SELECTIVE ACCELERATION IN COSMIC RAY SOURCE

J. Perez-Peraza
Universided Nacional Autonoma de Mexico
Instituto de Astronomia, Ciudad Universitaria, Mexico 20

The charge spectrum of cosmic rays, i.e. the elemental and isotopic composition of the "standard" component as well as that of the so called "anomalous" component may be determined at the level of their sources, during their propagation out of the source environments, or even at both levels by several processes that may act in favouring the enhancement of some species and the depletion of others relative to local abundances* or simply in conserving the composition of the site where they are accelerated. At the source level these processes may take place prior to acceleration, during acceleration, or after acceleration while the traversal, confinement and escape from the dense source environment. For instance in the case that the particle composition is determined by nucleosynthetic processes, these are supposed to have taken place before the acceleration (during normal stellar stages of evolution), during acceleration in connection for instance with spallation reactions or explosive nucleosynthesis, or even between two acceleration stages, injection and final acceleration, as well as outside of the sources during propagation, as is usually evoked in relation with the production of some light elements which are absent at the sources. However, as an alternative to nucleosynthesis process several other kind of processes may be involved in the determination of cosmic ray composition at the level of sources, as for instance, prior to the acceleration, in situ, by chemical or plasma processes, during acceleration by intrinsic features of the acceleration mechanism itself or after acceleration by effects of magnetic rigidity, etc.

In particular, I will discuss here an interesting alternative to determine the cosmic ray composition at the level of the sources which is able to explain some deviations of cosmic ray composition relative to local abundances, based on the effects of coulombian energy losses during the acceleration stage. It may be recalled that the necessicity of selectivity effects during acceleration has been often evoked to explain some features of the cosmic ray composition that cannot be explained by nucleosynthesis. It will be shown here that this kind of complementary process may or may not alter nucleosynthetic composition at the level of the sources, depending on whether the coulombian losses are important or not during acceleration.

Let us begin by displaying an overview concerning coulombian energy losses. No general expression is available to describe coulombian losses through all energy ranges where they take place, in terms of the degree of ionization of the target medium and with explicit dependence and the temperature of the same. The well-known formula of Bethe-Block has been developed

---

*Comparisons are conventionally made relative to the so called "universal" abundances or the "solar system" abundances (SS). When the effect of propogation on the particles are subtracted, a composition of particles is obtained at the instant of injection, which is known as cosmic ray source composition (CRSC). The ratio CRSC/SS shows that even prior to the propagation, the accelerated particles do not entirely match the observational stellar abundances; some heavy nuclei tend to be overabundant, while light elements seem to be underabundant. For solar particles, comparison is directly made with solar atmospheric abundances and although the composition varies from event to event there is also a general tendency of enhancement of some heavy nuclei.

for neutral media and then adopted to a fully ionized medium (e. g. Ginsburg and Syrovatsky (1964)) but even then the formulation is essentially independent of the temperature. In addition this formulation applies for losses in the high energy range, what is called the "cold gas approximation" or ionization losses. In the low energy range, i. e. in the domain of nuclear stopping and electronic stopping, what is called the "hot gas approximation" a lot of work has been done in order to take into account these kind of losses in atomic media, without considering the temperature of the medium. However, we know that the parameter of temperature plays a very important role in astrophysical conditions. It may be mentioned that some efforts have been made in the past to take into account either the degree of ionization, or the parameter temperature of the medium, but only for the high energy range, i. e. ionization losses (e. g. Hayakava and Kitao, 1956, Spitzer, 1962, etc.). Nevertheless an interesting formulation to describe energy losses through the entire energy range in terms of the temperature of the medium has been derived by Buttler and Buckingham, 1962, and Hayakawa & Aono, 1965. However, this only applies for a fully ionized gas independent of the degree of ionization of the target. We are also able to study coulombian energy losses through the entire energy range in atomic media by adding the contributions of nuclear stopping and electronic stopping as given by Lindhard et al., 1961, 1963 to the ionization losses in atomic media, as described by the Bethe-Block formula, although without any explicite dependence on the temperature. In the case of a fully ionized plasma of hydrogen, the energy losses may be described according to Buttler & Buckingham as follows :

$$\frac{dE}{dt} = \frac{-1.57 \times 10^{-35} N}{\beta} \frac{q^2}{A} \ln \Lambda \left[1.09 \times 10^{27} H(X_e) + 5.98 \times 10^{23} H(X_p) \right] \quad (eV/n.s) \qquad ..(1)$$

where the first and second term represent respectively the contribution of the target electrons and target protons to the energy loss of ions. T and N are the temperature and density of the medium; β , q and A are the velocity, charge and atomic mass of particles respectively,

$$\Lambda = \left[4.47 \times 10^{16} A \; \beta^2 \, (T/N)^{0.5} \right] / q$$

$\ln \Lambda$ = coulombian logarithm

$$X_e = 5.44 \times 10^4 \beta \, T^{-0.5}$$

$$X_p = 2.33 \times 10^6 \beta \, T^{-0.5}$$

$$H(X_e) = 0.88 \, \mathrm{erf}\,(X_e) - (1 + 5.48 \times 10^{-4}/A) \cdot X_e \cdot \exp(-X_e^2)$$

$$H(X_p) = 0.88 \, \mathrm{erf}\,(X_p) - (1 + 1/A) \, x_p \, e^{-X_p^2} .$$

Now, in order to study how the selectivity effects on the cosmic ray composition may appear during the acceleration stage, we proceed as follows : instead of analysing intrinsic features of a "hypothetical" acceleration mechanisms (which we do not know with accuracy, its efficiency and its dependence on charge and mass of particles), we reason on basis of more general grounds, whatever the acceleration mechanism involved, the fact is that acceleration is competing with deceleration by coulombian interaction in the high density media of the source : the effect of coulombian losses on particles of different masses and charges is fairly well-known. Therefore, this allows us to introduce some criteria for particle selectivity provided the acceleration process initiates from thermal energies with an acceleration efficiency which is not extremely high to completely ignore the energy losses. Under these circumstances, a given kind of ion is preferentially accelerated or depleted, depending on whether the acceleration rate is higher or lower than the energy loss rate at the beginning of the acceleration of thermal material. Reasoning on the basis of a graph (Fig. 1a), this means, that given nuclei will be depleted or preferentially accelerated, depending on whether the acceleration rate curve intersects or not, its corresponding energy loss curve : nuclear species which undergo such intersections will be effectively accelerated only if they have energy higher than the energy of intersection, in such a way, that probably only those of the extremely hot tails of their thermal distributions are effectively accelerated. These ions will appear depleted in relation to those that are free accelerated because their energy loss curves do not intersect the acceleration rate at the beginning of the acceleration process and therefore, any charged particle is susceptible to being accelerated. If the curves do not undergo intersection at low energies, they will not join at higher energies because as the energy increases the curves gradually move apart from each other, since the acceleration rate grows faster with energy than the energy loss rate. For the sake of illustration, shown in Fig. 1a are three arbitrary acceleration rates which in a log-log scale may be represented by lines of slopes one half, one and zero, and may be, for instance, associated respectively to a second order Fermi acceleration, to a Betatron or adiabatic heating and to some kind of shock wave acceleration or electrostatic acceleration : W is the total energy per nucleon, β the velocity of particles in units of the velocity of light and α is the acceleration efficiency. In Fig. 1a, the energy loss rate of protons in ionized hydrogen and the mentioned acceleration rate are illustrated : the points of intersection determine the threshold in energy (E_c, E'_c and E''_c) for effective acceleration. It should be mentioned that this kind of selectivity criterion have been previously suggested by Korchack and Syrovatsky, 1958, although in those days the behaviour of energy losses with temperature in the low energy range was not well-known, and therefore, the criteria of selectivity were developed at the maximum of ionization losses, because of the lack of knowledge of the patterns of the low energy loss curves. In addition, they assumed a situation in which all nuclear species in the source at a given temperature have the same charge state and that this does not change during acceleration within the dense local material. As we will discuss later this is not what is in general expected in cosmic ray sources.

Now, let us talk about the charge state of the ions at the beginning of the acceleration, which constitutes one of the main factors in determining the selectivity of particles during acceleration. In fact, the main effect of the temperature on the energy losses of particles at the beginning of the acceleration is through the charge state of ions. According to equation (1) stripped ions loose much more energy than, for instance, singly ionized ions. Therefore, in order to study the effect of energy losses on particle during acceleration, three main assumptions on the charge state may be analysed.

First : To consider the idealised suggestion of Korchack and Syrovatsky that all elements have practically the same charge state in the material of cosmic ray source and that it remains basically constant during acceleration.

Second : That all elements are initially fully stripped, for instance, because the local plasma temperature is very high, or because particles are injected into the acceleration region with relatively high energies, proceeding from a preliminary acceleration stage.

Third : A more general description, by considering that particles have initially their individual charge states according to the specific temperature of the source, and that their charge is changing with the increase in energy according to the processes of charge interchange. This implies that the particle charge varies from the local initial value to a value lower or equal than the atomic number, according to the following expression :

$$q = \left[\frac{Z_n - Q_L}{Z_n - Q_L - Z_{th}}\right] Z^*_{eff} + \left[\frac{Z_n - (Z_n - Q_L)^2}{Z_n - Q_L - Z_{th}}\right] (Q_L \leqslant q \leqslant Z_n) \qquad ..(2)$$

where
Q_L = local charge state
Z_n = atomic number
$Z^*_{eff} = Z_n \left[1 - \exp(-129\,\beta / Z_n^{0.66})\right]$ = effective charge
$Z_{th} = Z^*_{eff_{th}}$ = effective charge evaluated at the thermal velocity.

It will be shown that for a given degree of ionization of the target medium, the last alternative will allow for a great variety of selectivity effects according to the local temperature and the kind of acceleration rate involved.

Before analysing the last three assumptions, it must be mentioned that whatever the initial charge state of particles, and independent of the **degree of ionisation of the medium, the criteria of selectivity are defined at different energy levels, depending on the kind of acceleration rate considered.** As can be seen from Fig.1a for a rate of the kind $dE/dt = \alpha\,\beta^2\,W$ the selectively criteria will be defined at the level of nuclear stopping, where as for a mechanism with a rate $dE/dt = \alpha\,\beta\,W$ it would be defined at the level of electronic stopping, and for a rate of the form $dE/dt = \alpha\,W$, this would occur at the maximum of losses, where the ionisation begins to be predominant. Now concerning the first assumption on the charge state of particles, if an overall charge state for all nuclear species during the acceleration is assumed, it is obtained, at all energies, just what was predicted by Korchak and Syrovatsky : the lighter the elements, the stronger the energy losses are, in such a way that whatever the acceleration rate is, light elements may become depleted in relation to heavy elements. In Fig.1b, is illustrated this idealised case for an acceleration rate of the kind of the Fermi second order mechanism, andan overall charge state of two (protons are plotted only as a frame of reference). However, if under this assumption it is easy to explain heavy element enhancements we cannot consider it seriously because of the three following main objections : first because at least for the case of solar particle sources (solar flare regions) it is well-known from the works of Jordan 1969 and others, that for a given temperature the charge state of different elements display very different values. Secondly, because in high density sources the effective charge states do not remain constant but increase during acceleration as the coulombian electronic losses become dominant over the electronic capture (pickup) and finally, because the predicted enhancement is a monotonic one with atomic number, i.e. no light element may eventually be enhanced relatively to a heavier one. In fact, it is observed in galactic cosmic rays as well as in solar particles, that the general tendency of heavy nuclei enrichment is not precisely a monotonic one : this statement may be appreciated in the well-known plot of the ratio of CRSC/SS against atomic number, in the case of cosmic rays, (Fig. 1 of Prof. Biswas's lecture) and in plots of the over abundance factor of solar particles as is shown in Fig.1c, taken from the work of Cook et al., 1979. Concerning the second assumption, when particles are fully stripped, we can see in Fig.1d, that the sequence of energy losses at all energies, is such that the heavy elements are systematically depleted in relation with the lighter ones (this is true whatever the degree of ionisation of the medium). This is precisely in opposition to the general tendency of enrichment of the cosmic ray and solar particle in heavy nuclei. Therefore, at least from the point of view of selectivity effects from coulombian interactions, we can assume that very hot regions are not likely sources of cosmic rays, which is in agreement with what Prof. Reeves has stated in an earlier lecture, that a temperature of 10^4 °K may be relevant in cosmic ray sources. On the other hand, high energy particles that could eventually arrive at the acceleration region from a previous acceleration step, would not contribute significantly to the enrichment of heavy nuclei because this additional component would be depleted in heavy elements by ionisation. The observed enhancements of heavy nuclei is therefore a strong argument to support the fact that the main cosmic ray component is accelerated from thermal material. In relation with the third assumption on the initial charge state, it is found that the sequences of energy losses is highly assorted depending on the local temperature, because under these conditions the energy loss tendencies at the level of nuclear stopping are different from those at the level of electronic stopping, and such are the patterns, at the level of ionization losses. This is translated in a great amount of possibilities of particle enhancements and depletions according to the temperature of the source and the kind of acceleration process operating therein. These properties allow a certain amount of flexibility to explain enhancements or depletion which do not behave monotonically with the atomic numbers.

In Fig. 1e, is shown a typical solar flare situation where the charge state of particles correspond to a temperature of 10^5 °K. It can be appreciated that the sequence of the patterns of energy losses of some nuclei varies from one energy range to another. As discussed before, in the domain of ionisation losses, the tendencies are systematically such that the heavier the nuclei, the stronger the energy losses are, and this is what cannonically has been considered in cosmic ray physics. For the illustrated acceleration rate and efficiency values assumed, N, O and Fe are preferentially accelerated over C, ^{4}He, ^{3}He and H. However, at lower energies, in the domains of nuclear and electronic stopping, where particles are not still completely stripped, the sequence of losses depends on the charge state of particles according to the temperature of the region.

In Fig. 1 f, is shown the specific case of the pattern of the Iron and Oxygen energy losses for a temperature of $T = 8 \times 10^4$ °K and $N = 10^{12}$ cm^{-3}. It can be seen that for an acceleration rate of the kind, $dE/dt = \alpha \beta W$, the iron will be preferentially accelerated with respect to the oxygen if the acceleration efficiency fortuitously falls in the range 2.71 S^{-1} to 3.45 S^{-1} : for a value lower than 2.71 S^{-1} both ions would be depleted and for an efficiency higher than 3.45 S^{-1} both nuclei would be preferentially accelerated. On the other hand, if the acceleration rate were of the kind $dE/dt = \alpha \beta^2 W$, then the selectivity would be defined at the level of nuclear stopping, and therefore, the situation would be just the opposite, the oxygen could be preferentially accelerated relative to the iron (because the iron has a lower thermal energy than the oxygen, for some specific values of the acceleration efficiency the acceleration rate curve could intersect the energy loss curve of the iron without crossing the energy loss curve of the oxygen at the beginning of the acceleration). Owing to the high variety of possibilities for selectivity effects from the competition of acceleration and deceleration at the beginning of the acceleration, it is possible to explain, in the case of solar particles (Perez-Peraza and Lara, 1979) the so called, for instance, high -Z- rich events, the iron-rich events, events enriched in M elements (C, N, O) relative to Iron, with their different nuances, according to the temperature of the source and the acceleration mechanism involved. The charge spectrum of cosmic rays at the level of sources (C R S C) should be adequately reproduced if an appropriate knowledge of the charge state of elements at different temperature is available (as it is for solar flares) for the most plausible sources of cosmic rays. A promising candidate are supernovae since the material is thermalized during the lapse time between nucleosynthesis and acceleration (~ 1 to ~ 10 yrs.). Also it should be expected that this kind of selectivity effects, under a specific scenario may help in explaining some features of the composition of the anomalous component mentioned by Prof. Biswas in his lecture : more helium than protons, more N. Ne and O than C, whereas Mg, Si, S and Ar are depleted.

It is interesting to mention that in the particular case of solar particles, these kind of selectivity criteria allows to establish bounds in the acceleration efficiency, and in turn to draw some astrophysical implications about the physical parameters of the source and the hydromagnetic conditions prevailing therein : given a specific charge spectrum from a particular solar event, it is possible to find the adequate temperature and acceleration rate that explains the observational composition, such that by probing several densities, one may deduce the value of acceleration efficiency that fits better the time scales of the flare phenomenon. In Table 1, are illustrated some general examples of the charge spectra expected in solar particles, under different conditions of density and temperature, if the acceleration efficiency causally ranges within the indicated values.

Table 1

If it were expected :

Acceleration Region

T(^{o}K)	N(cm^{-3})	Enhancement	Events
		of Fe, ^{3}He, ^{4}He over H, C, N, O	Fe-rich low P/α ratios
2 x 10^4	10^{11}	= 0.27 - 0.52 (S^{-1})	
	10^{12}	= 2.6 - 11.6 (S^{-1})	
		of Fe, N, C, O over ^{3}He, H, ^{4}He	heavy-Z-rich
4 x 10^4	10^{10}	= 0.049 - 0.08 (S^{-1})	
	10^{11}	= 0.28 - 0.58 (S^{-1})	
	10^{12}	= 4.2 - 6.4 (S^{-1})	
		of Fe over lighter nuclei	Fe-rich
8 x 10^4	10^{10}	= 0.096 - 0.053 (S^{-1})	
	10^{11}	= 0.23 - 0.53 (S^{-1})	
	10^{12}	= 2.71 - 3.45 (S^{-1})	
		of Fe, ^{4}He over C, ^{3}He, N,O,H	Fe-rich Low P/α ratios
10^5	10^9	= 4.2 x 10^{-3} - 6.3 x 10^{-3} (S^{-1})	
	10^{10}	= 0.038 - 0.051 (S^{-1})	
	10^{11}	= 0.34 - 0.37 (S^{-1})	

Examples of preferential acceleration of some nuclei over others under different conditions of the source provided that the acceleration efficiency is fortuitelly comprised within the displayed ranges.

It has been discussed in this Workshop,the importance of the isotopic composition of Ne; in particular the observed value of ^{22}Ne/^{20}Ne ~ 7 in solar flare particles, as measured by the group of Chicago. To illustrate how the effect of coulombian interactions may be involved in the determination of cosmic cosmic ray abundances, we have here a very "economical" model, that must be taken only as a tool of exemplification . It is well-known that the flare plasma is a very inhomogeneous one from the point of view of temperature, ranging from

$\sim 10^4 \sim 10^8$ °K; suppose that due to some kind of chemical process of isotopic separation or any other process, ^{22}Ne is rather concentrated in the hot plasma of the flare, where its charge state becomes of the order of ~ 10, whereas ^{20}Ne has been predominantly concentrated in cooler regions where its charge state is ~ 4: therefore, if the acceleration efficiency of the involved process is relatively low, such that none of them is preferrentially accelerated, but they are subjected to depletion by Coulombian energy losses (with rate roughly $\sim q^2/A$). Therefore, the accelerated abundances would be in the order of $[(q^2/A)]\,^{22}\mathrm{Ne} \,/\, [(q^2/A)\,^{20}\mathrm{Ne})] \sim 7$.

Though beyond the scope of the present topic, it is interesting to mention some other astrophysical implications different from the selectivity effects during acceleration, in relation with the dependence of coulombian energy losses on the temperature of the target media .

It should be noted that within the frame of the autogenic hypothesis of Li, Be and B production by low energy particles, that is from 1-20 MeV/n, the canonical calculations have been derived taking into account the deceleration of particles with the Bethe-Block formulation, that is, quite independent of the temperature of the spallation volumes. This is not a bad approximation as far as the spallation volume is relatively cold, but for hot regions the energy losses of particles of some MeV/n fall within the range of electronic stopping, that is, qualitatively the energy loss rate is different, since instead of a shape of the kind $dE/dx \propto E^{-1}$ we have in this case $dt/dx \propto E^{+1}$, and even if we adopt the popular scenario of the production by high energy particles ($\gtrsim$ 100 MeV/n), that is, if we are in the range of ionisation losses, their effect is not the same in a hot source as in a cold source; therefore, the flux and the spectral shape of the primaries turns out to be different in order to explain the same value of the relative ratio of secondaries. Another interesting feature is to estimate the minimal energy of low energy particles that are able to leave their sources according to the different temperatures prevailing therein and to travel through the interstellar space, (independent of hydromagnetic effects) taking into account the inhomogenity of this medium from the point of view of temperature and density. This is interesting, since the energy losses have been over-estimated very often in this regard by means of the Bethe-Block formulation. An implication of the last one, in the possibility of heating some regions of the interstellar medium without producing a high degree of ionisation of the medium, since particles at the level of electronic and nuclear stopping are not able to ionise the target medium, but only to pick up the electrons of valence bond. In the domain of high energy particles it is interesting to take into account these effects of temperature, when the demodulation of the observed abundances in the interstellar medium is studied, in order to deduce the cosmic ray abundances of the sources (CRSC). It should be expected that a more adequate consideration of the temperature and density in the different regions of the interstellar medium traversed by particles, and in particular, in the plausible sites for spallations, may perhaps lead to some slight changes in the cosmic ray source abundances. In other words, if we place in the frame of the galactogenic hypothesis of H. Reeves for the production of Li, Be and B, the situation may be different if the spallation takes place in the hot galactic corona from that of the cold molecular clouds.

Acknowledgements

I would like to thank the Tata Institute of Fundamental Research for support through a visiting research membership. I am most grateful to Prof. S. Biswas and colleagues of TIFR for their kind hospitality.

References

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

Ginzberg, V.L. and Syrovatski, S.T., Origin of Cosmic Rays, Pergamon Press ('64).

Hayakawa, S. and Kitao, K., Prog. Theor. Phys., 16, 139 (1956).

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

Jordan, C. Mont. Not. R. Ast. Soc., 142, 501 (1969);

.... IBID 148, 17 (1970).

Korchack, A.A. and Syrovatsky, S.I., Soviet Phys., Doklady, 3, 983 (1958).

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

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

Perez-Peraza, J. and Lara, A.R., Proc. of the 16th I.C.R.C., Kyoto, 12, 259 (1979).

Spitzer, D., Physics of Fully Ionized Gases, Interscience (1962).

****

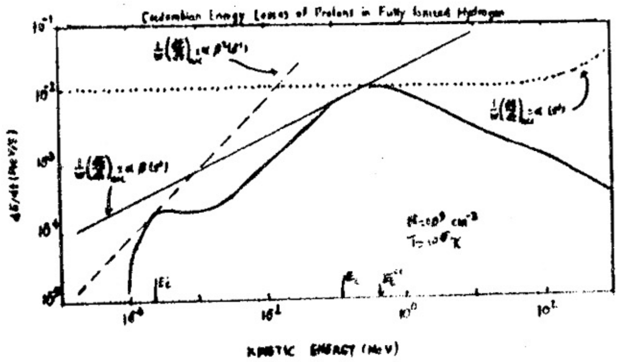

Fig 1a

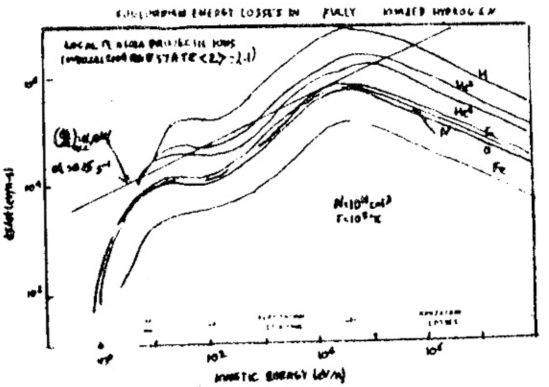

Fig 1,

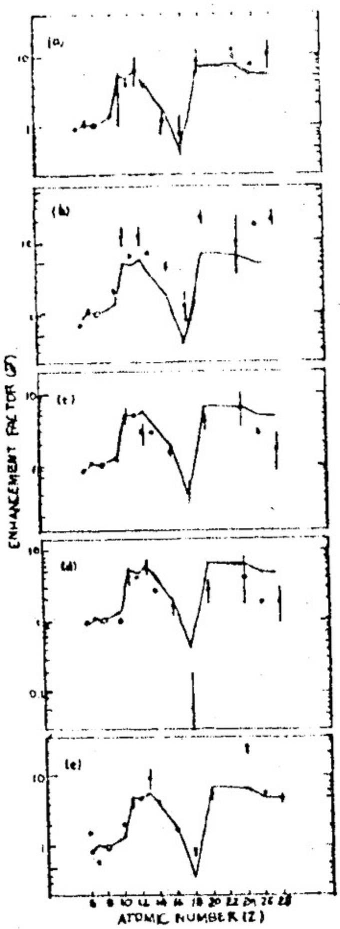

Figure 1c. Enhancement factor ℱ.
Solid line: $\mathcal{F}_i^*$, 4-flare average
Data points:
Panel 3a = Table 1, Col. a
3b b
3c d
3d e
3e GCR

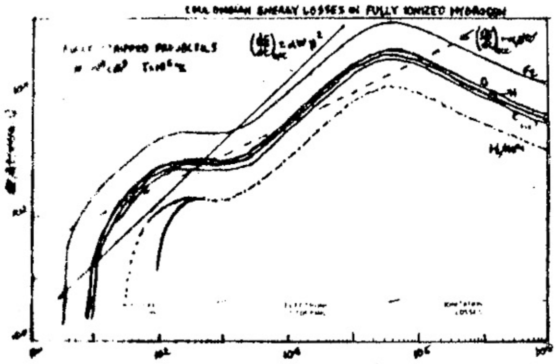

Fig 1d

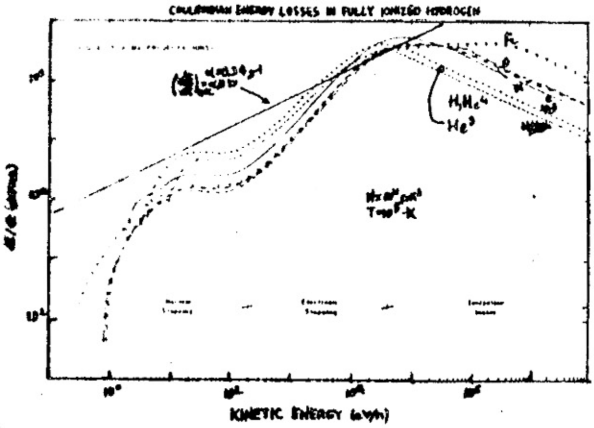

Fig 1e

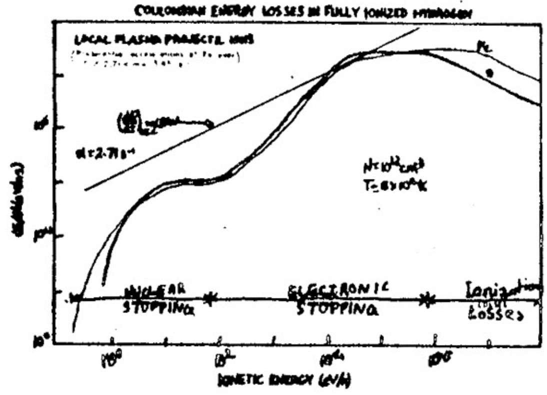

Fig 1f.

Fig 1