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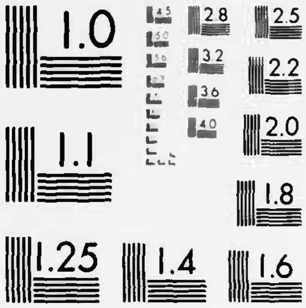

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SELECTIVE NON-RESONANT ACCELERATION OF ^{3}HE^{++} AND HEAVY IONS BY H^{+} CYCLOTRON WAVES

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UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
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SELECTIVE NON-RESONANT ACCELERATION
OF ^{3}HE^{++} AND HEAVY IONS
BY H$^+$ CYCLOTRON WAVES

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ABSTRACT

The abundance anomalies associated with ^{3}He-rich flares, are attributed to the *intrinsically* anomalous acceleration behavior of species with $\frac{A}{Q} < 3$, , in the presence of hydrogen cyclotron waves. While the overall model is along the lines of Fisk's (1978) proposal, the difficulties associated with triggering of nonhydrogenic cyclotron waves are avoided.

I. INTRODUCTION

One of the most intriguing results of energetic solar particle flux measurements at ~ 1 AU is the discovery of anomalous enhancements in the abundance of some ionic species during occasional "unusual" events, often called ^{3}He-rich flares (Ramaty et al. 1980 and references therein). Three different types of enhancements can be distinguished in these events:

i) the enhancement of the isotope ^{3}He by as much as 3.5 orders of magnitude, at energies ~ 1-10 MeV/nucleon.

ii) enhancement of heavy ($A > 4$) ions by a factor of 5-10.

iii) Deviations of other charge states from solar abundances.

These are often correlated during ^{3}He-rich flares. The most promising theoretical models consider a two stage acceleration process (Ibragimov et al. 1978, Fisk 1978); a preacceleration, or preheating stage due to wave-particle interactions, followed by a process requiring a threshold injection velocity such as a Fermi type acceleration (Möbius et al. 1982).

Of the above models the one proposed by Fisk (1978) seems to be the most successful in explaining not only enhancement type i) but types ii) and iii) as well. It is based on selective preheating of the ^{3}He and certain heavy ions such as Fe by resonant interaction with ion cyclotron waves. Such waves can be driven unstable by electron currents or ion beams. In a pure hydrogen plasma the ion cyclotron waves have frequency above the proton cyclotron frequency Ω_H (i.e. $\omega = (\Omega_H^2 + k_\perp^2 c_s^2)^{1/2} \simeq 1.2\text{-}1.4\Omega_H$. c_s is the sound speed) (Kadomtsev 1965). However, in the presence of noticable amount of doubly ionized $^4He^{++}$ and for some combination of drift velocities and plasma parameters, waves near the $^4He^{++}$ cyclotron frequency can be excited. Since $\omega \approx 1.2\Omega_{^4He^{++}} \approx \Omega_{^3He^{++}}$, $^3He^{++}$ can be resonantly accelerated. In addition, ions with $\frac{A}{Q} \approx 3.3$ and $\frac{A}{Q} \sim 4.5$ can be accelerated by the harmonics (i.e. $\omega = n\Omega_i - k_z v_z$) although less effeciently.

The subject of ion energization by ion cyclotron waves in multispecie plasmas has been recently examined by Papadopoulos et al. (1980), Singh et al. (1981, 1982), and Varvoglis and Papadopoulos (1982). It was noted that for wave amplitudes exceeding a threshold, which depends on $\frac{A}{Q}$, ion acceleration does not require resonance, but can be very strong even for significant frequency mismatch. The physical process responsible for this, is resonance overlapping. The general theory was given by Chirikov (1979), while its application to lower hybrid heating of fusion plasmas in several publications (Fukuyama et al. 1978, Karney and Bers 1977, Hsu 1982). It has been called non-resonant stochastic acceleration to be distinguished from the one requiring cyclotron resonance (i.e. $\omega = n\Omega_i - k_z v_z$)) and as first shown by Papadopoulos et al. (1980) exhibits a large selectivity in the ionic A/Q.

In this paper we revise the model advanced by Fisk (1978) by including the proper non-linear physics of particle energization by electrostatic ion cycltron waves (EIC). Our model retains two basic concepts of Fisk (1978). The energization by EIC waves and the need for a second stage acceleration. However there is no need for exciting $^4He^{++}$ cyclotron waves, since the dominant process is non-resonant and can be accomplished by hydrogen cyclotron waves. The $\frac{A}{Q}$ selectivity in the flux available for energization in the second stage process, enters through the non-linear saturation level $\frac{e\psi}{T_H}$, which in conventional theories (Dum and Dupree 1970, Palmadesso et al. 1974) depends on the current that drives the instability.

II. NON-LINEAR STOCHASTIC ACCELERATION

The non-linear energization of minority species, taken as test particles, by an EIC wave with typical frequency ω near Ω_H, and propagating perpendicular to the ambient magnetic field can be described as a diffusion in velocity space, even in the absence of resonance (i.e. $\omega - k_z v_z \neq n\Omega_i$) (Abe et al. (1981), Hsu (1982), Varvoglis and Papadopoulos (1982)), if

$$\frac{e\Phi}{T_H} \gtrsim \frac{1}{4} \frac{R(\nu)\ r}{(k_\perp R_H)^2\ n J_n(r)} \qquad (1)$$

In eqn. (1) Φ is the wave potential, $\nu = \frac{\omega}{\Omega_H} \frac{A}{Q}$, $n = [\nu + .5]$ (the integer nearest to ν), $r = (k_\perp R_H) \frac{A}{Q} \frac{v_\perp}{v_H}$, J_n is the n_{th} order Bessel function of the first kind, and R_H, T_H, V_H the gyroradius, temperature and thermal velocity of hydrogen, which is assumed to be the dominant species. $R(\nu)$ is a function whose details have been determined computationally by Hsu (1982), which for $\nu < 3$ oscilates around R=1 and approaches R=1 for $\nu > 3$. (Note that $\nu R(\nu) = P(\nu)$ is plotted in fig. 5 of Hsu (1982)). From (1), we can find the upper and lower limit of stochasticity in velocity space for a given $\frac{e\Phi}{T_H}$ value as done in Papadopoulos et al. (1980). Here we take a different approach and use (1) to determine the minimum value of $\left(\frac{e\Phi}{T_H}\right)_{thr}$ required for the lower velocity stochasticity limit to be equal or below the thermal speed V_j of a particular specie j. This implies that for $\frac{e\Phi}{T_H} > \left(\frac{e\Phi}{T_H}\right)_{thr}$ the bulk of the species will be preheated. Notice that for an isothermal plasma (by isothermal here we refer only to ion temperatures)

$$r = (k_\perp R_H) \frac{A^{1/2}}{Q} \frac{V_\perp}{V_j} \qquad (2)$$

The value of $\left(\frac{e\Phi}{T_H}\right)_{thr}$ can then be computed from (1) by considering the equality and solving for $\frac{V_\perp}{V_j} \approx 1$, which corresponds to

$$r = r_j \equiv (k_\perp R_H) \frac{A^{1/2}}{Q} \qquad (3)$$

(A and Q correspond to specie j). To be concrete we examine EIC waves with $\omega = 1.2\ \Omega_H$ and $(k_\perp R_H)^2 = 1.5$, which correspond to maximum linear growth (Kadomtsev, 1965). It is easy to see that for $\nu > 3.5$, which corresponds to $\frac{A}{Q} > 2.5$, $\left(\frac{e\Phi}{T_H}\right)_{thr} >> 1$ which is of course unrealistic. We can safely conclude that for $A/Q > 2.5$, only tail or suprathermal particles can be accelerated in an isothermal plasma. However in the region of small $\frac{A}{Q}$ the situation changes. This is seen from fig. 1, where $\left(\frac{e\Phi}{T_H}\right)_{thr}$ is shown as a function of $\nu = \frac{\omega}{\Omega_H} \frac{A}{Q}$ for $\nu < 3$. Two important effects are shown in fig. 1. First, in the region of $\frac{A}{Q} = 1.5\text{-}2$, which involves $^3He^{++}$ and $^4He^{++}$, $\left(\frac{e\Phi}{T_H}\right)_{thr} < 1$, so that bulk preheating of these species is possible. Second the threshold is a non-monotonic function of $\frac{\omega}{\Omega_H}$ and $\frac{A}{Q}$ (e.g. for $\frac{\omega}{\Omega_H} = 1.2$, $\left(\frac{e\Phi}{T_H}\right)_{thr} = .40$ for $\frac{A}{Q} = 1.5$ and .45 for $\frac{A}{Q} = 2.0$).

These results were confirmed in a test particle simulation of 100 ions with an initial Maxwellian distribution with $T_i = T_H$ interacting with hydrogen cyclotron waves at $\omega = 1.2\ \Omega_H$ with amplitude $\frac{e\Phi}{T_H} = 0.45$ propagating perpendicularly to a homogeneous static magnetic field. This amplitude is consistent with auroral observations, laboratory experiments (Kintner et al. 1978, Böhmer 1976) as well as theoretical estimates (Dum and Dupree 1970, Palmadesso et al. 1974). The result for

$^3He^{++}$ ions is shown in Fig. 2 for $t = 0$ and $t \approx 170\ \Omega_H^{-1}$. Note that in the case shown in Fig. 2 a value $\Delta k = \frac{k}{10}$ has been used as the wave spread.

From Fig. 2 we see that

i) apparently the lower velocty threshold r_{min} is in this case nearly zero, since the whole distribution seems to interact with the wave

ii) the maximum velocity is $r_{max} \approx 7$ which corresponds to $\sim 7\ v_{^3He} \approx 4\ v_H$, where $v_{^3He}$ is the thermal velocity of ^3He

iii) the acceleration time scale is $t \approx 150\ \Omega_H^{-1} \approx 0.2$ msec

iv) a considerable number of $^3He^{++}$ ions ($\sim 95\%$) have velocities greather than $v_{^3He}$.

Note that the energy ΔE absorbed by the ^3He ions in this acceleration process is trivial; e.g. for interaction region of the order of 10^3 km^3, $\Delta E \simeq 10^{12} - 10^{13}$ ergs.

The same parameters were used in a run with $^4He^{++}$ ions. Their distribution function was unaffected at all times, consistent with the fact that the wave amplitude was below threshold for this species. According to our scenario, almost all $^3He^{++}$ ions (but only the ions in the tail of the $^4He^{++}$ distribution) will be injected to the second stage acceleration. The $^3He^{++}/^4He^{++}$ ratio of the injected ions will depend on the exact profile of the second stage threshold function (e.g. its steepness), but, as shown by Fisk (1978), this ratio can easily attain values of order unity. If for instance the threshold function is a steep function at $v = 3v^3_{He}$, then $\sim 80\%$ of the ^3He ions in Fig. 2 will be injected, in contrast with only 0.0002% of the ^4He ions. Moreover, if the space averaged wave amplitude fluctuates with time, intermediate values of the $^3He^{++}/^4He^{++}$ ratio could result, from ~ 1 (amplitude consistently between 0.40 and 0.45) to the normal ~ 10^{-4} (amplitude consistently above .45). Note that, because the time scale for this acceleration mechanism is fast, even irregular msec fluctuations of the wave amplitude above threshold can efficiently contribute to particle acceleration, while grad B and finite k_z effects are not expected to affect the results.

IV. HEAVY IONS

The previous section focused on the $^3He/^4He$ anomalies during ^3He-rich events. In this section we discuss the implications of the mechanism to the acceleration of other ionic species; specifically the anomalies on various charge states of C, O and Fe ions, associated with ^3He-rich events (e.g. Anglin et al., 1977; Mason et al., 1979; Ma Sung et al., 1981).

a) C ions. The depletion of C in some ^3He-rich events (Mason et al. 1979) can be accounted by the same process that creates the $^4He^{++}$ depletions discussed before, since for the typical corona temperatures of ~ 2 x 10^6 °K almost all (> 90%) of C ions are in the +6 charge state, having the same, as the $^4He^{++}$ ions, $\frac{A}{Q} = 2$. For the rest of the C ions the wave amplitude threshold does not necessarily increase, so that C ions whith $Q \neq 6$ can be non-resonantly accelerated. As a result while the overall C flux in C-poor flares is low (~ $\frac{1}{10}$ of the normal, if we use the relative abundance of C^{+6} as a guideline) almost all of it should be in the C^{+5} state since this is the next more abundant after C^{+6}.

b) Fe ions: Ma Sung et al. (1981) and Klecker et al. (1982) found that in at least one ^{3}He-rich event Fe was in a higher than usual mean charge state (i.e. $\bar{Q} = 14$), with ions having as large Q as 18. These ions have $\frac{A}{Q} > 3$ and no major flux anomalies would be expected if their temperature is equal to T_H. If, however, their temperature $T_{Fe} \geq 6T_H$, values of $(\frac{e\phi}{T_H}) \approx .4-.5$, will result in accelerating a considerable fraction ($\gtrsim$ 10%) of the available states of Fe ions, as can be seen from eqn. (1). If we assume that $T_H \approx 10^6$ ^{0}K, large enhancement in Fe, ions would require $T_{Fe} > 6 \times 10^6$ ^{0}K in which case more than 99% of Fe will be in charged states with $Q \geq 15$. In our model we associate the enhancement of Fe^{+18}, with the presence in the first acceleration region of Fe with $T_{Fe} \geq 6T_H$, potentially convected from hotter regions.

c) O ions: For these ions also $\frac{A}{Q} \geq 3$, and the lower velocity threshold for acceleration will be the same for O^{+5} and O^{+6}. However the maximum acceleration energy (Papadopoulos et al. 1980) scales as $A^{5/2}$ $Q^{-3/2}$, so that larger O^{+5} fluxes can enter the second acceleration stage than O^{+6}, for the same initial states. This could cause an occasional O^{+5} enhancement in ^{3}He rich flares as seen by Ma Sung et al. (1981).

V. DISCUSSION AND CONCLUSIONS

In this paper we have attempted to attribute the abundance anomalies observed in ^{3}He-rich events, to the intrinsically anomalous acceleration behavior of minority species with $\frac{A}{Q} < 3$, in the presence of hydrogen cyclotron waves. The theory was based on the observations that for $\frac{A}{Q} < 3$,

(1) The threshold for bulk non-resonant acceleration is relatively low (i.e. $\frac{e\Phi}{T_H} = .4-.5$), and it is therefore possible to have ^{4}He/H and ^{3}He/H enhancements.

(2) Small variations in $\frac{e\Phi}{T_H}$ or the wave frequency ω, can produce major variations in the accelerated fluxes resulting in erratic behavior in the abundaace ratios of ions with $\frac{A}{Q} < 3$.

The present theory improves on the model presented by Fisk (1978) by avoiding the difficulties associated with the special conditions required to excite $^4\mathrm{He}^{++}$ cyclotron waves and its harmonics at large amplitudes, and treating properly the non-linearity associated with large amplitude acceleration. We should caution the reader that we have examined only one aspect in the chain of the acceleration events. A complete picture requires input on the plasma composition and temperatures at the preacceleration site and a description of the second stage acceleration processes. In this respect any observational support of our theory might be circumstancial. We feel, however, that the coincidence of the observed $\frac{A}{Q}$ region of anomalies, with the region of anomalies expected on the basis on intrinsic stochasticity behavior for hydrogen cyclotron waves cannot be coincidental.

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FIGURE CAPTIONS

Figure 1 Plot of $(\frac{e\Phi}{T_H})_{thr}$ versus $\nu = \frac{\omega}{\Omega_H} \frac{A}{Q}$ for electrostatic waves with $k_\perp >> k_z$. The A, B, C, D give the $^3He^{++}$ thresholds for $\frac{\omega}{\Omega_H} = 1, 1.1, 1.2, 1.3$, while the A′, B′, C′, D′ the corresponding $^4He^{++}$ threshold values.

Figure 2 The evolution of a Maxwellian distribution function of 100 $^3He^{++}$ ions interacting with hydrogen cyclotron waves for $t = 0$ (dashed line) and $t \approx 170\ \Omega_H^{-1}$ (solid line).

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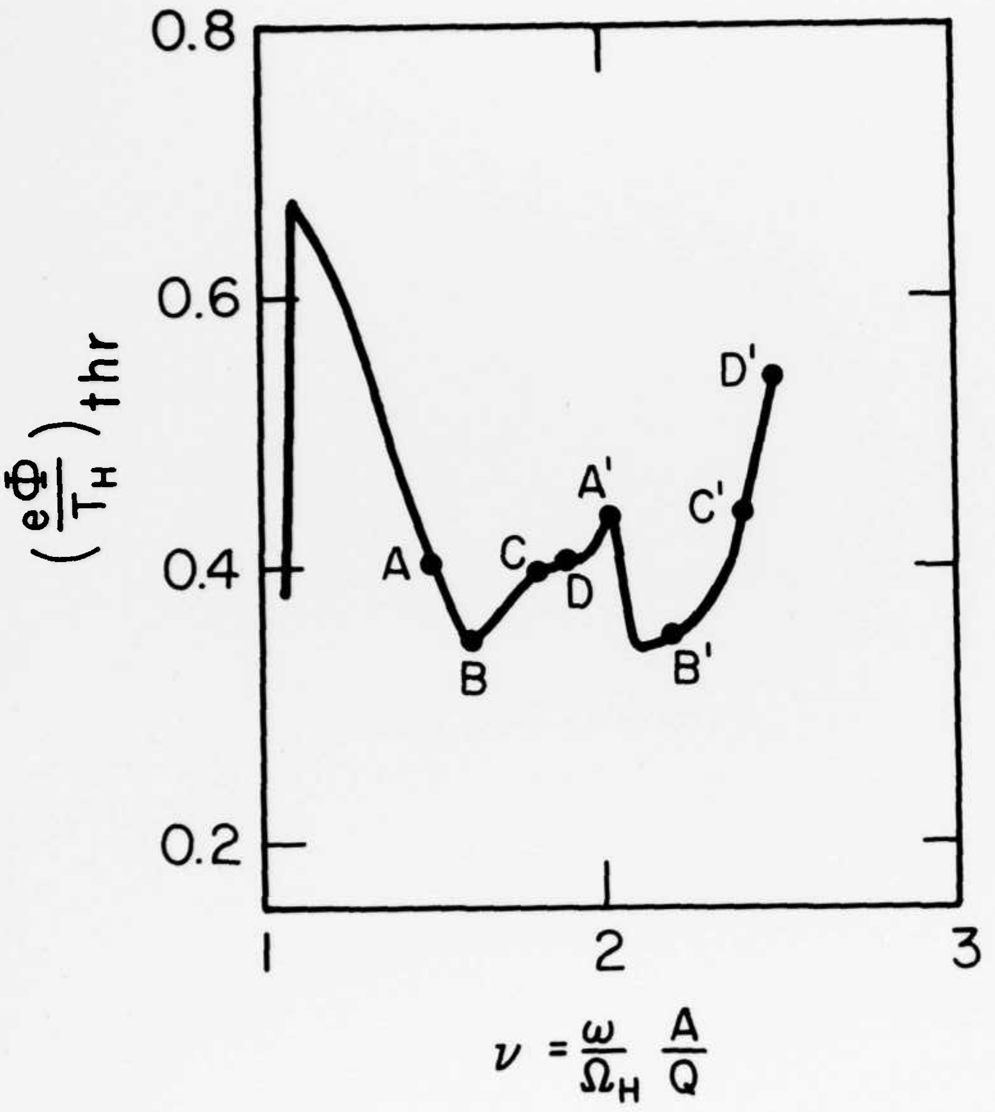
0.8
0.6
0.4
0.2
1
2
3
$\left(\frac{e\Phi}{T_H}\right)_{thr}$
$\nu = \frac{\omega}{\Omega_H} \frac{A}{Q}$
A
B
C
D
A'
B'
C'
D'

FIGURE 1

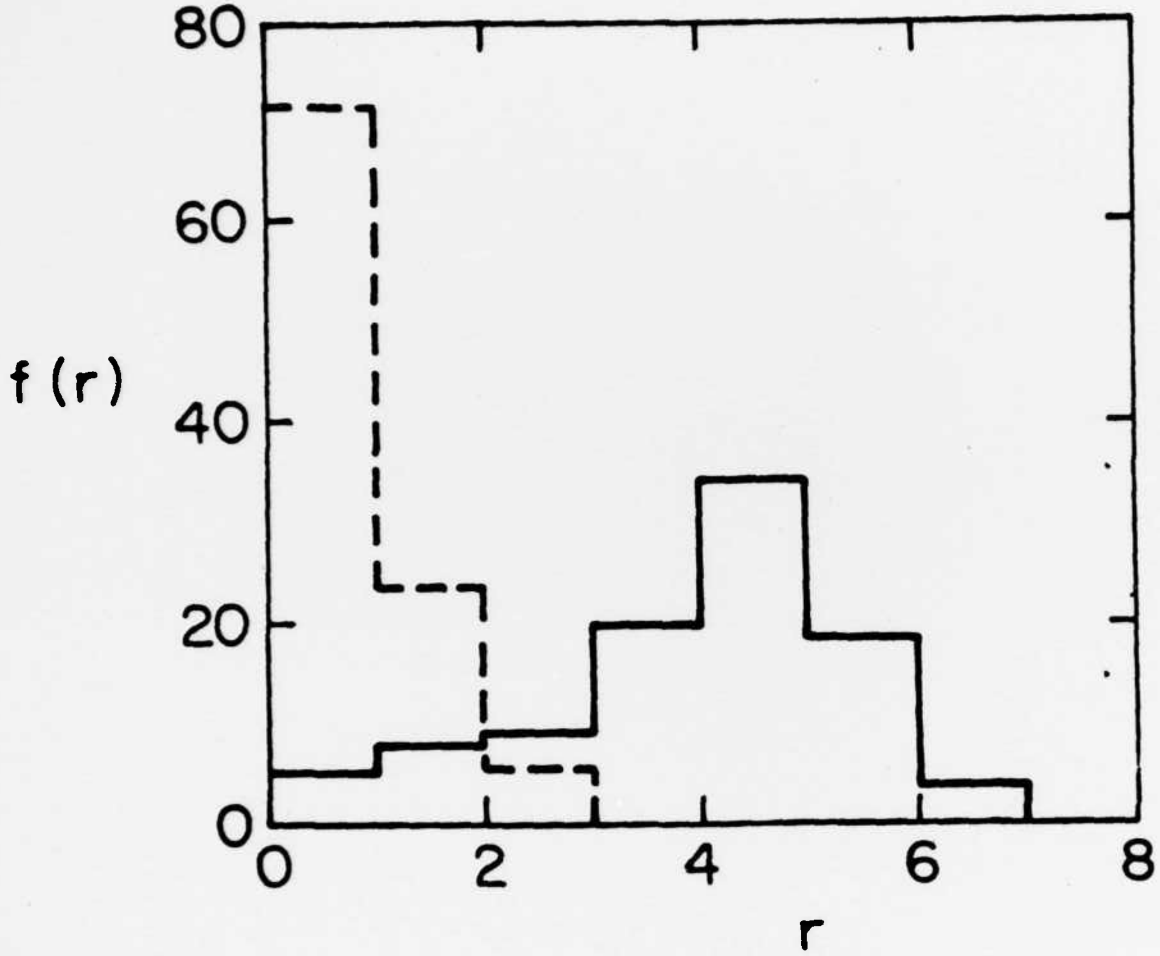

FIGURE 2

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