ISOTOPIC OVERABUNDANCES AND THE ENERGETIC PARTICLE MODEL OF SOLAR FLARES

R. Pérez-Enríquez and S. Bravo
Instituto de Geofísica, UNAM, Ciudad Universitaria
México D.F., 04510, MEXICO

ABSTRACT

According to the energetic particle model of solar flares particles are efficiently accelerated in the magnetic field loop of an active region (AR) by hydromagnetic turbulence. Based on this picture, we shall demonstrate that the isotopic overabundances observed in some flares are not a consequence of the flare itself but they are characteristic of the plasma in the AR. Only in the event of a flare releasing the plasma into the interplanetary space it is posible to observe this anomalous composition at spacecraft locations.

1. Introduction. The observation of an anomalous composition of solar flare particles from some events began as early as 1962 when Schaeffer and Zahringer measured a ratio of $^3He/^4He \sim 0.2$ for the Nov. 12, 1960 event, compared to the normal ratios in the solar atmosphere and in the solar wind of about 10^{-4} (Geiss and Reeves,1972). Since then, ratios of about one have been measured for these isotopes and substantial overabundances of Fe and another heavy elements have also been observed in the solar energetic particle flux. The characteristics features of the "rich" events have been reviewed by Ramaty et al. (1980), and Kocharov and Kocharov (1984).

Several models have been proposed for the explanation of such overabundances. The most successful are those in which the anomalous composition observed is the result of the acceleration of a preferentially preheated population at the time of the flare, the selective heating been caused by various instabilities generated in the plasma. There are two such plasma instabilities that seem to explain both the ^3He, and heavier ions overabundances observed: the Fisk's (1978) model which assumes that a current electrostatic instability leads to ion cyclotron waves which heat the ions by a resonant process, and the Ibragimov and Kocharov (1978) model which assumes that a high level of turbulence is present in the flare plasma giving rise to the production of ion sound waves with the consequent heating of the isotopes. The physical characteristics of the plasma assumed in both models are somewhat similar: They both requiered that the relative abundance of ^4He to H is already larger than normal -so the characteristic frequency of the plasma is closer to the gyrofrequency of the isotopes to be preferentially heated- and a value of β (the plasma to magnetic pressure ratio) smaller than one -to assure that the plasma remains confined to the magnetic field. There is, however, an important difference in the ratio of electron to ion temperatures (T_e/T_i) requiered by each mechanism to operate: ion cyclotron waves in Fisk's model requiere a value of about 10, while for the ion soun waves in the Ibragimov and Kocharov's model this ratio should be about 100.

Some observations seem to present problems to the requirements of these models. On the one hand, the X-ray emission detected by the SMM and Hinotori satellites (see reviews by Yoshimori et al., 1983; Chupp, 1983; Svestka and Shadee, 1983) seems to indicate that the β value of the plasma before and at the time of the flash of the flare is very near to one and not as low as requiered by both models. On the other hand, the coexistence of two different isotopes of Fe ($Fe^{11,12}$ and Fe^{17-20}) has been observed in the flare particle flux by MaSung et al. (1981), and Klecker et al. (1984), (see Table I), thus implying two different temperatures at the flare site. We shall show in the following sections that for the energetic particle model (EPM) no such difficulties exist, and that it can give an overall explanation of the observations.

TABLE I

Event	Overabundant Isotopes	Underabundant Isotopes
14-15 May,1974 (MaSung et al.1981)	^3He,Ne,Mg,Si, O,S,$Fe^{11,12}$ and $Fe^{16,17,18}$	C
Average of five events during 1978 and 1979 (Klecker et al.1984)	^3He,$Fe^{19\pm2}$	

2. The Plasma in AR's According to the Energetic Particle Model of Solar Flares. Here we shall limit ourselves to describe the characteristics of the energetic particle model (EPM) which are relevant to the problem of the production of the overabundances of ^3He and heavier nuclei in an AR;(for a more detailed discussion of the model see Pérez-Enríquez, 1985). In this model, particles from the coronal plasma are efficiently accelerated by hydromagnetic waves from the convective zone, as discussed by Hollweg (1984) in the contex of coronal heating, while they remain trapped in the intense bipolar magnetic field of an AR. Hence both the density and temperature of the plasma increase with time since the very appearence of the magnetic loop. In other words, the trapped plasma undergoes a dynamic evolution which may eventually lead to the ocurrence of a flare, in contrast with those models which assume that the plasma plays a pasive role in the generation of the flare and remains undisturbed until the flash.

Since the electrons move faster than the protons by a factor of ~ 43 at the same energy, a Fermi type of acceleration within the theory of Kulsrud and Ferrara (1971) will be efficient only for the ions and the electron population will gain its energy mainly from its interaction with the ions. Now, according to the theory of Kennel and Petschek (1966), the stable trapping of the particles can be mainteined as long as their energy E is below $E_c = B^2/8\pi n$, where B is the magnetic field, and n is the electron number density. As a consecuence of the Fermi acceleration there are everytime more ions beyond E_c which try to escape and as they do they generate their own resonant waves. The wave instability so produced will depend on the physical characteristics of the plasma in the AR such as the Te/Ti ratio, the β of the plasma and the relative abundance of ^{4}He to H.

a) <u>The T_e/ T_i , and β values</u>: As the energy of the electrons is "purely" of thermal nature, and the energy of the ions is mainly convective there will be a relative streaming between them, and thus, as described by Pérez-Enríquez (1985), a Buneman instability will take place with a growth rate $\gamma_B = \sqrt{3}/2\,(m_e/m_i)^{1/3}\,\omega_{pe}$. Here $m_{e,i}$ are the electron and ion masses respectively, and $\omega_{pe} = (4\pi n_e e^2/m_e)^{1/2}$ is the electron plasma frequency. For a value of $n_e = 3\times10^9$ cm^{-3}, $\gamma_B \approx 2.2\times10^8$ s^{-1} and T_e grows very fast while T_i does it much slower; so T_e/T_i increases with time reaching values as high as several hundreds as observed. In a similar manner, as the number density of particles in the region also tends to increase, so it does β . In other words, both T_e/T_i and β are growing functions of time and their schematic evolution is shown in Fig. (1). Notice that these functions are quite arbitrary, but here we are only interested in showing the increase of T_e/T_i and β with time. In the figure, t_F and t_{IK} correspond to the times where Fisk's or Ibragimov and Kocharov's models operate, respectively.

b) <u>The He to H ratio</u>: Since ^{4}He is four times heavier than H, it is expected to be more abundant at the bottom of the AR. In fact, from simple thermodynamic considerations, we obtain that the relative abundance of ^{4}He to H at the feet of a typical AR can be greater than that at the top by a factor as high as 100. So, the value of the ^{4}He to H ratio can be of about 10 at lower parts of the AR.

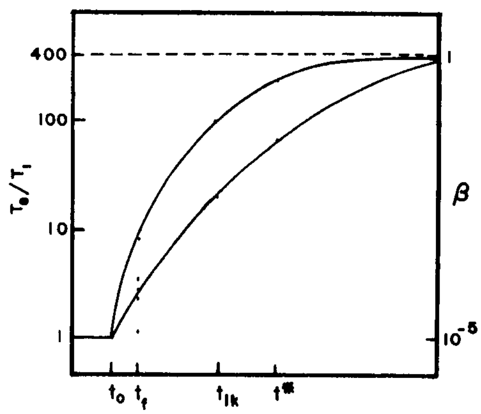

Fig.(1). Evolution of T_e/T_i and β in the active region(AR) from the initial time t_0 to a time t* , the time of the flare.

<u>3. Isotopic Overabundances and Conclusions</u>. The picture that comes out from all this is the following: due to the dynamic evolution of the plasma in the AR as described by the EPM, the requirements of the overabundance model are fulfilled at times t_F (for Fisk's model), and t_{IK} (for Ibragimob and Kocharov's model) as a consequence of such evolution (see Fig. 1). That is, the composition of the plasma in AR's also presents an evolution and so the especific composition to be observed in the interplanetary space will depend on how late in the life of the AR the flare takes place. A flare happening in the early stages of the development of an AR will send out into the interplanetary medium energetic particles with normal composition for no time has been given to the plasma to grow an overabundance (t* before t_F in the Figure), whereas if the flare happens later the energetic particles will present an anomalous composition. In other words, the overabundances observed are indeed a characteristic of the plasma in AR's and are not produced by the flare proper. The existence of two isotopes of iron (Table I) is also easily explained within the context of our model because different

temperatures are reached by the plasma at different stages of its evolution.

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