ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

RAPORTTEJA
RAPPORTER
REPORTS
2007:2

Waves and Acceleration of Relativistic Particles (WARP)

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Raportteja Rapporter Reports

No:2007:2 UDC 52

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Finnish Meteorological Institute
Space Research

ISBN 978-951-697-624-5
ISSN 0782-6079

Painopaikka: Yliopistopaino
Helsinki 2007

ILMATIETEEN LAITOS

Julkaisun sarja, numero ja raporttikoodi
Raportteja 2007:2

Julkaisija
Ilmatieteen laitos, Erik Palménin aukio 1,
00560 Helsinki
PL 503, 00101 Helsinki

Julkaisuaika

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Projektin nimi
WARP

Toimeksiantaja

Nimeke
Waves and Acceleration of Relativistic Particles (WARP)

Tiivistelmä

Waves and Acceleration of Relativistic Particles (WARP) on ehdotus neljän satelliitin konstellaatiomissiosta Euroopan Avaruusjärjestön tiedeohjelmaan Cosmic Vision 2015-2025 D/SCI/DJS/SV/val/21851. Mission kohteena ovat ulomman säteilyvyön relativististen elektronien kiihdykseen, kulkeutumiseen ja häviöön liittyvät plasma fysiikan prosessit. WARP:in neljä satelliittiä lentää pienenä tetraedrinä lähes ekvaattorilla radalla, jonka apogeen korkeus on n. 36000 km ja prerigeen n. 6000 km. Täyttääkseen tieteelliset tavoitteensa kaikki nejä satelliittia on varustettu identtisillä kenttä- ja hiukkasmittalaitteilla. Teknologinen valmius satelliitien ja mittalaitekokonaisuuden rakentamiseen on korkea ja se perustuu vahvaan euroopplaiseen osaamiseen. Sateliitit on suunniteltu laukaistavaksi Kourousta Soyuz Fregat 2B -raketilla. WARP:in arvioitu hinta on 275 miljoonaa euroa ja se on ESA:n M-luokan missio. Kaikki mittalaitteet rakennetaan PI-johtoisesti ja ne valitaan avoimen AO-prosessin kautta.

Julkaisijayksikkö

Luokitus (UDK)
52-854
520.6.05

Asiasanat
Säteilyvyöt, sateliittimissiot,
magnetosfääri

ISSN ja avainnimike
0782-6079
Raportteja - Rapporter - Reports

ISBN
978-951-697-624-5

Kieli
Englanti

Myynti
Ilmatieteen laitos / Kirjasto
PL 503, 00101 Helsinki

Sivumäärä 36
Hinta

Lisätietoja

FINNISH METEOROLOGICAL INSTITUTE

Published by
Finnish Meteorological Institute
Erik Palménin aukio 1, P.O. Box 503
FIN-00101 Helsinki, Finland

Reports 2007:2

Date

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Name of project
WARP

Commissioned by

Title

Waves and Acceleration of Relativistic Particles (WARP)

Abstract

Waves and Acceleration of Relativistic Particles (WARP) is a constellation mission proposed to European Space Agency in response to Call for proposals for Cosmic Vision 2015-2025 D/SCI/DJS/SV/val/21851. It is designed for detailed and comprehensive studies of the plasma physical processes leading to acceleration, transport and loss of relativistic electrons in the outer radiation belt of the Earth's inner magnetosphere. WARP consists of four identical spacecraft in a relatively tight tetrahedron constellation on a nearly equatorial orbit with an apogee altitude of about 36000 km and perigee of 6000 km. In order to fulfill its scientific objectives all spacecraft are equipped with a comprehensive suite of fields and particle instrumentation with a strong European heritage. The spacecraft and the model payload instruments have very high technology readiness. The satellites are suggested to be launched from Kourou with Soyuz Fregat 2B. WARP can be realized as an M-class ESA-only mission with the total cost to ESA being 275 Meuros, including a contingency of 50 Meuro. Instruments are assumed to be PI-provided and selected through an open AO process.

Publishing unit

Classification (UDC)
52-854
520.6.05

Keywords
Radiation belts, spacecraft
missions, magnetosphere

ISSN and series title
0782-6079
Raportteja - Rapporter - Reports

ISBN
978-951-697-624-5

Language
English

Sold by
Finnish Meteorological Institute / Library
P.O.Box 503, FIN-00101 Helsinki
Finland

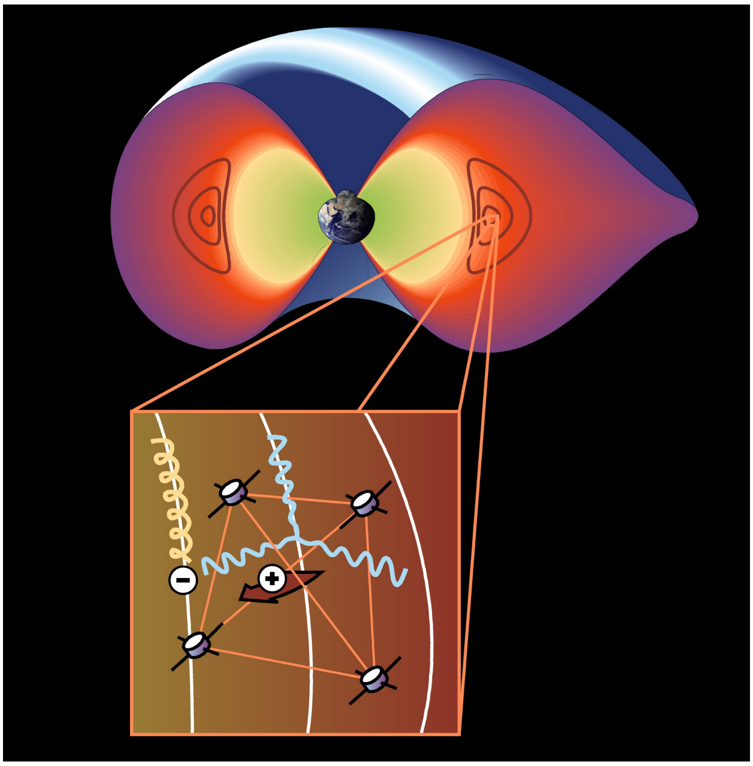
Pages 36
Price

Note

Proposal in response to Call for proposals for Cosmic Vision 2015–2025 D/SCI/DJS/SV/val/21851

WARP

Waves and Acceleration of Relativistic Particles



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Executive Summary

Main Objective:

The **Waves and Acceleration of Relativistic Particles (WARP)** mission will resolve the physical processes leading to **acceleration, transport and loss of relativistic electrons** in the Earth's radiation belt. Even if radiation belts were first discovered almost 50 years ago and have been found also around the giant planets in the Solar System, we still lack detailed understanding of the processes leading to their formation and evanescence. Resolving the particle acceleration mechanisms will provide key input to many astrophysical problems dealing with electrons moving at relativistic speeds. At present, the only two places where we can study the details of these processes are the terrestrial and Jovian inner magnetospheres. Of these, our space environment offers much better mass, power and telemetry budgets, and, most importantly, flying a multi-spacecraft constellation is economically feasible. The WARP mission will collect all key particle, field, and wave measurements and use the Earth as a "test laboratory" to answer major questions of the **dynamics, formation, and loss of relativistic particles around magnetized celestial objects**.

Constellation:

The Earth's magnetosphere is a giant particle accelerator energizing electrons and ions from a few eV up to hundreds of MeV through multi-step processes. Kinetic micro-scale processes involving electromagnetic fields and waves play an essential role in particle acceleration, loss and transport, and in coupling the different plasma populations together. WARP will perform detailed and comprehensive measurements of the spatially overlapping plasma populations in the plasmasphere, inner edge of the plasma sheet, ring current, and the radiation belts. It's instrumentation suite will resolve particle species in the energy range from a few eV up to several MeV. To address the role of the guide and wave fields, WARP also measures the electric and magnetic fields from DC up to several hundred kHz frequencies. **The comprehensive instrumentation together with a high telemetry budget and the tetrahedron constellation on an orbit optimized to inner magnetosphere physics makes WARP scientifically unique**.

A tetrahedron constellation of four spacecraft is the minimum requirement with which the separation of spatial and temporal effects can be achieved. Four spacecraft are also necessary for measurements of the motion and acceleration of boundaries as well as the determination of the electric currents with the curlometer technique. All these measurements are needed for detailed studies of the physical processes and for assessing the relative importance of the different elements. In order to make science closure on the main goals of the mission, WARP will address three interlinked major questions related to waves, currents, and plasmas in the inner magnetosphere.

Main questions:

Plasma waves: How do the plasma waves drive electron and ion acceleration, transport, and loss processes, and what determines the relative efficiency of the various wave modes?

Plasma currents: How does the perpendicular ring current couple to the magnetic field-aligned currents, and what are its effects on the wave-particle interactions and the large-scale transport?

Plasmas: How do the spatially overlapping plasma populations and the structured electromagnetic fields affect wave growth and particle energisation processes?

Mission:

As a first multi-spacecraft mission to the inner magnetosphere, WARP will fly in **closely spaced (100 – 1000 km separation) tetrahedron constellation** on an orbit inclined by about 20°, with perigee and apogee at about 6000 and 36000 km. In this orbit, the spacecraft spend a major portion of their time within the ring current and the outer radiation belt with an optimal tetrahedron configuration. The orbit covers the inner magnetosphere out to the particle source region in the magnetotail while avoiding the challenging radiation environment within the inner radiation belt.

The payload mass onboard each spacecraft is 80 kg (with 15%-margin), producing a total spacecraft mass of about 560 kg including fuel needed for constellation maintenance. An additional 670 kg of fuel is needed for all spacecraft to reach the final orbit. The four identical spinning (15 rpm) spacecraft will be launched from Kourou using the Soyuz Fregat 2B launcher. Even with four spacecraft, the total mission budget is well within the **M-class** frame with a **total cost to ESA of 275 MEuro**.

Building on strong European heritage in the instruments, the **technology readiness level for the scientific payload is high**, and the standard space physics instruments are relatively inexpensive. The **spacecraft bus and mission operations** will use heritage from the Cluster mission and **involve no major technological development**. As many recent missions (eg. Mars Express, VenusExpress, Rosetta) have led to new subsystem developments that allow for more favorable mass and power budgets, our numbers can be considered as conservative estimates.

The comprehensive instrument suite is needed for full 3D measurements of the gradients and motions of the plasmas and fields, but also provides a backup: Even if one of the instruments onboard a single spacecraft fails, a major part of the science can be recovered using information derived from the other instruments.

Cosmic Vision:

Recent advances from the Cluster mission have highlighted the need to launch a constellation mission focused to the electron acceleration processes in the inner magnetosphere. The WARP mission is urgently needed to resolve the ambiguities in the existing few observations and to conclusively verify and/or disprove the various theoretical arguments. The ESA 2015–2025 Cosmic Vision plan has identified *understanding of the Solar System* as one of its key topics. Especially, the plan calls for *studies of the plasma and magnetic field environments of the Earth*, which places WARP at the core of the Cosmic Vision scientific programme. **The WARP mission is highly ambitious and scientifically rewarding, is technologically feasible, and can be realized within a limited budget and rapid time frame**. We estimate the mission can be realized within 4 years from the start of the industrial contract.

Community:

WARP will serve the entire magnetospheric physics community in Europe and worldwide. Europe has a strong heritage starting from the GEOS and ISEE programmes, and **WARP will fill a gap in ESA's science plan** that at present includes no magnetospheric missions after Cluster. WARP is closely tied to the International Living With a Star programme targeting to resolve the causes and consequences of solar-driven activity in the near-Earth space. WARP serves also communities with interests outside the Solar System by improved understanding of relativistic particle acceleration applicable to exoplanets and other astrophysical objects. WARP results will also provide input for models for the radiation environment and "killer electrons" to be used in spacecraft design and operations.

Contents

1 Introduction

The goal of the WARP mission is to provide **comprehensive understanding of the processes leading to emergence and evanescence of relativistic electrons in a planetary magnetosphere**. Relativistic electron acceleration is known to take place around all planets with strong internal magnetic fields. For example, every 13 months the Earth is exposed to high-energy electrons escaping from the Jovian environment [2]. Generated in the "magnetic bottle" geometry of the Earth's dipolar field, the radiation belt electron fluxes vary significantly depending on the solar wind-driven magnetospheric activity. These electrons fill the space from geostationary region to inside navigation satellite orbits, and are known to be a major cause for serious spacecraft hazards, even loss of spacecraft. In the capacity of clarifying the "killer electron" dynamics, the WARP mission can serve the society also beyond the scientific community.

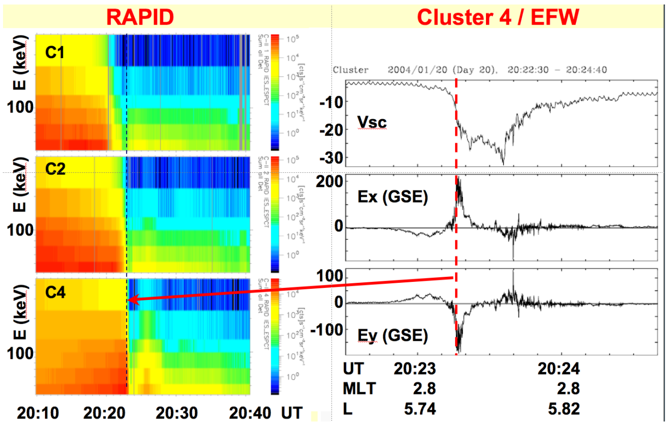

Figure 1: *An example of a 1-min time-scale motion of the outer edge of the radiation belt as observed by the Cluster spacecraft. The RAPID data covers the non-relativistic part of the radiation belt electrons (30–400 keV). Data from three spacecraft (left panels) shows a sudden steepening of the outer edge of the radiation belt associated with a fast growth of electric fields (right panel).*

The electron fluxes in the Van Allen radiation belts vary by up to five orders of magnitude on timescales from minutes to several days [1]. Figure 1 presents an example of a rapid change in the structure of the radiation belt. Within one minute, spacecraft separated by about 1000 km observed a clear difference in the boundary location and the speed of the boundary was measured to be about 30 km/s. On the other hand, Figure 2 displays such variations for almost one solar cycle [6]. The relativistic electron flux enhancements are shown in red as functions of time and distance from the Earth. Periodic variations appear on top of the solar cycle dependence showing a decrease in 1996 coincident with the sunspot minimum. The black curve superposed on the figure gives a ground-based geomagnetic index Dst, which decreases to values below zero when the ring current encircling the Earth enhances. The good correlation of the flux enhancements and Dst intensifications indicates that the relativistic electrons and ring current ion dynamics are coupled. Understanding of the **physics of the ring current – radiation belt coupling is a key target of the WARP mission**.

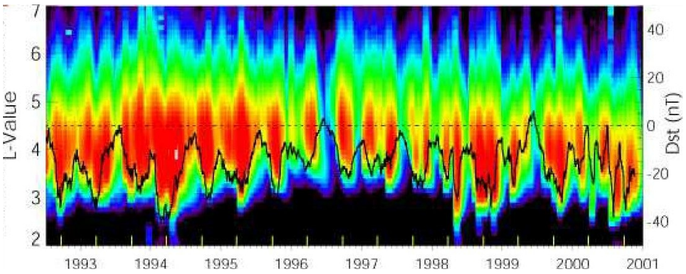

Figure 2: *Solar cycle time-scale variations of the relativistic electron (2-6 MeV) fluxes as function of time (year) and distance from the Earth (L-shell) as measured by the SAMPEX satellite. The black curve shows the ground-based activity index Dst, which is a measure of the ring current intensity. The electron flux intensifications (shown red) are strongly correlated with the Dst enhancements (from zero to negative values). (From [6])*

Coronal mass ejections drive solar wind shock waves that compress the magnetosphere and cause large magnetic storms, which produce largest distortions and fastest enhancements of the radiation belts. Fast solar wind streams drive weak storms with long recovery periods that produce some of the largest flux enhancements. Statistically it is known that about half of the storms result in net flux increase, 20% result in net decrease, and the rest show no change in electron fluxes [9]. A key question for WARP is to **determine the dominant acceleration mechanisms and their efficiencies** to explain these results. Understanding the relativistic electron flux variations as a product of a complex chain of events originating from solar activity, solar wind – magnetosphere interaction, and complex wave-particle interaction processes sets WARP at the core of the Cosmic Vision in directly addressing the question *How does the Solar System Work?* from heliospheric to electron scales.

Variations in the relativistic electron fluxes occur as a consequence of multiple acceleration and loss processes caused by **interactions between the various inner magnetosphere particle populations and the electromagnetic fields and waves**. While the low-energy particle environment sets up conditions for the waves to grow, the electromagnetic fields determine the large-scale particle trapping and transport simultaneously with acting as agents transferring energy between the particle species. The waves supported by the plasmas and the transport guided by the fields ultimately control the final net enhancement or decay of the relativistic particles. Figure 3 illustrates how WARP will resolve the physics of the coupling discussed in association with Figure 2: Only comprehensive multi-spacecraft measurements of particles, fields, and waves will allow for resolving the resonances, trapping, and propagation processes driving the electron dynamics.

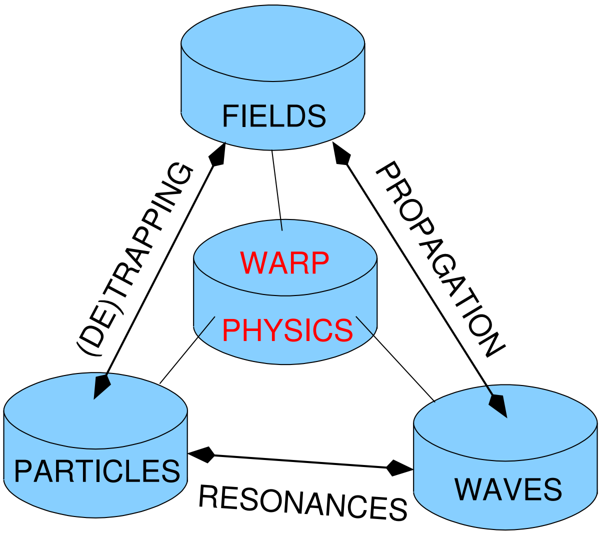

Figure 3: *Illustration of how the WARP constellation provides monitoring of resonances, propagation, and trapping by measuring particles, waves, and fields. (Note that all satellites will be identically instrumented). These measurements will result in new understanding of the physical processes that lead to the strong correlation of the relativistic electrons and the ring current as demonstrated in Figure 2.*

Earlier missions together with auxiliary solar wind and magnetospheric activity index data have been used to give the electron acceleration events a geophysical context, but observational limitations of the micro-scale processes have left the acceleration physics unresolved. Even if the observations have been highly limited by orbital constellation, telemetry, and payload constrains (eg. no instruments to detect the relativistic MeV particles), the Cluster spacecraft skimming the inner magnetosphere have shown the importance of the ring current and plasmasphere for the electron acceleration and loss [7]. While WARP will also benefit from auxiliary data from a variety of sources, they are not necessary for resolving the core physics of electron acceleration and loss.

2 Scientific Objectives

2.1 Background

Dynamics: Particles and large-scale fields

The inner magnetosphere contains five distinct particle populations coupled together via electromagnetic waves and fields. By far, the most energetic population is the inner radiation belt, which however mainly consists of cosmic ray particles (with energies of hundreds of MeV) that do not much interact with the magnetosphere other than being trapped in the geomagnetic field. The energetic particles of interest to the WARP mission are the more dynamic populations, such as the outer radiation belt relativistic electrons with energies above 500 keV and the ions carrying the ring current (energies up to ∼500 keV). These particles are believed to originate mainly from the plasma sheet, where the plasma temperatures range from a fraction of keV to 10 keV. The coldest (∼1 eV) plasma resides in the near-Earth plasmasphere populated by particles originating from the low-energy (∼0.1 eV) ionosphere. Figure 4 shows the relative locations of the plasmasphere, radiation belt, ring current, and plasma sheet as observed by the POLAR spacecraft during a magnetically quiet period when the plasmasphere was expanded and the ring current was weak and at relatively large distance from the Earth. Typically the radiation belts and ring current overlap, and the inner edge of the plasma sheet frequently intrudes into the ring current and radiation belt region.

In order to investigate physical processes in the inner magnetosphere, all these ions and electrons from eV to MeV energies, and multiple ion species, must be monitored simultaneously; this is one of the key requirements for WARP. Figure 5 illustrates how the overlapping inner magnetosphere particle populations are coupled via electromagnetic fields and waves.

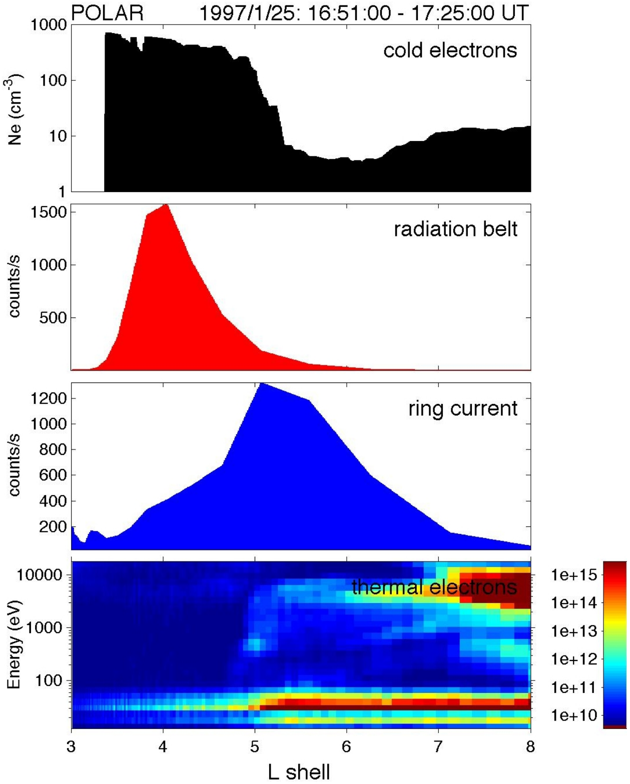

Figure 4: *An example of the relative locations of the plasmasphere, radiation belt, ring current, and plasma sheet (panels from top to bottom) as a function of distance from the Earth (L-shell), as measured by the POLAR satellite during a magnetically quiet period.*

The large-scale electromagnetic fields control the dynamics of the plasmasphere, the ring current, and the plasma sheet and therefore are key to the WARP mission. The radially inward-pointing co-rotation electric field controls the co-rotation of the plasmasphere with the Earth. The cross-tail electric field induced by the solar wind interaction in the plasma sheet defines the size of the plasmasphere (distance to the plasmapause) and the plasma convection speed from the tail to the inner magnetosphere. As the charged particles carry a current, they deform the magnetic field and thereby self-consistently change particle drift paths. The plasmasphere, ring current and radiation belt are highly dynamic in response to the solar wind-driven magnetospheric activity.

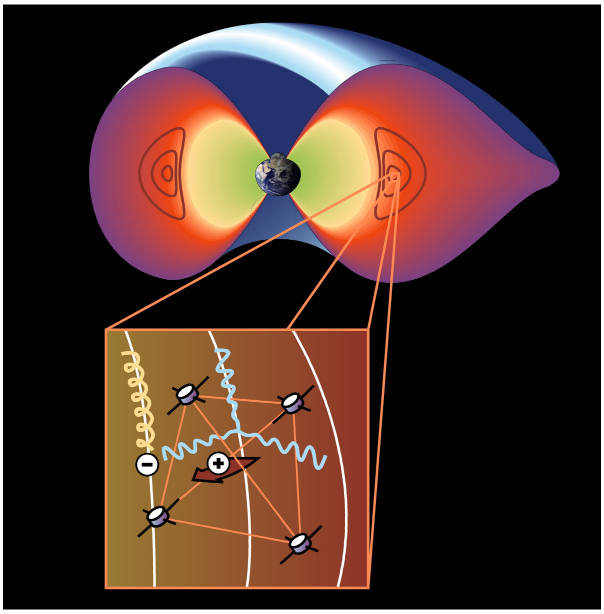

Figure 5: *Schematic drawing of the particle populations filling the quasi-dipolar flux tubes in the inner magnetosphere. Innermost region, appearing in yellow, is the plasmasphere, enveloped by the overlapping ring current and radiation belts. The dipole field lines are compressed on the dayside (to the left) and extended to a tail on the nightside (to the right). The WARP constellation will measure the various particle populations and their boundary motions, the electromagnetic fields and their variations as well as the wave modes present in that region.*

Acceleration:
Resonant interactions and waves

As discussed above, the large-scale convection electric field determined by the solar wind coupling with the magnetosphere is crucial in organising the Earthward plasma convection and thus providing a source population for the inner magnetosphere. Global scale fluctuations of these fields on time scales of the electron drift period around the Earth (∼10 min for a 1-MeV electron) can lead to betatron and Fermi acceleration via inward radial diffusion. Fluctuations break the third adiabatic invariant and scatter the electrons. Conservation of the first two adiabatic invariants then leads to acceleration of electrons diffusing toward the planet. Energy is efficiently transferred from the fluctuating fields to the particles, and the pitch-angle distributions become peaked near 90° [7].

Waves with frequencies comparable to the electron cyclotron frequency are able to break all three adiabatic invariants, which results in local electron acceleration and diffusion in both pitch angle and energy. The inner magnetosphere contains a large number of different wave modes, and even within one wave mode there are different characteristics that significantly affect the scattering efficiency. Figure 6 shows some examples of wave emissions recorded by the CRRES satellite and how these waves are expected to occur around the Earth. The multitude of the wave modes and their structuring in space and time makes the description of wave acceleration a challenging problem.

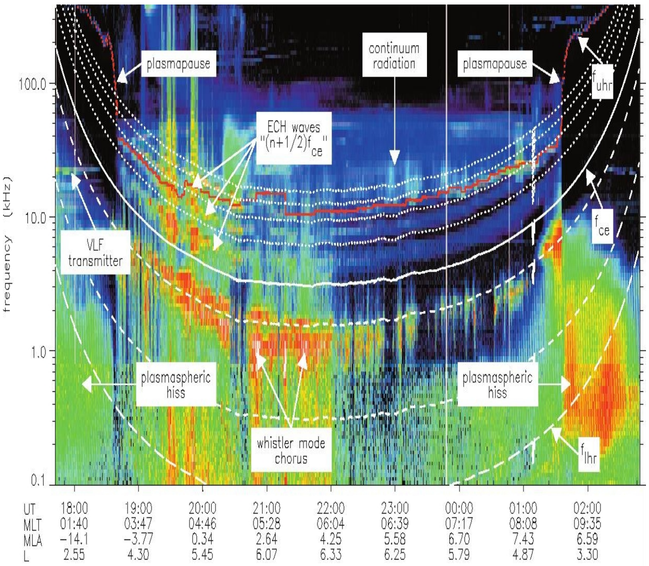

Figure 6: *An example of the wide variety of wave emissions in the inner magnetosphere as observed by the CRRES satellite. The wave intensity is shown color coded as a function of time (and L-shell giving the distance from the Earth) and frequency.*

Short inter-spacecraft separations down to 100 km are required to determine the wave k-vector using the k-filtering technique developed for Cluster multi-spacecraft observations [8]. As drift shell splitting, wave-particle interactions, and radial diffusion all affect the pitch-angle distributions, identifying the form and spatial gradients in the pitch angle distributions is one of the ways to distinguish between the different acceleration processes. The naturally occurring variations in the spacecraft separations between 100 – 1000 km are useful to determine the spatial extent of the processes as well as to separate temporal and spatial features.

Losses:
Particle and wave scattering

The large-scale magnetic field varies rapidly in response to changes in the solar wind driving. These variations modify particle transport and pitch-angles in the inner magnetosphere and lead to loss of trapped particles. For instance, during magnetic storms, the intense ring current can quickly distort the magnetic field to guide trapped electrons and ions on orbits that lead to outside the magnetosphere. The forming ring current develops a temperature anisotropy, which in regions where the ring current and plasmasphere overlap can generate electromagnetic ion cyclotron (EMIC) waves that in turn precipitate both ring current ions and radiation belt electrons.

Plasma sheet electrons and ions are injected into the inner magnetosphere, where ions can cause EMIC waves, and electrons can excite whistler mode chorus waves. These waves grow by scattering ~10 keV electrons into the atmosphere at small pitch angles, but they also scatter electrons to higher energies at large pitch angles that then remain trapped in the magnetic field (Figure 7). Whistler mode hiss is a highly efficient mechanism to scatter radiation belt electrons into the loss cone and into the Earth's upper atmosphere, while other wave modes supported by the plasmasphere also take part in both acceleration and loss processes.

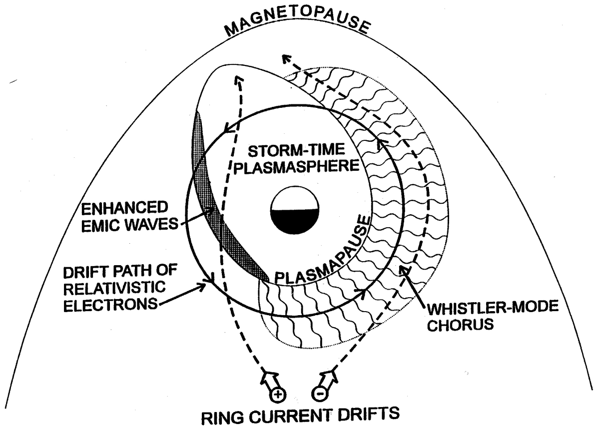

Figure 7: *Schematic picture of the coupling of the plasma populations, wave fields, and the relativistic electron acceleration (from [11]). The graph illustrates the typical locations of whistler mode chorus and EMIC waves and how the electrons and ions interact with these waves as they orbit around the Earth in different directions.*

Techniques:
Gradients and curlometer

The curlometer technique applies Ampère's law to compute the electric current as the curl of the magnetic field ($\mathbf{J} = \nabla \times \mathbf{B}/\mu_0$). In order to measure the gradients with sufficient accuracy, it is necessary to measure in a 3-dimensional tetrahedron configuration with appropriate distances between the spacecraft as well as to have accurate magnetic field measurements [12]. The Cluster mission was designed to provide the four non-coplanar simultaneous measurements that are needed to compute a 3D spatial gradient (in the outer magnetosphere). Even if the principle is simple, there are a number of practical challenges: random data errors need to be smaller than the differences measured by the spacecraft, systematic errors need to be minimized (requiring high-level intercalibration of the instruments), and the size of the measured structures has to be larger than the spacecraft separation. The recently developed least-squares gradient computation technique is less dependent on spacecraft configuration, includes automatic selection of relevant data, can handle data gaps, and provides error estimates. The vector-version of this technique, which can incorporate the divergence-free condition, results in a clear improvement over the original curlometer technique [8].

2.2 Science closure: Key questions and observations

Answering the questions of relativistic particle acceleration in the near-Earth space is one of the outstanding questions relating to all plasma physics in the universe. The same acceleration mechanisms function around the gas giants in the Solar System as well as around many more exotic, magnetized celestial bodies in the universe. **The objective of WARP is to study in an unprecedented detail the acceleration, transport, and loss of electrons and ions** (1 eV to relativistic) **as well as the coupling between different particle populations via electromagnetic fields and waves** by using state-of-the-art instrumentation developed during the past 10–15 years. Increased understanding of the physical processes will be used to develop improved models and theories for the acceleration and loss processes. When these models are coupled to the large-scale inner magnetosphere models, the theories can be tested against the WARP observations thus providing closure on the questions. The improved models can also be used to provide nowcasts and forecasts as well as post-event analysis tools of the near-Earth particle environment.

All science investigations of the WARP mission are intimately tied together. The relativistic electron population variations are the end product of a complex chain of processes involving the plasmasphere, the ring current, the plasma sheet source, and electromagnetic fields and waves, all of which occupy the same region of space, the inner magnetosphere. The electromagnetic fields accelerate particles, the induced currents and particle motions distort the fields, and the waves transfer energy between fields and particles. Thus, the investigations are focused on understanding each of the aspects individually, finally bringing together a complete picture.

The minimum requirement to achieve these goals is a closely separated four-spacecraft constellation mission in the near-Earth space that will perform the following:

Particles: Measure charged particles in the low-energy (~1 eV) plasmasphere, medium-energy (10 eV – 30 keV) ring current, and high-energy (MeV) outer radiation belt.

Fields: Measure the structure and dynamics of the electric and magnetic fields, including a detailed determination of the structure of electric currents and plasma convection.

Waves: Measure the characteristics of the electromagnetic waves that couple the different plasma populations and, thereby, through resonant interactions and scattering processes lead to relativistic electron acceleration and loss.

With the observations summarized in Table 1 WARP will provide **closure on the relative importance of the various acceleration, transport and loss processes of relativistic radiation belt electrons and ring current ions**. The table briefly defines the science objective, the physical parameter to be measured, and indicates whether four-spacecraft measurements are crucial for that particular measurement and science topic.

Objective	**Physical parameter**	**Measurement**	**4 s/c**
e^- **sources**			
Diffusion	RB e^- p-a, radial and E diffusion	e^- 0.1–10 MeV	Yes
Transport	Convection and radial transport	e^- 10–400 keV	Yes
WP interact	Source population for chorus waves	e^- 10–400 keV	
	Source population for whistler waves	e^- 1–30 keV	
e^- **losses**			
Mpause loss	Convection E-field, total B-field	e^- drift	Yes
	Low-frequency fluctuations, plasma density	DC E-field	Yes
	Currents (curlometer)	DC B-field	Yes
	Ring current, plasma pressure and gradients	Ions 20–500 keV, s/c pot.	Yes
	RC sources, charge-dependent processes	Ions Z and Q 1–500 keV	
	RC source population, anisotropies, energy transfer between species	Ions 0.001–30 keV	
WP interact	ULF waves, wave V_{ph}, resonant velocities, particle pitch-angles,	DC B-field	Yes
	EMIC, equatorial noise, LH waves	3-comp. AC B-field	
	EMIC, equatorial noise, LH waves, chorus, hiss, f_{pe} for density, k-vector and wave polarization	2-comp. AC E-field	Yes
	Wave bunching, solitary waves, electron holes	Wave form capture	
	RC and EMIC wave source pop's, anisotropies	Ions 0.001–30 keV	Yes
	Plasma boundaries, wave V_{ph}, resonant energies	Thermal to keV plasma	Yes
	Zero-potential for low-energy e^- measurements	s/c pot.	

Table 1: *From measurement objectives to instruments; last column indicates whether 4 s/c measurements are critical. Abbreviations: RB = radiation belt; p-a = pitch-angle; E = energy; pop. = population; pot. = potential; WP = wave-particle;* V_{ph} *= (phase) velocity; RC = ring current; LH = lower hybrid;* f_{pe} *= electron plasma frequency; ES = electrostatic, EM = electromagnetic.*

2.3 Mediators: Plasma and fields

Direct measurement of the ring current

The ring current is one of the main current systems in the planetary magnetospheres, and a physical understanding of its evolution with varying solar wind conditions is necessary for predicting and modeling the magnetospheric dynamics. It is probably the least probed current system in the Earths magnetosphere due to its partial overlapping with the radiation belt that many missions opt to avoid. However, the ring current is a central element for the overall structure and dynamics of the inner magnetosphere, both because of its direct response to increased solar wind driving and because it contributes in multiple ways to the acceleration and loss processes of the trapped particles. All earlier inner magnetosphere missions have used particle measurements to identify the ring current and to measure its magnitude. A truly unique product of WARP will be the **direct determination of the ring current, its sub-structures and temporal variations as well as its importance to the relativistic electron problem**. WARP will also for the first time provide **closure on the currents derived from the curlometer and from particle measurements**.

Present understanding of the ring current is primarily based on ground-based magnetic data and indices such as Dst and in-situ single-spacecraft ion observations. The first direct 3D current measurements in space using the curlometer technique were made by using data from the Cluster mission. However, it was only during three months in 2002 when the Cluster constellation was small enough for current determination. The few observations from that period show that the ring current is more structured and varies more rapidly than predicted by the present day models. WARP will update our **qualitative** understanding of the ring current dynamics to a **quantitative** state.

Understanding the relationship between the ring current and the energetic particle distribution functions is essential in order to determine the particle acceleration and loss processes. While the magnetic disturbances on ground can be used to categorize the level of magnetospheric activity, the current can be carried by a variety of particle populations having quite different distribution functions. In order to use the ground-based Dst index to estimate the acceleration and loss processes, it is necessary to understand which particles contribute to the total current, what are the characteristics of the particle distribution functions, and how they evolve in time. Similarly, spatial gradients in the current are essential in trapping and detrapping particles as well as contributing to the local electromagnetic field changes. Such gradients can be identified only with multispacecraft in-situ measurements in space.

One of the **key drivers for close constellation measurements is to determine the various spatial scales of the ring current**, which can be resolved using the naturally varying spacecraft separations. The simultaneous particle observations will allow us to evaluate how well the currents derived from curlometer and particle distributions are in agreement with each other and how these measurements correlate with the ground Dst index variations. The combination of field and particle measurements will provide the ion and electron drift paths, trapping boundaries, and adiabatic flux changes. The energy and spatial distribution as well as composition of the ring current ions will determine their role in wave-particle interactions, (eg. EMIC wave growth). The WARP measurements will be used to specifically investigate the following questions:

What is the ring current magnitude and altitude profile, including small-scale structuring, as function of geomagnetic activity and location in the magnetosphere, and how does it evolve in time?

What controls the asymmetric partial ring current, how does it couple to the upper atmosphere and ionosphere via Region 2 field-aligned currents, and what role does it have in coupling to the radiation belts?

What is the relative importance of the major ring current energization and loss processes, such as inward convection, radial diffusion, wave particle interactions, collisions, and charge exchange?

Answering these questions will resolve the still unknown characteristics of the ring current and its coupling to the other current systems as well as its association to ground measurements. It is known that the ring current is significantly enhanced during substorm and storm intervals, but the details of the current structuring have remained undiscovered due to lack of observations. The WARP mission will determine the large-scale dynamics and local structuring of the ring current, which in turn has effects on the relativistic electron trajectories as well as the acceleration and loss processes.

Plasma pressure tensor and its gradients

WARP will, for the first time, provide **direct measurements of the force balance in the magnetosphere** under changing solar wind driving conditions. Determination of the force balance in environments where plasmas of different properties are in direct interaction has also fundamental relevance in plasma and space physics as well as astrophysics well beyond the Earth's magnetosphere. All physics-based models require a detailed understanding of the force balance equation.

The ring current and radiation belts are believed to be fed by the plasma sheet (1–10 keV) particles convecting from the magnetotail into the inner magnetosphere, where the plasma pressure is mostly in the energetic ions in the energy range 40–200 keV. However, it is still unclear whether the ring current is mainly populated through continuous convection from the magnetotail or by sporadic injections associated with geomagnetic activity.

Gradients and anisotropies in the plasma pressure are associated with electric currents via the force balance equation

$$\mathbf{J} = \frac{\mathbf{B} \times \nabla p_\perp}{B^2} + \frac{p_\parallel - p_\perp}{B} \left(\nabla \times \frac{\mathbf{B}}{B} \right)_\perp ,$$

where $\mathbf{J}$, $\mathbf{B}$ and p are the electric current, magnetic field and plasma pressure, and subscripts $||$ and $\perp$ refer to the parallel and perpendicular directions with respect to the local magnetic field direction. Determining the plasma pressure and its gradients in three dimensions provides a complementary approach to examine the structuring and dynamics of the inner magnetosphere currents. The effects of the currents on the plasma pressure profile link the inner magnetosphere currents to the large-scale stability properties of the magnetospheric configuration.

The WARP constellation will be used to **evaluate the plasma pressure tensor, including its off-diagonal elements**. Specific questions related to the plasma pressure include:

What is the 3D plasma pressure distribution as a function of altitude and location in the magnetosphere, and what are the pressure gradient profiles in the inner magnetosphere?

How are the plasma pressure gradients related to the currents perpendicular and parallel to the magnetic field, and how is pressure balance maintained by the different plasma populations?

What are the characteristic spatial and temporal scales of the ion injections from the magnetotail into the inner magnetosphere, how do they propagate, and what is the relative importance of transport and local acceleration processes?

Answering these questions will determine the ring current source population, how the ring current is energized, and what is the role of ionospheric heavy ions in the inner magnetosphere dynamics. These investigations will also resolve how the energetic ions drive waves in the inner magnetosphere that in turn accelerate and/or scatter the relativistic electrons. These results together with the measurements of the low-energy plasmasphere will provide a comprehensive setting in which the electron acceleration and loss processes operate.

Plasmasphere and its structuring

The low-energy ion measurements combined with wave observations will quantitatively determine the location of the plasmaspheric material and the wave populations. WARP will provide unique measurements of the **3D temporal and spatial evolution of the structures at the plasmapause**, and assess their significance to the acceleration and loss of relativistic electrons.

The structure and dynamics of the cold plasmasphere is driven by the large-scale convection electric field and its variations, and appears to be highly structured and variable with local time as shown by global EUV images from the IMAGE satellite[10]. The Cluster mission has provided some limited but highly interesting multi-point observations of the plasmasphere. Unfortunately, similarly to the ring current determination, the inter-spacecraft separation is usually far too large for good 3D observations of the plasmaspheric structures.

During low geomagnetic activity the plasmasphere can extend out to geostationary orbit ($L = 6$), while during magnetic storms it is contracted well below 18 000 km altitude (inside $L = 3$). The plasmasphere hosts and maintains a variety of wave modes, including whistler mode plasmaspheric hiss, lightning-induced whistlers, and EMIC waves excited by interaction with the ring current [4]. All these wave modes measured by WARP couple directly to the relativistic electron problem.

As convection increases, part of plasmaspheric material can escape from closed drift paths to open trajectories, forming a large-scale plume where the material flows away from the plasmasphere and the Earth's upper atmosphere toward the dayside magnetopause. During high activity, the plasmapause has a complex shape and can fractionate to produce separated patches of plasmaspheric material outside the plasmasphere proper. As the plasma and waves within the plasmasphere interact with the ring current ions and radiation belt electrons, it plays a fundamental role in the dynamics of energetic trapped particles. Due to lack of in-situ observations, it is still unknown how the plasmaspheric erosion and refilling affect the ring current and radiation belt particles.

Through making detailed four-spacecraft measurements of the spatial scales and shapes of the plasmaspheric structures and their motion in the inner magnetosphere, WARP will address the following questions:

What are the generation mechanisms, dynamics, characteristics, and composition of plasmaspheric erosion and plumes, and how are the small-scale irregularities generated both inside the plasmasphere and near the plasmapause?

What is the relation between convection electric fields in the inner magnetosphere and plasmaspheric sub-corotation, and what processes govern the transition from corotation to outward expansion in the formation of plasmaspheric plumes?

What are the effects of the low-energy plasma distribution on the presence of electromagnetic waves, and what parameters control the generation of hiss and chorus waves?

Is there a causal relationship between severe erosion of the plasmasphere and penetration of the radiation belt electrons into the slot region?

These measurements will determine the dynamics of the small-scale structures around the plasmapause and resolve their role in the electron and ion acceleration and loss processes.

2.4 The end product: Waves and relativistic particles

The ultimate goal of WARP is to understand the acceleration and loss of relativistic electrons in the inner magnetosphere. Specific emphasis will be paid to the **observations of various wave modes within a wide range of frequencies together with detection of electron phase space density over a broad range of energies**. Four-spacecraft measurements will further allow us to examine drift-shell splitting and other radial gradients in the distribution functions as well as gradients in the azimuthal and field-aligned directions. The WARP mission will also be able to provide estimates of the radial diffusion rates over short distances.

A menagerie of wave species

The high-speed solar wind stream past the magnetopause boundary drives velocity-shear instabilities (eg. Kelvin-Helmholtz waves) and generates **ULF waves** inside the magnetosphere. These waves are believed to substantially increase radial diffusion and thereby enhance the high-energy electron acceleration at times when the ULF wave periods are close to the electron drift periods around the Earth. So far, most observations of the ULF waves come from ground-based instruments; there are only few observations of ULF waves inside the radiation belts that would have directly tested the efficiency of ULF enhanced radial diffusion.

The efficiency of radial diffusion depends on the local properties of the wave modes, such as the poloidal and toroidal properties of the waves, the mode number, and the extent to which the waves are present in different parts of the magnetosphere. In addition to direct in-situ observations of the ULF waves and their properties, WARP will be instrumented to measure the electron phase space density and its gradients to determine the effectiveness of inward radial diffusion during active times.

Whistler mode chorus waves grow by scattering plasma sheet electrons into the atmosphere. They accelerate energetic electrons via cyclotron resonance, where the wave frequency is Doppler shifted to the cyclotron frequency of the electrons [5]. For a broad band of observed waves the resonant energies can extend from about 10 keV to several MeV. The waves efficiently transfer energy from a large number of low-energy electrons to accelerate a smaller number to high energies. At high time resolution, chorus waves usually exhibit discrete elements that increase in frequency with time, superimposed on an enhanced broadband background.

Even if the chorus emissions have been known for decades, their source mechanism is not yet well understood. During its 3-month period of short separations in 2002, the Cluster mission produced interesting initial results, which clearly indicate the need for multipoint measurements for the source mechanism investigations. The WARP observations, optimized for the inner magnetosphere, will provide sufficient amounts of data to constrain and test theoretical analyses and simulations results of the chorus source mechanism. The generation of chorus waves is also closely connected to the local electron acceleration for which the chorus wave growth is an important element. The determination of chorus waves and their role in the electron acceleration requires both the multipoint measurements and the coordination between particle, field, and wave observations provided by the WARP mission.

Several types of waves can contribute to losses via precipitation into the atmosphere. Outside the plasmapause bursts of ~MeV electron precipitation can be caused by pitch-angle scattering by individual chorus wave elements as they propagate along the field line, making chorus waves contributors to both loss and acceleration of electrons. These precipitation bursts are caused by non-linear processes, which requires high time resolution observations from the WARP instrumentation. Inside the plasmasphere **plasmaspheric hiss**, **VLF transmitter signals**, and **whistlers generated by lightning** all contribute to electron losses. During the plasmasphere refilling in the magnetic storm recovery phase, these waves can be excited further out in the magnetosphere and extend the losses into the heart of the radiation belt. WARP will determine the relative efficiency of these processes.

One of the specific targets of the WARP mission is to measure the **electromagnetic ion cyclotron (EMIC) waves**. The waves propagate at frequencies just below the local gyrofrequency of hydrogen, helium, and oxygen ions, and are often observed to have left-handed to linear polarization with a smaller percentage of right-handed to linear polarization. The differently polarized modes resonate with electrons at different energies. EMIC waves typically occur in regions of high density near the plasmapause.

During a magnetic storm, the enhanced convection erodes the plasmasphere and simultaneously injects and energizes ring current ions. As the ring current enhances, conservation of the first two adiabatic invariants leads to a temperature anisotropy in the ion distributions. In regions where the ring current overlaps with the high-density plasmasphere, the temperature anisotropies can generate EMIC waves, which then cause ion precipitation. At the same time, the EMIC waves precipitate relativistic radiation belt electrons thus coupling the energy in the ring current to the loss of radiation belt electrons.

WARP will resolve the still open issue of EMIC wave occurrence and power inside the radiation belts as well as their effectiveness as a loss mechanism in a global scale. WARP will explore how, in the micro-scale, the energy is portioned between scattering the ions and scattering the electrons. In the large scale, WARP will address how the occurrence of EMIC waves depends on the interplay between ring current and plasmaspheric dynamics and how this affects the rate of decay of the radiation belts.

There are several outstanding questions related to the uplifting and acceleration mechanisms of supra-thermal heavy ions up to tens of keV during magnetic storms. All these ions (mainly helium and oxygen) originate from the Earth's upper atmosphere, where their initial energy is only about 0.1 eV. Heavy ions, once accelerated, can be significant contributors to the ring current; it has been estimated that during some storms the heavy ions can dominate the ring current energy density.

Observations of heated He^+ distributions associated with strong EMIC waves suggest that wave-particle interactions also play a role in transferring energy between different ion species within the ring current. EMIC waves propagate along the magnetic field and can resonate with heavy ions as they propagate into regions of higher field strength, and thus can transfer energy from hydrogen to thermal He^+ and O^+. EMIC waves generated by ring current protons can resonate with pre-heated oxygen inside the ring current, thus providing an energy transfer mechanism from H^+ to O^+.

Other types of waves, such as **lower hybrid waves and equatorial noise** can also resonate with both electrons and different ion populations and provide coupling mechanisms between particle species. WARP measurements of the wave modes together with detailed pitch-angle distributions will differentiate between the various energy transfer processes and their role in the ring current energization and decay as well as the coupling of the ion dynamics to the relativistic electron flux enhancements and decay.

Specifically, the WARP wave observations will target the following questions:

What are the spatial distributions of whistler mode chorus and EMIC waves, how do the source regions move, and what is their dependence on the magnetic configuration and small-scale structures of the plasmasphere and plasmapause?

What are the spectral characteristics of the various wave modes in their source region, including spatial scales, amplitudes, amplification and damping rates?

What is the relationship of the local wave populations and the local electron distribution functions, especially pitch-angle anisotropies and signatures of accelerated electrons?

Combining four-spacecraft measurements of the ion and electron distribution functions together with detailed observations of the wave modes will allow WARP to determine the local processes, and their relative efficiencies under different conditions, leading to relativistic electron acceleration and loss. Comprehensive observations over the mission lifetime will characterize the dependence of the relativistic electron diffusion rates on magnetic activity and the details of the solar wind driving conditions.

The WARP mission will significantly advance **understanding of the physics of tenuous plasmas and the mechanisms that allow charged particles to gain relativistic energies in magnetized planetary and astrophysical environments**.

2.5 Secondary science objectives

As an inner magnetosphere spacecraft constellation, WARP will be able to address a number of important scientific topics beyond the highly focused main goals of the mission. While these objectives may not all require a four-spacecraft constellation mission, the comprehensive instrumentation of the WARP satellites will bring substantial new understanding beyond what earlier missions have done.

Solar wind - magnetosphere coupling:

Combined with data from other magnetospheric missions, solar and solar wind observations, and ground-based instrumentation, WARP will comprehensively address the issue of the magnetospheric response to the solar wind driver. It is still poorly understood what solar wind parameters control the coupling. Furthermore, one of fundamental open issues is what fraction of the energy input from the solar wind into the magnetosphere is transferred into the ring current and radiation belt electrons.

Magnetosphere - ionosphere coupling:

WARP provides excellent opportunities to use combined space-borne and ground-based measurements to investigate the large-scale field-aligned current systems. Its orbit is best suited for observation of region 2 currents that couple the inner magnetosphere and the ring current to the ionosphere, but occasionally due to the orbit inclination and the dipole tilt angle effect, it will also be able to measure region 1 currents flowing to and from the plasma sheet at larger radial distances.

Magnetospheric dynamics:

WARP with other magnetospheric missions and ground-based instrumentation will provide significant new understanding of magnetospheric substorm processes and their relationship with the large-scale storm evolution and particle energization. Presently, one of the major questions in storm-substorm coupling concerns the relation of energetic particle injections and ring current enhancements; it is not known whether the ring current is fed by continuous convection or by periodic injections from the plasma sheet. Furthermore, our knowledge of the properties of the current wedge forming at substorm onset is mainly based on its ground signatures, while the associated field-aligned currents in space are poorly understood.

Measuring waves in space and on ground:

WARP will be able to address wave modes also other than those described in sections above, quantify their occurence, and resolve their generation mechanisms and relationships to other magnetospheric processes. Among such wave modes are, for example, the non-thermal continuum radiation and equatorial noise that are poorly known and understood. Field-line resonances are known from ground measurements, but details of their wave characteristics have not been determined. Together with ground-based magnetic data, the WARP constellation can establish the relationship between wave intensity and propagation characteristics observed in space and on ground. This will provide important information for future ground-monitoring of the VLF emissions and thereby potential periods when relativistic particles are accelerated. Similarly, WARP can address various magnetic pulsations associated with magnetospheric dynamics.

2.6 WARP in global context: Beyond the horizon

WARP results will benefit also areas not directly associated with the key scientific issues addressed by the mission. These include for example

Planetary and astrophysical questions:

The WARP mission objectives have relevance to all magnetized planetary and astrophysical objects. In particular, relativistic particles are produced in all strongly magnetized environments of the universe, eg. Jupiter and Saturn, which also have radiation belts. However, multipoint measurements of the generation and loss processes can only be obtained from the near-Earth space. In this regard, the WARP mission will provide input to studies of the dynamics and evolution of distant astrophysical objects such as planetary magnetospheres, stars, or pulsars.

Atmospheric forcing from above:

In the context of global warming, the upper atmospheric response to cosmic rays and radiation belt particle precipitation is of fundamental importance. It is clear that energetic particle precipitation has important effects on the upper atmosphere chemistry, dynamics, and energetics, but how and what is their significance is still unknown. By combining WARP observations with those of various atmospheric missions, we can quantify the effects of the energetic particles on the upper atmosphere.

Space weather:

The near-Earth space up to the geostationary distance hosts both a wealth of commercial satellites and the radiation belts. The “killer electrons” with energies around ∼1 MeV are most harmful, as they cause most of the spacecraft deep dielectric charging events and associated technical malfunctions. In addition to directly contributing to understanding the killer electron physics and dynamics, WARP will also bring increased understanding of the causes of all space weather hazards associated with magnetospheric storms.

Thus, in addition to solving its major space physics questions, WARP will provide both **direct and indirect input to astrophysics, Earth sciences, and space applications**.

2.7 Relation to other missions

While WARP has its unique scientific approach and set of scientific goals, there are both past and upcoming missions that partially overlap in science. In the following, we briefly comment on the missions closest in focus with the WARP mission.

The presently operative ESA magnetospheric flagship **Cluster** passes through the outer radiation belt at its perigee providing very limited spatial and temporal resolution. At perigee the satellites are in a pearls-on-a-string configuration, which provides us with only a 1D snapshot view; it was only for three months in 2002, when a (quite elongated) tetrahedron was available for 3D ring current and wave studies. However, the high perigee Cluster orbit misses the peak of the ring current and the radiation belts and consequently the payload was not configured to study the radiation belts: For example, the Cluster energetic electron and ion instrument RAPID measures only up to 400 keV, thus missing the relativistic electron population. Furthermore, RAPID has a limited energy and pitch-angle resolution due to the low telemetry rate. The thermal electron instrument PEACE is nearly always turned off near the perigee, which does not allow to evaluate the plasma sheet contribution to the ring current and radiation belts. The thermal ion instrument CIS is operated in RPA mode very rarely so that plasmaspheric ions are usually not measured. The 1D waveform data that are essential to the chorus observations are rarely transmitted because of limited DSN downlink time. Thus, while consisting of four satellites, WARP will be very different from Cluster in its scientific goals. In fact, it will focus on regions in the magnetosphere that Cluster hardly crossed and will not cross in the future.

Radiation Belt Storm Probes (RBSP) is a NASA two-satellite mission planned to be launched in 2012. The planned orbit is highly elliptic, with perigee and apogee at 500 and 30 600 km and inclination of 18°. For funding reasons, the selected payload and telemetry rate are quite limited compared Cluster and in particular to to the proposed WARP mission. Also using two satellites with very large separations, the mission is more geared towards the large scale synoptic investigations (see the STORMS proposal assessed during the F2/F3 selection process in 2000) instead of local 3D physical processes. However, the RBSP will provide excellent background information about the morphology of the radiation belts and the flux variations as a function of the geomagnetic activity being thus highly complementary to WARP.

CrossScale submitted as the response to the same call as WARP targets fundamental space plasma physical processes such as reconnection, shocks, shock acceleration, and turbulence in the solar wind and in the magnetosphere. The 10-spacecraft approach includes a wider variety of spatial scales (from electron to ion and fluid scales), but neither the constellation, instrumentation, nor data rates in the inner magnetosphere are suited for the relativistic electron problem. In terms of physical processes studied, regions covered, and multi-spacecraft vs. multi-instrument approaches, the WARP and CrossScale missions are highly complementary, although serving the same scientific community. In order to reach science closure, WARP has a more complex instrumentation and higher data rates per spacecraft, while still maintaining moderate costs well within the M class budget.

3 Mission Profile

3.1 Launcher requirements

WARP is expected to be launched from Kourou using Soyuz Fregat 2B. The launch will first take WARP to the geostationary transfer orbit from which the final orbit is reached using the upper stage of the launcher to lift the perigee and change the orbit inclination.

3.2 Orbit requirements

To fulfill the scientific mission goals the target orbit of WARP has a perigee of about 6000 km, an apogee of about 36000 km, and an inclination of up to 20°. These yield an orbital period of about 12 hours. Note that it is better to avoid the exactly 12-hour orbit due to resonances that will amplify the orbital perturbations due to the oblateness of the Earth.

The four satellites will be kept closely together in a tetrahedron formation within the distance range of about of 100 – 1000 km during the nominal life-time of the satellites of 2 years. There is no requirement for perfect tetrahedron formation. In fact, different inter-spacecraft distances as well as an evolving constellation will allow for different scientific focus areas, as discussed above. The minimum separation of 100 km is considered practical. However, if found advantageous from the orbital dynamics viewpoint, also smaller separations are acceptable.

The main motivations for lifting the perigee from GTO are: First, the orbit is more circular than GTO, which guarantees better satellite constellation near the perigee (compare with the string-of-pearls configuration of Cluster at perigee). Second, the orbit will always be above the inner radiation belt, thus reducing the need for radiation shielding. Third, a higher-perigee orbit will spend more time within the outer radiation belt and the ring current, which are the foci of the WARP mission.

The final inclination will be confirmed during the assessment study phase. There are both scientific and mission technical motivations for tilting the orbital plane. The inclined orbit will let the satellites to reach somewhat higher L-shells thus increasing the physically effective extent of the orbit, and let the satellites to spend more time in the regions away from the equatorial plane, as some of the scientifically important phenomena are more pronounced and easier to measure there than in the equatorial plane. Larger inclination also makes the angle between the velocity vector and the spin axis smaller, which increases the efficiency of the thrusters to maintain the desired satellite constellation.

No previous scientific spacecraft have been on exactly the same orbit. The closest examples are AMPTE/CCE (launch 1984) with perigee at 1 121 km, apogee at 49 671 km and inclination of 4.8°, and CRRES (launch 1990) with perigee at 350 km, apogee at 33 584 km, and inclination of 18°.

3.3 Ground segment requirements

The ground segment includes the WARP Operations Control Center (WOCC), ground receiving stations and communications network, as well as a dedicated WARP Data Archiving System (WDAS) for data distribution to the scientific community.

Ground stations communicate with the spacecraft via X-band communications systems that support all activities involved in the telemetry, telecommand and tracking functions. From the launch until all four spacecraft have reached their operating orbits and gone through the commissioning phase several ESA ground stations will be used to maximise the ground contact during the crucial activities. When the WARP mission has reached the nominal operations phase it will be primarily supported by one ESA receiving station.

WOCC will provide the necessary mission control functions for both the spacecraft and payload, as well as carry out the trade-offs between scientific requirements and the overall system resources. The responsibility for the mission operations rests with ESA. The WARP Science Team will serve WOCC by providing the science requirements to be taken into account through the WARP Science Operations Center (WSOC).

The WARP observations will be processed at WSOC and stored in WDAS, from which all Principal Investigators will be able to find their data. WDAS stores the raw data as well as takes responsibility of producing the calibrated high and low time resolution WARP science products that are stored permanently to be available for the science community.

4 Proposed Payload

4.1 Overview of payload elements

The WARP scientific payload consists of a traditional package of in-situ magnetospheric instruments with a strong heritage. In order to achieve the science goals described above it is necessary to measure the electric and magnetic fields as well as charged particles over wide energy and pitch-angle ranges. All four spacecraft have identical suites of instruments with identical interfaces with the spacecraft bus in order to keep the development and operations costs to a minimum.

Most onboard data handling will be performed by a centralized Payload Data Management System (PDMS) included in the spacecraft resources described in section 5.3. The instruments will also have individual data processing capacity, which in several cases is assumed to be shared by more than one instrument listed below, eg. the waveform capturing from AC electric and magnetic field instruments, and the low-energy electron and ion instruments.

All instruments will be PI-provided following an open instrument AO. The instruments described below are examples only, demonstrating high technology readiness.

In the following discussion we have used information of instruments flying onboard Cluster, Themis, Oersted and CHAMP spacecraft, the model payload of STORMS Assessment Study in the F2/F3 process in 2000, as well as in-house knowledge within the institutions of the proposing team. We first describe the proposed model payload instruments and list the most important requirements and critical items. The mass, power and telemetry requirements are collected to section 4.3.

Common requirements for the entire payload are **high magnetic cleanliness** (typical to all magnetospheric missions, eg. Cluster) and **careful intercalibration of the instruments onboard the four satellites**.

4.2 Instrument key characteristics

DC magnetic field instrument WMAG

Description and key characteristics:
The magnetic field is measured using two fluxgate magnetometers located on a 4-m boom.

Performance assessment with respect to science objectives: A magnetometer is a key instrument for the WARP mission. In addition to measuring the magnetic field, the observations will be used to determine the electric currents using the curlometer technique based on 4-point observations. Furthermore, the magnetic field direction is necessary for the interpretation of particle observations, and the magnetic field vector is needed by the electric field instruments to determine the ambient 3D electric field vector. The instrument will take 2 x 50 vector samples per second with a dynamic range from ±65536 nT to ±0.0625 nT (21 bits).

Pointing and alignment requirements:
The actual direction of the flux-gate assembly must be known with a precision of 0.1–0.2°.

Current heritage and TRL: Similar magnetometers have been flown onboard a large number of spacecraft, including Cluster. The heritage of the present sample is from Oersted, Astrid, CHAMP and SAC-C, and from the upcoming PROBA-2 and SWARM. Thus there are magnetometer designs in Europe with TRL = 9.

Critical issues: Boom deployment.

AC magnetic field instrument WMGW

Description and key characteristics: The wave magnetic field is measured with a traditional 3D assembly of search coil magnetometers. The sensor unit is located on a 4-m boom opposite to the DC magnetic field boom.

Performance assessment with respect to science objectives: Electromagnetic waves are main accelerators of charged particles in the inner magnetosphere and also important for the loss of particles. Sampling rate up to 100 000 samples per second is required. Spectral data are produced in two frequency ranges, 0.1–100 Hz and 0.1–50 kHz. Additionally, a specific waveform capture of three components up to at least 20 000 samples per second. Dynamic range $10^0 - 10^{-5}$ nT/$\sqrt{\text{Hz}}$; sensitivity requirement <1 pT/$\sqrt{\text{Hz}}$ at 10 Hz.

OBDH: Waveform capture analyzed jointly with WEFW waveform data (in either DPU).

Pointing and alignment requirements:
About 1° corresponding to the accuracy of the wave vector (or Poynting vector) analysis.

Operating modes: Multidimensional spectra and spectral matrices, waveform capture.

Calibration requirements: Instrumental response functions (amplitude and phase transfer functions).

Current heritage and TRL: Strong European heritage: GEOS 1 and 2, Galileo, Ulysses, Interball, Cassini, Cluster, Themis. TRL = 8–9.

Critical issues: Boom deployment.

Double probe electric field instrument WEFW

Description and key characteristics: Two-dimensional DC and AC electric fields are measured using two pairs of electric probes located on the tips of four 50-m wire booms in the spin plane of the spacecraft.

Performance assessment with respect to science objectives: The double probe instrument has versatile roles. In addition to local electric field measurements, it will be used to monitor the spacecraft potential that is a proxy for the background plasma density. The DC electric field sampling rate is 100 samples per second. The AC electric field are determined in two frequency ranges 0.1–100 Hz and 0.1–600 kHz, the latter at least in 128 steps. Waveform capture of 2 electric field components is sampled at least 20,000 samples per second.

OBDH: Onboard wave filtering; waveform capture analyzed jointly with WMGW waveform data (in either DPU).

Operating modes: Routine waveform and spectra; waveform capture; probe sweeps.

Calibration requirements: Instrumental response functions (amplitude and phase transfer functions).

Current heritage and TRL: Similar instruments have been flown on several magnetospheric spacecraft, including Cluster. TRL = 8–9.

Critical issues: Deployment of the booms will be a critical phase of S/C commissioning.

Electric field drift instrument WEDI

Description and key characteristics: In addition to WEFW, the electric field is measured by detecting the electron drift across electric and magnetic fields. WEDI determines the drift of two electron beams directed precisely perpendicular to the magnetic field by two Gun-Detector Units and thereby provides an absolute measurement of the perpendicular electric field using a geometric technique independent of plasma density, wakes, and S/C potential. Resources permitting the measurement should be performed utilizing two electron guns.

Performance assessment with respect to science objectives: The instrument has been shown to measure electric fields with a resolution of better than 5% and to achieve calibrations of the spin-axis component of the magnetic field to 0.3 nT. Given that the perpendicular direction of B and its magnitude are also determined, the full vector B is known with exceptional precision. Over 25 beam hits per second have been achieved. The measurement gives a reference point for both magnetic and electric field (double probe) measurements.

Pointing and alignment requirements: The two gun/detector units must face opposite directions, alignment ±0.5°, knowledge ±0.1°

Calibration requirements: Beam direction to approximately 0.5°. Gun current must be known to ∼5%, and sensor count response to 20%.

Current heritage and TRL: Similar instruments have been flown on several S/C, in particular on Cluster. TRL = 8–9.

Sounder and mutual impedance instrument, WSAM

Description and key characteristics: WSAM consists of a pulse transmitter, a sensitive radio receiver and a digital spectrum analyser. The WSAM transmitter will be connected to the conductive outer braids of the WEFW boom cables while the WEFW high-impedance preamplifiers will provide signals to the WSAM receiver electronics board.

Performance assessment with respect to science objectives: WSAM aims at the total plasma density evaluation and natural wave monitoring in the 1–600 kHz frequency range. In addition to the classical relaxation sounding technique used onboard Cluster, a mutual impedance mode will be implemented. The latter will allow the thermal electron temperature to be measured and the effective length of the WEFW antenna to be determined. The existence of a hot population may also be revealed and the hot to cold density and temperature ratios can be estimated with this technique, which requires no additional equipment compared with the relaxation sounder.

OBDH: Onboard FFTs.

Current heritage and TRL: Similar instruments have been flown on GEOS, Cluster, Mars 96, Viking, Rosetta. The mutual impedance mode was also successfully tested, though WHISPER on Cluster was not actually designed for that. TRL = 8–9.

Critical issues: WSAM receiver is sensitive to frequencies in the 1 kHz – 600 kHz frequency range. Spacecraft EMC levels should be as low as possible.

Time-of-flight thermal ion instrument WTOF

Description and key characteristics: Time-of-flight ion instrument located on a boom about 2–5 m from the S/C body (for example) on the top plate of the satellite.

Performance assessment with respect to science objectives: The instrument measures the background thermal ion composition (H^+, He^+, O^+) in the energy range 0–50 eV. Its task is to determine wave stop bands, and electron and ion resonant energies.

Current heritage and TRL: Similar instruments have been flown on many magnetospheric missions, including Cluster. TRL = 8–9.

Critical issues: Boom deployment.

Low-energy electron instrument WEL

Description and key characteristics: Low-energy electrons are measured using a traditional top-hat instrument with electrostatic deflection and microchannel plate detectors.

Performance assessment with respect to science objectives: The energy range will be 1 eV – 30 keV divided to 32 energy channels. For pitch-angle determination, polar angle resolution of 20° or better is required.

Pointing and alignment requirements: The top-hat entrance (2π ring) has to be located at the edge of the S/C to yield a 4π coverage after a half S/C spin.

Current heritage and TRL: Similar electron instruments have been flown on many magnetospheric missions, including Cluster. TRL = 8–9.

Critical issues: Observations in the eV-range require satellite potential control (see WSPOC below).

Low energy ion mass spectrometer WIMS

Description and key characteristics: Low-energy ions are measured with an ion mass spectrometer using traditional top-hat instrument with electrostatic deflection and time-of-flight determination. Particles are recorded with microchannel plate detectors.

Performance assessment with respect to science objectives: The energy range will be 1 eV – 30 keV divided to 32 energy channels, with mass separation covering at least H^+, He^+ and O^+. For pitch-angle determination polar angle resolution of 20° or better is required.

Pointing and alignment requirements: The top-hat entrance (2π ring) has to be located at the edge of the S/C to yield a 4π coverage after a half S/C spin.

Current heritage and TRL: Similar ion instruments have been flown on many magnetospheric spacecraft, including Cluster. TRL = 8–9.

Critical issues: Observations in the eV-range require satellite potential control (see WSPOC below).

Satellite potential control system WSPOC

Description and key characteristics: Satellite potential control is needed to perform exact plasma observations at energies close to the satellite potential. WSPOC reduces the positive spacecraft potential by emitting an ion beam at a few keV energy. The beam current sets an upper limit to the potential at $\sim$4 V for 20 μA or $\sim$2 V for 50 μA. Resources permitting two simultaneous ion beams by 2 units should be emitted. This instrument is expected to be integrated to another instrument, possibly the low-energy electron or ion instrument.

Current heritage and TRL: Cluster and Double Star ASPOC heritage. TRL = 8–9.

Mid-energy electron instrument WMEL

Description and key characteristics: Electrons in the mid-energy range are measured with an instrument applying magnetic deflection.

Performance assessment with respect to science objectives: The energy range will be 20 – 1500 keV divided to (at least) 16 energy channels, in order to have enough overlapping with low- and high-energy electrons. For pitch-angle determination polar angle resolution of 20° or better is required.

Pointing and alignment requirements: Sensor unit to be attached to the side/top of the S/C.

Current heritage and TRL: Similar electron instruments have been flown on many magnetospheric spacecraft (e.g., Polar and Cluster). TRL = 8–9.

Mid-energy ion instrument, WRC

Description and key characteristics: Ions in the mid-energy range are measured with an instrument applying magnetic deflection.

Performance assessment with respect to science objectives: The energy range 30 – 1500 keV covers the energies of the ring current carriers, which makes WRC a key instrument for the WARP mission. The energy range will be divided to (at least) 16 energy channels with sufficient mass resolution to resolve at least H^+, He^{++}, He^+ and O^+, but detection of heavier ions would also have significant scientific interest. For pitch-angle determination polar angle resolution of 20° or better is required.

Current heritage and TRL: Similar ion instruments have been flown on several magnetospheric spacecraft. TRL = 8–9.

High-energy electron instrument WREL

Description and key characteristics: Determining the processes of the production and loss of relativistic electrons is the ultimate goal of WARP. The relativistic electrons are measured with a solid state detector.

Performance assessment with respect to science objectives: The energy range will be 0.3 – 10 MeV divided to at least 16 energy channels. For pitch-angle determination polar angle resolution of 20° or better is required.

Current heritage and TRL: Similar electron instruments have been flown on several spacecraft. TRL = 8–9.

4.3 Summary of scientific payload

The scientific P/L is summarised in Table 2.

Some of the instrument mass estimates already include margins. In the total scientific P/L mass a margin of 16.7 % has been added to end up with 80 kg. The total P/L power consumption is estimated to 50 W.

Detailed allocations of telemetry have not been made for the individual instruments. Based on experience from other magnetospheric payloads the preliminary telemetry estimate for **a single spacecraft** is 100 kb/s divided as:

Fields and waves (WMAG, WMGW, WEFW, WEDI, WSAM):	50 kb/s
Plasma and particles (WTOF, WEL, WIMS, WSPOC, WMEL, WRC, WREL):	50 kb/s

Thus the data rate of each satellite is about 100 kb/s that is the same as the Cluster burst mode telemetry. Consequently the four spacecraft constellation produces about 35 Gb/day. Assuming the use of X-band telemetry, this can be transmitted within one to five hours depending on the telemetry station used.

Optional instrument

Resources allowing, an exospheric density and composition instrument (similar to STROFIO being developed for BepiColombo) could be added to the WARP payload. The mass and power requirements are 2 kg and 5 W. It is still in early phase of development and has considerably lower TRL than all other P/L elements. Note that we have not included this in the overall payload resource calculations below.

Instrument	**Characteristics**	**Mass and power**	**Heritage**
WMAG, DC magnetometer	Flux-gate magnetometer; 50 vector samples per second; on tip of 4-m boom	3.5 kg (sensors 300g; e-box 650 g; cables 400 g; boom 2 kg); 1 W	All m'spheric S/C
WMGW, AC magnetometer	Search coils; two ranges 0.1-100 Hz and 0.1-50 kHz; on tip of 4-m boom	5.5 kg (sensors 700 g, e-box 2 kg, cables 400 g, boom 2 kg); 2.5 W	Several m'spheric S/C
WEFW, DC and AC electric field instrument; also plasma density measurement	Langmuir probes, on tips of 4 50-m booms; DC 100 samples/s, AC in two ranges: 0.1-100 Hz, 0.1-600 Hz, latter in 128 steps	11 kg (sensors and e-box 5 kg, booms 6 kg); 5 W	Several m'spheric S/C, in particular Cluster EFW
WEDI, electric field with electron drift techniques	Electron gun(s), 1 measurement/s	7 or 12.5 kg (5.5 kg per gun&detector unit, controller 1.5 kg); 6-9 W	Cluster EDI heritage
WSAM, Sounder and mutual impedance instr	Pulse transmitter, receiver, digital spectrumen analyzer (uses WEFW booms)	1.5 kg; 2 W	Several m'spheric S/C, including Cluster
WTOF, thermal ion composition instrument	Time-of-flight instrument located on a boom.	5-8 kg; 5 W	Several m'spheric S/C, including Cluster
WEL, low-energy electron instrument	1 eV - 30 keV, 16 chs, top-hat, electrostatic deflection, MCP, pitch-angle resol TBD, dynamic range TBD	2 kg, 2 W (note DPU in WIMS budget)	Most m'spheric S/C, including Cluster
WIMS, low-energy ion mass spectrometer	1 eV - 30 keV, H+, He+, O+, 16 energy chs; top-hat, TOF, MCP; pitch-angle resol TBD, dynamic range TBD	4 kg, 6 W (incl joint DPU with WEL)	Most m'spheric S/C, including Cluster
WSPOC, satellite potential control	ASPOC-type of instrument	4 kg (two ion beams), 4-5 W	Cluster
WMEL, mid-energy electron instrument	10 - 1500 keV, 16 chs; magnetic deflection; pitch-angle resol TBD, dynamic range TBD	2 kg, 2 W	Several m'spheric S/C
WRC, Ring current ion instrument	30 - 1500 keV, H+, O+, 16 energy chs; magnetic deflection; pitch-angle resol TBD, dynamic range TBD	6 kg, 6 W (incl joint DPU with WMEL)	Several m'spheric S/C
WREL, high-energy electron instrument	0.3 - 10 MeV, ≥ 16 chs; solid state detector; pitch-angle resol TBD, dynamic range TBD	7 kg, 6 W	Several m'spheric S/C

Table 2: *WARP instruments, their characteristics, mass and power requirements, and heritage*

5 Spacecraft Key Factors

5.1 Configuration of satellites

The WARP mission consists of four spacecraft flying in a tetrahedron formation. Note that for achieving the science goals, the tetrahedron need not be regular. The orbit of the satellite constellation is eccentric with a perigee altitude at about 6000 km and apogee at about 36000 km altitude. The orbit is also slightly inclined by 20° with respect to the Earth's equator. The optimal satellite separations are from 100 to 1000 km during the mission nominal lifetime.

All WARP satellites are identical to each other. Each satellite is cylindrically shaped with its main axis perpendicular to the equatorial plane during the operations. The satellites are spin-stabilized with a spin rate of about 15 revolutions per minute around the main axis.

The WARP scientific payload instrument detectors are accommodated on the cylindrical surface as well as on the face plates of the satellite body. The electronics and batteries are located inside the satellite body. Struts inside the cylindrical body give the proper mechanical strength for the S/C. The payload configuration viewed from both face plate directions is shown in Figure 8.

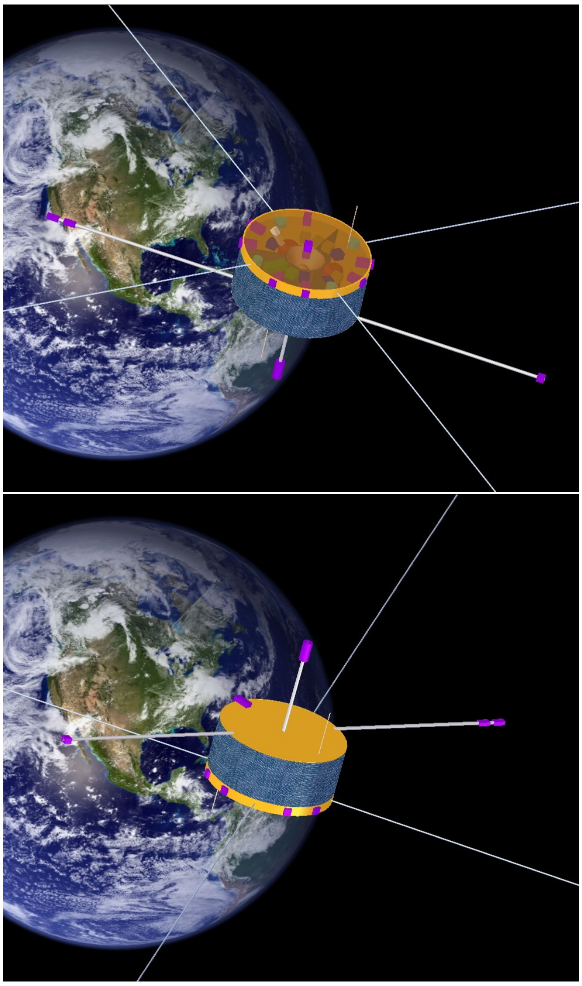

Figure 8: *The WARP scientific payload configuration viewed from the directions of the two face plates of the satellite's cylindrical body.*

5.2 WARP constellation generation and station keeping

The four WARP spacecraft will be launched to geostationary transfer orbit (GTO) with the Soyuz Fregat 2B launcher capable of lifting 3020 kg to GTO from Kourou. The total mass of the four WARP spacecraft including the scientific payload and the fuel to lift the perigee is about 2910 kg. The mass estimates are conservative and contain appropriate mass margins (16.7% for the instruments and 20% for the bus).

The restartable engine of the Fregat upper stage will be used at apogee to move the spacecraft from GTO to the nominal operational orbit. Figure 9 illustrates the change of inclination and the lifting of the perigee achieved with a single burn of the Fregat engine.

The desired tetrahedral configuration of the WARP spacecraft can be achieved by using three different orbits with the same period but slightly different eccentricity and inclination. Spacecraft 1 and 2 share the same orbit, with one flying slightly behind the other. Spacecraft 3 orbits at the same inclination, but with the

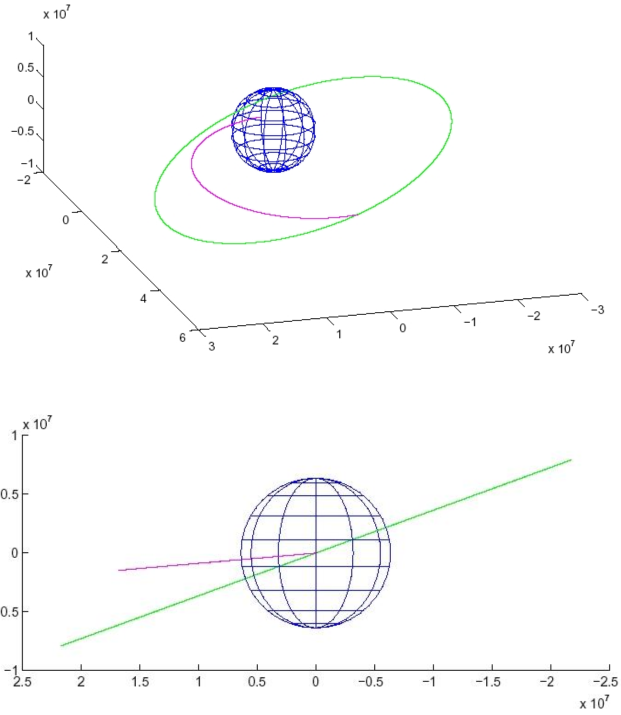

Figure 9: *The GTO orbit after the launch (purple) and the operational orbit after the apogee orbit insertion burn of the Fregat upper stage (green). The inclination is increased to about 20° and the perigee to 6000 km.*

apogee and perigee shifted to change the eccentricity. Spacecraft 4 uses an apogee and a perigee half-way between these orbits, and a different inclination.

The satellite formation is initially arranged to have a separation of 100 – 500 km. The orbits are optimized in order to maintain a good nearly regular tetrahedron for most of the time. However, due to the orbital geometry, the satellites will be in the same plane at least twice per orbit. Due to their different orbital parameters, the satellites will not be affected equally by orbital perturbations caused by the Earth's oblateness, the Moon and the Sun. The first of these, in particular, causes constant perturbations to two orbital parameters: the precession of the line of the apsides and the regression of the line of the nodes. The perturbations will lead to the gradual disintegration of the formation if corrective maneuvers are not performed.

Starting with a compact initial constellation, the natural divergence of the formation will be used to cover science that is best suited for each separation distance. For the mission objectives, a good solution is to allow different constellation configurations (up to a few 1000 km) regularly in all local time sectors, which would mean making larger orbital trimmings a few times a year to re-create the tight short-separation constellation. Such corrections include shifting the apogee and perigee to change the eccentricity of the orbit, and delay maneuvers where the satellite is temporarily placed on a slightly longer or shorter orbit to change its position on the operational orbit.

Given the relatively hazardous environment of the mission, a fall-back option to 3 spacecraft has been considered. In the case of a spacecraft failure, the mission can be reconfigured into an equilateral triangle, perpendicular to the orbit. Spatial and temporal variations can then still be separated using least-squares based gradient computation techniques (space and time-derivatives, including the curlometer), at least if there are no strong time variations over the time needed for the spacecraft to move over the typical s/c separation distance, so that most of the mission goals can still be achieved. For example, collecting observations from each satellite for 1 min covers a spatial length of 100 km, which is sufficient for the curlometer analysis. The resulting determination of the average current within a region 100 km across far exceeds the present knowledge of the currents in the inner magnetosphere. Furthermore, good current profiles can be obtained as the thickness of the ring current is of the order of 10 000 km.

5.3 Key spacecraft systems

The WARP scientific model payload consists of 12 instruments, some of which possess their own data handling capability. However, we propose that most of onboard data handling will take place in the payload data management system (PDMS), which is a part of the spacecraft systems. In addition to the main data processing functions, the PDMS schedules the scientific operations and sends the data to the telecommunication system. This approach will decrease the payload mass and facilitate effective communication between different instruments using each others' observations in onboard analysis. The WARP science payload uses proven technology and most of the payload parts have already flown onboard several missions. As discussed in the previous section, the TRL of the individual instruments is typically 8 or higher.

The WARP spacecraft are spin-stabilized, similar to the Cluster satellites. As also the payload resembles the Cluster instrument suite, the well-known satellite architecture is a cylindrical body with the height of 150 cm and diameter of 300 cm. The payload electronics boxes and the system service instruments are mounted on a platform inside the cylindrical spacecraft body. The batteries and other critical components are covered by thermal protection material. The key elements of the WARP spacecraft are illustrated in the spacecraft explosion drawing in Figure 10.

All system instruments and services of the spacecraft bus are heritage from earlier successful space missions with minor modifications. Hence the TRL of the WARP spacecraft bus ranges from 7 to 9. The four spacecraft will be packed on top of each other to fit within the fairing of the Soyuz Fregat 2B launcher.

The instrument mounting configuration is described in Figure 10. The pointing knowledge and the accuracy of the spin rate are of 0.1° and 10%, respectively. The spacecraft attitude control is achieved using cold gas thrusters.

Figure 10: *The main hardware parts of the WARP spacecraft are the cylindrical shell serving as the structural body with two faceplates, the instrument platform and a thermal protection layer. The instrument platform can also be realized as two smaller platforms to accommodate the key system devices in the vicinity of each other.*

The key functions of the WARP satellite bus are command and data handling, telecommunications, attitude control, power systems, thermal control, propulsion, pyrotechnics, structure, cabling and mechanisms. The total mass of one bus, including the scientific payload, is approximately 560 kg including including all margins. The estimated mass distribution is shown in Table 3. This estimate is based mainly on Cluster heritage from 20 years ago, and thus both the mass and volume requirements of the bus can be viewed conservative.

The command and data handling functions of the WARP spacecraft are implemented by three functional units. The WARP main data management system (WDMS) communicates with the ground-segment, controls all spacecraft systems, as well as commands the payload data management system (PDMS).

The spacecraft electric power is supplied by solar panels that are mounted on the cylindrical spacecraft body. The efficiency of the solar panels is expected to be 15%. The heat dissipated in the spacecraft systems and that arising from the radiation of the Sun and Earth are removed from the spacecraft by heat removal system consisting of a heat pump and radiators.

The four WARP spacecraft fly in a relatively tight constellation compared to the size of the orbits. This means that the ground link is available for all satellites at the same time and hence all four satellites will share the available communications link. The WARP orbital period of about 12 h means that the constellation will be at optimal visibility of any given station about twice per day, at almost opposite angles of true anomaly. This guarantees that the ground station will have at least one pass of the constellation at relatively low altitude almost every day. The low inclination of the constellation means that the Kourou ground station (at 5° latitude) has a view of the constellation at a high elevation angle, which makes it an ideal site for the main ground station. Which of the ESA stations will finally be used, will be decided in a later stage.

The transmission with X-band transponders will utilize Gaussian Minimum Shift Keying (GMSK) modulation scheme to provide a high spectrum efficiency and a reasonable demodulation complexity. A waveguide horn type antenna together with a slotted waveguide antenna (used eg. in Meteosat) will provide full hemispherical coverage. A quick analysis shows that WARP can downlink data at 2–3 Mb/s at Kourou or Maspalomas (15-m antennas) and at 25–30 Mb/s at New Norcia (35-m antenna).

As all WARP spacecraft are visible from the ground station at almost the same time, it is not plausible to restrict the data transmission to perigee passes only. While data transmission takes longer when the spacecraft are near the apogee, they also move slower, which allows them to be visible to the ground station for a longer period at a time. Figure 11 illustrates a possible communications link (Kourou) for the WARP satellites being of the order of 10 hours per day. The downlink requirement per satellite is of the order of 10 Gbits of data per day and hence daily data transmission takes about 1 to 1.5 hours for each WARP satellite (assuming a 15-m antenna).

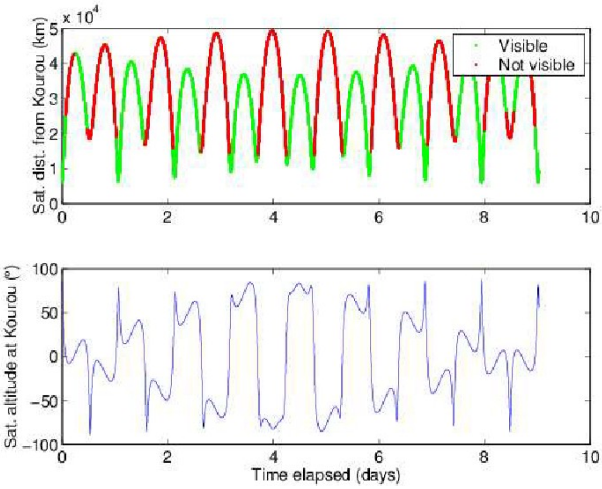

Figure 11: *The available communications link between the WARP satellites and the Kourou ground station over a period of approximately 10 days illustrated by the distance in kilometers between the WARP satellites and the Kourou station (upper panel) and by the altitude in degrees (lower panel). The periods of orbit marked in red are visible from Kourou.*

Warp Mission Mass Estimate

BUS	Mass
Command and data handling	25
Telecommunications	25
Attitude control	10
Power	70
Thermal control	20
Structure, cabling and mechanisms	105
mechanisms	15
harness	20
Propulsion and pyrotechnics	
pyros	5
propulsion (thrusters)	
Dry mass (2x4x10N + tanks)	5
Fuel	100
	400
20% margin for bus components	80

Payload		Mass
WMAG		3,5
WMGW		7
WEFW		11
WEDI		12,5
WSAM		1,5
WTOF		8
WEL		2
WIMS		4
WSPOC		4
WMEL		2
WRC		6
WREL		7
		68,5
Margin	17 %	11,65
Total payload with margin		**80**

Overall mass estimate for one satellite	
BUS (includes 20% margins)	480
Payload (include 15% margins)	80
	560
Fuel for change of orbit	**670**

Total launch mass	**2910**

Table 3: *Mass breakdown of the WARP mission including the four spacecraft and the services required to perform the change of orbit from the original GTO.*

5.4 Summary of overall resources

As shown in Table 3, the overall WARP mission mass including the four satellites, as well as the fuel for changing the inclination and lifting the perigee is 2910 kg. This includes 20% margins for the bus and 17% margin for the scientific payload. The fuel needed for the perigee lift is calculated for the total mass with margins.

The dimensions of the WARP spacecraft as indicated above comply with the fairing of the Soyuz Fregat 2B when the four spacecraft are stacked on top of each other inside the fairing.

The entire WARP constellation downlinks daily about 35 Gbits of data, which is realistic using the X-band antennas at ESA ground stations.

5.5 Environmental constraints

The spacecraft must be magnetically clean. This means that intrinsically magnetic as well as magnetically soft materials should be avoided. The basic requirement is that the magnetic activity can be identified and is clearly documented in the material data sheets.

The spacecraft must be electrically conducting to avoid differential surface charging and to provide electrically clean environment for electric field and low-energy electron and ion measurements.

The radiation environment is challenging, as the spacecraft will regularly cross the outer Van Allen radiation belt. The inner belt, which has harsher radiation environment belt is below the perigee of the WARP orbit. Hence the spacecraft body and radiation hardened electronics with latch-up protection is sufficient to guarantee nominal lifetime for the WARP mission.

5.6 Current heritage and technology readiness level

The spaceraft bus and all its key subsystems have a solid heritage based on earlier successful space missions. The overall TRL of the spacecraft bus systems can be considered to be 8. Most parts of the scientific payload also have solid heritage from the earlier missions, and most of the instruments have already flown in space. A few instruments are based on new innovative measurement concepts that have been succesfully tested in chambers simulating space conditions. The technology readiness level ranges from 7 to 9.

5.7 Procurement approach

Standard ESA procurement procedures assuming a PI provided payload.

5.8 Critical issues

There are no specific critical issues, although the boom deployment always introduces certain risk. From the technological point of view the WARP mission is a standard space mission. Attention will have to be paid to electromagnetic cleanliness and the radiation hardness.

6 Science Operations and Data Archiving

6.1 Science operations architecture and share of responsibilities

From the science operations viewpoint WARP is close to Cluster as a constellation mission. We propose a similar operations architecture and share of responsibilities, acknowledging all "lessons learnt" from Cluster operations.

6.2 Archive approach

We propose to follow the archiving approach developed in recent years at ESA. In particular the Cluster Active Archive has developed generic tools and data structures that successfully archive complex particle and wave data products from any magnetospheric mission in a user-friendly way.

All high and low time resolution science products ("level 2") from all instruments require detailed and time-consuming in-flight calibration where related observations from different instruments and spacecraft are cross-calibrated. This phase is necessary before full scientific advantage of the data can be taken and before they can be made available to the worldwide science community.

The archive should also produce a number of derived science products ("level 3") where data from a single or multiple instruments are used to derive scientific parameters, such as the electric currents (from the curlometer), Alfvén velocity, and plasma beta parameter.

6.3 Proprietary data policy

The WARP data policy will be open. The instrument PIs will have at most 6 months exclusive right to data, after which the data will be available to the worldwide science community through the WARP science data archive.

7 Key Technology Areas

7.1 Payload TRL level and technology development

All model payload elements can be realized with instruments of multiple spaceflight heritage. No specific technology development will be required for the payload unless the response to the instrument AO brings in some novel instruments and such instruments will be included in the payload based on their scientific merits.

7.2 Mission and spacecraft technology challenges

The spacecraft will be based on well-proven technologies. The inner magnetospheric orbit will require sufficient level of radiation tolerance and shielding but the requirements are well known.

The deployment and operations of four closely spaced satellites in the inner magnetosphere may be somewhat more challenging than is the case with Cluster. In particular, the relatively large angle between the spin axis and velocity vector requires careful planning of the configuration maintenance operations.

8 Programmatics and Cost

8.1 Mission management structure

The mission will be managed as a typical ESA solar-terrestrial/planetary mission with several instrument PIs.

8.2 Mission schedule drivers

None. There is no need for development of new technologies. The mission can be launched in 4 years from the start of the industrial contract.

8.3 Payload and instrument cost

All instruments will be provided by PIs and Co-Is selected through an open AO process with no cost to ESA.

As the costing of instruments in different ESA Member States and within different institutions varies widely, an exact cost estimate cannot be given at this stage. Following the old rule-of-thumb that a PI-provided payload costs approximately one third of the cost to ESA, we estimate the payload to cost about 100 Meuro to the Member States. This translates to typically 7–10 Meuro per instrument (ie. four identical flight copies of each individual instrument detailed in section 4).

8.4 Overall mission cost analysis

We follow the guidelines in Annex 4 to the AO. We note that the spacecraft technology is well-known, and consequently the price tag for S/C industrial activities will be about 100 Meuro.

The budget is challenging. The spacecraft and their operations must be "designed to cost". If down-scaling is needed, it will be done through simplifications and reductions of the operation costs. The number of spacecraft must not be reduced.

Activity	**Cost to ESA**
Pre-Implementation phase	5 Meuro
Total S/C industrial activities	100 Meuro
Launch services from CSG (Soyuz Fregat-2B)	40 Meuro
Ground segment (MOC and SOC)	50 Meuro
ESA internal costs	30 Meuro
Contingency	50 Meuro
Total	275 Meuro

Table 4: Summary of the WARP mission costs.

9 Dissemination and outreach

Scientific dissemination: WARP will provide major scientific discoveries in the field of space physics. These results will be published in international conferences and leading scientific journals such as Nature and Science and other more topical journals in the field of space physics. The WARP data will be publicly available through the WARP science data archives soon after the measurements are calibrated, which will facilitate wide international collaboration in scientific research.

Service to space weather users: WARP results will provide essential new links in our understanding of how space weather events harm technological systems and the risk the radiation poses to humans in space. The scientific results will be merged into operational models both for engineering and forecast purposes. Space engineers, spacecraft designers and spacecraft operators will take advantage of the increased understanding of the total doses, the rise and fall times of the particle events and the longer-term evolution of the flux levels. International space station and other manned programmes will benefit from the increased ability to monitor and nowcast the particle environment. The improved models will increase the reliability of short-term forecasts for launch, extra-vehicular operations and other activities that involve an increased risk to humans.

Education of students: Both undergraduate and graduate students will be involved in the WARP mission from early stage to data analysis. The solid physics scope of the mission gives a good foundation for students. Early involvement in development of measurement and data analysis techniques as well as solving problems dealing with instrument capabilities and calibration issues will teach the students to use data to their full capability, but realizing their limitations. The international efforts to unravel the physics related to the continuous generation of relativistic particles around the Earth and to space weather events will tie the local processes examined by WARP to the large-scale processes coupling the solar wind and the magnetosphere and provide the students with a comprehensive understanding of the Sun-Earth connection as well as space physics.

Involving the general public: Space weather and near-Earth space conditions with relativistic particles ("particles that are million times hotter than the Sun") are a topic that easily catches public attention. While school children from kindergarden to high-school are a special focus group for the WARP mission, the general audience will be approached also through public lectures and seminars. We will use the WARP data and models to develop animations of the variable particle environment surrounding the space to provide the scientific results in a format that is easily understandable. We will also continue our successful work together with school teachers and students aiming to become teachers to develop presentations and teaching kits suitable for a variety of age groups. All these materials will be actively distributed to schools during visits and through mailing lists and made available through the mission website.

Digital dissemination: From early phases on, we will have a mission website that will include both a scientific site and popular pages. The scientific data archive site will be used for providing data, publications, and presentations to other scientists. We will also host a scientific discussion forum that will be open for all interested scientists. The popular pages will be used to distribute public dissemination material and publicize the WARP results in a format accessible to the general audience. Special emphasis will be made to distribute the knowledge gained from WARP to a wider scientific audience, such as the planetary and astronomy communities.

10 List of Acronyms

CSG	Centre Spatial Guyanais
DPU	Data Processing Unit
EMC	Electromagnetic Compatibility
EMIC	Electromagnetic Ion Cyclotron (waves)
EUV	Extreme Ultraviolet
FFT	Fast Fourier Transformation
GMSK	Gaussian Minimum Shift Keying
GTO	Geostationary Transfer Orbit
MOC	Mission Operations Center
OBDH	On Board Data Handling
PDMS	Payload Data Management System
RPA	Retarding Potential Analyzer
SOC	Science Operations Center
TRL	Technology Readiness Level
ULF	Ultra-Low Frequency
VLF	Very Low Frequency
WDAS	WARP Data Archiving System
WDMS	WARP Data Management System
WOCC	WARP Operations Control Center
WSOC	WARP Science Operation Center

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ISBN 978-951-697-624-5
ISSN 0782-6079
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