The Origin and Acceleration of ^{3}He and Heavy Ions in the 2000 July 14 Event *

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Abstract According to the evolutionary properties of the flare, halo coronal mass ejection (CME), enrichments of ^{3}He ions in the energy range of 3.5–26 MeV nucl^{-1} and Ne, Mg, Si and Fe ions in the energy range of 8.5–15 MeV nucl^{-1}, we argue that the ^{3}He and heavy ions originate in the middle corona ($\sim$0.1–1 $R_\odot$) with well-connected open field lines to the Earth, where the magnetic reconnection leads to acceleration of the electrons and the production of type-Ⅲ burst during the decay phase of the soft X-ray emission. The acceleration of ^{3}He and heavy ions may have been accomplished in two stages: first H-He ion-ion hybrid waves may be easily excited by the energetic electron beams produced in the middle corona, and these waves are preferentially absorbed by ^{3}He and heavy ions due to their frequency being near the fundamental gyro frequency of the ^{3}He ions and harmonic gyro frequency of Ne, Mg, Si and Fe ions. These preheated ions escape into interplanetary space along the open field lines and may be further accelerated to tens of MeV nucl^{-1} by CME-driven shock. The theoretical calculations show that the ^{3}He and heavy ions may be accelerated to the energy of $\sim$ MeV nucl^{-1} by the ion-ion hybrid waves and be further accelerated to the energy of $\sim$ 100 MeV nucl^{-1} by the shock wave: these are basically consistent with the observations.

Key words: Sun: abundances — waves — shock wave — acceleration of particles

1 INTRODUCTION

Enrichment of ^{3}He and heavy ions (i.e., Ne, Mg, Si and Fe), characteristic of impulsive flares, have been studied for more than three decades. It is found that they are generally associated with nonthermal energetic electron-rich events (Reames et al. 1988; Reames 1999 and references therein; Ho et al. 2001; Wang et al. 2006) and are related to the peculiar ratio of charge to mass (Mazur et al. 1996; Reames 1999). Although the abundance of ^{3}He ions is not correlated with the abundance of heavy ions, such as Ne, Mg and Fe, they all have a similar power-law distribution in the energy region of 20 keV–10 MeV nucl^{-1}, which probably means that the ^{3}He and heavy ions preheated in different ways may be finally accelerated by the same mechanism (Reames et al. 1994; Mason et al. 1994; Reames et al. 1997; Mason et al. 2000; Torsti et al. 2002).

In order to explain the above observations, many theoretical resonant-absorptive models in one or two stages have been proposed. The main idea of one stage is that plasma waves, excited by current instability or energetic electron beams, are resonantly absorbed by ^{3}He and heavy ions with the peculiar ratio of charge to mass (Temerin & Roth 1992; Miller & Viñas 1993; Roth & Temerin 1997; Paesold et al. 2003). The two-stage models are suggested when the similar distribution of the energetic ^{3}He and heavy ions is considered:

^{3}He and the heavy ions preheated by resonant waves are further accelerated to high energies by stochastic Fermi acceleration and turbulent Alfvén wave (Fisk 1978; Zhang 1995, 1999; Desai et al. 2001; Wang 2001; Wu et al. 2002 and references therein).

The 2000 July 14 event was a mixed one, including the impulsive flare and long duration particle fluxes with enrichments of ^{3}He and heavy ions (Mäkelä & Torsi 2001). Although the flaring active region is near the disk center and has no access to Earth-directed open field lines, there are rich type-III bursts in the middle corona as a signature of the energetic electrons (Klein et al. 2001). So it provides us a good example to study the origin and acceleration of ^{3}He ions in the energy region of 3.5–26 MeV nucl^{-1} recorded by the Chinese FY-2 satellite (Zhu et al. 2004). In this paper, we first review the multi-wavelength observations including the impulsive flare, CME-driven shock waves and the flux of ^{3}He with the unusually high energy range from 3.5 to 26 MeV nucl^{-1} on 2000 July 14 (Section 2), then, assuming that only a few energetic electrons are injected into the H, ^{4}He and electron plasma, we study the instabilities excited by them for reasonable parameter values (Section 3) and the two-stage acceleration of ^{3}He ions (Section 4). Finally, a discussion is in Section 5.

2 OBSERVATION OF THE ^{3}HE-RICH EVENT OF 2000 JULY 14

Shortly after 10:00 UT on 2000 July 14, a filament erupted and a class X5.7/3B flare occurred in AR9077 near the disk center at $22° N$ & $7° W$. In association with this flare, a bright, fast, halo coronal mass ejection (CME), a rich variety of particle signatures at 1 AU and decimetric to hectometer radio emissions in the interplanetary space, were observed and extensively studied (Manoharan et al. 2001; Klein et al. 2001; Reiner et al. 2001).

Figure 1 shows the time curves of the ^{3}He and ^{4}He ions fluxes at Earth recorded by Chinese FY-2 satellite (Lin et al. 2000; Zhu et al. 2004), with a time resolution of 16.4 s. FY 2 circles the Earth in a geosynchronous orbit like the Goes satellite, but at 180 degree in longitude apart. The flux-time profile of energetic protons with energy above 10 MeV from FY-2 was checked with data from Goes, and was found to have a similar evolution. The average flux of >10 MeV protons on 2000 July 15 was about 1.6×10^4 cm^{-2} s^{-1} from FY-2, was saturated in Goes (Wang et al., internal report).

It can be seen from Figure 1 that: (1) the counts of ^{3}He reached a first maximum at about 18:00 UT on July 14 and a second maximum at about 22:00–23:30 UT on July 15; (2) the ratio of ^{3}He/^{4}He is about 0.1 in the energy range of 3.5–26 MeV nucl^{-1}, much larger than the coronal value (about 0.0005). Hence, it is a ^{3}He-rich event. In addition, Mäkelä & Torsi (2001) analyzed the energetic particle fluxes of Ne, Mg, Si and Fe ions in the energy region of 8.5–15 MeV nucl^{-1} measured by the Energetic and Relativistic Nucleon and Electron (EREN) experiment. The time profile of these ions is similar to ^{3}He profile (Fig.1) and the flux also approaches the first maximum at $\sim$17–18 UT July 14 (fig. 2 of Mäkelä & Torsi 2001).

In order to study the ^{3}He acceleration process, we should first find out the time when the energetic ^{3}He ions were injected into interplanetary space. If we assume that they travelled through 1.3 AU along the spiral field lines at a speed v with no scattering, then the excess travel time of the ^{3}He ions in the energy range of 3.5–26 MeV nucl^{-1} with respect to the photons at 1 AU is about 38–117 min. The counts of energetic ^{3}He ions (Fig.1) started to rise at about 13:17 UT (for a 3σ excess above background). Therefore, the release time near Sun was about 11:20–12:37 UT. According to Yohkoh hard X-ray observation (Masuda et al. 2001), the hard X-ray emission on 2000 July 14 started to increase at about 10:12 UT, peaked at about 10:27 UT and ended at about 10:30 UT. So, considering the time profile of ^{3}He, the poor earthward magnetic connection of the flaring active region, and especially the duration of the flux, we may infer that the energetic ^{3}He ions did not result from the impulsive flare.

Klein et al. (2001), after analyzing the multi wavelength observations, especially the image at decimetric and metric radio waves, argued that the suprathermal electrons and relativistic protons that escaped to the Earth were accelerated in association with the restructuring of magnetic field in the western hemisphere at $(0.1–1) R_\odot$ above the photosphere, and in the same time, the hectometric type -II burst was excited by the reconfiguration processes in the middle corona. In addition, according to the frequency-drift properties of type-II radio emissions in the frequency range from 1 to 14 MHz observed by the WAVES experiment on board the Wind spacecraft and their relationship with the halo-CME, the coronal and interplanetary shocks may all be driven by the fast CME (Tang & Dai 2003). The velocity of shock was about 1700 km s^{-1} near Sun and 1100 km s^{-1} near the Earth. Using the inferred height-time plots of shock (fig. 4 of Reiner et al.
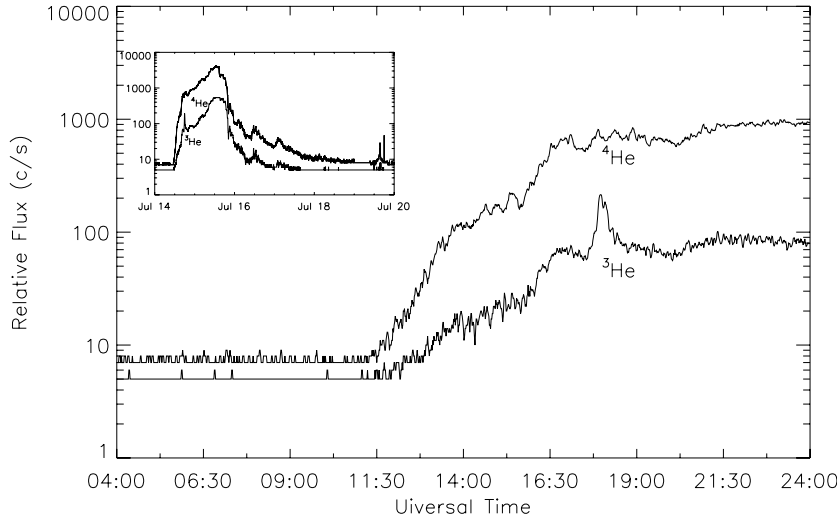
Fig. 1 Flux of ^{3}He and ^{4}He in the energy range 3.5–26 MeV nucl^{-1}. The data are from FY-2 satellite.

2001), we find that, during 10:30–12:40 UT, the shock rose from 5 $R_\odot$ to above 30 $R_\odot$. So, a plausible explanation for the energetic ^{3}He ions is that they were preheated in the middle corona through the waves excited by rich energetic electrons, and then further accelerated by CME-driven interplanetary shock. In the following, assuming that only a few electron beams interact with the ambient H, ^{4}He and electron plasma, we examine which waves will be excited and how the ^{3}He ions are selectively heated, then, whether these preheated ^{3}He ions could be further accelerated to tens of MeV by diffusive shock wave driven by CME.

3 PROPERTIES OF LOW FREQUENCY WAVE EXCITED BY ENERGETIC ELECTRON BEAMS

Wang (2001) first suggested that H-He ion-ion hybrid wave may be excited and used to explain the ^{3}He abundance in the low corona on the cold plasma approximation. Now, we will extend their work to the middle corona and numerically solve the dispersion relation including the temperature effect.

When the energetic electron beams run through the plasma with H, ^{4}He and electrons along the magnetic field lines, low-frequency electromagnetic waves may be excited. The dispersion equation for the resonant branch can be expressed as

$$A = \varepsilon_{11} \sin^2 \theta + 2\varepsilon_{13} \sin \theta \cos \theta + \varepsilon_{33} \cos^2 \theta, \tag{1}$$

where ε_{ij} are the dielectric tensor components, θ is the pinch angle between the magnetic field and the wave vector $\boldsymbol{k}$. In the beam-plasma system, $\varepsilon_{ij} = \varepsilon_{ij}^p + \varepsilon_{ij}^b$, where ε_{ij}^p are the dielectric tensor components of the hot multi-ion plasma and ε_{ij}^b are the dielectric tensor components of the monoenergetic electron beams.

Considering that ^{3}He-enrichment events are usually associated with rich energetic electron beams, we assume that their number density n_b is much less than the ambient plasma density n_e: $n_b \ll n_e$. So the ambient plasma distribution is approximately given by the Maxwellian and the current along the magnetic field is nearly zero.

For low frequency waves ($\omega < \Omega_H$, where Ω_H is the hydrogen cyclotron frequency), we have

$$|\omega - n\Omega_\alpha|/(\sqrt{2}k_\parallel v_{T\alpha}) \gg 1, \Omega_e/k_\parallel v_{Te} \gg 1,$$

and only the $n = 0$ and $n = 1$ terms for H, ^{4}He and electrons in equation 5.2.2.4 of Akhiezer et al. (1975) are retained, then the dielectric tensor components may be expressed with $\varepsilon_{13}^p \approx 0$, as follows:

$$\varepsilon_{11}^p \approx -\sum_\alpha \frac{\omega_{p\alpha}^2}{\omega^2} \frac{e^{-a_\alpha}}{a_\alpha} \frac{2\omega^2}{\omega^2 - \Omega_\alpha^2} I_1(a_\alpha), \tag{2}$$

$$\varepsilon_{33}^p \approx -\frac{\omega_{pe}^2}{\omega^2}e^{-a_e}I_0(a_e), \qquad (3)$$

where $\omega_{p\alpha}$ and Ω_α are respectively the plasma and cyclotron frequencies of particle α, representing either H ion, He ion or electron. The functions $I_0(a_\alpha)$ and $I_1(a_\alpha)$ are respectively the zeroth and first order modified Bessel functions with $\omega_{p\alpha} = (4\pi(Ze)^2n_\alpha/m_\alpha)^{1/2}$, $\Omega_\alpha = ZeB/m_\alpha c$ and $a_\alpha = k_\perp^2 v_{T\alpha}^2/\Omega_\alpha^2$. The symbols $k_\parallel$ and $k_\perp$ are respectively the parallel and perpendicular component of the wavenumber to the magnetic field.

As $n_b \ll n_e$, the electron beam terms can be ignored except the term of Cherenkov resonance $\omega \approx k_\parallel u$. So, the dielectric tensor of the monoenergetic electron beams ε_{ij}^b may be simplified to $\varepsilon_{11}^b \approx 0, \varepsilon_{13}^b \approx 0$ and

$$\varepsilon_{33}^b \approx -\frac{\omega_{pb}^2(1-\beta^2)^{3/2}}{(\omega - k_\parallel u)^2}, \qquad (4)$$

where $\omega_{pb} = (4\pi e^2 n_b/m_e)^{1/2}$ is the plasma frequency of the electron beams, $\beta = u/c$, and c, n_b, u are, respectively, the light velocity, electron beam density and velocity (Akhiezer et al. 1975; Wang 2001).

In order to study under what conditions the H-^{4}He ion-ion hybrid waves are easily excited, we substitute Equations (2)–(4) into Equation (1) and solve it with typical values in the complex frequency plane with Mathematica 4.0 program for different propagation angles θ, different injection energy of energetic electron beams, different ratios of $n_{^4He}/n_H$ and different density of energetic electron beams. The results are shown in Figure 2, where the ambient plasma density is 10^7 cm^{-3}, temperature 10^6 K, and the magnetic field 10 Gauss. In these figures, the normalized frequency ω_r/Ω_H is marked by a solid line, and the normalized growth rate γ/Ω_H is drawn with a dashed line with an amplified factor of 10 times (5 times in Figure 2(d)).

From Figure 2(a), we can see that unstable H-^{4}He ion-ion hybrid waves may be excited, the growth rate γ_m and the frequency domain depend on the propagation angle. For θ equals 88 $^\circ$, 89°, 89.5°, the maximum frequency ω_{rm} equals $0.84\,\Omega_H$, $0.688\,\Omega_H$, $0.60\,\Omega_H$, and the maximum growth rate γ_m, $0.039\,\Omega_H$, $0.033\,\Omega_H$, $0.019\,\Omega_H$.

In principle, the power law distribution of nonthermal electrons other than the single energy beams should be considered in solving the equations. From Figures 2(b), we can see that the energy of the energetic electron beams has little effect on the unstable waves and monoenergetic electron beams is a good approximation. In Figure 2(c), the ratio of the $n_{^4He}/n_H$ has also little influence on the dispersion relation. From Figure 2(d) when the density of electron beams increases from 10^4 to 10^6 cm^{-3}, the growth rate increases about 5 times, while the frequency changes little. In addition, when the ambient plasma density varies from 10^5 to 10^7 cm^{-3} and the magnetic field strength varies from 1 to 10 Gs, the dispersion curves are similar to Figure 2(a).

In summary, the ion-ion hybrid wave may be easily excited by a few energetic electron beams ($n_b = 0.0001 \sim 0.01 n_e$) near the ^{3}He fundamental frequency on a time scale of $0.01\,\Omega_H^{-1} = 3 \times 10^{-3} s$ with plausible parameter values. The growth rate depends on the propagation angle and the density ratio of the electron beams to the ambient electrons, while the ratio $n_{^4He}/n_H$ and the energetic electron energy from 5 keV to 30 keV have little influence on the growth rate.

4 TWO-STAGE ACCELERATION OF ^{3}HE AND HEAVY IONS

Figures 2(b) shows that, when we take $n_b=10^4$ cm^{-3}, E_b=5–30 keV, $n_{^4He}/n_H$=0.125 and $\theta = 89^\circ$, the frequency of unstable waves is in the range 0.51–0.72Ω_H. Considering the ion cyclotron frequency Ω_α=Z/A Ω_H, only the fundamental frequency of ^{3}He ions located in this region is near the maximum growth rate. So, ^{3}He ions may easily resonate with the waves and absorb the waves' energy. For the other heavy ions in the corona (list in Table 1, Nakazawa et al. 1996), ^{56}Fe^{+12-16} can have the third harmonic resonance with H-He ion-ion hybrid waves, ^{20}Ne^{+8}, ^{24}Mg^{+10} and ^{28}Si^{+12} can have the second harmonic resonance with H-He ion-ion hybrid waves when these waves propagate in a decreasing magnetic field (Wang 2002) or when the propagation angle is near 88° (Figure 2(a)), hence, these heavy ions are enriched. While ^{4}He^{+2}, ^{12}C^{+6} and ^{16}O^{+8} are almost fully stripped in the corona, they may have no resonance and no enrichment. All of these are consistent with the observations (Mäkelä & Torsi 2001).
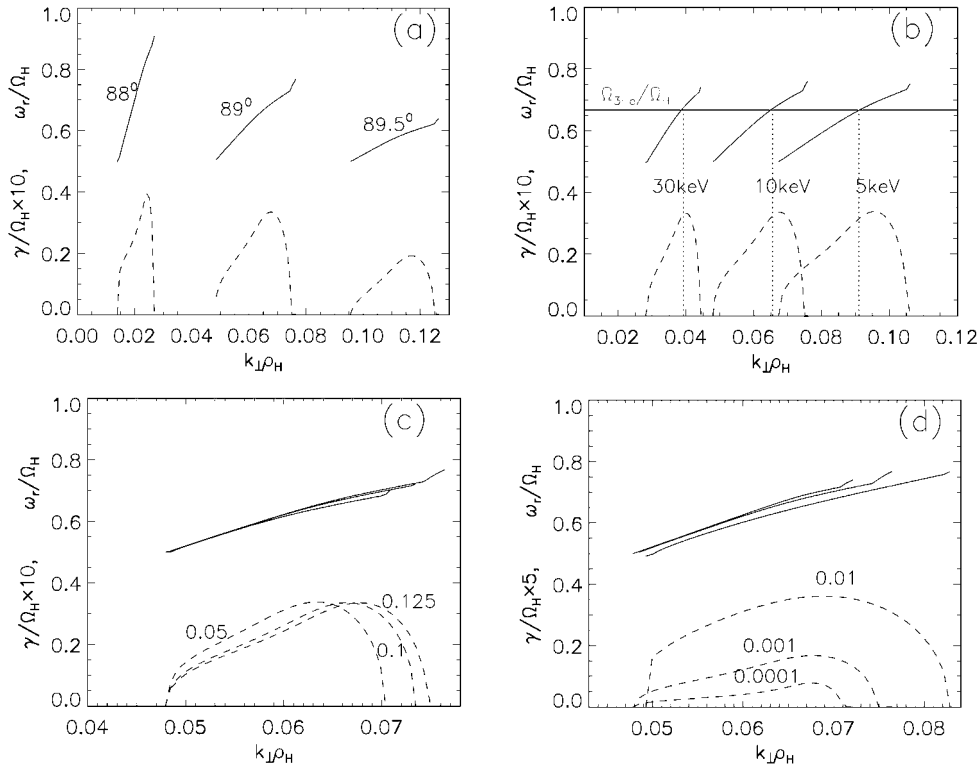
Fig. 2 Frequency ω_r (Solid line) and the growth rate (dashed line) of the H-He ion-ion hybrid wave as function of perpendicular wavenumber for different parameters. (a) Three different propagation angles with $E_b = 10\,\mathrm{keV}$, $n_{^4\mathrm{He}}/n_\mathrm{H} = 0.125$ and $n_b = 10^5$ cm^{-3}; (b) Three different injecting energies of E_b; (c) Three different ratios of $n_{^4\mathrm{He}}/n_\mathrm{H}$; (d) Three different ratios of n_b/n_e, the other parameters in Fig. 2(b–d) are the same as those in Fig. 2(a), with propagation angle $89°$.

Table 1   Charge to Mass Ratio of Some Heavy Ions in the Corona of Temperature 2×10^7 K (Nakazawa et al. 1996)

ion	^{20}Ne^{+8}	^{24}Mg^{+10}	^{28}Si^{+12}	^{56}Fe^{+12-16}	^{4}He^{+2}	^{12}C^{+6}	^{16}O^{+8}
z/A	0.4	0.416	0.428	0.214–0.286	0.5	0.5	0.5

Furthermore, test particle simulation was widely used to estimate the energy of ^{3}He and heavy ions that are accelerated by electromagnetic waves (Miller & Vinas 1993; Temerin & Roth 1992; Roth & Temerin 1997; Paesold et al. 2003). The results have shown that these particles may reach $\sim$MeV energy.

Due to the much longer duration of ^{3}He and heavy ions as compared with that of the flare, their similar shapes and the relation to propagation of shock wave (figs. 1 and 2 of Mäkelä & Torsi 2001), we argue that these preheated ions will be further accelerated to tens of MeV nucl $^{-1}$ by Sun-Earthward shocks driven by halo-CMEs after they have escaped into interplanetary space.

After analysing several SEP events, Kahler (1994) pointed out that the peaks of energetic particle injections occurs when the CME rises from 5 to $15\,R_\odot$. The above analysis shows that the onset of the energetic ^{3}He ion injections (11:20–12:37 UT) occurred when the shock wave rose from 5–10 to $30\,R_\odot$ (Reiner et al. 2001). The shock velocity u_{sh} inferred from the drift velocity of type-II radio burst was about

1700 km s^{-1} near the Sun (Chertok et al. 2001). Therefore, the particles with velocities above u_{sh}, ie., with initial energies above $E_i > 0.5m/ZV_{\text{sh}}^2 = 15$ keV nucl^{-1}, may be further accelerated by the shock wave.

Ellison & Ramaty (1985) inferred that the shock acceleration time is:

$$\tau_a \approx 2 \times 10^{-4} \frac{f(E - E_i)_{\text{MeV}}}{Z^* B_{100}(u_{\text{sh}}(u_{\text{sh}} - v_{\text{A}}))_{1000}}, \tag{5}$$

where E_i and E are the initial and final energy in units of MeV, B is the magnetic field in units of 100 Gs, u_{sh}, v_{A} are respectively the shock and Alfvén velocity in units of 1000 km s^{-1} (in this paper, since the solar wind velocity V_1 is larger than v_{A} in the interplanetary, the latter is substituted by the solar wind velocity). From the interplanetary plasma and magnetic field parameters of the CME-driven shock disturbance observed at the Sun-Earth L1 point by PM/SOHO and MFI/Wind (fig. 8 of Manoharan et al. 2001), the magnetic field strength is about 50 nT. Assuming the magnetic field B varies as R^{-2} (Wang & Sheeley 1990), we may estimate that the value of B is about 1–0.1 Gauss at 5–15 $R_\odot$ and the average value is about 0.5 Gauss. Taking V_1=600 km s^{-1}, $\tau_a \approx E$ s for ^{3}He with $f = 100$. So, it requires 3×10^2 s to accelerate ^{3}He ions to about 100 MeV nucl^{-1}. As the shock travelled across 5–15 $R_\odot$ in about 4×10^3 s, the particles may be further accelerated. However, the acceleration efficiency of shock decreases very fast when the energy of particles is above tens of MeV (Ellison & Ramaty 1985; Klein & Trottet 2001 and references therein). So, Equation (5) may not be useful in describing the further acceleration.

In summary, due to the magnetic disturbance in the middle corona, the electrons accelerate and excite H-He ion-ion hybrid waves which are resonantly absorbed by ^{3}He ions through fundamental waves and heavy ions by harmonic waves. These pre-accelerated ions with $\sim$MeV energy go out along the open magnetic field, meet the shock wave and accelerate further to the order of 100 MeV.

5 DISCUSSION

The high energy ^{3}He-rich event on 2000 July 14 was so far one of a few events associated with a large two-ribbon flare and halo CME events (Torsti et al. 2002). After an analysis of the multiwavelength data, we showed that the ^{3}He and heavy ions are not from the flaring active region, but originate from the middle corona where the magnetic reconstruction accelerates the electrons, which then excite ion-ion hybrid waves and selectively preheat ^{3}He and heavy ions. After escaped into the corona, they were further accelerated to tens of MeV nucl^{-1} by shock wave driven by CME. So, they have similar time profiles. The theoretical calculations are basically consistent with the observations.

More recently, Wang et al. (2006) investigated the solar origin of 25 ^{3}He-rich particle events during 1997–2003, they found that the magnetic reconnection takes place near the open and closed field lines in these events, and in some events, there were no flares. As we know, the electrons may be accelerated to tens of keV by induced electric field during magnetic reconnection (Wu et al. 2005 and references therein), excite H-He ion-ion hybrid waves, then resonantly heated ^{3}He and heavy ions with peculiar ratio of mass to charge, and finally lead to enrichment of energetic ^{3}He and heavy ions. These enhanced particles escaped along the open field lines, and may be further accelerated by shock wave or cascading Alfvén waves with similar power-law distribution (Wu et al. 2002). In the future, more ^{3}He-rich events with multiwavelength data including the evolution of magnetic field, X-ray and microwave emissions near the solar surface, radio emissions in interplanetary and energetic particle spectrum near the Earth should be analyzed, for a better understanding of the physical nature of ^{3}He-rich particle events.

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