The role of large amplitude upstream low-frequency waves in the generation of superthermal ions at a quasi-parallel collisionless shock: Cluster Observations

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Abstract

The superthermal ions at a quasi-parallel collisionless shock are considered to be generated during the reformation of the shock. Recently, hybrid simulations of a quasi-parallel shock have shown that during the reformation of a quasi-parallel shock the large amplitude upstream low-frequency waves can trap the reflected ions at the shock front when they try to move upstream, and then these reflected ions can be accelerated several times to become superthermal ions. In this letter, with the Cluster observations of a quasi-parallel shock event, the relevance between the large-amplitude upstream low-frequency waves and the superthermal ions (about several keV) have been studied. The observations clearly show that the differential energy flux of superthermal ions in the upstream region is modulated by the upstream low-frequency waves, and the maxima of the differential energy flux are usually located between the peaks of these waves (including the shock front and the peak of the upstream wave just in front of the shock front). These superthermal ions are considered to be originating from the reflected ions at the shock front, and the modulation is caused due to the trapping of the reflected ions between the upstream waves or the upstream waves and the shock front when these reflected ions try to travel upstream. It verifies the results from hybrid simulations, where the upstream waves play an important role in the generation of superthermal ions in a quasi-parallel shock.
1. Introduction

Collisionless shocks are of great interests in space and astrophysical environments, because they can effectively convert bulk energy into thermal energy and accelerated particles in the shock transition region (Lee, 1983; Zank et al., 2000; Li et al., 2003; Lembège et al., 2004; Guo & Giacalone, 2013). According to $\theta_{Bn}$ (the angle between the shock normal and upstream magnetic field), shocks can be categorized into two types: quasi-perpendicular shocks ($\theta_{Bn} > 45^\circ$) and quasi-parallel shock ($\theta_{Bn} < 45^\circ$). These two types of shocks have quite different structures (Biskamp and Welter, 1972; Quest, 1988; Schwartz, 2006). The supercritical shocks can reflect a part of incoming ions back to the upstream. In a quasi-perpendicular shock, these reflected ions just gyrate in the magnetic field around the foot region and then directly return back to and then transmit the shock (e.g. Yang et al., 2009). However, in a quasi-parallel shock, the reflected ions can escape far upstream and excite low-frequency waves. As these waves grow to a sufficiently large amplitude, they can interact with the high-speed incoming plasma. Such a process makes the structures of the quasi-parallel shock very complicated (Gosling et al., 1982; Burgess et al., 2005; Lucek et al., 2008).

In the upstream region of a quasi-parallel shock, the energetic ions with energies from ten keV up to several hundred keV have been detected by many spacecraft (e.g. Trattner et al., 1994; Kis et al., 2004). Steady state diffusive shock acceleration theory is used to explain the high energy tail of these energetic ions associated with shocks (e.g. Axford et al., 1977; Scholer et al., 1985; Blandford and Ostriker, 1978). According to the diffusive shock acceleration theory, low-frequency waves upstream of a quasi-parallel shock can scatter the energetic ions in pitch angle, and these ions can then cross the shock back and forth many times, leading to spatial diffusion of these particles and acceleration at the shock. This process is very slow, but the particles can gain sufficiently high energy. However, such process only works efficiently for the non-thermal particles, which requires that there are plenty of superthermal particles as a source of seed particles. Therefore, some pre-acceleration
processes are needed to accelerate the thermal population to the superthermal population (Zank et al., 2001).

Previous simulations results have indicated that the generation of superthermal ions at a quasi-parallel shock is related to the reformation of this shock. The reformation is an inherent property of a quasi-parallel shock (e.g. Burgess et al., 1989). As the upstream waves convected back to the shock front by the upstream plasma, these waves grow to large amplitude. When the amplitude of the waves exceeds that of the shock, a new shock front is formed and the reformation process is finished. Such a reformation process of a quasi-parallel shock has also been confirmed by in-situ observation (Lefebvre et al., 2009). This reformation is a cyclic and periodical behavior of a quasi-parallel shock. With a one-dimensional (1-D) hybrid simulation, Scholer and Burgess (1992) pointed out that the generation of the superthermal particles, upstream wave, occurrence of reflected ions and the shock reformation cannot be considered separately but are closely interconnected. With hybrid simulations, Lyu and Kan (1990, 1993) concluded that the superthermal ions upstream of a quasi-parallel shock are predominately leakage ions from the downstream, which is regulated by the large amplitude waves in the shock transition region. In contrast, after performing large-scale 1-D hybrid simulations of quasi-parallel shocks, Scholer (1990) showed that most of the superthermal ions don’t come from the leakage of downstream ions. They found that the incident thermal ions can be reflected and trapped in the shock transition region, and then these ions can be accelerated to superthermal energies during the period of the trapping. Furthermore, Kucharek and Scholer (1991) found that the main acceleration mechanism from the thermal ions to the superthermal energies are the grad $B$ drift within the coplanarity plane and wave-particle scattering in the shock front. Recently, Su et al. (2012a) investigated the ion dynamic at a supercritical quasi-parallel shock and separated the upstream ions into three parts: the directly transmitted, downstream thermalized and superthermal ions. They found that the superthermal ions are the ions which are reflected at the beginning of a reformation cycle, and still in the upstream region of
the new shock front at the end of this reformation cycle. Su et al. (2012b) further found that the superthermal ions can stay in the region between the old and new shock fronts for a quite long time, and are accelerated every time they are reflected by the new shock front. This mechanism provides a possible way to generate the superthermal ions for the further diffusive acceleration process. Therefore, the generation of the superthermal ions at a quasi-parallel shock is closely related to the upstream low-frequency waves.

In this paper, by analyzing a quasi-parallel shock event with the observation of the Cluster Mission, we find that the superthermal ions (about several keV) in the upstream region are modulated by the large-amplitude low-frequency waves and the maxima of the flux of the superthermal ions are always located between the peaks of the waves or the shock front and the peak of the waves just in front of the shock front. We propose that the modulation of the superthermal ions by the low-frequency waves in the upstream region of the quasi-parallel shock can be the results of the trapping of the reflected ions in the upstream waves when these reflected ions go upstream. It implies that the superthermal ions are generated when the reflected ions are trapped by the upstream waves, and then get accelerated.

2. Observation results

In this paper, we present Cluster observations from a quasi-parallel shock crossing: 21:25-21:40UT on 29 March 2002. We use the magnetic field data with 4s resolution from the Fluxgate Magnetometer (FGM) [Balogh et al., 2001]. The FGM data also have a high resolution time series which is 22 Hz. Plasma data used in this study are taken form the Cluster Ion Spectrometer (CIS) instrument which measures ions fluxes in the energy range 0.005–26 keV [Rème et al., 2001]. The CIS consists of the Hot Ion Analyzer (HIA) with no species discrimination using a top hat electrostatic analyzer, and the Composition and Distribution Function analyzer (CODIF) which combines a top hat analyzer with a time-of-flight spectrometer to identify major species. In this event, the data of ion moments have the resolution of 4s, omnidirectional differential energy flux is with 8s resolution, and the ion 3-D
distribution has a low resolution of 12s.

On 29 March 2002, the separations of 4 Cluster spacecraft are about 100 km. These 4 spacecraft crossed the bow shock from the upstream region to the downstream region around 21:34UT. The locations of the Cluster spacecraft are shown in Figure 1. This crossing occurs at about (7.16, -7.56, -8.65) \( R_E \) in the Geocentric Solar Ecliptic (GSE) coordinate system. Using the shock timing analysis (Schwartz, 2000), the angle \( \theta_{Bu} \) between the interplanetary magnetic field and the shock normal is \( \sim 28^\circ \), so the shock observed by the Cluster mission is a quasi-parallel shock. This shock is supercritical with an Alfven Mach number of the upstream solar wind \( M_A \sim 6.0 \). In the upstream, the average magnetic field is \( |B| \sim 5.5 \) nT; the ion temperature is \( T_p \sim 120eV \) and the ion density is \( n_p \sim 4.5 \) cm\(^{-3}\). Therefore, the plasma beta (the ion thermal to magnetic pressure) in the upstream is \( \beta \sim 3.6 \).

Figure 2 shows the magnetic field components and ion distributions. From the top to the bottom panels, there are the three components and the intensity of the magnetic field with 4s resolution, and spectrograms of the ion energy flux from CIS/CODIF for C1 and C3. All the parameters are in the GSE coordinate system. The shock front is observed by C1 at the time 21:34:29UT. As shown in Figure 2, there are plenty of ultralow frequency (ULF) waves in the upstream region of the shock. These ULF waves can not only be observed in the magnetic field intensity, but also found in all the three components. Although these waves have a broadband frequency spectrum, the main period of the upstream ULF waves is about 40s. C1 and C3 observed similar ion energy flux because of the small interspacecraft separation. In the energy flux spectra of ions, two distinct ion populations are clearly observed in the upstream region. The lower energy one (about 0.8 keV) is the incoming solar wind. The higher energy one (from 3 keV to 10 keV) is the superthermal ions. The superthermal ions are hotter and more tenuous as compared to the incoming solar wind.
In order to study the relationship between the superthermal ions and the upstream ULF waves, we select ions with the energy 4.0keV and then do a comparison between the energy flux of these ions and the intensity of the waves. Figure 3(a) shows the intensity of the magnetic field (dark blue line) and the ion energy flux with the energy 4.0keV (black line) which are observed by C1. The particle energy flux is strongly modulated by the upstream ULF waves. The high fluxes of superthermal ions are always located between two adjacent peaks of the upstream waves or the shock front and the nearest peak of the upstream waves, and the low fluxes of superthermal ions are always observed near the peaks of the waves. This relevance can be seen more clearly around the waves with the largest amplitude which are marked by streaks. In three light blue streaks, the peaks of the upstream waves are accompanied with the local minima of the particle energy flux. While in six red streaks the peaks of the particle energy flux are accompanied with the local minima of the waves. We also find an interesting thing that such relevance also roughly exists in the other waves with small amplitude. In Figure 3(a), we should noticed that there is a small peak of the particle energy flux in the region between the shock front and the nearest peak of upstream wave which is marked by a green streak. It indicated that the modulation also happens near the shock front. Furthermore, the level of the particle energy flux with 4.0keV generally tends to decrease away from the shock front.

Figure 3(b) shows the ion energy flux spectra in the streak 4 (light blue line, which is obtained during the time interval 21:32:47-21:32:55) and streak 5 (red line, which is obtained during the time interval 21:33:23-21:33:31) which are both marked in Figure 3(a). Compared with the spectra in streak 4, there is a higher superthermal ion flux (about several keV) in streak 5. However, the solar wind ions in streak 5 are with the energy about 0.45keV, which is quite smaller than that in streak 4 (about 0.6-0.8keV). It indicates that the source of the superthermal ions could not be the local incoming solar wind ions. Figure 3(c) shows the ion energy flux spectra along the parallel (red solid line) and antiparallel (red dashed line) directions in streak 5. It can be found that most of solar wind ions move along the magnetic field line but a
certain part of superthermal ions move to the opposite direction. All these features imply that the superthermal ions could be related to the reflected ions by the shock. Additionally, C3 also observed the same things shown in Figure 3.

Typical ion distributions shown in Figure 4 can provide more information of the superthermal ions. Figure 4 shows the projections of ion distributions observed by C1 in the $v_x - v_y$ space at the different times which are marked by streaks 1-3 and 5 in Figure 3(a). Because of different resolutions of omnidirectional differential energy flux shown in Figure 3 (about 8s) and the 3-D ion distribution (about 12s), the other 2 red streaks marked in Figure 3(a) have no suitable 3-D ion distributions. In Figure 4, we only show the part of ions with energy greater than 3keV. All four distributions are highly non-gyrotropic, and most of superthermal ions are concentrated in the area with a negative $v_y$. In this event, the dominated component of the motional electric field is $E_y \approx V_x B_z$ ($V_x$ is the speed of solar wind, and its value is about -300km/s). This negative $E_y$ can cause the particle acceleration along the $-y$ direction when these particles are trapped by the upstream waves or the shock front. So there is one possibility that these superthermal ions can get acceleration by the motional electric field. Similar results are also observed by C3.

3. Conclusions and Discussion

Our observation results of one quasi-parallel shock event by Cluster show that the energy flux of superthermal ions in the upstream region is modulated by upstream ULF waves and the maxima of the energy flux are usually located between the peaks of these waves (including the shock front and the nearest peak of the upstream wave). The observed ion distributions suggest that the superthermal ions come from the reflected ions by the shock, and can be accelerated by the motional electric field.

Nowadays the shock diffusive acceleration is widely accepted as the mechanism for generations of the high-energy ions associated with shocks. However, in order for
particles to be accelerated by shock diffusive acceleration, their initial energy should exceed a definite threshold (e.g. Zank et al., 2001). Therefore, a pre-acceleration mechanism which accelerates ions out of thermal populations to superthermal ions is necessary. The generation of the superthermal ions in quasi-parallel shocks has been demonstrated in 1-D hybrid simulations: a part of the upstream ions are at first reflected by the shock, and they may be trapped between the shock front and the nearest peak of the upstream low-frequency waves, or between the peaks of these waves. These trapped ions are then further accelerated in the shock front or the upstream waves via shock drift acceleration (SDA, see Su et al. 2012b). The maxima of the superthermal ions flux should be located between the peaks of the upstream waves, or the shock front and the nearest peak of the waves.

Therefore, the trapping of the reflected ion in the upstream waves plays an important role in the generation of superthermal ions at quasi-parallel shocks. In this way, the reflected ions can be accelerated many times by the motional electric field associated with the upstream waves and the shock front via SDA, which generates the superthermal ions. Our observations of a quasi-parallel shock event by Cluster clearly show the modulation of the superthermal ions by the upstream waves, and these superthermal ions are associated with the motional electric field in the upstream waves and shock front. Our observations give evidence that the upstream low-frequency waves in a quasi-parallel shock play an important role in the generation of the superthermal ions. These upstream waves trap the reflected ions, which are then accelerated to be superthermal ions by the motional electric field in the upstream waves or near the shock front, as demonstrated by hybrid simulations of quasi-parallel shocks (e.g. Scholer 1990; Su et al., 2012b).

From a theoretical point, the trapped ions in the upstream waves and shock front are accelerated by the associated motional electric field when the upstream waves are convected towards the shock front. As the upstream waves approach to the shock front, the amplitude of the upstream waves grows larger. At last, the upstream waves interact with the shock front, and a new shock front is formed. This is reformation
process of a quasi-parallel shock. Several works have already pointed out the importance of the reformation for the generation of superthermal ions, and they conclude that the reflected ions by the quasi-parallel shock can gain energy by SDA (e.g. Scholer 1990; Kucharek and Scholer, 1991; Su et al., 2012b). Unfortunately the temporal and spatial behavior of magnetic field cannot be well distinguished in our event. So it’s very hard to study the reformation process of the quasi-parallel shock. However, our observations demonstrate the importance of the upstream waves in the generation of superthermal ions in a quasi-parallel shock. This is also a critical point of the acceleration of the reflected ions at a reformed quasi-parallel shock, which has been pointed out in previous hybrid simulations (Su et al., 2012b).
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References


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**Figure Captions**

Figure 1. Locations of 4 Cluster spacecraft in GSE coordinate system. The black line corresponds to the position of the shock front. The black, red, green, blue triangles represent C1, C2, C3 and C4, respectively. The ‘D’ represents the downstream while the ‘U’ represents the upstream.

Figure 2. From the top to the bottom panels, they are the three components and the intensity of the magnetic field with 4s resolution, the ion energy flux spectrograms from CIS/CODIF for C1 and C3 with 4s resolution. All the parameters are in the GSE coordinate system. The ‘D’ represents the downstream while the ‘U’ represents the upstream.

Figure 3. (a) The comparison between the ion energy flux in the energy channel 4 keV (black line) and the intensity of the magnetic field corresponding to the ULF waves (dark blue line) observed by C1. The six red streaks mark several special times when the extreme values of ion energy fluxes are observed, while the blue streaks mark several special times when the peaks of the upstream waves are observed. The green streak marks a high ion energy flux near the shock front. (b) The blue line is the ion energy flux spectra observed in streak 4, and the red line is the ion energy flux spectra observed in streak 5. (c) The ion energy flux spectra in streak 5 in the parallel (red solid line) and antiparallel (red dashed line) directions.

Figure 4. The projection of ion distributions in the velocity space measured by CIS/CODIF in unit of phase space density ($s^3/km^6$) observed by C1 at the time (a)21:26:09 UT, (b) 21:27:33 UT, (c) 21:32:35 UT and (d) 21:33:23 UT. Only
the distributions of superthermal ions with the energy greater than 3eV are plotted.