A 2D Self-consistent Sub-critical shock wave : analysis of the shock front dynamics and its associated ion / electron foreshocks

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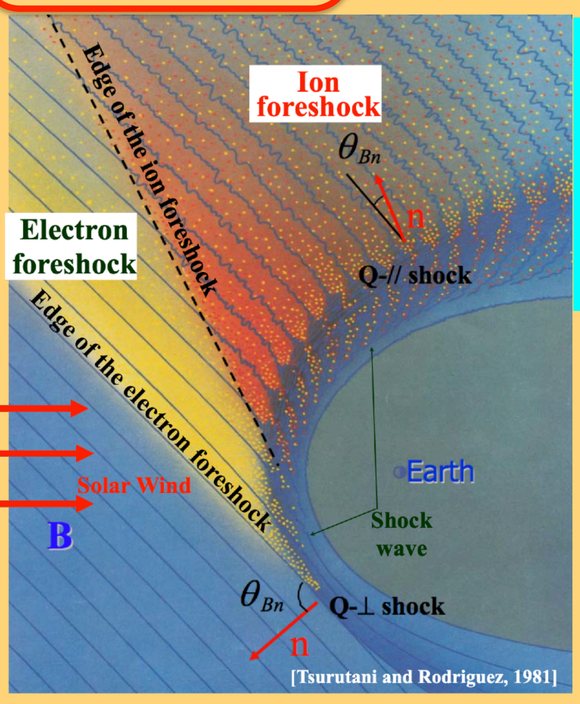
Abstract

Previous numerical works on electron/ion foreshocks observed upstream of a curved shock have been already performed within a self-consistent approach based on 2D PIC simulation (Savoini et Lembege, 2010, 2013, 2015), but are restricted to a supercritical regime only. Present two dimensional PIC (Particle in cell) simulations are used in order to analyze the features of a curved shock and associated foreshocks in a subcritical regime. In order to investigate the dynamic of each electron and ion backstreaming populations, we compare both supercritical and sub-critical configuration which allows us to define precisely the characteristics of each population in terms of initial velocity and/or their upstream position to the Θ_{Bn} angle (angle between the local shock normal and the interplanetary magnetic field IMF). Then, results allow to clarify the following questions: what is the impact of the subcritical regime (i) on the persistence of each electron/ion foreshock respectively ?, (ii) in the case the persistence is confirmed, how the location (along the curved front) and the angular direction of each foreshock edge are affected ?, and (iii) how the mapping of upstream local distribution functions are impacted ? Preliminary results will be presented and compared with those already obtained for a supercritical shock.

Motivations



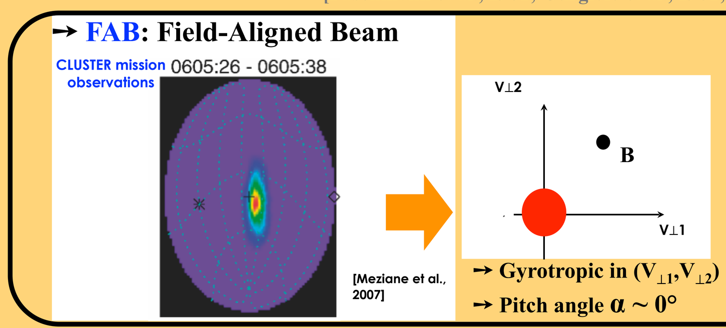
Evidence of electron and ion foreshocks upstream of quasi-perpendicular bow shock:
- Experimental data [Paschmann et al., 1981; Gurgiolo et al., 1981; Fuselier et al., 1986, 1995; Thomsen et al., 1983; Eastwood et al., 2005; Kucharek, 2008]
- Recent PIC numerical simulations [Savoini and Lembège, 2015]
  - → Self-consistent 2D Full-particle simulations
  - → Good agreement with experimental data

Present motivations
- → Impact of the low Ma on the bow shock features ?
- → do both foreshock persist in low Ma regime ?
- → Comparison of both foreshock populations between low and high M_A regimes?

Main features of Ion Foreshock

for $45° \leq \Theta_{Bn} \leq 90°$ **Experimental evidence of TWO distinct backstreaming ion populations** [Paschmann et al., 1981; Gurgiolo et al., 1981; Fuselier et al., 1986, 1995; Thomsen et al., 1983; Eastwood et al., 2005; Kucharek, 2008]

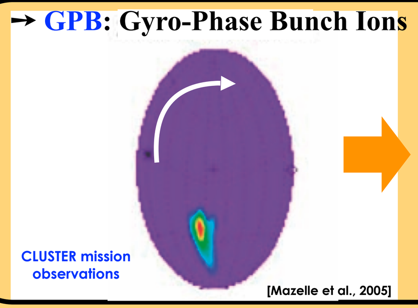
→ **FAB**: Field-Aligned Beam



- → Gyrotropic in $(V_{\perp1},V_{\perp2})$
- → Pitch angle $\alpha \sim 0°$

FAB:
- *Specular reflection* with μ =cte or μ ≠ cte [Sonnerup, 1969; Schwartz et Burgess, 1984; Gosling et al., 1982]
- *Leaked* (magnetosheath) *ions* *(but now unlikely)* [Tanaka et al., 1983; Thomsen et al.]
- *Diffusion* of gyrating ions
  - by upstream fluctuations [Giacalone et al., 1994]
  - by ramp fluctuations (rippling) [Kucharek et al., 2004; Bale et al., 2005]

→ **GPB**: Gyro-Phase Bunch Ions



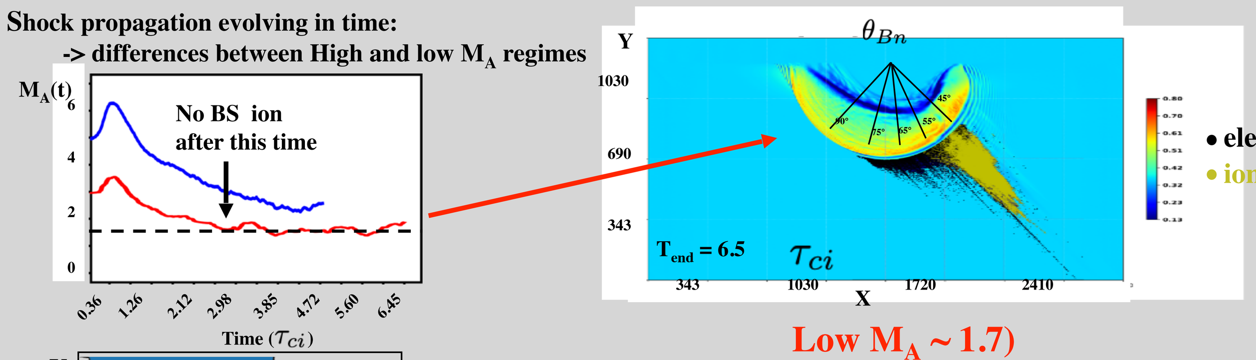
- → Non Gyrotropic in $(V_{\perp1},V_{\perp2})$
- → Pitch angle $\alpha \sim 20°$

GPB:
- *gyrating ions* at the ramp [Gurgiolo et al., 1981, 1983]
- *Wave synchronisation* [Mazelle et al., 2003; Hamza et al., 2006]
- *Beam-plasma Instability* [Hoshino and Terasawa, 1985]

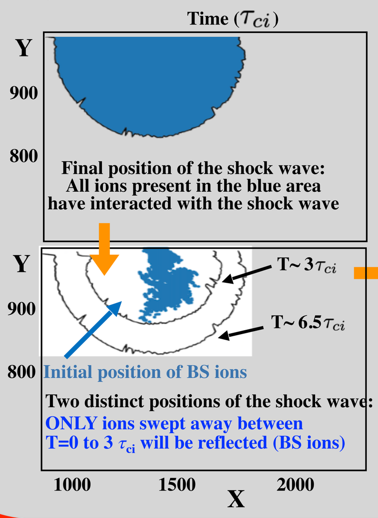
Both populations have been recovered by full PIC simulations in high M_A $Q_\perp$ shock [Savoini et Lembege, 2015, 2020]

Condition for ion Foreshock formation

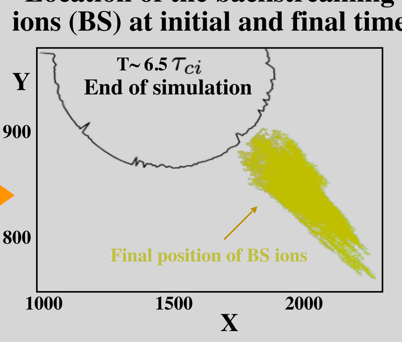
Shock propagation evolving in time:
-> differences between High and low M_A regimes



Low $M_A \sim 1.7$)



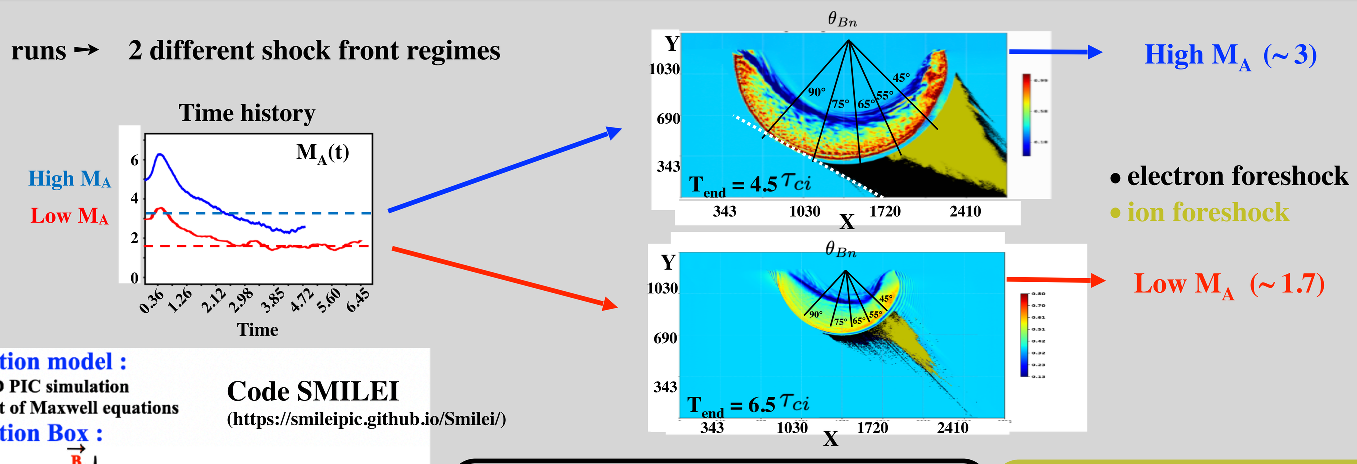
Location of the backstreaming ions (BS) at initial and final time



Ion Foreshock: Evidence of BS ions strongly depends of M_A in Low M_A regime ;
- → Evidence of a critical Mach Number to generate backstreaming ions (BS)
- → No backstreaming ion for $T > 3\ \tau_{ci}$
- → Critical Mach Number : $M_A^* \sim 1.8$

Simultaneous evidence of electron and ion Foreshocks

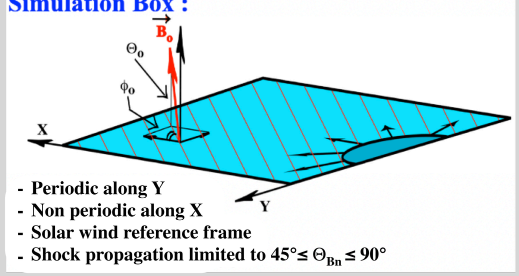
Two runs → 2 different shock front regimes



Simulation model :
- 2-1/2D PIC simulation
- full set of Maxwell equations

Code SMILEI (https://smileipic.github.io/Smilei/)

Simulation Box :



- Periodic along Y
- Non periodic along X
- Solar wind reference frame
- Shock propagation limited to $45° \leq \Theta_{Bn} \leq 90°$

Electron Foreshock:
Evidence for all values of M_A

High M_A:
- → edge starts at $\theta_{Bn} \sim 88°$
- → spatial extension is very large

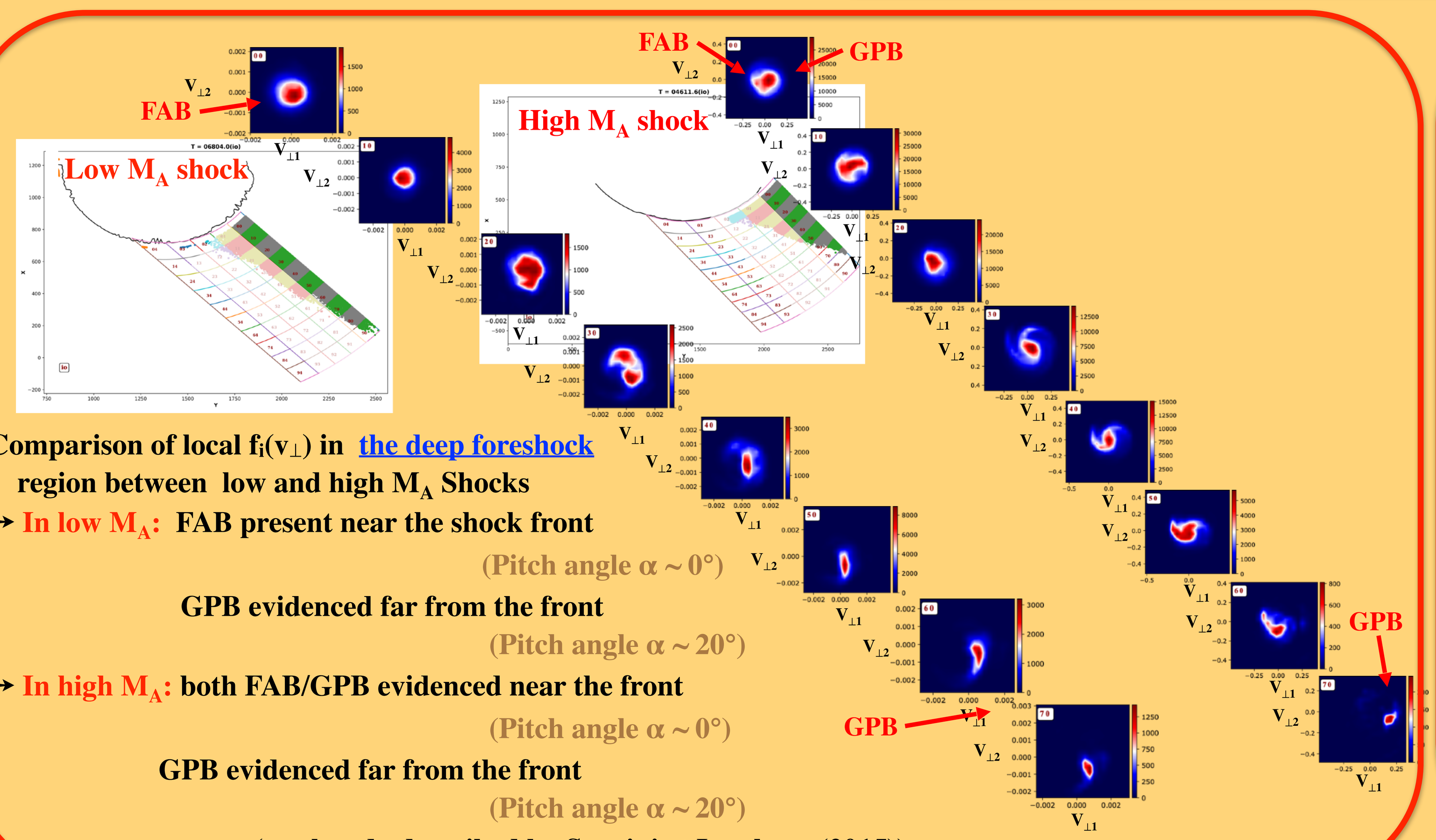
Low M_A :
- → edge starts at ~ 87°
- → lower efficiency for producing high energy electrons

Ion Foreshock:
Evidence depends on M_A regime

High M_A:
- → edge at starts $\theta_{Bn} \sim 58°$
- → spatial extension is large

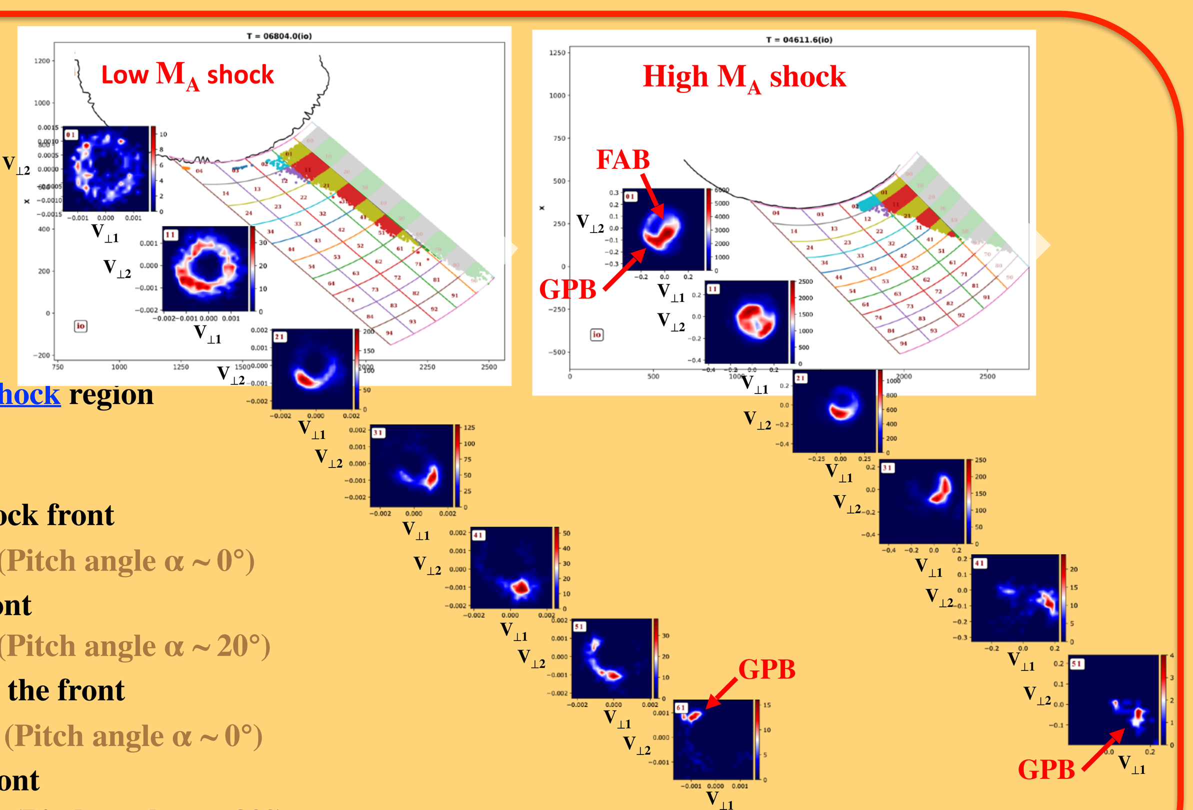
Low M_A
- → edge starts at ~ 55°
- → US spatial extension is limited

Ion Foreshock: Local distribution F $(V_{\perp1}, V_{\perp2})$



Comparison of local $f_i(v_\perp)$ in the deep foreshock region between low and high M_A Shocks
- → In low M_A: FAB present near the shock front (Pitch angle α ~ 0°)
  GPB evidenced far from the front (Pitch angle α ~ 20°)
- → In high M_A: both FAB/GPB evidenced near the front (Pitch angle α ~ 0°)
  GPB evidenced far from the front (Pitch angle α ~ 20°)

(as already described by Savoini et Lembege (2015))



Comparison of local $f_i(V_\perp)$ at the edge of foreshock region between low and high M_A Shocks
- → In low M_A: FAB not evidenced near the shock front (Pitch angle α ~ 0°)
  GPB evidenced far from the front (Pitch angle α ~ 20°)
- → In high M_A: both FAB/GPB evidenced near the front (Pitch angle α ~ 0°)
  GPB evidenced far from the front (Pitch angle α ~ 20°)

(as already described by Savoini et Lembege (2015))

Conclusions: comparison High / Low M_A shock (Preliminary results)

Electron Foreshock; unchanged features are:
- → persists in both M_A regimes
- → electron edge is along the IMF direction
- → electron foreshock always more extended than ion foreshock

The few differences are :

High M_A Shock
- → stronger percentage of BS electrons: > 2% of the SW electrons
- → Important upstream extension of the electron foreshock
- → higher energisation of BS electrons

Low M_A Shock
- → lower percentage of BS electrons: only 0.6% of the SW electrons
- → restricted upstream extension of the electron foreshock

Ion Foreshock: more differences (than for electrons) as follows:

High M_A Shock
- → Foreshock region begins around $\theta_{Bn} \sim 57°$
- → Important upstream extension of the ion foreshock
- → Local $f(V_{\perp1}, V_{\perp2})$ shows that:
  1) At the edge: both FAB & GPB near the front; but only GPB far from front
  2) Deeper in the foreshock: FAB observed near the front but only GPB far from the front

as already described in details by [Savoini and Lembege, 2015]

Low M_A Shock
- → Evidence of an Ion foreshock only for $M_A \geq M_A^*$ (~ 1.8)
- → Foreshock region begins around $\theta_{Bn} \sim 53°$
- → Local $f(V_{\perp1}, V_{\perp2})$ shows that
  1) at the edge: no FAB (near /far from the front) only GBP population evidenced (far from front)
  2) deeper in the foreshock: no changes versus the high Ma case