ON THE ION REFLECTION PROPERTIES OF THE QUASI-PERPENDICULAR EARTH'S BOW SHOCK

H. Kucharek[(1)], E. Moebius[(1)], M. Scholer[(2)], R. Behlke[(3)], C. Mouikis[(1)], P. Puhl-Quinn[(1)], L.M. Kistler[(1)], T. Horbury[(4)], J. Eastwood[(5)], S.D. Bale[(6)], and C. Mazelle[(7)]

[(1)]University of New Hampshire, Space Science Center, 39 College Road, Durham, NH, 03824, USA
[(2)]Max-Planck-Institut fuer Extraterrestrische Physik, GERMANY
[(3)]Department of Astronomy and Space Physics, Uppsala University, SWEDEN
[(4)]Imperial College, London, UNITED KINGDOM
[(5)]NASA GSFC, UNITED STATES
[(6)]University of California, Berkeley, UNITED STATES
[(7)]CESR/CNRS, FRANCE

ABSTRACT

Recent multiple spacecraft observations by Cluster revealed that field-aligned ion beams appear to emerge from the gyrating ions in the ramp of a quasi-perpendicular shock created by the same reflection process. A closer look at recent findings show that effective scattering in pitch angle within the shock ramp during the reflection may also be needed to produce these beams at higher shock normal angles. Obviously, ion reflection, transmission and wave particle scattering depend on shock parameters, such as Mach number, plasma beta and shock angle. However, how important are these parameters relative to each other for these processes? Furthermore, the internal dynamics, structure of the shock and the cross-shock potential may also be important. A better understanding would provide very useful information about the ion reflection and transmission process at perpendicular shocks in general for other disciplines such as astrophysics. A survey of shock crossings for a wide range of plasma conditions such as shock normal angle, Mach number, and plasma beta has been compiled and investigated in detail in order to determine the major controlling parameters. In this database we included information about the cross shock potential and magnetic field profile at the shock, as well as the global dynamics of the shock. We will report on dependence of variability of different ion distributions such as the gyration and escaping ions on these various parameters.

1. INTRODUCTION

Early space missions explored the foreshock region of the Earth's bow shock and its variety of ion distributions. At the upstream edge of the ion foreshock energetic (> 10keV) Field Aligned ion Beams (FAB) of low densities are present. These beams originate from a fraction of the incoming solar wind accelerated by shock drift acceleration at the quasi-perpendicular portion of the Earth's bow shock. In addition to shock drift acceleration, leakage of ions out of the magnetosheath is thought to contribute to this distribution, in particular for low energy beams. These lower-energy FABs excite low frequency monochromatic waves. Ions are trapped in these waves, which leads to the formation of gyro-phase bunched ion distributions. Efficient wave particle scattering is thought to be the basic mechanism that scatters a gyro-phase bunched distribution into an intermediate distribution. Upstream of the quasi-parallel regime of the Earth's bow shock diffusive particle distributions are found. These distributions consist of 150keV-200keV ions and they are nearly isotropic. These distributions are accompanied by large amplitude magnetic fluctuations.

Although significant progress has been achieved in understanding the global dynamics of the ion distributions in the foreshock region, some underlying production mechanisms are still not fully understood. In particular it is unclear what causes and what controls ion reflection at the quasi-perpendicular Earth bow shock. In this paper we will address these topics by reviewing the recent results obtained from Cluster data. We organized the paper as follows: after reviewing the current theoretical models for ion reflection and ion beam formation we will present results from Cluster obtained from a survey of bow shock crossings during the year 2001. In this survey we studied the intensity of field-aligned ion beams and their dependence on solar wind conditions, magnetic field topology and shock dynamic. Furthermore, we investigated the dependence of ion reflection on wave-particle interaction and cross shock potential.

2. THEORETICAL MODELS

Ion reflection and formation of field-aligned ion beams have been studied for several decades. A number of models to produce FAB's have been proposed but none of these models explains all features observed in measurements. Furthermore, in some of the models the ion reflection mechanism is assumed but not explained.

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Sonnerup (1969) showed that solar wind protons could easily be energized to a rather energetic ion beam if the bow shock managed to turn the incoming ions around in such a way that they left the shock reasonably well field-aligned after reflection. In this model it is assumed that the particle energy was preserved in the de Hofmann Teller-frame (dHT) and the motion remained field-aligned after reflection, but he did not specify a reflection process. In an observational study with ISEE data Paschmann *et al.* (1980) showed that the peak energy of ion beams as a function of the magnetic field orientation relative to the solar wind and to the shock normal agreed well with the prediction of this model. This scenario is also referred to as "**adiabatic reflection**" because of the apparent conservation of the magnetic moment μ. However, these observational studies of the reflection process by Paschmann *et al.* (1982) and in simulations Leroy *et al*. (1981, 1982) also showed that μ is by no means constant during ion reflection at the quasi-perpendicular bow shock.

Alternatively FAB's be produced by that have been heated downstream of the shock and **leakage out of magnetosheath.** In an idealized model Edmiston *et al.* (1982) proposed that plasma is heated and thermalized in a thin layer at the shock. They calculated how ions from a hot Maxwellian distribution in this layer could return upstream. Schwartz *et al.* (1983) proposed a modified version of this model. They suggested that magnetosheath particles are **accelerated by the shock potential mainly along the shock normal** and that its component parallel to the magnetic field constitutes the resulting guiding center motion back upstream.

A more **self-consistent non-local model** has been proposed Tanaka *et al.* (1983). This model is based on observations by Paschmann *et al.* (1982), simulations by Leroy *et al.* (1981), and the work by Edmiston *et al.* (1982) and can be described as follows: solar wind encounters the quasi-perpendicular section of the bow shock, part of the incoming solar wind distribution is specularly reflected and creates a gyrating ion distribution that is swept downstream. The high perpendicular temperature of this distribution is the source of free energy for electromagnetic ion **cyclotron (EMIC) waves downstream** of the shock. Subsequent efficient pitch angle scattering produces particles with a high enough velocity parallel to the magnetic field so that they can escape upstream. Tanaka *et al.* (1983) pointed out that this model is consistent with a large fraction of the beams observed by Paschmann *et al.* (1980), but fails to explain the most energetic ion beams. Furthermore, these models could not be distinguished on the basis of the range of parallel velocities of the FAB's observed in the Earth's foreshock region by ISEE-2

3. RECENT CLUSTER OBSERVATIONS

A Cluster study by Kucharek *et al.* (2004) suggests a resolution of the question where the beams originate. They analysed several quasi-perpendicular shock crossing with CIS and followed the spatial and temporal evolution of the reflected and transmitted ion

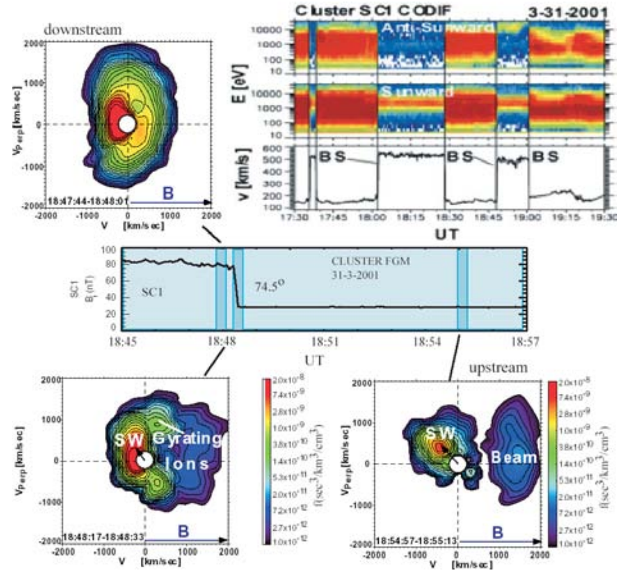

Figure 1 Upper right corner: Energy spectrum in earthward, sunward direction, and solar wind velocity for a sequence of bow shock crossings. The magnetic field (middle panel) and the ion distributions are shown for the outbound crossing at 18:48UT.

populations across the shock. Figure 1 shows a composite plot of data for March 31, 2001. The top right corner we show the energy spectra and the magnetic field during a sequence of bow shock crossings of

spacecraft 1. The upper panel shows the earthward direction, the middle panel the sunward direction at which one observes the solar wind at energy of 1keV. At 18:48 SC1 observes an ion beam in the earthward spectrum. During this crossing we show snapshots of the distribution function, downstream, at the shock ramp, and upstream of the shock.

The middle panel shows the magnetic field as a function of time, and in the lower/upper panel the ion distributions, parallel and perpendicular to the mean interplanetary magnetic field, orientation indicated by arrows, are shown for three different locations: downstream, at the ramp, and upstream of the bow shock. The dark blue shaded areas in the magnetic field profile indicate the integration times for the ion distributions. Downstream, the shape of the ion distribution is more elongated perpendicular to the magnetic field. The phase space is filled with ions up to a parallel velocity of 1000 km/s. In the shock ramp gyrating ions appear, whose phase space density extends in parallel velocity, substantially exceeding the limit of $v \approx 1000$ km/s. Upstream of the shock (right hand distribution), this part of the distribution decouples from the core and forms a collimated beam along the mean interplanetary magnetic field. Note that the beam occupies a portion of the phase space that is empty downstream. From quantitative studies of ion energies in this event it appears as if the basic escape condition is violated and the conditions are far from reflection under conservation of energy at the very high shock normal angle of this event (74.5°). These beam ions should not be able to escape upstream. The most recent results and the fact that none of the current models for the formation of the FAB's is able to explain all of their features makes it worthwhile to investigate ion reflection and ion beam formation with Cluster data. In the following sections of these paper we present an alternative source mechanism for ion beam production and we support this model with recent results form Cluster observations

4. AN ALTERNATIVE MECHANISM

None of the above mentioned models seem to be able to explain all features of the field aligned ion beams. In some of the models ion reflection is assumed but the reflection mechanism is not explained. These most recent observations seem to raise even more questions about particle escape mechanism. Based on these recent observations we present a new possible mechanism (Bale *et al*, 2005, Kucharek *et al*. 2005) that is based on the idea of direct reflection and subsequent scattering. In Figure 2 we shows a schematic view of this mechanism. Ions will escape upstream if after a final encounter they have sufficient parallel guiding center velocity to prevent their return to the shock surface. Ions that are finally located in the thick dark portion of this circle marked "Escape" have persistently a positive normal velocity and will escape. These ions have nearly the maximal beam speed as deduced using adiabatic reflection (Sonnerup, 1969), although the new picture hints at potential microscopic processes. The Sonnerup model would predict a narrow (-point like) distribution. In the new model however a larger portion (- similar to the upstream distribution in Figure 1) of the circle will result in escaping particles, and it is uncertain what the center of the total population would be.

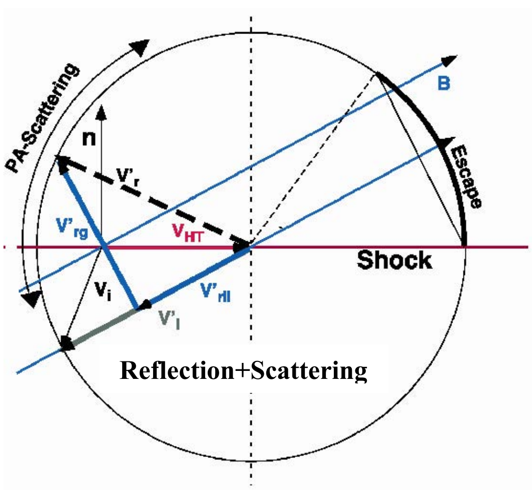

Figure 2 Schematic view of an alternative reflection mechanism.

This new mechanism requires ion reflection and efficient wave particle scattering. Both processes highly depend on the solar wind plasma conditions, magnetic field topology upstream of the shock and turbulence at an inside the shock ramp. Furthermore, shock dynamics could have an impact on ion reflection/escape at the shock. In the following section we review all these quantities in view of ion reflection/ion beam formation.

5. SOLAR WIND CONDITIONS

Supercritical shocks start to reflect ions because thermalization downstream is not sufficient to dissipate the incoming solar wind. Therefore, it seems to be obvious that ion reflection and thus the intensity of FAB's depend on solar wind parameters such as density, velocity, and magnetic field that determine the Alfvenic Mach number of the shock. An initial survey of Cluster data showed that the gyrating distribution does not significantly depend on the Mach number. However, the intensity of the field-aligned ion beam increases with increasing Mach number. This indicates that stronger shock waves produce more intense field-aligned ion beams at an unchanged level of gyrating ions. Since the gyrating ions seem to be the source of field aligned ions other processes control their intensity. These results will be presented in more detail elsewhere (Kucharek *et al* 2005a).

6. MAGNETIC FIELD TOPOLOGY

Ion escape from the Earth's bow shock depend strongly on the angle between the interplanetary magnetic field and the shock normal direction. Ion will propagate upstream of the shock if their gyro-center velocity is larger than the convection speed of solar wind toward the downstream direction. Assuming that cross-field diffusion is small and ion escape will become smaller with increasing shock normal angle. Experimental evidence has been provided by early measurements by Ipavich *et al.* 1988 using ISEE data. A sharp decrease of the intensity of upstream propagating beams ions has been observed when the angle values approach a shock normal angle of 58 degrees. No beams have been observed for larger than 62 degrees. The sharp decrease if the beam intensity has also been confirmed by recent Cluster observations. In addition to these observations Cluster results also show low intensity ion beams emerging from the shock at even larger θ_{Bn} then the critical shock normal angel. These ions seem to violate the escape conditions. However, a note of caution may be in order at this place. This simple dependence on the local shock normal angle is a direct consequence of the assumption of a planar, featureless, and stationary bow shock. In a way, the predicted and often observed energy dependence on θ_{Bn} may just reflect the necessary escape condition for ion beams. In it is assumed implicitly that the dHT frame is natural frame of reference, which implies that the reflection and scattering happens in this frame and for a comparison with observations that all parameters for the transformation are known and reasonably constant over the integration period. Any motion of the shock and/or local structures that deviate from a planar shock with the assumed normal may complicate a quantitative comparison with a specific model or even with the simple escape condition. This result indicates that the current reflection models seem to be too simple. The dynamic and the internal shock structure need perhaps to be included.

6.1 SHOCK DYNAMICS AND STRUCTURE

The Earth's bow shock is very dynamic. The solar wind ram pressure compresses the bow shock as it increases and decompresses as the pressure decreases. This in turn leads to a movement of the bow shock closer/away from the Earth. Large surface waves are a result of this dynamic movement. Furthermore, waves produced in the shock ramp by the interaction of solar wind ions and ions gyrating at the shock ram impose a wave pattern known as shock "ripples". This dynamics causes variations of the local shock normal direction although the global shock normal direction is unchanged. Therefore, even when the escape conditions are not fulfilled locally they can be fulfilled in a neighbouring area magnetically connected to the spacecraft. This could explain the existence of these low intensity ion beams observed at very high shock normal angels. The impact of the shock dynamic is currently under investigation.

7. WAVE PARTICLE SCATTERING

The recent observation with Cluster that the beam distribution and the specularly reflected ions are intimately connected and that the beam appears to emerge from the wing of the combined distribution. (Moebius *et al*., 2001) provides important evidence of the processes responsible for the beam. Early work (Burgess and Schwartz, 1984) showed how pure dc fields at the shock could lead to some reflected ions suffering multiple encounters with the shock, as confirmed in later self-consistent simulations (Leroy and Winske, 1983; Burgess, 1987).

Particles will escape upstream if after a final encounter they have sufficient parallel guiding center velocity to prevent their return to the shock surface. Certainly, particles finding themselves in the thick dark portion of this circle marked "escape" in figure 2 that have persistently positive normal velocity and will escape. Whether it is best to describe this scenario, as pitch angle diffusion/scattering is debatable. Scattering due to

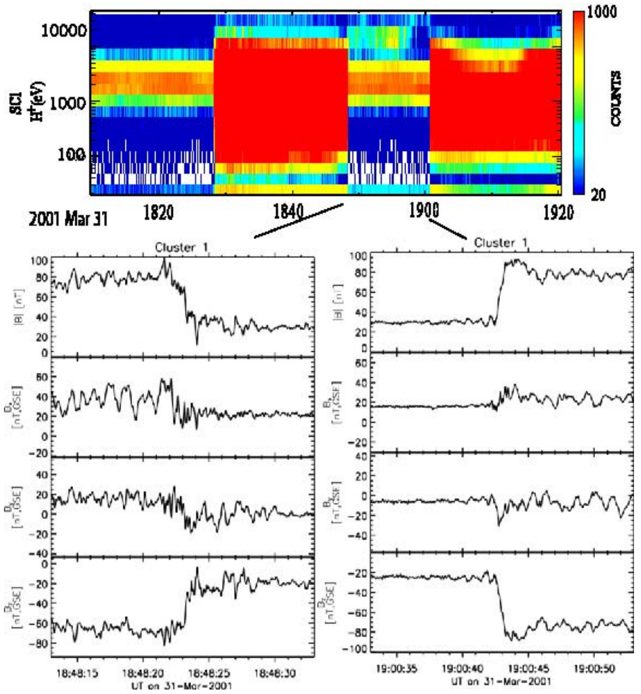

Figure 3 Top: energy spectra as measured from SC1 at 18:20-19:20UT at 3/31/2001. Bottom: Magnitude and the components of high-resolution magnetic field for the out-bound and the in-bound crossing indicated by the lines. A higher wave activity is observed during the outbound crossing.

fluctuations and irregularities in the shock fields (e.g., within the foot, ramp, and/or overshoot regions) almost certainly does not preserve kinetic energy in the dHT-frame, as such fluctuations propagate at relatively small speeds relative to the bulk plasma flow. Nonetheless, they may play a role if they are associated with the appearance of gyrating/reflected ions.

Figure 3 shows three consecutive bow shock crossings. The outbound crossing at 18:48UT is associated with a reflected beam whereas the inbound crossing at 19:00UT shows no beam. The figure shows a higher wave activity in and at the shock ramp for the outbound crossing. This seems to indicate an association of the appearance of beam ions with wave activity inside the shock ramp. However, observations cannot decide if the waves create the beam or vice versa. Numerical simulations only will be able to answer this question because additional waves or wave damping can be added which artificially controls wave particle interaction.

8. CROSS SHOCK POTENTIAL

Another controlling parameter for ion reflection is the so-called cross shock potential. Ions have larger gyro radii and penetrate deeper into the shock than electrons. Thus their different turning points create two separated sheets of opposite electric charge with an electric field pointing upstream perpendicular to the shock. This field accelerates electrons through the shock and decelerates ions. The resulting potential created is called cross-

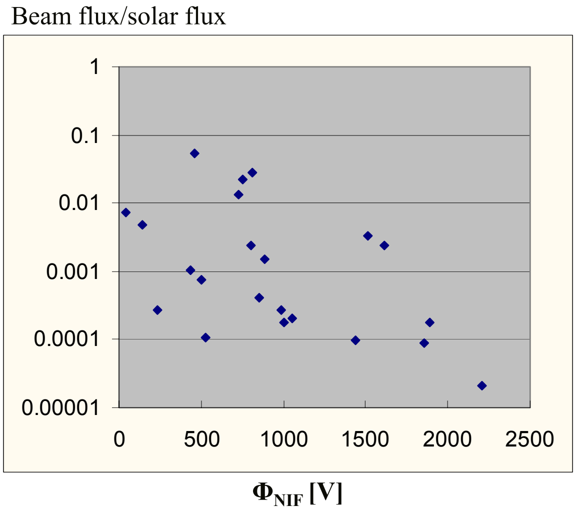

Figure 4 Ion beam flux normalized to the solar wind flux as a function of the shock potential in the normal incident frame.

shock potential. If the total energy of the incoming solar wind ions exceeds the potential drop it penetrates the shock, otherwise it is reflected. Reflected ions gyrate about the upstream magnetic field with large gyro radii and move in the direction of the motional electric field gaining energy from it. They may have multiple encounters with the shock and will finally be convected downstream. This potential can be measured in situ by EFW on board Cluster. First results (see Figure 4) indicate that there is a dependence of the intensity of these field-aligned ion beams on the cross shock potential. The beam intensity decreases for higher values of the cross shock potential in the Normal Incidence Frame (NIF). This seems to be counter-intuitive because a higher potential should be able to reflect more ions. However, numerical simulations showed that reflected ions originate out of the energetic wings of the ion distribution. The intensity of these wings of approaching solar wind is reduces when approaching the cross shock potential. The higher the potential the lower are the intensity of the reflected ions. However, a more detailed study is needed to support this statement.

9. SUMMARY

We investigated the reflection properties and the mechanism of the ion beam formation at the quasi-perpendicular Earth's bow shock by using Cluster data. For this study we combined data from CIS, the Flux Gate Magnetometer (FGM), and the Electric Fields, and Waves (EFW) instrument onboard Cluster spacecraft. Specifically we explored the dependence of the intensity of the gyrating (reflected) ions and intensity of upstream propagating ions on the solar wind parameters, the magnetic field topology, the shock dynamic, and the internal shock structure. The results of these investigations showed that

●The intensity of gyrating ions seems not to depend on the shock Mach number whereas the intensity of beam ions increases with increasing Mach number.

●Ion beams decrease in intensity with increasing shock normal angle. However, low intensity beams are observed large shock normal angels. These ions seem to violate the escape conditions at the shock.

●Shock dynamics and structure seem to be important for the production of low intensity ion beams.

● Processes right in the shock ramp and the dynamics of the shock itself seem to be responsible for these ion beams. Small-scale structures can cause deviations of the average $\theta_{Bn.}$ Both can modify the critical conditions so that ions can escape upstream.

● The results show that there is strong indication that wave particle scattering is important for the escape of ions upstream of the bow shock.

● There seem to be no significant impact of the cross shock potential in the gyrating ions but the intensity of the beam ions decrease with increasing potential.

A detailed statistical study on the relative importance of these parameters with respect to each other is currently in progress in order to determine the most critical parameters.

10. CONCLUSIONS

Cluster provided many new detailed insights into the ion reflection and beam formation at the quasi-perpendicular Earth's bow shock. However, these new detailed observations raise also a number of open questions. For instance, how does the intensity of gyrating ions and FABs correlate with the cross-shock potential, the shock structure, the magnetic field, and the upstream solar wind conditions at high and low Mach number supercritical shocks? These issues and the importance of wave particle interaction inside the shock front are currently investigated.

However, observations alone will not be able to answer all question related to this topic because sensor will detect the fields and ion distributions produced by several processes. The combination of observational efforts and numerical models is needed to disentangle these processes that occur on different scales. For instance multidimensional hybrid simulations allow to us investigate processes on scales of ion gyro-orbit. The impact of the shock dynamic and structure on ion reflection can be investigated in detail. Furthermore, these simulations will also allow us to explore wave particle scattering that is proposed as a possible reflection mechanism. Processes on electron scales may also be important for ion reflection. Full particle simulation will provide us new insights into the ion reflection properties of the Earth's bow shock in particular and quasi-perpendicular shocks in general.

Finally, there is the global aspect. These reflected escaping ion population propagate upstream, create waves by ion/ion beam instabilities, while it is convected downstream by the solar wind. Waves and the remaining ion population may enter the quasi-parallel regime and mediated the foreshock region of the quasi-parallel Earth's bow shock. A team of researchers at the International Space Science Institute (ISSI) is Bern is addressing these issues in detail by using Cluster data.

11. ACKNOWLEDGEMENT

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