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Special Section:
Cluster 20th anniversary: results from the first 3D mission

Key Points:
- Selected science results achieved by Cluster are presented
- Operation of the mission for 20 years, challenges and technical difficulties are reported
- Science is enhanced by combining with other constellations and by making all Cluster data available to the public

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Cluster After 20 Years of Operations: Science Highlights and Technical Challenges

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Abstract The Cluster mission was the first constellation using four identical spacecraft to study Sun-Earth connection plasma processes. Using four spacecraft in a tetrahedron shape, it could measure, for the first time, 3D quantities such as electrical currents, plasma gradients or divergence of the electron pressure tensor and 3D structures such as boundaries, surface waves or vortices. Launched in pairs in July and August 2000, on two Soyuz rockets from Baikonur, the four spacecraft have been collecting data continuously for more than 20 years. The mission faced many challenges during the years of operations as some spacecraft subsystems had a lifetime of a few years beyond the initial two-year mission. The major one was to operate without functioning batteries and to successfully pass short and long eclipses, up to 3 h long, without damaging the on-board computers and transmitters and without freezing the fuel. More than 1,000 eclipses have been successfully passed since 2010 using a specially made procedure which switches off the complete spacecraft before entering into eclipse and switches it on when the Sun is again illuminating the solar panels. During 20 years, many discoveries and science results have been published in more than 2,700 scientific papers. A few highlights are presented here, focusing on how varying the spacecraft separation was essential to achieve the science goals of the mission. The Cluster Science Data System and the Cluster archive allows public access to all science data as well as spacecraft ancillary data.

1. Introduction

As long ago as the 1960s, scientists realized that the full understanding of plasma processes at work in the Earth's environment required multi-point measurements. Jim Dungey was an early proponent of such measurements, floating the idea as part of initial discussions on European cooperation in space (Taylor et al., 2015). But the idea did not progress until, about 40 years ago, a group of scientists (Gerhard Haerendel, Alain Roux, Michel Blanc, Goetz Paschmann, Duncan Bryant, Axel Korth and Bengt Hultqvist) proposed Cluster following an ESA call for missions to "focus on small-scale structures and macroscopic (MHD) turbulence which arise in many places of the magnetosphere." The proposal was submitted to ESA in 1982.

After a long process of studying, descoping, negotiating with other space agencies, in particular NASA, and eventually merging Cluster with the SOHO mission into the ESA solar terrestrial science programme (Escoubet et al., 2013), four years later, Cluster and SOHO were selected in February 1986 by the ESA Science Programme Committee, as the first cornerstone of the ESA Horizon 2000 programme.

This was only the beginning of ups and downs (Escoubet et al., 2015) to achieve the Cluster science dreamt of by their proposers. The largest drawback was the loss of the four Cluster spacecraft due to the failure of the maiden Ariane 5 launch on June 4, 1996. The four Cluster spacecraft and 44 instruments had been built on time in four years and four months, from April 1991 to July 1995 (Credland et al., 1997; Escoubet et al., 1997). The launch campaign started in August 1995 for a launch planned in January 1996. In November 1995, the launch campaign was interrupted and the spacecraft were put into storage because the Ariane 5 was not ready. The launch campaign re-started in February 1996 and the launch took place on June 4, 1996. Unfortunately, 40 s after launch, the rocket exploded as a result of a specification and design errors in the guidance software (Lions et al., 1996).

On that day, the ESA Science Director, Roger-Maurice Bonnet promised to the Cluster Principal Investigators (PI) that Cluster would be rebuilt and re-launched, even though he did not yet know how to realize this. Indeed, four years later, thanks to the newly made European-Russian Starsem launch company, the four

Cluster spacecraft were launched in pairs on two Soyuz rockets in July and August 2000. A few weeks later the Cluster constellation started its scientific investigations as laid down by its proposers. On the occasion of his 80th anniversary celebration, Roger-Maurice Bonnet stated that among all missions he was responsible for, the one he was most proud of was Cluster.

2. Technical Challenges

Technical and scientific challenges came regularly along the 20 years of operations. The dedicated operational teams, starting with the instrument PI teams, the Joint Science Operation Centre team (JSOC) and the flight control team at the European Space Operations Centre (ESOC) have made Cluster a success through them all. A few particular highlights were:

1. overcoming eclipses with on-board computer switched-off as well as the entire spacecraft
2. recovering the spacecraft after 3 days of telemetry loss
3. recovering the 5 wave instruments with their power relay stuck
4. tilting one spacecraft by 45 degrees to achieve three-dimensional wave measurements
5. achieving the smallest distance between two independent spacecraft of 2.5 km without active inter-spacecraft ranging or GPS receiver

The main goal of the Cluster team, originally and now, is to keep the Cluster mission making new science discoveries. To achieve this, the Cluster spacecraft were required to be magnetically very "clean" and are carrying a special type of non-magnetic battery which used silver and cadmium. Lithium-ion batteries, which are also non-magnetic, did not exist in the late 1980s when the spacecraft were designed. Silver-cadmium batteries were expected to last 3 years, due to the degradation of the cathode. Thanks to the careful management by the Cluster team, they provided enough power for 5 years. After that time, some batteries failed; the reduced power required the Cluster flight control team to start managing carefully the switching off of selected payloads and sub-systems to adapt to the energy available.

However, all the batteries eventually stopped working after nine years of operations and something had to be done for the satellites to survive Earths eclipses occurring regularly (typically every 2.5 days over a period of 3–4 weeks each winter, and over 1–2 weeks each summer). The only way to continue operating the spacecraft was to switch-off the spacecraft around eclipses. An automatic procedure was prepared to speed-up the recovery and to give more time to operate the scientific instruments, with a small ESOC flight control team. Up to now, the spacecraft underwent successfully more than 1,000 eclipses.

On February 4, 2010, after a short eclipse, Cluster 1 stopped accepting commands and telemetry could not be received (only an un-modulated carrier). Attempts to reboot the spacecraft and switch to the redundant on-board computer failed, as none of the on-board computers started the boot process. After three days of telemetry loss, a young engineer in the team, looking at electrical schematics, suggested that the problem could come from a flag in the memory of the switchover controller. Following this lead, the team managed to switch the spacecraft into survival mode and then successfully recovered the spacecraft. The problem has since been fully understood and it is related with the slow power ramp-up during certain eclipse conditions, that causes an undervoltage condition that the spacecraft reacts to by asking a switch over of the processor to the redundant unit, while the team was attempting in the blind to switch on the original prime processor. These conditions are now predictable; the logic is automatically reset during recovery and the problem is avoided.

On March 5, 2011, an anomaly occurred in the digital wave processor (DWP) controlling the five wave instruments. We could not switch-on the instrument anymore since it was drawing too much current and a latch current limiter of the spacecraft was switching it off soon after. Long investigation was necessary since such failure can have dramatic effects on a spacecraft, leading to its loss if such current monitoring system fails. It was found that all relays providing currents to all five instruments remained open after the anomaly occurred–DWP usually switches on two or three instruments simultaneously but not five. After analyzing ground tests performed 20 years earlier, the DWP technical manager could predict the current raise profile and better understand the problem. The solution found to overcome this problem was to try allowing more current to flow to the instrument using both the main and redundant current lines simultaneously.

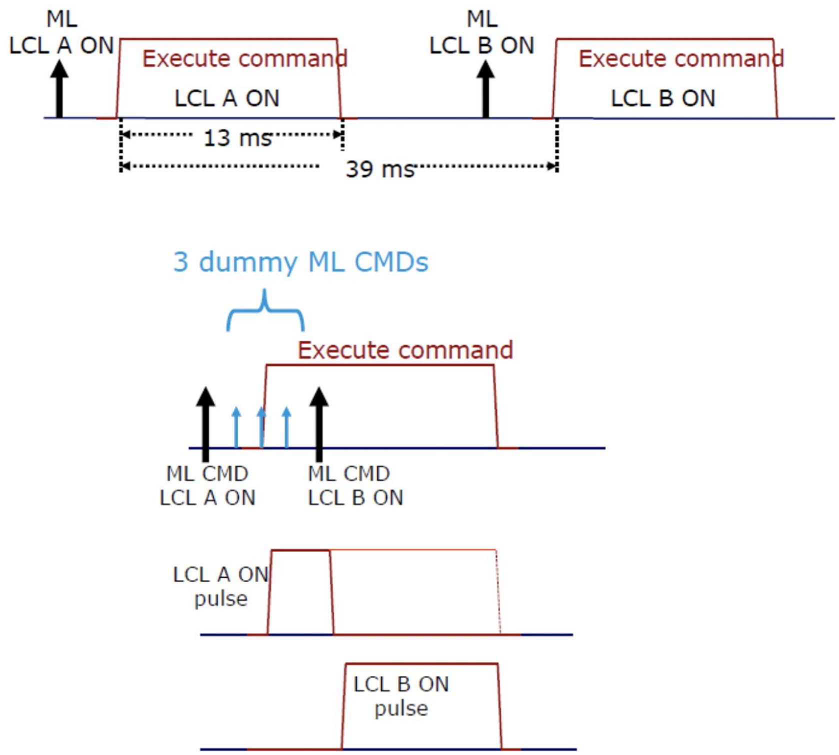

Figure 1. Top: original design of power on commands (fastest time between two commands is 39 ms). Bottom: solution to send two commands within 11 ms by changing the command register within one execute command (courtesy Gunther Lautenschläger, Airbus, Germany).

However, it turned out that it seemed impossible to switch-on both current lines quickly enough since each required a single command, separated by 39 ms (Figure 1). The "trick" found by the flight control team was to use only one execute command and to change the command register after a few ms. After the second attempt the instrument was successfully recovered on June 1, 2011 (for more details on the recovery see Escoubet et al., 2015).

In September 2004, the WHISPER (electric waves and sounder) PI proposed to tilt one Cluster spacecraft with respect to the others. The goal was to study the non-thermal continuum (a natural electromagnetic emission from the magnetosphere), in order to observe its polarisation and then find the position of its source, which was not well known at the time. Tilting a spacecraft is a major risk since there is always a possibility to lose power if the solar panels are not pointing toward the Sun. ESOC, Airbus and ESTEC experts studied carefully all possible risks on the spacecraft and instruments and proposed to implement it in May 2008. This date was chosen since it was away from the eclipse seasons and the spacecraft spin axis was perpendicular to the Sun-Earth line, minimizing possible power problems. Cluster 3 was successfully tilted by 45 degrees for a month. The unique science results are described in Décréau et al. (2013).

More recently, to study electromagnetic emissions responsible for the acceleration of particles in the radiation belts, the PI of the digital wave processor (DWP) proposed having two spacecraft move as close as possible to each other to investigate wave particle interactions at electron scales. The goal was to reach a separation distance of 5 km or less. Careful maneuvering and monitoring was required to execute such maneuvers since there is no active inter-spacecraft ranging on Cluster and the spacecraft have to be controlled from the ground. The accuracy on the position of each spacecraft using ground ranging is around 0.1 km. Since the cross-section of each spacecraft, with two 88 m long tip-to-tip wire booms, is also about 0.1 km, a few kilometers separation is approaching the accuracy limit. With careful maneuvering and monitoring the team managed to achieve a separation of 4 km between Cluster 3 and Cluster 4 on September 19, 2013. This first achievement paved the way to future tight formations to study the Earth's bow shock at even smaller scales:

with 3 km separation reached in January 2016 and 2.5 km achieved in December 2018. This is the smallest distance ever achieved between two magnetospheric spacecraft without active ranging or GPS receivers.

3. Cluster Operations

Two operation centers are in charge of the spacecraft and instrument operations: the European Space Operations Centre (ESOC) at Darmstadt (Germany) and the Joint Science Operations Centre (JSOC) at Rutherford Appleton Laboratory (RAL) (United-Kingdom).

ESOC is the ESA main centre for the operations of the ESA spacecraft. Its tasks are to:

1. Maneuver the four spacecraft at regular intervals to achieve the formation required by the science objectives;
2. Operate the spacecraft and instruments;
3. Collect and distribute the data to the PI and Co-I institutes.

For the Cluster mission to reduce costs and obtain agreement to re-built it from ESA Science Programme Committee (SPC), it was decided to operate the four spacecraft with a single ground-station (initially two ground stations had been planned). The science requirement of collecting an amount of data equivalent to 50% of the orbit in Normal mode could still be fulfilled using more flexible solid-state recorders. After 1 year of operations, it was however realized that collecting data over 50% of the orbit was missing important events such as Southern cusp crossings and geomagnetic storms and substorms. A special request was therefore approved by SPC, together with the 1st extension of the mission for 3 years, to add a second ground station to collect data over 100% of the orbit, starting in June 2002. Adding 15% (equivalent to 1.5 h) of burst mode to 100% normal mode, made a total of 115% normal mode equivalent.

Initially, due to network limitations, the distribution of data was made on CD-ROMs (1–3 per day) to all CoI institutes (about 70). This was a major task for ESOC since many manual activities were necessary to burn, package and send so many CD-ROMs to different addresses. With the rapid improvement of internet bandwidth, this was replaced five years later (2006) by online distribution through the Cluster active archive, located at ESTEC at that time, now located at ESAC.

To collect wideband wave data at very high temporal resolution with microsecond time accuracy, a special mode was built on the spacecraft for the Wide Band instrument (WBD) (see Gurnett et al., 1997). This mode of operation required the use of up to four ground stations, from the NASA Deep Space Network (DSN), to acquire the four spacecraft data simultaneously in real time. The Cluster spacecraft were therefore using ESA ground stations for normal and burst mode data collection from all instruments and NASA ground stations for high resolution WBD data. Special coordination activities were required to synchronise ESA and NASA ground station schedules. Since 2015, NASA DSN station support was stopped and WBD data collection is now made using the Czech ground stations from Panska-Ves.

The system put in place by ESOC returned data very successfully during the 20 years of operations (Figure 2) and more burst mode data could be obtained recently (up to 140% Normal mode equivalent) by optimizing the data downlink systems, improving planning and modeling of link budget predictions, adding Multiple Spacecraft per Aperture, and not collecting data during eclipses.

ESOC Flight Dynamics engineers have played a major role in maneuvering the spacecraft towards the targets specified by the science working team (SWT). The idea to form two tetrahedra along the orbit, to maintain a good 3D configuration over a major part of the orbit, was suggested by one of them. They also played a great role in fuel optimisation while always managing to fulfill science goals proposed by the SWT, guest investigators and early career scientists. It was only with their skills that we managed to approach two spacecraft to 3 km from each other (see Section 4 below).

Early in the mission it was realized that the coordination of 4 spacecraft, 44 instruments and 96 sensors, required a special team dedicated to this activity. The Joint Science Operation Centre was setup at RAL in 1993 (Dunford et al., 1993). JSOC is responsible of three main tasks (Hapgood et al., 1997, http://www.jsoc.rl.ac.uk/):

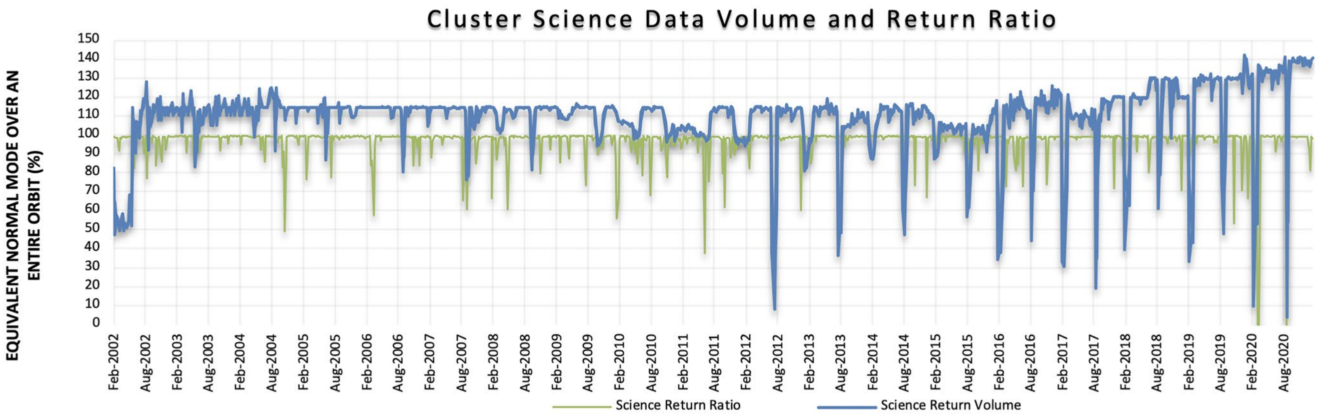

Figure 2. Amount of data return by ESA ground stations (not including NASA DSN). Blue line: amount of data relative to a full orbit in normal mode (NM). An amount above 100% indicates the data volume of burst mode (BM) returned. Initially the data return was around 50% of the orbit, then increased to 115% in June 2002 (equivalent to the full orbit in NM and about 1.5 h in BM). More recently by optimizing the scheme and sometimes combining two spacecraft dumps to one ground station, we could achieve 140% (equivalent to the full orbit in NM and more than 4h in BM in 54 h orbit). Green line: the return ratio shows the percentage of data generated that was retrieved to Ground (data losses are mostly due to anomalies). The spikes since 2012 in the blue line correspond to eclipse seasons, when due to loss of batteries less data is collected.

1. Planning activities
2. Commanding of the instruments
3. Monitoring science and instrument status

The 44 individual instruments required a robust system to ensure that no commands were missed during observations or if a PI team had not managed to send observation requests on time. It was decided to build top level modes for each instrument that would be used in the various regions crossed by the spacecraft (radiation belts, magnetosphere, magnetotail, cusp, magnetosheath and solar wind). Together with a database and a set of rules dictating where to apply the various instruments' modes, JSOC could distribute to each instrument team the draft command sequence files that could be modified or not by the team. After all modifications for the 44 instruments are received, they are then merged into a single timeline file that is sent every week to ESOC. Figure 3 shows the number of records, which is a measure of the number of command sequences, sent to ESOC for the 44 instruments. We observed peaks in the number of command sequences at the beginning of the mission, when PI teams and JSOC were learning how to operate the instruments, and in 2009–2012 when the spacecraft reached the lowest perigee, 250 km altitude with Cluster 2, which required more mode switching than usual. Typically, JSOC sends between 5,000 and 6,000 command sequences every week to ESOC.

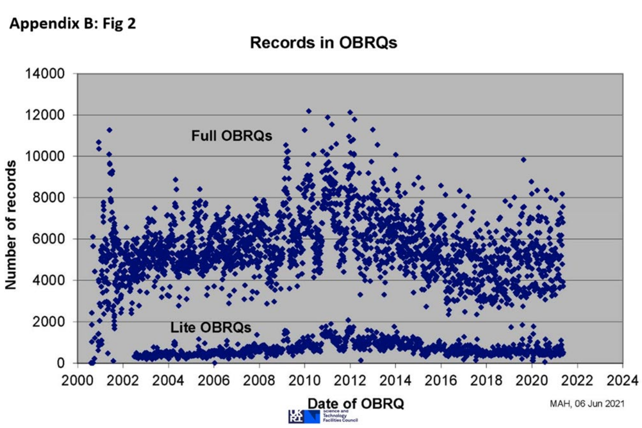

Figure 3. Cluster number of records in the observational requests (OBRQ) sent each week to command the Cluster instruments from JSOC to ESOC. The full OBRQ contains all command sequences from all instruments and all spacecraft while the lite OBRQ is an initial simple version with the magnetometer command sequences only.

JSOC is also producing planning information to help the instrument team operate their instruments. Based on predicted orbits, scientific events such as magnetopause, bow shock and neutral sheet crossings are made available as well as geometric (GSE) and magnetic (L shell, magnetic local time and invariant latitude) positions (Hapgood et al., 1997). The magnetic positions are used to switch to stand-by or off radiation sensitive instruments in the Van Allen belts as well as predicting the crossing of the polar cusp. JSOC also develops the Cluster Master Science Plan, which is based on the predicted orbits, scientific events and the PI requests for the burst mode operations. This plan incorporates information about the Earth and Moon eclipses and maneuvers and defines the distribution of the normal and burst modes and no-data-taking periods for every orbit on each spacecraft, taking into account the agreed-upon data volume. These telemetry sequences are then used in the spacecraft commanding.

In addition, with input from the ESOC flight dynamics team, JSOC produces a long-term orbit file (super LTOF) which includes predicted

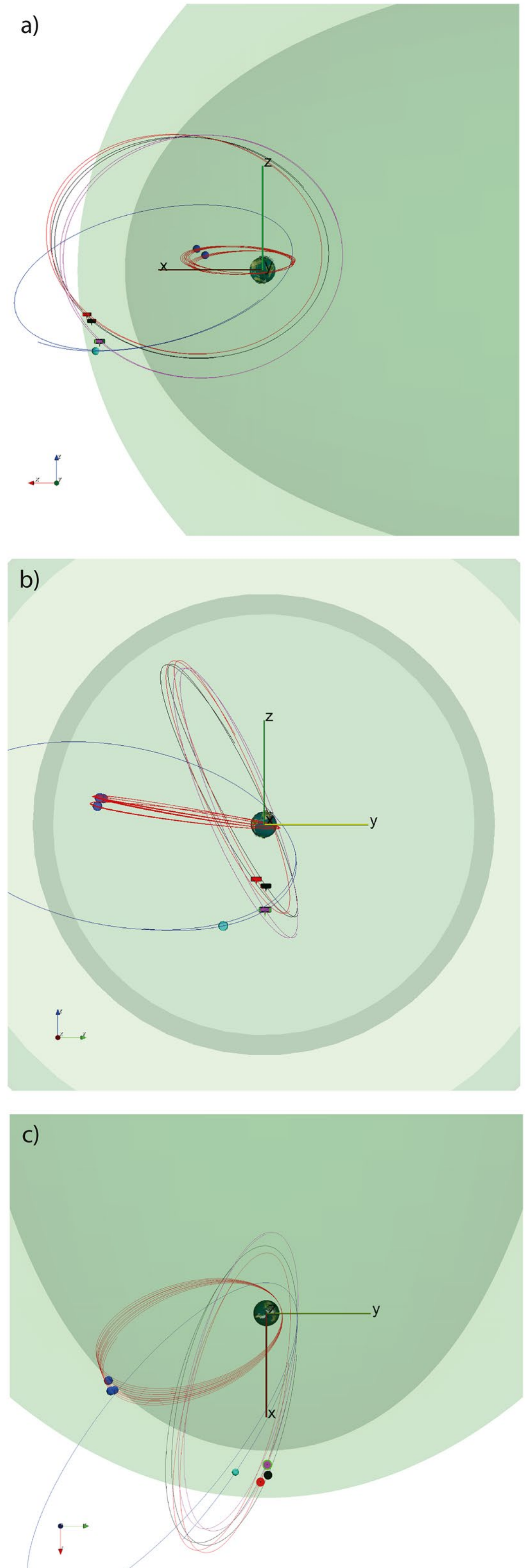

Figure 4. Position of Cluster, MMS, and THEMIS with respect to the main boundaries of the magnetosphere using Orbit Visualisation Tool (ovt.irfu.se) in March 2021. Upper left in XZ_{GSE} plane and Upper right in YZ_{GSE} plane and Lower left in XY_{GSE} plane. Cluster 1, 2, 3, and 4 are in black, red, green and magenta, MMS1 is in cyan and THEMIS-A, D and E are in blue.

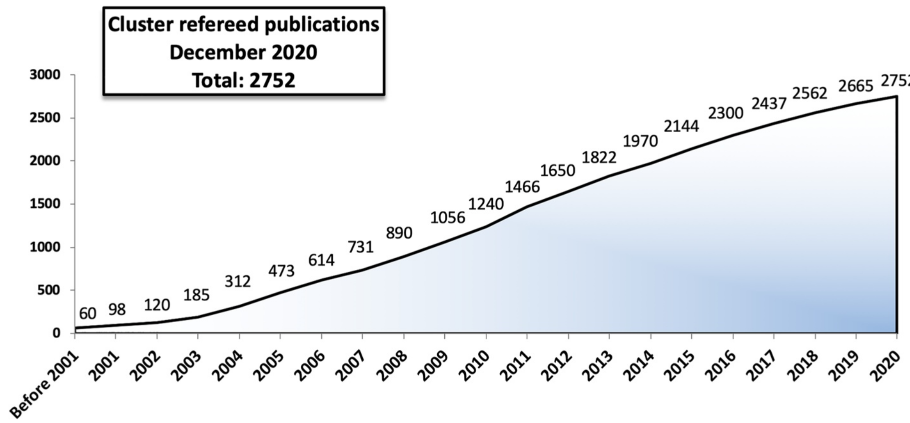

Figure 5. Cumulative Cluster refereed publications as a function of year from launch up to December 2020. The red area at the bottom of the plot shows the Double Star mission publications.

positions for future planning and reconstituted position for past positions. This is transferred every few months to NASA SSCweb for coordination with other spacecraft. The position of the spacecraft can be visualized together with other spacecraft in the magnetosphere in 3D with the main regions of the magnetosphere modeled and the distances from the main boundaries (bow shock, magnetopause) indicated using the Orbit Visualisation Tool (OVT) (https://ovt.irfu.se/). Figure 4 shows the Cluster, MMS and THEMIS orbits in March 2021 during a conjunction event where Cluster and MMS are near the bow shock and THEMIS-A, D, E near the magnetopause. This will enable a study of the bow shock at multi-scales from 16 to 22 km with the MMS constellation, from 70 km to 2.3 R_E with Cluster, while the separation between Cluster and MMS will be between 2.9 and 3.7 R_E and three of the THEMIS spacecraft separated from 0.25 up to 1 R_E at the magnetopause.

4. Science Highlights

Refereed and non-refereed publications, as well as PhD theses, are compiled every month and listed on the Cluster web page (see https://sci.esa.int/web/cluster/-/48262-publications-and-phds). Up to end December 2020 Cluster data were used in 2752 refereed papers (Figure 5). The first few years of the mission showed a low publication rate of about 30 papers/year due to the time required for calibrating and understanding the data but starting in 2004 the rate was above 100 papers/year with a maximum in 2011 with 234 papers. The publication rate is still above 100 papers/year after more than 20 years, showing the continuing interest in, and quality of the Cluster data.

The International Space Science Institute (ISSI) book on "Analysis Methods for Multi-spacecraft Data," edited by Paschmann and Daly (1998), is one of the most cited book within the community. The work on that book started at ISSI a few weeks after the Cluster I launch failure, in 1996. At their first meeting, the authors, devastated by the loss of Cluster spacecraft, decided to continue with the book, despite the big uncertainties on the Cluster rebuilt. The book is describing the methods to analyze data from clusters of spacecraft from resampling and spatial interpolations to computation of gradients, curls and discontinuities parameters. The authors revisited the analysis methods in 2008 using lessons learned from their applications to the Cluster data (Paschmann and Daly, 2008).

The Cluster community publishes not only in specialized space physics journals such as Geophysical research Letters, Journal of Geophysical Research and Annales Geophysicae, but also in journals of broader scientific interests, including Science, Nature, Physical Review Letters, Astrophysical Journal, Physics of Plasmas and Space Weather journals, which

Table 1
Cluster Publications Classified in Most Used Journals

Journals	Number of papers
Nature/Science	30
Astrophysical Journal (inc. Lett.)	118
Physical Review Letters	74
Physics of Plasmas	84
Geophysical Research Letters	267
Journal of Geophysical Research	1,022
Annales Geophysicae	557
Other	757

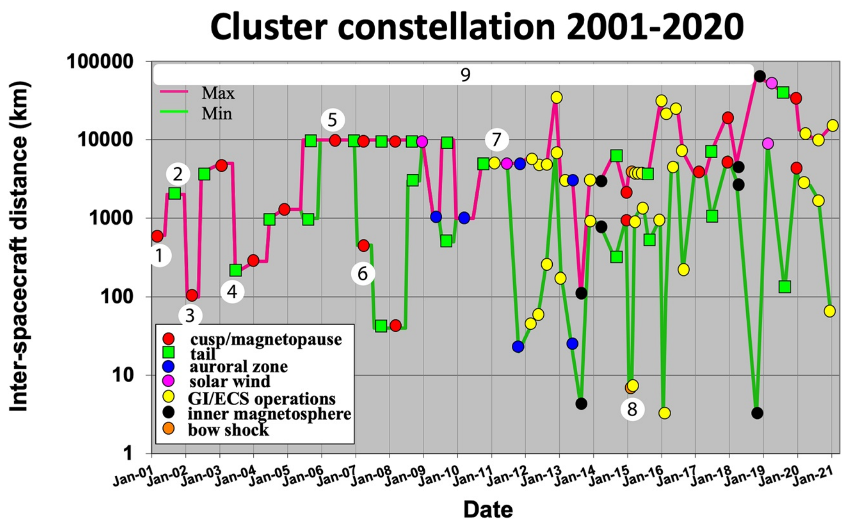

Figure 6. Cluster spacecraft separations over the 20 years of operations. The green and magenta lines show the minimum and maximum distances between two Cluster spacecraft. When the green line is visible, a multi-scale configuration was used. Cluster 3 and Cluster 4 are on the same orbit and allow very small (2.5 km) or very large (60,000 km) distance between them by drifting one versus the other along their orbits. The numbers in white circles indicate the constellation geometries and the time intervals used in the papers described in Section 2.

illustrates the wide interest in Cluster results, including those that address fundamental issues in plasma physics. The number of publications in each journal is presented in Table 1.

We have selected science highlights that use Cluster data spread over 20 years, covering various plasma scales in the magnetospheric regions studied with the Cluster constellation. The spacecraft separations achieved during 20 years are shown in Figure 6 from the smallest at 3 km up to the largest around 60,000 km. We have marked with a number the separation distances which were used for the highlighted papers presented below.

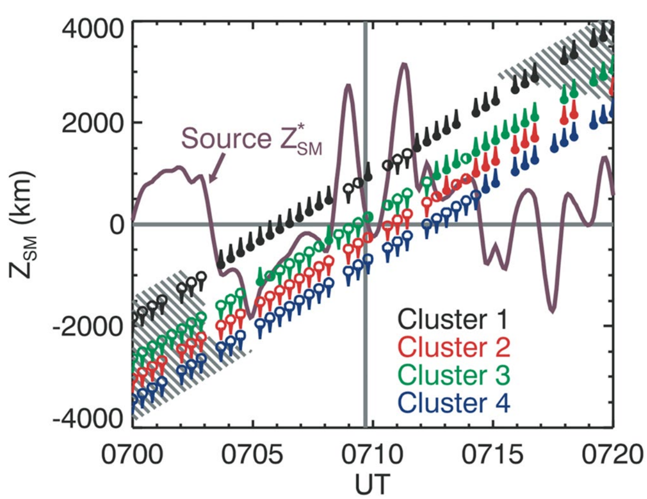

Figure 7. Position of the four Cluster spacecraft (in classical colors, C1 in black, C2 in red, C3 in green and C4 in blue, see http://www.jsoc.rl.ac.uk/pub/cluster_ids.php) in Z_{SM} as a function of time. The four spacecraft crossed the magnetic equator between 07:06 UT (C1) and 07:12 UT (C4). The direction of the parallel pointing flux is indicated by the symbols along each spacecraft trajectory (empty for Southward direction and solid for Northward direction). The gray line indicates the chorus source's central position (adapted from Santolik et al., 2004).

4.1. Chorus Emission Size and Position During a Storm

At the beginning of the Cluster mission, in spring 2001, we placed the spacecraft in a tetrahedron scale size of 600 km in the polar cusps (Number 1 in Figure 6). Cluster first results using these data together with ground-based observatories, in particular EISCAT, are reported in the Cluster special issue of Annales Geophysicae of 2001 (see Escoubet et al., 2001 and reference therein). Two tetrahedra were placed in the Northern and Southern cusp which allowed keeping a not-too-deformed tetrahedron throughout most of the orbit around apogee. At perigee on the other hand, due to orbital mechanics, the spacecraft followed a string-of-pearls configuration varying from 450 km for the two closest spacecraft (C2 and C3) and up to 1,650 km for the two most separated ones (C1 and C4). Such string of pearl configurations are very useful for observing temporal change in plasma structures on varying time scales. Santolík et al. (2004) used such a configuration to study chorus emissions during a major storm (Dst = −358 nT) on March 31, 2001. Whistler-mode chorus emissions are believed to be produced by energetic electrons (tens of keV in energy) when crossing the magnetic equator. For the first time, with four identical spacecraft crossing the magnetic equator, the source of chorus emission could be characterized in unprecedent detail. Santolík et al. (2004) demonstrated that chorus sources are not static but fluctuate around the equator within 1,000–2000 km on time scales of minutes (Figure 7). The shaded areas on Figure 7 indicate the low electromagnetic

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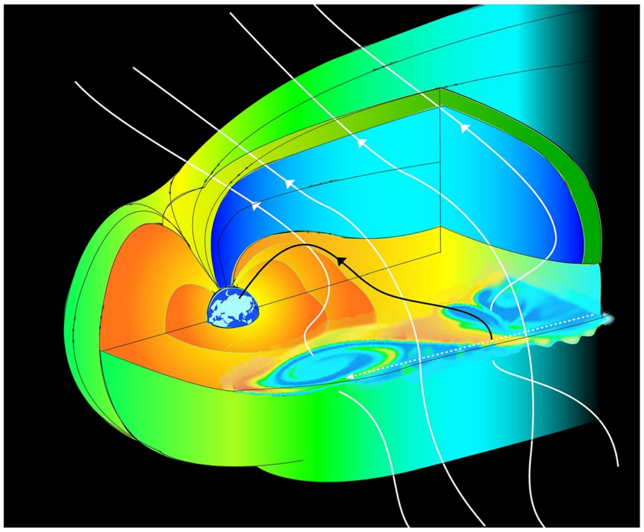

Figure 8. 3D cut-away view of Earths magnetosphere. The Kelvin-Helmholtz vortices discovered by Cluster on November 20, 2001 are sketched on the dusk flank of the magnetosphere. The magnetic field lines from the solar wind are shown in white and the ones from the Earths magnetosphere in black. The white dashed line shows the trajectory of the four Cluster spacecraft in relation to the anti-sunward-flowing vortical structures (courtesy H. Hasegawa).

planarity, which gives a dimension of the chorus source in the range 3,000–5,000 km, perpendicular to the geomagnetic equator.

4.2. Kelvin-Helmholtz Waves Rolled-Up Into Vortices

For the first magnetotail crossing with Cluster in summer 2001, we formed two tetrahedra on each side of the plasmasheet to keep a good tetrahedron formation during the entire crossing of the plasmasheet (about 10 h). The separation distance between the four spacecraft was 2,000 km (Figure 6 Number 2). In the fall, the spacecraft were still separated by 2,000 km and crossed the magnetopause on the dusk side. Since the crossings occurred around apogee, the spacecraft were skimming the magnetopause and observed it for prolonged time intervals (>12 h). During one such prolonged magnetopause crossing, Hasegawa et al. (2004) identified quasi-periodic plasma and magnetic field perturbations lasting more than 13 h. By looking at the differences in density, plasma flow and magnetic field between the four spacecraft, they demonstrated that the spacecraft located further inside the magnetosphere was measuring a higher density than the ones further outside. With the support of magnetohydrodynamic (MHD) simulations they explained the observations as Kelvin-Helmholtz waves rolling up into vortices (Figure 8). Such a mechanism is one of the mechanisms which allow solar wind plasma to enter the magnetosphere. Although Hasegawa et al. (2004) did not detect signs of magnetic reconnection around the vortices, later on Nykyri et al. (2006) observed signatures of the small-scale magnetic

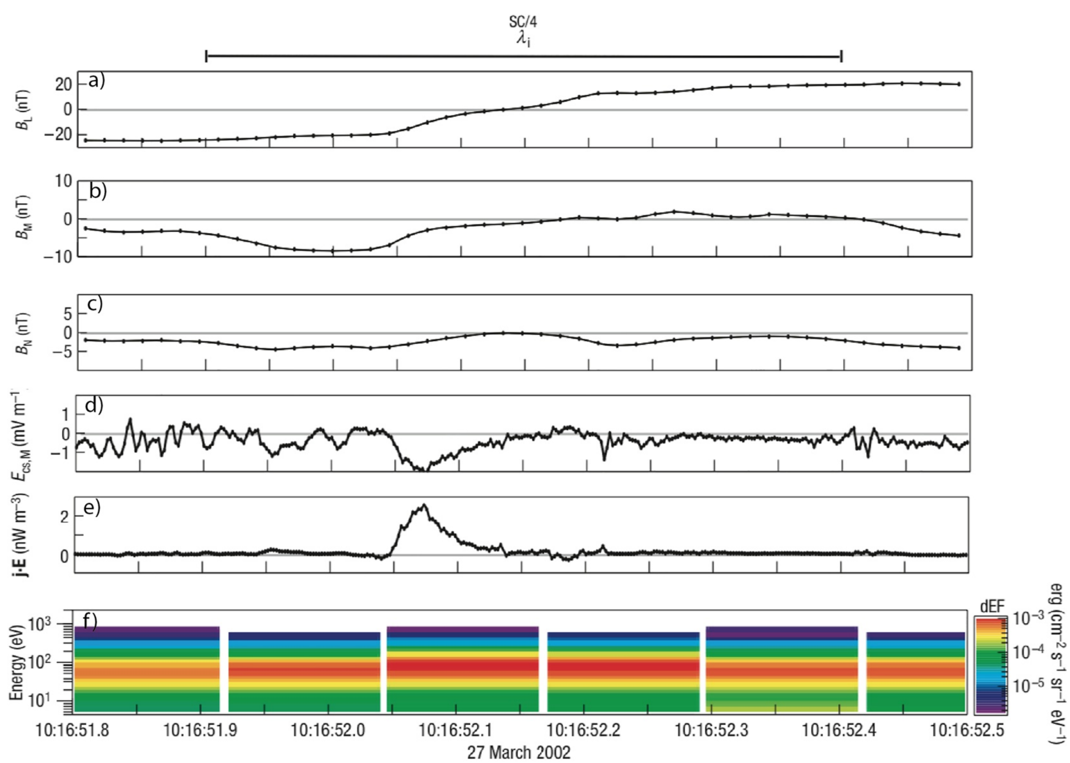

Figure 9. Current sheet observed by Cluster 4 in the turbulent magnetosheath on March 27, 2002 (adapted from Retinò et al., 2007). Panels a–c show the magnetic field in LMN coordinate system, Panel d the tangential electric field in the current sheet frame, Panel e the quantity E.j and Panel f the electron spectrogram, using 2D cuts at 120 ms time resolution.

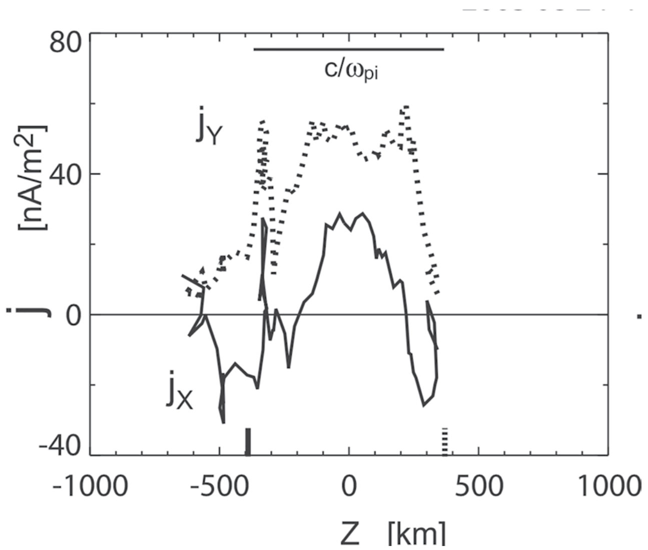

Figure 10. Current density profile for the current-sheet crossing on 24/08/2003. X (solid line) and Y (dotted line) components of the reconstructed profiles of current density using temporal/spatial gradient of the cross-tail component (from Nakamura et al., 2006).

reconnection occurring due to the twisting of the magnetopause within Kelvin-Helmholtz vortices. Follow-up results on Kelvin-Helmholtz instability based on Cluster but also Themis and Geotail data are reviewed in (Masson & Nykyri, 2018).

4.3. Reconnection in a Turbulent Magnetosheath

Before the Cluster 1 launch in 1996, the plan was to go to a minimum inter-spacecraft distances of 600 km within the cusp. After the first launch failure, an ISSI international team on Small Scale Plasma Structures led by S. Schwartz and G. Paschmann revisited the AMPTE IRM and UKS spacecraft measurements at the dayside magnetopause, magnetosheath, and bow shock. They recommended to the Cluster project in April 2000 that the spacecraft separation distance be reduced to 100 km. With the agreement of the science working team, those distances were achieved at the beginning of the second year of operations (Figure 6 Number 3). The data set collected by the spacecraft turned out to be one of the most popular in the community since it allowed computation of 3D quantities such as current or gradients of small scales plasma structures and also the use of electromagnetic waves analysis tools such as k-filtering or the wave telescope to identify the various electromagnetic waves present at the same time (e.g., Alexandrova et al., 2009; Narita et al., 2006). One of these results was published in Nature Physics by Retinò et al. (2007). It was the first study showing that magnetic reconnection signatures are observed in a turbulent plasma. Figure 9 shows that reconnection was on-going since the data included observation of (1) the reversal of the B_L component, (2) the out-of-plane electric field ($E_{CS,M} < 0$) and (3) the normal magnetic field ($B_N \neq 0$). Furthermore, energized electrons were also observed within the current sheet (Figure 9 panel f). Retinò et al. (2007) showed that the reconnection rate was fast with $R = 0.1$.

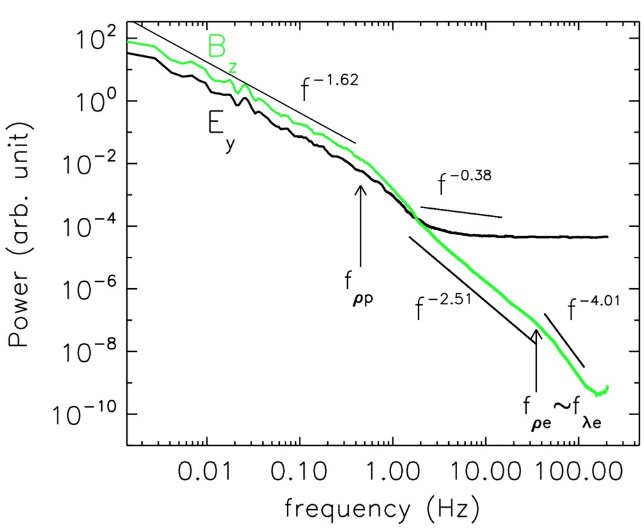

Figure 11. Turbulent cascade spectra in the solar wind from large scales (10^5 km) down to small scales (∼3 km) as measured by the Cluster spacecraft. The magnetic and electric field spectra are shown in green and black. The solid lines show the slopes in three frequency bands. Above 2 Hz, Ey is almost flat and is due to the noise floor being reached (adapted from Sahraoui et al., 2009).

4.4. Thickness of Thin Current Sheets

The magnetotail study required larger spacecraft separation than at the dayside boundaries and the first two tail crossings were sampled with inter-spacecraft distances around 2,000 and 4,000 km. However, for the 3rd year crossings, PI teams wanted to investigate the plasmasheet at closer inter-spacecraft distances to focus on thin current sheets. The spacecraft constellation formed was a tetrahedron of 200 km in size (Figure 6 Number 4). Nakamura et al. (2006) analyzed the characteristics of thin current sheets and their evolution during a substorm in August 2003. The thickness of the thin current sheets could be quantified for the first time, it was found to be comparable to the ion skin depth around 500–900 km (Figure 10), suggesting that the Cluster spacecraft were located within the ion diffusion region. Furthermore, Nakamura et al. (2006) showed that during two rapid crossings of thin current sheets moving tailward, the thin current sheets had multiple peaks with some of them exceeding 50 nA/m^2 (on 4s averaged data). Such values were more than 10 times larger than typical currents observed in the plasma sheet.

4.5. Solar Wind Turbulence

It is known that the temperature of the solar wind is decreasing with the distance from the Sun more slowly than a simple adiabatic expansion would predict. For many years, turbulence has been suggested to play a role in this heating process. Turbulence cascade starts when large regions

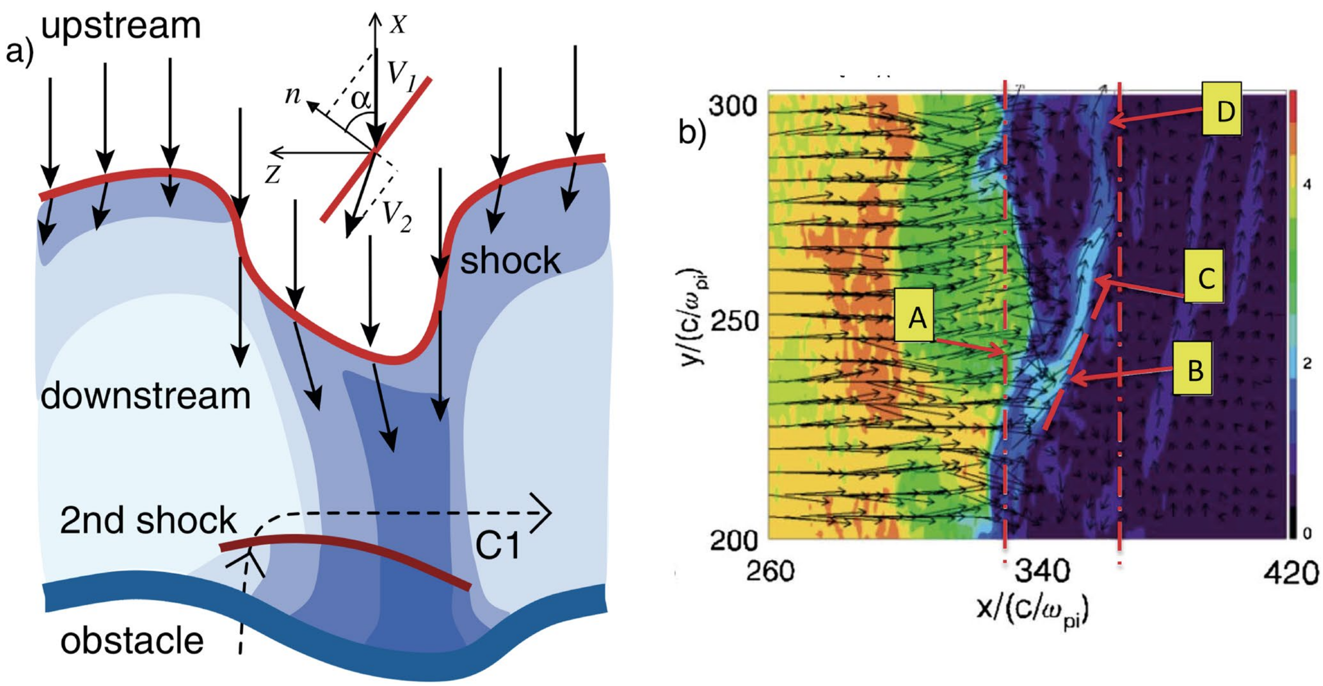

Figure 12. (a) Sketch of a bow shock ripple and its interaction with the solar wind flow. On each side of the ripple the flow is decelerated by the shock. In the ripple, the flow is only slightly decelerated and deflected (from Hietala et al., 2009). (b) 2D hybrid simulations showing the ion flows (vectors and isocolors) (from Hao et al., 2016). Note the picture on panel b is rotated 90 anti-clockwise compared to panel (a) The letter A marks the bow shock ripple, and B, C and D mark the HSJs.

with one velocity encounter other regions with different velocities and produce large vortices that breaks up into smaller ones. This process continues until the smallest scales are reached, when vortices disappear and the energy is converted to heat. Before the Cluster era, exactly at which scale turbulence heats the plasma composing the solar wind remained unclear. Using the first large-scale spacecraft separation of 10,000 km with data obtained in March 2006 (Figure 6 Number 5), Sahraoui et al. (2009) measured the energy cascade from large scales (10^5 km) down to electron scale at a few kilometers (Figure 11). The magnetic spectra showed two break points, where the slope becomes steeper as frequency increases, at 0.4 and 35 Hz, corresponding to the proton and electron scales. Furthermore, the slope obtained above the electron scale was in agreement with theoretical predictions. This result (Sahraoui et al., 2009), together with other solar wind turbulence investigations (e.g., Bale et al., 2005; Alexandrova et al., 2009), is one of the most cited Cluster results.

4.6. Supermagnetosonic Jets in the Magnetosheath

Magnetosheath high speed jets (HSJs) are strong plasma flows (of ions and electrons) with speed almost reaching the solar wind speed. Being downstream of the nominal shock location, they should be decelerated at the shock and their observations was therefore a surprise (Nemecek et al., 1998). Using the Cluster constellation measuring multi-scales between 950 km (distance between C3 and C4) and 10,000 km (distance between C1 and C2), Hietala et al. (2009) advanced a possible explanation for the non-deceleration of the solar wind structures. A bow shock ripple with a size of 7,000–15,000 km (Figure 12a) would allow fast flows to go through due to the large angle (up to 90°) between the flow direction and the shock normal. Bow shock ripples were indeed observed previously with Cluster at the bow shock (Moullard et al., 2006). More recently, Hao et al. (2016), using 2D hybrid simulations, showed that ULF waves in the foreshock convecting downstream could form such ripples at the bow shock through which HSJs can form and propagate downstream (Figure 12b).

Table 2
List of Guest Investigators Selected by ESA to Perform Cluster Investigations in 2015–2016 and 2020–2021

Guest investigator	GI proposal title	Laboratory	Implementation period
Olga Alexandrova	Study of the dissipation range of solar wind turbulence	Meudon Observatory, France	February and March 2015
David Burgess	Ion pickup coupling in the solar wind associated with thruster operations	QMUL, UK	March 2015
M Dunlop	Coordination of Cluster/Swarm for FACs	RAL, UK	June 2015
Yulia V. Bogdanova	Mid-altitude cusp properties, dynamics, small-scale plasma structure and ion outflow: simultaneous Cluster measurements at different MLT sectors	RAL, UK	November and December 2015
Yuri Khotyaintsev	Multi-spacecraft Investigation of Electron Scales at Bow Shock	IRF-U, S	January 2016
Primoz Kajdic	Magnetic reconnection in the solar wind: search for small-scale events	ESA/ESTEC, NL	February 2016
Xochitl Blanco-Cano	Upstream transients and their influence on the bow shock and magnetosheath	Mexico University, Mexico	April 2016
Claire Foullon	Magnetopause boundary layer: evolution of plasma and turbulent characteristics along the flank - repeats	Exeter University, UK	May–June 2016
Patrik Krcelic	North-south asymmetries in the polar cusps and its influence on ion outflow: experimental determination of mirror forces	Max Planck, Germany and University of Zagreb, Croatia	January and May 2020
Pavel I. Shustov	Investigation of sub-ion magnetic holes in the dipolarized plasma sheet: ion-electron energy exchange and magnetosphere-ionosphere interaction on small scales	Space Science Institute, Russian Academy of Sciences, Moscow, Russia	August–September 2020
S. Toledo-Redondo	Constraining the meso-scale of magnetic reconnection at the Earth's magnetopause using MMS - Cluster conjunctions	IRAP/CNRS, France	December 2020–March 2021

Note. Earlier investigations in 2011–2013 can be found in Escoubet et al. (2015). Up to 10 orbits were dedicated to each investigation. The details of spacecraft and instrument requirements as well as the spacecraft formation can be found at https://sci.esa.int/web/cluster/-/51547-guest-investigator-operations.

4.7. Energetic Electrons at the Magnetopause

To enhance Cluster science for the extension of the mission in 2011–2012, it was decided to turn Cluster into a "plasma physics" observatory. Similar to Astrophysics observatories, we opened a call for ideas for new investigations to use a maximum of 10 orbits and to define the configuration of the constellation and of the instruments. A second call was opened in 2014 and a third in 2019. The list of the investigations implemented in 2015 and 2020 is given in Table 2. The first of these proposals was implemented to collect data of energetic electrons (4–400 keV) with high spatial resolution (9 polar and 16 azimuthal angular bins at spin resolution for all 8 energy bins). This was done via a special mode on the spacecraft (normal mode 3) and a special mode of the RAPID instrument. The science goal was to find the source of energetic electrons observed poleward of the cusp. Walsh et al. (2012) analyzed the collected data and observed bursts of energetic electrons on three Cluster spacecraft (spacecraft separation at that time was around 5,000 km, see Figure 6 Number 7) coinciding with increases in the rate of dayside reconnection (Figure 13). Using pitch-angle information they could trace the origin of the energetic electrons to the dayside region where field lines were opened by reconnection allowing energetic electrons to escape along the magnetopause.

4.8. Kilometre Scale of Bow Shock Structures

Dimmock et al. (2019) have studied the Earth's bow shock with unprecedent details, revealing how the energy is partitioned and particles accelerated. Two of the Cluster spacecraft, which flew 7 kilometers apart through Earth's bow shock, were used in the study (Figure 6 Number 8). It was found that the magnetic field obtained by the Cluster 3 and Cluster 4 spacecraft differed significantly (Figure 14). This showed that small-scale magnetic field structures exist within the wider bow shock and indicates that such structures favor the

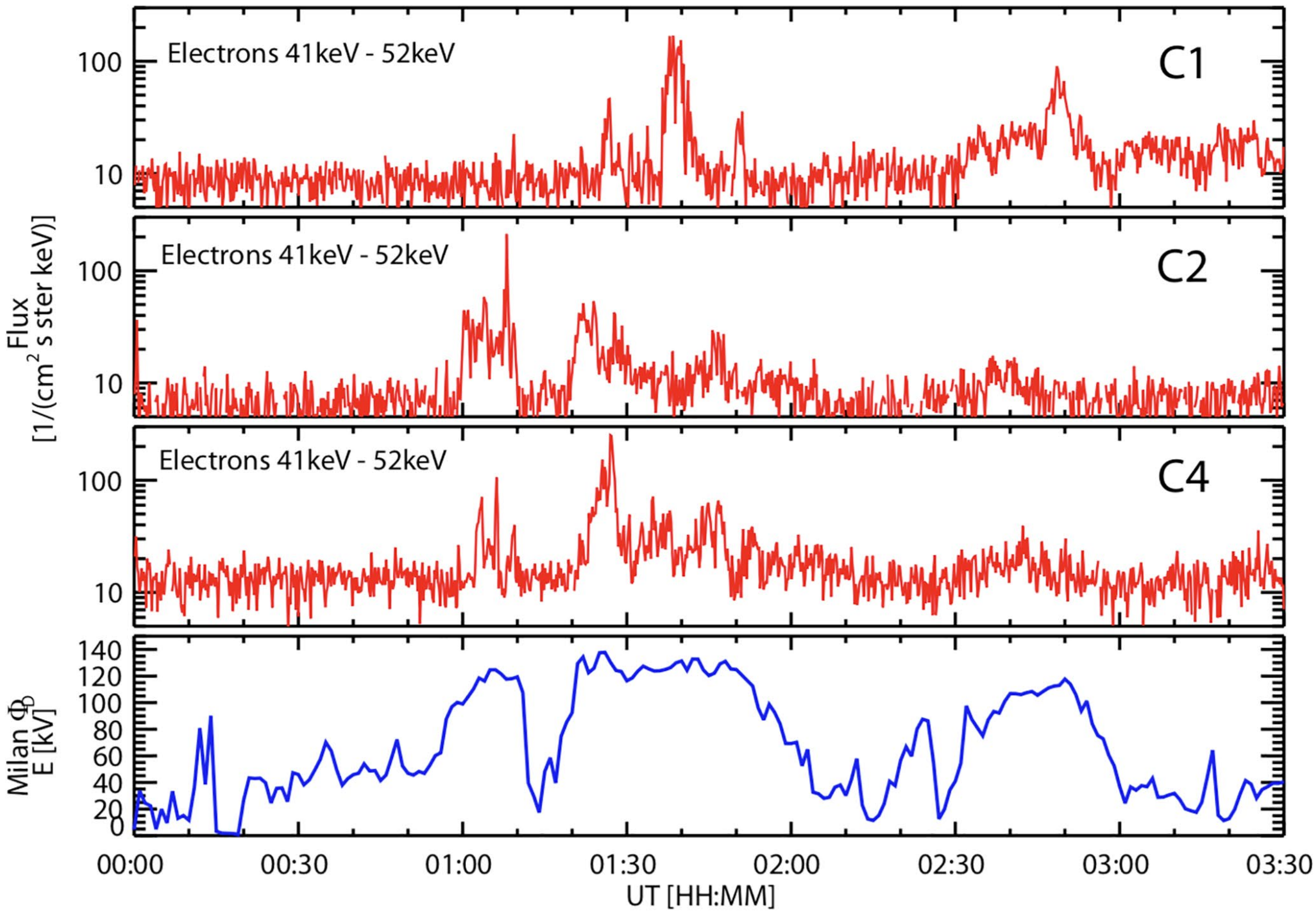

Figure 13. Flux of energetic electrons between 41 and 52 keV (top three panels) on C1, C2, and C4 and the reconnection potential (bottom panel). The bursts of electrons coincide with the maximum of reconnection expected at the dayside magnetosphere (from Walsh et al., 2012).

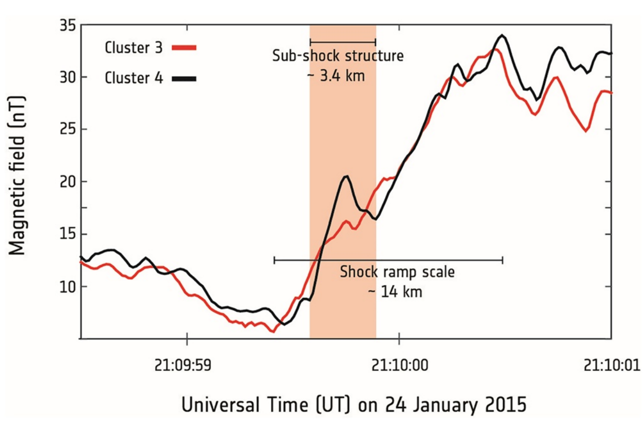

Figure 14. Magnetic field modulus measured by Cluster 3 (red) and Cluster 4 (black) on January 24, 2015. The bow shock is shown as the large increase of magnetic field from 21:09:59.5 and 21:10:00.5 UT. In the middle of the shock a sharp peak of magnetic field is measured by Cluster 4 and not by Cluster 3 (orange region) (From Dimmock et al., 2019).

breaking of plasma waves in the near-Earth environment. These structures were a few kilometers in size, similar to the scales of the electron gyro radius, and located in a thin and variable part of the shock. These observations agree well with the gradient catastrophe model (Krasnoselskikh et al., 2002) which predicts that the shock front becomes unstable and that dynamic structures are formed with spatial scales of electron inertial length within the shock ramp.

4.9. Energetic Iron Ions

The energetic particle instrument on board Cluster has a special diagnostic mode which has enabled scientists to identify iron (Fe) ions, a very rare species in geospace. Based on 18 years of Cluster data (Figure 15), Haaland et al. (2020) derived a statistical map of their presence not only in the different regions of the magnetosphere crossed by Cluster but also in the near Earth solar wind, detected on average around 9% of the time. Moreover, the amount of iron was found to be modulated by geomagnetic disturbances and solar activity (Figure 15). The existence of single ionized iron ions (Fe^+) in the Earths environment was discovered by the GEOTAIL mission a few years prior (Christon et al., 2017). Cluster not only confirmed these earlier results but due to its wide spatial coverage, it also provided a better picture of that species' presence, including inside

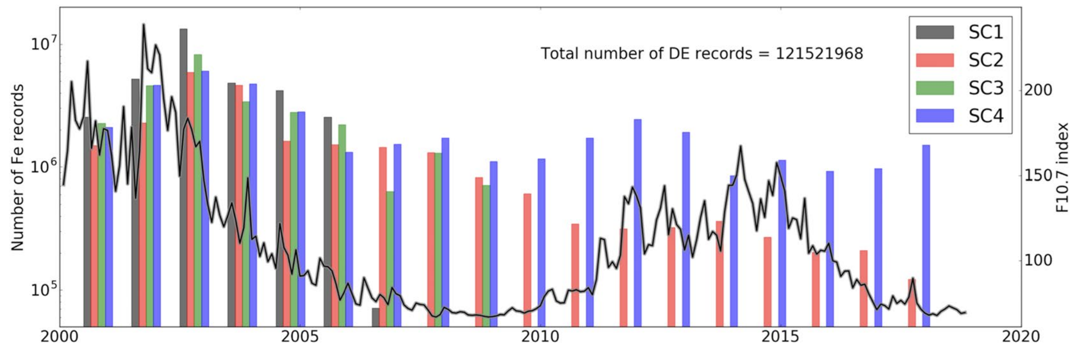

Figure 15. Number of events showing Fe+ ions detected by Cluster from 2001 to 2019 (from Haaland et al., 2019). The F10.7 index is shown as a black line.

the inner magnetosphere, a region not crossed by GEOTAIL. However, there remains the central question: what is the source of the ionized iron? Christon et al. (2017) suggested that the iron observations was to be sourced from the mesosphere and meteorite ablation. However, no clear correlation between detection of suprathermal iron and meteor showers, including possible sputtering off the Moon, has been found in the Cluster statistics. The Cluster results question whether these ions can be locally accelerated from the ionosphere, and instead suggest they are of solar wind origin.

5. Cluster Data Distribution: Cluster Science Data System and Archive

When the Cluster mission nominal phase started in February 2001, the access to data was done via the Cluster Science data system (CSDS). CSDS was setup to allow a fast and reliable exchange of good quality data among Principal Investigators, Co-Investigators and the general public. It was decided to define it, implement it and test it before launch to maximize the science return of the Cluster mission once the first data arrived (Daly, 2008). The system was developed under limited internet bandwidth, in the early 1990s, and made an efficient use of available data rates to exchange data between centers. The system combined nine data centers and two operation centers (Figure 16) interconnected through dedicated internet lines to guarantee access of data to all users (these dedicated lines were later replaced by public internet when its bandwidth exceeded that of the dedicated lines). CSDS is still running nowadays and providing summary (1 min resolution) and prime (4s resolution) parameters from all instruments as well as auxiliary data. At

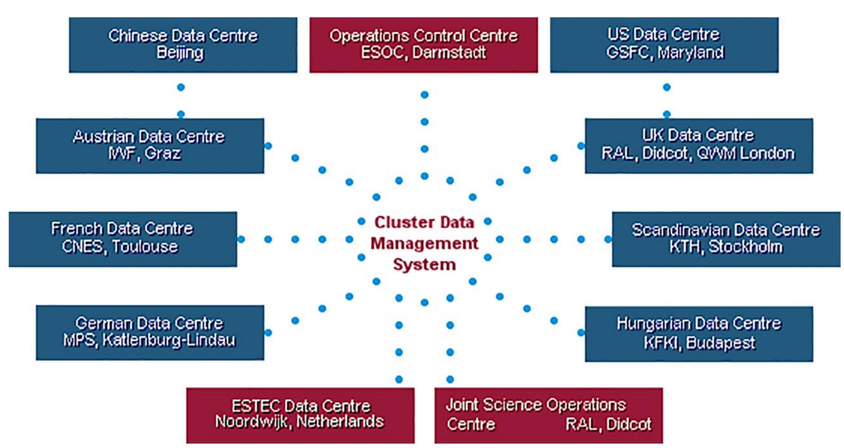

Figure 16. The Cluster Science Data System made of nine interconnected data centers (7 in Europe, 1 in USA and 1 in China) and two operation centers (ESOC and JSOC). The system that manages the exchange of data is the Cluster Data Management System developed by Rutherford Appleton Laboratory, UK.

Figure 17. The Cluster Science Archive front page (https://csa.esac.esa.int) where users can search, plot, download all Cluster data.

the beginning of the mission, a science user was contacting the Principal Investigator (PI) of the instruments of interest for high resolution Cluster data.

Following a request to archive Cluster high resolution data from Chris Harvey (then Director of the Centre des Données de Physique des Plasmas, France) and Dominique Lequeau (then Director of the Centre d'Etude Spatiale des Rayonnements now Institut de Recherche en Astrophysique et Planétologie) and to facilitate the access to high resolution data, the ESA Director of Science at the time, David Southwood, decided to create the Cluster Active Archive (CAA). The term "Active" was included to show that it would be a live archive that included data as the mission was continuing to acquire them. The archive had two components with (a) a core archive team dedicated to the reception, verification, processing and distribution of data and (b) a distributed team with a person in each PI team producing the calibrated data from each instrument and sending them to the archive. It included ESA support to the PI teams since the data required to be in a specific format (cluster exchange format, for more information https://www.cosmos.esa.int/web/csa/documentation) and calibrated with a high level of accuracy. The CAA was open to the public in 2006 and allowed to further increase the scientific output of the mission as can be seen in the increase of publication rate (Figure 5). The CAA became the Cluster Science Archive in 2014 and moved from ESTEC to ESAC (Figure 17). With more than 2,300 science users, the CSA continues to serve the community both through the user interface and through its command line interface. A recent improvement was the possibility to retrieve data in International Solar Terrestrial Physics common data format, making it compatible with the Space Physics Environment Data Analysis Software and other software. This allows users to combine easily Cluster data with those from other magnetospheric missions (such as MMS, THEMIS, Geotail, etc.) and address multi-scales plasma physics science.

6. Cluster Awards

Over the years Cluster has received many awards for excellent team work as well as awards for individual scientists who made substantial contribution to the Cluster mission (Table 3). Among those, ESA awarded the 2000 launch award to the team of scientists and engineers who had worked on the implementation of the mission and a few years later, in 2004, NASA presented the group achievement award. In 2013, after many technical achievements (see above section on technical challenges), ESA gave its annual team award to the Cluster team. More recently, in 2019, the Royal Astronomical Society presented its Group Achievement Award to the Cluster science and operation teams "for their continued success ensuring the operations and scientific exploitation of the European Space Agency's Cluster mission."

Table 3
List of Cluster Team Awards and Individual Awards

Cluster team awards	
2000	ESA Cluster launch award
2000	Popular science best of whats new award
2004	NASA group achievement award
2005	ESA Cluster 5th anniversary award
2010	International Academy of Astronautics Laurels for team achievements
2013	ESA team award
2015	ESA 15th anniversary award
2019	Royal Astronomical Society Group Achievement Award
Individual awards	
2004	Forest S. Mozer (Berkeley U., USA), Cluster EFW CoI, received EGU Hannes Alfvén Medal
2005	Margaret Kivelson (UCLA, USA), Cluster FGM CoI, received EGU Hannes Alfvén Medal
2006	Donald A. Gurnett (Iowa U., USA), Cluster WBD PI, received EGU Hannes Alfvén Medal
2006	Steve Schwartz (QMW, UK), Cluster UK data system scientist and PEACE co-I, received RAS Chapman medal
2007	Charles W. Carlson, (Berkeley U., USA), Cluster CIS CoI, received EGU Hannes Alfvén Medal
2008	Andre Balogh (IC, UK), Cluster FGM PI, received RAS Chapman medal
2008	Victor A. Sergeev (St. Petersburg U., Russia), received EGU Julius Bartels Medal
2008	Rickard N. A. Lundin (IRF-K, Sweden), Cluster CIS CoI, received EGU Hannes Alfvén Medal
2009	Jean-Andre Sauvaud (CESR, France), Cluster CIS CoI, received EGU Julius Bartels Medal
2010	Karl-Heinz Glassmeier (TU Braunschweig, Germany), Cluster FGM CoI and Cluster data centre implementation working group, received EGU Julius Bartels Medal
2012	Jonathan Eastwood (IC, UK) received COSPAR Yakov B. Zeldovich medal
2012	Jolene Pickett (Iowa U., USA), a Cluster WBD PI, received the State of Iowa Board of Regents Staff Excellence
2012	Professor Zuyin Pu (Pekin U., China), RAPID/CIS/FGM CoI, received AGU International Award
2012	Andrew Fazakerley, Cluster and Double Star PEACE PI, received the Royal Astronomical Society Chapman Medal
2013	Steve Milan, Cluster Ground based representative, received RAS Chapman medal
2013	Mike Hapgood (RAL, UK), Cluster JSOC project scientist, received RAS service award
2013	Goran Marklund (RIT, Sweden), Cluster EFW CoI, received EGU Hannes Alfvén Medal
2014	Rumi Nakamura (IWF, Austria), Cluster CIS/EDI/FGM CoI, received EGU Julius Bartels Medal
2016	Stephen Fuselier (SWRI, USA), Cluster CIS CoI, received EGU Hannes Alfvén Medal
2018	Margaret Kivelson (UCLA, USA), Cluster FGM CoI, received RAS gold medal
2019	Masatoshi Yamauchi (IRF-K, Sweden), Cluster CIS team, received EGU Julius Bartels Medal
2019	Dan Baker (Colorado U.), Cluster RAPID CoI, received EGU Hannes Alfvén Medal
2020	Qiugang Zong (Peking U., China), Cluster RAPID CoI, received EGU Hannes Alfvén Medal

7. Summary and Conclusions

After 20 years of successful operations, Cluster is continuing to acquire unique data sets in complement to other currently operated magnetospheric missions such as NASA MMS and THEMIS, JAXA Arase and Geotail, ESA Swarm and CAS CSES missions. Synergy with the new ESA/CAS SMILE mission, to be launched at the end of 2024, will allow to compare for the first time global magnetospheric images of the dayside magnetosphere and auroras with in-situ Cluster measurements. The Cluster mission concept proposed almost four decades ago by a group of European scientists to ESA took a long time to be implemented, almost two decades, and became one of the most successful ESA missions. During two decades of operations a number of challenges were overcome by the dedicated teams of scientists and engineers who had found innovative solutions to continue the operations of the four spacecraft. Among these, overcoming eclipses without any working batteries, recovering the spacecraft after 3 days of telemetry loss, recovering the 5 wave instruments with their power relay stuck, tilting one spacecraft by 45 degrees and achieving the smallest distance between two independent spacecraft (2.5 km) were particularly challenging and required skills and dedication as well as a high degree of professionalism.

The Cluster inter-spacecraft distances were changed 75 times during the first 20 years of operations, collecting data over a wide range of scales in key regions of the magnetosphere that will be analyzed for many years to come. Nine science results are presented in this paper that used various inter-spacecraft distances from small scales of 7 km up to large scales of 10,000 km to highlight the physical processes that can be studied from electron up to fluid and global scales. Cluster observed the smallest structure during shock reformation as well as solar wind turbulence cascade from large scales down to electron scales for the first time.

The Cluster mission remains the only multi-spacecraft magnetospheric mission with a quasi-polar orbital plane. Hence, Cluster is highly complementary to other currently operational magnetospheric missions which are all orbiting near the equatorial plane or at low altitude. It can therefore make measurements in areas not reached by other spacecraft such as the polar cusp or plasma mantle. This is of utmost importance for conjunction studies addressing global scales of the magnetosphere (e.g., Escoubet et al., 2020) or building empirical models of the magnetosphere (Andreeva & Tsyganenko, 2018 and references therein). The Cluster mission has been extended up to the end 2022 and a further extension is in preparation up to the end 2025. The four spacecraft will re-enter the Earth's atmosphere on 2024/09 (C2), 2025/11 (C1), 2026/08 (C3) and 2026/08 (C4), finishing a very productive and successful mission.

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Data Availability Statement

The data used in this paper can be obtained from the Cluster Science Archive (csa.esac.esa.int).

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