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Solar radio bursts as a tool for space weather forecasting

Les sursauts radio solaires : un outil de prévision pour la météorologie de l'espace

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A B S T R A C T

The solar corona and its activity induce disturbances that may affect the space environment of the Earth. Noticeable disturbances come from coronal mass ejections (CMEs), which are large-scale ejections of plasma and magnetic fields from the solar corona, and solar energetic particles (SEPs). These particles are accelerated during the explosive variation of the coronal magnetic field or at the shock wave driven by a fast CME. In this contribution, it is illustrated how full Sun microwave observations can lead to (1) an estimate of CME speeds and of the arrival time of the CME at the Earth, (2) the prediction of SEP events attaining the Earth.

R É S U M É

La couronne solaire et son activité peuvent perturber l'environnement spatial de la Terre. Les éjections coronales de masse (CME) sont des instabilités à grande échelle qui conduisent à l'éjection dans l'espace interplanétaire du plasma et du champ magnétique qui le confine. D'autres perturbations viennent des particules solaires de haute énergie (SEP). Elles sont accélérées au cours de la variation explosive du champ magnétique ou par l'onde de choc qu'engendre une CME rapide. Dans cet article, on illustre comment des observations du Soleil entier en micro-ondes peuvent conduire (1) à estimer la vitesse d'une CME et son temps d'arrivée à la Terre, (2) à la prévision des événements solaires à particules qui atteignent la Terre.

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1. Introduction: solar activity and space weather

The solar corona is a plasma structured by magnetic fields. They emanate from the convective zone below the visible photosphere. Because of the ubiquitous plasma motions in this zone, magnetic fields continually emerge into the solar atmosphere and interact with already existing structures. This situation may lead to the storage and occasional explosive release of energy. The eruption of coronal magnetic structures into the interplanetary space – coronal mass ejections (CMEs) – and the release of charged particles with high, sometimes relativistic energies, are typical signatures. The solar energetic particles (SEPs) are accelerated from about 100 eV in the thermal corona to energies which on occasion may exceed 1 GeV for protons. This may happen in electric fields induced during the explosive variation of the coronal magnetic field or at the shock wave driven by a fast CME.

When intercepting the Earth, CMEs compress the magnetic field and transfer energy into the magnetosphere during a geomagnetic storm. The quantitative impact depends on whether or not the orientation of the magnetic field within and around the CME enables magnetic reconnection with the magnetic field of the Earth. There is therefore no unique parameter to describe the geo-effectivity of a CME. During a strong geomagnetic storm, the magnetopause, which is usually above 10 Earth radii above the ground at the subsolar point, can be pushed down to about 5 Earth radii. The dissipation of electrical currents induced in the ionosphere heats and ionises the high atmosphere in the polar regions, disturbing radio communications and the navigation of spacecraft and aircraft.

Energetic particles may create a supplementary strong ionisation of polar regions of the Earth's atmosphere and thereby perturb radio communications during several days. They may affect the functioning of spacecraft outside the Earth's magnetosphere or in polar orbits, launcher and space vehicle operations, and astronaut safety. Relativistic nucleons create secondary particles in the atmosphere that also cause ionisation and excess radiation, which may reach aircraft altitudes.

The effects of CMEs and SEPs on human activities are discussed in many publications. The reader is referred to [1] for a recent historical account, to [2] for a detailed discussion of extreme space weather events, and to, *e.g.*, [3] for an overview of the physical processes involved in Sun–Earth interactions.

Methods to alert about the arrival of solar disturbances in the space environment of the Earth are potentially useful tools to mitigate hazards. The travel times of CMEs to the Earth range from about 15 h [4] to a few days. Protons of a few tens of MeV travel the distance within a few tens of minutes. These are typical advance warning times when the alert is triggered by one of the early signatures of the eruption, for instance electromagnetic emissions. Longer warning times could be envisaged if one understood the details of the eruption process and its precursors. But no operational scheme of this kind could be devised so far.

In this contribution, two aspects of radio emission as a forecasting tool will be illustrated, namely the arrival of coronal mass ejections and of energetic particles at 1 AU. We start with the description of a simple scenario of solar eruptive activity.

2. Solar eruptions, radio emission, and space weather

Transient enhancements of solar radio emission, called radio bursts, are generated when electrons are accelerated to energies well above their thermal energy in the quiet corona. The cartoons of Fig. 1 depict major features of a magnetic eruption in the solar corona, which leads to a coronal mass ejection (CME) and a flare. The pre-eruptive configuration (Fig. 1a) is a current-carrying magnetic flux rope, defined by the helicoidal magnetic field lines within the flux rope (light blue) and around (black). The Lorentz force of this configuration is directed upward, since the magnetic field lines are more densely packed below the flux rope than above. The upward Lorentz force is balanced in equilibrium by the downward-directed Lorentz force exerted by the surrounding coronal magnetic field, whose field lines are plotted in orange. An excess upward force can be generated for instance when plasma motions in the photosphere twist the magnetic field in one foot of the flux rope. When this happens, the flux rope is lifted by the Lorentz force (Fig. 1b), ambient coronal plasma and the embedded magnetic field are convected from both sides towards the region where it was located before, and oppositely directed magnetic fields can reconnect. This is illustrated in Fig. 1b and c for two field lines, with the reconnection happening in a limited region schematically indicated by the yellow symbol of an explosion. New magnetic field is then added to the flux rope (the upper part of the field line drawn in red colour), and new magnetic loops form in the low corona.

A 2D projection of this situation is depicted in Fig. 1d, together with the consequences of the magnetic reconnection: charged particles accelerated in transient electric fields induced in and around the reconnection region, and electromagnetic emissions excited by these particles in different regions of the erupting configuration. Hard X-rays and gamma-rays are generated respectively by electrons and ions through collisional processes, which are most efficient in the dense low atmosphere. Radio emission is generated by energetic electrons in different regions. Microwaves are mostly gyro-synchrotron emission of electrons with energies of hundreds of keV to a few MeV in the newly reconnected loops below the CME (Fig. 1c, d), which contain also hot plasma emitting soft X-rays.

Fig. 2 is an illustration of full-Sun soft X-ray and radio emission during a major solar flare/CME. The soft X-ray emission in the bottom panel shows the slowly evolving thermal plasma: the sudden heating from about two million to above ten million K leads to the sudden rise, followed by a slow decay, which may last several hours. The top panel shows radio emission. Microwave frequencies (*e.g.*, 8800 MHz) are of interest in the following.