ISSN 0038-0946, Solar System Research, 2015, Vol. 49, No. 2, pp. 139–145. © Pleiades Publishing, Inc., 2015.
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Solar Radiation Pressure as a Mechanism of Acceleration of Atoms and First Ions with Low Ionization Potentials

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Received July 18, 2013

Abstract—Calculated results are presented for solar radiation pressure acting on atoms and first ions. For some of these particles, radiation pressure exceeds the gravitational attraction and can accelerate them to large velocities. A comparison of the results with ionization potentials shows that the maxima of radiation pressure on neutral atoms coincide with the minima of the first ionization potentials (FIPs). This relationship is even more apparent for first ions. The minima of the second ionization potentials (SIPs) coincide with the radiation pressure maxima for a number of ions such as Be II, Mg II, Ca II, and the neighboring elements. Thus, radiation pressure may serve as a possible mechanism of acceleration of pickup ions and energetic neutral atoms (ENA) coming from an inner source (zodiacal dust and sungrazing comets). These atoms and ions, which are not typical of the solar wind, are formed as a result of the disintegration of comets or meteor showers near the Sun and can accelerate and reach the Earth's orbit as part of the solar wind. Doubly ionized atoms have resonance lines in the UV range, where solar radiation pressure has no apparent impact on the particle dynamics; thus, the proposed acceleration mechanism can only be applied to neutral atoms and first ions with low potentials of the subsequent ionization.

Keywords: radiation pressure (light pressure), FIP effect, interplanetary medium, elemental composition of the solar wind, sungrazing comets

DOI: 10.1134/S0038094615020057

The first attempts to assess the effect of radiation pressure on the various atoms and ions in the solar atmosphere were undertaken in the early 20th century (Milne, 1926). At that time, due to a lack of data on oscillator strengths, it was difficult to infer about the effect of radiation pressure on atoms and ions.

Now, when scientists have data on the oscillator strengths f_l for many atomic and ionic lines (Verner et al., 1994), it is possible to calculate radiation pressure for the most abundant elements. In 1990, we made a prediction about the intensity of the resonance emission of atoms and ions trapped around the Sun due to the disintegration of comets and meteor showers and the evaporation of zodiacal dust (Shestakova, 1990). The lifetimes of some atoms and ions were calculated and Ca II chosen as the most promising ion for optical observations.

By searching for the calcium ion emission in the H and K lines of Ca II near the Sun during the total solar eclipse of February 26, 1998, researchers found a large emission region in the range of elongations from 3.5° to 18° to the west of the Sun (Gulyaev and Shcheglov, 1999). The observations were analyzed (Shestakova, 2004) to find that the emission source for so large a region could not have been a single body, e.g., a comet. It was likely a meteor shower extending into a Sun-approaching orbit at a distance of roughly $2r_{\rm sol}$, where $r_{\rm sol}$ is the solar radius. Bzowski and Królikowska (2004) suggested that pickup ions and energetic neutral atoms (ENAs) might come from an inner source, i.e., zodiacal dust and sungrazing comets. According to the opinion voiced by Bzowski and Królikowska (2004) and the calculations on the thermal destruction of rocks in the composition of cometary nuclei (Shestakova and Tambovtseva, 1998), the disintegration of comets begins at distances of $40r_{\rm sol}$. This process leads to the appearance, within the said region, of dust and, eventually, cold gas, which is delivered by comets and zodiacal dust.

In this paper we calculate the solar radiation pressure on the atoms and first ions of the elements with known oscillator strengths for transitions from the ground level. It turned out that many of the atoms and ions can be accelerated by radiation pressure to different speeds and manifest themselves in the composition of the solar wind.

It could be productive to compare this factor with the anomalies in the chemical composition of the solar wind, which are known as the FIP effect (first ionization potential). In this paper we consider radiation pressure as a mechanism of acceleration of pickup ions and ENAs coming from an inner source.

CALCULATION METHOD

The force of radiation pressure F_l at the center of a resonance line is found from the formula:

$$F_l = \alpha_l \frac{\pi}{c} \frac{F_\lambda \chi_l}{(r/r_{\text{sol}})^2}, \quad (1)$$

where $\alpha_l = \pi e^2 \lambda_l^2 f_l / m_e c^2$ is the absorption coefficient in the line according to Allen (1977) (for ref.: Allen, C. W., Astrophysical Quantities, 1st ed., The Athlone Press, London, 1955), where e and m_e are the electron charge and mass; λ_l and f_l is the central wavelength and strength of the oscillator for the l the transition; c is the speed of light; F_λ is the average radiation intensity across the solar disk within a unit interval of wavelengths in a continuous spectrum between the lines (Makarova et al., 1998); χ_l is the residual intensity at the center of the line expressed in fractions of unity (the continuous spectrum F_λ is assumed to be unity; χ_l was determined from (Kurucz et al., 1984); and r/r_{sol}) is the distance from the Sun's center in solar radii.

The radiation pressure F_i on the ith atom or ion is the sum of all the pressures in all the resonance lines l:

$$F_i = \sum_l F_l. \quad (2)$$

The greater the atom's oscillator strength and the intensity of the solar spectrum at a given wavelength, the stronger the radiation pressure.

The subsequent behavior of the atom or ion depends in large part on its lifetime in the radiation field and the radiation pressure to gravity ratio: $\beta = F_i/F_g$. If $\beta > 1$, the element is accelerated away from the Sun. Since the forces acting on different atoms and ions are different, their terminal velocities are also different. This circumstance may explain the spatial separation of elements as they are moving away from the Solar System and the formation of clouds enriched with various elements. Inhomogeneities or anomalies in the chemical composition of the solar wind can be detected in the Earth's orbit or somewhere at the periphery of the solar system.

RADIATION PRESSURE CALCULATION RESULTS

Table 1 gives the results of the calculations of β for atoms with a zero radial velocity. The calculations used the radiation energy at the center of the corresponding resonance line of the solar spectrum, which is the residual intensity and amounts, in some cases, to a small fraction of the continuous spectrum. The value $\beta_{\max}$ corresponds to atoms with high Doppler velocities. The calculations of $\beta_{\max}$ used the radiation energy in the continuous spectrum. Table 2 gives the corresponding values β and $\beta_{\max}$ for ions. The energy distribution in the solar spectrum for the radiation pressure calculations was taken mainly from (Makarova et al., 1998; Kurucz et al., 1984) and for hydrogen and Mg II ions from (Bocchialini and Vial, 1994).

Table 2 shows only those ions for which the radiation pressure $\beta_{\max} \geq 0.005$.

It is evident from the tables that radiation pressure has the greatest effect on alkali atoms, beginning from Li. They have a powerful resonance doublet near the solar spectrum maximum. The radiation pressure for the Li atom exceeds the force of gravity by a factor of 223 (Shestakova, 2005). The other alkali metals (Na, K, and Rb) are also highly susceptible to radiation pressure ($\beta > 25$). The next radiation pressure maximum corresponds to the Na atom. When calculating the effect of light pressure in deep resonance lines, researchers need to consider their shape. In the solar spectrum, residual intensity at the center of the deep lines of the Na I doublet is about 5% of the continuous spectrum. If an atom has a zero radial velocity relative to the Sun, the Doppler shift relative to the line's center is also zero. In this case, the radiation pressure is, according to our calculations, $F_{\text{rad}} = 4.3F_g$. However, since it exceeds the force of gravity, the atom begins to accelerate and gain radial velocity directed away from the Sun.

The greater the Doppler shift corresponding to a given radial velocity, the stronger the radiation pressure. The latter is at a maximum when the velocity of an atom is high enough for the wavelength of the light absorbed by the atom to move, due to the Doppler shift, from the line core to the level of the continuous spectrum. In this case, the force of radiation pressure F_{rad} for the Na atom is greater than the force of gravity F_{g} by a factor of 81.3.

However, this acceleration process for alkali atoms is rather short in time because they have a low FIP and are quickly ionized by the solar UV radiation.

Their lifetime near the Sun is rather short, e.g., at a distance of six solar radii, Na atoms are ionized in 27 s (Shestakova, 1990). The quantity of Na atoms in the line of sight in the region of circumsolar sublimation was estimated by Delone et al. (2008) from observations during the total solar eclipse of March 29, 2006. It turned out that the quantity of the said atoms in the line of sight was 2×10^8 atom/cm^2 or less.

The atoms of the second column of the Periodic Table, such as Mg, Ca, etc., fit much better into the above process. They also have deep resonance lines near the solar spectrum maximum and sufficiently strong radiation pressure given a zero initial radial velocity relative to the Sun. However, they have a sufficiently long lifetime to accelerate to high velocities. Thus, according to the calculations in (Shestakova, 1990), the lifetime of a Ca atom until the next ionization at a distance of $6r_{\text{sol}}$ is 1.6×10^2 s and that of a singly ionized atom is 1.5×10^5 s. For Mg these values are 1.2×10^3 and 5.2×10^5 s, respectively. Comparing these values, it is easy to see that the lifetime of first ions of Ca and Mg is two to three orders of

Table 1. Atoms

No.	Element	β	β_{max}	No.	Element	β	β_{max}
1	H	1.0	1.3	39	Y	10.4	15.4
2	He	0	0	40–41	Zr, Nb	No data on f_l	
3	Li	223	223	42	Mo	2.5	8.4
4	Be	–	3.6	43–44	Tc, Ru	No data on f_l	
5	B	–	0.2	45	Rh	1.7	2.2
6–10	C–Ne	0	0	46	Pd	No data on f_l	
11	Na	4.3	81.4	47	Ag	1.1	3.0
12	Mg	1.4	13.7	48	Cd	0.21	0.22
13	Al	0.3	7.4	49	In	0.60	2.7
14	Si	–	0.30	50	Sn	–	0.40
15–18	P–Ar	0	0	51–52	Sb, Te	No data on f_l	
19	K	8.65	56.5	53	I	–	0.0003
20	Ca	2.0	63.3	54	Xe	0	0
21	Sc	10.25	29.4	55	Cs	0.13	0.16
22	Ti	1.7	17.1	56	Ba	15.4	22.7
23	V	2.5	10.9	57–62	La–Sm	No data on f_l	
24	Cr	0.76	18.3	63	Eu	11.6	12.7
25	Mn	0.25	6.2	64–68	Gd–Er	No data on f_l	
26	Fe	0.11	2.5	69	Tm	0.59	0.86
27	Co	0.04	0.75	70	Yb	5.7	8.1
28	Ni	0.04	1.1	71–76	Lu–Os	No data on f_l	
29	Cu	0.17	5.1	77	Ir	–	0.036
30	Zn	–	0.26	78	Pt	No data on f_l	
31	Ga	0.5	2.9	79	Au	–	0.14
32	Ge	–	0.41	80	Hg	–	0.005
33, 35	As, Br	0	0	81	Tl	0.20	0.73
34, 36	Se, Kr	No data on f_l		82	Pb	–	0.21
37	Rb	24.1	25.6	83	Bi	0.047	0.31
38	Sr	15.7	32.6				

Table 2. Ions

No.	Element	β	β_{max}	No.	Element	β	β_{max}
4	Be II	5.5	24.5	25	Mn II	–	0.94
5	BII–BIII	0	0–0.1	26	Fe II	–	0.52
12	Mg II	1.2	5.9	30	Zn II	–	0.04
13	Al II	0	0.005	38	Sr II	0.90	14.7
20	Ca II	1.7	15.8	39	Y II	0.45	1.61
21	Sc II	0.9	13.0	48	Cd II	–	0.08
22	Ti II	0.46	8.1	56	Ba II	1.07	11.9
23	V II	–	0.5	60	Nd II	0.68	1.79
24	Cr II	–	0.02	70	Yb II	0.44	3.0

magnitude greater than that of neutral atoms. After the first ionization, they become ions similar to the Li atom with more powerful resonance lines shifted into the UV region, but they are still near the solar radiation maximum. A special experiment on the observation of Ca II ions in the line λ 3933 Å in the outer solar corona was conducted by Gulyaev and Shcheglov (1999) during the total solar eclipse of February 22, 1998. It was shown experimentally that Ca II ions can move at a speed

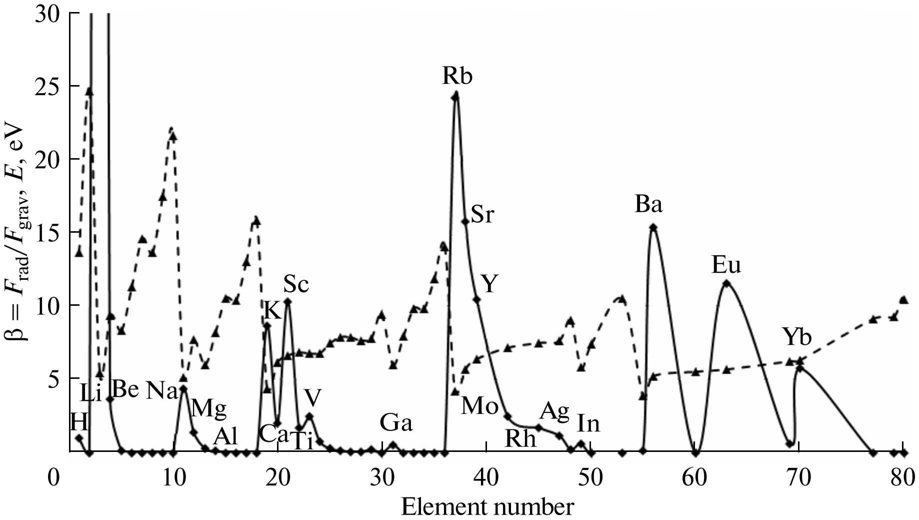

Fig. 1. Radiation pressure to gravity ratio (solid line) for atoms with zero radial velocities relative to the Sun and the first ionization potential (dashed line) depending on the number of the element.

of the order of, or even higher than, the speed of the solar wind within 30 solar radii.

It was shown in (Shestakova, 2013) that the nearer to the Sun Ca ions are when they are separated from the parent body, the higher the speed to which the ions are accelerated. In general, the dynamic analysis showed that Ca ions leaving the parent body's orbit at distances less than $15r_{sol}$ can accelerate under the influence of light pressure to speeds exceeding 400 km/s, which corresponds to the speed of the solar wind in the Earth's orbit.

Hydrogen, the most abundant element, can show a very interesting behavior; according to Bocchialini and Vial (1994), β for hydrogen changes constantly near a critical value equal to unity. This variability is associated with the variation of the line L_α, which is formed in the chromosphere. As a result, radiation pressure acts on the hydrogen atoms in the photosphere in the same direction as the force of gravity, and the H atoms in the upper photospheric layers seem to grow 1.5–2 times heavier. Outside the corona, where there may exist neutral H atoms as a result of the disintegration of comets and meteor showers, radiation pressure acts in the direction opposite to gravity. Since the atoms, which have become weightless after the separation from the parent body (comet), already have substantial orbital velocities, a small additional acceleration would be enough for them to become part of the solar wind. In this case, immediately after the separation from their parent bodies (sungrazers), H atoms have velocities typical of the solar wind near the Earth's orbit.

Radiation pressure has virtually no effect on noble gases (the eight column of the Periodic Table). Doubly ionized atoms have resonance lines in the UV range, where solar radiation pressure has no visible effect on particle dynamics; therefore, radiation pressure does not matter much for them either.

COMPARISON OF RADIATION PRESSURE WITH IONIZATION POTENTIALS

The calculated results for radiation pressure were compared with the available data on ionization potentials (Fig. 1) to reveal a coincidence between the maxima of radiation pressure on neutral atoms (continuous line) and the FIP minima. These include Li, Na, Mg, K, Sc, V, Ga, Rb, Sr, Y, Mo, Rh, Ag, Ba, Eu, and Yb.

The coincidence between the radiation pressure maxima and secondary ionization potential (SIP) minima is even more apparent for first ions (Fig. 2). The SIP minima indicate a number of ions such as Be II, Mg II, Ca II, Sr II, and Ba II and the neighboring elements with larger numbers.

Ions like Mg II have powerful resonance lines in the solar spectrum; the radiation pressure of these lines can accelerate the ions (which had already been accelerated before the first ionization, when they had been neutral atoms) to high speeds.

Figure 3 shows the positions of the atoms, except H and Li, with zero radial velocities relative to the Sun. The chemical symbols of the atoms for which $\beta > 1$ are written near the corresponding dots. The next radiation-pressure leader after Li is Rb.

Figure 4 is generally similar to Fig. 3, but, since some of the atoms have deep absorption lines in the solar spectrum, the leadership has changed. After gaining a high speed and moving (in wavelength) from the deep absorption line to the continuous spectrum due to the Doppler shift, such elements as sodium, calcium, and potassium are subjected to stronger radiation pressures.

Figures 5 and 6 are similar to those for atoms, but the level of radiation pressure is markedly lower. There are no alkali metals in these diagrams because after the first ionization they become similar to noble gases in

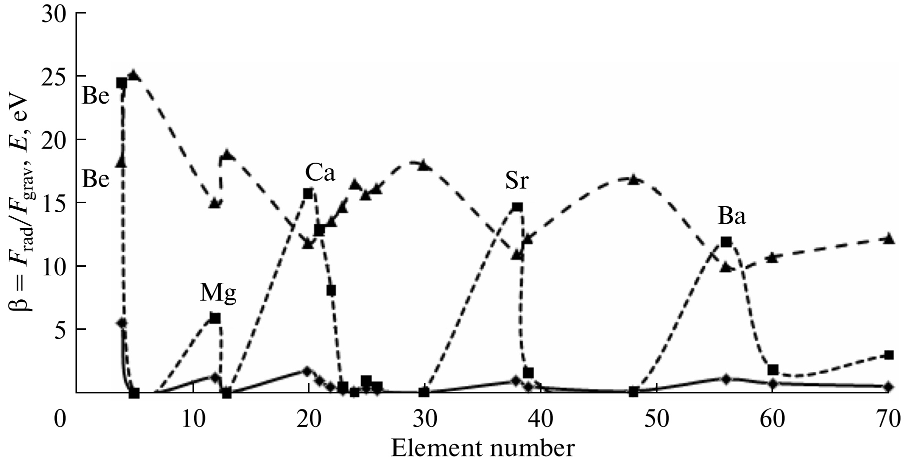

Fig. 2. Radiation pressure to gravity ratio (solid line) for ions with zero radial velocities. The line with short dashes is for high-velocity ions. The upper dashed line shows the second ionization potential.

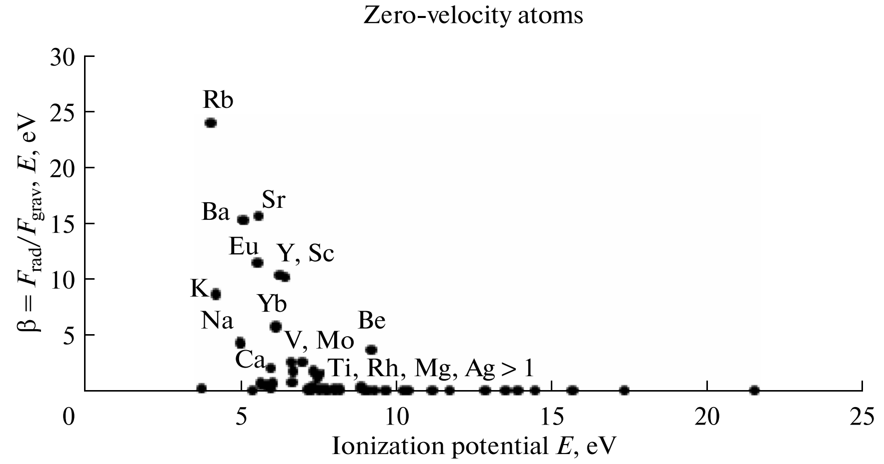

Fig. 3. Radiation pressure and ionization potential (in eV) for atoms with zero radial velocities.

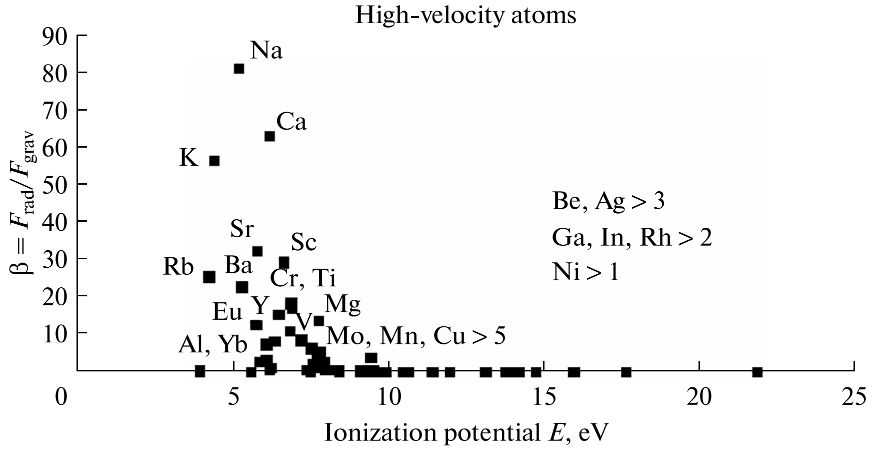

Fig. 4. Radiation pressure and ionization potential (in eV) for atoms with high radial velocities.

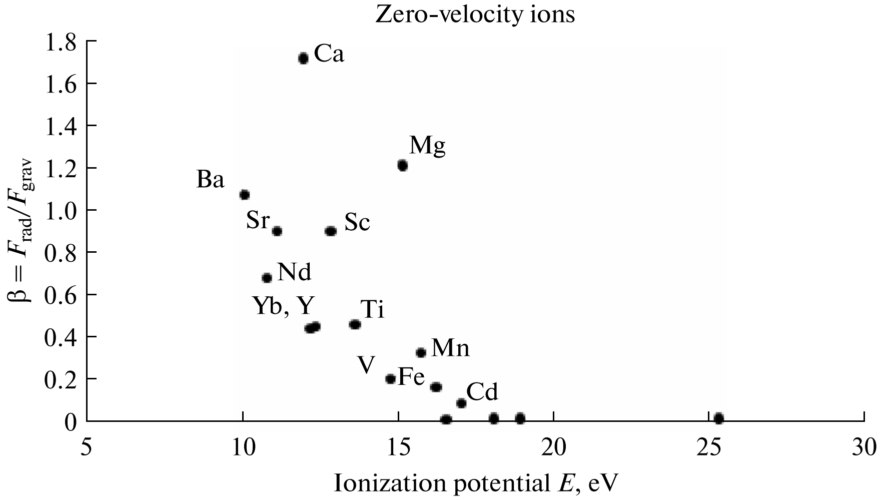

Fig. 5. Radiation pressure and ionization potential (in eV) for ions with zero radial velocities.

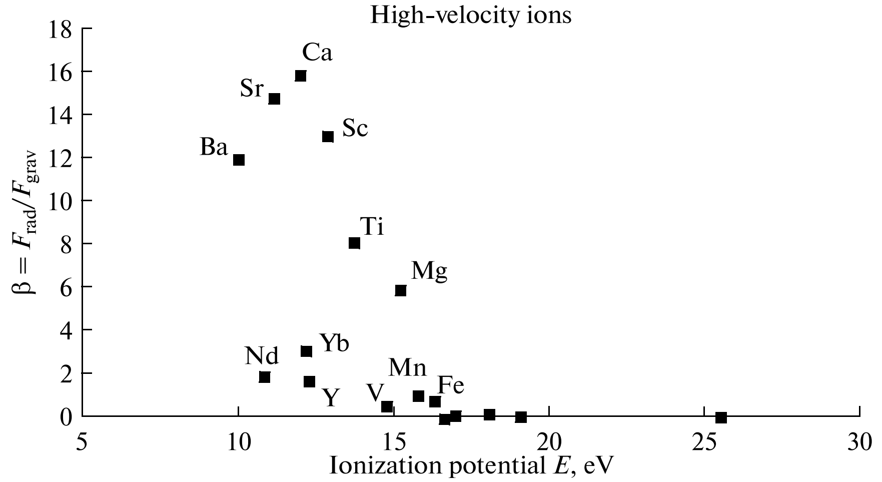

Fig. 6. Radiation pressure and ionization potential (in eV) for ions with high radial velocities.

terms of radiation pressure effects. The leaders are the atoms of the second column in the Periodic Table, which now behave like alkali metal atoms (Ca, Mg, and Ba).

It should be noted that most of the atoms separating from the parent bodies (comets) near the sublimation region already have high orbital velocities, and the parent bodies' orbits are, as a rule, parabolic. Thus, we can treat ions as high-velocity particles and formulate conclusion on the basis of Fig. 6, from which it is evident that the list of ions with a low degree of ionization can be largely expanded.

CONCLUSIONS

It can be concluded that the most abundant elements among those of the second column in the Periodic Table, which have a high level of radiation pressure both as atoms and as ions (Be, Ca, Mg, Ba, and Sr), are the most promising ones in terms of search in the composition of the solar wind in the Earth's orbit. There are also promising elements in other columns (Figs. 3–6), which also have a high radiation pressure (Sc and Ti). It is most likely that, having been accelerated by radiation pressure in the neutral state, these elements already have nonzero radial velocities at the time of the ionization. Interestingly, apart from the above mentioned "radiation pressure-active" columns in the Periodic Table, there are also "active" rows: the fourth row, which begins with K, and the sixth row, which begins with Rb. Of interest also is the eighth row, which begins with Cs and contains rare-earth metals (lanthanides). Those of them with known oscillator strengths have a high β both as atoms and as ions.

Despite the lack of data on oscillator strengths for the tenth row of the Periodic Table, the actinide group, which contains radioactive elements such as Th, U, etc., may be expected to behave similarly to the lanthanides. In this respect it is easy to see what Lebedinets (1981) meant by saying that the dust of noctilucent clouds was found to contain significant amounts of Hf, Th, U, and other heavy elements, which had come, he believed, from the solar wind.

The contribution of heavy ions in the solar wind was measured using CELIAS (Charge, Element, and Isotope Analysis System) and SOHO (Solar and Heliospheric Observatory) to find (Bochsler, 2007) an excess of Na, Al, Ca, Cr, Mg, Fe, and Si. According to the data in (Giammanco et al., 2008), which were also obtained using CELIAS, there is also an excess of K, Na, Al, Ca, Mg, S, and P for the slow solar wind. It is evident from these results that almost all the above elements, except for S and P, are subjected, in a varying degree, to radiation pressure.

Doubly ionized atoms have resonance lines in the UV range, where solar radiation pressure cannot have a noticeable effect on particle dynamics; therefore, the proposed mechanism of acceleration can be applied only to neutral atoms and first ions with low first and second ionization potentials.

As to the search for anomalies in the chemical composition of the solar wind, which are due to the scattering of cometary and meteor matter near the Sun, we could recommend to focus on H atoms and, among heavy elements, on Mg and Ca as atoms or first ions against the background flux of protons, α particles, and noble gas nuclei.

Speaking about the search for the resonance emission of singly ionized elements in the circumsolar region, it is most promising to search for emission in the line Mg II λ 2795 Å because Mg has a greater cosmic abundance and lifetime than Ca. Therefore, the expected intensity of emission (Shestakova, 1990) is roughly an order of magnitude greater than in the line Ca II λ 3933 Å.

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Translated by A. Kobkova