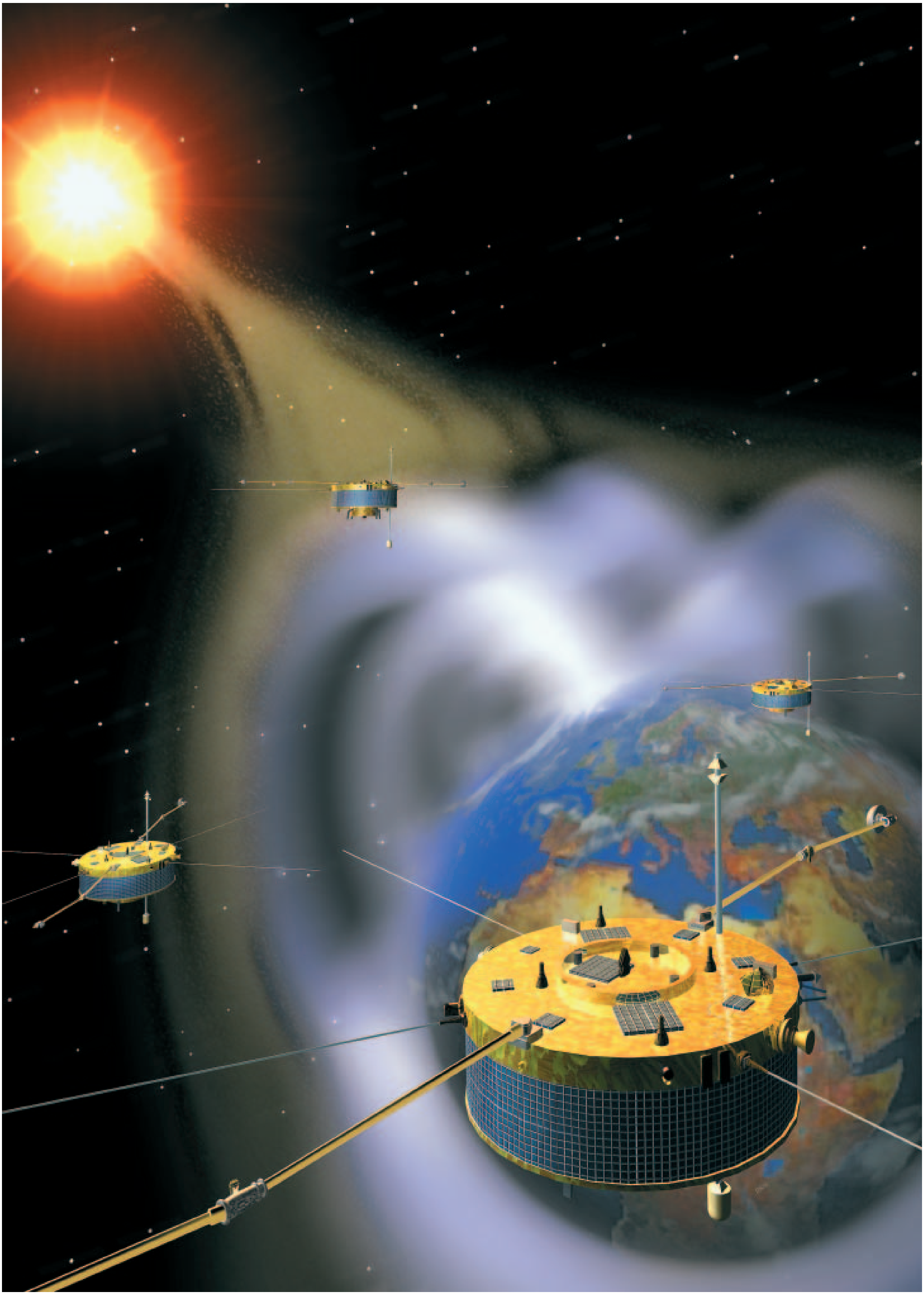

Rumba, Salsa, Samba and Tango in the Magnetosphere

- The Cluster Quartet's First Year in Space

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Introduction

Cluster is one of the two missions – the other being the Solar and Heliospheric Observatory (SOHO) – constituting the Solar Terrestrial Science Programme (STSP), the first 'Cornerstone' of ESA's Horizon 2000 Programme. The Cluster mission was first proposed in November 1982 in response to an ESA Call for Proposals for the next series of scientific missions.

The four Cluster spacecraft were successfully launched in pairs by two Russian Soyuz rockets on 16 July and 9 August 2000. On 14 August, the second pair joined the first pair in highly eccentric polar orbits, with an apogee of 19.6 Earth radii and a perigee of 4 Earth radii. The very accurate orbital injection and low fuel consumption mean that spacecraft operations could continue for at least two more years after the nominal two-year mission.

This is the first time that the Earth's magnetic field and its environment have been explored by a small constellation of four identical spacecraft. Preliminary results show that, as predicted, with four spacecraft we can obtain a detailed three-dimensional view of the Sun-Earth connection processes taking place at the interface between the solar wind and the Earth's magnetic field.

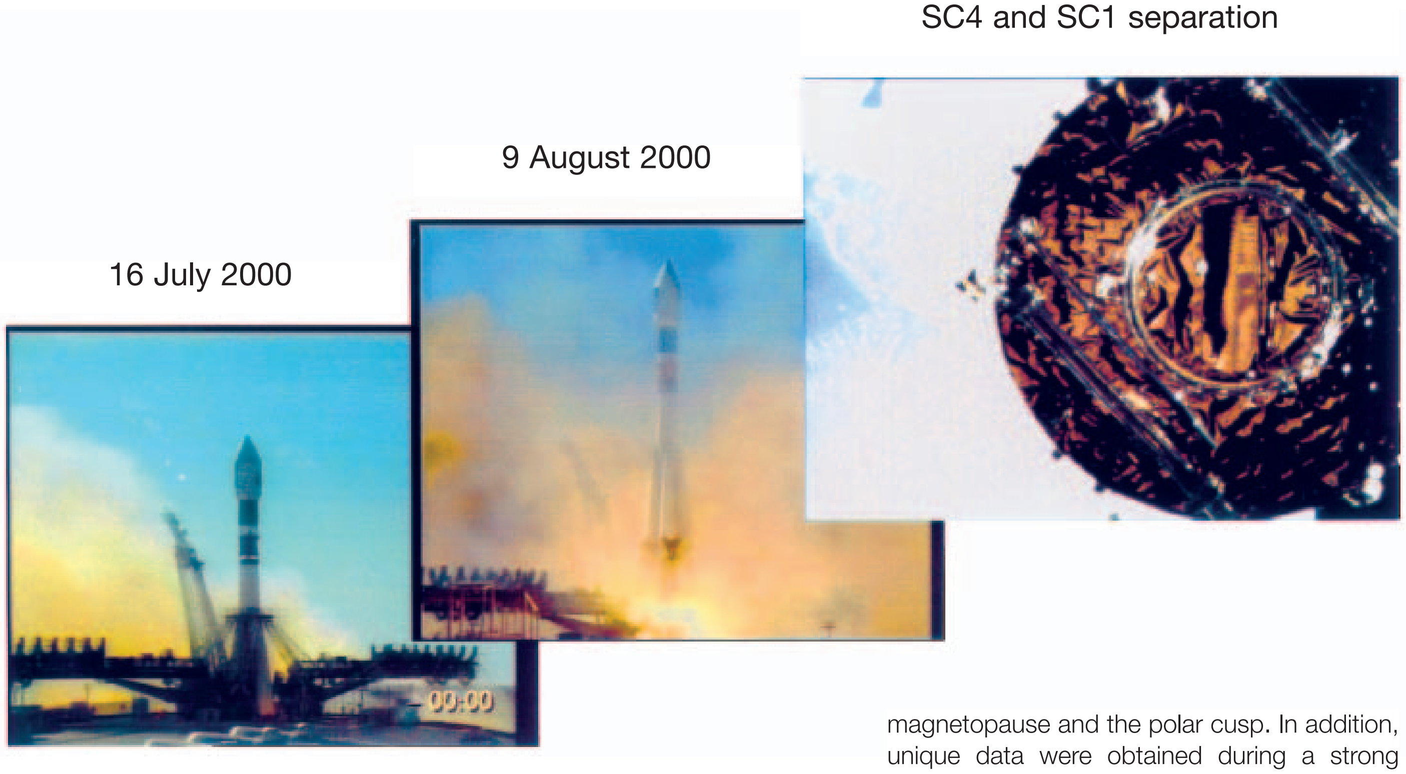
After the Ariane-5 launcher failure on 4 June 1996 and the destruction of the four original Cluster spacecraft, the Cluster scientists convinced the ESA Science Programme Committee (SPC) that it was essential for the European scientific community to rebuild the mission. This was agreed by the SPC in April 1997. In the meantime, SOHO, launched in December 1995, had begun to make some very exciting discoveries about the Sun and its environment. Now, with the successful launch of the rebuilt Cluster satellites, the STSP Cornerstone is complete and it is possible to combine these two missions in order to study the full chain of processes from the Sun's interior to the Earth.

Launch and commissioning phase

When the first Soyuz blasted off from the Baikonur Cosmodrome on 16 July 2000, we knew that Cluster was well on the way to recovery from the previous launch setback. However, it was not until the second launch on 9 August 2000 and the proper injection of the second pair of spacecraft into orbit that we knew that the Cluster mission was truly back on track (Fig. 1). In fact, the experimenters said that they knew they had an ideal mission only after switching on their last instruments on the fourth spacecraft.

After the two launches, a quite lengthy verification phase for all spacecraft subsystems and the payload of 44 instruments (Table 1) started. The 16 solid booms, eight for the magnetometers and eight for communications, were successfully deployed. A few days later, the spacecraft had to survive the first long eclipses, with up to 4 h of darkness, which they did with very good performances from the onboard batteries.

Then started the verification phase for the 11 sets of instruments. This phase was complicated by the fact that, to perform their measurements, some instruments had to deploy very long wire antennas. These 44 m antennas altered the spin rate of the spacecraft, which was incompatible with the particle instruments that needed a fixed spin rate. Altogether, more than 1100 individual tasks were performed on the instruments. At the end of this phase, in early December, a two-week 'interference campaign' was conducted to test how much the instruments influenced each other. After successfully testing all the instruments, the nominal operations phase began on 1 February 2001. Some of the results that are presented below were obtained during the commissioning and verification phase.


16 July 2000

9 August 2000

SC4 and SC1 separation

Figure 1. The two launches of the Cluster spacecraft on two Soyuz-Fregat rockets, on 16 July and 9 August 2000. An onboard camera took 27 pictures when Rumba-SC1 separated from Tango-SC4. Tango is shown in the upper-right corner. The Earth can be seen in the background

The Earth's magnetosphere is a very large volume of space extending about 65 000 km in the Sun's direction, and more than two million km in the opposite direction. The Earth's magnetic field dominates this space. Without the continuous flow of plasma (electrically charged particles) from the Sun, the Earth's magnetic field would be a dipole with a symmetric magnetic field around the polar axis. Instead, the solar wind compresses the magnetosphere on the front side and shapes it into a long tail in the anti-sunward direction (Fig. 2). During the first months of operations, the spacecraft orbits allowed Cluster to visit key regions of the magnetosphere – the bow shock, the magnetopause and the polar cusp. In addition, unique data were obtained during a strong solar storm that occurred in November 2000.

Table 1. The 11 instruments on each of the four Cluster spacecraft

Instrument	Principal Investigator
ASPOC (Spacecraft potential control)	K. Torkar (IWF, A)
CIS (Ion composition)	H. Rème (CESR, F)
EDI (Plasma drift velocity)	G. Paschmann (MPE, D)
FGM (Magnetometer)	A. Balogh (IC, UK)
PEACE (Electrons)	A. Fazakerley (MSSL, UK)
RAPID (High-energy electrons and ions)	P. Daly (MPAe, D)
DWP * (Wave processor)	H. Alleyne (Sheffield, UK)
EFW * (Electric field and waves)	M. André (IRFU, S)
STAFF * (Magnetic and electric fluctuations)	N. Cornilleau (CETP, F)
WBD * (Electric field and wave forms)	D. Gurnett (IOWA, USA)
WHISPER * (Electron density and waves)	P. Décréau (LPCE, F)

** Wave Experiment Consortium (WEC)*

The bow shock

The bow shock is the surface that forms in front of the Earth's magnetosphere when the supersonic solar wind slams into it at a speed of about 400 km/s (around 1.5 million km/h). This is similar to the shock wave (or sonic boom) when a plane flies faster than the speed of sound in the atmosphere. The bow shock slows down the solar wind and deflects it around the magnetosphere. In the process, the particles – electron and ions – are heated and the strength of the magnetic field is increased. Intense electromagnetic waves are also produced at the shock.

Figure 3 shows the electric waves detected by the WHISPER instrument during two crossings of the bow shock by the four Cluster spacecraft. On the plot, which covers a period of 40 minutes, the wave frequency is shown as a function of time. The power of the waves is plotted in false colours: red/brown for the most intense and blue for the less intense.

The bow shock is characterised by an intense wave-emission enhancement below 20 kHz that is observed around 08:25 and 08:35 UT. The crossings do not occur at the same time for all spacecraft due to their different positions, which were about 600 km from each other at that time. The right panel of Figure 3 shows the spacecraft configuration at the first crossing, when they were located on the right flank of the bow shock. A closer view of the spacecraft configuration is shown in the middle-right and bottom-right panels.

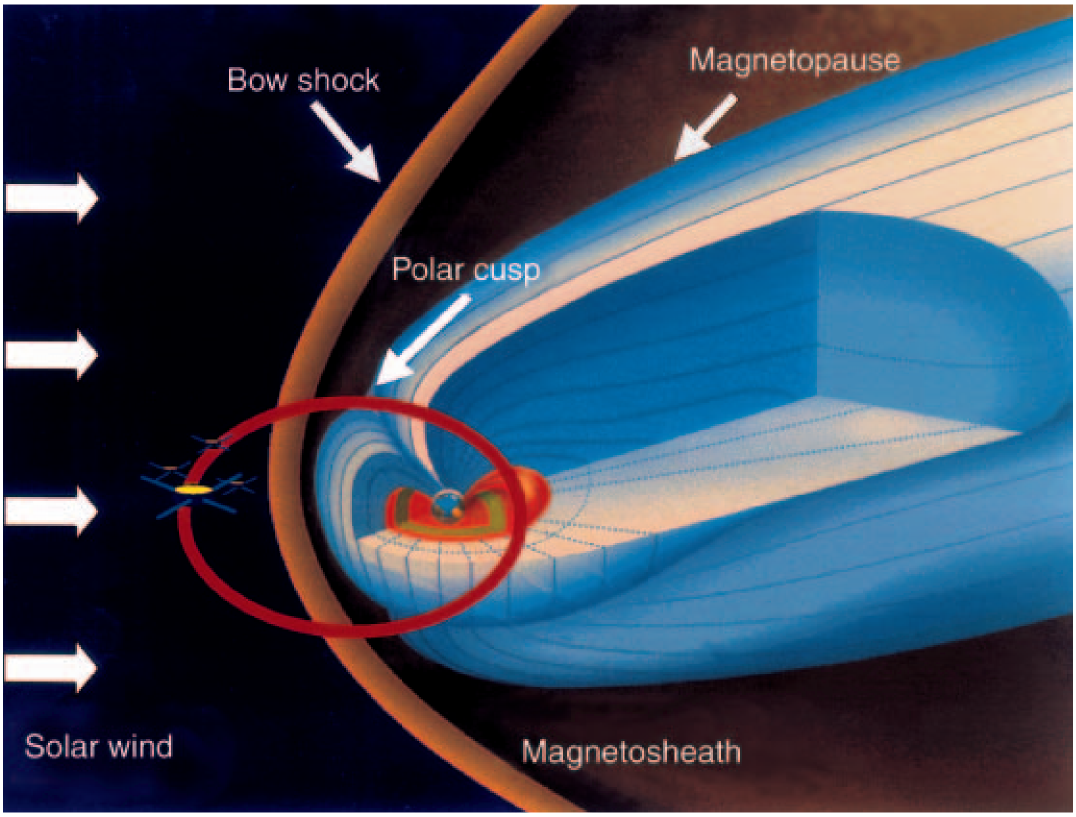
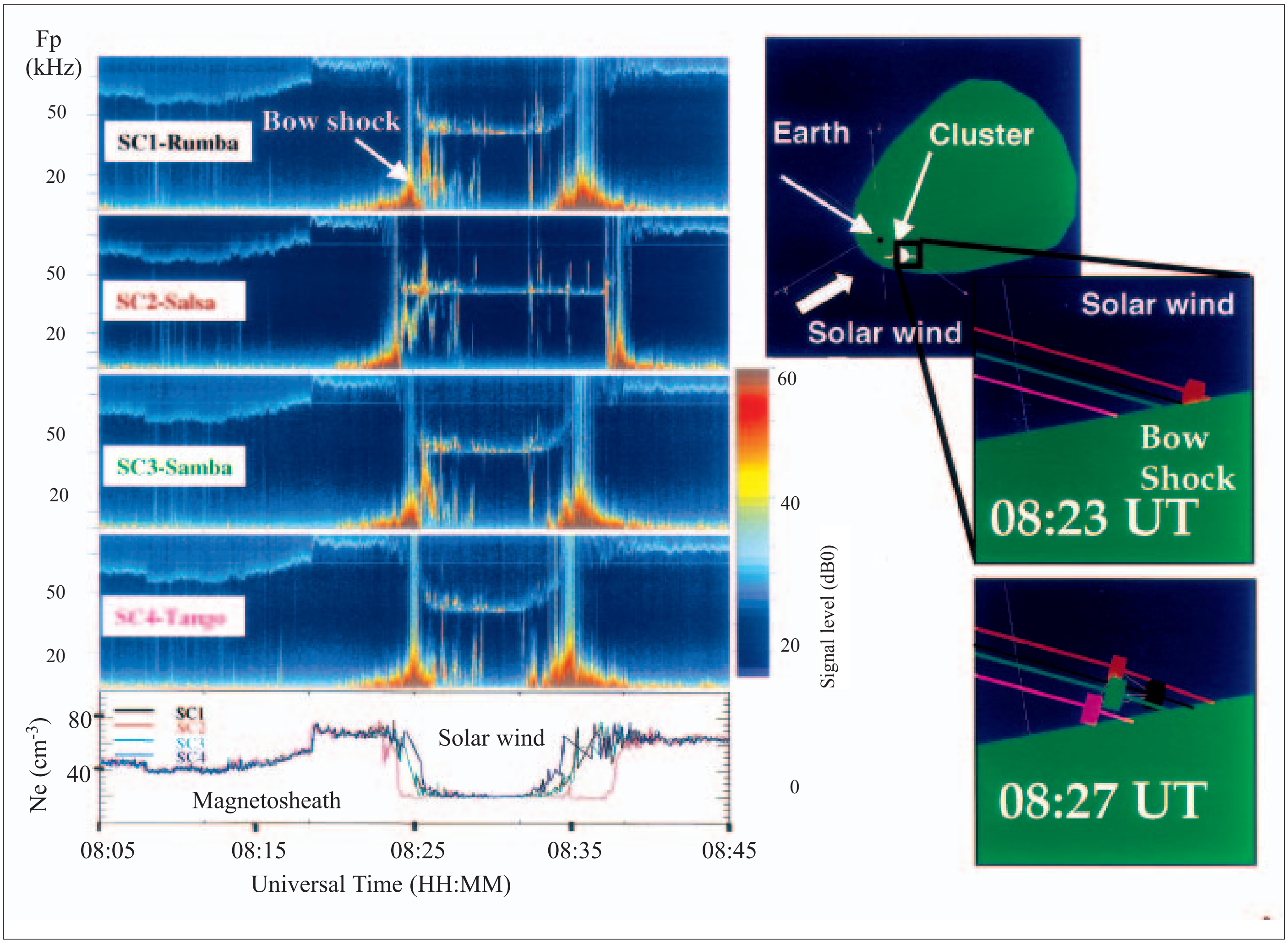


Figure 2. The Cluster orbit and the regions crossed during the first phase of the mission

Figure 3. Bow-shock crossings by each of the four Cluster spacecraft on 22 December 2000. The left panels show the frequency/time spectrograms of the electric waves observed by the WHISPER instrument. Between about 08:25 and 08:35 UT, the spacecraft were in the solar wind. The diagrams on the right show the Cluster configuration during the bow-shock crossing, in an overall view (upper panel) and two enlarged views at 08:23 UT (middle panel) and 08:27 UT (bottom panel). The spacecraft and their trajectories are colour-coded: spacecraft 1 (Rumba-SC1) is shown in black, Salsa-SC2 in red, Samba-SC3 in green, and Tango-SC4 in magenta. Data courtesy of WHISPER Principal Investigator, P. Décréau (LPCE, France)



Since the bow shock usually moves faster than the spacecraft, the latter can be considered immobile with the bow shock is moving through the group. This motion is due to an increase in the pressure of the solar wind (acting like a piston) on the magnetosphere, which pushes the bow shock closer to the Earth. It is clear from the figure that spacecraft 2 crossed the bow shock first, and then the other spacecraft followed. A few minutes later, around 08:35 UT, the pressure decreased again and the bow shock crossed the spacecraft in the opposite direction.

The second crossing was a little different because the wave emission appears slightly broader and stronger. Emission of electric waves at the plasma frequency is seen on the spectrograms as a light blue line. From this emission, the absolute electron density of the plasma can be deduced (shown in the lower panel).

At first, the satellites were flying through the magnetosheath (Fig. 2), which is characterised by a high particle density of between 40 and 70 cm^{-3}. After the crossing of the bow shock, the density in the solar wind decreased to around 20 cm^{-3}. An interesting difference between spacecraft 2 and the other spacecraft is observed before the spacecraft again crossed the bow shock at around 08:35 UT. Spacecraft 1, 3 and 4 observed a gradual increase in density from 20 to 70 cm^{-3}, which took about 3 to 4 min, while on spacecraft 2 this increase was very sharp, taking less than 1 min. This is an interesting observation, which shows that the bow shock can have different properties on quite short spatial scales, typically less than 600 km. Further studies will be conducted to understand the small-scale structures of the bow shock.

Figure 4 is another example of a bow-shock crossing. Here the magnitude of the magnetic field is plotted as a function of time for the four spacecraft. In the supersonic solar wind (upstream of the bow shock), the magnetic field is low, around 10 nT in this example, and high in the decelerated solar wind or magnetosheath (downstream of the bow shock), at around 30 nT. The bow shock was first hovering very close to spacecraft 2, from 06:50 to 07:03 UT, as seen in the multiple drops in its magnetic-field data, then moved sunward of all four spacecraft from 07:03 to 07:12 UT. Later, from 07:12 to 07:19 UT, it stayed between spacecraft 2 and the other three spacecraft. The crossing of the bow shock by the four satellites gives, for the first time, a direct measurement of the bow-shock speed - between 5 and 6 km/s.

The magnetopause

Inside the bow shock is the magnetopause, the external boundary of the Earth's magnetic field. The magnetopause is characterised by a discontinuity of the magnetic field, a sudden change in particle distribution function and large emissions of electromagnetic waves. In the following example, the magnetic field and the wave data will be used to study its geometry.

The top panel in Figure 5 shows the north-south component (B_z) of the magnetic field and

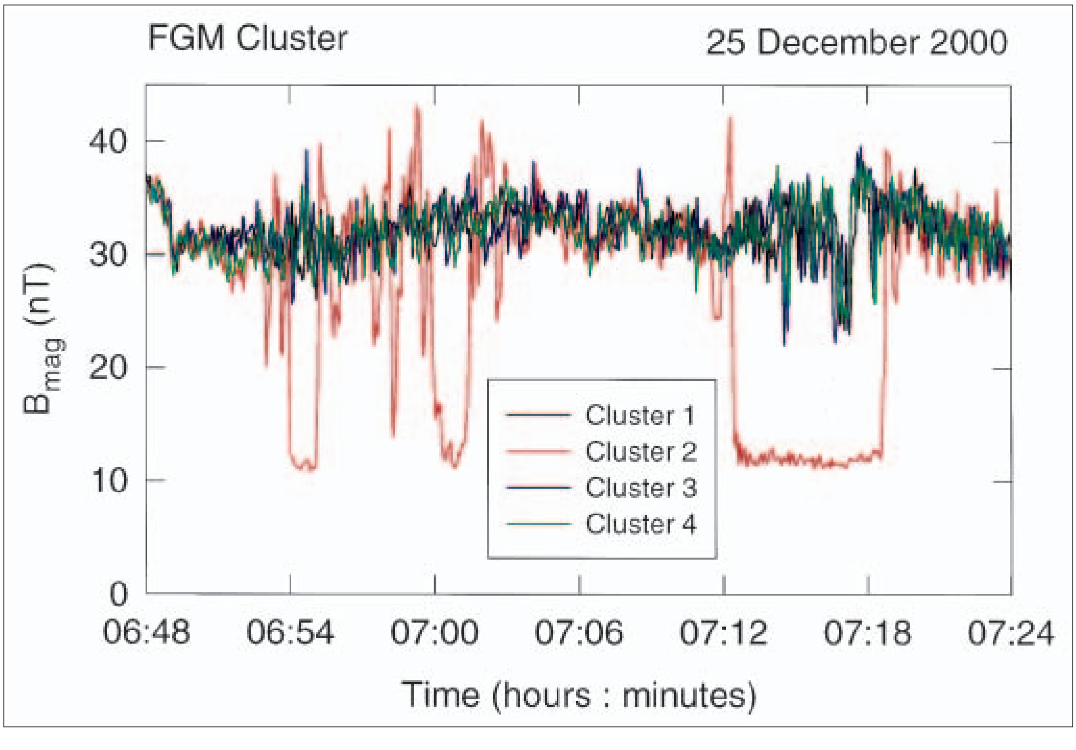


Figure 4. Multiple bow-shock crossing by Salsa-SC2 on 25 December 2000. The magnitude of the magnetic field from the FGM instrument is plotted as a function of time. A high value means that the spacecraft are in the magnetosheath, and a low value means that they are in the solar wind. The frequent drops in the magnetic field on Salsa-SC2 indicate the bow-shock crossings. Data courtesy of FGM Principal Investigator, A. Balogh (Imperial College London, UK)

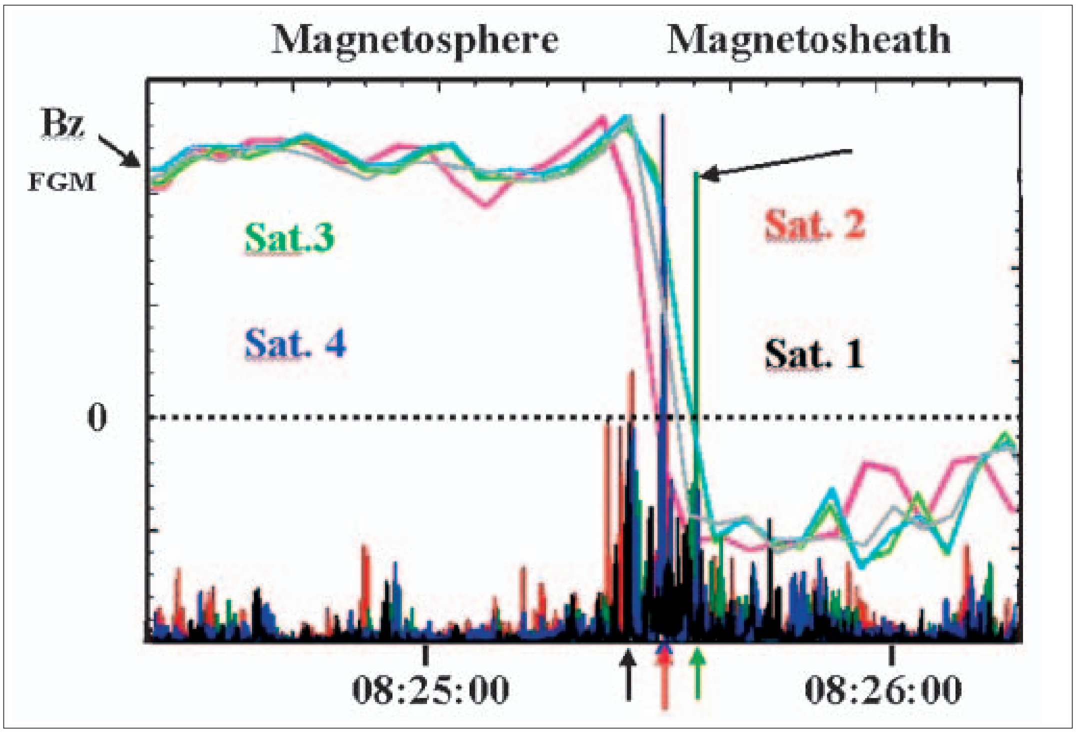
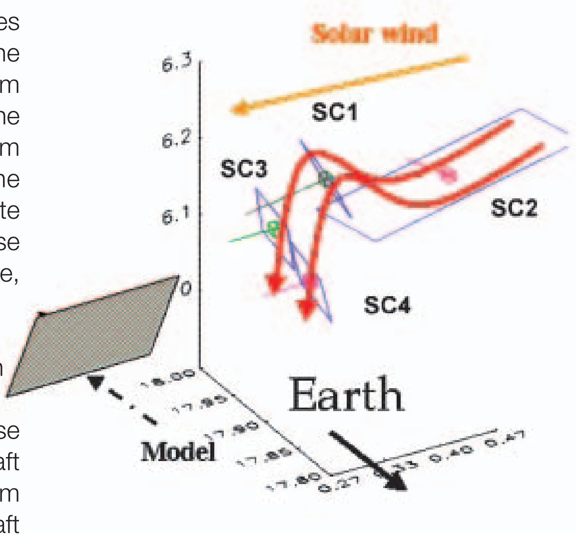


Figure 5. Magnetopause crossing by the four spacecraft on 10 December 2000. The B_z component of the magnetic field is plotted as a function of time (high value means inside the magnetosphere, and low value means outside). In addition, the integrated wave power from the STAFF instrument is plotted as a function of time. The maximum in the wave power (marked at the bottom by an arrow) indicates the magnetopause crossing. The diagram at the bottom shows the magnetopause surface and its normal plane detected by the four spacecraft. A wave passing by the spacecraft is shown in red.
Data courtesy of STAFF Principal Investigator, N. Cornilleau-Wehrlin (CETP, France), and FGM Principal Investigator, A. Balogh (Imperial College London, UK)

the total emission power of the magnetic waves generated around the magnetopause. The magnetopause is defined by the maximum power of the waves corresponding to the change in sign of B_z. The arrows at the bottom of the plot show the exact time of the magnetopause crossing. It is interesting to note that spacecraft 1 crossed the magnetopause first, then spacecraft 2 and 4 at the same time, and finally spacecraft 3.



Using a minimum-variance analysis, which means looking for a system where the variations in B are minimal, the magnetopause plane can be defined for each spacecraft crossing. The result is shown in the bottom panel of Figure 5. The individual spacecraft positions as well as the magnetopause plane are shown. It is clear that spacecraft 1, 3 and 4 detected the magnetopause in approximately the same plane, while spacecraft 2 detected it in an almost perpendicular plane. This observation cannot be explained by a usual planar magnetopause surface, but instead by a wave propagating along the magnetopause. The speed of this wave has been estimated at around 70 km/s. A simulation of this wave is shown in Figure 6. It is clear from this example that all four spacecraft are needed to measure the three-dimensional properties of the magnetopause. With two or three spacecraft, we could have missed the wave.

The polar cusp

The polar cusp is the 'window' above the northern and southern polar regions where the particles from the solar wind can penetrate directly into the magnetosphere (Fig. 7, top panel). Given their location at the outer boundary of the magnetosphere, the polar cusps react rapidly to changes that occur in the solar wind. For instance, when the solar wind changes from a north- to a south-pointing magnetic field, the cusp moves to lower latitudinal positions. On the other hand, when the solar-wind magnetic field changes to an azimuthal direction, the polar cusp moves longitudinally. The motion of the cusp is, therefore, a key element in the Sun–Earth interaction.

Until now, the polar cusp had only been observed by single spacecraft, so its motion could only be deduced indirectly from statistical analysis by combining many crossings. With Cluster, four spacecraft are visiting this region for the first time, allowing the speed of the polar cusp to be measured directly.

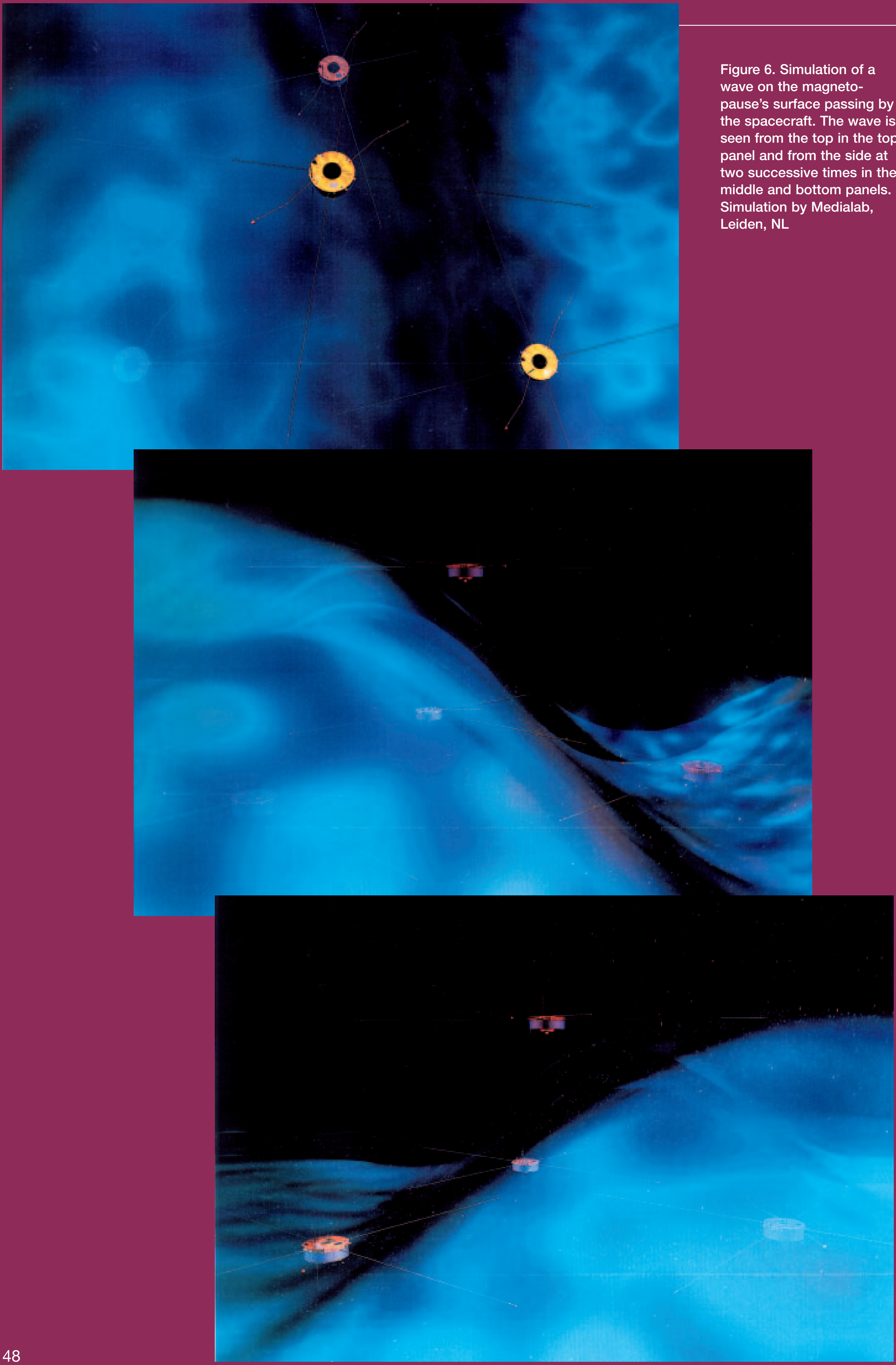


Figure 6. Simulation of a wave on the magnetopause's surface passing by the spacecraft. The wave is seen from the top in the top panel and from the side at two successive times in the middle and bottom panels. Simulation by Medialab, Leiden, NL

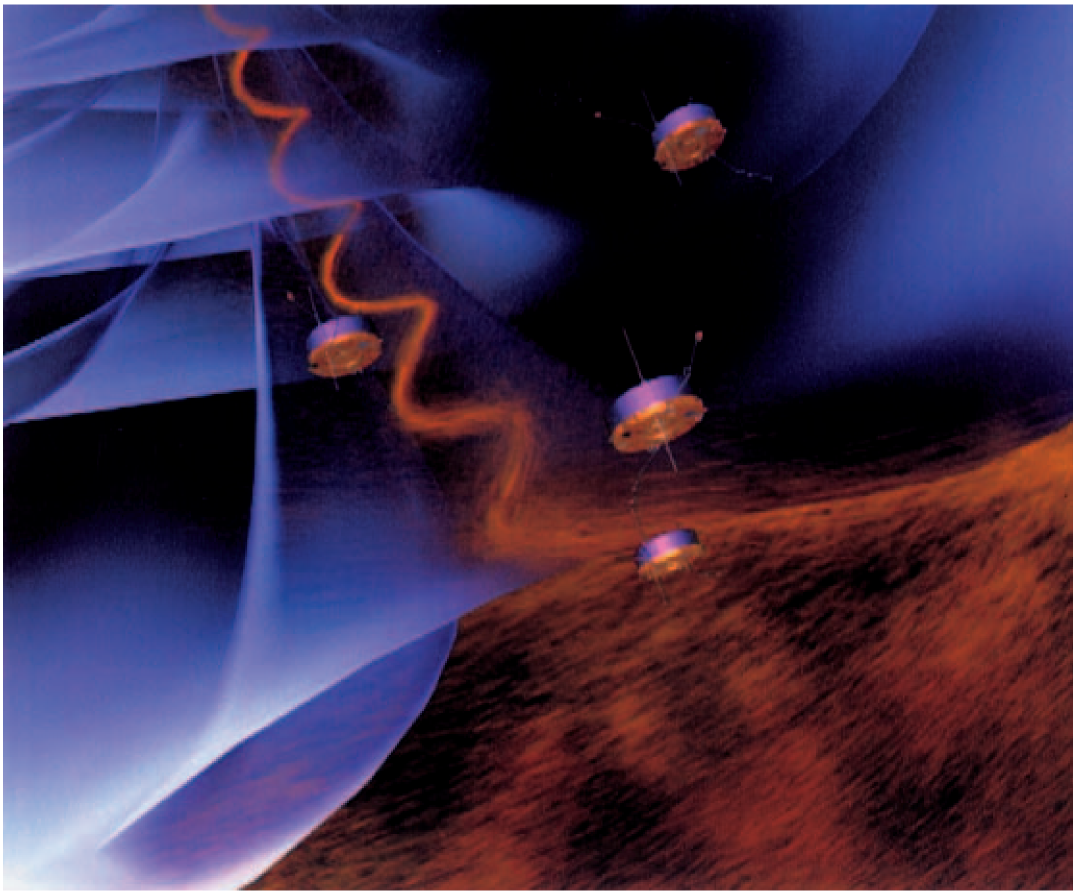
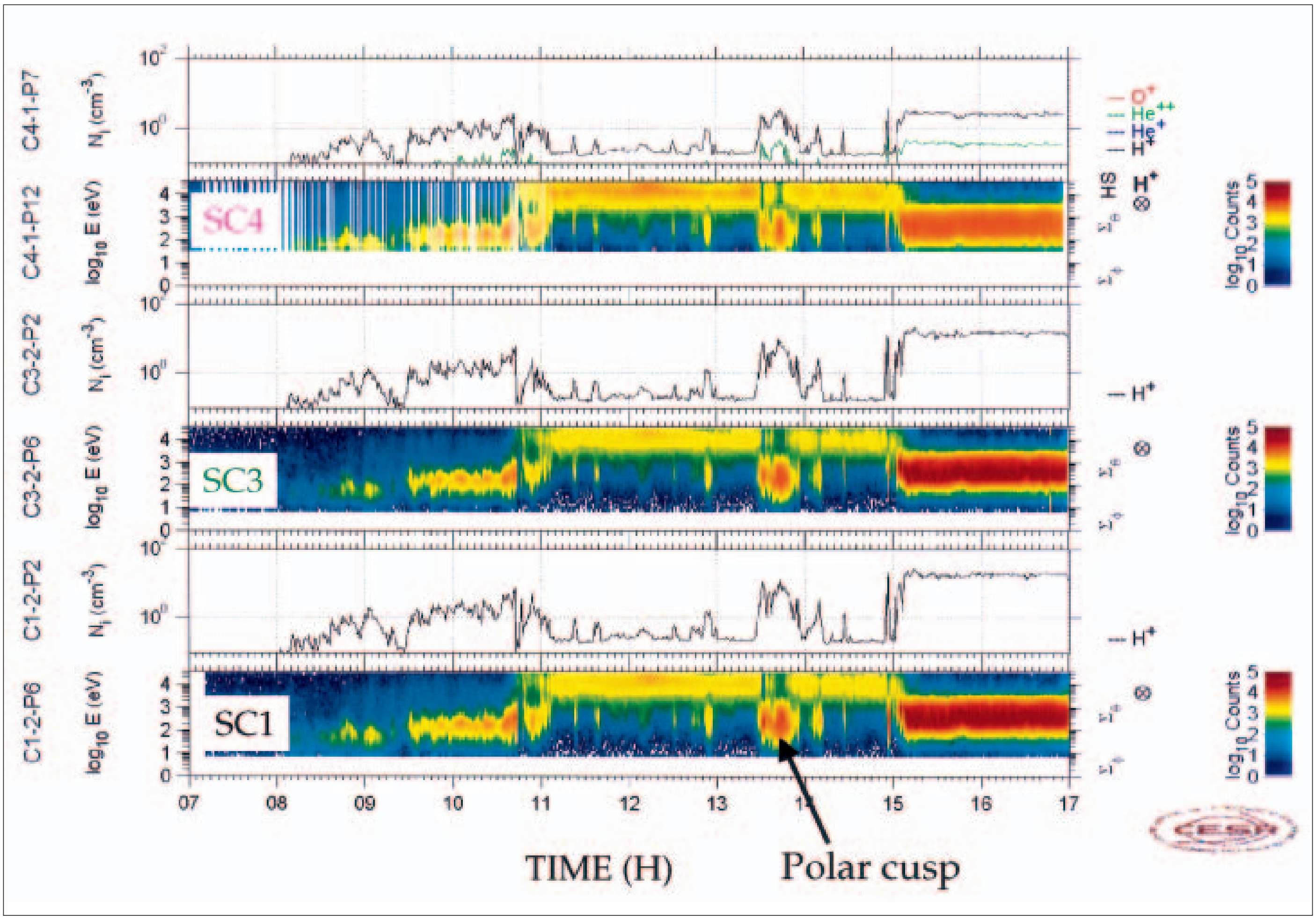


Figure 7. Cusp crossing on 14 January 2001. Top panel: sketch of the polar cusp with the four spacecraft. Bottom panel: energy/time spectrograms of ions from Rumba-SC1, Samba-SC3 and Tango-SC4. The total ion density is also plotted in the panel above each spectrogram.
Data courtesy of CIS Principal Investigator H. Rème and Co-Investigator J.P. Bosqued (CESR, France)



The bottom panel in Figure 7 shows the data from the ion detectors on spacecraft 1, 3 and 4 in the cusp region. The spacecraft were moving from above the pole at around 09:00 UT to the magnetosheath after 15:00 UT (Fig. 2). In between these two regions, the spacecraft crossed the polar cusp for about 30 minutes at around 13:30 UT. A few other shorter crossings of the polar cusp are also visible before and after that time.

The polar cusp is characterised by ions, mainly H^+ and He^{++} of solar origin, with energies between 100 eV and a few keV. On the large time scale shown in this figure, all spacecraft show the same data. However, as we will see below, clear differences are visible if we look at more detailed data. The top panel in Figure 7 sketches the spacecraft entering the polar cusp. Two spacecraft are in the cusp, one is at the border, and the fourth one is still outside. The precise timing of the crossing by each spacecraft and the spacecraft position will give the speed of the cusp.

This crossing on 14 January 2001 was supported by ground-based data sets, as the Eiscat and Superdarn radars were just below the spacecraft and providing additional information on the cusp region (Fig. 8). In fact, just before the cusp crossing by Cluster, the radar detected a change in ionospheric convection, which was an indication that the cusp was moving towards the east (bottom-right panel). This motion is sketched in Figure 9.

The left panel is a view from the Sun and shows the motion of the cusp towards the Cluster position (blue dot). The right panel shows the electron data for one of these cusp crossings by the four spacecraft. The entry of the spacecraft into the cusp is marked by a red arrow and the exit by a white arrow. It is clear that the entry and exit do not occur at the same time for each spacecraft. Using the time of the crossing and the position of the spacecraft, we can estimate that the polar cusp was moving at between 10 and 30 km/s. This is the first time that the speed of the cusp has been measured directly.

Solar storm in November 2000

With the Sun now at maximum activity in its 11-year cycle, numerous powerful solar storms are expected to occur. On 8 November 2000, the fourth biggest storm since 1976 was detected by SOHO. A huge cloud of plasma, in the form of a Coronal Mass Ejection (CME), was directed towards the Earth (Fig. 10). About 8 min later, the WHISPER instrument on Cluster detected the first consequence of the storm – an intense

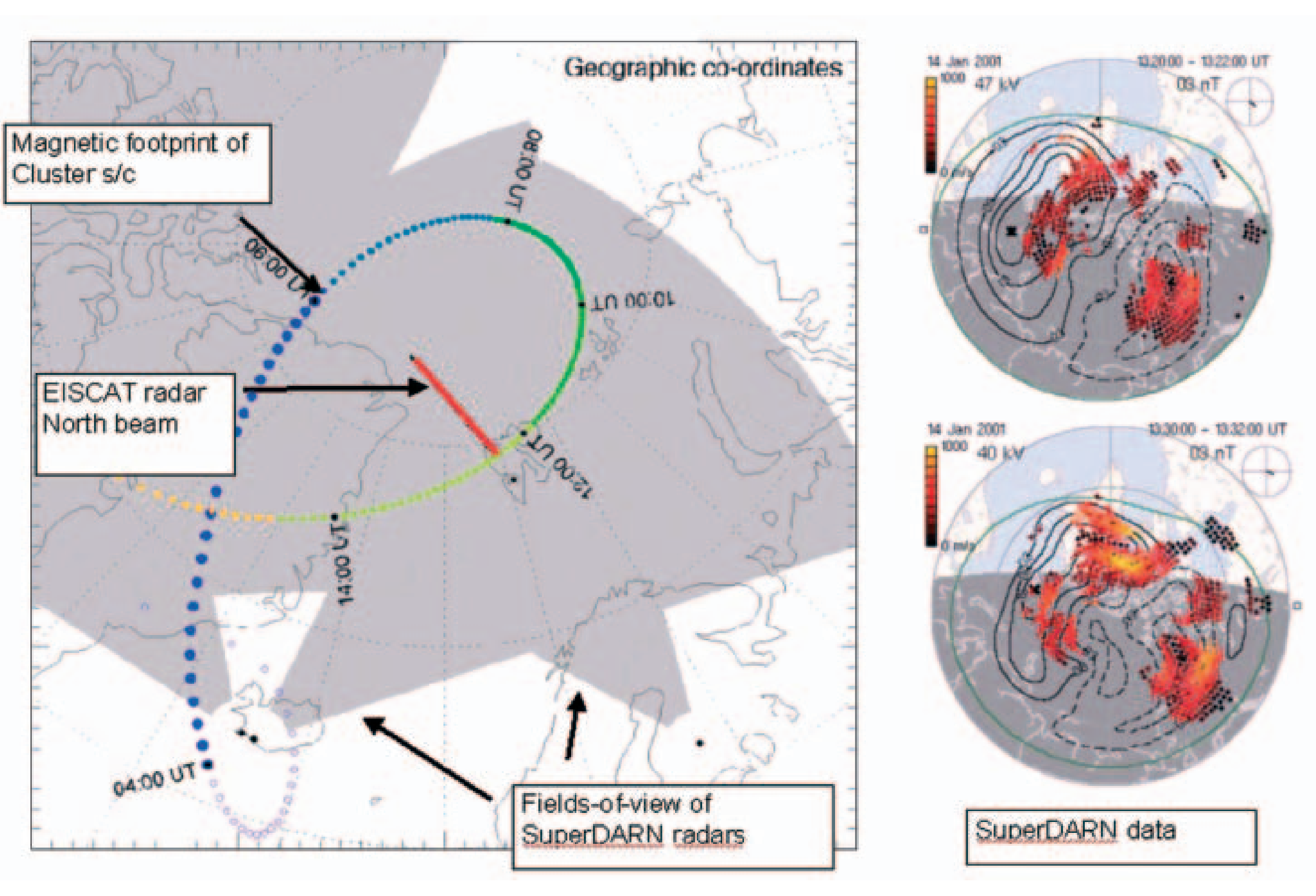


Figure 8. Ground-based radar observations on 14 January 2001. The left panel shows the projection of the Cluster trajectory over the northern polar cap. The fields of view of the Eiscat (red) and Superdarn (grey) radars are indicated. The right panels show the plasma convection pattern recorded by Superdarn at 13:20 UT (top) and at 13:30 UT (bottom). An enhancement of the flow towards the east is detected at 13:30 (yellow bright spot in the centre of the figure). Data courtesy of H. Opgenoorth (Uppsala, Sweden), M. Lockwood (RAL, UK) and R. Greenwald (APL, USA).

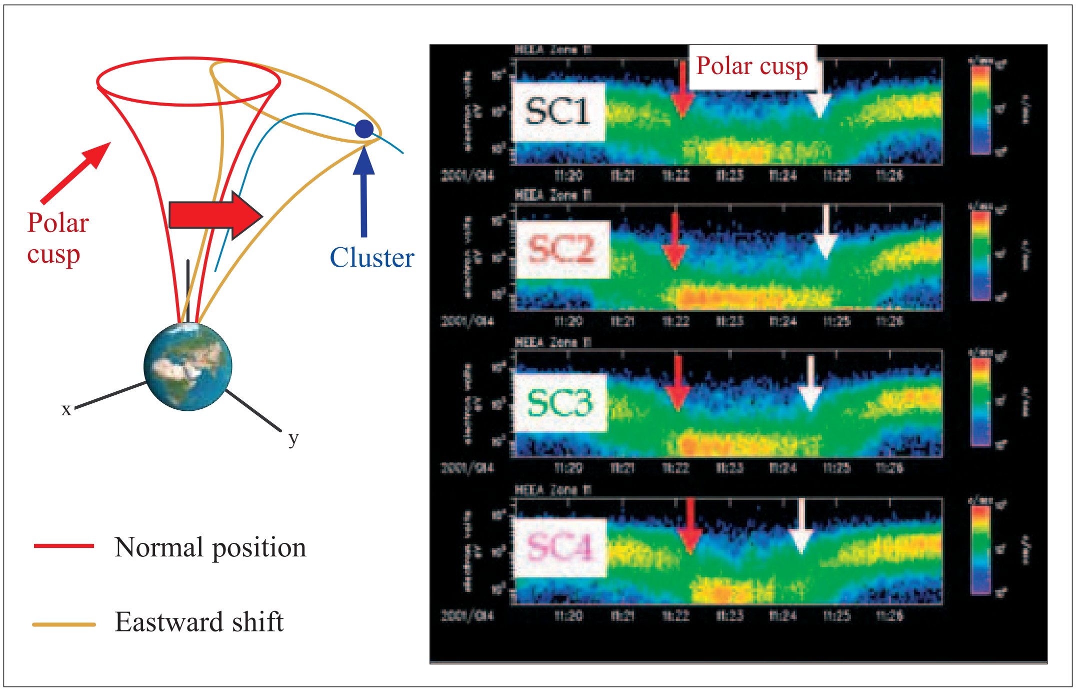
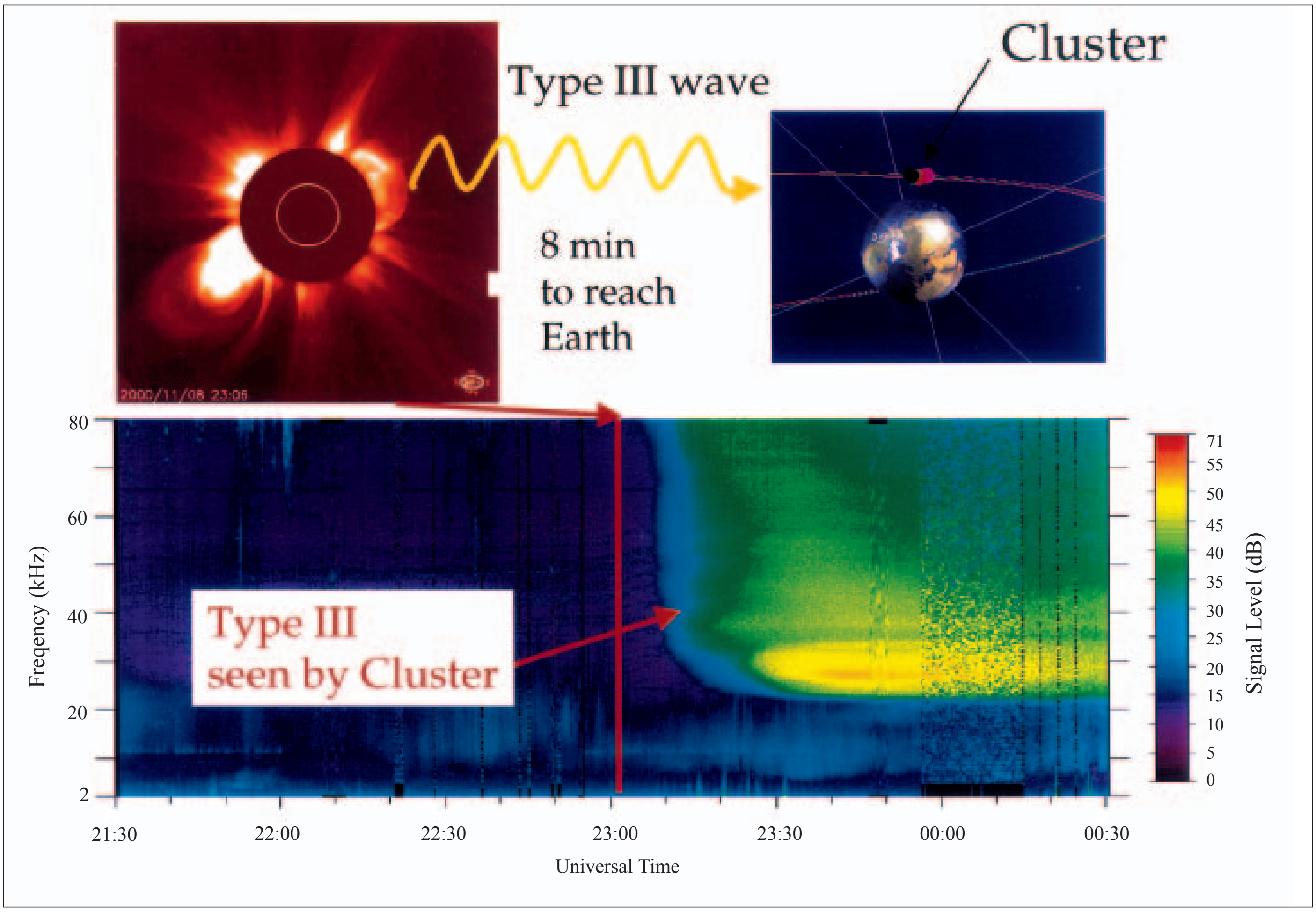


Figure 9. Detailed data obtained during the cusp crossing on 14 January 2001. The left panel sketches the motion of the cusp towards Cluster, which enabled the spacecraft to enter the cusp unexpectedly. The right panels show the energy/time spectrograms of the electron population observed by the four spacecraft. The red arrows indicate when the spacecraft entered the cusp, and the white arrows when they left the cusp.
Data courtesy of PEACE Principal Investigator, A. Fazakerley (MSSL, UK)

radio emission from 20 kHz to above 80 kHz. Then, about 20 min later, the first energetic protons accelerated during the storm arrived at the Earth (Fig. 11). Their flux was 100 000 times higher than during quiet conditions.

These particles penetrate spacecraft and instruments and may damage vital components. In fact, single-event upsets, due to bit flips in the solid-state memory, were detected on-board Cluster about 100 times more often than under normal conditions. The last manifestation of the storm, which occurred about 1 day later, was the arrival of the CME. This acted as a piston on the magnetosphere and reduced its size by half.

Figure 10. Solar storm on 8 - 10 November 2000. The SOHO image taken on 8 November is shown in the upper left panel. The position of Cluster is shown in the upper-right diagram. The frequency/time spectrograms showing the electric field wave measurements are shown at the bottom. The large band emission (from 20 to more than 80 kHz) is observed on Samba-SC3 about 8 min after the storm started on the Sun.
Data courtesy of WHISPER Principal Investigator, P. Décréau (LPCE, France)



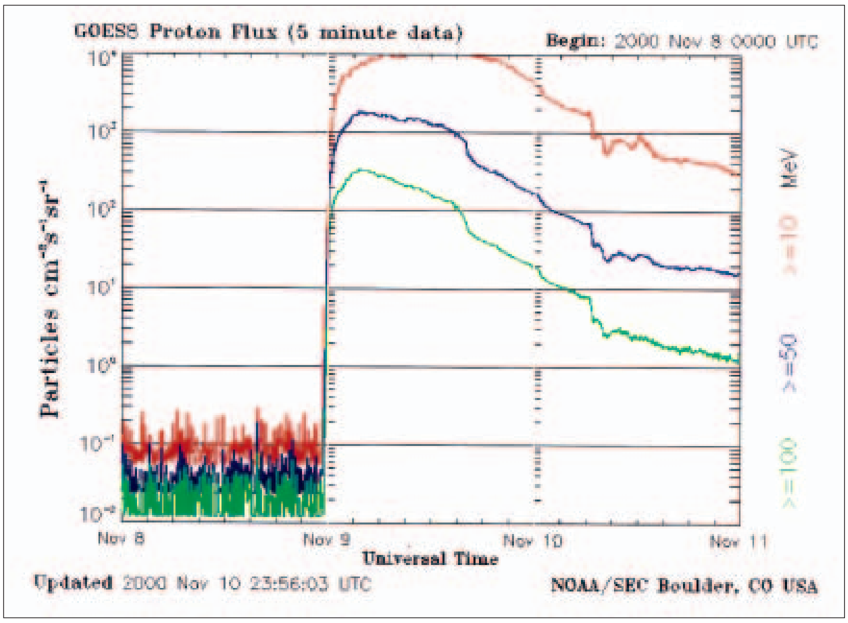


Figure 11. Protons produced during the solar storm on 8 November 2000. The flux is plotted for different proton energies, from above 10 MeV to above 100 MeV. The protons were still reaching the Earth, although with decreasing fluxes, several days later. Data courtesy of NOAA/SEC Boulder, USA

When we received the early warning from SOHO that the storm was coming, we decided to record data for about one day on each Cluster spacecraft. Although not all instruments were operating at that time due to on-going commissioning activities, the FGM magnetometer was switched on and so it was able to detect Cluster's first excursion outside the magnetosphere.

Figure 12 shows the magnetohydrodynamic (MHD) model that simulates the magnetosphere's status during the storm. This model reproduces the global interaction of the solar wind with the magnetosphere. All key physical parameters - magnetic field, density and temperature - are calculated in three dimensions using solar-wind data measured by the Wind spacecraft upstream of the bow shock. In the top panel, the magnetosphere is shown in dark blue, while to the left the magnetosheath is shown in green/yellow, and further to the left the solar wind is in light blue.

Due to the increased pressure coming from the solar wind at 07:00 UT, the colours of the above regions changed slightly, the solar wind becoming light yellow and the magnetosheath becoming red. Before the arrival of the cloud, at 05:48 UT, the magnetosphere was normal (top panel) and Cluster was located inside it. After the CME's arrival (bottom panel), the magnetosphere was compressed to about half of its normal size, and Cluster passed outside it and into the solar wind for many hours. This was about 10 days earlier than expected by the mission team.

Figure 13 shows the magnetometer data from one excursion outside the magnetosphere

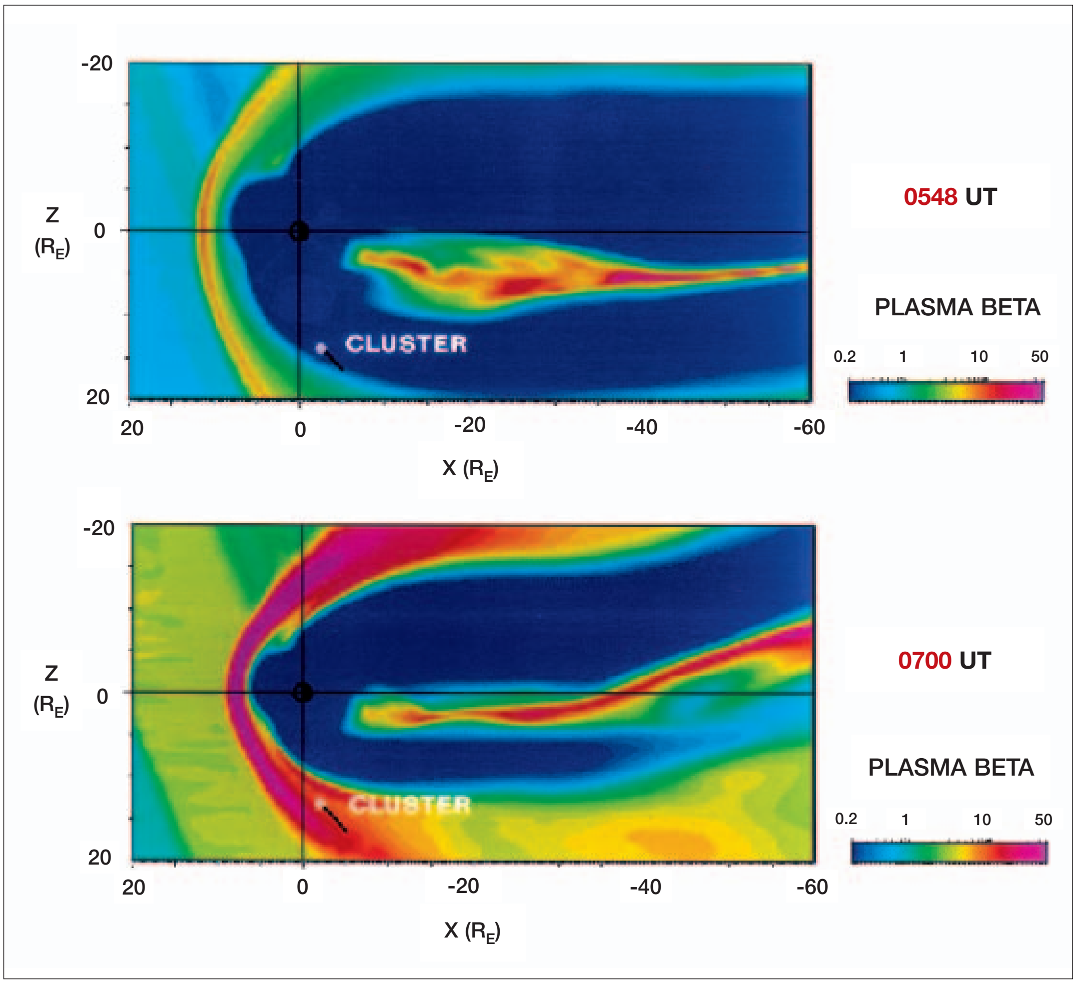


Figure 12. Magnetohydrodynamic (MHD) model of the magnetosphere on 10 November 2000. The top panel shows the magnetosphere before the arrival of the CME at 05:48 UT, and the bottom panel after the arrival of the CME at 07:00 UT. Data courtesy of J. Berchem (UCLA/IGPP, USA)

during the storm. Each spacecraft successively crossed the magnetopause, in agreement with the model shown on the right. The order of the crossing, starting at 06:02 UT, was first spacecraft 2 (Salsa-SC2), then Tango-SC4, then Samba-SC3, and finally Rumba-SC1. A few minutes later, starting at 06:03:30, Rumba-SC1, Samba-SC3, Tango-SC4 and Salsa-SC2 re-entered the magnetosphere in succession. The speed of the spacecraft was relatively slow compared to the motion of the magnetopause, so it should be seen as if the magnetopause was going back and forth through the spacecraft. The order of exit and entry is reversed, indicating that the magnetopause kept the same orientation during its motion.

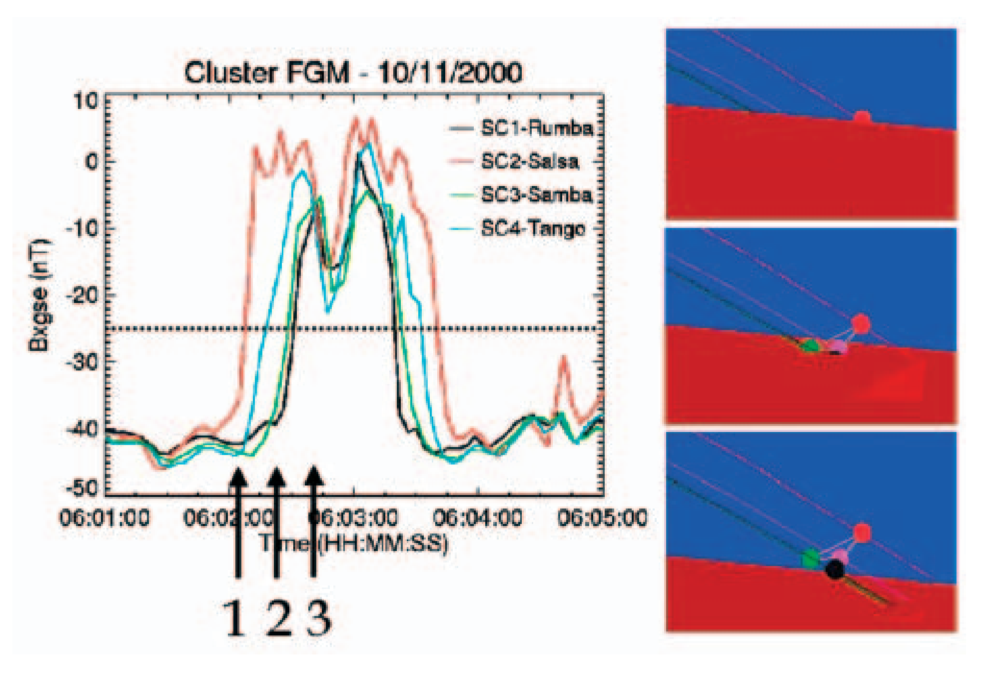


Figure 13. Magnetopause crossing during the solar storm on 10 November 2000. The left diagram shows the magnetic-field component B_x as a function of time as recorded on the four Cluster spacecraft: Rumba-SC1 in black, Salsa-SC2 in red, Samba-SC3 in green and Tango-SC4 in blue. B_x is negative inside the magnetosphere and positive outside it. The three right-hand diagrams show the configuration of the four spacecraft as they crossed the magnetopause in succession.
Data courtesy of FGM Principal Investigator, A. Balogh (Imperial College London, UK).

Conclusion

During just the first few months of operations, the Cluster spacecraft have fully demonstrated their ability to provide substantial advances in magnetospheric physics. For the first time, structures in the magnetosphere have been studied in three dimensions, which will bring new knowledge of the processes taking place during the interaction between the Sun and Earth.

The bow shock was captured between the four spacecraft, enabling its geometry and speed to be determined for the first time. Waves on the magnetopause were also directly observed for the first time and further studies of these should bring new insights into magnetic reconnection processes. The polar cusp, a moving window on the solar wind, was observed by the four spacecraft and its speed was measured for the first time. More data have been obtained in these regions and will allow scientists around the world to perform systematic studies of the physical processes involved.

Another main target of the Cluster mission is the magnetotail, where magnetic reconnection, current disruptions and particle acceleration are taking place. During the next few months, Cluster will look for the first time at the spatial variation of these processes, casting new light on the geomagnetic substorms that are responsible for the intense auroras on the night side of the Earth.

Acknowledgements

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