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On the Energy Dependence of the Relative Contributions Ionospheric and Solar Sources of the Ring Current Protons

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Abstract. The energy dependence of a fraction of ring current protons of ionospheric origin is calculated using the *AMPTE/CCE* data for a typical magnetic storm ($D_{st} = -120$ nT). It is shown that at $L = 6 \div 7$ (L is the McIlwain parameter) this fraction monotonically decreases from $\sim$ 83 to $25 \div 30\%$ with an increase in proton energy from 5 to 315 keV and is $30 \div 40\%$ at energy $40 \div 50$ keV corresponding to the maximum of proton energy density at $L = 6 \div 7$. It is evident that the core of the ring current ($L = 3.7 \div 4.7$) is enriched by solar protons with $E \sim 10 \div 200$ keV during storm main phase (the maximum effect is achieved at $E \sim 20 \div 50$ keV).

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1 Introduction

Numerous experimental results obtained in the last 30 years testify that the ionosphere is an important source of hot magnetospheric plasma along with the solar wind. The ratio of these sources strongly differs both in different magnetospheric regions and in different energy ranges.

The Earth's radiation belts, to which geomagnetically trapped particles with energy, E, more than several hundreds of keV belong, are fed, in the main, by the solar source, and the ion composition of the belts is close to the solar wind composition (see reviews [1,2]). For example, according to the ISEE-1 data, the ratio of the fluxes of carbon and oxygen ions (nuclei) with $E/M_i \sim 1$ MeV (M_i is the ion mass in relation to the proton mass) is $\sim 0.5 \div 1.9$ in the belts [3], which is close to this value in the solar wind and essentially differs from values of $\sim 10^{-5}$ for the ionospheric source.

In contrast to the belts, for trapped particles of lower energies (from several tens to several hundreds of keV) which belong to the storm ring current (RC), the solar wind and the ionosphere are equitable sources: the solar source dominates in some storms, and the ionospheric source in others (see review [4]). The estimations of relative contributions of these sources to the RC are of great importance in order to study the mechanisms of particle acceleration and transfer, as well as the general mechanisms of circulation of hot plasma in the magnetosphere.

In quiet periods and for the majority of geomagnetic storms, during which measurements of the ion RC composition are performed, protons which could be of both solar and ionospheric origin make the main contribution to the RC energy (see [4]). During storms the fluxes of O^+ ions in the RC are also considerably increased, but their contribution to the total RC energy approaches to the proton contribution only on the main phase and in the beginning of the phase of recovery of giant (with $|D_{st}| > 300$ nT) storms [5,6].

Therefore, correct determination of the ratio of fractions of protons of ionospheric and solar origin is of principal importance for the physical interpretation of the dynamics of ion composition of hot magnetospheric plasma, which is observed on satellites. For example, the ratio of fluxes O^+/H^+ with $E/Q_i = 0.9 \div 16$ keV (Q_i is the ion charge in relation to the proton charge) in the region of geosynchronous orbit ($L \sim 6 \div 7$) gradually decreases during the geomagnetic activity decay and in quiet periods (see, for example, [7]). It was concluded from this fact that the solar source dominated [7]. However, one can see from the data presented in [7] that not only the ratio of fluxes O^+/H^+ decreases, but also He^{2+}/H^+. If one considers that protons are, in the main, of solar origin, it follows from these facts that the solar source dominates in the above indicated periods. In this case, decreasing ratio He^{2+}/H^+ is explained by the fact that He^{2+} ions lifetime in the geomagnetic trap is less than proton lifetime. But if one considers that protons of such energies are, in the main, of ionospheric origin, from these facts it follows that the ionospheric source dominates, and protons prevail in the composition of ionospheric ions.

2 Procedure of the Analysis

Identification of particles with the source is performed, first of all, according to the particle charge. For example, ions O^+, He^+, N^+, and O^{2+} usually are attributed to the ionospheric source, while ions He^{2+}, C^{6+}, and O^{6+} with charges close to charges of their nuclei are ascribed to the solar source.

Such a classification is based on the fact that there are no ions with $M_i > 1$ and $Q_i \approx Z_i$ in the ionospheric source (Q_i and Z_i are the charges of ion and its nucleus in relation to the proton charge), while the probability that ionospheric ions lose practically all electrons (at collisions with atoms of the exosphere) is close to zero. However, the probability of the inverse process (electron capture and Q_i decreasing) for RC ions is rather significant. The method of identification of the particle source by a value of Q_i for ions well operates in the outer regions of the trap, where the concentration of atoms of the exosphere is insignificant, and ions have no time to be recharged. It works even more reliable in the plasma sheet (PS) of the magnetospheric tail.

However, this method is obviously unsuitable for RC protons.

Estimations of the fractions of protons of ionospheric and solar origin in the RC (or in PS) were performed on the basis of comparison of mean partial concentrations of various ion components in the RC/PS and in the solar wind [8,9]. According to this procedure, the total proton concentration (a) in RC/PS consists of concentrations of the protons of ionospheric (a_i) and solar (a_s) origin, and a fraction of ionospheric protons in RC/PS is equal to

$$\frac{a_i}{a} = 1 - \frac{b/a}{n_1}, \tag{1}$$

where b is the concentration of one component of multiply charged ions (He^{2+}, C^{6+}, O^{6+}, *etc.*) in RC/PS, and n_1 is the mean value of the ratio b/a in the solar wind. In this case, it is considered that all multiply charged ions in RC/PS are of the solar origin.

In [8], concentration [He^{2+}] was taken as 6, and it was assumed that $n_1 = 2\%$, while, in [9], the total concentration [C^{6+}] + [O^{6+}] was taken as b and it was assumed that $n_1 = 0.08\%$.

However, the estimations of fractions of RC protons of the ionospheric and solar origin presented in [8,9] essentially differed. Moreover, it follows from calculations made in [8,9] that some conclusions about variations of contributions of the ionospheric and solar sources in the RC during geomagnetic disturbances contradict each other (see the detailed comparative analysis of these results in [10]).

One could suppose that these disagreements are connected with faster (in comparison with protons) charge exchange of multiply charged ions at small L. However, for PS, where we can neglect ion charge exchange, such a procedure leads to stronger contradictions [10].

The measurements of the ion RC/PS composition on ISEE-1 [8] and AMPTE [9] were performed in different energy ranges, but for PS it was impossible to explain the discrepancy of estimations and conclusions in [8] and [9] by this difference [10].

Relation (1) follows from the identity $a = a_i + a_s$ and from the condition of equality of the ratios a_s/b in RC/PS and in the solar wind. However, the latter is not obvious and, generally speaking, it can be invalid: when solar plasma penetrates into the magnetosphere, the ratio of concentrations of various ion components can vary. In addition, the ratio a_s/b in the solar wind strongly varies (see, for example, [11]).

In [10], a more accomplished method of estimation of contributions of the ionospheric and solar sources to the hot magnetospheric plasma is presented, which takes into account possible variations of parameter n_1 and of the efficiency of the ionospheric source. For a fraction of protons of ionospheric origin in RC/PS, this method leads to the following expressions:

$$\frac{a_i}{a} = \frac{b'/b - a'/a}{b'/b - H} \tag{2}$$

$$\frac{a'_i}{a'} = \frac{b'/b - a'/a}{b'/b - H} \frac{H}{a'/a}, \tag{3}$$

where [He^{2+}] concentration is taken as 6, primed and not primed quantities refer to the disturbed and quiet periods of measurements, respectively, and

$$H = \frac{a'}{a} \frac{n_1 - b'/a'}{n_1 - b/a} = \frac{a'_i}{a_i}. \tag{4}$$

Parameter H plays a very important role in our method. The analysis of dependence of this parameter on n_1 and of the experimental data on a'/a, b/a, and b'/a' allows us to remove discrepancies in estimations of a fraction of ionospheric protons in RC/PS which are obtained when relation (1) is used, as well as to find relative efficiencies of the ionospheric source for various ion components (H^+, He^+, N^+, O^+, *etc.*).

The dependence of H on n_1 has two branches (modes). It is shown in [10] that for all available data on the ion RC composition, the relations $b/a < b'/a'$ and $H < a'/a$ are valid (the lower branch of function $H(n_1)$), while for the PS data at $10 < r < 23$ (r is the distance from the Earth's center in the Earth's radii), the relations $b'/a' < b/a$ and $a'/a < H < \infty$ take place (the upper branch of function $H(n_1)$).

The main source of errors in our method is a faster charge exchange of He^{2+} ions in comparison with protons, which leads to underestimation of the fraction of solar protons in the RC. As L decreases, the error connected with it quickly increases, but at $L = 5 \div 7$ it does not exceed, according to our calculations, i.e. 10% in quiet periods and decreases by factors of tens to hundreds during magnetic activations.

Estimations of the ratio of contributions of the ionospheric and solar sources obtained by this method for n_1 ([He^{2+}]/[H^+]) = $2 \div 7\%$ using the data of GEOS-1, GEOS-2, ISEE-1, SCATHA, AMPTE/CCE, and AMPTE/IRM are in good agreement with each other [10]. According to these estimations, in quiet PS at $r = 10 \div 23$ there are approximately equal numbers of protons of ionospheric and solar origin ($50 \pm 5\%$), while during substorms the fraction of ionospheric protons in PS increases up to $75 \pm 5\%$. In quiet RC more than 70% of protons are of ionospheric origin, and during magnetically active periods the fraction of solar RC protons increases by a factor of $1.5 \div 3$.

Dependences of these estimations on the distance of an observation point to the Earth, particle energy, the level of geomagnetic activity and the solar cycle phase, as well as the stability of these estimations against variations of the ion composition of the solar wind are considered in [12]. It is demonstrated that although during giant storms the contribution of the ionospheric source to the oxygen RC component sharply increases, the contribution of the solar source to the RC energy density, which is reflected in the proton RC component, approaches to the contribution of the ionospheric source.

Using the satellite data on partial ion concentrations it was obtained in [12] that the fraction of ionospheric protons in differential concentration of the proton component in PS almost does not depend on particle energy, and this fraction decreases with an increase of proton energy in the RC. However in [12] only partial ion concentrations in intervals $E/Q_i = 0.1 \div 17, 0.1 \div 32, 1 \div 16, 10 \div 315$, $30 \div 310$, and $25 \div 230$ keV were considered and actually the energy dependence of the fraction of protons of ionospheric origin [H_i^+]/[H^+] was analyzed only for the range $0.1 \div 30$ keV.

3 Results of Analysis of Experimental Data

Here the results of our calculations of the energy dependence of a fraction of protons of ionospheric origin in the range 5-315 keV are presented. We use the AMPTE/CCE data [13,9] obtained in a quiet period (September 3, 1984) and in the beginning of the recovery phase (September 5, 1984) of t a typical storm ($D_{st} \approx -120$ nT), when the storm RC are already symmetrized and only begins to disintegrate.

We find from these data: at $L = 6 \div 7$ the ratio of differential concentrations [He^{2+}]/[H^+] on the recovery phase of the storm increases from 0.8 to 4% with a growth of E/Q_i from 5 to 315 keV, while at $L = 3.7 \div 4.7$ this ratio has a clean-cut minimum ($\approx 0.3\%$) at $E/Q_i = 85 \pm 15$ keV and increases up to $\approx 1.5\%$ at $E/Q_i = 5$ and 315 keV.

During this storm AMPTE/CCE has crossed the magnetopause, and in [9] the mean value [He^{2+}]/[H^+] = 2.5% in the magnetosheath is presented for this period. However, when we substitute the value $n_1 = 2.5\%$ and experimental values [He^{2+}]/[H^+] for RC at $L = 6 \div 7$ presented in [13, 9] into formula (1), at $E/Q_i > 100$ keV we obtain negative values, for the fraction of ionospheric protons. The segment with negative values of parameter a'_i/a' having no physical meaning also appears when one uses formulas (2-4) and $n_1 = 2.5\%$, though in this case it is shifted to $E/Q_i \sim 300$ keV.

The occurrence of such a segment is explained by the fact that plasma comes into the magnetosheath not only from the solar wind, but also from the magnetosphere (see, for example, [9]), and the averaged (over time and particle energy) value [He^{2+}]/[H^+] in the magnetosheath is less than in the solar wind. There-

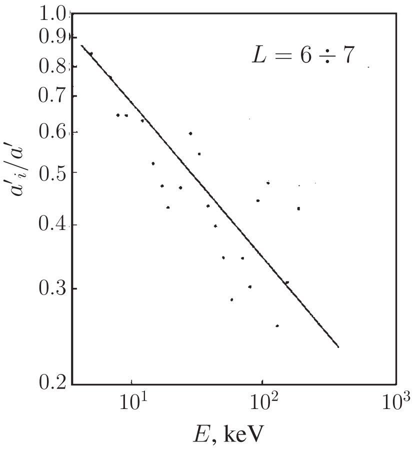

Figure 1. The energy dependence of parameter a'_i/a' at $L = 6 \div 7$ in the beginning of the recovery phase (September 5, 1984) of a typical storm.

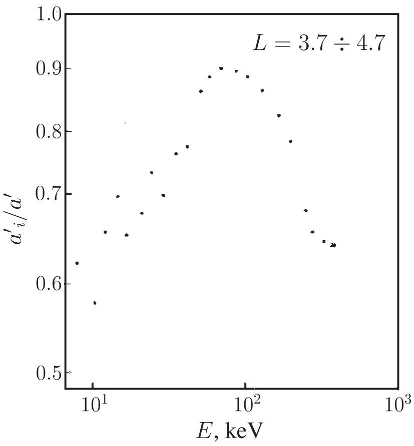

Figure 2. The same as in Figure 1 for $L = 3.7 \div 4.7$.

fore, in our calculations of the energy dependence of parameter a'_i/a' on the recovery phase of the storm on September 4-7, 1984 by the AMPTE/CCE data, whose results are shown in Figires 1 and 2, we accept the more realistic mean value for the solar wind $n_l([He^{2+}]/[H^+]) = 4\%$.

It is seen from Figure 1 that at $L = 6 \div 7$ with an increase of energy from 5 to 315 keV parameter a'_i/a' decreases from ~ 83 down to $25 \div 30\%$. For such L and E it is possible to neglect the error associated with ion charge exchange. At an energy corresponding to the maximum RC proton energy density (for the period under study this energy at $L = 6 \div 7$ was $40 \div 50$ keV [13,9]) the fraction of ionospheric protons is $30 \div 40\%$. In [10], using the same data at $L = 5 \div 7$, the integral (averaged over the range of $E = 10 \div 315$ keV) value $a'_i/a' = 60\%$ was obtained.

It was stated previously that at $L = 6 \div 7$ protons are mainly of ionospheric or solar origin at $E < 10$ keV and at $E > 10 \div 20$ keV, respectively [7,8].

At $L = 3.7 \div 4.7$, as it is seen from Figure 2, the parameter a'_i/a' is $\sim 60 \div 62\%$ at $E = 5$ and 315 keV and increases up to 90% at $E = 85 \pm 15$ keV. In this range it is necessary to take into account the charge exchange of ions H^+ and He^{2+}: at $E \approx 20$ keV the charge exchange lifetime of ions H^+ and He^{2+} are equally; at $E < 20$ keV for He^{2+} its time more than for protons, but at $E > 20$ keV its time less than for protons; at $E \sim 60 \div 100$ keV the energy dependence of lifetime the ions He^{2+} have distinctly minimum [14]. At the lowest (< 10 keV) and at the highest (~ 300 keV) energies considered in this report, charge exchange leads to insignificant effects on parameter a'_i/a'.

Our calculations show that in view of ion charge exchange the maximum in the energy dependence of parameter a'_i/a' at $L = 3.7 \div 4.7$ decreases down to $\sim 65 \div 80\%$ and is shifted to $E \sim 100 \div 200$ keV, and at $E/Q_i \sim 20 \div 50$ keV parameter a'_i/a' decreases down to $30 \div 50\%$.

The results of calculations obtained for $L = 3.7 \div 4.1$ correspond to enrichment of the RC core during a storm by solar protons with $E \sim 10 \div 200$ keV (the maximum effect is reached at $E \sim 20 \div 50$ keV). Previously the effect of enrichment of the storm RC by solar protons was noticed in [10,12] using integral estimations of parameter a'_i/a'.

4 Discussion of Results

The critical and the most essential free parameter in our calculations is the ratio of concentrations and [He^{2+}] in the solar wind, the parameter $n_1 =$ [He^{2+}]$/$[H^+]. In some periods considerable deviations of this parameter from its mean value (4%) accepted in our calculations are observed. Therefore, it is necessary to consider the stability of estimations and conclusions obtained here concerning the variations of this parameter.

Since $a'_i/a' \equiv 1 - a'_s/a'$ and $a'/a'_s \propto n_1$, the RC parameter a'_i/a' decreases with decreasing n_1, and all points in Figures 1 and 2 are shifted downward, while with increasing n_1, the RC parameter a'_i/a' increases, and points in Figures 1 and 2 are shifted upward. The character of the energy dependence of RC parameter a'_i/a' is invariable in this case, but because of the logarithmic representation, the slope of line in Figure 1 becomes steeper in the first case (the downward shift of points) and flatter in the second case (the upward shift of points). The maximum in Figure 2 in the first case is narrowed, and in the second case it is spread. The depth of a dip in the energy dependence of a'_i/a' at $L = 3.7 \div 4.7$ in the first case increases and in the second case decreases.

For the storm under consideration the mean value of parameter n_1 could not be less than 2.5% (at $n_1 < 2.5\%$ the values of a'_i/a' would be negative in the wide energy range) and could not considerably exceed 4% (it would also manifest itself in the magnetosheath).

It is seen from Figures 1 and 2 that during the storm the maximum values of the RC parameter a'_i/a' approached 1. Therefore, an increase of parameter n_1 up to $5 \div 7\%$ leads to a small upward shift of maximum calculated values of a'_i/a': $\Delta(a'_i/a') < 10\%$ at $L = 6 \div 7$ (Figure l) and $< 10 \div 20\%$ (taking charge exchange into account) at $L = 3.7 \div 4.7$ (Figure 2). In this case, the character of the energy dependences of parameter a'_i/a' does not vary.

Parameter n_1 can vary not only when converting from solar wind to the magnetosheath (which is considered above), but also when plasma penetrates into the magnetosphere, as analyzed in [12]. These effects influence the absolute values of computed quantities, but they do not change the character of the basic regularities (for more details see [12]).

Note that in coronal mass ejections (CME/ICME), as well as in corotating interaction regions (CIR) of the heliosphere, [He^{2+}]/[H^+] can reach $10 \div 30\%$ (see, for example, [11]). The interactions of such structures with the magnetosphere are usually accompanied by giant storms (with $|D_{st}| > 300$ nT). When the simultaneous data on the ion composition of the solar wind (magnetosheath) and RC are available, as in the storm considered here, our method of estimation of the fractions of RC protons of ionospheric and solar origin can be used for giant storms also. But at present we have no sufficiently complete data set for such events.

5 Conclusion

Calculations carried out using the AMPTE/CCE data for a typical magnetic storm show that a fraction of ring current protons of ionospheric origin at $L = 6 \div 7$ monotonically decreases from ~ 83 down to $23 \div 30\%$ with an increase of the proton energy from 5 to 315 keV, and at energy $40 \div 50$ keV corresponding to the maximum energy density of RC protons at $L = 6 \div 7$ is $30 \div 40\%$. It is shown that during the active phase of a storm the core of the ring current ($L = 3.7 \div 4.7$) was enriched by solar proton with $E \sim 10 \div 200$ keV (the maximum effect is reached at $E \sim 20 \div 50$ keV).

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