VI. Solar Energetic Particles

VI.1 Flares, Shocks and Acceleration?

We have talked about particle acceleration at shocks. This occurs in a big way, when the sun ejects material with speeds much higher than the solar wind speed (coronal mass ejections (CMEs)) which form a strong shock. Here at times very intense particle acceleration is observed, which we can describe with the tools that we studied at the Earth's bow shock. However, the situation is complicated by the origin of these shocks. This can be viewed in a similar way as the bow shock acceleration is complicated by the occasional presence of energetic particles from the Earth's magnetosphere.

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In substantial reconfigurations of solar magnetic field in flaring regions magnetic energy is transferred into heating, acceleration and expulsion of solar material. Observed are

- emission of light, x-rays and particle acceleration
- emission of energetic electrons and ions
- often mass ejection from the sun

However, mass ejection may appear by the same token, when a large filament (prominence) is ejected from the sun's atmosphere, sometimes without a noticeable flare.

Let us approach these phenomena from the observation of energetic particles. In fact, the first association of energetic particles with activity on the sun was found as cosmic rays on the ground with large ionization chambers, almost simultaneously with the observation on the sun. The following interpretation that has spawned a lot of detailed work is now often coined the "flare myth". Namely all following observations of energetic particles, either directly associated with observations on the sun or sometimes even without direct evidence, was put into a framework, where it came from flares on the sun, except perhaps the observation of energetic particles directly associated with a shock passing the observing satellite. ***Viewgraph***

<u>Transport</u>

The ions are transported outward with the solar wind and diffuse, i.e. their time structure gets smoothed. All observed temporal, spectral and directional features were subsequently put into a framework with the sun being the main source.

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The difference between scatter-free (along the B-field) and convective-diffucsive transport was invoked to explain observed differences.

Solar wind $$\frac{1AU}{V_{sw}} = 1.5 \bullet 10^8\, km / 500\, km/\sec = 3 - 10^5 \sec \approx 3\, days$$

It takes for example ≈20 days to 16 AU for medium energy (MeV/Nucleon) particles, i.e. ≈3 times faster than the solar wind, but by far not as fast as the speed of the energetic ions → diffusive transport.

There are also substantial differences in the observation at different longitudes. Charged particles travel easterly along field lines, i.e. at a certain position west of the actual flare is the optimum location to get the particles.

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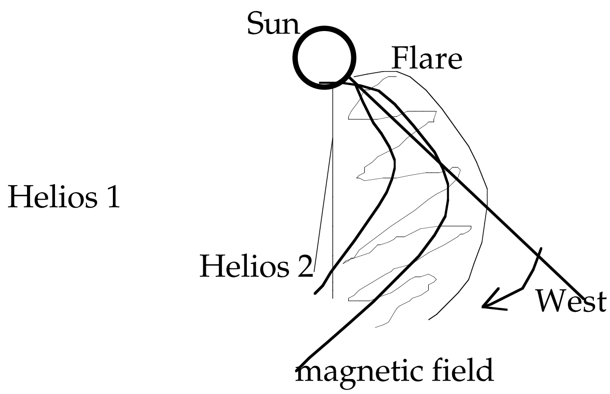
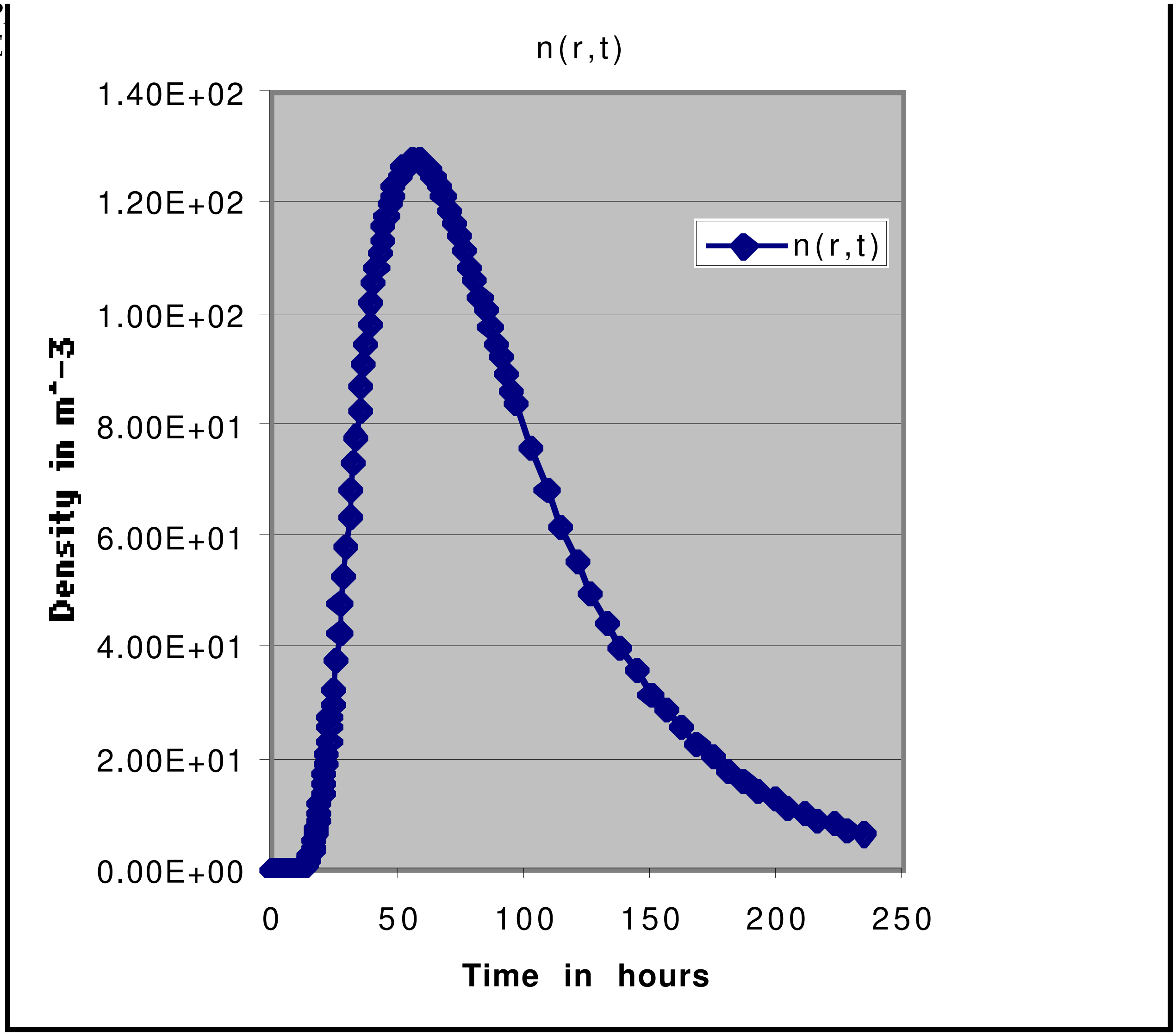


With good connection the particles are seen with a sharp rise (almost scatterfree at the beginning) and slow decay (diffusive). Smaller diffusion coefficients (lower energy and/or across B) lead to a slow rise also. What do I mean by this? If you recall the solution of Problem 2) in Homework#6, diffusive transport scales with the diffusion coefficient

$$n(r',t) = \frac{N_o}{\sqrt{4\pi\kappa t}^3} e^{-\left(\frac{r'^2}{4\kappa t}\right)}$$

If we ignore convection for a moment, we see that a larger diffusion coefficient shrinks the time scale, i.e. for κ twice as large the same conditions are observed at location r already after half the time t is elapsed. A sharply peaked time profile therefore calls for a large κ or long mean free path.



Electrons are generally less affected by scattering, because the wavelength of the magnetic fluctuations is much longer than their gyroradii.

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However, to see electrons there has to be a relatively good magnetic connection.

Because most of the events looked so complicated, scientists started with the simple ones that could be readily interpreted. They arrived at an explanation with diffusion in interplanetary space that seemed to call for a mean free path length of ≈ 0.1 AU at low energies. This was called the Palmer consensus after a paper in 1982. This value was also what we used for the transport of pickup ions, and at first it seemed confirmed by the observations (again the easy ones!).

However, it was observed that the energetic particle events came in two flavors.

VI.2 Two Classes of Solar Energetic Particle Events

Not only the connection determines the temporal profile of the energetic ion fluxes.

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These differences can only be seen for events, which are well connected magnetically. Otherwise we could blame the difference on transport effects, and this was done extensively early on. Events associated with activity on the eastern sun have good connection and seemed to show often very short rise and decay times (incompatible with diffusion theory, scatter-free along the field). They were dismissed as not diffusive.

Events with ion emission of only a few hours are called
- Impulsive Events

The others were coined as
- Large Flares or Long Duration Events

Impulsive	Long Duration
- well connected	- seen everywhere on sun
	Viewgraph
- low ion fluxes	- high ion fluxes
- high e/p ratio	

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but they were all interpreted as solar flares and the particles were thought to come from these flares. For the differences in flux, time profile and spectra transport effects were invoked.

Energy Spectra

With the temporal profiles, which are at different energies, one has to be careful in assembling the energy spectra:

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Most commonly integration over the entire event is performed. The spectra in large flares are again not pure power laws, although these flares are associated with shocks. If modeled with shock acceleration, the loss of the ions out of the acceleration region has to be considered. However, there is also a different possibility, and we will come to this next week.

Ion Composition

Finally, let's examine the composition of the energetic particles. Maybe this can tell us more about their origin, in the same way, as magnetospheric particles and bow shock particles could be distinguished. Large flares show a relatively stable composition with one peculiarity:

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Compared to the local standard composition (from meteorites, etc.) those elements with low ionization energy are overabundant (≈ factor of 4). This is the so-called First Ionization Potential or FIP effect. When compared with

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Photosphere	→ overabundant
Corona	→ same
SW	→ same

I.e. the enrichment occurs, when the ions are lifted into the corona. Probably it helps to be an ion already in the photosphere to make the way up. The mechanism is still not understood and will be under study with SOHO (to be launched in October).

However, even more puzzling are the drastic overabundances observed in the small impulsive flares.

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Compared to "He", Fe gets enriched up to a factor of ≈30, and most spectacularly ^{3}He may be overabundant up to >10,000 over ^{4}He. The natural ratio is $^3\mathrm{He}/^4\mathrm{He} = 4 \bullet 10^{-5}$.

The ratio can be >1 in flare ions.

Now we have a great set of tools to differentiate the two different event types, and we can see a different behavior on a statistical basis. Whereas Impulsive Events are observable only in the particle population when they come from eastern longitudes, Gradual strong events seem to come from everywhere ***Viewgraph***
Why this difference? It was said that Impulsive (weak events) can only emit particles along the field lines, diffusion across field lines is very weak. Strong flares were though to produce huge disturbances in the corona, thus allowing transport across longitudes.
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Impulsive events were thought make it only into a pristine environment with low wave activity. This interpretation received a big blow when an impulsive event was observed riding on the ejecta of a large event. ***Viewgraph***.
How could these particles know that they had to behave scatterfree, whereas the others apparently didn't obey this rule? Since these short impulsive events are the ones that always can be identified with individual events on the sun, maybe these are the real solar particles and signify the transport from the sun to us. What do we get, if we make this assumption? ***Viewgraph***
Time profile and anisotropy both can be explained with the same mean free path, and surprise, surprise it turns out to be 0.5 - 1 AU, much larger than reported earlier. This is also in line with the recent observation of effects on pickup ions. The anisotropies observed also require such large mean free path lengths.

More recently with ACE we have observed beautiful time dispersions of energetic particles that are in full agreement with this new paradigm. High energy particles arrive first, then low energy particles, and the diffusive effects are so weak that high energy particles are already gone when low energy particles arrive.

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What does this teach us for the other large gradual events? They can be perfectly explained with acceleration at the shock wave that leaves the sun.

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Now even the different behaviors at different locations with respect to the origin of the CME and shock make sense. Particles are accelerated at different types of shocks (Quasi-parallel and quasi-perpendicular) and thus how different spectra. The different time profiles are now not solely transport effects, but also effects of connection to different parts of the shocks in time sequence.

What does this tell us in a nut shell about the two types of events?

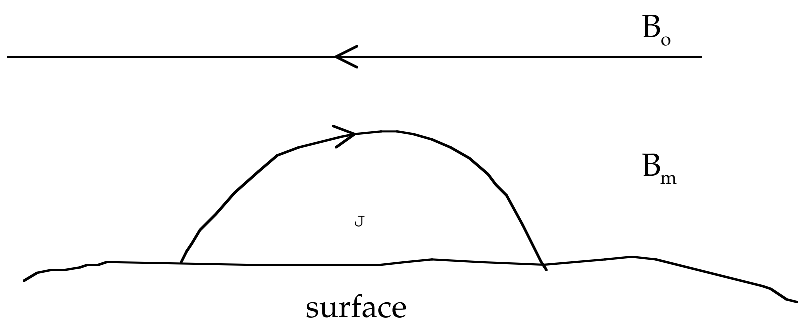
- the particles of the Impulsive Events probably come directly from the sun, from a flare
- the particles of the Gradual Events probably come from the shock that runs into interplanetary space. And this shock may arise from a strong flare, if confirmed, but it may also be generated by a disintegrating prominence, without a flare.

However, in both cases there needs to be a strong energy source at the sun that produces these violent effects. And this is where we go next.

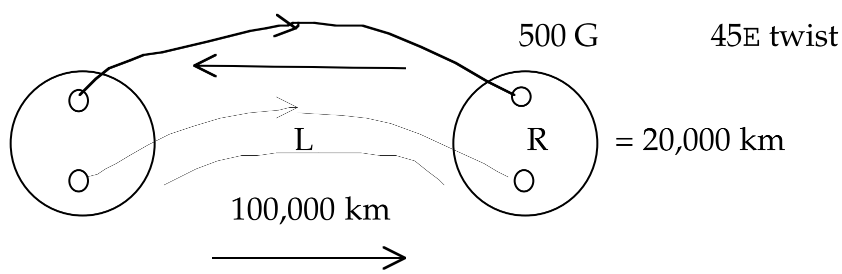
Kirk et al., p. 98-100, p. 56-68
Termpaper, Jun Lin 1999

VI.3 The Flare Process

To tackle the flare process, i.e., the physical process which converts magnetic energy into kinetic energy, let's start again with the observations. Flares occur on the sun in conjunction with sun spots, i.e. regions where magnetic flux emerges from below the surface into already existing field structures. This leads to either convection of flux tubes with opposite polarity towards each other:



or over the course of days to a twisting of flux tubes due to the differential rotation of the sun.



In both cases energy is stored in the solar atmosphere.

The total energy stored when 45E twist is achieved.

$$W = \frac{1}{2} \bullet \frac{B^2}{2\mu_o} L \bullet \pi R^2 = \frac{1}{2} \bullet \frac{(5 \bullet 10^{-2})^2}{8 \bullet \pi \bullet 10^{-7}} 10^8 \pi (2 \bullet 10^7)^2 \approx \underline{\underline{6 \bullet 10^{25}\, J}} \qquad \text{(VI.3\_1)}$$

This is sufficient for a large flare. Smaller regions with less twist can do for smaller flares.

The way, how the additional flux emerges and into the previous environment, may determine the flare type. The rise of a strong flux tube into a crossed field may give rise to a detachment of a plasmoid and a reconfiguration of the old field lines such that the geometry is open to the outside.

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Plasma is ejected into space, particles are accelerated, and they can easily escape. The photosphere underneath is heated in two strips left and right of the flare site. This has been associated with the generation of large (long duration) flares. From their geometry they are often called

<u>two ribbon flares</u>

If magnetic flux with opposite polarity emerges into a relatively strong field the

Viewgraph

reconfiguration may take place in the lower layers of the old magnetic field, like under a blanket. No ejection of plasma results
→ no shock wave
→ only few energetic particles may emerge.

The underlying physical process for the observed reconfigurations of the magnetic field is **reconnection**.

<u>Reconnection</u>

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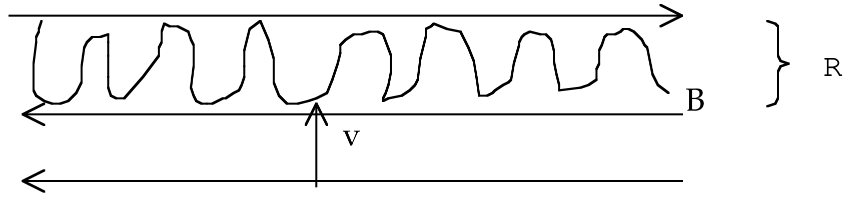
i.e. connection of the opposite field lines in an x-type configuration. Let us explore this basic configuration, which can be applied to all more complicated field structures, in a simple 2-D picture.



For the counter-flow of magnetic field, the equation:

$$\frac{\partial \vec{B}}{\partial t} = \nabla x (\vec{v} \, x \, \vec{B}) + \eta \nabla^2 B \qquad \text{(VI.4\_2)}$$

applies, where in a stationary case $\partial \vec{B} / \partial t = 0$. The convection of field is balanced by diffusive destruction of field in the center. The diffusion speed is therefore

$$v_d = \frac{\eta}{l} \qquad \text{(VI.4\_3)}$$

For given plasma conditions we get $\eta = \frac{1}{\mu\sigma}$. For realistic conductivities v_d can only become reasonably large by making l small!

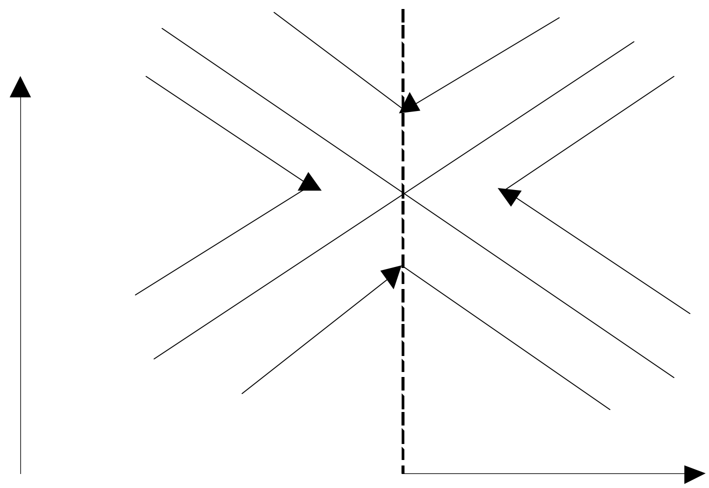
For example $\eta = 1 \, m^2/sec$ in an active region

$$l = 100\,km : v_d \approx 10^{-5}\, m/sec$$

Qualitatively reconnection allows
- change of the B topology
- conversion of the magnetic energy into heat in the plasma

- creation of currents and electric fields ($\vec{v} \times \vec{B}$) and shock waves
  $\rightarrow$ acceleration of particles

Let's move to a 2-D field and inspect the x-point of the B-field in an idealized configuration.



$B_x = y$: $B_y = x$
field lines $y^2 - x^2 = \text{const.}$

$$j = \frac{1}{\mu_o} \nabla \times \vec{B} = \frac{1}{\mu_o}\left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right) = \frac{1}{\mu_o}(1-1) = 0$$

This configuration is stable.

$\vec{j} \times \vec{B} = -\nabla P$ everywhere

If this x is distorted as in a case where two sets of field lines are pushed together:

$B_x = y$; $B_y = \alpha^2 x$ $\alpha^2 > 1$

$$\Rightarrow \quad j = \frac{1}{\mu_o}(\alpha^2 - 1)$$

which has the property to fulfill

$$\frac{\partial}{\partial x}\left(B_y + iB_x\right) = \frac{1}{i\partial y}(B_y + iB_x)$$

The initial state has $B_y + iB_x = z$
and $B_y + iB_x = (z^2 + L^2)^{1/2}$ for the current situation $L = 0$ is equivalent to our first case, and still

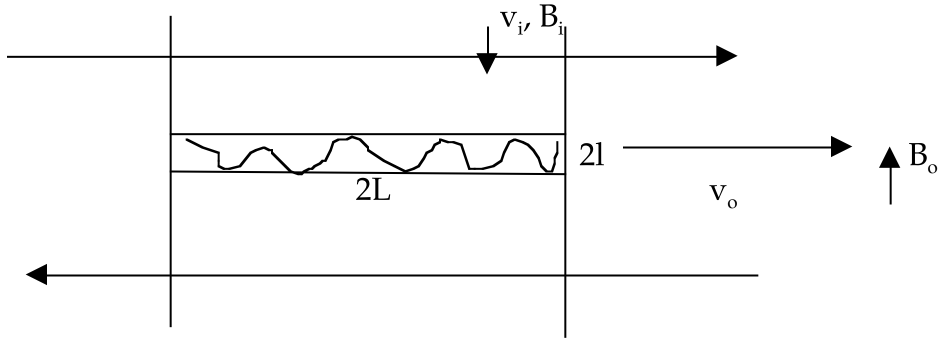
$B_y + iB_x \rightarrow z$ for $2 >> L$

It is a problem equivalent to one with a cut in the complex z-plane, where the current is represented by the residual.

Steady-State Reconnection

- Sweet-Parker Model

Assume a current sheet with l << L



The current density

$\boldsymbol{j} = \nabla \times \vec{\boldsymbol{B}}$ represents the change in B across 2l by $2B_i$.

$$j \approx B_i / \mu_o l \qquad \text{(VI.4\_6)}$$

This current generates a force along the current sheet which accelerates plasma

$$(\vec{j} \times \vec{B})_x \approx j \bullet B_o = \frac{B_i B_o}{\mu_o l} \qquad \text{(VI.4\_7)}$$

B_y

for $\quad 0 = \frac{d(\rho\vec{v})}{dt} = \frac{d\rho}{dt} \bullet \vec{v} + \rho\frac{d\vec{v}}{dt} \text{ and } \frac{d\rho}{dt} = -\rho\nabla\vec{v}$

stationary

we get $\quad \vec{j} \times \vec{B} = \rho\frac{d\vec{v}}{dt} = \rho(\vec{v}\nabla)\vec{v}$

$$\rho(\vec{v}\nabla)v_x \approx \rho\frac{v_o}{L}v_o = \frac{B_i B_o}{\mu_o l} \qquad \text{(VI.4\_8)}$$

$B=0$ requires $\quad B_o/l \approx B_i/L$

$$\frac{v_o^{\,2}}{L} = \frac{B_i^{\,2}}{\rho\mu_o k} = V_{Ai}^{\,2} \qquad \text{(VI.4\_9)}$$

i.e. the plasma leaves at the Alfvèn speed of the original plasma.
The inflow speed v_i is determined by the magnetic diffusion

$$v_i = \eta / l \text{ and } 4\rho L \bullet v_i = 4\rho l \bullet v_o$$

$$\Rightarrow \quad Lv_i = lv_o = lV_{Ai} \qquad \text{(VI.4\_10)}$$

together $\quad Lv_i^2 = \frac{\eta}{l} \bullet l v_{Ai} \quad \Rightarrow \quad \frac{v_i^2}{v_{Ai}^2} = \frac{\eta}{v_{Ai} V}$

$$\text{or} \qquad M_i = \frac{1}{\sqrt{R_{mi}}} \qquad \text{(VI.4\_11)}$$

Where M_i is the Alfvèn Mach. # of the inflow and R_{mi} the magnetic Reynolds #.

Because generally η is small $\Rightarrow$ R_m large

$\Rightarrow$ M_i small $\qquad v_i << v_{Ai}$

The inflowing electromagnetic energy density (Poynting flux) is

$$\vec{E} \, x \, \vec{H} \quad \Rightarrow \quad E \bullet \frac{B_i}{\mu_o} = v_i \frac{B_i^2}{\mu_o}$$

This has to be compared with the kinetic energy:

$$\frac{(K.E.)_i}{(M.E.)_i} = \frac{\frac{1}{2}\rho v_i^2}{B_i^2 / \mu_o} = \frac{v_i^2}{2 v_{Ai}^2} << 1$$

The outflowing magnetic energy is

$$\frac{E \bullet B_o}{\mu_o} l = \frac{v_o B_o^2}{\mu_o} l << \frac{B_i^2}{\mu_o} v_i L$$

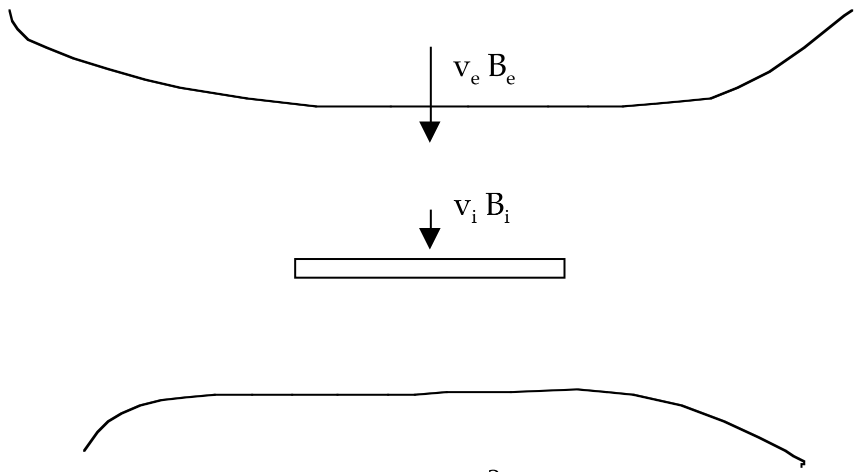
But with $v_o B_o = v_i B_i$

$$\frac{(K.E.)_{out}}{(M.E.)_{in}} \frac{\frac{1}{2}\rho v_o^2 (v_o l)}{v_i B_i^2 L / \mu_o} = \frac{\frac{1}{2} v_o^2}{v_{Ai}^2} = \frac{1}{2} \qquad \text{(VI.4\_12)}$$

50% of the original magnetic energy goes into bulk flow, the rest into an electric field and finally into heating!

$M_i = \frac{v_i}{v_{Ai}}$ is also the (now small reconnection rate).

What, if we have a forced inflow.



i.e. $$\frac{M_i}{e} = \frac{v_i}{v_e}\frac{v_{Ae}}{v_{Ai}} = \frac{B_e}{B_i} \bullet \frac{B_e}{B_i} = \frac{B_e^{\,2}}{B_i^{\,2}}$$

with $v_i B_i = v_e \bullet B_e$

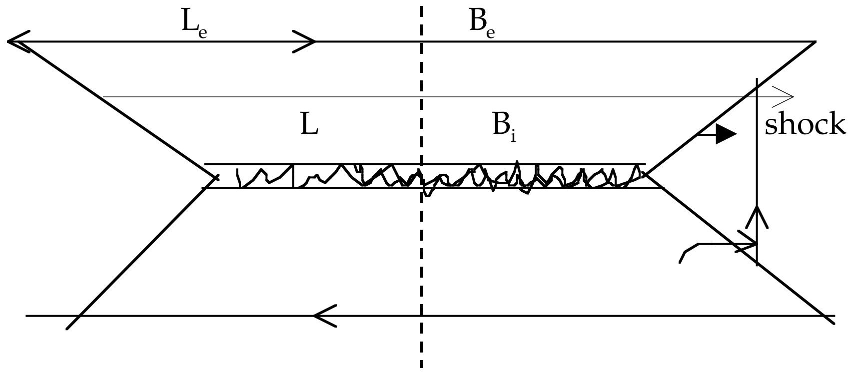
Reconnection is defined as fast, if

$M_e >> M_i$

This requires: $B_i >> B_e$ i.e. <u>flux pile-up</u> or

Petschek Reconnection

In this case the reconnection region is very small. Petschek computed contribution to B from the current through the "cut" in the sheet.



Outside the region with size L_e the magnetic field remains unaffected. The transport of the field into the new configuration occurs across a shock, where the new normal component of the magnetic field (after shock crossing) is maintained by the current through the cut (contribution of the pole).

$$j \cdot L = \frac{1}{\pi} 2 \int_L^{L_e} \frac{2B_N}{x} dx$$

$$B_i = B_e = \frac{4B_N}{\pi} \log \frac{L_e}{L} = B_e \left(1 - \frac{4M_e}{\pi} \log \frac{L_e}{L}\right)$$

i.e. the field is reduced!

By assuming $B_i \approx \frac{1}{2} B_e$

$$M_{e\,\max} \approx 0.01 \ \ still \ll 1$$

but reasonably larger than the Sweet-Parker reconnection rate.

For conditions in an active region:

$$V_e = V_o = M_e V_A = \frac{5 \bullet 10^{-2}}{\sqrt{4\pi \bullet 10^{-7} 1.6 \bullet 10^{-27} \bullet 10^{14}}} \bullet 0.01 \eta_e = 10^{14}\, m$$

$$= 30{,}000\, km/s \ \cdot 0.01 = \underline{\underline{300\, km/s}}$$

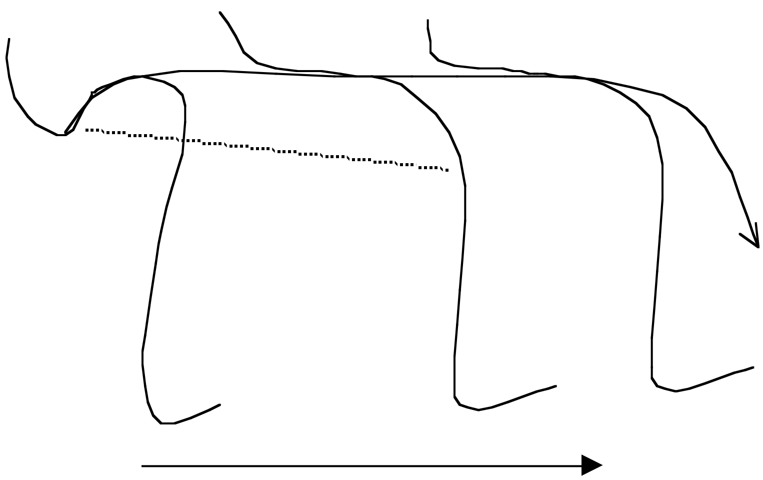
Flare Trigger?

Now we have the process, which does the trick and efficiently transfers energy into particles. However, the time scales are still long compared with the observations, if we use typical flare sizes.

$$l = 5 \bullet 10^6\, m \text{ and } \tau_d = \frac{l^2}{n}$$

We arrive at $\tau_d \approx 10^{11}$ sec
If we want to get time scales of hours: 10^4 sec
We need: $l \approx 1$ km
The initial phases of a flare are even faster. As a way out a filamentation process into thin current strips is proposed, which is suggested to be triggered by an instability.

Theorists are working on ideas to move the magnetic field configuration through equilibrium, which changes their potential, for example, in the following way:



However, this modeling is still in flux. For example, Priest and Forbes (1980) treated a current, which rises in the solar atmosphere, as a possible configuration to trigger the start of a flare.

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Particle Acceleration

As we can see recommendation produces 3 ways to accelerate particles.

- strong electric fields (both types)
- shocks (in 2 ribbon fluxes)

and - turbulent acceleration

Direct acceleration on E-fields is not sufficient in either flare type. Shock acceleration together with a loss process may explain the observations in large flares.

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However, there is an additional promising possibility: The current produced in the reconnection site is responsible for plasma turbulence. This strong wave activity can lend to 2nd order Fermi acceleration. Using such process also leads to a good fit of observations. Unfortunately, do the largest differences sow up only at very low energies.

Solar Helium-3 Rich Events

Yuri E. Litvinenko

April 18, 1995

1. Introduction

The solar flare is the process of magnetic energy release in the lower solar corona, accompanied by plasma heating, generation of fast MHD flows, particle acceleration up to a relativistic energies and generation of various plasma emissions. One of the most curious phenomena occurring during flares is the enrichment of the accelerated particle flux by some of ion species. In particular, the ^{3}He isotope is known to be accelerated preferentially with respect to ^{4}He in some flares (see Reames *et al.*, 1994 for a recent review of observational data). Statistically, ^{3}He-rich events strongly correlate with sunspots and flares. Up to a thousand of ^{3}He-rich events per year are registered on the visible solar disk at the maximum of the solar activity. The rate is at least a factor of 50 less during the minimum. It is not clear, however, whether the size of ^{3}He-rich events is restricted from below and, if it is, whether this limiting size changes with the solar cycle or not.

Under typical conditions of the quiet solar atmosphere, the density of ^{3}He ions is only ˆ5 • 10^{-4} of that of ^{4}He. Since a typical concentration of ^{4}He in flaring regions is 10^9 cm cm^{-3} (¯10% of the hydrogen concentration), it means that the number of ^{3}He ions in the flare volume V¯ 10^{26} cm^3 is 5 • 10^{31}. A significant part of these is accelerated during a ^{3}He-rich flare. In fact, the enhancements in the ^{3}He/^{4}He ratio by a factor of 10^3 —10^4 are observed, whereas about 10^{30} — 10^{31} ^{3}He ions are accelerated during a typical event up to energies of a few MeV, so that their total energy can be >10^{25} erg. The acceleration is known to occur in a time less than 10 s, implying the energy gain rate of a few hundred kV per second. Measurements of ^{3}He energy spectra showed them to be power-laws with spectral indices of about 2 and steeping at the energy ≤10 MeV (Reams *et al.*, 1992).

The first report of an unusually high ^{3}He/^{4}He ratio dates as far back as 1962 (Scheffer and Z hringer, 1962). A radiochemical study of a satellite material revealed that ^{3}He "might be about 10% of the solar flare particles". Later studies confirmed the existence of ^{3}He-rich events (Hsieh and Simpson, 1970; Dietrich, 1973; Kocharov and Kocharov, 1984). Up to now, however, the wealth of observational data has not received an exhaustive theoretical explanation. The purpose of this report is to briefly describe the observational properties of ^{3}He-rich events (Hsieh and Simpson, 1970; Dietrich, 1973; Kocharov and Kocharov, 1984). Up to now, however, the wealth of observational data has not received an exhaustive theoretical explanation. The purpose of this report is to briefly describe the observational properties of the ^{3}He-rich solar events and the models suggested to explain them. The last section treats the possibility of preferential acceleration and ^{3}He particles in the vicinity of reconnecting current sheets of solar flares and also delineates some of the open questions facing theoretical models.

2. Observational properties of ^{3}He-rich events

Pallavicini *et al.* (1977) were seemingly the first to distinguish between two physically distinct classes of solar flares: impulsive and gradual. Impulsive flares are compact; they occupy a volume ˜10^{26}-10^{27} cm^3 and occur at a lower height (<10^4 km). They are characterized by faster rise and decay times, shorter durations (tens of minutes) and a higher energy density (10^2 —10^3 erg/cm^3). Flares of this class produce strong impulsive X-ray and gamma-fluxes, while their proton fluxes are relatively small. Finally, there is no association of the impulsive events with prominence eruptions or coronal mass ejections. Gradual flares, on the other hand, are long-duration events (hours) with a larger volume (˜10^{28} —10^{29} cm^3) and greater height ($5 \bullet 10^4$ km). They have longer rise and decay times and a lower energy density (10 —10^2 erg/cm^3). They are characterized by large observable proton fluxes and are frequently associated with prominence eruptions, possibly triggering the flare (though the last statement is by no means unanimously accepted; see the review by Bai and Sturrock, 1989).

Magnetic field configurations are also different in impulsive and gradual flares. The former demonstrate the closed, loop-like structures: magnetic field lines, originating at the solar surface, eventually return to it. No considerable restructuring of the field is observed in the course of the flare. Alternatively, magnetic field during the graduate events has a cusp-like, helmet structure, involving open magnetic field lines. As the flare progresses, successively higher and higher layers of the preexisting configuration start producing the flare emissions.

Differences between the impulsive and graduate solar flares can be explained if the mechanism responsible for the energy release is identified. The present consensus is that the flare is the release of magnetic free energy, that is the difference between the energy of the actual magnetic field and the energy of the potential field with the same distribution on he photosphere. Copious observational evidence and theoretical considerations indicate that the energy release occurs by dint of magnetic reconnection — interaction of magneticfields that have antiparallel components (magnetic reconnection in solar flares was reviewed by Somov, 1992). The place where the field lines are driven together and forced to reconnect is termed the reconnecting current sheet, because of its shape and the high electric current density inside it.

The strong magnetic field and its gradients in low-lying loops result in fast reconnection in the impulsive flares, leading to large energy release rate. At the same time, the total energy released is relatively small because of a smaller volume occupied by the flare. The strong electric field, necessarily arising during the reconnection process, produces beams of accelerated electrons. They, in turn, efficiently produce X-ray and gamma-emission in the dense chromospheric plasma. Protons can also be accelerated by the electric field. They move into the dense plasma layers and generate nuclear gamma-lines in so-called gamma-ray impulsive flares (see the classification by Bai and Sturrock, 1989). The protons themselves, however, are trapped by the strong magnetic field (at least a few hundred Gauss) and hence are not able to leave the solar atmosphere. They cannot enter interplanetary space where interaction of a new, relatively weak magnetic flux with a strong preexisting one (the so-called emerging flux model, Heyvaerts *et al.,* 1977). No visible restructuring of magnetic field is expected to occur in the course of the flare.

The physical picture is different in gradual flares, in which relatively weak magnetic fields are slowly reconnecting, whereas a larger flare volume allows for a larger total energy output. Particles are believed to be accelerated at the fronts of shock waves, which are an inevitable consequence of the interjection of large flares with the solar atmosphere. Because the shock wave mechanism gives preference to protons, whereas the electric field is relatively weak, the efficiency of proton acceleration is higher than that of electrons. The protons freely escape into the interplanetary space by moving along the open magnetic field lines. This is the explanation of the high proton/gamma-ray ratio in flares of this type. As far as the flare trigger is concerned, magnetic reconnection is initiated by the erupting prominence that rises in such manner that magnetic field lines become stretched or even open. Reconnection is necessary in order to restore the field configuration.

A natural conclusion that can be drawn from the above data is that particle acceleration in impulsive flares occurs in the region of primary energy release, possibly in the vicinity of the reconnecting current sheet. On the other hand, the acceleration process during gradual flares takes place at the fronts of coronal or interplanetary shock waves.

Returning to the preferential acceleration of ^{3}He ions, the existing observational data clearly indicate that it occurs during the impulsive flares. Virtually all solar ^{3}He-rich events are associated with impulsive 2 to 100 keV electron events, though many electron events are not accompanied by detectable ^{3}He increases (Reames *et al.,* 1985). ^{3}He-rich flares exhibit fast temporal behavior; ^{3}He particles stream along the magnetic field lines, just as the accelerated electrons do.

Another evidence for ^{3}He acceleration occurring in impulsive flares is provided by the dependence of the ^{3}He/^{4}He ratio upon the proton flux I_p (Kocharov and Kocharov, 1984). Analysis of observational data shows that the highest ^{3}He enrichment takes place in events with low proton fluxes:

$$\left(\frac{^3\mathrm{He}}{^4\mathrm{He}}\right)_{\max} \sim [\mathrm{I}_{\mathrm{p,max}}(\approx 10\mathrm{MeV})]^{-0.4}. \qquad (1)$$

Since small proton fluxes are characteristic of impulsive flares, one infers that the ^{3}He enrichment is the highest in impulsive flares. ^{3}He-rich events can also be identified with radio and X-ray emission generated by accelerated electrons in impulsive flares.

Conditions for occurrence of ^{3}He-rich events can be further clarified by considering the so-called high-Z" events —enrichments of the solar particle flux in heavy ions such as 0, Si, Fe. The relationship between the heavy-ion enrichment does not correlate with that of ^{3}He. It seems that ^{3}He-rich flares are also heavy-ion rich, but not *vice versa*. The heavy-ion enrichments appear to be independent of energy or particle flux, suggesting that the enrichments exist in the coronal material before the particle acceleration to MeV energies takes place. Thus the ^{3}He enrichment process operates at coronal sites that are enriched in heavy ions due to other reasons, but the process itself does not preferentially heat the heavy ions (Mason *et al.,* 1986). Furthermore, the measurements of mean ion charges in ^{3}He events showed that the ions are highly ionized: the average mean charge of Si was found to be close to 14 (implying fully ionized Si) and that of Fe 20.5 $\pm$ 1.2 (Luhn *et al.*, 1987). The high degree of ionization implies that ^{3}He acceleration occurs close to the coronal sites that are heated up to 2 • 10^7 K prior to or during the acceleration.

Therefore, theoretical models attempting to explain the unusually high ^{3}He/^{4}He ratios observed during these solar flares should take the following facts into account: (1) Preferential acceleration occurs in impulsive flares, characterized by strong electric fields in the reconnection region. (2) Magnetic field at the acceleration site is a few hundred Gauss or higher. (3) The acceleration mechanism can be related to electron beams generated during the flare. (4) Coronall plasma enrichments by heavy ions appear to be a prerequisite for the ^{3}He events. (5) The preferential ^{3}He acceleration occurs in the hot coronal plasma with a temperature possibly approaching 10^7 K. The following section describes some of the models suggested to explain ^{3}He-rich events.

3. Theoretical models

Let us start by mentioning some of the older models, which were generally discarded by now. They were reviewed, e.g., by Kocharov and Kocharov (1984).

According to early models, ^{3}He is produced by nuclear reactions during solar flares, in particular by spoliation reactions. Though spallation is the principal mechanism for ^{3}He production in galactic cosmic rays, it is unlikely to work during the solar flares. Nuclear reactions would result in the production of deuterium and tritium along with ^{3}He, which are not observed. Essentially, the spallation theories required the deuterium and tritium production to be suppressed. That led, however, to extreme requirements on the temperature and density in the flare region. Moreover, no explanation was given for enhancements in heavier elements that may accompany ^{3}He-rich flares.

Another class of models treats particle interaction with Langmuir and ion-acoustic turbulence, which can be described by a diffusion equation in momentum space for the particle distribution function $f = f(\mathrm{p},t)$:

$$\frac{\partial f}{\partial t}=\frac{\partial}{\partial p_i}D_{ij}\frac{\partial}{\partial p_j}f. \tag{2}$$

The idea behind the turbulent heating mechanism was the following. The diffusion coefficient D_{ij} depends on the particle charge and the mass numbers Q and A in such a way that $^3He^{+2}$ and some of the heavy ions diffuse faster in momentum space and hence gain energy preferentially in comparison with ^{4}He and hydrogen. The model ran into difficulty because it required the electron temperature to be below $5\bullet10^4$ K in the acceleration region, i.e. 2 orders of magnitude lower than observed. It was also necessary to invoke a second accelerating mechanism in order for the particles to gain the energy of a few MeV in a few seconds. It does not seem to be natural that the second (non-discriminating) mechanism should act in perfect accord with the turbulent heating, giving rise to the large number of ^{3}He events. From the theoretical viewpoint, Weatherall (1984) re-derived the expressions for the diffusion coefficient D_{ij} (for both Langmuir and ion-acoustic waves) and showed that the relations used before did not contain the proper dependence on ion charge Q. (Note, for clarity, Q is not necessarily equal to the ion nuclear charge Z.) This casted strong doubt upon the turbulent heating mechanism.

An ingenious model for ^{3}He and heavy-ion enrichment was suggested by Winglee (1989). The model makes use of the fact that plasma heating during the impulsive flares leads to "chromospheric evaporation" —motion of plasma outward, into the corona. Initially, electrons move much faster than ions. This results in the establishment of an ambipolar electric field and corresponding potential difference ϕ, which are necessary to maintain electric charge and current neutrality. The resulting field accelerates the ions to velocities

$$v_i=\sqrt{2\frac{q_i}{m_i}}\ \sqrt{Q/A} \tag{3}$$

Thus a differential motion between the various ion species, moving along the magnetic field lines, is established. This kind of flow, however, is unstable to the ion multi-stream instability. Numerical simulations showed that the instability can lead to energy transfer to ^{3}He and heavy ions. Unfortunately, this model is difficult to reconcile with the observations showing the absence of correlation between the chromospheric evaporation and ^{3}He-rich events (Reames *et al.*, 1994).

The model that seems to be the most promising today is that of ^{3}He acceleration by ion cyclotron waves which are excited in a narrow frequency range by unstable electron beams at the Landau resonance. As distinct from the earlier models, it is not the dependence upon Z and A, but rather the condition for the resonant wave-particle interaction, that is crucial for the energy increase rate. In other words, for a particle of species i to interact strongly with a wave, it must satisfy the linear resonance condition:

$$\omega - k_{||} v_{||} = n\Omega_i, \qquad (4)$$

where ω is the wave frequency, $k_{||}$ is the component of the wave vector parallel to the external magnetic field B, $v_{||}$ is the parallel particle velocity, $\Omega_i = QeB/(Am_pc) = Q\Omega_H/A$ is the particle gyrofrequency, n is an integer number. The resonant interaction is most effective for $n = 1$.

In a pure hydrogen plasma, ion-cyclotron waves occur only in a narrow frequency band just above the hydrogen gyrofrequency Ω_H. However, in the presence of a considerable amount of $^4He^{+2}$, the waves are also excited in the frequency range between the so-called two-ion resonance frequency w_{2Ir} and the hydrogen gyrofrequency Ω_H (for details see Smith and Brice, 1964). The two-ion resonance frequency is defined by the formula

$$\Omega_{2Ir} = \frac{1}{2}\Omega_H \sqrt{\frac{1+2n_{He}/n_H}{1+n_{He}/2n_H}} \approx \frac{1}{2}\Omega_H\left(1+\frac{3}{4}n_{He}/n_H\right). \qquad (5)$$

The two-ion resonance appears only for a sufficiently large ^4He concentration:

$$n_{He} > \frac{Q}{A}\frac{B^2}{4\pi m_p c^2} \approx 2 \bullet 10^5\,\mathrm{cm}^{-3}, \qquad (6)$$

where the magnetic field magnitude of $B = 100G$ is assumed. This condition is certainly satisfied in the solar atmosphere. The ^3He isotope, with the Q/A ratio of 2/3, is the only ion under coronal conditions whose gyrofrequency lies between ω_{2Ir} and Ω_H; thus, only this ion can be preferentially accelerated by resonating with the waves. Other ions, such as ^4He and H, are not resonant and hence can be accelerated only nonresonantly, i.e. on a much slower time scale.

Fisk (1978) was the first to use this idea to explain ^3He-rich events. Fisk considered the electrostatic ion-cyclotron waves and derived a formula for the ion heating rate dT_i/dt in terms of the properties of the wave spectrum. Numerical integration showed that ^3He ions can indeed be heated much faster than ^4He.

Though being theoretically quite attractive, Fisk's model encountered a number of difficulties. First, it required the ^4He density in the corona to be unreasonably large (0.2 of the hydrogen density) in order to explain the generation of the electrostatic ion-cyclotron waves. Second, restriction of the theory to the case of purely electrostatic waves was not justified in the presence of electron beams and magnetic field associated with them. Third, the wave-particle interaction was not efficient enough to provide the necessary acceleration to MeV energies; hence the second phase of particle acceleration was still required.

Attempts to improve Fisk's model did not seem successful until the appearance of the paper by Temerin and Roth (1992), who expanded the treatment by considering the electromagnetic ion-cyclotron waves generated by electron beams in a plasma with realistic concentration of ^4He (cf. Temerin and Lysak, 1984). It turned out that these waves, propagating almost perpendicular to the magnetic field, can acquire a substantial fraction (a few percent) of the electron beam energy and can efficiently accelerate ^3He in a one-stage process up to several MeV.

The process of kinetic energy gain by ions interacting with the waves can be explained as follows. Consider a charged particle moving in the plane perpendicular to a constant magnetic field **B** = (0, 0, B) under the action of the wave electric field **E** = ($E(x,t)$,0,0). The equation of motion is easily reduced to that of the perturbed harmonic oscillatory for the x coordinate:

$$\ddot{x}+\omega_i^2 x=\frac{q_i}{m_i}E(x,t), \qquad (7)$$

$$\dot{y}=-\omega_i x. \qquad (8)$$

Now a solution can be found in terms of the Fourier transport of *E* (see, e.g., Landau and Lifshitz, 1960, ⁄22), allowing one to obtain an expression for the average "transverse" kinetic energy $w = m(\dot{x}^2+\dot{y}^2)/2$:

$$\langle w(t)\rangle=\frac{q_i^2}{2m_i}\int_0^t dt'\int_0^t dt''\exp[i\omega_i(t''-t')]\langle E(x',t')E(x',t')E(x'',t'')\rangle. \qquad (9)$$

Because the integrand $\langle E(x',t')E(x'',t'')\rangle$ is just the wave correlation function *R(x" —x', t" —t')*, the properties of accelerated particles are seen to be determined by the properties of the wave spectrum.

The energy gain rate can also be estimated by using the quasilinear plasma theory (e.g., Davidson, 1972). The result in the limit of large parallel phase velocities, used by Temerin and Roth (1992), is as follows:

$$\left\langle\frac{dw}{dt}\right\rangle=32\omega^2\frac{Q^2}{A}\frac{e^2}{m_p}\int dk\, W(k,n\Omega_i)\sum_n\frac{n^2 J_n^2(k\rho)}{(k\rho)^2}. \qquad (10)$$

Here *k* is the wave vector, ρ is the particle gyroradius, J_n are the Bessel functions, and *W* is the wave energy density, which is expressed in terms of the Fourier transform of the wave correlation function *S(k,ω)* as *W(k,ω) = S(k,ω)/*8π. Temerin and Roth (1992) used formula (10) to find the ^{3}He energy gain rate for the $n = 1$ resonance. The result was that acceleration to a few MeV can occur in a time of 0.1 —1 s, closely corresponding to $W_{turb} \approx 10^{-5}$ erg/cm^3. This takes place for the rms wave electric field equal to 5 V/cm, a value confirmed by direct measurements of electric fields in the solar atmosphere (for a review, see Foukal and Hinata, 1991).

Miller and Vinas (1993) recently developed the model further, by solving the hot plasma dispersion relation for the wave number, frequency and growth rate of the unstable ion-cyclotron waves, and also by taking into account other unstable modes. The results of Temerin and Roth (1992) were essentially confirmed.

The next logical step in construction of the detailed model for ^{3}He enrichments is the determination of the particle spectrum (Miller *et al.*, 1993). This can be done by solving the Fokker-Planck equation for the distribution function *f = f(w,t)*:

$$\frac{\partial f}{\partial t}=\frac{\partial}{\partial w}D(w)\frac{\partial f}{\partial w} \qquad (11)$$

(here the nonrelativistic energies are assumed). Calculations made so far by Miller *et al.* (1993) demonstrated the formation of an extremely flat distribution with a steepening at an energy of a few MeV. Much work remains to be done in this direction, though, if the peculiarities of observed spectra are to be interpreted.

4. Acceleration of ^{3}He in current sheets and remaining problems

As was discussed above, there exist causal relationships among various solar flare manifestations, such as electron beam generation, strong heating of the coronal plasma, turbulence generation and preferential ^{3}He and heavy-ion acceleration. According to present views, these manifestations are interrelated not only causally, but also as being part of a single physical phenomena — magnetic reconnection in the current sheet (Somov, 1992, 1994).

High-temperature turbulent current sheets, which are thought to be responsible for energy release during the main phase of flares, are sufficiently hot to explain the high ionization of heavy ions. Theoretical models predict the temperature to be $\sim 2 \bullet 10^7$ K prior to, or during, the ^{3}He acceleration.

The fact that the ^{3}He enrichment process is not responsible for the heavy-ion enrichment (Mason *et al.*, 1986) finds a natural explanation in the model of Mullan and Levine (1981), according to which the heavy ions are preaccelerated by converging plasma flows before entering the current sheet. Once inside the sheet, the ions are accelerated by the electric field, associated with reconnection, and become highly ionized.

The same electric field accelerates electrons to velocities exceeding the threshold for current instabilities. An inevitable result of the instabilities is the development of turbulence in the current sheet. The ion-cyclotron instability can be excited more easily than the ion-acoustic instability. This is especially true in small flares. Thus the ion-cyclotron turbulence energy can be as high as 10^{-4} — 10^{-3} of the thermal plasma energy, quite enough toassure the preferential ^{3}He acceleration according to the above discussed models. The only essential assumption is that ^{3}He is in resonance with the waves, whereas ^{4}He is not.

Therefore, there are good reasons to believe that the preferential ^{3}He acceleration in some of impulsive solar flares is a consequence of resonant interaction of the ions with electromagnetic ion-cyclotron waves, resulting from the current instability in reconnecting current sheets where the flare energy is released. A unified theory for energy release and particle acceleration in solar flares might explain the preferential ^{3}He acceleration as a three-step process: (1) formation of current sheets and generation of electron beams during the main phase of the flare; (2) excitation of electromagnetic ion-cyclotron waves by the beams unstable at the Landau resonance; (3) ^{3}He acceleration through the gyroresonant interaction with the waves.

Many questions concerning ^{3}He-rich events still remain to be answered. It is not clear whether the instability is efficient enough to provide the turbulence energy, necessary to accelerate as many 10^{31} ^{3}He ions up to MeV energies. It has not yet been demonstrated that all this energy goes to accelerate the ions at the gyroresonance, and is not lost in some other process. The details of heavy-ion acceleration are not understood. It would be also of considerable importance to explain not only a typical energy of particles, but also the formation of the ^{3}He energy spectrum. Numerical calculations of Miller *et al.* (1993) do not conform with observations that show a spectral steepening or break at energies of about 10 MeV, which leads to an increase in the effective spectral index from ~ 2 to ~ 3.5. The above-mentioned calculations predict the spectrum to be flat below the break and very steep above it. The position of the break itself is essentially a free parameter of the model. More careful study of processes of energy gain and loss is necessary to eliminate this discrepancy.

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