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V. V. Lobzin, Vladimir Krasnoselskikh, M. Bosqued, Jean-Louis Pinçon, S. J. Schwartz, et al.. Non-stationarity and reformation of high-Mach-number quasiperpendicular shocks: Cluster observations. *Geophysical Research Letters*, 2007, 34 (5), pp.265 - 275. 10.1029/2006GL029095 . insu-01556657

HAL Id: insu-01556657

<https://insu.hal.science/insu-01556657>

Submitted on 5 Jul 2017

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Nonstationarity and reformation of high-Mach-number quasiperpendicular shocks: Cluster observations

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Received 14 December 2006; accepted 5 February 2007; published 9 March 2007.

[1] A set of experimental data is presented for a high-Mach-number ($M_f = 5$) quasiperpendicular ($\theta_{Bn} = 81^\circ$) bow shock layer crossed by Cluster spacecraft on 24 January 2001 at 07:05–07:09 UT. The measurements of magnetic field, spectra of electric field fluctuations, and ion distributions reveal that the shock is highly nonstationary. In particular, the magnetic field profiles measured aboard different spacecraft differ considerably from each other. The mean frequency of downshifted waves observed upstream of the shock ramp oscillates with a characteristic time comparable with the proton gyroperiod. In addition, the reflection of ions from the shock is bursty and a characteristic time for this process is also comparable with the ion gyroperiod. All of these features in conjunction are the first convincing experimental evidence in favor of the shock front reformation. **Citation:** Lobzin, V. V., V. V. Krasnoselskikh, J.-M. Bosqued, J.-L. Pinçon, S. J. Schwartz, M. Dunlop (2007), Nonstationarity and reformation of high-Mach-number quasiperpendicular shocks: Cluster observations, *Geophys. Res. Lett.*, *34*, L05107, doi:10.1029/2006GL029095.

1. Introduction

[2] Shock waves are usually considered to be nonlinear waves that cause irreversible changes of state of the media and from macroscopic point of view they are stationary (for a review, see, e.g., *Tidman and Krall* [1971]). However, in the very beginning of the collisionless shock physics *Paul et al.* [1967] hypothesized that high-Mach-number shocks can be nonstationary, and the first unambiguous evidence of the nonstationarity was obtained by *Morse et al.* [1972] in the laboratory experiments.

[3] In the 1980s, new evidence of shock front nonstationarity were found. In particular, *Vaisberg et al.* [1984] reported low frequency oscillations of the ion flux in the Earth's bow shock. Later *Bagenal et al.* [1987] observed a similar phenomenon in the Uranian bow shock. In addition, numerical simulations performed by *Leroy et al.* [1982] with the use of the 1-D hybrid code showed that the front structure of perpendicular shocks varies with time, for example, the maximum value of the magnetic field exhibits

temporal variations with a characteristic time of the order of ion gyroperiod, the magnitude of these variations being about of 20% if the parameters are typical for the Earth bow shock ($M_A = 8$ and $\beta_{e,i} = 0.6$, where M_A is the Alfvén Mach number, $\beta_{e,i}$ is the ratio of the thermal and magnetic pressures). They also found that for $M_A = 10$ and $\beta_{e,i} = 0.1$ the ion reflection was bursty, oscillating between 0% and 70–75%. Hybrid modeling of perpendicular shocks with very high Mach numbers was carried out for the first time by *Quest* [1986]. He found that the ion reflection in the shocks can be periodic, the stages with 100% ion reflection alternating with the stages of 100% ion transmission. As a result, instead of a stationary structure, observed were a periodic wave breaking and shock front reformation. Later *Hellinger et al.* [2002] reexamined the properties of perpendicular shocks with the use of the 1-D hybrid code and observed the front reformation for a wide range of parameters if upstream protons are cold and/or Mach number is high. *Scholer et al.* [2003] and *Scholer and Matsukiyo* [2004] in their 1-D full-particle simulations with the physical ion to electron mass ratio reproduced the reformation of exactly and approximately perpendicular high-Mach-number shocks in plasmas with $\beta_i < 0.4$ and demonstrated an importance of modified two-stream instability for the reformation process.

[4] *Krasnosel'skikh* [1985] and *Galeev et al.* [1988a, 1988b] proposed models describing the shock front instability due to domination of nonlinearity over dispersion and dissipation. This instability results in a gradient catastrophe within a finite time interval. Several aspects of the model, including the role of nonlinear whistler oscillations and existence of a critical Mach number above which a nonstationarity appears, were developed in further detail and more rigorously by *Krasnoselskikh et al.* [2002] and complemented by numerical simulations with the use of the 1-D full particle electromagnetic code with a small ratio of electron and ion masses, $m_e/m_i = 0.005$. It was shown that the transition to nonstationarity is always accompanied by disappearance of the phase-standing whistler wave train within the shock front. Moreover, for large Mach numbers the nonstationarity manifests itself as a periodic ramp reformation, which influences considerably the ion reflection, in particular, the reflection becomes bursty and sometimes the ions are reflected from both old and new ramps simultaneously.

[5] The four-spacecraft Cluster mission gives much more opportunities for experimental studies of the shocks. The first examples of some aspects of shock nonstationarity were presented by *Horbury et al.* [2001]. They analyzed magnetic field data for two quasiperpendicular shocks, with moderate and high Alfvén Mach number. While for mod-

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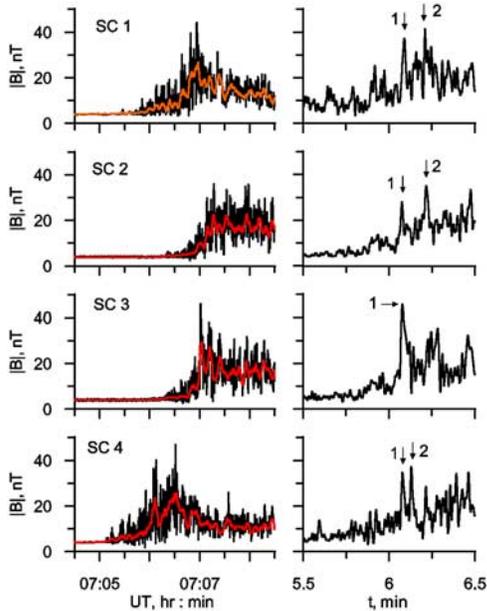


Figure 1. The magnetic field profiles obtained by FGM experiments aboard four Cluster spacecraft during the Earth's bow shock crossing on 24 January 2001. (left) High-resolution magnetic field data (black line) and the data obtained by sliding averaging over 4 s time intervals (red line). (right) Vicinity of overshoots, with large peaks in the magnetic field magnitude. Oscillations with frequencies higher than 2 Hz were removed. To emphasize the similarity and differences of the profiles, the data for the first 3 spacecraft are shifted with respect to that for the 4th one.

erate M_A the shock profiles measured by different spacecraft were approximately the same, with the exception of a small-amplitude wave activity in the foot, for high M_A the amplitude of the fluctuations attains ~ 10 nT, making profiles considerably different for different spacecraft. However, *Horbury et al.* [2001] argue that these fluctuations stop before the ramp and do not appear to disrupt the shock structure; on the other hand, they don't reject an opportunity that the fluctuations may be signatures of the unsteady shock reformation.

[6] In the present paper, using Cluster observations, we provide a convincing evidence that high-Mach-number quasiperpendicular shocks are nonstationary, moreover, a quasi-periodic shock front reformation takes place.

[7] The remainder of the paper is organized as follows. In section 2, we present a typical example of quasiperpendicular, supercritical, high- β , and high-Mach-number shock observed aboard Cluster spacecraft. Using different experimental data, it was shown that the shock considered is highly nonstationary. Section 3 contains a discussion of arguments favoring the front reformation for this particular bow shock crossing. The main results of the paper are summarized in section 4.

2. An Example of a Typical Crossing of Nonstationary Quasiperpendicular Shock Wave

[8] The present study began from analysis of magnetic field profiles for several crossings of the quasiperpendicular

part of the Earth's bow shock by Cluster spacecraft from January to May 2001. Magnetic field waveforms in the frequency range 0–10 Hz were measured by the triaxial flux gate magnetometers (FGM) [*Balogh et al.*, 1997]. It was found that nonstationarity seems to be typical for shocks with relatively high Mach numbers. Both from numerical simulations and experiments it follows that the details of nonstationary behavior of the shock front may depend strongly not only on the fast mode Mach number, M_f , but on the upstream $\beta_{e,i}$, as well as on the angle between the upstream magnetic field and the shock normal, θ_{Bn} . For a detailed study, we have chosen a shock which was observed on 24 January 2001 at 07:05:00–07:09:00 UT and can be considered as a typical quasiperpendicular, supercritical, high- β , and high-Mach-number shock wave. Indeed, from the available experimental data and with the use of the multi-spacecraft timing algorithm described by *Schwartz* [1998] the following estimates were obtained: $\beta_e = 1.7$, $\beta_i = 2.0$, $\theta_{Bn} = 81^\circ$, $M_A = 10$, and $M_f = 5$.

[9] For shock crossing under investigation the magnetic field data were obtained from FGM experiment giving 67.2 measurements per second. The time profiles of the magnetic field magnitude are shown in Figure 1 (left), together with the data averaged over 4 s time intervals. All the profiles can be considered as quite typical for high-Mach-number quasiperpendicular shock waves. From the averaged data shown by red lines we observe that the shock front consists of a foot, a ramp, and at least one overshoot-undershoot cycle. The small-scale oscillations of large amplitude are superimposed on this large-scale structure. To check whether these fluctuations are consistent with plane waves activity, we computed the degree of polarization for the magnetic field waveforms obtained from STAFF experiment [*Cornilleau-Wehrin et al.*, 1997]. By definition, the degree of polarization approaches a unity if and only if the most of the energy is associated with a plane wave [*Samson and Olson*, 1980]. It was found that between the forward edge of the shock and the magnetic overshoot the oscillations in the frequency range 3–8 Hz have a high degree of polarization (greater than 0.7) and this polarization is elliptical. This wave activity can be considered as a whistler wave train nested in the shock [*Galeev et al.*, 1988a, 1988b; *Krasnoselskikh et al.*, 2002].

[10] Obviously, the presence of whistler oscillations, due to their high amplitude, influences considerably a large-scale shock structure. Indeed, averaging of magnetic field data reveals two regions resembling overshoots for SC4; for SC1 there is only one maximum; the profiles for other spacecraft seem to be more complicated. It follows from these considerations that the concepts of both overshoot and ramp, which must precede it, become ambiguous for such nonstationary shocks. Instead, we can speak about short large-amplitude structures embedded into the shock transition, with the forward edge of one of these structures playing a role of ramp.

[11] Figure 1 shows that the magnetic field profiles measured aboard different spacecraft differ considerably from each other. Obviously, the number of large-amplitude peaks, their amplitudes, as well the positions within the shock front, are different. The waves observed by different spacecraft in the foot region are also different. In particular, from Figure 1 (left) it is easily seen that the time interval

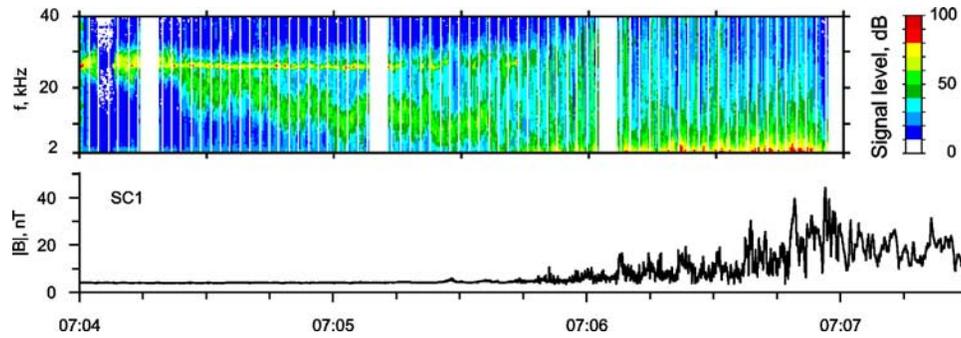


Figure 2. (top) Electric field spectra and (bottom) magnetic field profile obtained during the Earth's bow shock crossing on 24 January 2001 aboard SC1. The frequency-time spectrogram is measured by the Whisper experiment. The vertical white bands correspond to the time intervals when no data were obtained in the natural wave mode. The wave intensity is color coded with the reference level of $10^{-7} V_{\text{rms}} \text{ Hz}^{-1/2}$. The magnetic field profile is obtained by FGM experiment. The time scales for the both panels are the same.

between the beginning of the wave activity at the forward edge of the shock and the ramp crossing may differ by 10–20 s. This difference is substantial as compared with the duration of crossing of typical elements of the shock structure.

[12] The distinctions found between observations aboard different spacecraft are related to the temporal variations of the shock front structure rather than to the spatial ones, because the spacecraft separation is comparable with shock front thickness. Indeed, the distances between spacecraft lie within the range 380–980 km. The foot thickness estimated with the use of theoretical formula derived by *Schwartz et al.* [1983] is equal to 550 km, in reasonable agreement with the observations, while the total shock front thickness is considerably larger. On the other hand, the maximum time lag between the crossings is about $3 T_{Bi}$, where T_{Bi} is the ion gyroperiod, for this event $T_{Bi} = 15.5$ s. This time lag is larger than the period of the shock reformation.

[13] Relying on theoretical considerations and results of numerical simulations, *Krasnoselskikh et al.* [2002] argue that such kind of nonstationarity is closely related to nonlinear whistler wave trains embedded into the shock front and this is a typical property of the quasiperpendicular high-Mach-number shocks.

[14] Large-amplitude structures in the magnetic field profiles in the overshoot region or in its vicinity have a characteristic time of about 2 s. To observe more clearly both the similarity and differences for these profiles, oscillations with frequencies higher than 2 Hz were removed by Fourier-filtering technique. Then we found the optimum time shifts giving maximum correlations between the profiles of filtered magnetic field magnitude. The cross-correlation coefficients were calculated for profile fragments that last ~ 35 s and include a portion of foot and the entire overshoot region. The highest correlation was found between SC1 and SC2 data, while the lowest one was between SC3 and SC4 data, in accordance with visual observations of shifted profiles shown in Figure 1 (right). An additional analysis of the relative position of spacecraft tetrahedron and the shock reveals that the similarity of the shock profiles seems to depend first of all on the time interval between the shock crossings and/or the spacecraft separation measured along the shock normal rather than on the distance along the shock surface, in accordance with our

interpretation that the observed variations are temporal rather than spatial.

[15] Another evidence favoring the nonstationarity of this bow shock crossing comes from WHISPER measurements. In the passive mode of operation this experiment provides electric field spectra of natural emissions in the 2–80 kHz frequency range [*Décroux et al.*, 1997]. The frequency-time spectrogram obtained by WHISPER experiment aboard SC1 is shown in Figure 2, together with the magnetic field profile with the same time scale. The bow shock crossing can be identified by a substantial enhancement of the electric field fluctuations within the frequency range 2–5 kHz. For SC1, maximum intensity for these oscillations is observed at 07:06:48 UT.

[16] One of the most obvious feature of the spectra is the presence of intense waves in a vicinity of the plasma frequency, $f_{pe} = 27$ kHz, and the downshifted oscillations. The most intense is a narrow-band Langmuir emission with a frequency in the vicinity of f_{pe} . As compared with Langmuir waves, the power density of downshifted oscillations is usually smaller, while the frequency band they occupy is considerably wider and can be as large as 15–20% of the central frequency. Both the plasma waves and downshifted oscillations are considered to be typical for electron foreshock region. It is commonly believed that Langmuir waves are generated due to a plasma-beam instability, while for downshifted oscillations suggested were two different mechanisms, the plasma-beam interaction [see *Lacombe et al.*, 1985; *Fuselier et al.*, 1985] and the loss-cone instability of electron cyclotron modes [*Lobzin et al.*, 2005].

[17] The mean frequency of the downshifted oscillations is not approximately constant but varies within the range 0.2–1.0 f_{pe} . In addition, there exists a tendency for a large shift to occur in the vicinity of the shock front, while near the edge of the electron foreshock the shifts are considerably smaller. However, this tendency exists only on large time scales of about 1.0–1.5 min. For smaller scales, ~ 10 –15 s, there are the large-amplitude variations of the mean frequency of downshifted oscillations.

[18] The peculiarities of the spectra described above can be explained as follows. The downshifted oscillations are produced by energetic electrons, which are reflected by the bow shock and move almost along the magnetic field lines.

Because the solar wind is quiet during the time interval considered (indeed, Figures 1 and 2 show that there are no significant variations of the magnetic field; the plasma bulk velocity is also approximately constant in the foreshock), the observed evolution of the wave spectra can be attributed only to variations of suprathermal electron fluxes which are reflected from the bow shock and form the “rabbit ears” in the electron distributions upstream of the shock [Lobzin *et al.*, 2005]. The reflection of electrons by a nearly perpendicular bow shock was studied by Leroy and Mangeney [1984] and by Wu [1984]. They argue that the main characteristics of the distribution function of the reflected electrons depend first of all on the angle between the shock normal and upstream magnetic field, θ_{Bn} , and to a lesser extent on the ratio of the maximum magnetic field to its upstream value and on the electrostatic potential jump in the de Hoffmann-Teller frame. Resulting from shock front nonstationarity, slow variations of the effective normal of the reflecting part of the shock will lead to considerable variations of number density, energy of reflected electrons, and/or loss-cone angle, thereby producing the observed variations of the downshifted wave spectra. Both theoretical considerations and numerical modeling show that a characteristic time of the shock front oscillations or reformation is comparable with the ion gyroperiod [see Leroy *et al.*, 1982; Krasnoselskikh *et al.*, 2002; Scholer *et al.*, 2003]. The time scale of the spectra variations is also comparable with T_{Bi} in accordance with our interpretation.

3. Evidence for Shock Front Reformation

[19] As was noted above, the magnetic field profiles for the shock under consideration has several nonstationary features. In this section, we consider large-amplitude structures, with a characteristic time of about 1–2 s and present the arguments in favor of front reformation for this particular bow shock crossing. Figure 1 (right) shows the portions of the magnetic field profiles obtained after low-pass filtering and relative shift to show clearly the correspondence between the elements observed aboard different spacecraft. For three spacecraft there are two large and narrow peaks in the overshoot region and its vicinity, while for SC3 there is only one peak in the corresponding region (see Figure 1 (right), where these peaks are shown by arrows and numbered). The amplitudes of these peaks, both absolute and relative, differ for different spacecraft. In addition, the distance between two adjacent peaks also varies, being the smallest for SC4 and the largest for SC2. Moreover, a single peak observed aboard SC3, which is the highest and has relatively large width, probably, may be formed due to coalescence of two separate peaks. The observed peaks in the overshoot region can be considered as a part of nonstationary whistler wave packets, which were argued to be an intrinsic element of the quasiperpendicular supercritical shock front structure [Krasnoselskikh *et al.*, 2002]. To test this statement, an analysis of the polarization of these peaks with the use of minimum-variance technique was performed. The results provide additional evidence in favor of shock front nonstationarity. Indeed, the corresponding elements have different hodograms, which can be rather complicated. However, some of the elements have approximately circular polarization

typical for large-amplitude whistlers [Galeev *et al.*, 1988a; Krasnoselskikh *et al.*, 2002].

[20] Comparison of magnetic field profiles, which are shown in Figure 1, with the results of numerical simulations of high-Mach-number shock reformation [Krasnoselskikh *et al.*, 2002] reveals a doubtless resemblance between them. Indeed, for large Mach numbers, a quasiperiodic shock front reformation was observed in the simulations, with whistler wave packets playing a crucial role. At the first stage of the reformation cycle, a small-amplitude whistler perturbation upstream of the ramp is formed, then the perturbation grows up and moves towards the ramp. When its amplitude exceeds that of the ramp, this disturbance begins to play a role of a new ramp, while the old one moves downstream. The experimental results shown in Figure 1 resemble 4 different snapshots for the same shock undergoing the reformation.

[21] The strongest evidence favoring the shock reformation comes from the CIS experiment, which measures the ion composition and full three-dimensional distributions for major ions with energies up to 40 keV/e [Rème *et al.*, 1997]. The time resolution of the measurements is about one spacecraft spin, 4 s. Figure 3 shows 8 snapshots obtained at the forward part of the shock foot, where the disturbances of the solar wind magnetic field are still small. Shown are the number of counts vs V_x and V_y in the GSE coordinate system; with respect to the 3rd velocity component, V_z , an integration was performed. Reflected ions are observed for the first time at 07:05:16 (see the maximum of the number of counts in the quadrant corresponding to $V_x < 0$ and $V_y < 0$ in the first snapshot). In the time interval from 07:05:16 to 07:05:44, the position of this maximum in the velocity space does not change considerably. In addition, there exists another population of reflected ions in the quadrant corresponding to $V_x < 0$ and $V_y > 0$. From the snapshots it is easily seen that the numbers of counts corresponding to the reflected ions show approximately periodic variations with a very large modulation depth and a period of about 8 s (a half of proton gyroperiod T_{Bi}). To confirm this statement, we performed a summation of the number of counts corresponding to these populations, the results are approximately proportional to the corresponding number densities, n_i . The temporal evolution of these number densities normalized with respect to the corresponding maximum values for the time interval considered is shown in Figure 3 (bottom). The quasiperiodic variations seem to be more pronounced for the first population, with the minimum-to-maximum ratio being as low as $\sim 3\%$. The number of counts for the second population also varies with approximately the same period, in phase with that for the first one. It is worth noting that the minimum number of counts corresponding to the reflected ions in this region is greater than the “background noise” by a factor of 5, far beyond experimental errors, while for the maximum number of counts this factor is as large as ~ 30 if the “noise” level is estimated in the unperturbed solar wind just before the shock crossing.

[22] The observed peculiarities of the ion dynamics resemble the features found in the numerical simulations presented in the work of Krasnoselskikh *et al.* [2002], where a quasiperiodic front reformation was observed for quasiperpendicular shocks with high Mach numbers. In particular, when a leading wave train before the ramp

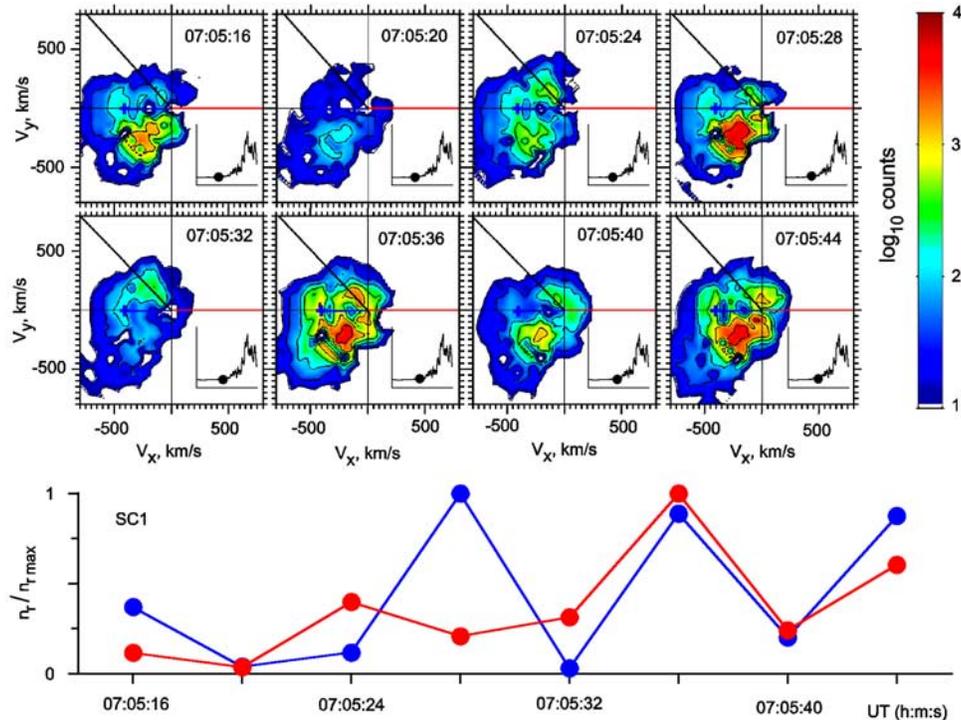


Figure 3. (top) Ion velocity distributions obtained from CIS measurements within the forward part of the foot for the Earth's bow shock crossing on 24 January 2001 aboard SC1 and (bottom) temporal variations for the relative number of counts corresponding to reflected ions. The distributions were calculated in the GSE coordinates. In the bottom panel, a blue line corresponds to ions with $V_y < 0$, while a red line shows the data for $V_y > 0$. Strong variations of n_r , especially for $V_y < 0$, show that the reflection of ions is bursty. The relative positions where the measurements were made are indicated by the dots on the magnetic field profiles shown as inserts.

attained a large enough amplitude, a new population of reflected ions appeared upstream of the precursor. In other words, the reflection of ions is not stationary, instead, it is quasiperiodically modified during the reformation process. In this case spacecraft, which moves slowly across the shock, will observe a quasiperiodic appearance/disappearance of reflected ions, in accordance with experimental results outlined above.

4. Conclusions

[23] In this paper we presented a set of experimental data for the high-Mach-number ($M_f = 5$) quasiperpendicular ($\theta_{Bn} = 81^\circ$) bow shock crossed by Cluster spacecraft on 24 January 2001 at 07:05–07:09 UT. The structure of this shock gives a clear evidence of its nonstationary behavior. In particular, the magnetic field profiles measured by FGM experiments aboard different spacecraft differ considerably from each other. First of all, this difference is clearly seen for large-amplitude oscillations, which have relatively short scales of about 1–2 s and resemble nonlinear whistler soliton-like structures. WHISPER measurements reveal the presence downshifted oscillations within the electron foreshock, with nonmonotonic variations of their central frequency, the characteristic time for these variations is comparable with the proton gyroperiod, $T_{Bi} = 15.5$ s. From the analysis of data from CIS experiment it follows that the reflection of ions from the shock is also highly nonstationary. Moreover, it is shown that the reflection is bursty and a characteristic time for this process is also comparable with

the ion gyroperiod. From numerous numerical simulations of quasiperpendicular shocks it is well-known that for high Mach numbers the shock becomes nonstationary, moreover, a front reformation can take place with a characteristic time comparable with ion gyroperiod. The combination of the features outlined above for the bow shock crossing under consideration is the first convincing experimental evidence favoring the shock front reformation.

[24] **Acknowledgments.** The authors are thankful to H. Kucharek, T. Dudok de Wit, and B. Lefebvre for useful discussions. This work was partially supported by le Studium program.

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