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^{3}He-rich solar flares

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Abstract. A new subgroup of ^{3}He rich solar flares is found on reanalysing the global data. ^{3}He/H ratio as a function of maximum proton flux at an energy of about 10 MeV shows a break-up of the data into two groups. The first group follows the anticorrelation of ^{3}He/H ratio with the proton flux, as expected in the plasma process acceleration models. But the second group has a constant ^{3}He/H ratio as a function of maximum proton flux. This is not in conformity with the plasma process models. But this is expected in models where the nuclear spallation reactions are responsible for the production of ^{3}He. It is also found that the same break-up into two distinct groups follows if one plots the location of the flares in the solar disc. The first group is more or less confined to the west limb of the Sun, whereas the second group is more widely spread out across the solar disk.

Keywords. Solar cosmic rays; solar particle events; ^{3}He rich solar flares.

1. Introduction

During the last decade a new class of solar flares has been observed in which there is a very high enhancement of ^{3}He/^{4}He ratio of a few percent compared to solar value of $\sim 5 \times 10^{-4}$ (Hsieh and Simpson 1970; McDonald *et al* 1975; Hurford *et al* 1975; Klecker 1981; Kocharov *et al* 1983 and Fisk 1983).

It was found that the large enrichment of ^{3}He seen in many flares is not followed by a simultaneous enrichment of ^{2}H or ^{3}H. Further, it was found that many of the ^{3}He rich events had an enrichment of heavy nuclei and especially iron. However there were several flares in which ^{3}He enrichment was not followed by heavy nuclei enrichment. Moreover, in the flares for which the ^{3}He enrichment was small, ^{2}H and ^{3}H measurements were not available. However, no detailed study of the relationship of ^{3}He enrichment to the flare location has been made.

Several models have been proposed to explain this class of events. Basically the models can be classified into two categories; one in which the nuclear reactions play a dominant role as in the models of Ramaty and Kozlovsky (1974) and Colgate *et al* (1977), and the other based on plasma processes leading to a preferential enrichment of ^{3}He and heavy ions (Fisk 1978, 1983; Ibragimov and Kocharov 1977). A new mechanism of preferential enrichment of ^{3}He alone due to radiation pressure has been proposed by Hayakawa (1983). It is clear from the work done so far that identification of a single dominant process for all the events is extremely difficult. As already mentioned the nuclear reaction models will predict a simultaneous enrichment of ^{2}H and ^{3}H, which are not observed for the highly enriched ^{3}He events. Again there are events in which ^{3}He enrichment is not accompanied by the simultaneous enrichment of heavy and iron nuclei (Mason *et al* 1980). Further the dependence on the atomic structure demanded by the plasma processes has not been unambiguously measured (Dietrich and Simpson 1978; Reames and von Rosenvinge 1981). Hence it becomes necessary to classify the observations into various groups. It is then possible to explain the origin of individual classes to one type of model. Such an attempt is presented below.

2. Experimental data

Several observations of ^{3}He-rich events have been presented so far (see for a summary Zwickl *et al* 1978; Ramaty *et al* 1980; Klecker 1981 and Kocharov *et al* 1983). However in all these presentation the emphasis has been on ^{3}He/^{4}He ratio as well as the data pertaining to other nuclides like ^{2}H, ^{3}H or heavy nuclei. However, if nuclear reactions are responsible for the enrichment, a direct correlation of ^{3}He with the proton flux is expected. That is, ^{3}He/H ratio should be a constant as a function of proton flux. Hence we have made an attempt to study the variation in the abundance of this ratio with maximum proton flux. For this purpose a plot of ^{3}He/H ratio as a function of proton flux was made. This is shown in figure 1 and the values are given in table 1. The data has been taken from the summary of Ramaty *et al* (1980). We could not use later data, because it was not possible to obtain the maximum proton flux associated with these events. It can be seen from figure 1 that there is a clear separation of ^{3}He rich events into two distinct groups. One group corresponds to a proton flux of 10^{-3} to 10^{-1} P/(cm^2 sr sec MeV). This group has an anti-correlation with the proton flux in accordance with plasma models as was pointed out by several authors (Dubinsky *et al* 1981; Pesses 1981). But above a proton flux of 1 P/(cm^2 sr sec MeV), there is a new group of events having a constant ^{3}He/H ratio.

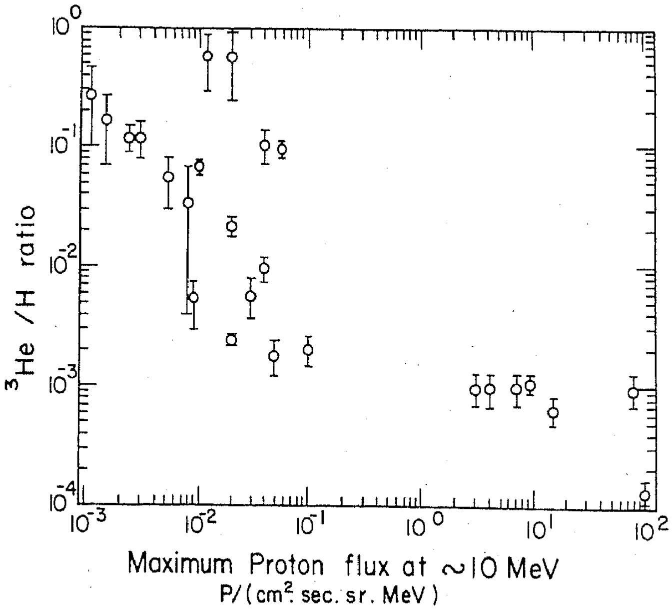

Figure 1. ^{3}He/H ratio *vs* maximum proton flux for ^{3}He rich solar events (data from Ramaty *et al* 1980). A new subgroup of ^{3}He rich event is seen distinctly separated in the events for maximum proton flux greater than 1 P/(cm^2 sec sr MeV).

Table 1. Details of ^{3}He rich events.

Date of the Flare	Location	^{3}He/^{4}He	^{4}He/H	Max. proton flux at 10 MeV (P cm^{-2} sr^{-1} sec^{-1} MeV^{-1})	^{3}He/H
19 April 1968	W62, N20	0·13 ± 0·04	0·042 ± 0·003	9×10^{-3}	$(5·46 \pm 1·72) \times 10^{-3}$
23 April 1968	—	0·08 ± 0·0	0·031 ± 0·002	2×10^{-2}	$(2·48 \pm 0·16) \times 10^{-3}$
29 April 1968	—	0·16 ± 0·05	0·011 ± 0·001	5×10^{-2}	$(1·76 \pm 0·57) \times 10^{-3}$
11 May 1968	—	0·14 ± 0·02	0·069 ± 0·002	4×10^{-2}	$(9·66 \pm 1·41) \times 10^{-3}$
5 May 1969	W72, N09	0·53 ± 0·07	0·041 ± 0·002	2×10^{-2}	$(2·2 \pm 0·3) \times 10^{-2}$
28 May 1969	W59, N10	1·52 ± 0·1	0·4 ± 0·2	$1·2 \times 10^{-2}$	$(6·1 \pm 3·1) \times 10^{-1}$
29 May 1969 (02 to 21 hr)	W66, N12	0·71 ± 0·06	0·15 ± 0·03	4×10^{-2}	$(1·1 \pm 0·2) \times 10^{-1}$
29 May 1969 (21 to 20 hr)	W76, N12	0·35 ± 0·03	0·28 ± 0·01	6×10^{-2}	$(9·8 \pm 0·9) \times 10^{-2}$
30 July 1970	—	0·45 ± 0·06	0·16 ± 0·01	10^{-2}	$(7·20 \pm 1·1) \times 10^{-2}$
14 May 1971	—	0·07 ± 0·02	0·085 ± 0·009	3×10^{-2}	$(5·95 \pm 1·81) \times 10^{-3}$
30 June 1971	Uncertain	0·25 ± 0·05	0·0083 ± 0·0004	10^{-1}	$(2·08 \pm 0·43) \times 10^{-3}$
15 February 1973	No flare patrol possible with A.R. ~ W60	0·21 ± 0·07	0·27 ± 0·03	$5·3 \times 10^{-3}$	$(5·67 \pm 1·99) \times 10^{-2}$
29 June 1973	—	2	0·06 ± 0·02	3×10^{-3}	$(1·2 \pm 0·4) \times 10^{-1}$
20 February 1974	—	0·63 ± 0·10	0·19 ± 0·02	$2·5 \times 10^{-3}$	$(1·2 \pm 0·2) \times 10^{-1}$
19 March 1975 (18–22 hr)	Region 571	0·8 ± 0·2	0·21 ± 0·07	$1·5 \times 10^{-3}$	$(1·7 \pm 0·7) \times 10^{-1}$
19 March 1975 (22-06 hr)	W130 S13 OR S73	1·7 ± 0·6	0·16 ± 0·06	$1·1 \times 10^{-3}$	$(2·7 \pm 1·4) \times 10^{-1}$
20 March 1975	W110	0·38 ± 0·2	0·097 ± 0·034	$8·0 \times 10^{-3}$	$(3·7 \pm 2·3) \times 10^{-2}$
13 May 1969	—	0·12 ± 0·03	0·0081 ± 0·0005	4	$(9·72 \pm 2·5) \times 10^{-4}$
8 June 1969	—	0·09 ± 0·02	0·007 ± 0·0003	15	$(6·66 \pm 1·50) \times 10^{-4}$
28 September 1969	E02, N09	0·18 ± 0·05	0·0056 ± 0·0003	7	$(1·01 \pm 0·29) \times 10^{-3}$
2 November 1969	W90, N16	0·077 ± 0·02	0·0134	80	$(1·03 \pm 0·27) \times 10^{-3}$
30 May 1970	W31, S08	0·12 ± 0·02	0·0093 ± 0·0004	9	$(1·12 \pm 0·19) \times 10^{-3}$
25 June 1970	E11, N10	0·13 ± 0·03	0·0079 ± 0·0005	3	$(1·03 \pm 0·25) \times 10^{-3}$
25 January 1971	W50, N19	0·02 ± 0·01	0·0055	100	$(1·10 \pm 0·55) \times 10^{-4}$

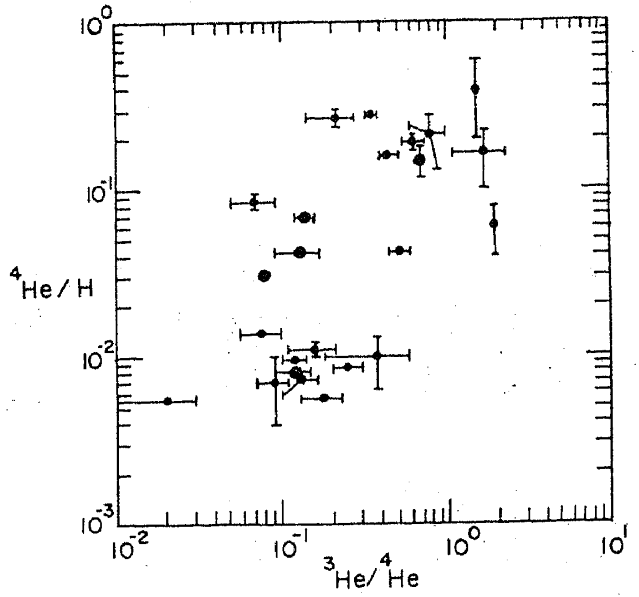

Figure 2. ^{4}He/H ratio *vs* ^{3}He/^{4}He ratio for ^{3}He rich solar flares. The ^{3}He events belonging to a new subgroup as shown in figure 1 correspond to the cluster of events with ^{3}He/^{4}He ratio between 0·1 and 0·4 and ^{4}He/H less than 0·2.

The break-up into two groups can be seen in figure 2 also where a plot of ^{4}He/H ratio as a function of ^{3}He/^{4}He ratio is plotted. From the plasma models it is expected that all the enrichment must correspond to events with ^{4}He/H ratio larger than 0·2. However we find a cluster of events with ^{3}He/^{4}He 0·1 to 0·4 corresponding to a ^{4}He/H ratio less than 0·2. Most of these events have a constant ^{3}He/H ratio. Unfortunately, for some of these events no information on the heavy nuclei enrichment is available. It is possible that there may not be any heavy nuclei enrichment accompanying the He enrichment. They may belong to the third group of flares with the enrichment of ^{3}He due to radiation pressure as suggested by Hayakawa (1983).

In order to find out any information about the location of the flares and the group to which they belong, we plot in figure 3 the location of the flare in the solar longitude along with the ^{3}He/^{4}He ratio. It is seen that the ^{3}He rich events of the first group are more or less confined to the western limb of the Sun. The other events show a much larger spread of longitudes on the solar surface.

3. Discussion

The new subgroup of ^{3}He rich events emerging from the above analysis has the following characteristics. In all these events (i) ^{3}He/^{4}He ratio is less than 0·2 (ii) ^{4}He/H ratio for these events is less than 0·02. Unfortunately, for all these events no information on the enrichment of heavy nuclei is available. The plasma process suggested by Fisk (1978) and others requires a value greater than 0·2 for the ratio of ^{4}He/H in the ambient medium (Ramaty *et al* 1980). Since these events do not have this value, it seems quite likely that the plasma effects may not be dominant in the source regions of these flares. Further the plasma processes require an anticorrelation of ^{3}He/H ratio with the proton

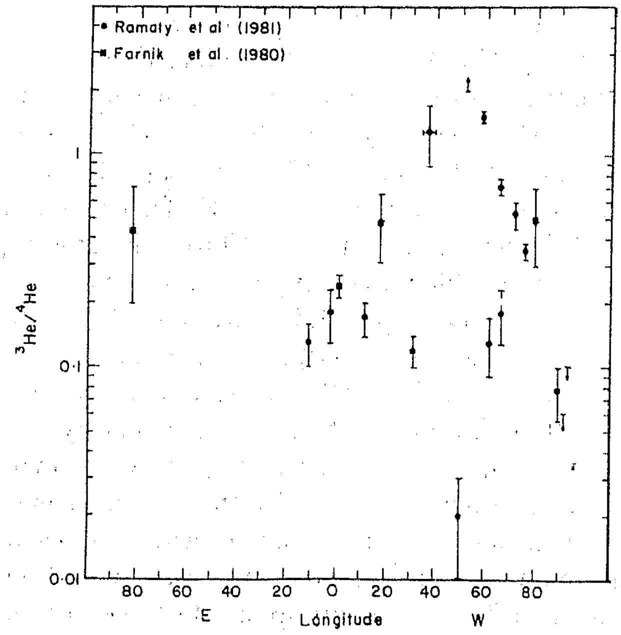

Figure 3. Solar longitude distribution of ^{3}He rich events; the new subgroup of ^{3}He events identified in figure 1 belong to the events with ^{3}He/^{4}He ratios between 0·1 and 0·4. In this figure these are seen to be spread over the solar disc, in contrast to the other subgroup of events which are concentrated in the western part of the solar hemisphere.

flux. This also is not the case for this class of events. The constant ^{3}He/H ratio is a natural consequence of a model in which the high energy protons travel the same amount of matter leading to a spallation production of ^{3}He. Hence this seems to be the natural process for the formation of this group of events.

Next we examine the question of the amount of matter traversed by the particles. We estimate that the amount of ^{3}He expected in these events correspond to a matter traversal of about 2 g/cm^2 of matter. Recent observations have demonstrated that some of the ^{3}He rich events have not traversed more than 50 mg/cm^2 of matter (Mewaldt and Stone 1983). However the data includes only two ^{3}He rich events and it is likely that the events studied do not belong to this group of events. Also, it should be noted that the measurements of grammage of matter correspond to particles that has escaped a flare region in open magnetic loops. In closed loops where particles do not escape easily, the effective grammage travelled may be much larger. Under such closed loop conditions special spallation effects required to explain the absence of ^{2}H and ^{3}H may exist. It is necessary to study the amount of matter traversal corresponding to the specific group of events rather than an average of many flares. Further the recent solar gamma ray observations confirm that nuclear reactions do occur quite often during flares (Rieger *et al* 1983).

One argument regarding the possible role of trapping near the flare sites have to be mentioned here. While the experimental observations correspond to the particles which have escaped out into the interplanetary medium, the kinematics of the reactions as well as the trapping processes might preferentially allow the escape of ^{3}He and not ^{2}H or ^{3}H. This suggestion has been investigated by Ramaty and Kozlovsky (1974) and Rothwell (1976). Rothwell (1976) considered the magnetic mirror trapping of orthogonally directed spallation products. But it is seen that the maximum enrichment will yield a ratio of $^2H/^3He$ of about 1/20 only. This, however, is not sufficient for explaining all the ^3He enriched flares. But the regrouping of these flares into the two groups demonstrates that the second group which has a low $^3He/H$ ratio predicts the ^2H and ^3H enrichments, which are below the present detection thresholds. Hence perhaps the improvement of the current experimental techniques to detect ratios of $^2H/H$ of a few times 10^{-6} will be able to confirm the validity of the nuclear reaction model for this subgroup of events.

Another important aspect of the problem which has not been considered so far is the location of the flare and the enrichment observed. It is well known that the flares located in the western limb of the Sun have an easy passage to earth and hence the particles produced in flares in the western limb reach near the earth along the magnetic field lines connecting the Sun and the earth. This is the most plausible reason why locations of the flares associated with ^3He enriched events for the first group with small associated proton flux are confined to the western hemisphere of the Sun as shown in figure 3. This is supported further by the fact that since the first group of events is associated with very small-sized flares they require an easy passage that can ensure the observation and detection of these flares near earth. The second group of ^3He rich events belong to the relatively larger solar flare events with the maximum proton flux greater than 1 P/cm^2 sec sr MeV. Thus being larger events, they tend to reach us from almost all longitudes.

4. Conclusions

The present study leads us to the following conclusions: (i) The ^3He rich events can be classified into two groups. (ii) The classification which is dependent on the accompanying proton flux seems to suggest different sources of origin of these flares. (iii) One group of events can be well understood on the basis of the plasma effects suggested by Fisk (1983) and Ibragimov and Kocharov (1977) while the second group may have its origin in nuclear spallation. (iv) The first group of ^3He events is due to small events and hence are mostly western limb events whereas the second group belonging to large events is nearly uniformly distributed in solar longitudes.

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