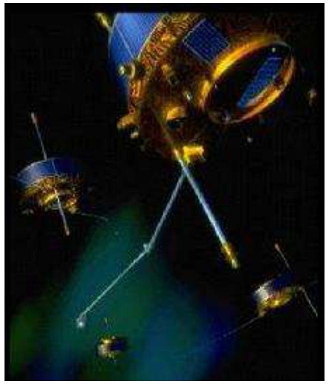
Geospace Revisited, Rhodes (Greece), 15-20 September 2014

Ion acceleration at the Earth’s parallel bow shock: what can we learn from Cluster?



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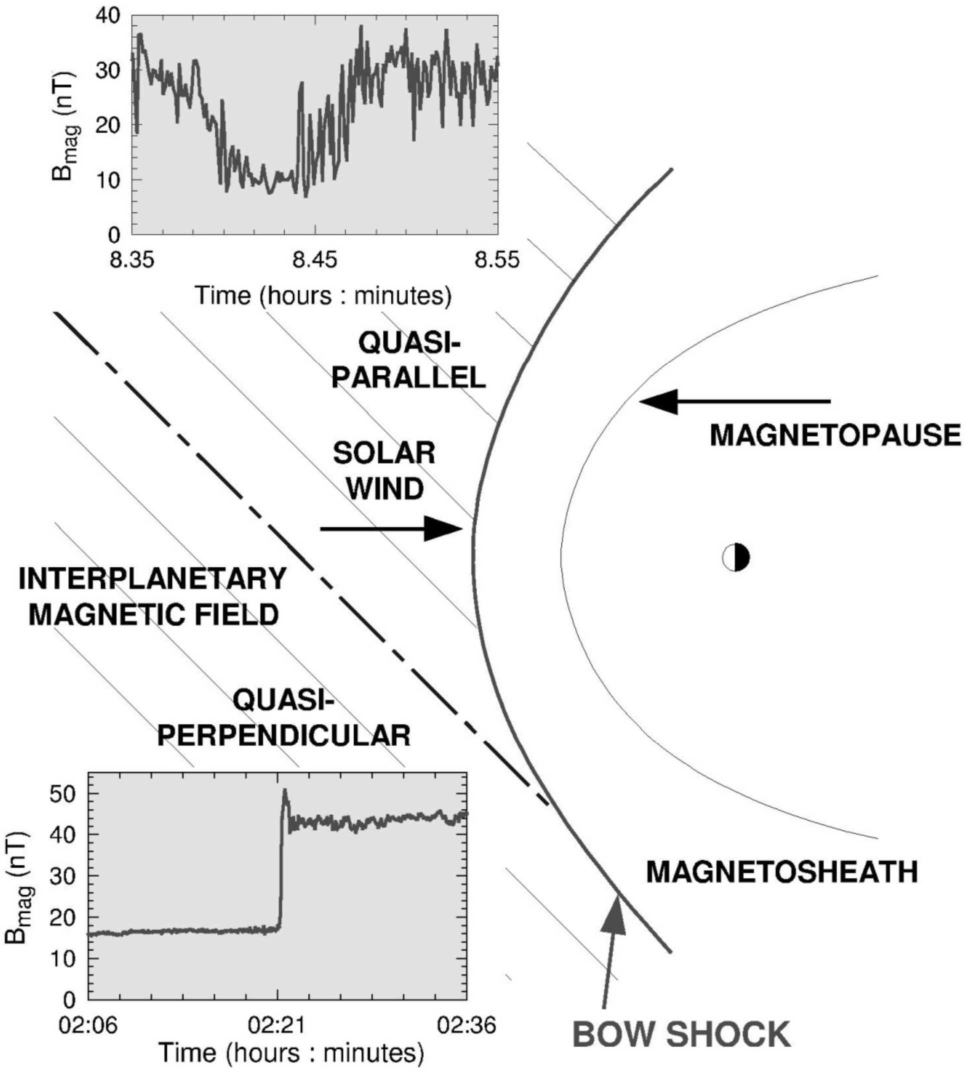
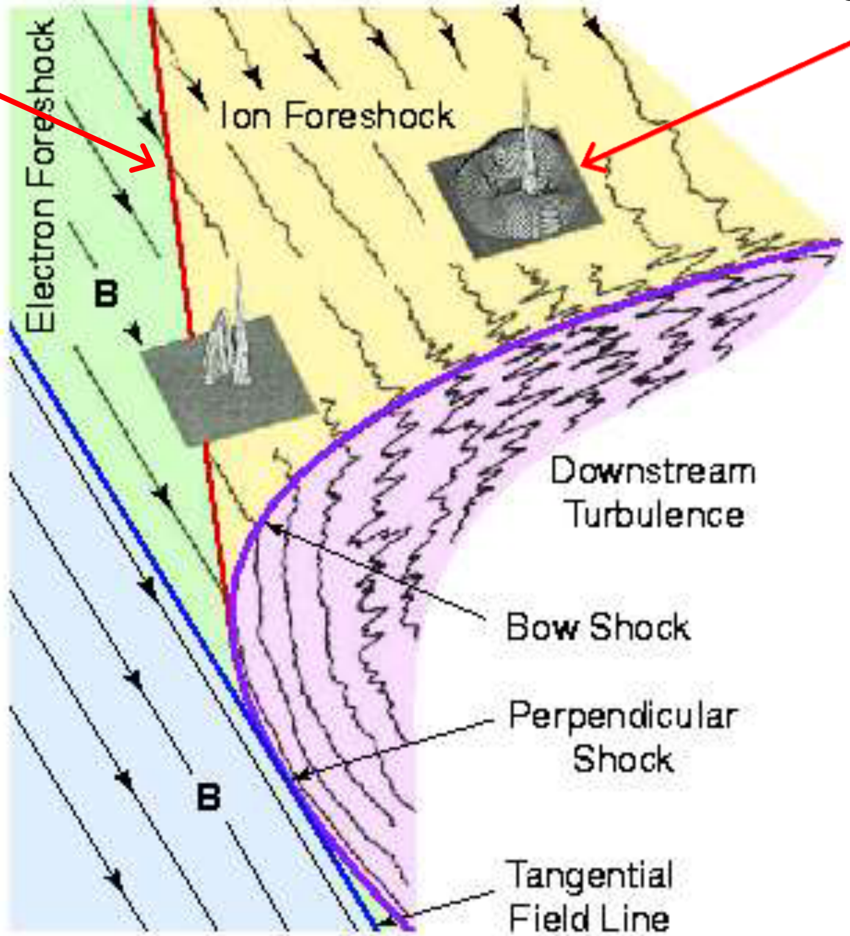
HUNGARY'S RENEWAL

The project is supported by the European Union and co-financed by the European Social Fund.


40
30
20
10
0
B_mag (nT)
8.35
8.45
8.55
Time (hours : minutes)
QUASI-PARALLEL
SOLAR WIND
MAGNETOPAUSE
INTERPLANETARY MAGNETIC FIELD
QUASI-PERPENDICULAR
50
40
30
20
10
0
B_mag (nT)
02:06
02:21
02:36
Time (hours : minutes)
MAGNETOSHEATH
BOW SHOCK

Energized ions upstream of Earth's bow shock



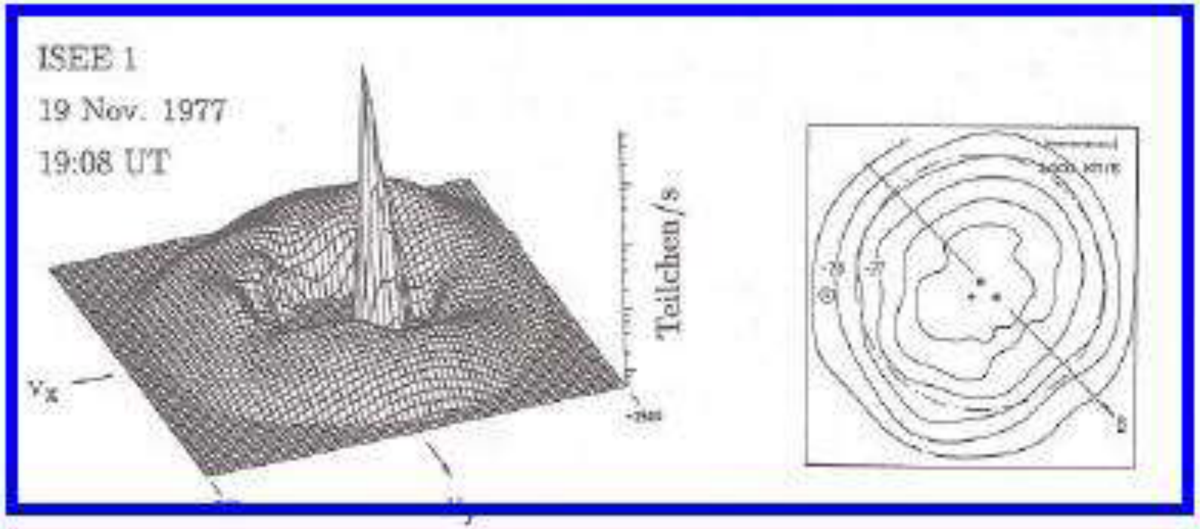
quasi-parallel

field aligned beam (FAB)

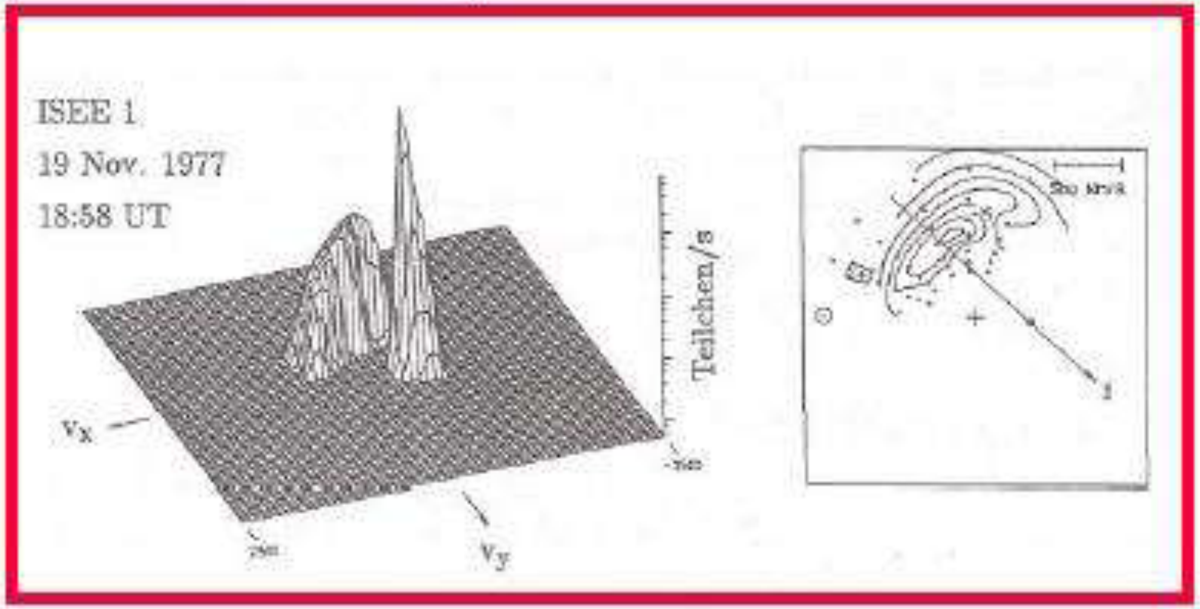
diffuse ions

quasi-perpendicular

typical Diffuse and FAB ion distributions



E≈10-300 keV



E≈4-7 keV
($v \approx 2v_{sw}$)

Paschmann et al (1981)

The major mechanism responsible for particle acceleration by shock waves is the

Diffusive Shock Acceleration (DSA)
or
first-order Fermi acceleration

the acceleration to work efficiently there are some important conditions to be satisfied

as shown by

Malkov & O'C Drury (2001), Reports on Progress in Physics

D. Burgess, E. Möbius & M. Scholer (2012), Space Sci Rev

These conditions are:

a) some initial „seed” population (i. e., a lower energy supra-thermal ion population) should be created upstream or downstream of the shock that should be able to cross the shock front;

>> the question of injection

b) there should exist scattering centers or objects around the shock front in its vicinity that will deviate particles from their free motion and will result in turning them to opposite direction

>> pitch-angle scattering

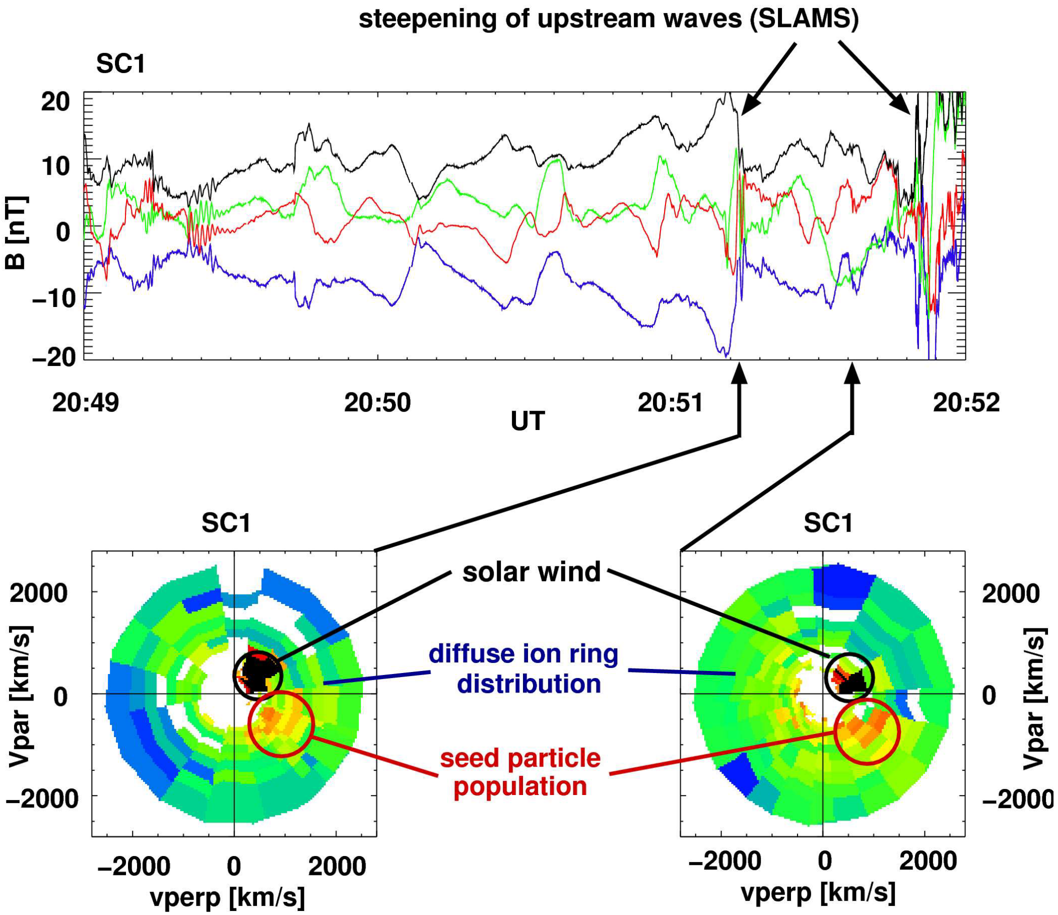
c) the exponential spectra of diffuse ions:

>> free escape boundary?

Injection

Gyro-surfing (or gyroresonant surfing) acceleration proposed by:

Kuramitsu, Y., & Krasnoselskikh, V. 2005,
Physical Review Letters, 94, 031102



Evidence of gyrosurfing acceleration mechanism found.

The mechanism is capable of producing seed particles in abundance.

(*done in cooperation with V. Krasnosselskikh and O. Agapitov*)

Kis et al., 2013, Astrophysical Journal

Pitch-angle scattering of diffuse ions

Physical processes related to diffuse ions in front of the Earth’s quasi-parallel bow shock:

1. Pitch-angle scattering of diffuse ions by magnetic waves

2. Excitation of magnetic waves by diffuse ions

>>> the diffuse ions are scattered by self-generated waves !

These two physical processes together form a highly complex, feedbacked system, where the energetic ions and the waves influence each other continuously. (This ultimately results in acceleration of ions at the bow shock)

The result of spatial diffusion (scattering)against convection is:
the density of diffuse ions falls off exponentially from the shock front into the upstream region along the magnetic field line.

Previous work:

-using single spacecraft data
-had to be done on a statistical basis

Recent work:

-using multi-spacecraft data for the first time (Cluster)
-investigation of individual events becomes possible
-Cluster: separating the temporal and spatial variations

This study:

3 upstream ion events:

2003, 18th February, high solar wind velocity, vsw = 626 km/s

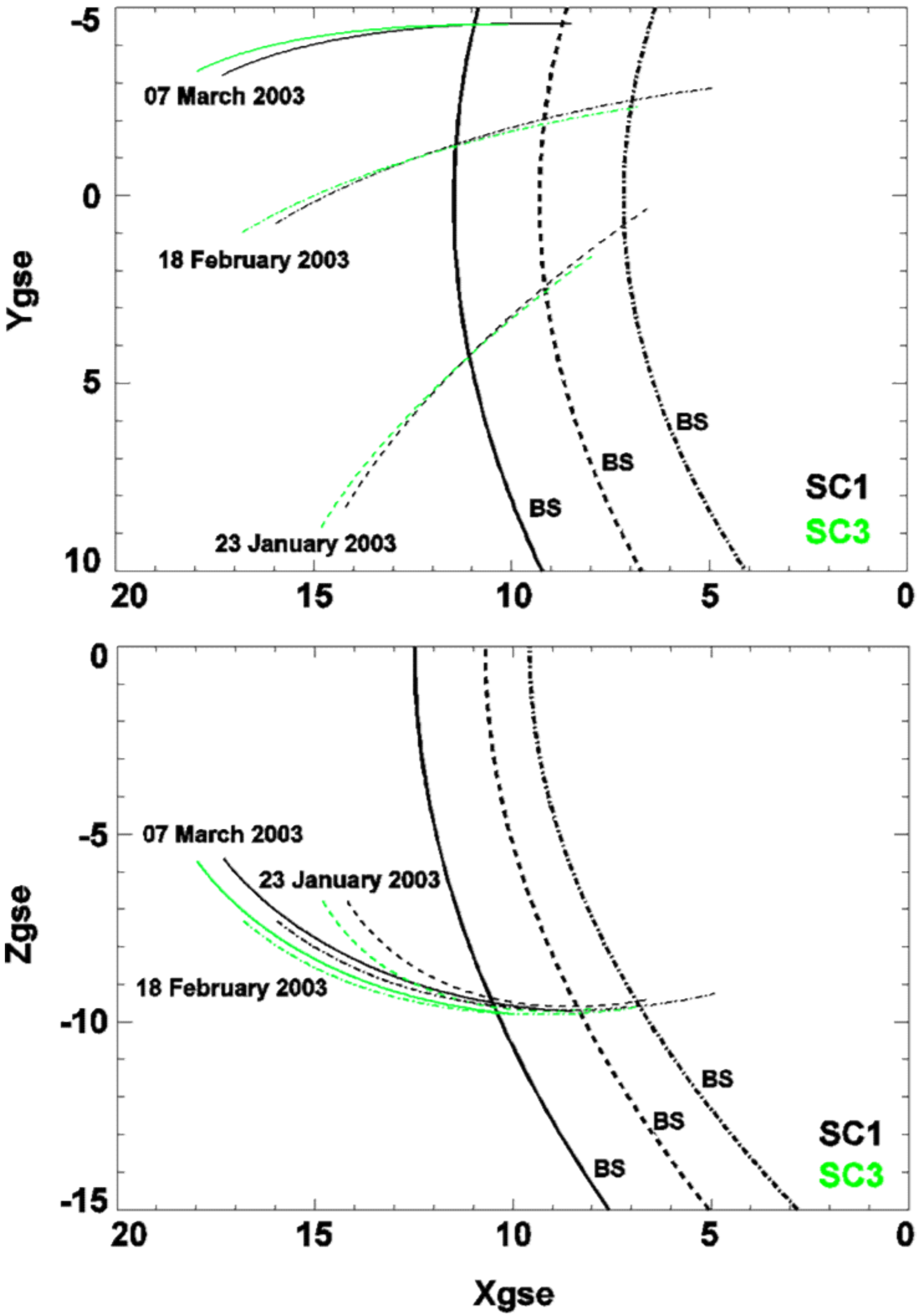
2003, 7th of March, medium solar wind velocty, vsw = 485 km/s

2003, 23rd of January, high solar wind velocity, vsw = 636 km/s

data from SC1 and SC3

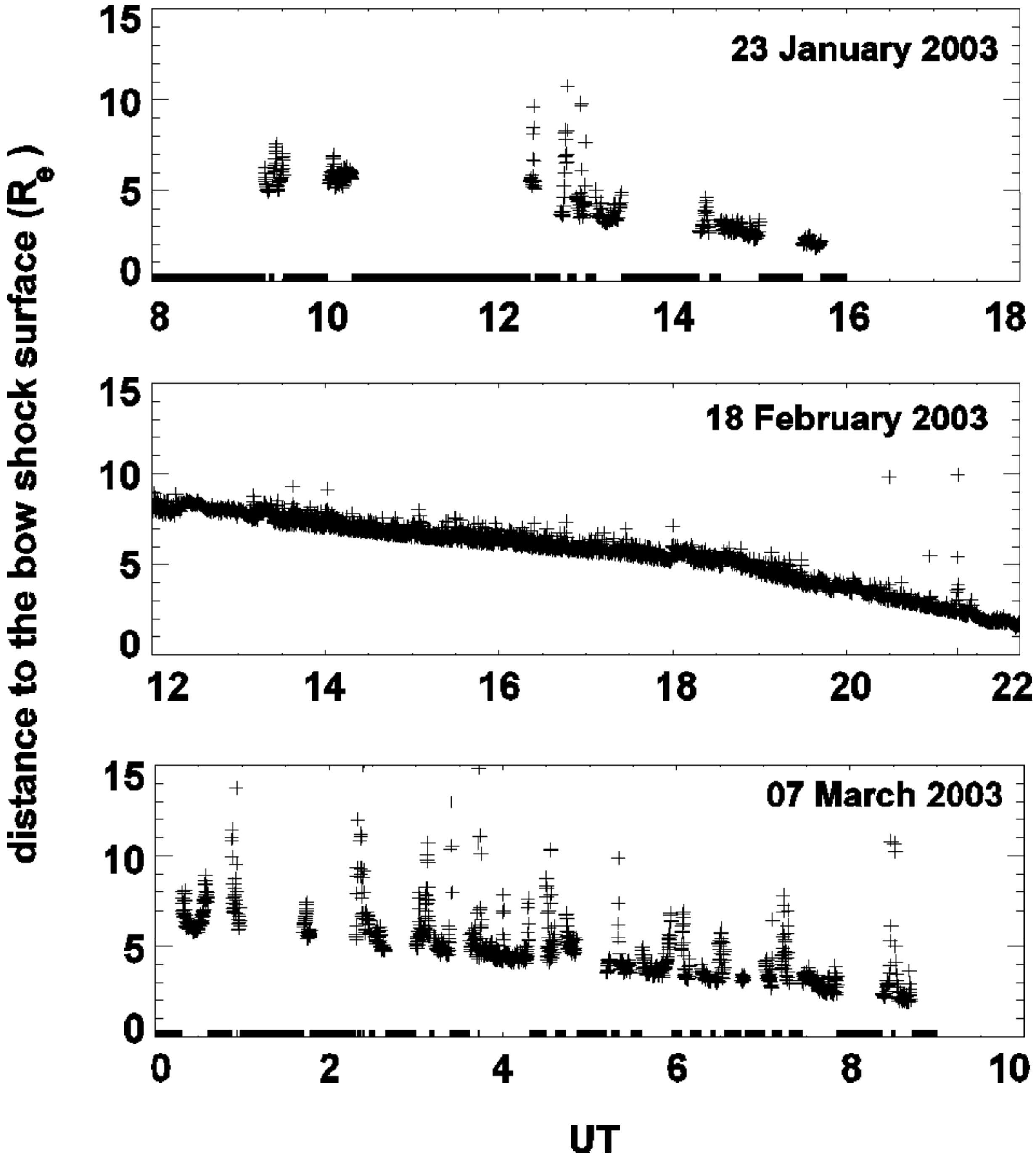
- CIS-HIA partial ion density data, between 10-32 keV
  (four energy ranges: 10-13, 13-18, 18-24, 24-32 keV)

- FGM high resolution data

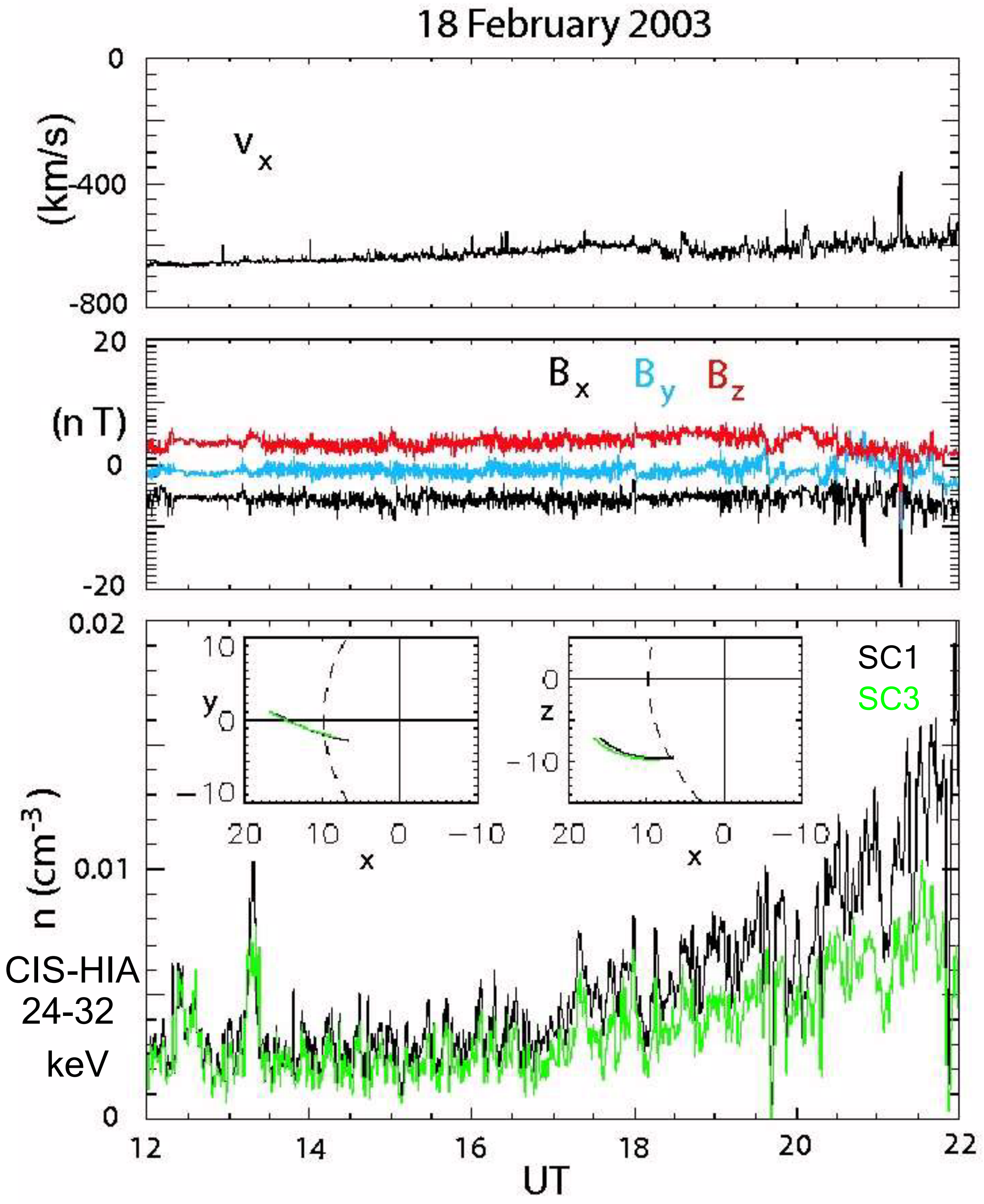

-5
0
5
10
Ygse
07 March 2003
18 February 2003
23 January 2003
BS
BS
BS
SC1
SC3
20
15
10
5
0
0
-5
-10
-15
Zgse
07 March 2003
23 January 2003
18 February 2003
BS
BS
BS
SC1
SC3
20
15
10
5
0
Xgse

Determination of the distance to the bow shock and of the ion density gradient

1. Using a bow shock model surface
2. Scaling the model to the actual (observed) crossing
3. Modifying the scaling according to variations in the solar wind pressure
4. Calculating the individual SC distances to shock intersection point along the local magnetic field line
5. Using the partial density differences at the two spacecraft and the difference in the SC distances for calculating the spatial gradient
6. The obtained gradient values were then attributed to the average distance of the two spacecraft from the shock

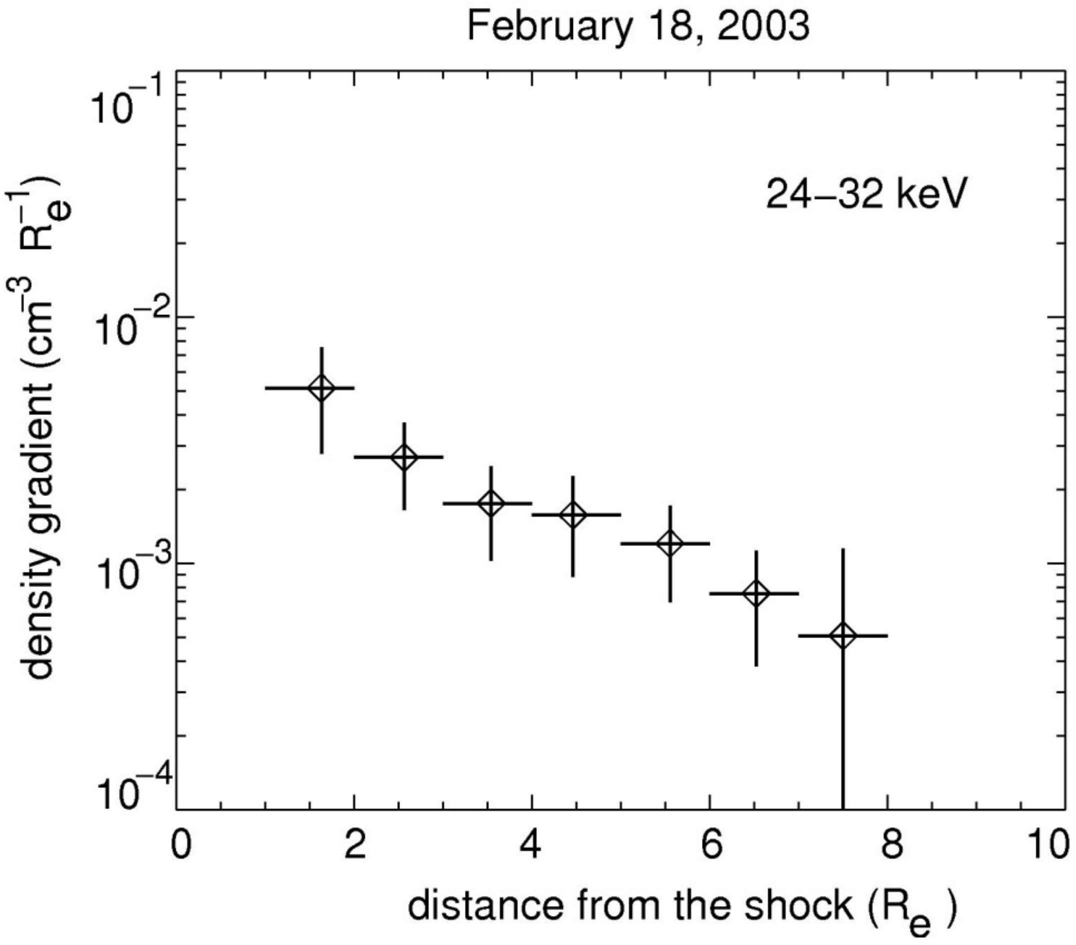


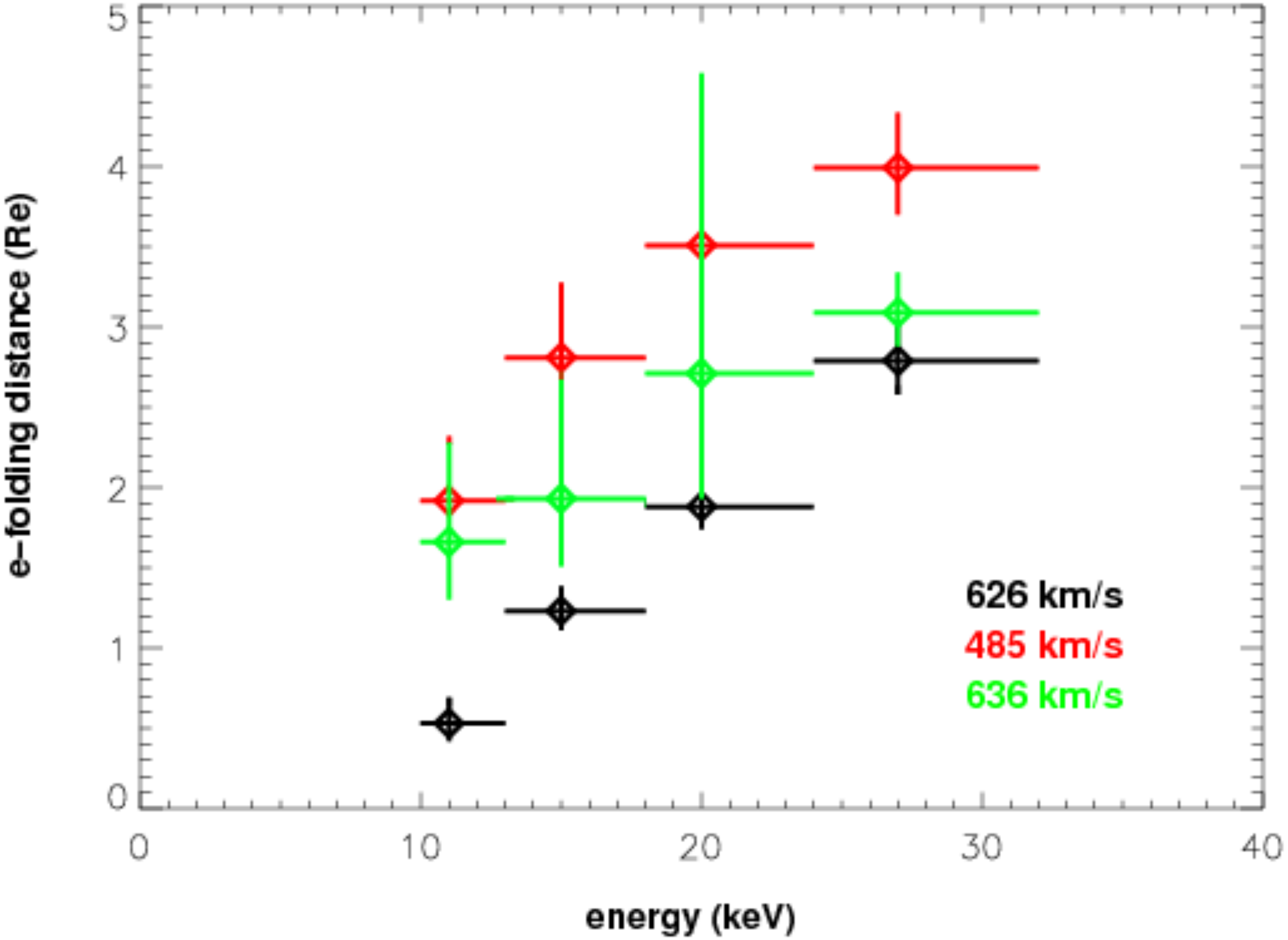
distance to the bow shock surface (R_e)
23 January 2003
18 February 2003
07 March 2003
15
10
5
0
8
10
12
14
16
18
12
14
16
18
20
22
0
2
4
6
8
10
UT



high solar wind velocity
upstream ion event

The upstream ion gradient was determined at different distances from the bow shock.
The distance to the bow shock was calculated by using a model bow shock surface (Peredo et al. 1995) that has been adjusted accorind to the changes in the solar wind density and velocity.


February 18, 2003
24–32 keV
density gradient (cm^{-3} R$_e^{-1}$)
distance from the shock (R$_e$)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10


e-folding distance (Re)
5
4
3
2
1
0
0
10
20
30
40
energy (keV)
626 km/s
485 km/s
636 km/s

Diffusion coefficient determination

$$L(E) = \frac{\kappa(E)}{V_{sw}}$$

$$\kappa(E) = \frac{V_{part}}{3} * \lambda(E)$$

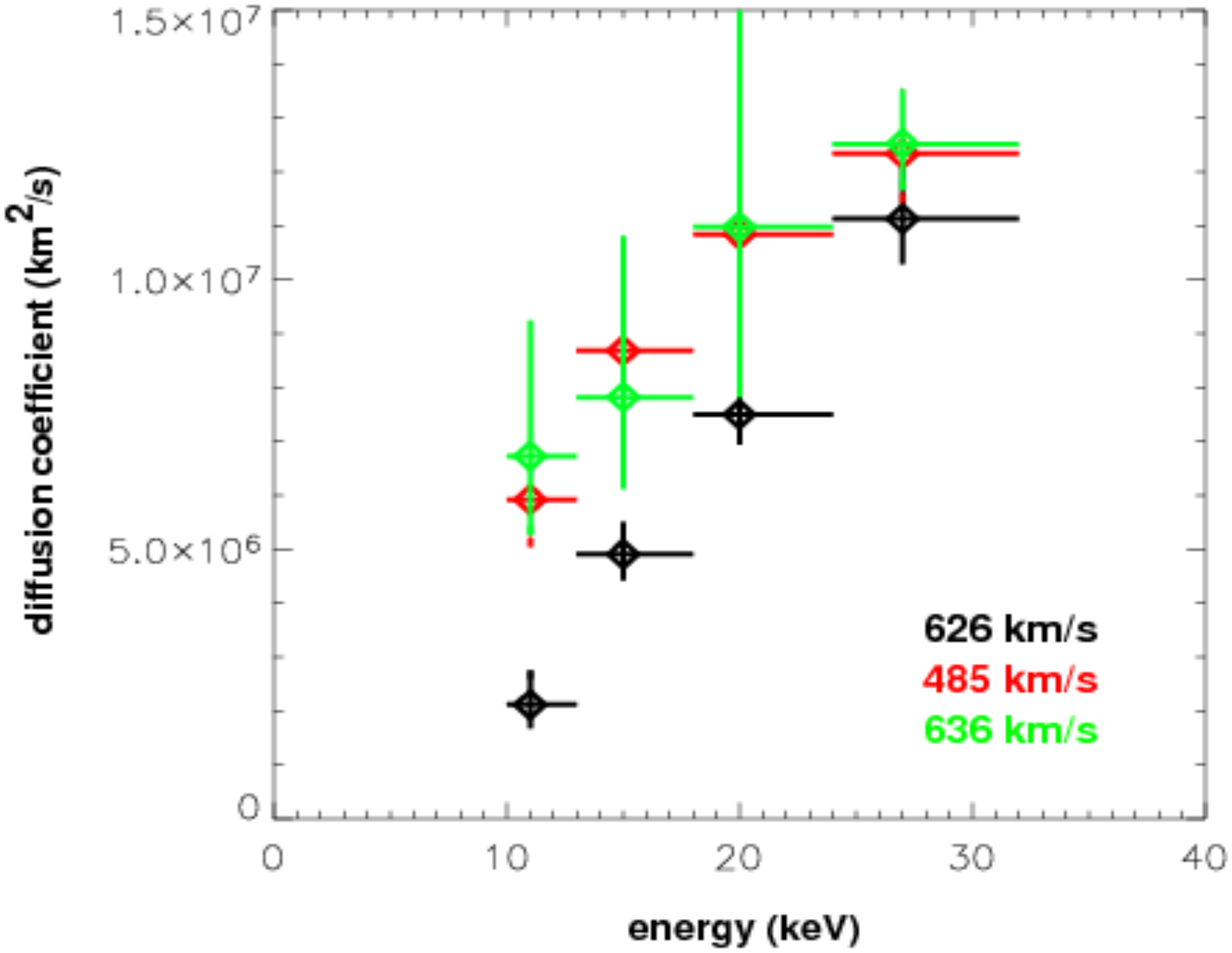
$L(E)$: e-folding distance

$\kappa(E)$: diffusion coefficient

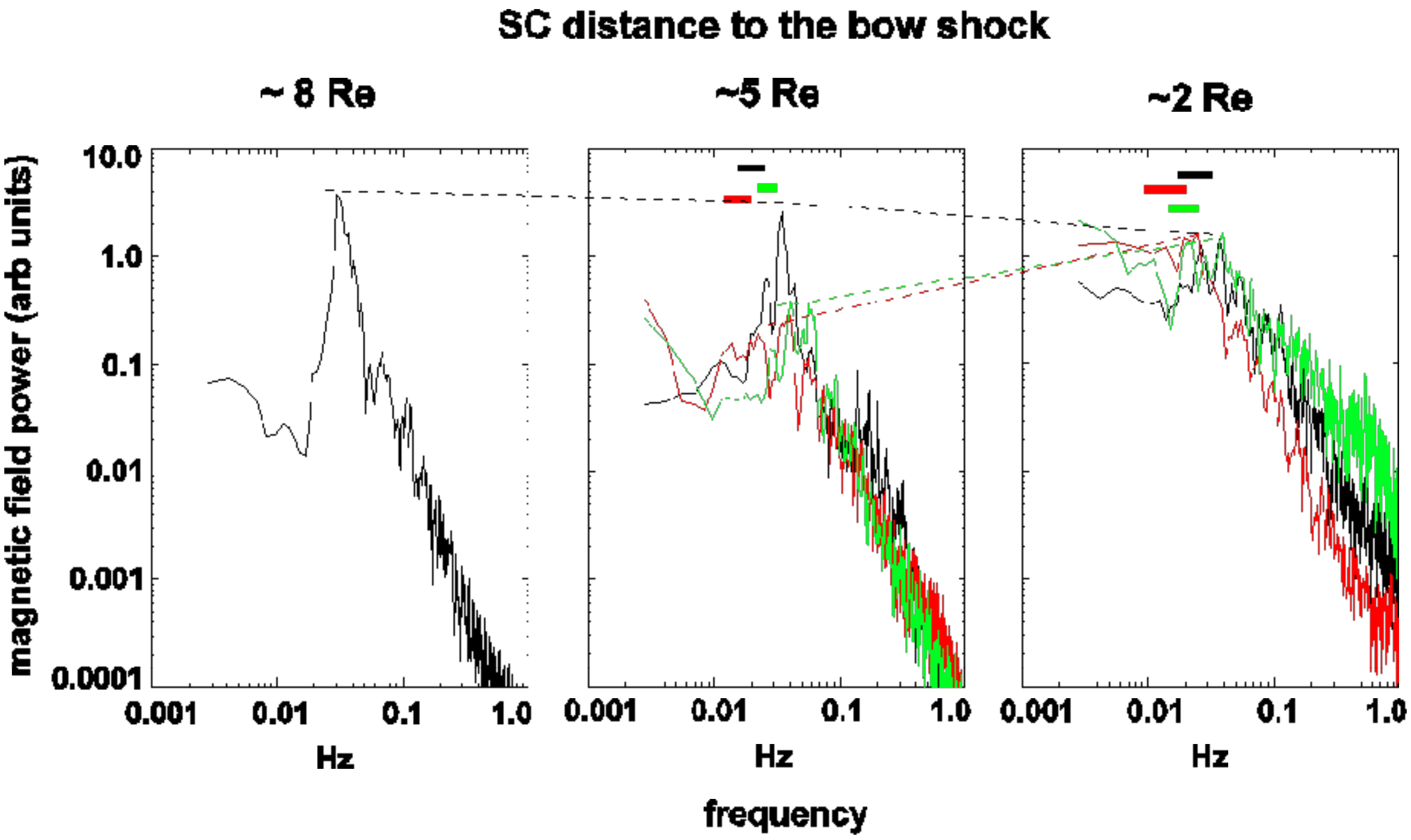
V_{sw} : solar wind velocity

V_{part} : energetic particle velocity

$\lambda(E)$: mean free path

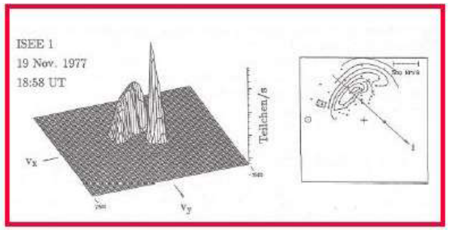


The diffusion coefficients match well at higher energies, but at lower energies there is an increasing difference between the three cases.

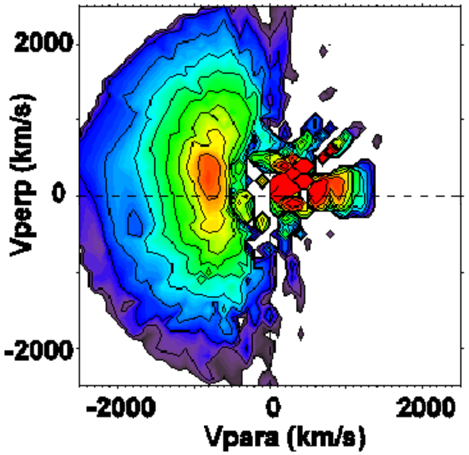


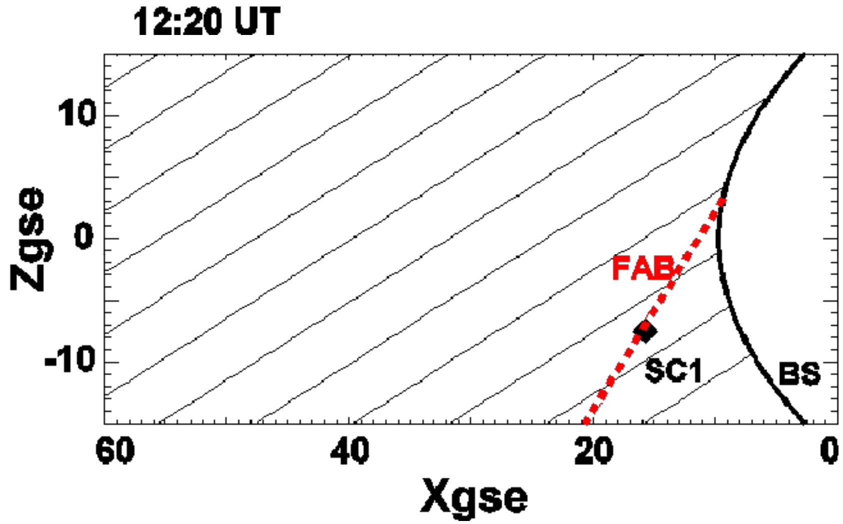
Evolution of transversal wave power as function of distance from the bow shock

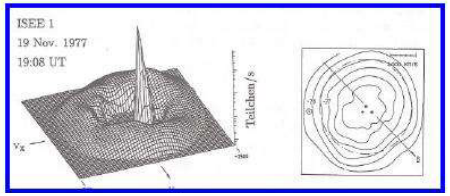
18 February 2003



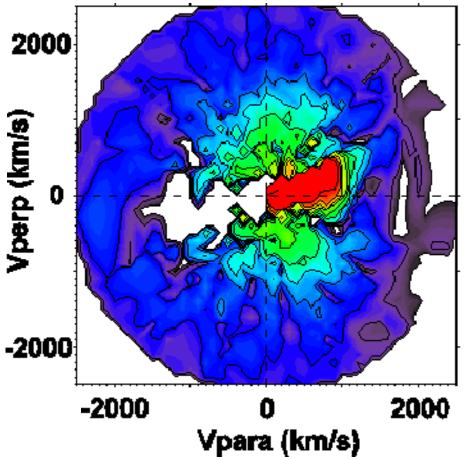
Field aligned beam
ion distribution

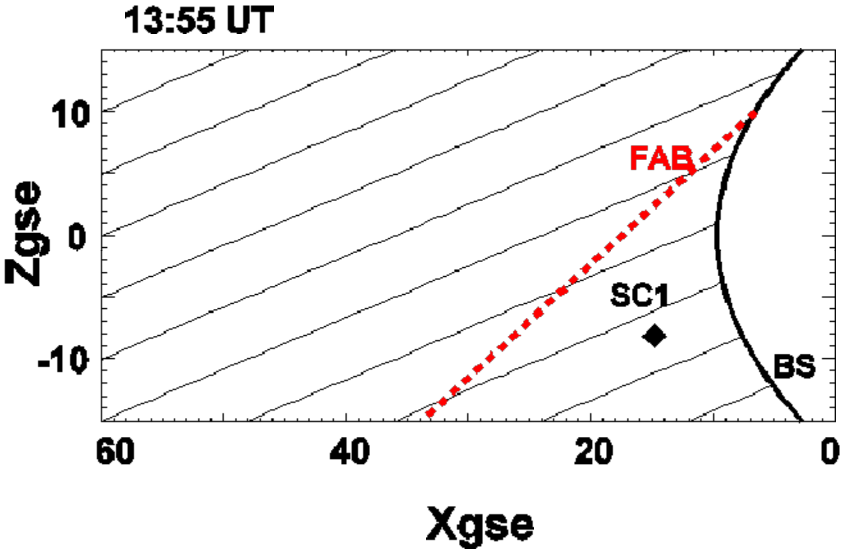


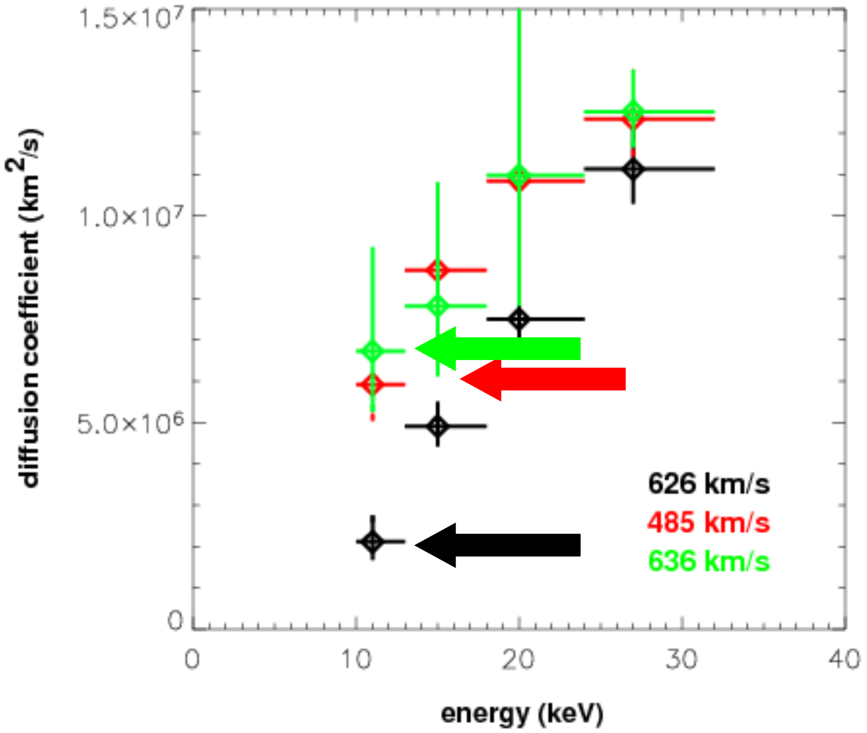


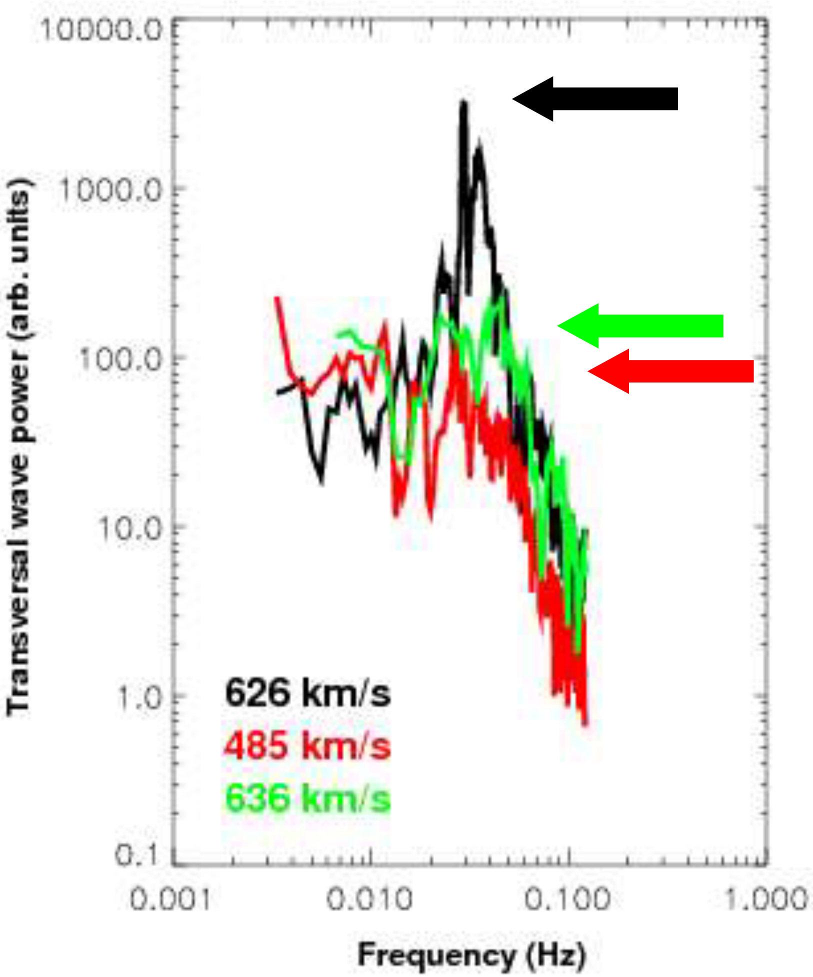


Diffuse ion distribution





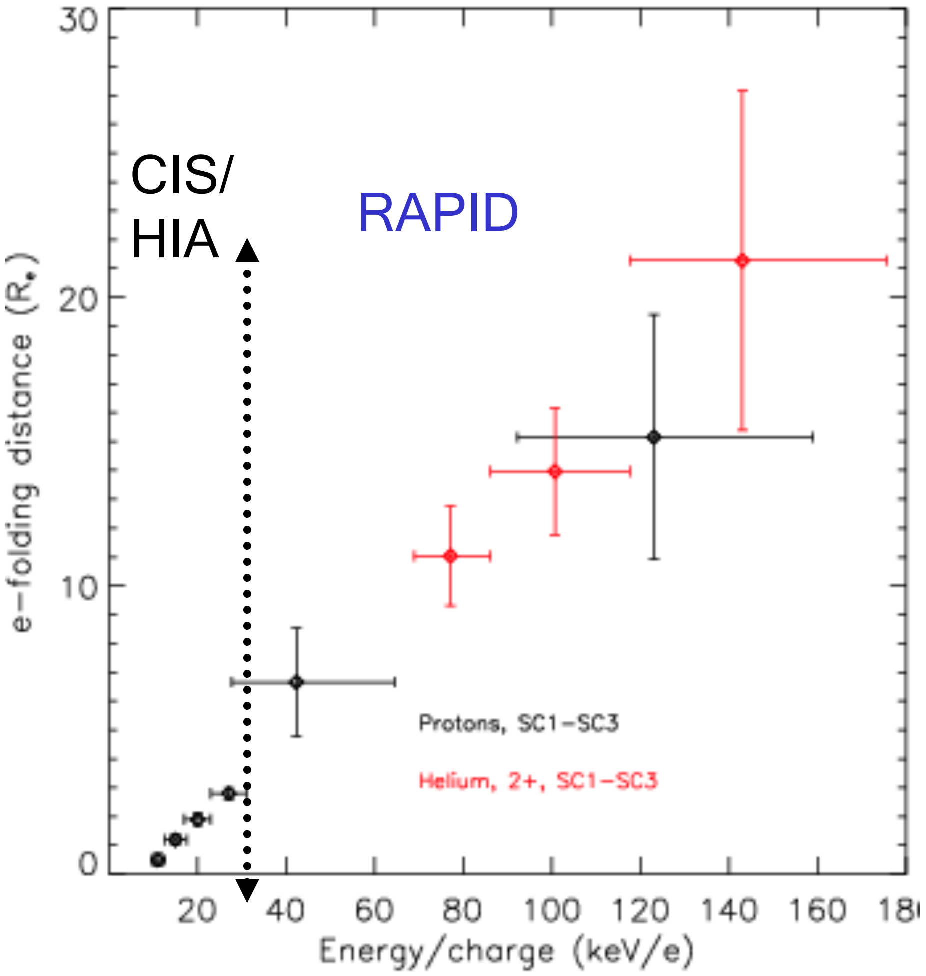




at about 10 keV ion energy the scattering in the quasi-parallel region is dominated by the quasi-perpendicular region through the convected waves generated by the FAB -- > enhanced diffuse ion scattering

Question: how often does this happen? Is it an extraordinary or a common case?

What happens on 30-160 keV ion energies?

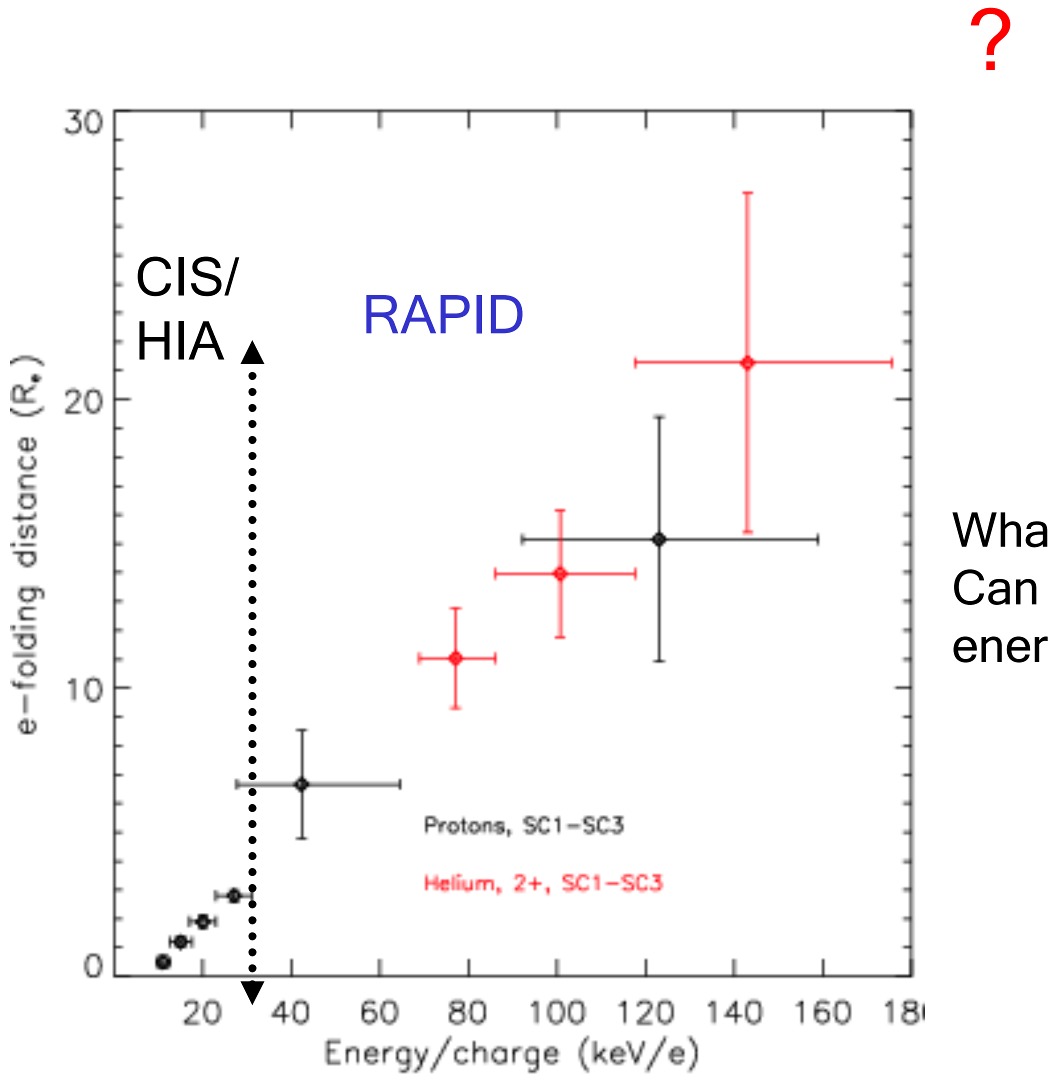


-extended analysis of the February 18, 2003 high solar wind velocity upstream ion event to higher energies using data from the RAPID instrument

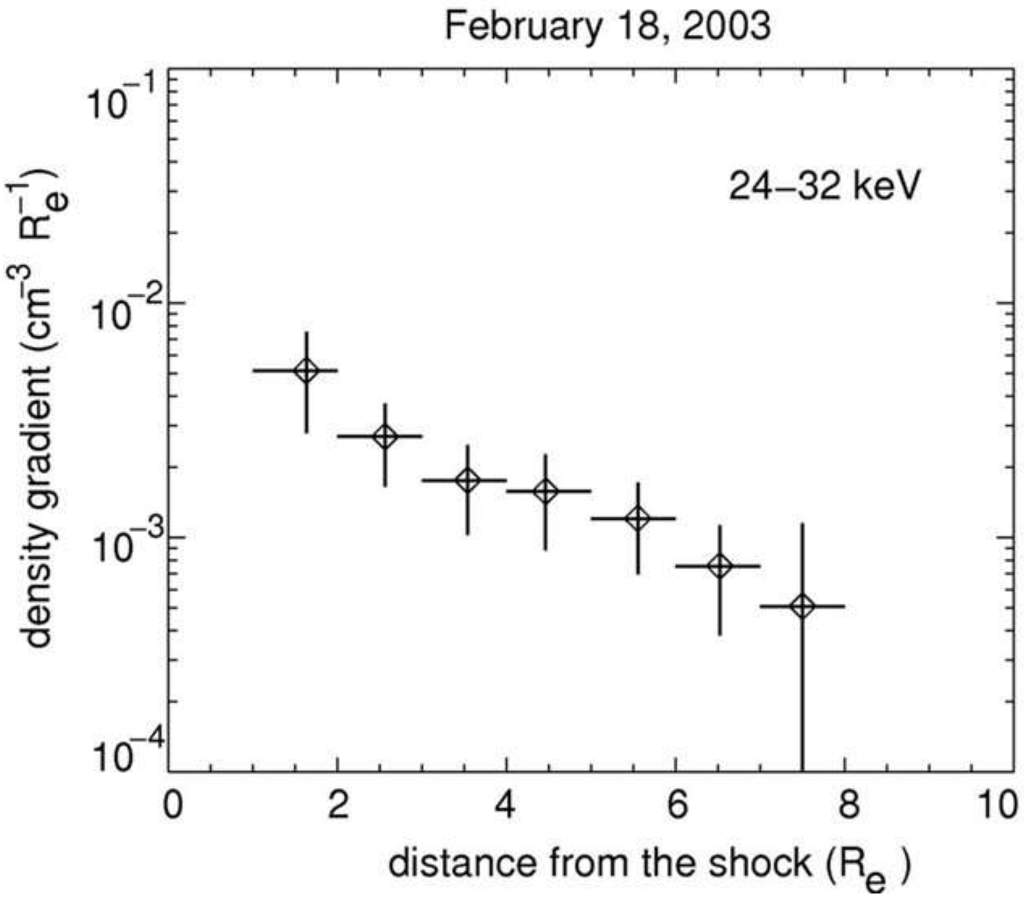
-the partial density of high energy ions falls off exponentially in the upstream direction: clear evidence of diffusive transport and acceleration also in the case of high energy ions

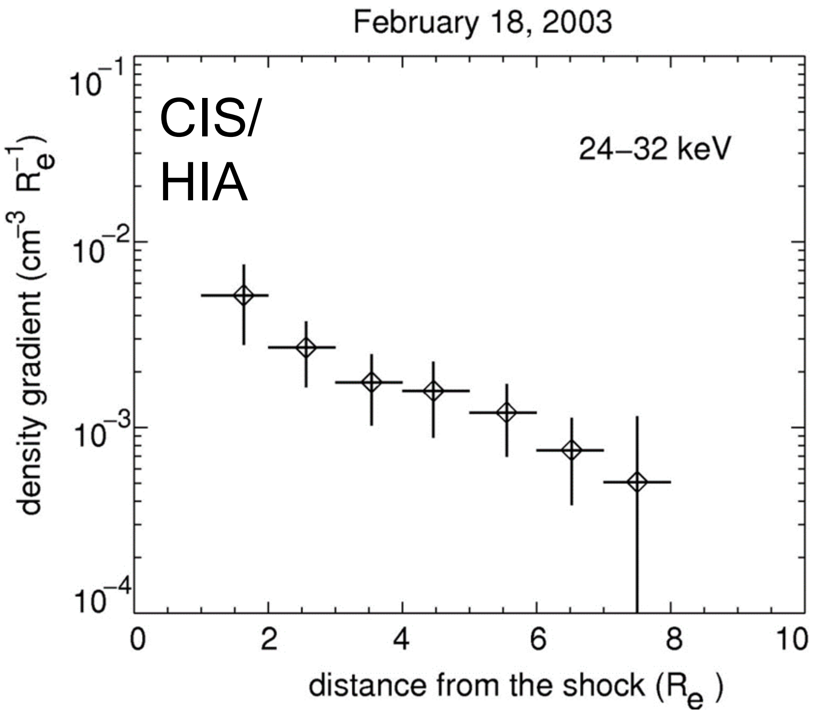
-the e-folding distances in the case of lower (10-32 keV, CIS/HIA) and higher (30-160 keV, RAPID) energy ions match each other very well.

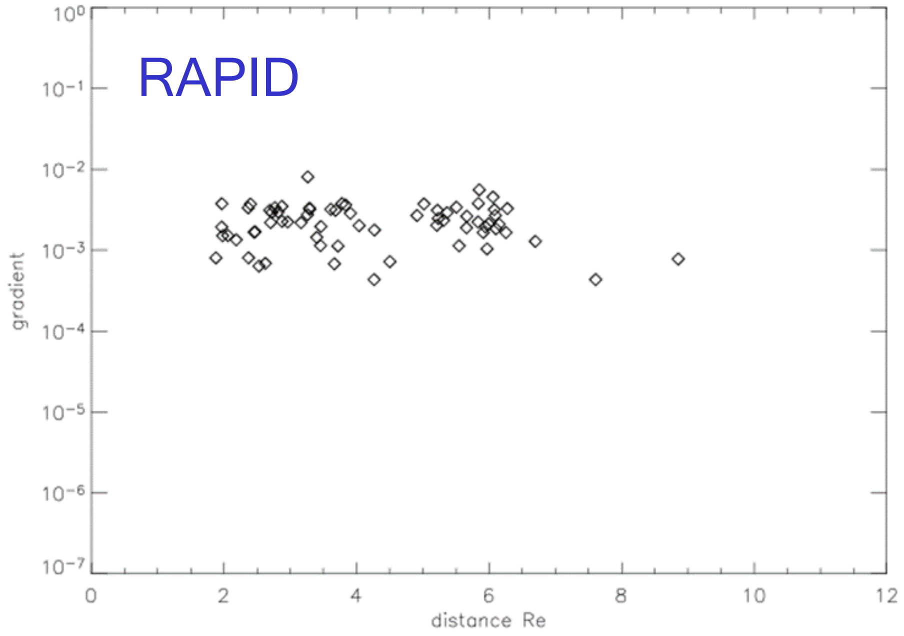
(Kronberg et al., 2009, JGR)



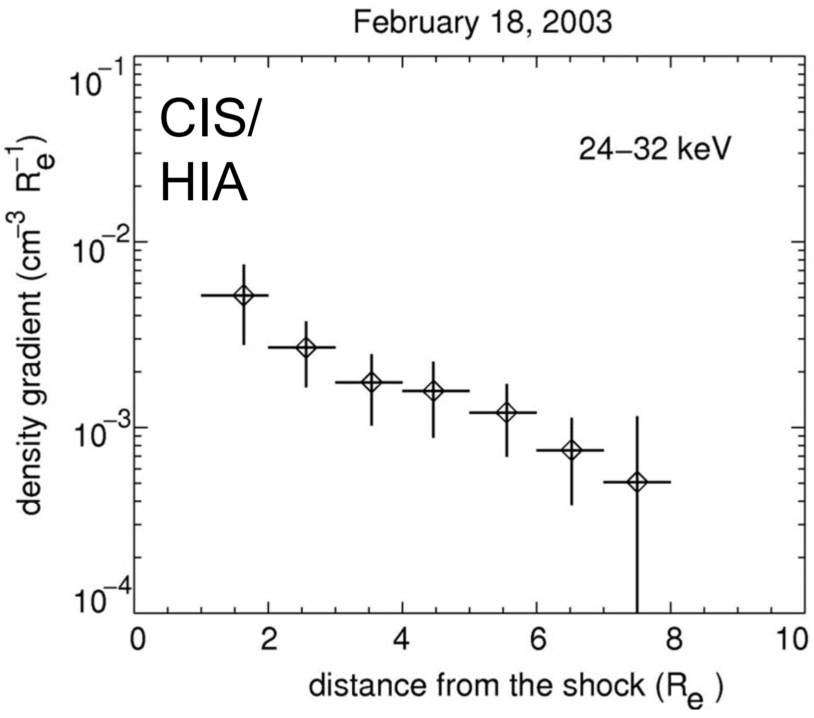
What happens to ions above 160 keV?
Can the shock accelerate ions to any energy?

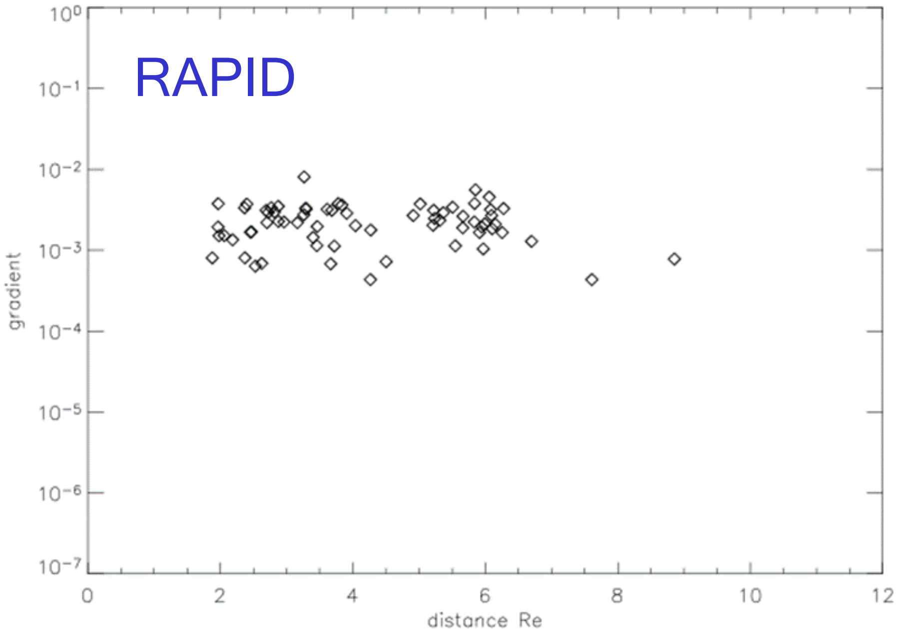

February 18, 2003
24–32 keV
density gradient (cm^{-3} R$_e^{-1}$)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
distance from the shock (R$_e$)





Constant gradient vs. distance =
no exponential profile in partial density on higher energies





Constant gradient vs. distance =
no exponential profile in partial density on higher energies

Is this the free escape boundary?
Or just a consequence of the time of connection?

Summary and conclusions

We found observational evidence of a mechanism that is capapable to produce seed ions for injection.

The various e-folding distance values and the different diffusion coefficients show that the scattering process can change significantly from event to event.

The waves excited by the FAB are convected deep into the foreshock region where they interact with the diffuse ions.

When the intensity of the FAB excited waves is high, these waves scatter efficiently the diffuse ions which results in unusually small diffusion coefficients at lower diffuse ion energies (i.e., 10-18 keV).
This „forced scattering” makes the diffusive acceleration more efficient.
Question(s): how often does this happen? Is it usual or is it „only” an extraordinary case?

At higher ion energies the scattering process is changed subtantially.

Acknowledgements

We thank the Cluster Active Archive for the high quality data.

This study was supported by the TAMOP-4.2.2.C–11/1/KONV-2012-0015 (Earth-system) project sponsored by the EU and European Social Foundation,

by OTKA PD 78674 national research fund,

and the Bolyai Research Grant for excellence.

Thank You!