Ions Gyro-Resonant Surfing Acceleration by Alfven Waves in the Vicinity of Quasi-Parallel Shock

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Processus d’accélération en astrophysique

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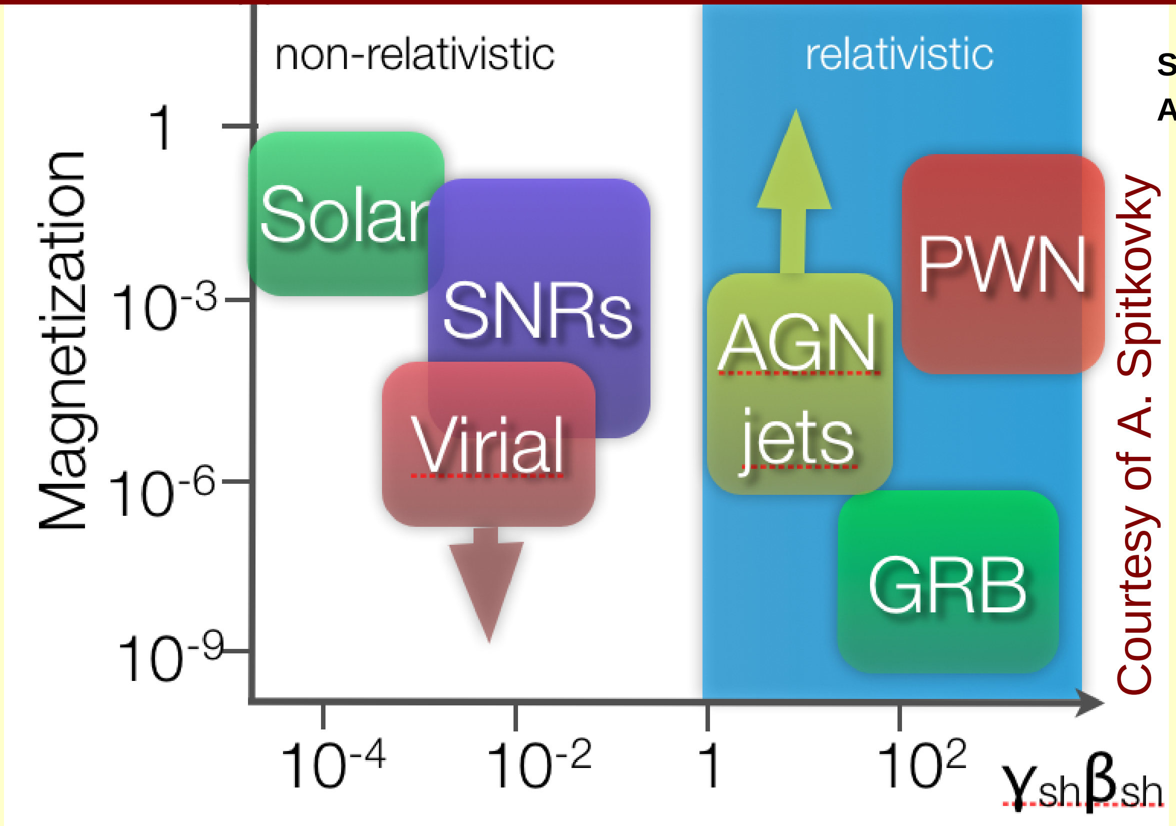
Outline

- Solar system shocks. Bow Shock: continuously observed shock wave with different geometric properties
- Diffuse ion population
- Gyro-resonance acceleration (GRA)
- GRA with magnetic field inhomogeneity
- Experimental properties of GRA

Solar system shocks



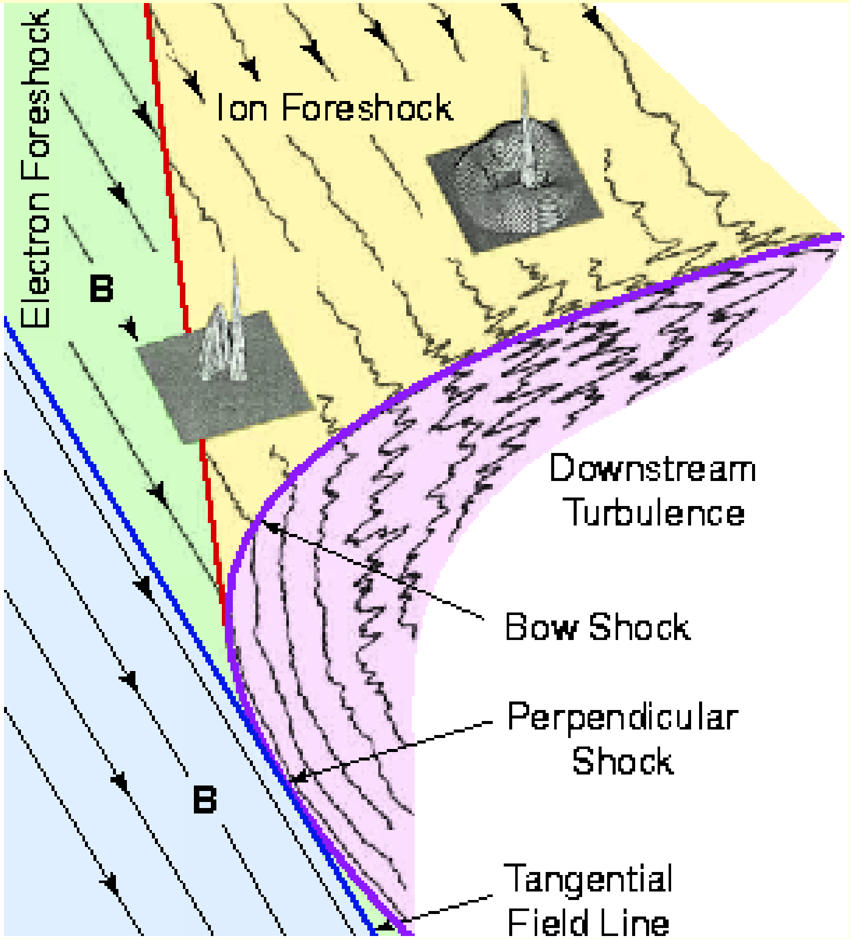
SNR - supernova remnant
AGN - active galactic nucleus

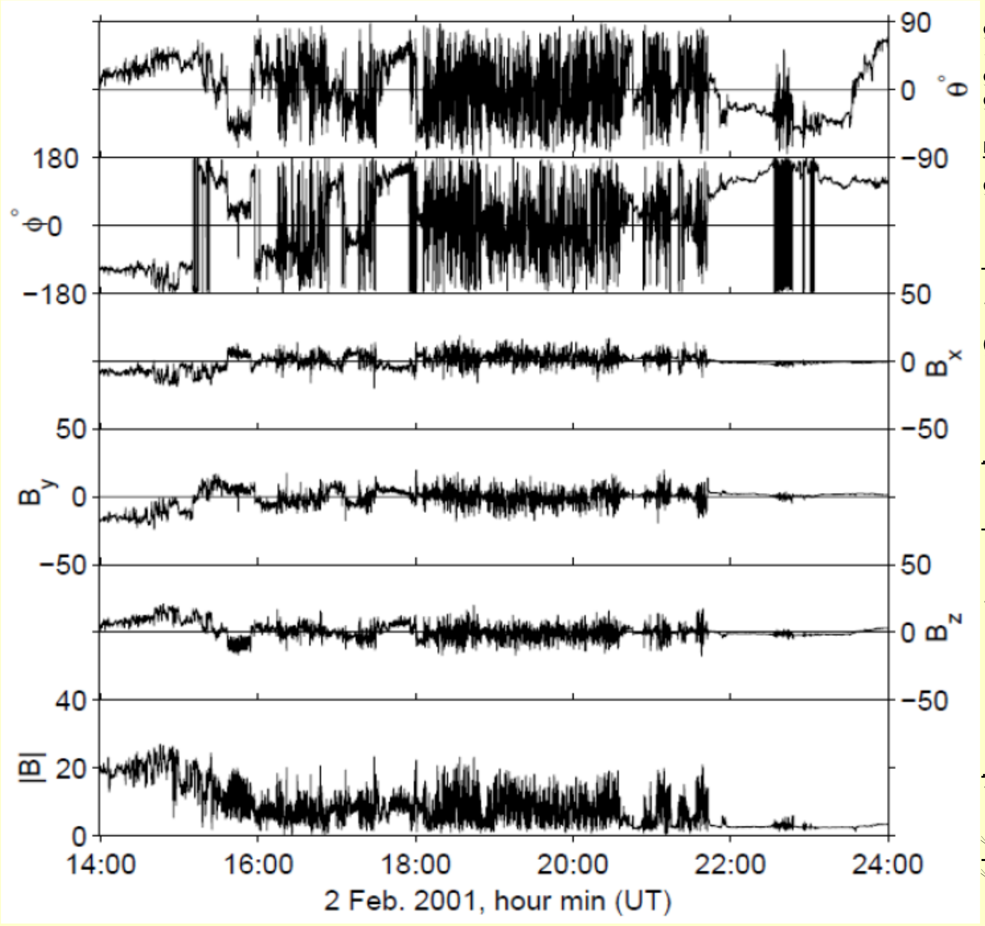
Mean free path due to Coulomb collisions is:

- 1 AU in the Solar system
- 1000 pc in Supernova Remnants
- 10^6 pc in galaxy clusters

Mean free path >> all scales of interest. Shocks must be mediated without any collisions but through interaction with collective self-consistent fields

The Earth Bow Shock





Geometry of the bow-shock of the Earth magnetosphere

$Q_{||}$ bow-shock crossing by Cluster

SLAMS in the vicinity of the Earth Bow Shock

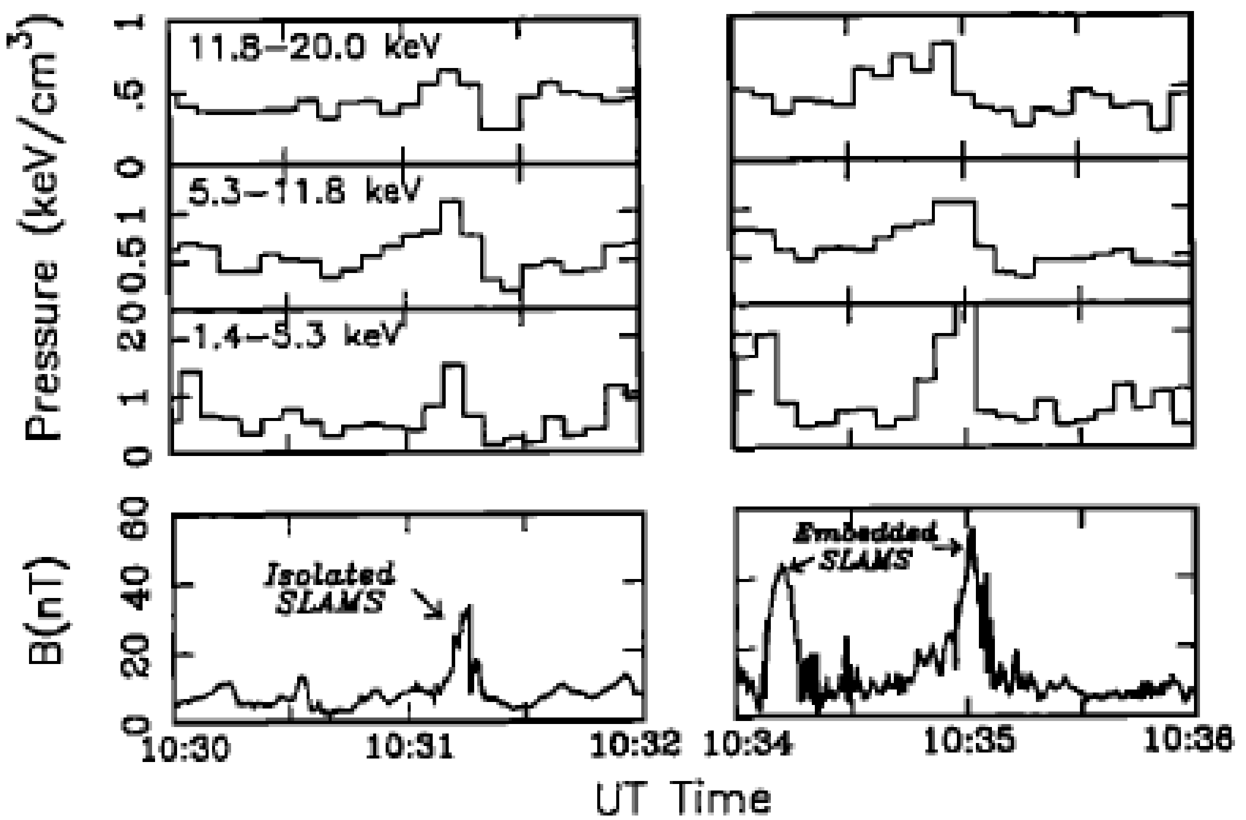


Fig. 1. Magnetic field magnitude and associated ion pressure signatures as viewed in the AMPTE/UKS spacecraft frame of reference of two SLAMS identified by Schwartz et al. [1992, c. f. Figures 6, 7, 14 and 15 which study the field structure and plasma signatures for these two events].

Giacalone, Schwartz and Burgess, 1993

SLAMS in the vicinity of the Earth Bow Shock

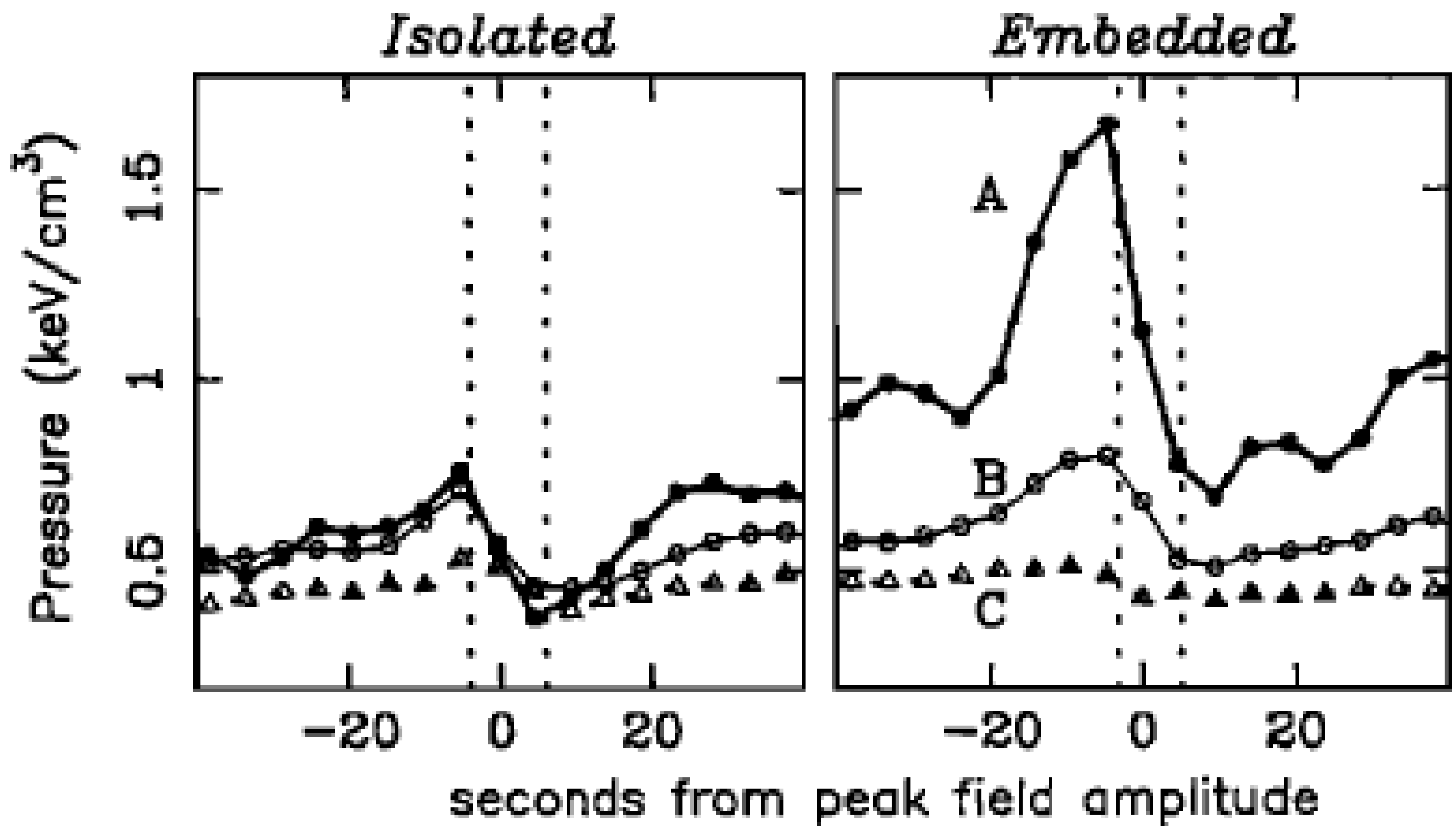


Fig. 4. Results of the superimposed epoch analysis of the spacecraft frame pressure for sub–populations of (A) 1.4–5.3 keV, (B) 5.3–11.8 and (C) 11.8–20 keV ions.

Giacalone, Schwartz and Burgess, 1993

Diffuse ions upstream of Earth's bow shock

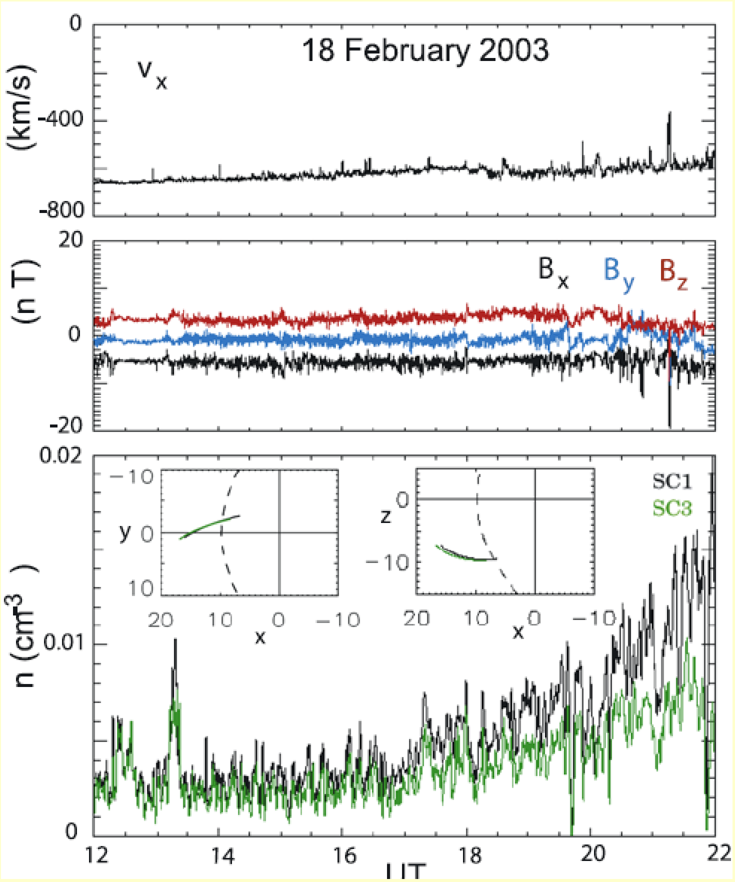
Diffusive ions are nearly isotropic, energetic (~150 keV) ions observed upstream of the Bow Shock under quasi-parallel conditions

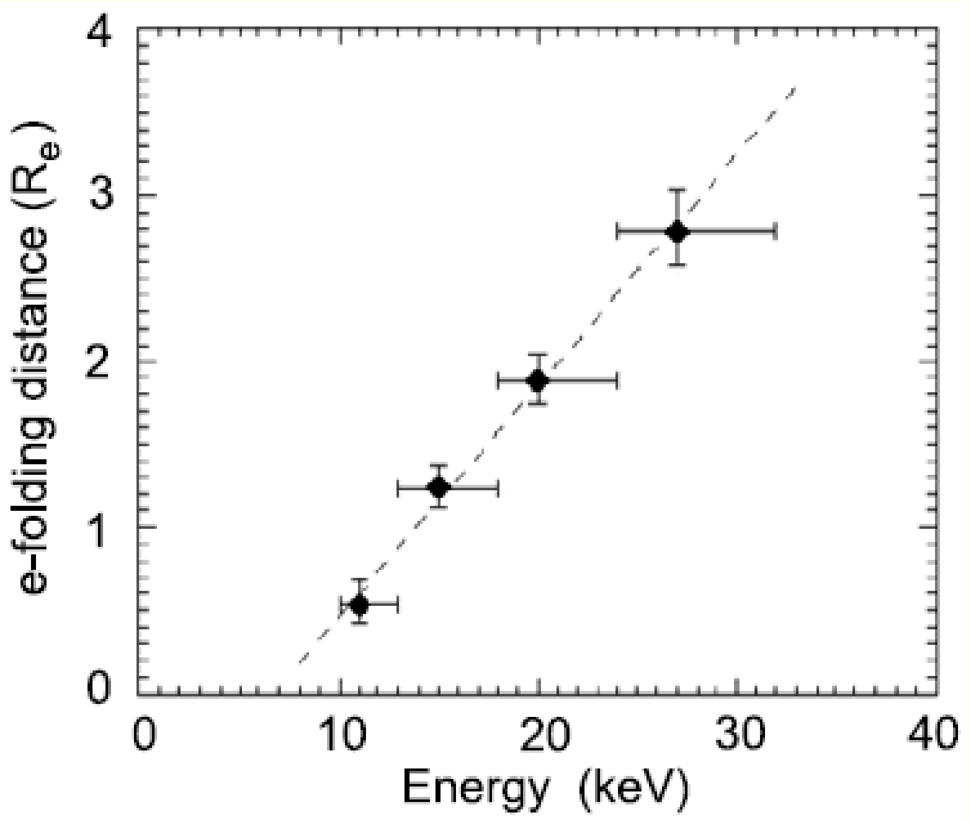
Strong correlation known between the diffusive ions and upstream wave filed intensity

Suggestive of 1st order Fermi acceleration. In this case Fermi picture predicts N(E) falls exponential with distance from the shock L(E)~E

Cluster can **directly** observe this gradient

Diffuse ions upstream of Earth's bow shock





The gradients in 4 energy channels ranging from 10 to 32 keV energy channels decrease exponentially with distance. The e-folding distance of the gradients depends approximately linearly on energy and increases from 0.5 Re at 11 keV to 2.8 Re at 27 keV (from Kis et al. 2004).

Gyro-Surfing acceleration

The idea of gyro-surfing acceleration was proposed by Kuramitsu and Krasnoselskikh *PRL2005*.
Three factors are necessary:

1. Circularly polarized wave
2. Particle polulation wich satisfy the resonance condition with the wave
3. Electrostatic field along the background magnetic field

All these three factors are usual for the vicinity of the Earth quasi-parallel Bow Shock. This allows to expect observation of the effective energy transport to the transverse component of the ion kinetic energy

Gyro-resonant mechanism of particle acceleration

components of particle velocity

Circular electromagnetic wave: $\mathbf{B}_\delta = \mathbf{B}_\delta(\phi)$ and $\mathbf{E}_\delta = \mathbf{E}_\delta$

$$\left(v_\parallel, v_{\perp 1}, v_{\perp 2}\right) \rightarrow \left(v_\parallel, v_\perp, \theta\right)$$

$$\mathbf{B}_\delta \perp \mathbf{B}_0 \qquad |\mathbf{B}_\delta| = const$$

$$\mathrm{rot}\mathbf{E}_\delta = -\frac{1}{c}\frac{\partial \mathbf{B}_\delta}{\partial t} \qquad \mathrm{div}\mathbf{E}_\delta = 0$$

wave-phase

$$\phi = \int \mathbf{k}\,d\mathbf{r} - \omega t$$

$$v_\phi = \omega / |\mathbf{k}|$$

Equation of motion

$$\frac{dv_{\perp 1}}{dt} = \frac{q|\mathbf{B}_0|}{mc} v_{\perp 2} + \frac{q|\mathbf{B}_\delta|}{mc}(v_\parallel - v_\phi)\sin\phi$$

$$\frac{dv_{\perp 2}}{dt} = -\frac{q|\mathbf{B}_0|}{mc} v_{\perp 1} - \frac{q|\mathbf{B}_\delta|}{mc}(v_\parallel - v_\phi)\cos\phi$$

$$\frac{dv_\parallel}{dt} = \frac{q|\mathbf{B}_\delta|}{mc}\left(v_{\perp 2}\cos\phi - v_{\perp 1}\sin\phi\right)$$

$$\frac{dv_\perp}{dt} = \frac{q|\mathbf{B}_\delta|}{mc}(v_\parallel - v_\phi)\sin(\phi - \theta)$$

$$\frac{dv_\parallel}{dt} = -\frac{q|\mathbf{B}_\delta|}{mc} v_\perp \sin(\phi - \theta)$$

$$\dot{\theta} = -\frac{q|\mathbf{B}_0|}{mc} + \frac{v_\parallel - v_\phi}{v_\perp}\frac{q|\mathbf{B}_\delta|}{mc}\cos(\phi - \theta)$$

First approximation $\dot{\theta} \approx -\dfrac{q|\mathbf{B}_0|}{mc}$

Gyroresonance $\dot{\phi} - \dot{\theta} = 0$

$$v_\parallel = \dot{\phi}/k + v_\phi = \dot{\theta}/k + v_\phi$$

$$\frac{dv_\perp}{dt} = \frac{q|\mathbf{B}_\delta|}{mck}\dot{\theta}\sin\phi_0$$

$$\frac{dv_\parallel}{dt} = -\frac{q|\mathbf{B}_\delta|}{mc} v_\perp \sin\phi_0$$

$$\dot{\theta} \approx -\frac{q|\mathbf{B}_0|}{mc}$$

One needs to compensate Lorentz force of wave

Effect of Electrostatic field

$$\begin{cases} \dfrac{dv_\perp}{dt} = \dfrac{q|\mathbf{B}_\delta|}{mck}\dot{\theta}\sin\phi_0 \\ \dfrac{d v_{\text{P}}}{dt} = -\dfrac{q|\mathbf{B}_\delta|}{mc} v_\perp \sin\phi_0 \\ \dot{\theta} \approx -\dfrac{q|\mathbf{B}_0|}{mc} \end{cases}$$

Lorentz force can be compensated by electrostatic field (see Kuramitsu & Krasnoselskikh 2005 PRL)

$$|\mathbf{B}_0| = const, \frac{d\dot{v}_{\text{P}}}{dt} = 0$$

$$\begin{cases} \dfrac{dv_\perp}{dt} = -\dfrac{q^2|\mathbf{B}_\delta||\mathbf{B}_0|}{m^2c^2k}\sin\phi_0 \\ 0 = \dfrac{qE_{\text{P}}}{m} - \dfrac{q|\mathbf{B}_\delta|}{mc} v_\perp \sin\phi_0 \end{cases}$$

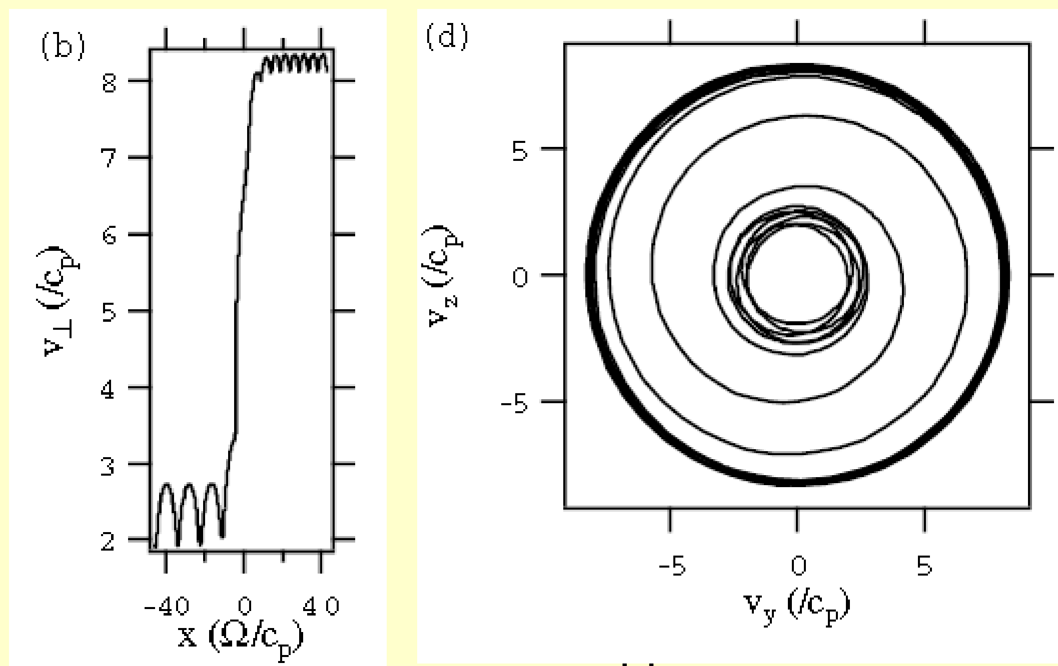
Growth of energy

$$\frac{1}{2}\frac{dv_\perp^2}{dt} = -\frac{q^2|\mathbf{B}_0|E_{\text{P}}}{m^2ck}$$

$$\frac{v_\perp^2 m}{2} = -\frac{q^2|\mathbf{B}_0|E_{\text{P}}}{mck}t$$

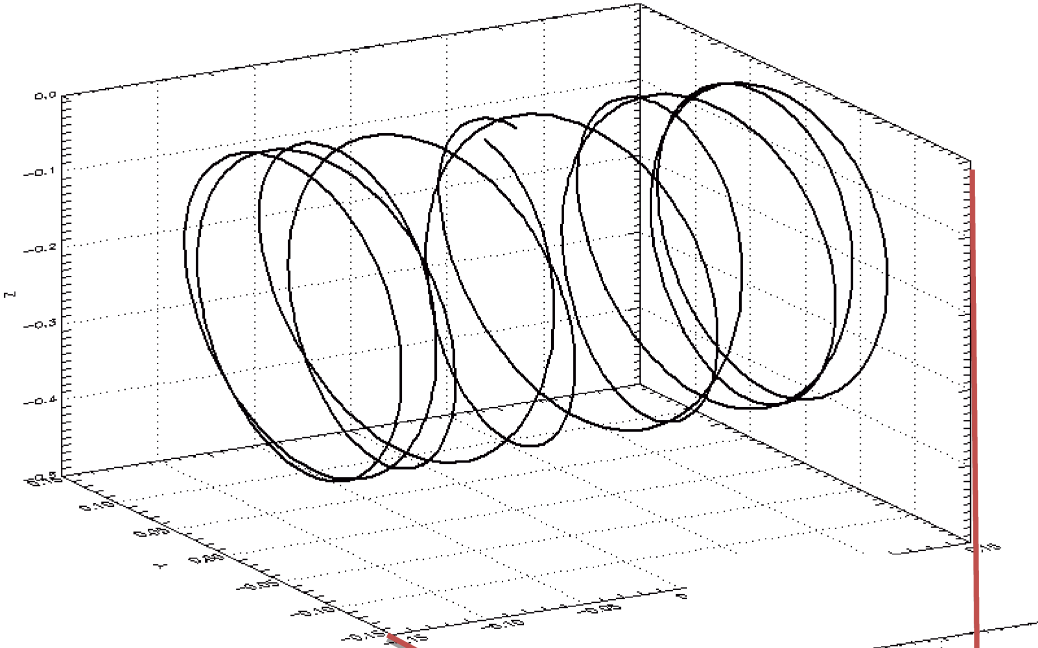
Particles gain energy in the system with $E_{\parallel}<0$

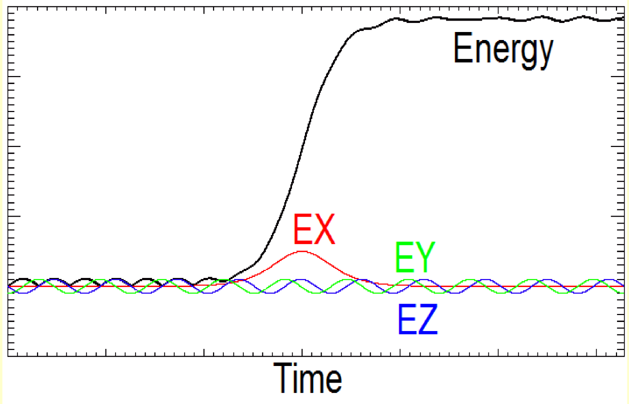
Trajectory in plane perpendicular to the background magnetic field



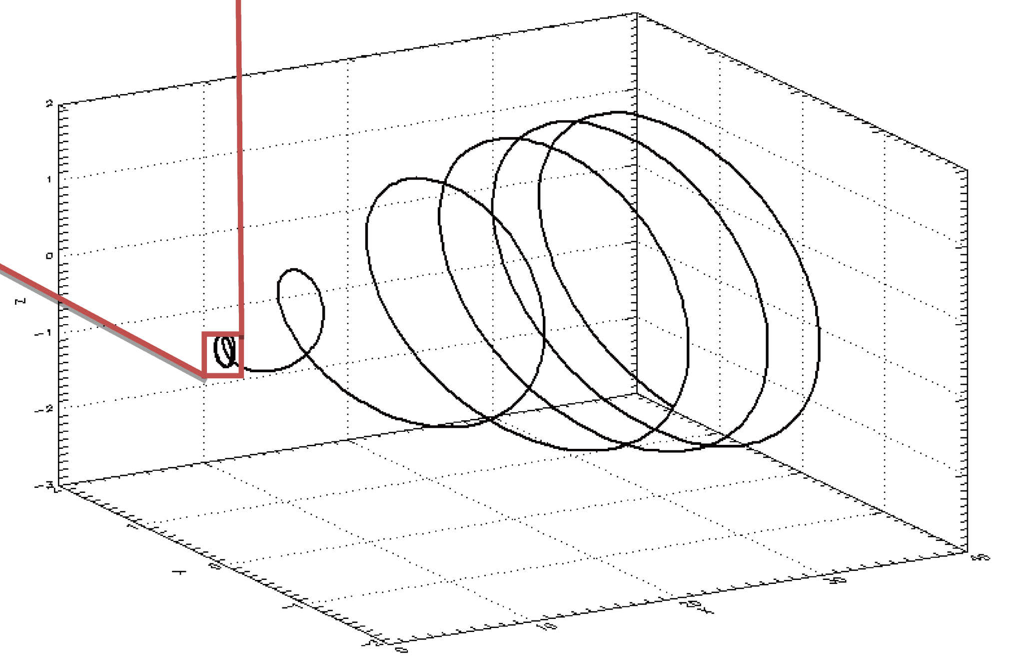
(Kuramitsu & Krasnoselskikh 2005 PRL)

Particle trajectory in the wave field





Particle trajectory and energy dynamics in a wave field with moving boundary



Effect of the Magnetic field inhomogeneity

Wave-phase

Lorentz force can be compensated by inhomogeneity of magnetic field

$$\phi = kz - k\int \nu(x)dx - \omega t$$

$$v_\phi = \omega / k = const \qquad \Omega_{0x} = qB_{0x}/mc$$

$$\mathbf{B}_0 = B_x \mathbf{e}_x + B_z(x)\mathbf{e}_z \qquad \nu(x) = B_x / B_z(x) = 1$$

Equations of motion in gyro-resonance

$$\begin{cases} \dfrac{dv_\perp}{dt} = v_\perp \dfrac{\nu}{1+\nu^2}\dfrac{d\nu}{dt} + \dfrac{q|\mathbf{B}_\delta|}{mc}(v_\parallel - v_\phi)\sqrt{1+\nu^2}\sin\phi_0 \\ \dfrac{dv_\parallel}{dt} = v_\parallel \dfrac{\nu}{1+\nu^2}\dfrac{d\nu}{dt} - \dfrac{q|\mathbf{B}_\delta|}{mc} v_\perp \sin\phi_0 \\ v_\parallel = -\dfrac{q|\mathbf{B}_0|}{mck} + v_\phi \end{cases}$$

Initial conditions: $(v_{\perp 0}^2, \nu_0)$

$$\Rightarrow \quad v_\perp^2 = v_{\perp 0}^2 + \frac{\Omega_{0x}^2}{k^2}\left[\frac{2\omega}{\Omega_{0x}}(\nu_0 - \nu) + \frac{1}{\nu_0^2} - \frac{1}{\nu^2}\right]$$

$v_\perp^2 > v_{\perp 0}^2$ **Energy gain corresponds to** $\nu_0 > \left(\Omega_{0x}/2\omega\right)^{1/3}$

$$\max\left(v_\perp^2 - v_{\perp 0}^2\right) = v_\phi^2 \left(\frac{\Omega_{0x}}{\omega}\right)^{4/3}\left(2\bar{\nu} + \frac{1}{\bar{\nu}^2} - 2\right) \qquad \bar{\nu} = \nu_0 \left(\frac{\Omega_{0x}}{2\omega}\right)^{1/3}$$

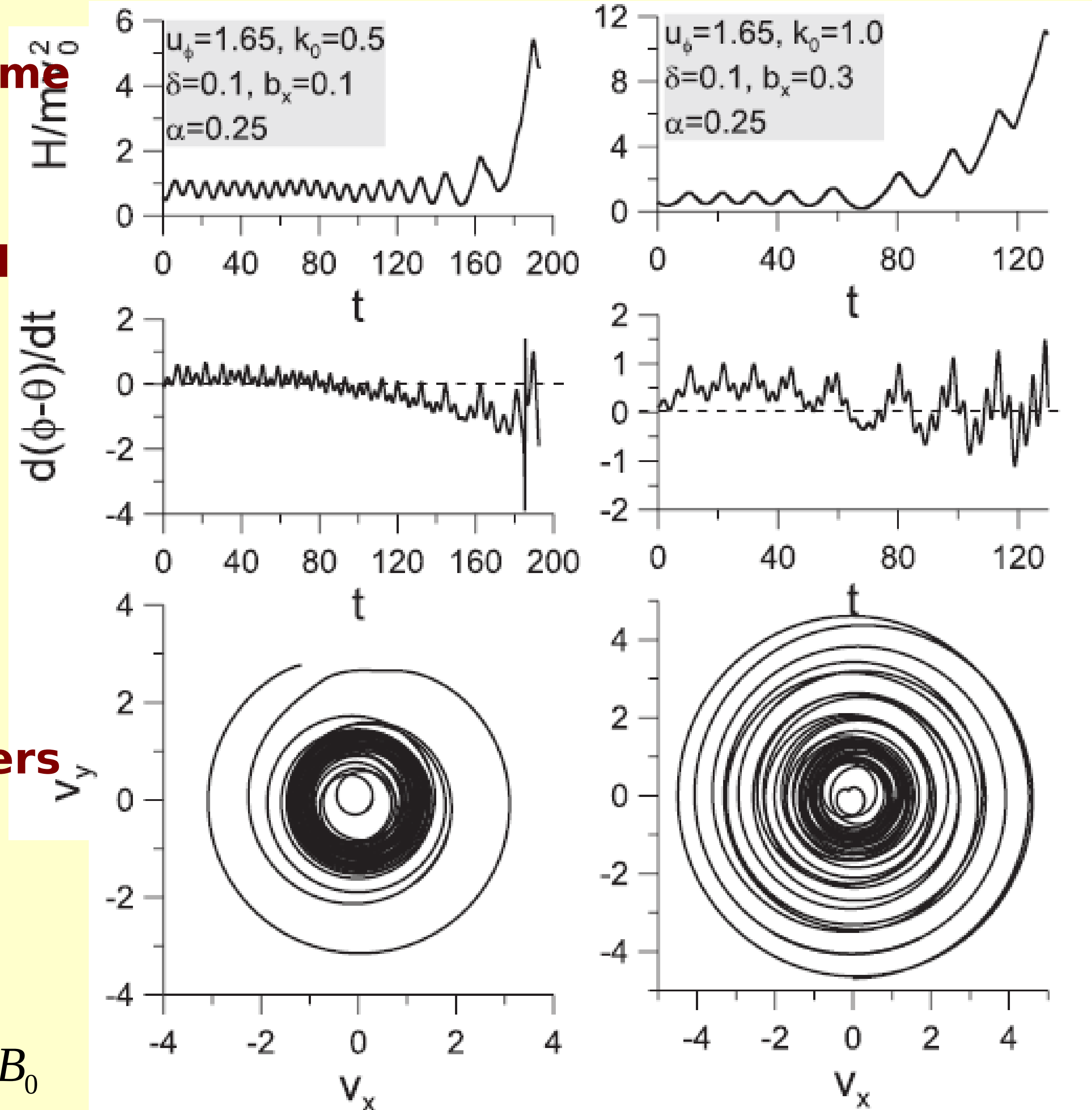
Particle trajectories

ergy as function of time

ergy gain correspond
resonant condition

$$d(\phi-\theta)/dt=0$$

rajectory in plane
erpendicular
o magnetic field



System parameters

$$B_z=B_0(1+\alpha x/\rho_0)$$

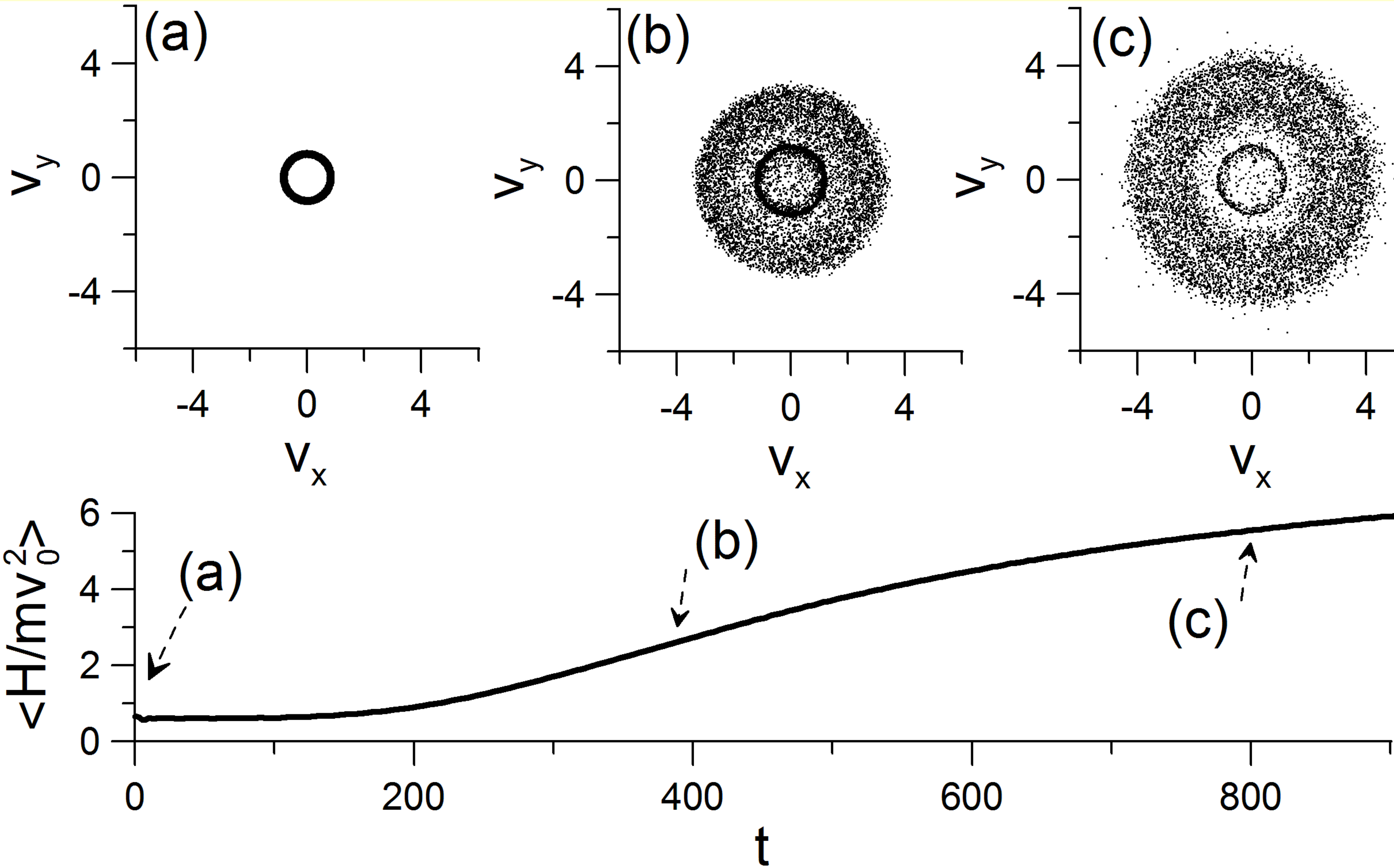
$$\delta=B_\delta/B_0,\ b_x=B_x/B_0$$

$$\rho_0=v_0 mc/qB_0$$

$$u_\phi=v_\phi/v_0,\ k_0=kv_0 mc/qB_0$$

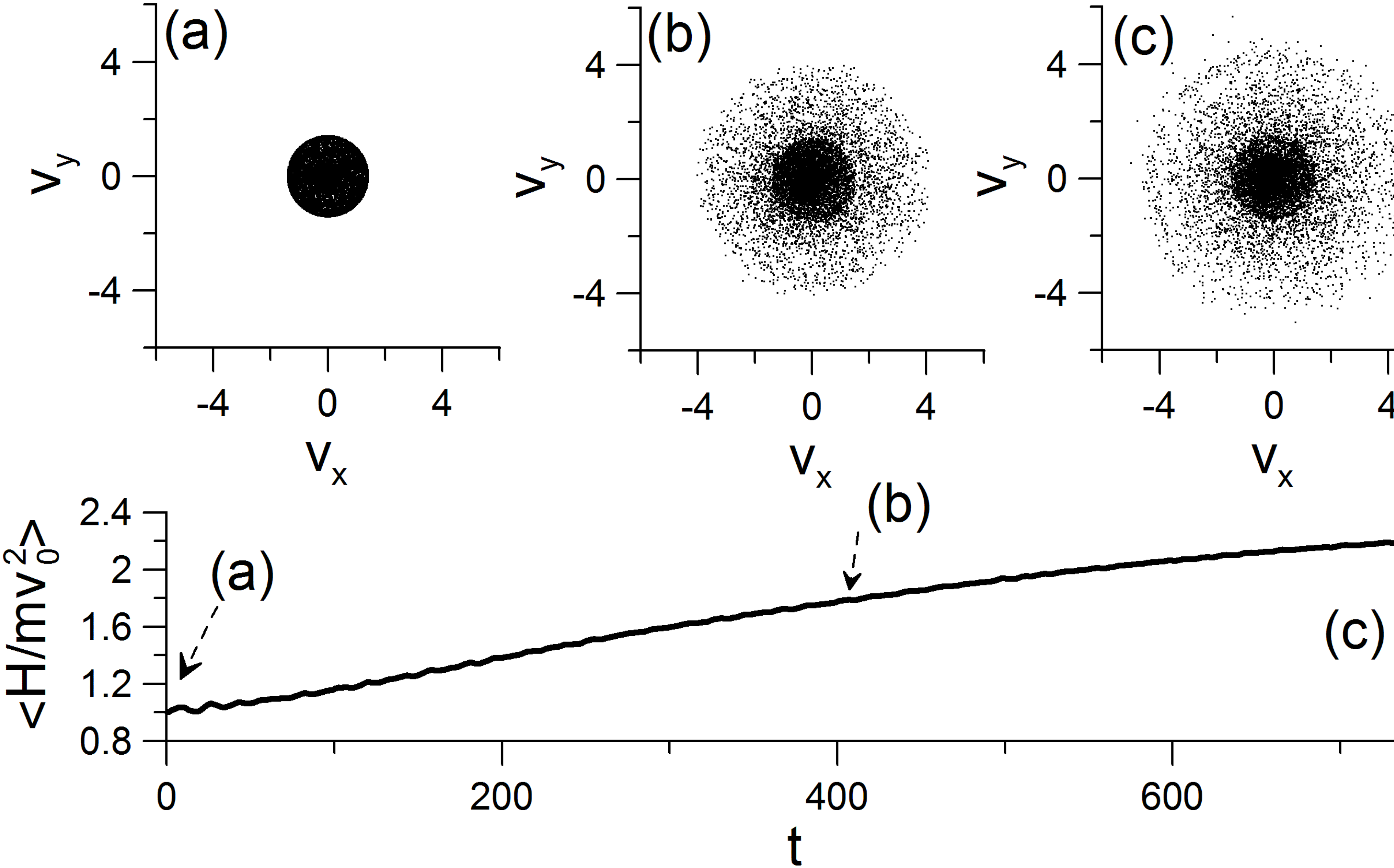
Energy distribution

resonant particles are considered

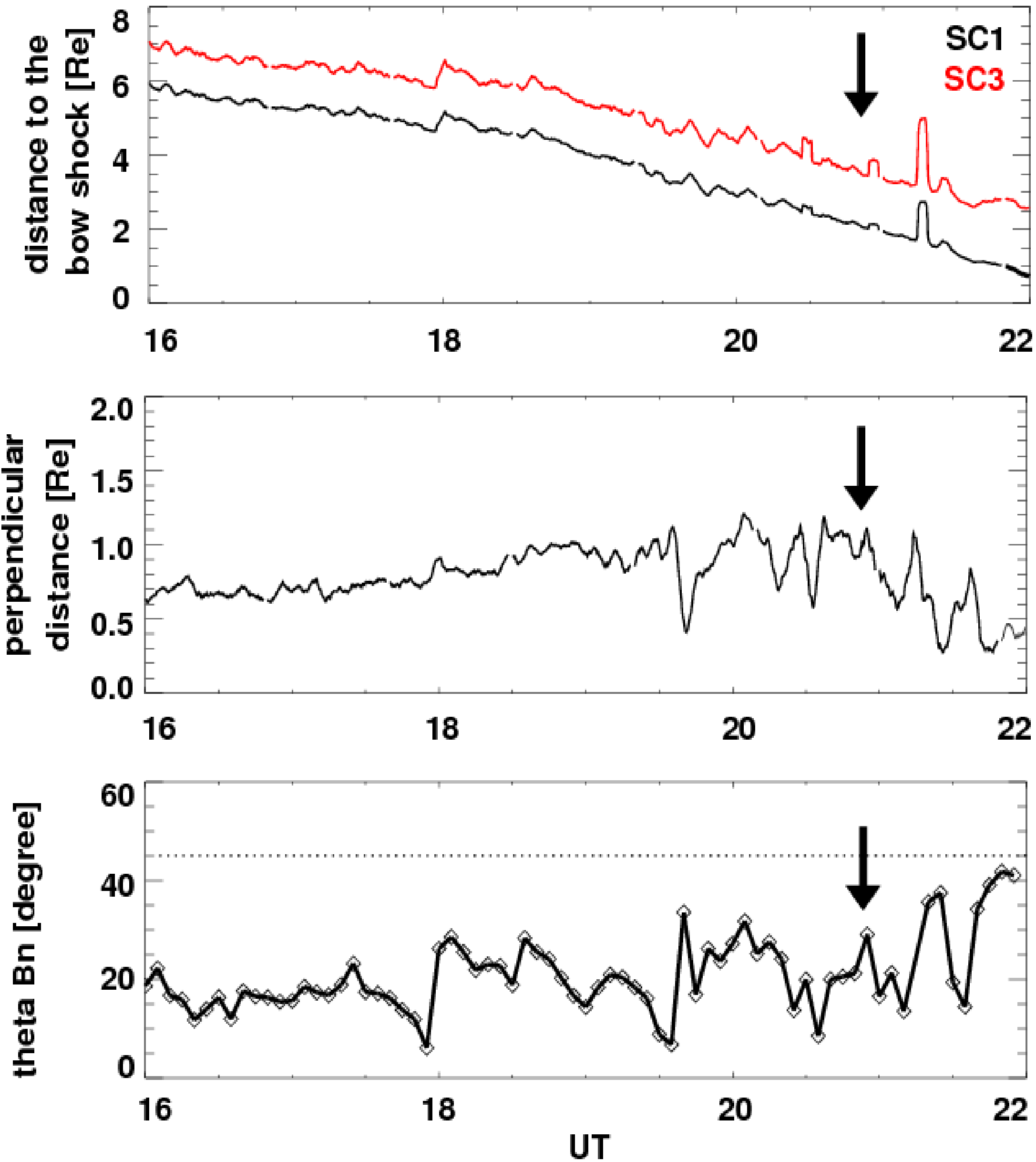


Energy distribution

All ensemble with initial energy v_0 is



The upstream ion event on 18th of February, 2003

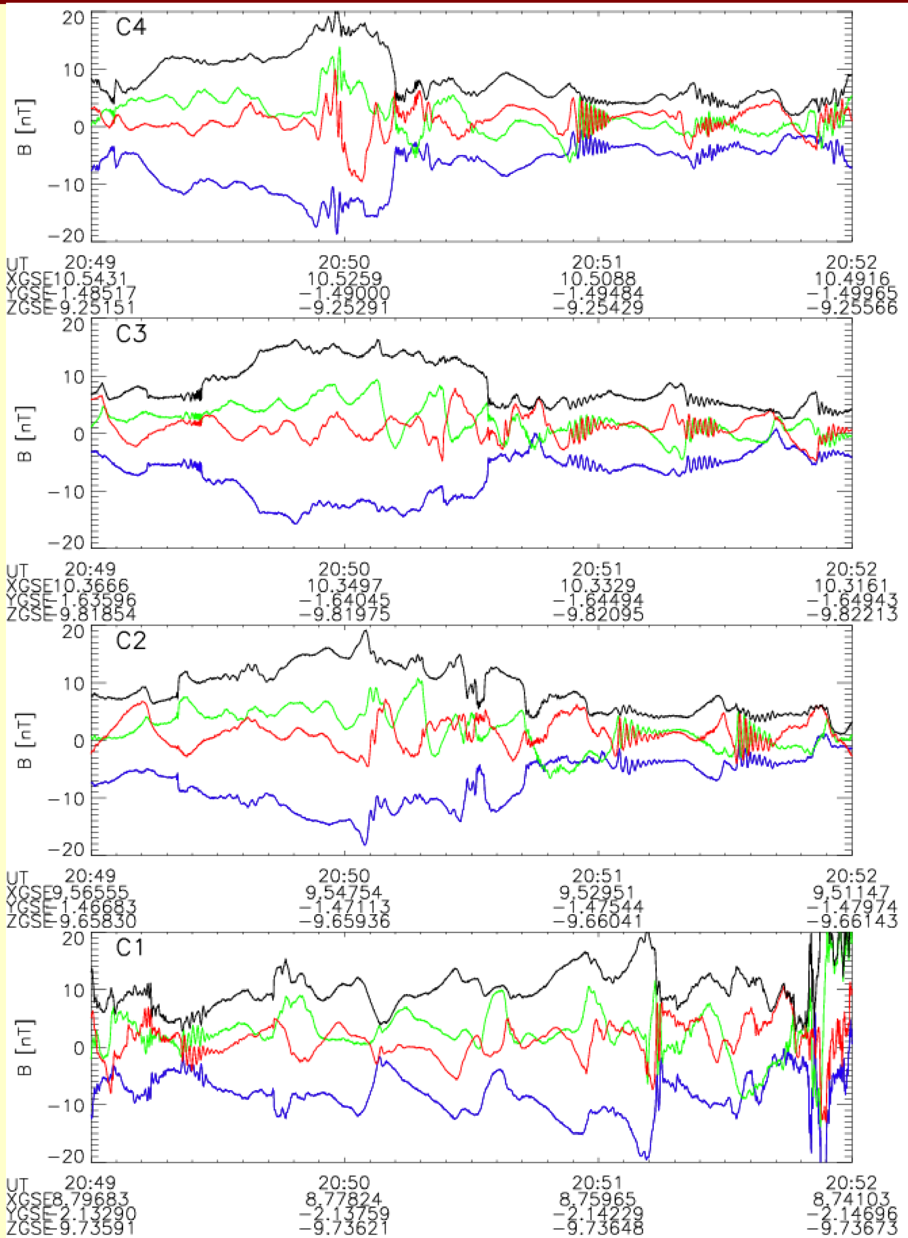


The distance of SC1 (black) and SC3 to the bow shock along the magnetic field line; it can be observed that SC1 was situated closer to bow shock while SC3 was situated further upstream.

The distance between the two spacecraft in the perpendicular direction (i.e., related to the direction of the local magnetic field).

The angle between the local magnetic field and the bow shock normal direction. The black arrow marks the time period of the detailed analysis when the seed particle population was recorded.

Magnetic field measurements



velocity value about 490 km/sec in a frame of Cluster spacecraft.

V_A=80-100 km/sec

wave frequency in a frame of the solar wind is equal to 0.2 Hz

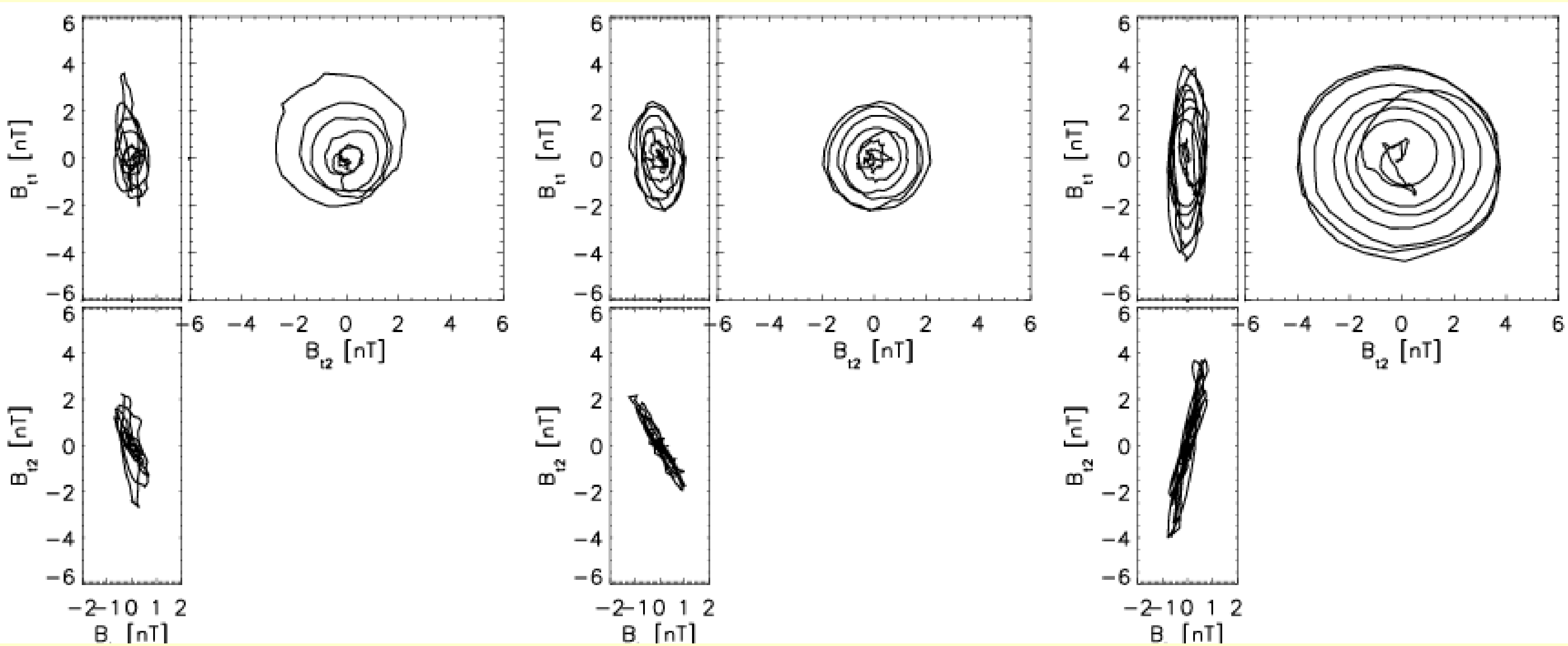
the wavelength 350-490 km.

The resonance conditions for ions trapping by the wave field:

$$\Omega_i = \vec{k}\vec{V}_i - \omega_{wave}$$

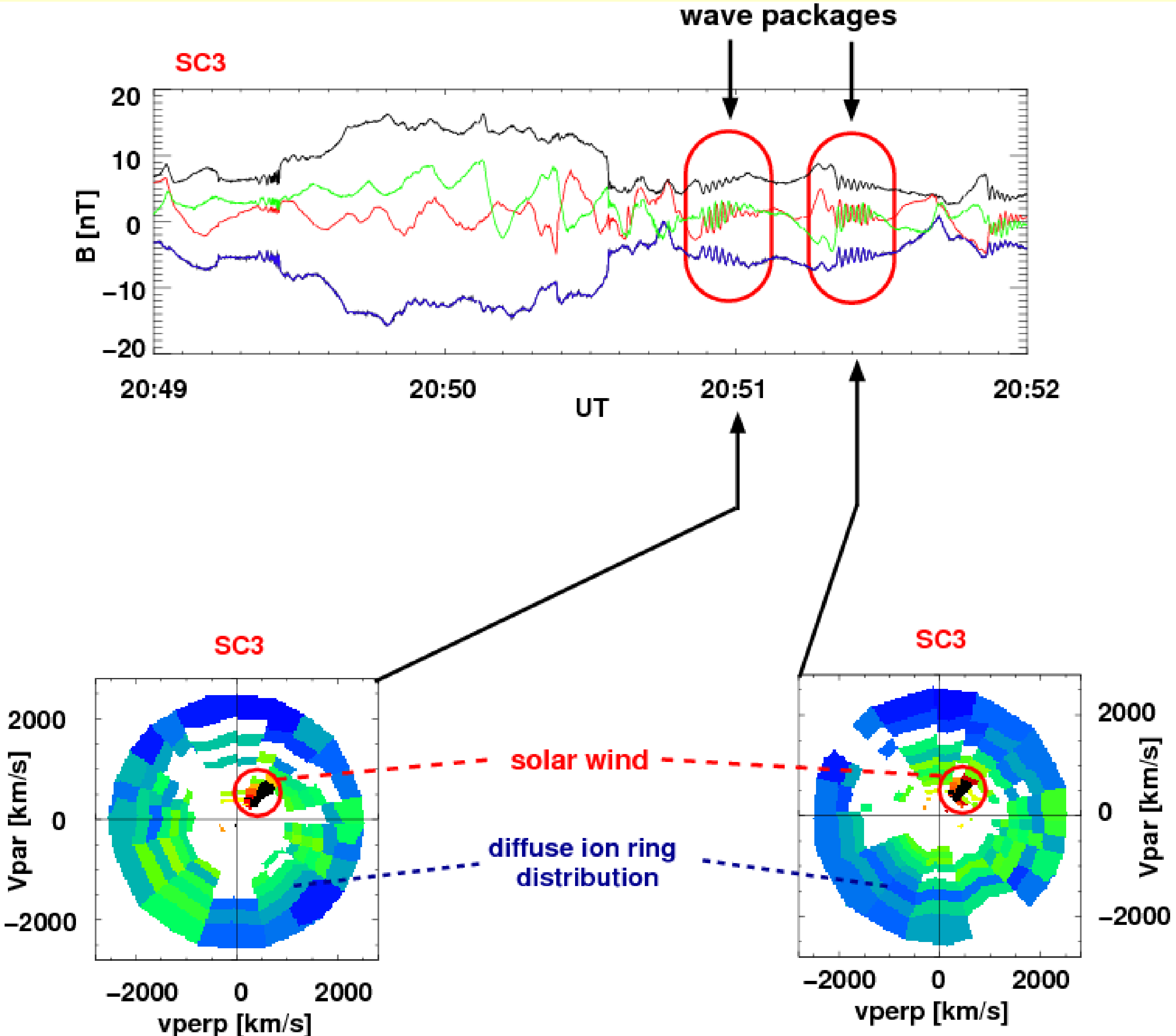
are satisfied for diffusive reflected ions with velocity about 400 km/sec

Wave polarization



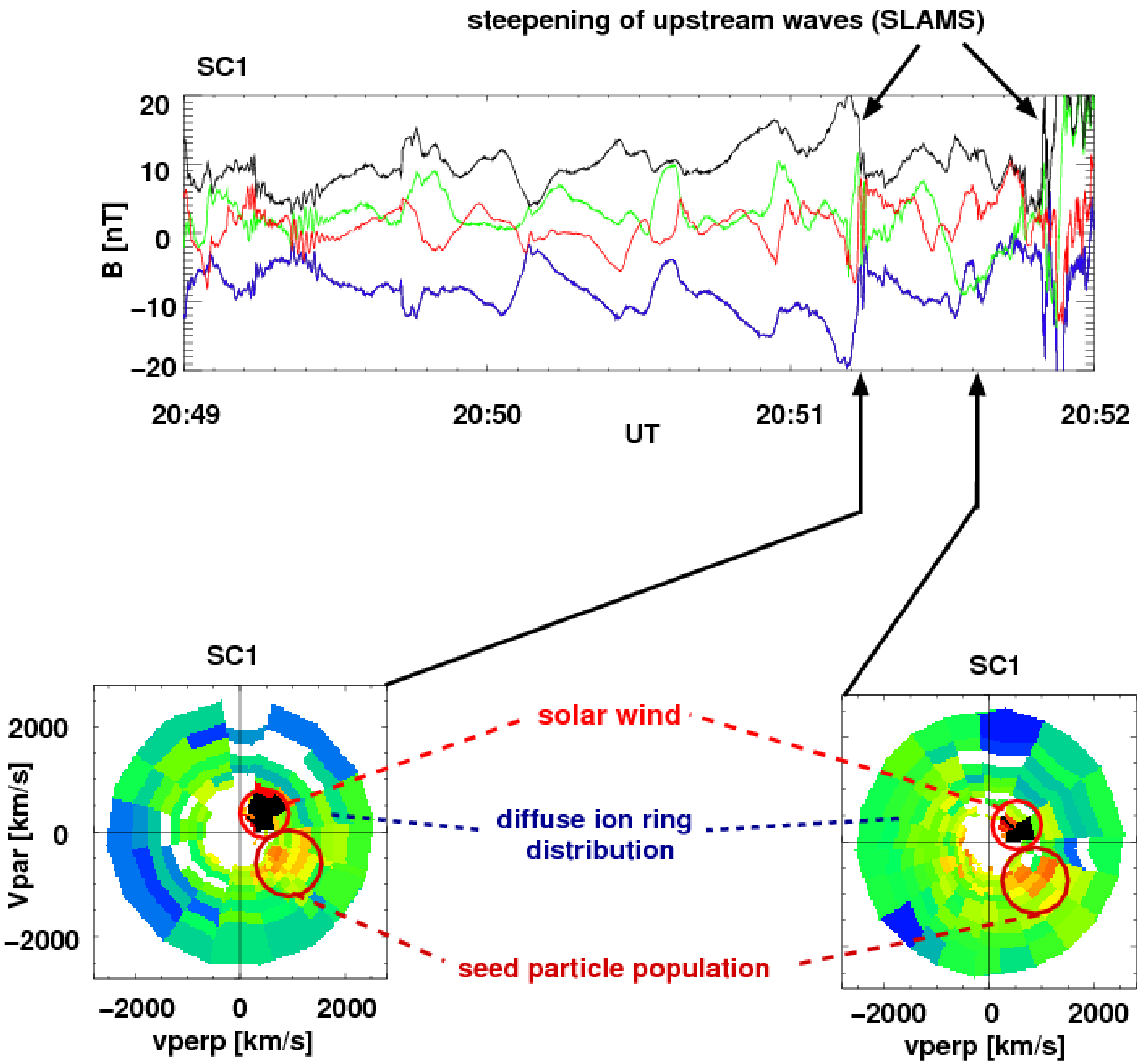
The hodograms of the three wave packets observed by Cluster spacecraft in the MVAB reference frame. It can be clearly seen that all three wave packets consist of circularly polarized transversal waves.

Particle fluxes



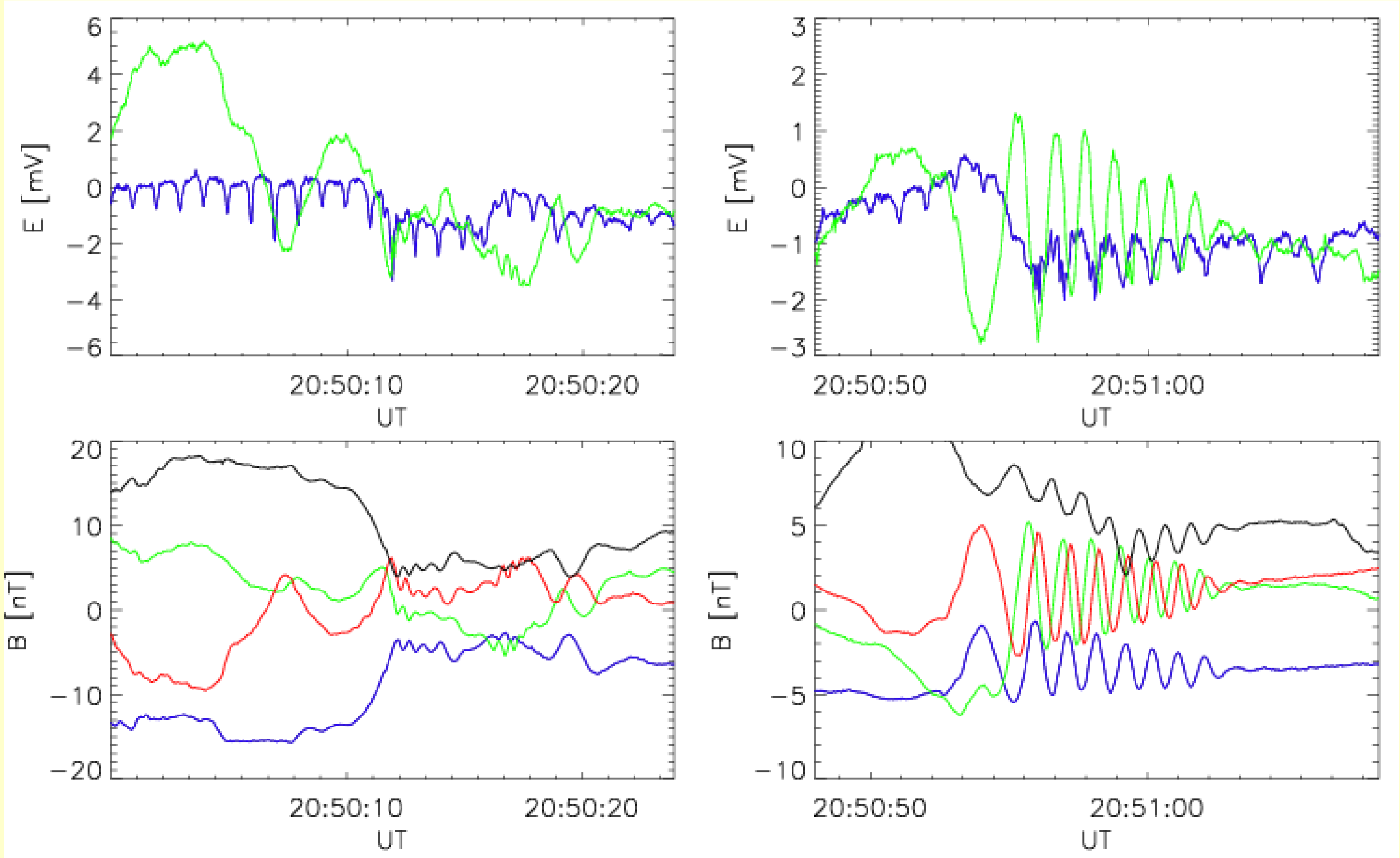
The magnetic data recorded by SC3; the first two wave packets are highlighted (red). Attached to this upper panel there are two ion distributions in velocity space taken at the times by SC3 when of the two first wave packets were observed. The two ion distributions presents quite similar characteristics: the highly isothropic ring of the diffuse ions can be observed together with the marked beam-like distribution of the solar wind.

Particle fluxes



the magnetic field detected aboard C1: the SLAMS boundaries are marked with arrows. Here the ion distributions are shown in the close vicinity of the magnetic boundary. Besides the ring of diffuse ions and the solar wind beam (both marked on the figure) it can be observed a highly concentrated beam-like distribution in the antiparallel direction related to the solar wind beam. It can also be seen that the velocity of the ions forming the beam is slightly higher than of the ions forming the solar wind beam; typical characteristics of a seed ion population

Electric field on the boundary



The electric field X (in blue color) and Y (in green color) component values recorded by the EFW instrument onboard SC4. The units are in mV/m at the time interval when the magnetic field structure was observed, which can be seen in the lower panel. It can be clearly observed that at the magnetic boundary (lower panel) there is no significant jump in the electric field value.

Conclusions

In spite of the differences between astrophysical and Earth bow shocks there are several important and crucial for the acceleration problem questions, which can be identified and studied in details by in situ observation of physical processes involved into acceleration in the solar system

We provide observational evidence of the formation of the so-called seed particles in the foreshock region for the first time. Our results based on multipoint simultaneous measurements in front of the Earth's quasi-parallel bow shock show that the **gyroresonant surfing acceleration on the magnetic field inhomogeneity is indeed an effective ion acceleration mechanism** capable of producing the seed ions which is an essential element of the diffusive shock acceleration