejection of iron atoms (Fulle et al. 2007), alkali atoms should mainly be ejected from dust, which should be mostly ejected from the comet nucleus into the sunward sector of the coma. Before reaching the observation slit, the atoms must cover at most 10^5 km (i.e., the apex distance) in the anti-sunward direction, which requires the flight times $\Delta t_{\mathrm{Na}} = 9.510^3$ s and $\Delta t_K = 1.210^4$ s, respectively. Taking into account the photoionization lifetimes listed in Table 1, the original Na/K ratio would increase by a factor three, so that we cannot exclude an original solar ratio Na/K = 15.5 (Asplund et al. 2009). In other words, what we actually observed was the beginning of the alkali tail, where K is depleted versus sodium by its shorter photoionization lifetime. In order to cover the same distance of 10^5 km, lithium atoms need a flight time $\Delta t_{\mathrm{Li}} = 4.110^3$ s. Taking into account its photoionization lifetime (Table 1), we get an increase of the original Na/Li ratio by a factor two only, very far from the factor of eight required to match the solar ratio Na/Li = 10^3 (Asplund et al. 2009) to the observed one. The required factor of eight would be observed at 710^5 km from the nucleus, corresponding to 12′, a distance impossible to accept since the slit tracking was done on the brightest inner coma with a mean diameter of 3′. We conclude that lithium in the comet C/2011 L4 is depleted by a factor $\geqslant 4$ with respect to the solar ratio.

4. MODEL OF ALKALI TAILS OF COMET C/1965 S1 (IKEYA-SEKI)

Sodium and potassium were detected in the spectra of the comet C/1965 S1 (Ikeya-Seki) at a distance $r = 0.14$ AU, when the comet was receding from the Sun at a velocity of 110 km s^{-1} (Preston 1967). We consider the observed intensities of the alkali lines Na λλ5889.9510 and K I λλ7698.9645 measured by Preston (1967), $I_{\mathrm{Na}}/I_K = 80$ and $I_{\mathrm{Na}}/I_{\mathrm{Li}} \geqslant 1.310^4$, respectively. By means of the g factors reported in Table 1, we obtain Na/K = 50 ± 11 and Na/Li $\geqslant 3.310^4$ which are values in close agreement with those measured in C/2011 L4. Preston (1967) obtained even higher values assuming excitation mechanisms more complex than fluorescence. However, the resulting excitation temperatures are quite different among different atoms, and their physical interpretation is difficult. Due to the intensity of sodium lines, these were saturated in the photographic spectra obtained, so that we cannot exclude that the sodium lines were optically thick. However, since sodium is by far the most abundant among alkali atoms, we can assume that optical thickness affected potassium (and lithium if any) much less than sodium. This would further increase the ratios listed above. We assume that the alkali atoms must cover an anti-sunward distance of 410^4 km (exactly matching the slit length of 1′ used in the spectrograph setup) after they are ejected by the dust in the sunward coma. In order to cover such a distance, the atoms need flight times $\Delta t_{\mathrm{Na}} = 1.910^3$ s and $\Delta t_K = 2.210^3$ s, respectively. Taking into account the photoionization lifetimes listed in Table 1, the original Na/K ratio would increase by a factor of eight, more than required to match an original solar Na/K ratio. Therefore, an original solar Na/K ratio would remain consistent with observations even if the Na/K ratio in the alkali tail had been a factor of three higher due to optically thick sodium lines. On the other hand, lithium atoms need a flight time $\Delta t_{\mathrm{Li}} = 7.810^2$ s. Taking into account its photoionization lifetime, we get an increase of the original Na/Li ratio by a factor of only, very far from the factor 4 of 33 required to match the solar Na/Li ratio to the observed one. We conclude that lithium was depleted with respect to the solar abundance in comet C/1965 S1 too, by a factor $\geqslant 8$, even more constraining than in the comet C/2011 L4. The actual detection of lithium in future bright comets may help to understand if such a depletion is original in comet nuclei, or is due to a less efficient process of extraction with respect to other alkali atoms.

We thank Jacques Crovisier for his comments which significantly improved the original manuscript, and Pierluigi Selvelli for useful discussion on atomic emission processes.

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