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^{3}He RICH SOLAR FLARES

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Abstract

The various observational features of the ^{3}He rich solar flares like their characteristics and association with other phenomena are discussed. It is shown that ^{3}He rich flares split into two distinct groups, if one plots the ^{3}He/H ratio as a function of maximum proton flux at an energy of about 10 MeV. ISEE 3 observations have shown that ^{3}He rich events are associated with impulsive non-relativistic electron events. Observations made with the same spacecraft have shown the poor association of ^{3}He rich events with Type II bursts and coronal mass ejections, unlike the other energetic particle events. Implications of these observations, on any possible model for the origin of ^{3}He rich events, are highlighted.

Introduction

The earliest indications of ^{3}He rich events from the Sun were the observations of Schaeffer and Zahringer (1962) that ^{3}He/^{4}He ratio is of the order of 0.2 in the materials of the Discoverer 17 satellite exposed to the intense solar flare of November 12, 1960. However due to atmospheric contaminations, they were unable to demonstrate conclusively that the events were indeed solar in origin. The first definite identification of ^{3}He rich events with solar flares was the work of the Chicago group (Hsieh and Simpson, 1970) who determined the mean ^{3}He/^{4}He ratio of $(2.1 \pm 0.4) \times 10^{-2}$ from several flares in 1967. This conclusion was supported by latter observations which showed that the ^{3}He/^{4}He ratio can go upto as much as unity and sometimes even higher (Anglin et al, 1973; Dietrich, 1973; Garrard et al, 1973). Now more than one hundred such events are known (see for a summary Ramaty et al, 1980; Kocharov and Kocharov, 1984; Kahler et al, 1985). These studies have revealed the characteristics of these events and their correlation with other solar phenomena. These will be briefly summarised along with the theoretical ideas (on the anvil), leading to a consistent model explaining these diverse observations.

Characteristics of ^{3}He Rich Events

a) Correlation with other species

The main characteristics of ^{3}He rich events if of course the high enrichment of ^{3}He. The ratio varies from event to event, but typically the values range from a few times 10^{-2} to order of unity. As against these the typical abundance for the solar atmosphere and solar wind are about 10^{-4} (Geiss and Reeves, 1972). The ratio in solar wind varies, sometimes increasing to very nearly 10^{-2}, but these increases are not at all correlated with the ^{3}He rich events (Ramaty et al, 1980).

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Very few of the events are accompanied by energetic proton events (Kahler et al, 1985). Actually the correlation with maximum proton flux at 10 MeV yields a very important clue to the classification of these events. ^{3}He/^{1}H ratio as a function of maximum proton flux at 10 MeV is shown in Fig.1. It can be seen from this figure that there is an inverse correlation of ^{3}He/^{1}H ratio with maximum proton flux. But beyond a maximum proton flux of 1 p/Cm^2.Sr.Sec.MeV, the ratio remains constant. This gives an indication that probably there are two classes of ^{3}He rich events (Ramadurai et al, 1984).

Many ^{3}He rich events are accompanied by simultaneous enrichment of heavy nuclei ($Z > 6$) and especially Fe (Anglin et al, 1977; Zwicki et al, 1978; Mason et al, 1980; Ma Sung et al, 1981; Klecker et al, 1982; 1984). Similarly many Fe rich events are accompanied by ^{3}He enrichment. But this correlation between the two class of events is not very strong, as there are some ^{3}He rich events which are not Fe rich and a few of the Fe richevents are not ^{3}He rich (Kahler et al, 1985).

One important further data about the correlation with other species is the absence of detection of any ^{2}H and ^{3}H increases along with ^{3}He rich events.

b) Correlations with other Solar Phenomena

We have already noticed that ^{3}He rich event is not in general associated with energetic proton event at all. However if there is any common process of acceleration for energetic proton event (EPE) and ^{3}He rich event such a correlation is expected. In addition one can look for correlations of ^{3}He rich event with other solar phenomena like Type II Bursts, Coronal Mass Ejections (CME), non relativistic electorn events eatc. Such correlation studies have become available as a result of the experiments aboard the spacecraft ISEE-3.

While there is a tight correlation of EPE with metric type II Bursts, out of 66 ^{3}He rich events observed during 1979 to 1982, it was found that such correlation above random chance level does not exist (Kahler et al, 1985).

The EPE are always associated with CMEs suggesting an important role for coronal shocks in proton acceleration. But in the case of ^{3}He rich events, there is no association (Kahler et al, 1985). During the period 1979 to 1982, CME data are available for the time period of 45 ^{3}He rich events. But only 2 of the CMEs are associated with ^{3}He rich events, suggesting lack of correlation.

Out of the solar energetic particle emissions, non-relativistic, 2-100 KeV, solar electron events are the most frequent. Further these events are closely associated with Type III Bursts, X-ray Bursts and the flash phase of solar flares. By studying the association of ^{3}He rich event with such non-relativistic electron events (NEE), one will be able to determine whether ^{3}He rich events arise when ^{3}He are accelerated at the flash phase of the solar flares. Since NEE occurs at the rate of several per day, such correlation studies are possible only if ^{3}He rich events have fast temporal behaviour and the instruments have relatively high time resolution. Such studies were made using ISEE 3, by Reames et al (1985) following the studies of the time histories and angular distributions during individual ^{3}He rich events by Reames and Von Rosenvinge (1983). These studies revealed that the ^{3}He and the electrons exhibit nearly scatter free propagation in the interplanetary medium and the times of onset and maximum for the ^{3}He and electron increases are closely related by velocity dispersion. Further in one event (1979 May 17), the event-averaged energy spectra of electrons and ^{3}He have the same spectral slope at approximately the same particle velocities. This indicates that the acceleration is velocity dependent.

Theoretical Ideas Leading to a Model for ^{3}He Rich Flares

a) Surface Nuclear Reactions

The first model to be proposed was the high energy nuclear reactions on the solar surface (Ramaty and Kozlovksy 1974). When it became clear that even kinematical arguments are not going to explain the absence of detectable amounts of ^{2}H and ^{3}H, some ingeneous plasma trap was invoked by Colgate et al (1977). In this plasma trap thermonuclear reactions can occur which lead to the burning of ^{2}H and ^{3}H. The necessary parameters of the plasma trap are:

number density $n \sim 10^{15}$ Cm^{-3}
ion temperature $T_i \approx 2 \times 10^9$ °K
and Confinement time for ^{2}H and ^{3}He $\gtrsim 10$ seconds.

Such a trap can arise by scatter-free traversal of 100 MeV protons through a filament of diameter 140 cm and 2×10^9 cm long leading to a current flow of 10^{10} A along the field lines. But this model yields large fluxes of gamma rays, which are not observed so far (Kocharov and Kocharov, 1984). Further the enrichment of heavy nuclei which are seen in many of the flares, cannot be explained by this model.

However it should be borne in mind that the lack of detection of ^{3}H and ^{2}H apply only to very large enrichment like ^{3}He/^{4}He ratio of unity. But for those flares where there is only modest enrichment of ^{3}He with ^{3}He/^{4}He ratio of about 10^{-2} the deuterium fluxes accompanying them are below the present detection thresholds (Ramadurai et al, 1984). Thus it is possible that for these modestly enriched flares, nuclear reactions are distinct possibility. This conclusion is strengthened by the fact that those flares, which have some modest enrichment, form a distinct group with constant ^{3}He/^{1}H ratio as a function of maximum proton flux at 10 MeV as seen in Fig.1. Constant ^{3}He/^{1}H ratio is expected if the amount of material traversal is constant and the proton flux is increased. The amount of ^{2}H and ^{3}H expected in this case are below the detection threshold of present day detectors.

b) Two Step Processes

The acceleration of ^{3}He is considered to be a two-step process. In the first step there is a preacceleration which injects particles into the flare acceleration process with enhanced abundance of ^{3}He. These processes can again be divided into two classes, the first being the radiative acceleration suggested by Hayakawa (1983) and the other is the plasma acceleration process, originally suggested by Ibragimov and Kocharov (1977) and Fisk (1978).

Radiative Process

This considers an initial push of ^{3}He ions by the radiation pressure due to helium resonance lines. Helium emits strong lines at 584 Å (He I) and 304 Å (He II) in the chromosphere. If the temperature is greater than 10^4 °K, these lines are Doppler broadened. The ^{3}He ions with a thermal velocity of about $7.5 \times 10^5 \, T_i^{1/2}$ cm Sec^{-1} are resonant with the Doppler broadened resonance lines of ^{4}He *and hence get* a preferential acceleration due to radiation pressure. However this does not explain the enrichment of heavy ions simultaneously with ^{3}He enrichment. So this mechanism may be operative under those conditions where ^{3}He enrichment is not followed by enrichment of heavy ions. The acceleration can take place as long as the charge state of ^{3}He is not changed. This immediately points to a site of low density like the coronal cool regions.

Plasma Models

In this model the preacceleration is due to wave-particle interactions. The second stage acceleration demands a threshold injection velocity like Fermi type acceleration. Several versions of these processes are suggested, the earliest being the induced scattering of Langmuir waves by ions (Ibragimov and Kocharov, 1977). This was further modified to include ion acoustic waves (Kocharov and Orischenko, 1983). It is seen that scattering of ion acoustic waves is more efficient by nearly five orders of magnitude compared to the scattering of Langmuir waves (Kocharov and Kocharov, 1984).

One great advantage of this process is the ready explanation of the mass dependence (A) of the observed ^{3}He rich flares. Since the diffusion coefficient is proportional to A^{-2}, ^{3}He is preferentially enriched. The excitation of ion acoustic waves is favoured under strongly non-isothermal conditions with $T_e/T_i > 100$, where T_e and T_i are the electron and ion temperatures respectively. However the charge dependence of the diffusion coefficient, assumed by these authors have been shown to be in error (Weatherall, 1984) and hence the enrichment factor is not likely to be as great as claimed by these authors. Further the conditions which are most likely to prevail in the accelerating regions is likely to favour the $T_e/T_i < 10$ unlike the strong non-isothermal conditions favoured by these authors. Under these conditions ion cyclotron waves are more easily excited rather than the ion acoustic waves (Kindell and Kennell, 1971). Hence this is discussed next.

In a low β plasma with T_e/T_i less than 10, when electrons drift relative to the ions, parallel to magnetic field, at speeds small compared to the electron thermal speed, but in excess of the ion thermal speed, electrostatic ion cyclotron waves are likely to be excited. In a pure hydrogen plasma, the ion cyclotron waves have a frequency ω, above the proton cyclotron frequency Ω_H given by

$$\omega = (\Omega_H^2 + K_\perp^2 C_S^2)^{\frac{1}{2}} \simeq 1.2 - 1.4\Omega_H$$

where C_S is the sound speed. However in a multi-species plasma with enriched abundances of helium and heavy ions, like in the base of the solar corona, electrostatic ion cyclotron waves can also be excited in the frequency range between doubly ionized helium and proton cyclotron frequencies. In the case where the helium abundance is substantial, more than 10% in fact waves in this range are more readily excited than the waves above the proton cyclotron frequency.

$$\text{Since} \quad \omega \simeq 1.2\, \Omega_{^4\text{He}^{++}} \approx \Omega_{^3\text{He}^{++}}$$

doubly ionized ^{3}He can have resonant acceleration. In addition ions with mass/charge ratio of 3.3 and 4.5 can be accelerated by the higher harmonies, less efficiently. This can be seen from Fig.2. While doubly ionized Helium-4 does not get heated much, $^3\text{He}^{++}$ acquire large thermal speeds and hence are injected into the acceleration process with velocities above threshold. Thus a natural increase in the ratio of ^{3}He/^{4}He arises purely from the conditions of plasma existing in the accelerating regions.

While Fisk model is the most successful of all the models suggested so far, the model has the difficulty of explaining two observational features. As can be seen from Fig.2, the model predicts too strong heating of protons. As a result H/^{4}He ratio turns out to be too high compared to the observations. This difficulty can be removed by assuming injection velocity threshold for the acceleration process to be dependent on charge/mass ratio. The model predicts an inverse correlation of ^{3}He/H ratio with the maximum proton flux. This correlation is seen for several flares, but as has been emphasized earlier, beyond a proton flux of 1 P/Cm^2.Sr.Sec.MeV, the ratio becomes constant. Further, for these flares, the He/H ratio seem to be less than 10%, as can be seen from Fig.3. Since for the resonant acceleration by ion cyclotron waves, it is necessary to have a high ^{4}He abundance, for those flares with low ^{4}He abundance,

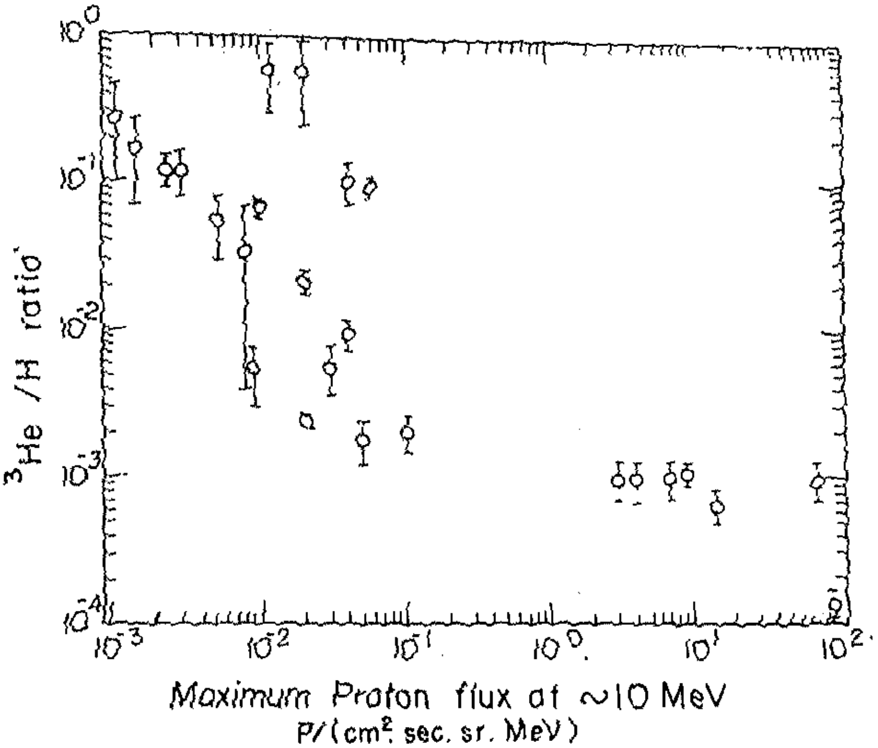

Fig.1. ^{3}He/H ratio as a function of maximum proton flux at about 10 MeV (Ramadurai et al, 1984).

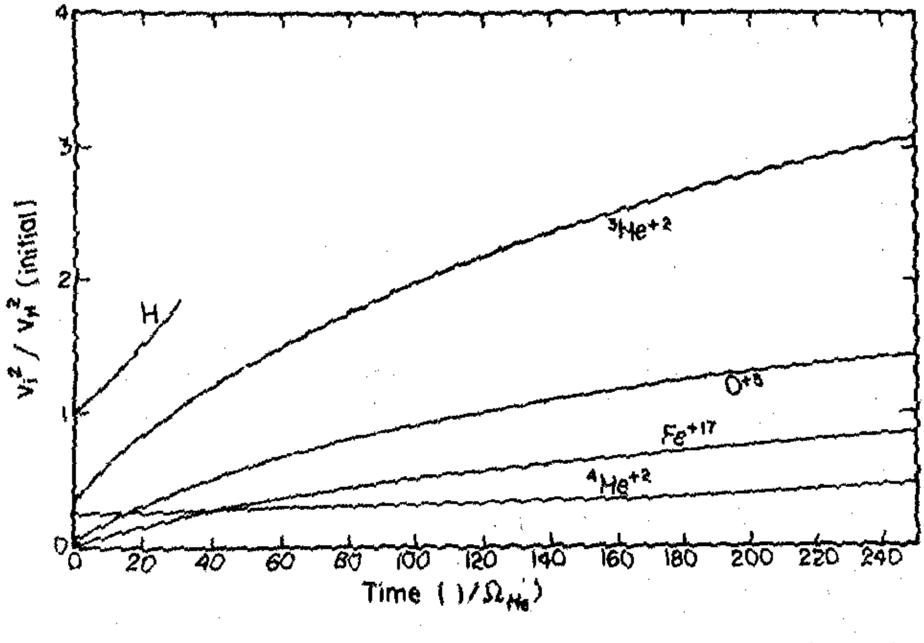

Fig.2. The increases in the square of various ion thermal speeds with time that result from Fisk model. The ion thermal speeds are compared to the initial proton thermal speed V_H (initial). Initially the ions are assumed to be at equal temperaturues (Fisk, 1978).

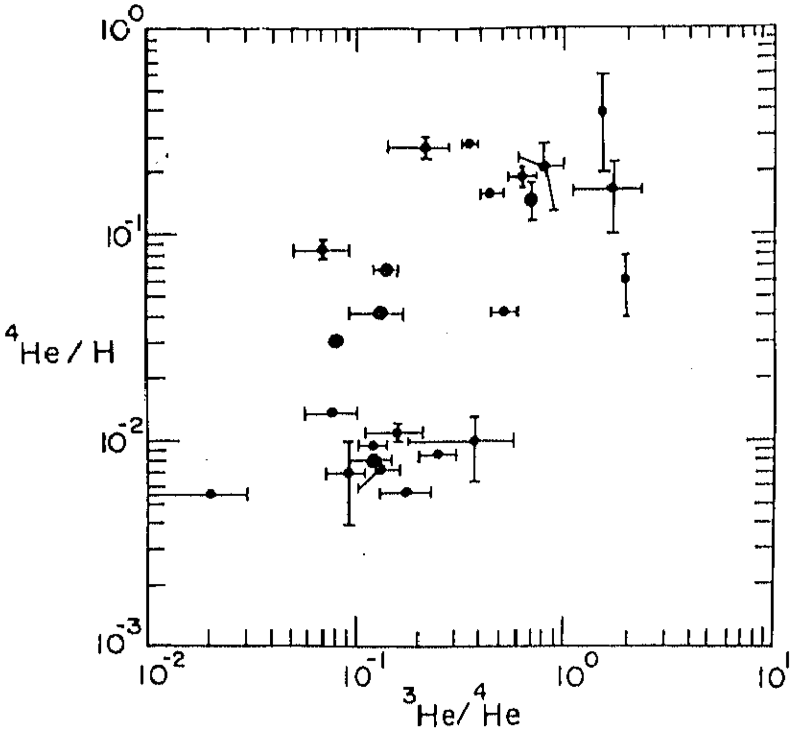

Fig.3. ^{4}He/H ratio as a function of ^{3}He/^{4}He. Notice the clustering of points around ^{4}He/H of about 10^{-2} (Ramadurai et al, 1984)

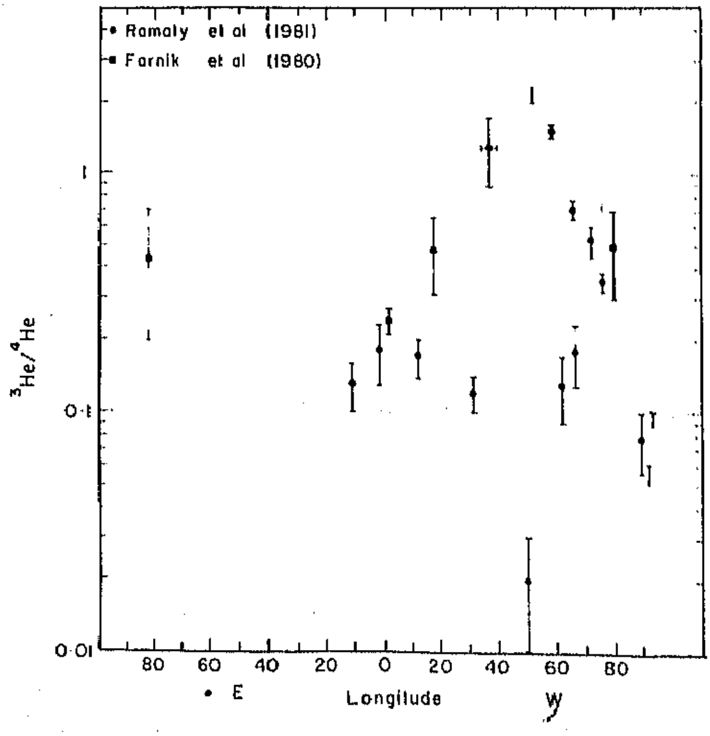

Fig.4. ^{3}He/^{4}He as a function of heliographic longitude (Ramadurai et al, 1984).

this model faces genuine difficulty. This difficulty for the ion cyclotron wave model is sought to be removed by invoking non-linear effects, as shown by Varvoglis and Papadopoulos (1983).

The revision of Fisk model to include proper non-linear physics of particle energization by electrostatic ion cyclotron waves removes the stringent requirement of enhanced helium abundance. This is achieved by the physical process called resonance overlapping. Here ion acceleration does not require resonance, but can be strong even for significant frequency mismatch. So the acceleration can be achieved by hydrogen cyclotron waves themselves. The required charge/mass dependence is achieved through the non linear saturation level $e\phi/T_H$, where e, ϕ and T_H are the electronic charge, the wave potential and hydrogen temperature respectively. It is shown by Varvoglis and Papadopoulos, that this is capable of preheating considerable number of doubly ionized ^{3}He ions, above the threshold for stochastic acceleration. This procedure is capable of explaining the enrichment of heavy nuclei too. But as emphasized by Varvoglis and Papadapoulos (1983) "Complete picture requires input on the plasma composition and temperatures at the preacceleration site and a description of the second stage acceleration processes". However coincidence of the observed charge/mass ratio anomalies with the region of anomalies expected on the basis of intrinsic stochasticity behaviour of hydrogen cyclotron waves, is suggestive of the basic soundness of the approach adopted by these authors.

Discussion and Conclusion

The basic features of ^{3}He rich solar flares like the enrichment of ^{3}He, accompanied many times with the increase of heavy nuclei abundances, can be explained broadly by invoking a two stage acceleration process. Here there is preheating of the species leading to the preferential acceleration of ^{3}He nuclei above the injection threshold for the second stage acceleration. For this purpose scattering of the ions off Langmuir waves, ion acoustic waves and ion-cyclotron waves, have been suggested. While all of them seem to be capable of qualitatively explaining the ^{3}He enrichment, and of heavy nuclei enrichment most often concomitantly, the details of the process demand inclusion of non-linear effects. In this respect it is important to keep in mind the observation of Melrose (1983) "Preacceleration mechanisms which draw a small fraction of the ions out of the tail of a Maxwellian distribution will lead to unacceptably low abundances for accelerated ions due to the slower speeds of the heavier ions".

Some attempts have been made to make a detailed comparison of ^{3}He rich observations with other solar phenomena like Type II Bursts, Coronal Mass Ejections, Non-relativistic Electron Events etc. But as of now a detailed model of ^{3}He rich flare treating the two stages of acceleration in detail, describing the expected consequences of the model and comparing these predictions with the new available detailed observations, remains a fond hope.

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