Sun, heliosphere and magnetospheres

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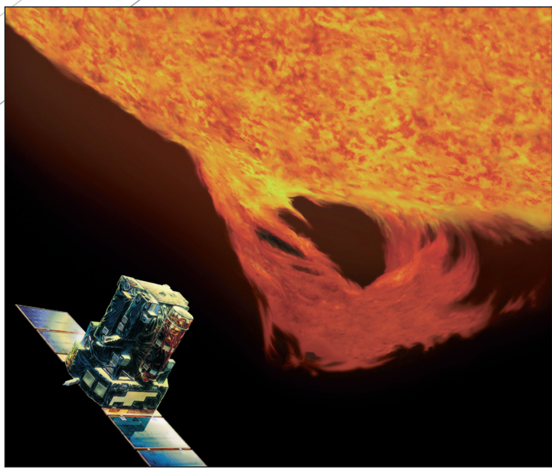
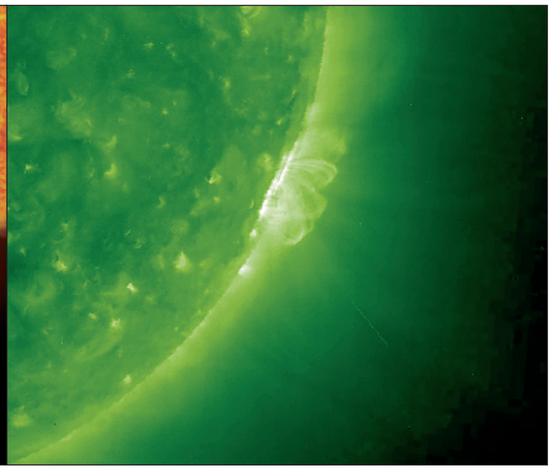


[Fig. 1]



[Fig. 2]

Sun and heliosphere physics

The study of the Sun and the exploration of the internal heliosphere have obviously benefited from the continuation during the last four years of the SOHO and Ulysse data analysis. They have also taken advantage of the first observations of STEREO and the continuation of data analysis from various opportunity missions such as RHESSI and WIND.

Tridimensional reconstruction of solar corona structures

The STEREO mission enabled to establish for the first time not only the third dimension, but also the dynamics of structures observed in the solar corona (Fig. 5) The observation of our star's polar regions done by these probes enabled to start understanding "polar plumes", whose structure is not well understood yet, but which could have a major role in accelerating the solar wind. Until now, doubts existed as to the very nature of these objects: are plumes magnetic field tubes or alignment effects in the line of sight? Results show that in fact both types of structures can exist simultaneously.

First detections of interplanetary nano-dust at 1 AU

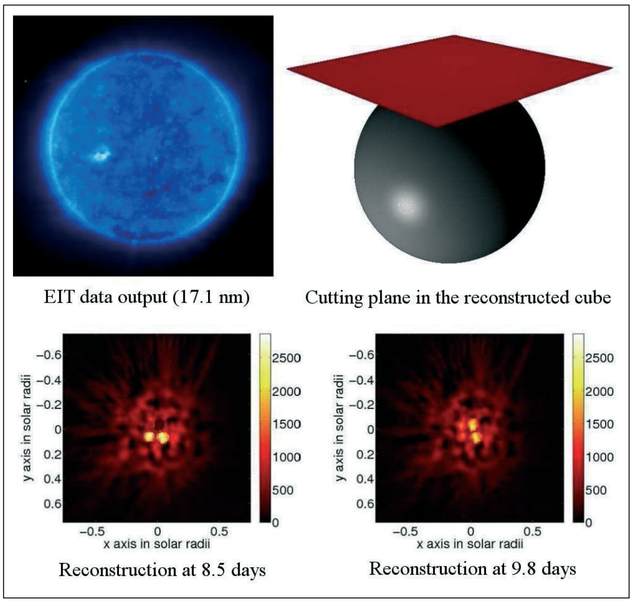
Thanks to the special configuration of the STEREO probes' electrical antennas, the on-board radio receptors have observed a great number of very-short quite-intense electrical impulsions. These impulsions are due to the impact of dust on the satellites of dust which sublimates as a consequence of the energy deposited and gets ionized by UV radiation from the Sun. The observed intensity and fluxes of these impacts have enabled to determine that they were in fact due to dust a few nanometers in size, accelerated by the interplanetary convection field to velocities close to that of the solar wind.

Physics of the Earth and planetary magnetospheres

Earth magnetosphere physics greatly benefited from the Cluster mission, the first real example of multi-satellite mission which inspired others such as MMS and THEMIS at NASA for example. This mission, still being exploited, helped to gain a great amount of knowledge on the global structure of the Earth's magnetosphere as an astrophysical prototype of the interaction between a low-collision supersonic plasma and a highly magnetized object itself possessing an internal source of plasma. The spatial distribution of the different regions of this magnetosphere and their dynamics are globally understood, even though fundamental questions remain on their interconnections (such as the physics behind the ionosphere-magnetosphere interaction in the auroral zone). Global simulations and their comparison with observations are also improving.

First observations of reconnection in giant vortices

The observations of the Cluster satellites have shown the mechanisms of magnetic reconnection in giant plasma vortices (approximately 40 000 km) localized on the sides of the Earth's magnetopause. These vortices are the result of



[Fig. 3]

Kelvin-Helmotz instabilities. They help solar wind penetration in the magnetosphere. These observations show that Kelvin-Helmotz instabilities and magnetic reconnection, which were until now identified as two distinct phenomena, can coexist under certain conditions.

First detection of a ring system around a planetary satellite

The MIMI experiment on the Cassini spacecraft showed the existence of a ring system around Rhea, Saturn's second biggest satellite after Titan. It is made of around 75% of water ice. Rhea's rings are made of solid particles measuring up to 1 m in equatorial orbit around the satellite, thus forming a disk. Their detection was made possible by the absorption signatures they induce on energetic electron populations in Saturn's magnetosphere, measured by MIMI in the vicinity of Rhea. This is the first detection of a ring system around a planetary satellite.

The mystery of the variable radio period of Saturn

Measurement of the internal rotation of giant planets is based on their magnetospheric radio emissions during auroras. For Jupiter the precision reaches 10^{-6}, but for Saturn the radio period measured by the RPWS radio receptor reveals variations of ±1% (±6 min on a timescale of ~10 h 40 min). Even though this variation of Saturn's radio period remains a mystery highly debated over by the scientific community, it was recently proved that solar wind speed variations around Saturn could partly be the cause of these variations. The imagery capabilities of RPWS are being used to try to measure the internal rotation, taking into account the effect of the solar wind.

Measurements of atmospheric escape rates

The measurements from Mars Express and Venus Express enabled to establish more precisely the general configuration of the magnetic obstacle induced by the interaction of the solar wind with the ionospheres of Mars and Venus. The first measurements of the escape rate of some ions proved that the atmospheric erosion phenomenon is real.

Coupling between mediums and physical processes

The major part of the visible Universe is found in the form of highly ionized plasmas. We now know that the dynamics and behavior of these plasmas are ruled by three major physical processes: shocks, magnetic reconnection and plasma turbulence.

Discovery of Alfvén vortices in space plasmas

Mechanisms behind energy dissipation from large down to small scales and ultimately towards constituent particles of low-collision plasmas are still unknown. Measurements performed on board the Cluster satellites in the polar cone and the magnetosheath allowed to discover and identify vortex structures at different scales. These structures, thought to be Alfvén vortices, could be primary components of the turbulence in magnetized plasmas and play a major role in particle, movement and energy transfers in these regions of the Earth's magnetosphere. More recently, such vortices were also observed in the magnetosheath of Jupiter thanks to observations from Cassini.

Space weather and Sun/climate relations

Effect of solar events on the Earth

A major magnetic storm occurred during a coordinated measure campaign (May 28–May 30, 2003) between the SOHO and Cluster satellites and the SuperDARN and EISCAT radars. The data that were acquired enabled to study the chronology and mechanisms of transmission of the various perturbations resulting from solar eruptions and associated coronal mass ejections: interplanetary shocks, magnetosphere compression, intensification of convection and ionospheric currents, up to the effect on the orbits of low-altitude satellites and GPS measures.

The Space Situational Awareness program of ESA

France confirmed at the ESA Ministerial Council on November 2008 its participation in the Space Situational Awareness program which includes a space weather element. The aim of this program is to establish a catalogue of currently orbiting satellites, to ensure the follow-up of space debris, to determine the impact of the space environment (space weather) and to monitor potentially dangerous asteroids for Earth.

Weather science will develop in Europe as a SHM field of study. The first step of this program (2009-2011) is to prepare a future operational system within ten years, which will be based mainly on existing ground means (solar telescopes, magnetometers, etc.) but which could also be completed by dedicated instruments on board commercial satellites.

Fig. 1*: Artist's impression of SOHO, dedicated to the study of the Sun and the heliosphere. It is a joint ESA/NASA mission that was launched on December 2, 1995.*
Fig. 2*: CME and coronal loops in action (April 9, 2010).*
Fig. 3*: Tridimensional reconstructions obtained thanks to STEREO.*

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Anthropogenic ionospheric perturbations observed by DEMETER.

Perturbations ionosphériques d'origine humaine observées par Déméter.

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Abstract

One of the scientific objectives of DEMETER is the study of ionospheric anomalies in relation with the anthropogenic activity. Its scientific payload consists of waves and plasma experiments. Flying over the inhabited continents during several years allows to record events which will be shown in this paper. Their analysis demonstrates that perturbations are observed in the ionosphere at the altitude of the satellite.

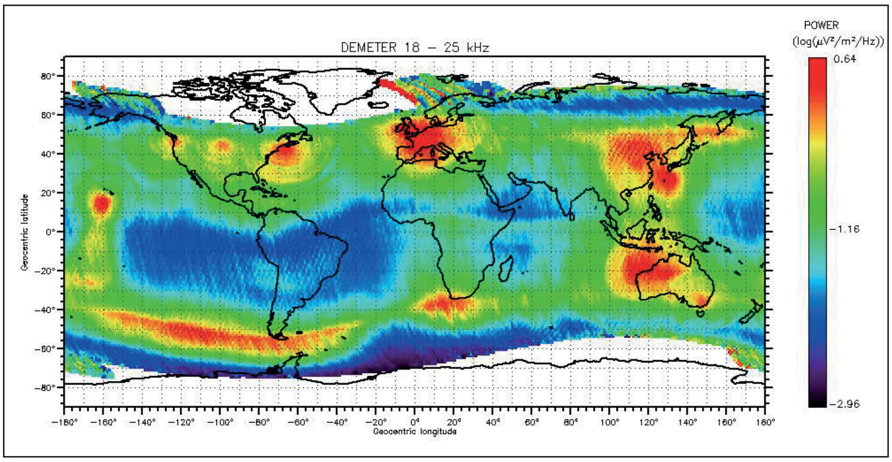
Un des objectifs principaux de Déméter est la recherche des perturbations ionosphériques qui peuvent être associées à l'activité humaine. Sa charge utile comporte des expériences ondes et plasma. Le survol des régions habitées pendant plusieurs années permet une étude d'événements développée dans cet article. Cette analyse montre que des perturbations sont observées dans l'ionosphère à l'altitude du satellite.

DEMETER is a micro-satellite (130 kg) with a low-altitude (660 km) and nearly polar orbit. It was launched by CNES in June 2004, and at the time of writing this paper (April 2010), it is still in operation. The orbit is nearly sun-synchronous (10.30 LT – 22.30 LT). The main scientific objectives of the DEMETER experiment are to study the disturbances of the ionosphere due to the seismo-electromagnetic effects, and due to anthropogenic activities (Power Line Harmonic Radiation, VLF transmitters, HF broadcasting stations). Its payload measures waves in different frequency ranges and also some important plasma parameters (ion composition, electron density and temperature, energetic particles). Data and plots are available through a web server (http://demeter.cnrs-orleans.fr) dedicated to the project.

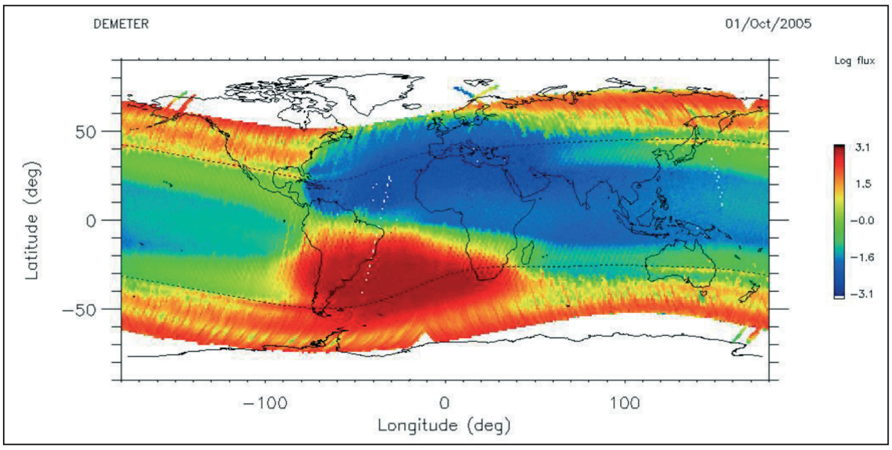
Waves induced by man-made activities

The Power Line Harmonic Radiation (PLHR) is made of ELF and VLF waves radiated by electric power systems at the harmonic frequencies of 50 Hz or 60 Hz. The PLHR propagation in the magnetosphere was first revealed by ground observations. Before DEMETER, direct observations by satellites were rather rare because their intensity in the ionosphere is weak unless they have been enhanced through a wave-particle interaction mechanism in the equatorial region. The frequencies of the lines always correspond to high order harmonics (>1 200 Hz) because they are the frequencies which are really emitted on ground. Due to both the complete Earth coverage of DEMETER and the duration of the mission, many events have been recorded. A systematic study of DEMETER observations of PLHR was performed. It showed that the frequency spacing of the lines corresponds well to the base power system frequency at possible generation regions. The observed lines very often drift in frequencies and are not exactly separated by 50 Hz or 60 Hz. They are called Magnetospheric Line Radiations (MLRs), and their generation mechanism is not well determined. One hypothesis is that they are most probably due to a nonlinear interaction between electrons and the coherent waves. The possibility that MLRs are due to PLHR has been discussed in Nemec *et al*. (2009) [1]. There are indications that PLHR influences the atmosphere-ionosphere-magnetosphere coupling. This problem requires serious attention because the electrical power consumption is always increasing in the world. Nonlinear interactions between electrons and PLHR can participate in the precipitation of electrons from the slot region into the radiation belts.

The VLF ground-based transmitters are mainly used for military communications. They emit waves at fixed frequencies which propagate in the Earth-ionosphere waveguide. But there are irregularities in the ionosphere and these waves can also be observed by satellite. Fig. 1 shows the locations of the main VLF transmitters. From left to right one can first see a peak in intensity in Hawaii where there is a VLF transmitter. In the region of the Americas, the peaks in intensity in the Northern Hemisphere correspond to the locations of three powerful VLF transmitters. The prominent VLF signal levels in the Southern Hemisphere conjugate regions are the corresponding signals that have propagated with substantial spreading in longitude. In Europe, there are also three powerful transmitters but they are relatively close to one another so that a single broad peak is observed. The corresponding Southern Hemisphere conjugate region of the European peak is also evident. Farther to the East, Australia is the only country in the Southern Hemisphere where there are two VLF transmitters, which both produce VLF peaks, together with the corresponding geo-magnetically conjugate regions. DEMETER has shown that there is a heating of the ionosphere above the most powerful transmitter: North-West Cape (NWC) in Australia [2]. The waves which cross the ionosphere and propagate in the opposite hemisphere can also perturb the particles in the radiation belts as it is shown by Sauvaud *et al*. (2008) [3] in Fig. 2. First, one can see an increase of the flux in the South Atlantic anomaly as expected because the intensity of the Earth's magnetic field is much lower at this location. Second, the effect of the VLF transmitter located on the North-West coast of Australia is clearly revealed. The precipitated electrons start to drift eastwards from the longitude of the transmitter in the Southern Hemisphere as well as in the Northern Hemisphere at the conjugate location and they follow the L = 1.7 lines.



[Fig. 1]



[Fig. 2]

Fig. 1*: Global map of the electric field intensity in a frequency band between 18 kHz and 25 kHz during night time. The data are an average of three years (2006-2007-2008). The intensity is colour-coded according to the scale on the right. Due to the operations, the plot is limited to invariant latitudes equal to 65° [2].*
Fig. 2*: Geographical distribution of the 200 keV electron flux measured by the particle detector onboard DEMETER. The dashed lines indicate when the L-value is equal to 1.7 at the satellite altitude [3].*

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RHESSI: X-ray/γ-ray diagnostics of particle acceleration in solar flares.

Rhessi : diagnostics X et γ des particules accélérées dans les éruptions solaires.

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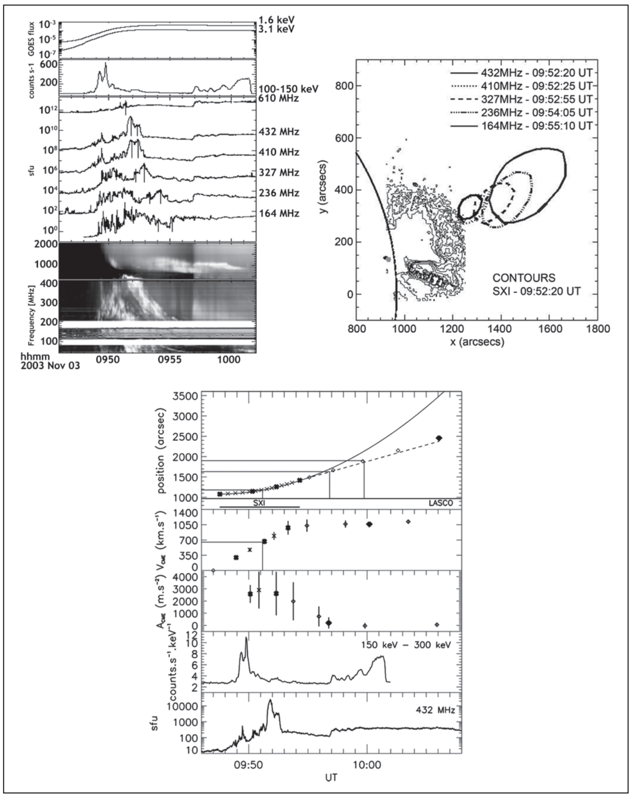
Abstract

The RHESSI mission, in orbit since February 2002, studies particle acceleration and energy release in solar flares through imaging spectroscopy of hard X-ray/gamma-ray continua emitted by energetic electrons and of gamma-ray lines emitted by energetic ions. We illustrate here some of the pioneering results obtained on the emitting sites of energetic electrons and ions and on the link between flares, particle acceleration, shocks and coronal mass ejections.

La mission Rhessi en orbite depuis février 2002 a pour but l'étude de la libération d'énergie magnétique et de l'accélération des particules dans les éruptions solaires grâce à des mesures de spectro-imagerie dans le continuum X/gamma et dans les raies gamma respectivement émis par les électrons et les ions énergétiques. Nous illustrons ici quelques résultats novateurs sur les sites d'émission des électrons et des ions et sur le lien entre éruptions, accélération de particules et éjection de masse coronale.

Before the launch of the Reuven Ramaty High-Energy Solar Spectroscopic Imager mission (RHESSI) [1], Hard X-Ray (HXR) and Gamma-Ray Line (GRL) observations had been obtained for two solar cycles. HXR emissions had been observed for thousands of flares and GRL emissions had been detected for some 30 flares, providing information on the number and energy spectra of electrons and ions accelerated in solar flares. However, both HXR and GRL spectroscopy were performed with limited spectral resolution: no spatially resolved observations were available for X-ray emissions above 100 keV (originating from Bremsstrahlung radiation of relativistic electrons in the solar atmosphere) neither for GRL emissions (from nuclear reactions of energetic ions with the solar atmosphere) so that no information was available on the location of the interaction sites with the atmosphere and emitting sites of energetic ions and electrons above 100 keV.

The RHESSI mission is designed to investigate particle acceleration and energy release in solar flares through imaging and spectroscopy of HXR and GR Bremsstrahlung continua emitted by energetic electrons and of GRLs produced by energetic ions. RHESSI provides unique observations of high-energy processes of the Sun and addresses the fundamental questions of particle acceleration. The instrument consists of an imager made of nine bi-grid rotating modulation collimators in front of a



[Fig. 1]

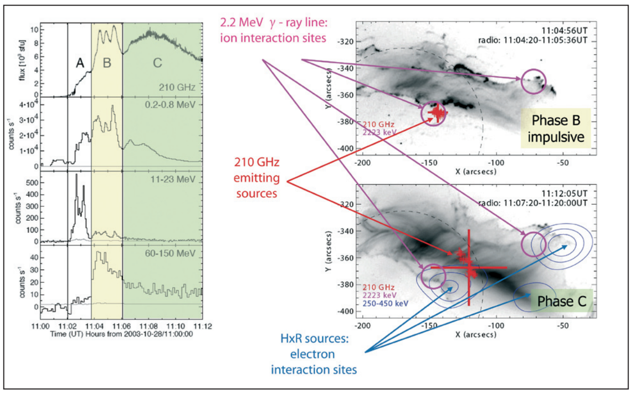
spectrometer made of nine cooled germanium detectors. It provides observations in the broad energy range from soft X-rays (3 keV) to gamma-rays (17 MeV). The spatial resolution depends on the photon energy (from 2 arcsec at low energies to 36 arcsec in the MeV domain) with a full Sun field of view. The energy resolution ranges from less than 1 keV at low energies, to 5 keV at 5 MeV. RHESSI has observed more than 50 000 events, with 30 events above 300 keV, and 29 events with GRL emission. A review of the results obtained with the RHESSI mission will be presented in a dedicated volume of Space Science Reviews [2]. We highlight here two results obtained by French members of the RHESSI team.

Electron acceleration and Coronal Mass Ejection (CME) dynamics

The association between flares and CMEs (large-scale magnetically-structured plasmas expelled from the Sun) has given rise to a hot and controversial debate. CMEs sometimes occur without flares and vice versa, but the largest flares tend to be associated with fast and energetic CMEs. Several studies combining RHESSI observations of HXR flares with coronagraph observations show that the CME acceleration profile and the electron acceleration phase revealed by strong HXR emissions are strongly coupled. This is shown at the bottom of Fig. 1 [3] where a good temporal association is found between the acceleration phase of a soft X-ray rising loop (Fig. 1 right) associated with the onset of a CME and the HXR emission observed by RHESSI above 150 keV. This observation thus supports models which predict a strong magnetic connection between the initiation and early acceleration of the CME and the energy release in the associated flare.

High energy relativistic electrons and ions: γ-ray and sub-millimeter observations

The very intense gamma-ray flare of October 28, 2003 (Fig. 2) produced emissions observed at energies above 60 MeV with RHESSI and the SONG experiment on Coronas-F. It exhibited the typical signature at energies above 60 MeV of radiation arising from the decay of π_0 mesons (*i.e.* indicative of the production of more than 200 MeV/nuc ions in the solar atmosphere) [4]. This high energy flare was associated with sub-millimeter emission above 200 GHz [5]. Furthermore, a strong increase of the radio flux between 200 GHz and 400 GHz was observed showing that this radiation is not linked to the radio synchrotron emission seen at lower frequencies. Fig. 2 [6] shows that the onset of the impulsive component of the sub-millimeter emission (phase B) is simultaneous with the start of the radiation above 60 MeV, *i.e.* the start of more than 200 MeV/nuc ion acceleration. The 210 GHz source size is compact (<10 arcsec) in this phase and its location is co-spatial with the site of interacting ions (revealed by the 2.2 MeV line emission site) but not the site of interacting electrons. In phase C, when no impulsive sub-millimeter emission and no strong emission above 60 MeV are observed, the sub-millimeter sources are quite different. The close correlation in time and space of the impulsive sub-millimeter emission and of the strong production of neutral pions thus suggests that synchrotron emission from charged pion-decay positrons could be responsible for the sub-millimeter emission. However some discrepancy remains regarding the magnitude of the predicted emission. The origin of this sub-millimeter component thus remains a challenging topic of discussion.



[Fig. 2]

***Fig. 1**: from [3] Left: GOES/RHESSI X-ray fluxes, radio fluxes (Trieste and Nançay) and radio spectrum (PHOENIX and OSRA); Right: Contours of the radio sources and of the GOES/SXI image showing the soft X-ray loop. Bottom: Time evolution of the height, velocity, acceleration of the X-ray loop and CME and of the X-ray and radio fluxes.*
***Fig. 2**: from [6] Left: 210 GHz sub-millimeter radio flux (KOSMA) and X-ray/γ-ray fluxes (SONG/CORONA-F); Right: radio imaging at 210 GHz (red crosses), UV (background image from TRACE), X-rays and gamma-rays from RHESSI (blue and purple contours from [7] in phase B and C showing respectively electron and ion interaction sites.*

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