X-693-74-142

PREPRINT

NASA TM X- 70661

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(NASA-TM-X-70661) THE ACCELERATION OF HEAVY NUCLEI IN SOLAR FLARES (NASA) 20 p HC $4.00 CSCL 03B
N74-26269
Unclas
G3/29 40322

KUNITOMO SAKURAI

MAY 1974

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

THE ACCELERATION OF HEAVY NUCLEI IN SOLAR FLARES

by

Kunitomo Sakurai*
Radio Astronomy Branch
Laboratory for Extraterrestrial Physics
NASA, Goddard Space Flight Center
Greenbelt, Md 20771

ABSTRACT

The overabundance of heavy nuclei in solar cosmic rays of energy $\leqslant$ 5 Mev/nucleon is explained by taking into account the pre-flare ionization states of these nuclei in the region where they are accelerated. A model is proposed which considers two-step accelerations associated with the initial development of solar flares. The first step is closely related to the triggering process of flares, while the second one starts with the development of the explosive phase. Further ionization of medium and heavy nuclei occurs through their interaction with Kev electrons accelerated by the first-step acceleration. It is suggested that the role of these electrons is important in producing fully ionized atoms in the acceleration regions.

*NASA Associate with University of Maryland, Astronomy Program

1. Introduction

It is known that the measurement of the chemical composition of solar cosmic rays is very important in the understanding of the acceleration mechanism of these particles and the chemical composition of the solar atmosphere. In fact, the study of the acceleration mechanism must consider the chemical composition of solar cosmic rays in reference to that of the sun because the comparison between these two compositions would give us an information as to how solar cosmic rays are accelerated and then ejected into outer space (e.g., Sakurai, 1974).

With decrease of the observable lower limit of cosmic ray energy because of the improvement of observing techniques on-board satellites, the discrepancy between the chemical abundances of solar cosmic rays and those of the solar atmosphere has become known in regard to the overabundance of the heavy nuclei in solar cosmic rays of energy $\leqslant$ 5 Mev/nucleon (e.g., Price et al., 1971; Cowsik and Price, 1971; Armstrong and Krimigis, 1971; Armstrong et al., 1972). However it is also known that, for solar cosmic rays of energy $\geqslant$ 10 Mev/nucleon, their nuclear abundances are very similar to those of the solar atmosphere (e.g., Biswas and Fichtel, 1964, 1965; Bertsch et al., 1969, 1972, 1973; Price, 1973). This difference mentioned above may be related to the acceleration processes of solar cosmic rays in or near the flare region (Mogro-Capero and Simpson, 1972a,b; Cartwright and Mogro-Capero, 1972, 1973).

At present, on the development of solar flares, we have a lot of observational materials regarding particle and electromagnetic radiations. They are considered in estimating the real processes of solar flares. By taking into account the developmental pattern of solar flares, we will here consider the acceleration of the heavy nuclei of solar cosmic rays in solar flares. In particular, discussion will be given on the origin of the overabundance of the heavy nuclei in solar cosmic rays in the low energy range ($\lesssim$ 5 Mev/nucleon).

2. Ionization States of the Heavy Nuclei in Pre-Flare Condition

It seems likely that solar cosmic ray nuclei and relativistic electrons are simultaneously accelerated in the region different from that in which the Hα emissions are generated (e.g., de Jager, 1969; Svestka, 1966, 1969; Sakurai, 1971a). It is estimated that the former region, hereafter called "acceleration region," is located higher up in the solar atmosphere, the density of which is 10^8 to 10^{10} particles per cm^3 (Sakurai, 1971a; Kane and Lin, 1971). The temperature of this region seems to be equal to that of the medium surrounding this region, say, 10^4 to 10^6 ^oK. Furthermore, the intensity of the ambient sunspot magnetic fields is estimated to be 10 to 100 gausses above the active sunspot groups (Sakurai, 1971a). Since this region seems to be thermally in quasi-equilibrium before the onset of a flare, the ionization states of the iron-group particles are estimated by using the results calculated by Jordan (1969,1970). The result for the relative abundances of the iron atoms in different ionization states is shown in Fig. 1. This figure shows that the most iron atoms are not fully ionized, but are in the charge states from FeIX to FeXVII in the medium of temperature 10^6 - 4 x 10^6 ^oK. If this temperature is reduced to $\sim$ 2 x 10^5 ^oK, for example, the ionization states are highly reduced to be FeVI to FeVII. A similar situation also occurs in the Ni atoms for the temperatures as mentioned above (e.g., Jordan, 1970). Even the oxygen and silicon atoms are not fully ionized in the medium of these temperatures.

The results obtained here, therefore, suggest that there are a number of heavy ions not fully ionized in the acceleration region before a flare starts. These ions seem to be accelerated to high energy in association with the development of the explosive phase of a flare, though some of them seem to become more ionized through various processes accompanied by the acceleration. Therefore, it seems unlikely that all of the heavy ions are fully ionized before they are accelerated.

Furthermore, the temperature of the Hα flare region is estimated as $\leqslant$ 10,000 ^{o}K on the solar disk (e.g., Svestka, 1969; de Jager, 1969). This suggests that the heavy ions are not fully ionized in this region, too. Therefore, we may say that, in the Hα flare and acceleration regions, the heavy atoms like Fe and Ni are only partially ionized. This means that, if we would have observed the bared heavy nuclei in solar cosmic rays, we should find out the mechanism producing these particles in the acceleration region or its vicinity.

3. Development of Solar Flares and Its Relation to the Acceleration of Heavy Nuclei

Solar flares are initiated when some instability is triggered in sunspot magnetic fields above active regions. It seems likely that this instability produces instantaneous acceleration of particles in the region where a flare is triggered. Although we do not know yet how long this acceleration continues, it is thought that both microwave impulsive and hard X-ray bursts are generated by energetic electrons (10-100 Kev) produced by this instantaneous acceleration (e.g., Frost, 1969; Kane, 1973). As well known, type III radio bursts are also often associated with these bursts. This acceleration seems to be independent of the development of the explosive phase, though, of course, considered as the precursor of this phase. This phase seems to be initiated with the generation of shock waves in the flare region (e.g., Wild et al., 1963). These waves would be produced as a result of the development of the instability mentioned above. In fact, shock waves are formed in association with the beginning of the explosive phase (e.g., Wild, et al., 1963; Sakurai, 1971b; Svestka, 1970).

It seems likely that solar cosmic ray protons and heavier nuclei are maintly secondly accelerated during the explosive phase (Ellison et al., 1961; Svestka, 1970; Sakurai, 1965a, 1971b). Therefore, we may say that there must exist two steps for particle acceleration; i.e., the instantaneous and the "secondary" acceleration. The durations for these two accelerations seems to be less than 10 sec. and 100-300 sec., respectively. These results necessarily require that the acceleration efficiency is very high for these two accelerations.

As shown above, energetic electrons seem to be produced by the instantaneous acceleration. Since this acceleration also seems to be effective for protons and other nuclear particles, it may be possible to assume that these particles are accelerated to the energy of $\leqslant$ 5 Mev/nucleon, although it does not seem that this acceleration produces particles of sub-relativistic or relativistic energies. Since the heavy nculei as the iron group are not fully ionized, their acceleration efficiency is usually different from the particles fully ionized. At present, it is thought that the Fermi acceleration is most plausible for the explanation of the observed results on the rigidity spectra and the nuclear abundance of solar cosmic rays of energy $\geqslant$ 10 Mev/nucleon (e.g., Hayakawa et al., 1964; Sakurai, 1965 b,c; Wantzel, 1965). It seems likely that this acceleration mechanism is also applied to explain the acceleration of particles of energy $\leqslant$ 5 Mev/nucleon. If this is the case, for these low-energy particles, this mechanism is expressed as

$$\frac{\partial R}{\partial t} = \eta \frac{A}{Z} \frac{M_o c^2}{e} , \tag{1}$$

where R, η, M_o, e,c and t are the particle rigidity, the coefficient of the Fermi acceleration, the rest mass and electronic charge of the particle, the light speed and time, respectively. Here, A and Z are the mass and charge numbers of the particle, respectively. In the case which particles are not fully ionized (see Fig. 1), the charge number must be reduced according to the ionization state of the particles. In this case, we have to use the effective charge number Z^*, which is smaller than Z. This means that the acceleration efficiency is higher for the particles with Z^* than those with Z. Thus the charge states of the accelerated particles tend to produce an excess for the number of these species in comparison with the photospheric abundances.

Most of these accelerated particles would be ejected into outer space without farther acceleration in the explosive phase. Some fraction of these particles would be ionized fully through their interaction with Kev electrons simultaneously accelerated by the instantaneous acceleration, and then further accelerated to higher energy (say, $\geqslant$ 10 Mev/ nucleon). This "secondary" acceleration takes place during the explosive phase. In this case, for medium and heavy nuclear particles, the ratio A/Z is about equal to 2. Therefore, the acceleration efficiency is almost the same for all these nuclear particles (e.g., Sakurai, 1965b,c).

Since the ionization potentials for the electrons in the lowest energy states of these particles are given by

$$\varphi \cong 13.56\ Z^2 \quad \text{eV}, \qquad (2)$$

the values of these potentials tend to increase with the charge number of particles. For examples, these values are given 13.56 and 9156.6 eV for hydorgen and iron atoms, respectively. Because this ionization potential is very high for the iron-group atoms, it seems difficult for all of these atoms to be fully ionized by their interaction with

Kev electrons accelerated by the instantaneous acceleration mechanism as mentioned earlier. However, the most medium nuclei would be completely fully ionized. The minor fraction of fully ionized heavy nuclei, which would be accelerated to energy $\geqslant$ 10 Mev/nucleon, would thus produce a slight deficit as seen in the abundance of the heavy nuclei of solar cosmic rays of this energy, though nearly the same as that of the photosphere of the Sun. Such deficit could be seen in the results obtained by Fichtel and co-workers, though not conclusive (e.g., Fichtel, 1971; Biswas, 1972; Bertsch et al., 1972, 1973). As mentioned above, this deficit of heavy nuclei in the abundances of solar cosmic rays seems to be highly dependent on the physical processes in the acceleration region, associated with the behavior of accelered particles. The model presented here suggests that the charge states of heavy nuclei and the overabundance of the heavy nuclei in solar cosmic rays are both strongly dependent on the manner of the development of parent flares. In particular, the chemical composition of the particles of energy $\geqslant$ 10 Mev/nucleon is considered as a result of their ionization by bombarding Kev electrons accelerated in the instantaneous process, as mentioned earlier.

Roughly speaking, the iron group abundances of solar cosmic rays of energy $\geqslant$ 10 Mev/nucleon are similar to that of the photosphere, though a bit low (e.g., Bertsch et al., 1969, 1972, 1973). From this fact, we have concluded that the "secondary" acceleration during the explosive phase may be identified as the Fermi mechanism (e.g., Hayakawa et al., 1964; Sakurai, 1965b,c; Wentzel, 1965). Therefore, the overabundance in the heavy nuclei of energy $\leqslant$ 5 Mev/nucleon may have been produced during the initial stage of a flare development, during which the particles partially ionized are mainly accelerated simultaneously with electrons of Kev energy. The latter seem to become not only the source of microwave impulsive and hard initial X-ray bursts, but also work as an agent to ionize the former while they are further accelerated.

4. Overabundance of Heavy Nuclei in Solar Cosmic Rays.

When the iron-group atoms are not fully ionized, the acceleration rate becomes charge-dependent because A/Z^* is not nearly equal to 2, but larger than 2. Hence these atoms would be more easily accelerated to higher energy.

If equation (1) is applied, the final rigidity R_o is given as

$$R_o = \eta \frac{A}{Z^*} \frac{M_o c^2}{e} \tau_c + R_i , \tag{3}$$

where τ_c and R_i are respectively the confinement time in the acceleration region and the initial rigidity of the particle (see, Sakurai, 1974). In the above equation, we have replaced Z by Z^*, because the atoms under consideration are partially ionized. The final rigidity obtained above is an important factor because the integrated rigidity spectrum of the accelerated particles is expressed as

$$N(R) = K_o \exp (- R/R_o), \tag{4}$$

where K_o is determined by the acceleration efficiency, the injection rate and the confinement time τ_o (e.g., Roederer, 1964; Sakurai, 1974). In principle, therefore, the excess of partially ionized particles with effective charge Z^* is estimated by calculating the factor K_o. However, it does not seem easy to estimate which factor in K_o is important to produce the overabundance in the medium and heavy nuclei of low energy solar cosmic rays ($\leqslant$ 5 Mev/nucleon).

Because $Z^* < Z$, the confinement time τ_c is also shorter for partially ionized atoms than for fully ionized atoms if the initial rigidity is the same for these atoms. Hence, after acceleration, these partially ionized atoms can first escape from the acceleration region into outer space. In the initial stage of the flux increase of solar cosmic rays of energy $\leqslant$ 5 Mev/nucleon, these partially ionized atoms would, therefore, be first observed near the earth's orbit. These particles would thus contribute to the overabundance in the heavy nuclei of low-energy solar cosmic rays.

5. Concluding Remarks

As shown in Fig. 1, it seems that the medium and heavy nuclei are not fully ionized in the acceleration region before the development of the explosive phase of flares. During this phase, some of these nuclei would be fully ionized by their interaction with bombarding Kev electrons generated by the instantaneous acceleration. Hence the generation of these electrons seems to be very important for the development of solar flares and associated accelerations of various particles (e.g., Kane, 1973). In this paper, we have proposed a model for solar cosmic ray acceleration by considering two-stage acceleration called the "instantaneous" and "secondary" accelerations. The latter works mainly during the explosive phase of flares. The former is related to the initial stage of the flare development associated with some instability triggering a flare, although we do not know yet the mechanism which initiates a flare (e.g., Sakurai, 1974). Our model presented here is different from that which was considered by Cartwright and Mogro-Capero (1972) with respect to the ionization states of various atoms before the onset of flares in acceleration region.

I would like to acknowledge useful discussion with Dr. S. Biswas.

References

Armstrong, T.P. and Krimigis, S.M., 1971, J. Geophys. Res., 76, 1230.

Armstrong, T.P., Krimigis, S.M., Reames, D.V. and Fichtel, C.E., 1972, J. Geophys. Res., 77, 3607.

Bertsch, D.L., Fichtel, C.E. and Reames, D.V., 1969, Astrophys. J., 157, L53.

Bertsch, D.L., Fichtel, C.E. and Reams, D.V., 1972, Astrophys. J., 171, 169.

Bertsch, D.L., Fichtel, C.E., Pellerin, C.J. and Reames, D.V., 1973, Astrophys. J., 180, 583.

Biswas, S., 1972, Indian J. Radio and Space Phys., 1, 19.

Biswas, S. and Fichtel, C.E., 1964, Astrophys. J., 139, 941.

Biswas, S. and Fichtel, C.E., 1965, Space Sci. Rev., 4, 709.

Cartwright, B.G. and Mogro-Capero, A., 1972, Astrophys. J., 177, L43.

Cartwright, B.G., and Mogro-Capero, A., 1973, High-Energy Phenomena on the Sun, ed. by R. Ramaty and R.G. Stone, p. 393, NASA, GSFC X-693-73-193.

Cowsik, R. and Price, P.B., 1971, Physics Today, 24, No. 10, 30.

de Jager, C., 1969, Solar Flares and Space Research, ed. by C. de Jager and Z. Svestka, p. 1, North-Holland Pub., Amsterdam.

Ellison, M.A., McKenna, S.M.P. and Reid, J.H., 1961, Dunsink Obs. Pub., 1, 53.

Fichtel, C.E., 1971, Phil. Trans. Roy. Soc. London, A270, 167.

Frost, K.J., 1969, Astrophys. J., 158, L159.

Hayakawa, S., Nishimura, J., Obayashi, H. and Sato, H.,, 1964, Prog. Theor. Phys. Suppl. No. 30, 86.

Jordan, C., 1969, Mon. Not. Roy. Astron. Soc., 142, 501.

Jordan, C., 1970, Mon. Not. Roy. Astron. Soc., 148, 17.

Kane, S.R., 1973, IAU Symp. No. 57, Coronal Disturbances, Australia.

Kane, S.R. and Lin, R.P., 1971, Solar Phys., 23, 457.

Mogro-Capero, A. and Simpson, J.A., 1972a, Astrophys. J., 171, L5.

Mogro-Capero, A. and Simpson, J.A., 1972b, Astrophys. J., 177, L37.

Price, P.B., 1973, Space Sci. Rev., 15, 69.

Price, P.B., Hutcheon, I., Cowsik, R. and Barber, D.J., 1971, Phys. Rev. Letters, 26, 916.

Roederer, J.G., 1964, Space Sci. Rev., 3, 487.

Sakurai, K., 1965a, Rep. Ionos, Space Res. Japan, 19, 405.

Sakurai, K., 1965b, Pub. Astron. Soc. Japan, 17, 403.

Sakurai, K., 1965c, Rep. Ionos. Space Res. Japan, 19, 421.

Sakurai, K., 1971a, Pub. Astron. Soc. Pacific, 83, 23.

Sakurai, K., 1971b, Solar Phys., 20, 147.

Sakurai, K., 1974, Astrophys. & Space Sci., in press

Svestka, Z., 1966, Space Sci. Rev., 5, 388.

Svestka, Z., 1969, Solar Flares and Space Research, ed. by C. de Jager and Z. Svestka, p. 16, North-Holland Pub., Amsterdam.

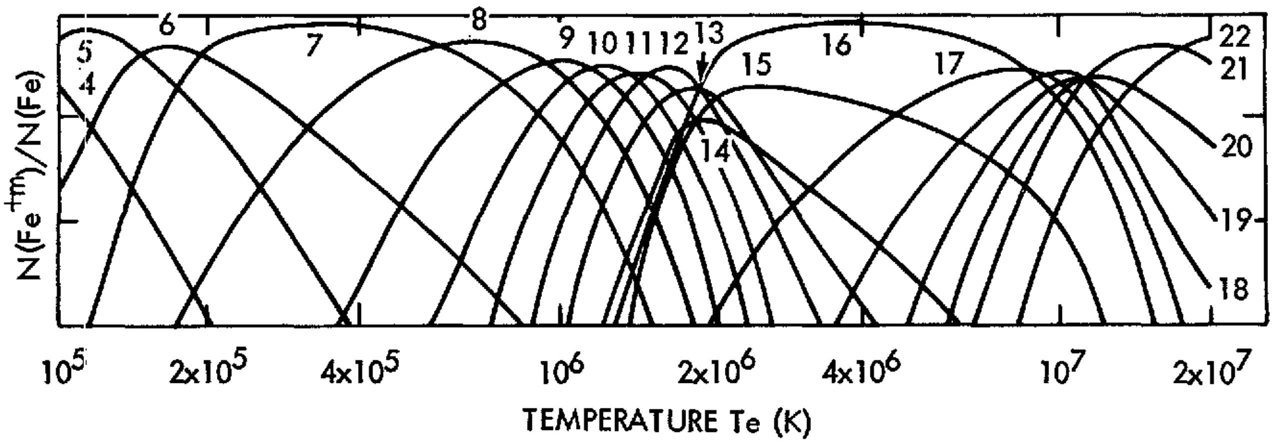
Svestka, Z., 1970, Solar Phys. 13, 471.

Wentzel, D.G., 1965, J. Geophys. Res., 70, 2716.

Wild, J.P., Smerd, S.F. and Weiss, A.A., 1963, Ann. Rev. Astron. Astrophys. 1, 291.

Caption of Figure

Fig. 1 - The ionization equilibrium of Fe ions (Jordan, 1969). This situation seems to be observed in the region where a solar flare occurs.



THE IONIZATION EQUILIBRIUM OF Fe IONS