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THE REQUIRED RANGE FOR THE ACCELERATION EFFICIENCY WHEN PARTICLES UNDERGO ENERGY LOSSES

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It is studied how the effect of Coulombian Energy losses on particles is, in the cases when these losses are important during the acceleration process. The effect of particle selectivity on basis to the depression of some nuclear species by energy losses is discussed under different assumptions about the target medium, the acceleration rate and the charge state of particles. To know whether these effects are present or not we derive quotes in the required acceleration efficiency in order to describe some typical abundance ratios in solar events. It is obtained that these quotes are constrained to narrow bands, implying a fortuitous character for the acceleration efficiency, however the values are quite similar to those derived by other means.

Introduction

The fact of whether energy losses on solar particles are important or not is highly controversial, since a global analysis of the flare phenomenon shows some features that tend to support the deceleration and even Coulombian thermalization of some particles, whereas other evidences seem to indicate that few amount of matter has been traversed by particles. Here, we want to point out that, if Coulombian losses are important while particles undergo acceleration (i.e. the acceleration efficiency is relatively low) several effects of particle selectivity may be imposed depending on the physical conditions of the source, such as the degree of ionization, temperature and density. A manner to determine whether these effects are present or not may by done by establishing the quotes imposed by Coulombian losses to the acceleration efficiency in order to have preferential acceleration of certain nuclear species over others, and to compare them to the values predicted by other means, or, to search from inherents features of definite acceleration mechanisms, whether these values may be justified or not during a given solar event. The criteria followed to establish these quotes are based on the fact that a given kind of ion is going to be free-accelerated when the acceleration rate (assumed independent of charge and mass) does not intersect its corresponding energy loss curve, in which case these nuclear species are preferentially accelerated in relation to those for which the acceleration and deceleration curves intersect at some energy. In the later case, particles need to have an energy higher than the so called injection energy, such that most likely only those of the extremely hot tails of particle thermal distributions are picked up by the acceleration process, or, because they proceed from a preliminar acceleration stage. Therefore, the enhancements appear because all nuclear species that are not affected by energy losses and that are present in the acceleration volume are susceptible of being accelerated, whereas those for which the losses are not negligibles, under the conditions of a given acceleration efficiency, are limited by a threshold in energy. It may be mentioned that if the Fermi mechanism is concerned even the free-accelerated particles need to have velocities higher than the characteristic Alfven velocity. To derive the required quotes, the comparison between the acceleration and deceleration rates need to be done not strictly at the maximum of losses, because the predicted curves are very flat around it (which at least in neutral media it is well confirmed by experimental data) but at an specific energy such that the curves do not intersect at any other energy.

Coulombian Energy losses

There are not at present general expressions to describe Coulombian energy losses through all the energy range where they take place (i.e. including nuclear stopping, electronic stopping and ionization) in terms of the degree of ionization of the medium and with explicit dependence on the temperature of the medium. However, two extreme situations may be analysed through all the energy range, energy losses in neutral and in fully ionized media. If the target medium is fundamentally composed of Hydrogen, the border between these two assumptions in the solar atmosphere is around 1.65×10^4 °K. For a fully ionized Hydrogen the expressions given by Buttler and Buckinghan, (1962), or, Itikawa and Aono (1965) may be used. The former authors give for the contribution of the target electrons and protons to the loss the following rate

$$^{*}-\frac{dE}{dt} = \frac{1.57\times10^{-35}N}{\beta}\,\frac{Q^2}{A}\,H(x)\ln\Lambda \qquad (eV/n.s) \qquad (1)$$

where $x_e = 5.44\times10^4\beta T^{-0.5}$, $H_e(x_e) = 0.88\,\mathrm{erf}(x) - (1 - 5.48\times10^{-4}/A)x_e e^{-x_e^2}$ and $\ln\Lambda$ is the Coulomb logarithm. For a neutral medium the theory has been developed to fit experimental data, such that the formulation is given independent of temperature: the expression of Lindhard et. al. (1963) for nuclear stopping may be rewritten as

$$-\left(\frac{dE}{dt}\right)_{n.s.} = \frac{1.19\times10^{-8}NQ^{1.5}\mathcal{E}^{0.775}\exp\left[-(\mathcal{E}^{0.5}-0.009)^{0.84}\right]}{\left[(1+Q^{0.66})^{0.5}(1+A)A\right]^{0.5}} \qquad (eV/n.s) \qquad (2)$$

where $\mathcal{E} = aAE/e^2Q(1+A)$, $a = 0.885a_0(1+Q^{0.66})^{-0.5}$, a_0 is the Bohr radius and e the electron charge. For the electronic stopping we have from Lindhard and Scharff (1961)

$$-\left(\frac{dE}{dt}\right)_{e.s.} = \frac{0.0787\,NQ^{1.16}\beta^2}{A(1+Q^{0.66})^{1.5}} \qquad (eV/n.s) \qquad (3)$$

the curve of energy losses through all the energy range in neutral media is obtained by the combination $(dE/dt)_T^{-1} = (dE/dt)_{n.s.}^{-1} + (dE/dt)_{e.s.}^{-1} + (dE/dt)_{ion}^{-1}$, where the ionization losses are given by the well known Bethe-Block formula in atomic media (Ginzburg and Syrovatsky, 1964).

The Acceleration Models

Three general models may be analysed (1) when particles proceed from a relatively cold region (particles are injected with energies lower than the thermal energy in the acceleration region), (2) when the main accelerated particle population belongs to the local plasma, and (3) when particles proceed from a hot region, or, are injected from a preliminar acceleration stage with relatively high energies. The first model was described in paper SP 2-22 (these proceedings). To analyse models (2) and (3) the following assumptions may be made about the charge state Q of particles: 1st that particles enter into the acceleration process in a fully stripped state ($Q \simeq Z$), which within the frame of both models would correspond to a very hot plasma ($T > 10^7$ °K), or, to a preliminar acceleration up to energies of 20 Mev/n in model (3), 2nd, to consider an overall charge state for all nuclear species of the medium,

* *Where Q and A are respectively the charge and atomic mass.*

$H(x) = \xi_1 H_e(x_e) + \xi_2 H_p(x_p)$; $x_p = 2.33\times10^6\beta T^{-0.5}$, $H_p(x_p) = 0.88\,\mathrm{erf}(x_p) - (1+1/A)x_p e^{-x_p^2}$

$\Lambda = \left[4.47\times10^{16}A(T/N)^{0.5}\beta^2\right]/Q$; $\xi_1 = 1.09\ldots203296\times10^{27}$

$\langle Q \rangle \simeq 1 \sim 2$ (when the temperature is around $10^4 \sim 10^5$ °K) which represents an idealization to the case of model (2), and, 3rd, to consider a more realistic figure, within the frame of model (2), by normalizing the charge to the local charge states at the beginning of the acceleration process, just as described in paper SP 2-22 (in eq.(3) and Table 1), in this form the particle charge increases as their velocity is being increased by the acceleration process. It must be noted that although the energy loss expressions in neutral media do not depend explicitly on the temperature, a dependence has been introduced in the case of model (2) through the normalization to the local charge states. Concerning the acceleration rate, several assumptions may be considered (e.g. Wentzel, 1965); in order to avoid invoking a definite acceleration mechanism we analyse two general assumptions: a rate of slope one-half in the scales of Figs. 1 to 6, of the form

$$\frac{1}{w}\left(\frac{dE}{dt}\right) = \alpha\beta \quad (s^{-1}) \tag{4}$$

often expressed in ev/n.s as $(dE/dt) = \alpha(E^2 + 2uc^2E)^{0.5}$, where α is the acceleration efficiency, W the total energy and uc^2 the atomic mass unit, and on the other hand, a steeper acceleration rate slope one given as

$$\frac{1}{w}\left(\frac{dE}{dt}\right) = \alpha\beta^2 \quad (s^{-1}) \tag{5}$$

Results and discussion

If the acceleration concerns high energy particles (in the range of ionization losses for a given temperature and density) proceeding from another acceleration stage, whatever the assumptions made, the heavier the nuclei the stronger its Coulombian depression is, and therefore no enhancement of heavy nuclei may be expected. Furthermore, He^3 is depressed in relation to He^4. This is illustrated through Figs. 1 and 3-6. Therefore let us disregard model (3) and concentrate on model (2) as far as Z-rich and He^3-rich events are concerned. This is supported by the fact that at least for the Fermi mechanism, degradation of turbulence does not allow for effective acceleration of high energy particles (Eichler, 1979). The main results may be summarized as follows.

(1) Whatever the charge state of particles, or, the ionization degree of the medium is considered, the criteria for particle selectivity with an acceleration rate of slope one are determined at the energy levels where the nuclear stopping prevails, whereas for a rate of slope one-half the criteria are determined at higher energies by the effect of electronic stopping (e.g. Fig 1).

(2) If particles are fully stripped during acceleration (very hot region) no enhancements of heavy nuclei or He^3 may be expected, since the sequence of energy losses does not favor He^3 and heavy particles through all the energy domain of losses (Fig. 1).

(3) When an overall charge state is considered, the sequence of energy loss tendencies favors the preferential acceleration of heavy ions (although He^3 is depressed in relation to He^4); however this idealization invoked by Korchak and Syrovatsky (1958) in relation with heavy cosmic ray enrichment, is not valid in the particular case of the solar atmosphere, as can be appreciated from Table 1 of paper SP 2-22. In Fig. 2 we have illustrated this assumption for the case that C and heavier nuclei are preferentially accelerated over He^4 and lighter nuclei, in which case the acceleration efficiency should be such that $0.15 < \alpha < 0.89$ s^{-1}. (Since the same tendency is obtained for every assumption in the acceleration rate, the charge states and the ionization of the local plasma, we also disregard this simplification because it does not furnish an accurate description of more realistic situations, according to the results discussed below).

(4) When the acceleration of local thermal particles is considered, the sequence of the energy loss tendencies is highly assorted depending on the local temperature. The high sensibility to this parameter, either in a neutral or in a fully ionized medium, appears from the normalization to the local charge states, Q_L. In addition, at $T < 10^7$ °K when the ions are not fully stripped, the energy loss tendencies at low energies due to nuclear stopping are different from that of the electronic stopping at higher energies, such that depending on the kind of acceleration rate, the criteria for preferential acceleration are also different. This is translated in a great amount of possibilities for particle enhancements and depressions according to the temperature of the source, allowing to explain for instance, Z-rich events, Fe-rich events, events with enhancements of N and O but not of C, etc., but not He^3-enhancements may be expected. We have illustrated in Figs, 3 and 4 some examples of preferential acceleration in fully ionized media and in neutral media on Figs. 5 and 6. Fig. 3 shows and example of preferential acceleration of Fe, H, He^4 and He^3 for the case of an acceleration rate of slope one. In the example of Fig. 5 a preferential acceleration of heavy nuclei over H, He^3 and He^4 would be obtained in a medium of $T = 8 \times 10^3$ °K and $N = 10^{13} cm^{-3}$ provided that the efficiency is such that $0.0406 < \alpha < 0.098\ s^{-1}$. However it must be taken into account that an enhancement of He^3 over He^4 may be also in general expected if an injection stage of the kind presented in paper SP 2-22 takes place. In the last example for instance, only the high energy tails of the He^3 and He^4 thermal distributions of the injected particles would be picked up by the acceleration process. In table 1 we give some typical values of the acceleration efficiency in a fully ionized medium, assuming some examples of particle enhancements. The predicted ratios among different ions may be calculated by following some similar method to that derived in relation with the He^3/He^4 ratio. Finally, it must be pointed out that the derived quotes of the acceleration efficiency in densitites of 10^9-$10^{11} cm^{-3}$ are of the same order than those derived by Ramaty, (1979), from γ-ray lines; we support thus, acceleration of local thermal particles with a relatively low acceleration efficiently such that, in general, energy losses are not completely negligibles.

Acceleration medium		Expected enhancements	Particle fluxes
T(°K)	N(cm^{-3})	Fe,He^3,He^4, over H,C,N,O, if:	Fe-rich events low p/α ratios (He^3-rich potentially)
2×10^4	10^{11}	$\alpha = 0.27 - 0.52\ (s^{-1})$	
	10^{12}	$\alpha = 2.6 - 11.6\ (s^{-1})$	
		Fe,N,C,O over He^3,H,He^4 if:	
4×10^4	10^{10}	$\alpha = 0.049 - 0.08\ (s^{-1})$	High-Z-rich events
	10^{11}	$\alpha = 0.28 - 0.58\ (s^{-1})$	(He^3-rich potentially)
	10^{12}	$\alpha = 4.2 - 6.4\ (s^{-1})$	
		Fe over lighter nuclei if:	
8×10^4	10^{10}	$\alpha = 0.046 - 0.053\ (s^{-1})$	Fe-rich events
	10^{11}	$\alpha = 0.23 - 0.53\ (s^{-1})$	(He^3-rich potentially)
	10^{12}	$\alpha = 2.71 - 3.45\ (s^{-1})$	
		Fe,He^4 over C,He^3,N,O,H, if:	
10^5	10^9	$\alpha = 0.0042 - 0.0063$	Fe-rich events
	10^{10}	$\alpha = 0.038 - 0.051$	low p/α ratio
	10^{11}	$\alpha = 0.34 - 0.37$	(no He^3-enhancements expected)

TABLE 1

Figure 1

COULOMBIAN ENERGY LOSSES IN FULLY IONIZED HYDROGEN

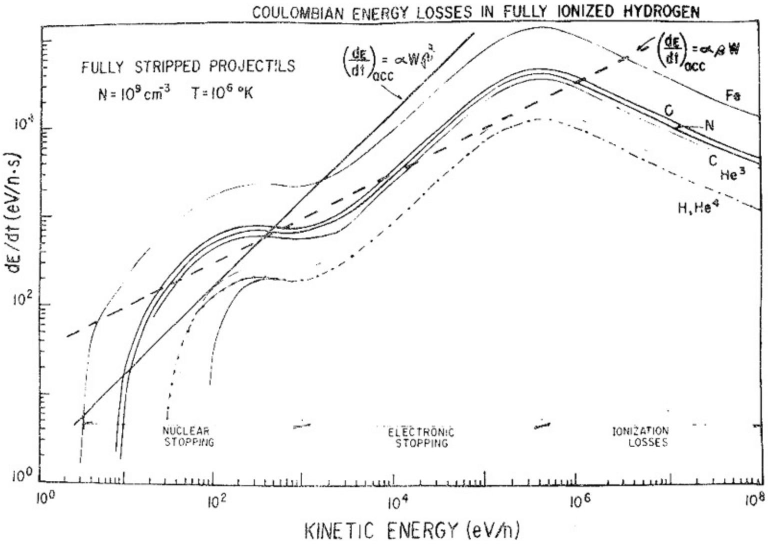


Figure 2

COULOMBIAN ENERGY LOSSES IN FULLY IONIZED HYDROGEN

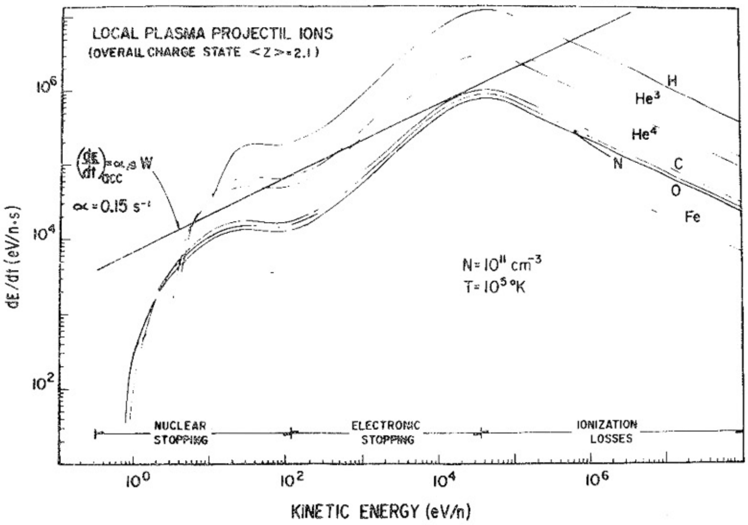


Figure 3

COULOMBIAN ENERGY LOSSES IN FULLY IONIZED HYDROGEN

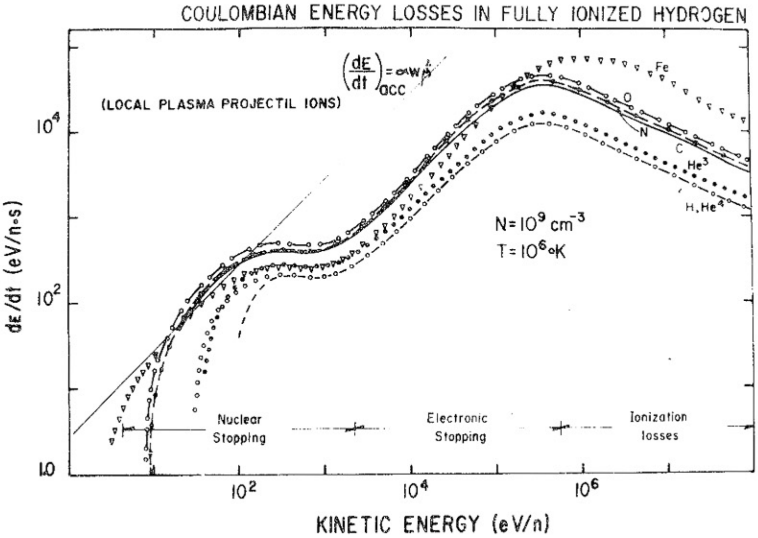


Figure 4

COULOMBIAN ENERGY LOSSES IN FULLY IONIZED HYDROGEN

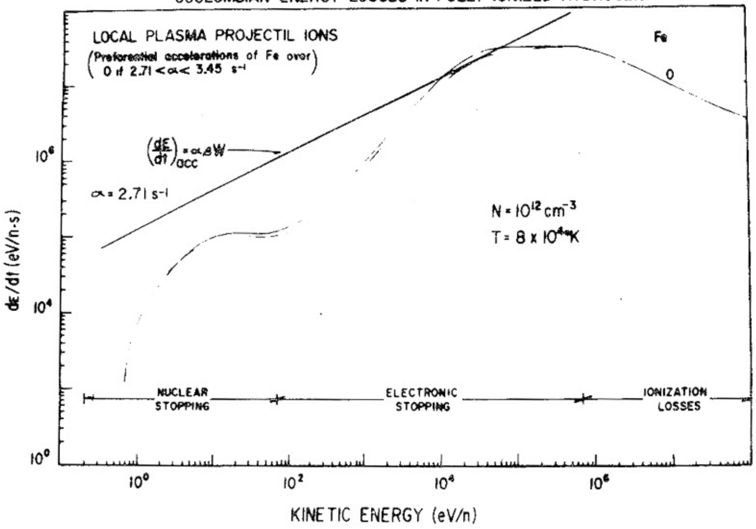


Figure 5

COULOMBIAN ENERGY LOSSES IN NEUTRAL HYDROGEN

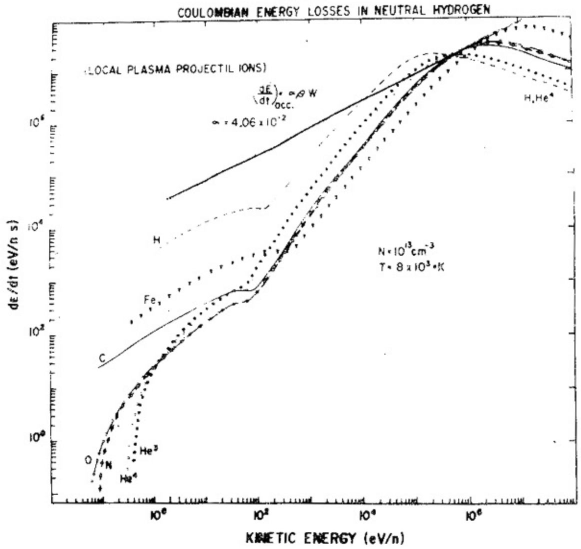
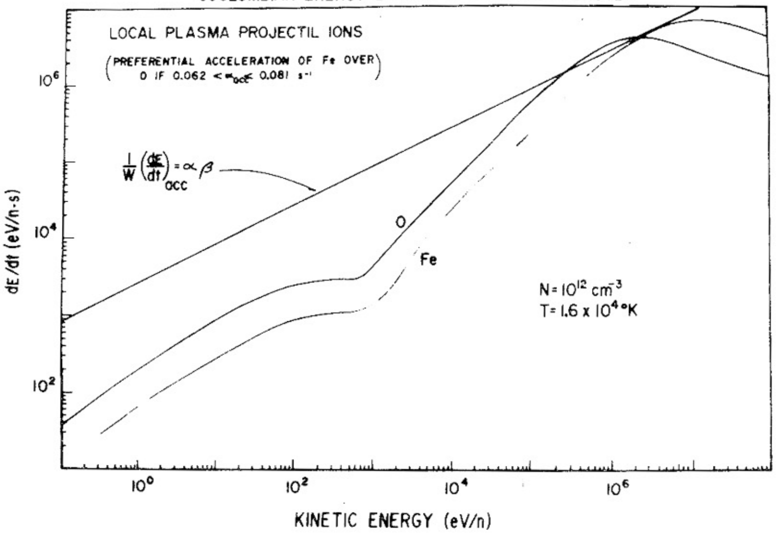


Figure 6

COULOMBIAN ENERGY LOSSES IN NEUTRAL HYDROGEN



References

Buttler, S.T. and Buckingham, M.J., 1962, Phys. Rev. 126, 1

Eichler, D., 1979, Ap. J. 229, 409

Ginzburg, V.L. and Syrovatsky, S.I., 1964, The Origin of cosmic Rays, Pergamon Press

Itikawa, Y. and Aono, O., 1965, Phys. Fluids, 9, 1259

Lindhard, J. and Scharff, M., 1961, Phys. Rev. 124, 128

Lindhard, J. Scharff, M. and Schiott, H.E., 1963, Mat. Fys. Dan. Vid. Selsk. 33, 1

Ramaty, R., Invited paper, La Jolla Workshop, January 1979

Wentzel, D.J., 1965, J.G.R., 70, 2716