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C. R. Physique 19 (2018) 36–42

Contents lists available at ScienceDirect

Comptes Rendus Physique

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Radio Science for Humanity/Radiosciences au service de l'humanité

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

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ARTICLE INFO

Keywords:
Sun: particle emission
Sun: radio radiation
Sun: coronal mass ejection
Solar–terrestrial relations

Mots-clés :
Soleil : émission de particules
Soleil : émissions radio
Soleil : éjection coronale de masse
Relations Soleil-Terre

ABSTRACT

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.

RÉSUMÉ

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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https://doi.org/10.1016/j.crhy.2018.01.005

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.

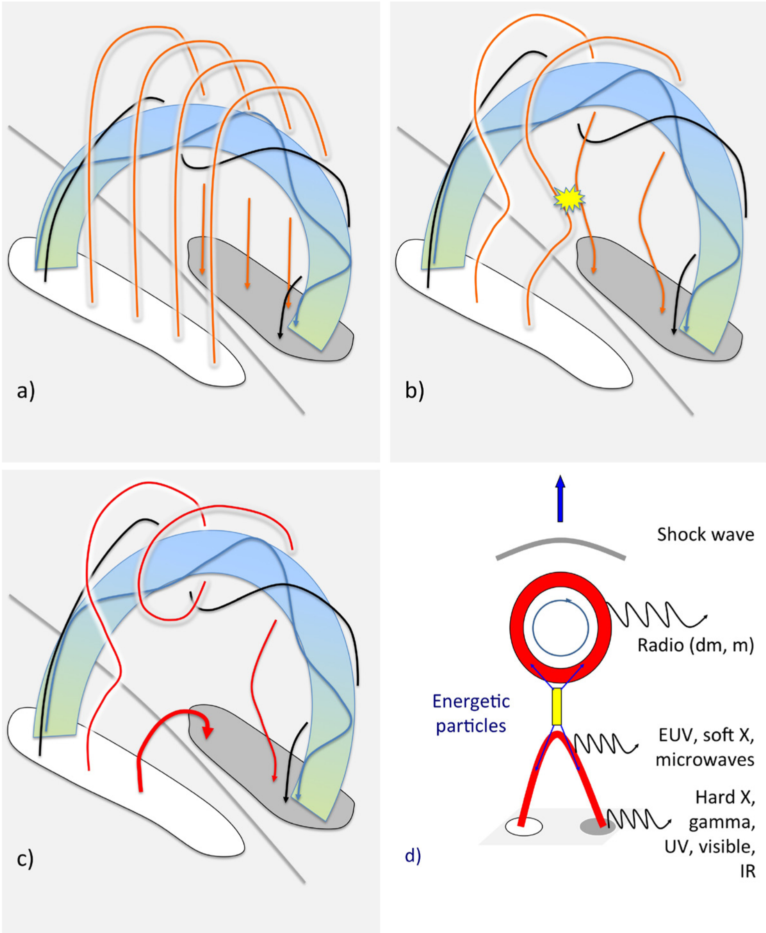

Fig. 1. Cartoon scenario of the magnetic field configuration around a magnetic flux rope in the solar corona (a), and of its evolution during the liftoff of a coronal mass ejection (CME; b, c). The white and grey-shaded areas indicate opposite magnetic polarities in the photosphere, the grey line is the line where the vertical photospheric magnetic field is zero. Figure (d) shows a two-dimensional cut of (c). From [5].

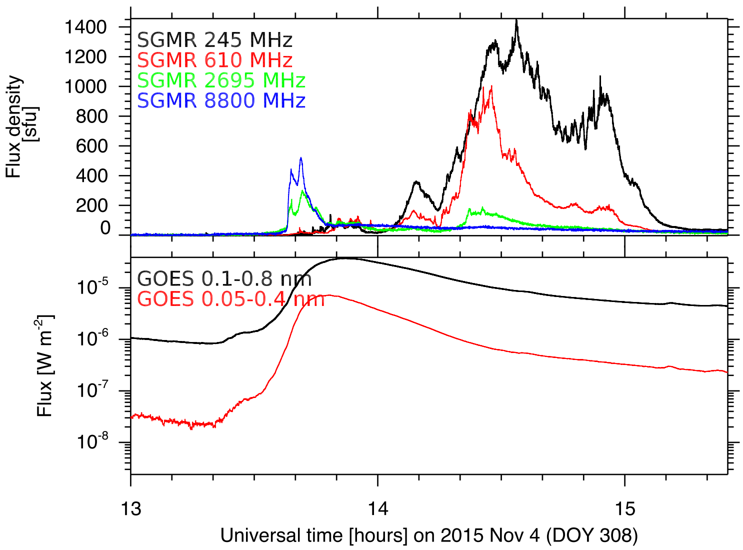

Fig. 2. Time history of whole-Sun X-ray and radio emissions during a solar flare/CME event. *Bottom*: soft X-rays in two wavelength ranges (GOES satellites, NOAA). *Top*: radio waves at selected frequencies (RSTN, US Air Force). From Marqué et al. (2017, submitted to *Journal of Space Weather and Space Climate*).

The close relationship between the CME liftoff, particle acceleration and electromagnetic emissions sketched in Fig. 1 suggests that one might use one phenomenon that is easy to observe or is an early signature of the eruptive event to infer information on the other. We focus below on the use of microwaves to forecast CME speed and the probability of SEP events.

3. Radio emission as a space weather forecasting tool

3.1. Speeds and interplanetary propagation times of coronal mass ejections

CMEs are usually observed in white light by coronagraphs, which artificially occult the bright emission of the solar disk. CMEs can hence only be observed in projection onto the plane of the sky. Those travelling at about right angles from the line of sight are readily visible, and their propagation speed can be easily measured by localising the front of the CME in successive images. It is much more difficult to discern CMEs that propagate along the line of sight. Observing earthward-propagating CMEs with a coronagraph on the Sun–Earth line, such as the LASCO instrument aboard the SoHO mission (ESA/NASA), is hence intrinsically difficult. No direct measurement of the earthward speed of such a CME can be obtained with the classical coronographic observing technique.

We established an empirical relationship between the speed of CMEs originating near the solar limb and the fluence of the associated soft X-ray [6] and microwave bursts [7]. The CME speed was measured in the coronographic images from SoHO/LASCO [8], and is available in the CME catalogue generated and maintained at the CDAW Data Center by NASA and The Catholic University of America, in cooperation with the Naval Research Laboratory.[1] Since the CMEs originate near the solar limb, one can assume that they propagate at angles near 90° with the line of sight, and that their speed can be measured with little distortion by foreshortening. The microwave data were provided by the four ground-based RSTN observatories.[2] The comparison of the data sets shows a correlation, with broad scatter, between the microwave fluence, especially at the higher frequencies (*e.g.*, 8800 MHz), and the CME speed in the plane of the sky. Such a relationship had been found by others, albeit rarely with a well-defined selection of limb-CMEs. It is not just empirical, but reflects the physical link between CME acceleration, plasma heating and electron acceleration below the rising flux rope in the cartoon scenario of Fig. 1. A quantitative analysis of the physical relationship between soft X-ray flux and CME speed in such a model was conducted by [9]. The derived empirical relationship now allows us to estimate a CME speed when we know the fluence of the soft X-ray or microwave burst. This is especially possible when the CME propagates earthward, because then the burst source is expected to be near the centre of the solar disk, and well visible from the Earth.

It is well known from past observations that fast CMEs in the corona, with a speed well above typical solar wind speeds (~ 400 km·s^{-1}), decelerate during their interplanetary propagation. This is due to the accumulation of plasma in front of the outward-propagating magnetic obstacle. Empirically, the deceleration was related in a linear way to the initial speed of the CME by [10]. We fed the CME speed inferred from the microwave and soft X-ray fluences to this empirical law to predict the arrival times at the Earth's orbit of eleven Earth-directed CMEs originating on the solar disk. The predicted arrival times were compared with those derived from the in situ measurements of the plasma and magnetic field parameters. The magnetic structure is often preceded by a shock wave and a turbulent sheath plasma behind it.

The predicted and observed CME arrival times are compared in Fig. 3. The solar events are ordered by the heliographic longitude where the CMEs originate. The ordinate shows the difference between predicted and observed arrival times. The zero value corresponds to the exact prediction, positive values to cases where the CME is observed to arrive before the predicted time. The black vertical lines show the time intervals between the arrivals of the shock wave and the magnetic obstacle of the CME. The red horizontal lines mark prediction errors of ±12 h. The different symbols and colours distinguish the origin of the CME speed estimate: microwave fluence at 9 GHz (red filled squares), soft X-ray fluence (green asterisks), and an empirically corrected speed derived from coronographic observations (blue filled circles). The predictions using soft X-rays and microwaves are of comparable quality. Notable features are that (1) on average the CME arrival is predicted too early (bias towards the lower half of the figure), and (2) the predictions tend to be better for CMEs originating from the western solar hemisphere (right part of the figure). This is not a coincidence: a detailed analysis shows that, in most cases (7/11), the Earth intercepts the flank of the CME (events labelled "F"), and only in four events is the vicinity of the nose seen by the spacecraft (events labelled "N"). At the time when the flank is detected at the Earth, the nose is already beyond the Earth's orbit. This is consistent with the early prediction. The systematic relationship between the early arrival and the eastern heliographic longitude of the parent activity suggests furthermore that the prediction can be corrected. A detailed description of this work is in [7]. The comparison with other prediction methods and with the observations shows that soft X-ray or microwave fluence is a valuable tool to predict the CME arrival, with the supplementary advantage that these fluences are known at the time when the CME is still behind the occulting disk of contemporary coronographs. The first warning can hence be issued very early, when the CME is still close to the Sun.

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[1] http://cdaw.gsfc.nasa.gov/CME_list/index.html.

[2] https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-radio/rstn-1-second/.

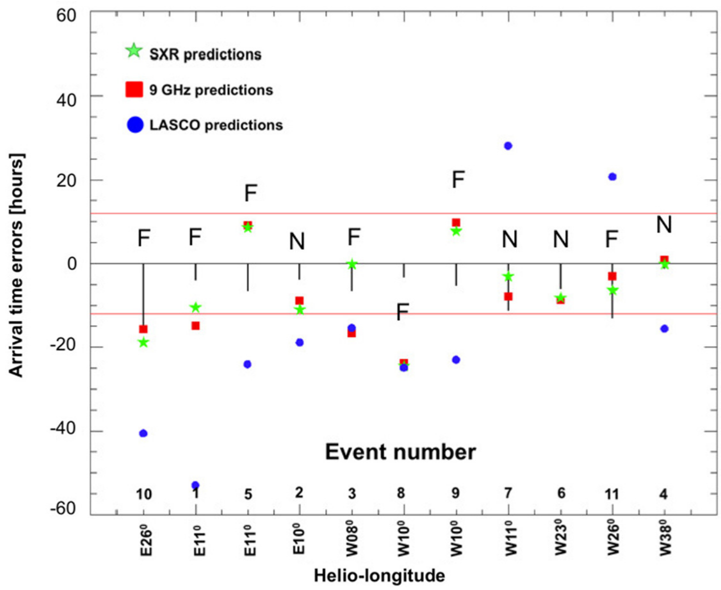

Fig. 3. Difference between observed and predicted CME arrival times at the Earth for eleven CMEs ordered by the heliographic longitude of their origin. From [7].

3.2. Solar energetic particle (SEP) events

SEP events are associated with solar flares and CMEs, which we collectively call eruptive events in the following. The only practicable forecasting strategy is presently to infer the SEPs to come from the first observations of the eruptive activity in the corona. Several different but complementary approaches have been developed.

The UMASEP scheme, developed at the University of Málaga [11], combines the monitoring of solar soft X-ray emission and of solar protons at energies between a few MeV and a few hundreds of MeV, using GOES measurements. Simultaneous rises in the soft X-ray flux and the particle intensity are considered as an indicator that an SEP event is to occur. We conducted an exploratory study to see if the soft X-ray data can be replaced or complemented by microwave observations referring to the gyrosynchrotron emission of mildly relativistic electrons accelerated in the associated flare. The motivation is twofold: from a physics viewpoint, microwave emission produced by non-thermal electrons may be expected to be more closely related to SEP acceleration than soft X-rays, which are emitted by the plasma heated during the solar eruption. From an empirical viewpoint, the derivative of the soft X-ray time profile is known to mimic the time profile of microwave emission from non-thermal electrons [12]. This can be seen during the soft X-ray burst in the bottom panel of Fig. 2. The microwave emission (first burst) is strong during the rise, and has decayed to background near the maximum of the soft X-ray burst in the (0.1–0.8) nm band.

We constructed an uninterrupted series of microwave flux densities at 4995 and 8800 MHz during a 13-months interval from December 2011 to December 2012. The input data were the daily light curves observed at the four RSTN observatories. Data were cleaned such as to reduce discontinuities at the transition between two observatories, which are due to calibration problems, incorrect antenna pointing and other instrument failures. The light curves are shown in Fig. 4. Numerous solar bursts are visible. During this period nine SEP events with origin on the western hemisphere were detected by the GOES satellites. The microwave time profiles were fed to the UMASEP prediction scheme instead of the soft X-ray derivative. The key findings for this thirteen months period with nine SEP events are summarised as follows.

- The probability of detection (POD) is 7/9 events. It is the same as in the traditional UMASEP scheme, where the derivative of the soft X-ray time profile is correlated with the SEP intensity.
- The false alarm rate (FAR) is zero for the microwave data at both frequencies considered, 1/8 when soft X-rays are used.
- The warning time, *i.e.* the time between the forecast and the instant where the SEP intensity exceeds the official event threshold used by NOAA, is slightly improved with the microwave light curves over the soft X-rays (30.7 *vs.* 26.4 min).

This shows that microwave data improve the prediction, especially because they are rarer phenomena than soft X-ray bursts. The soft X-ray bursts reveal the heating of coronal plasma during a flare – a process that may or may not be accompanied by particle acceleration. Major microwave bursts need the acceleration of electrons to relativistic energies. Using microwave bursts therefore avoids numerous small and purely thermal fluctuations of the soft X-ray emission. It is to be noted, however, that a few moderately strong SEP events are not related to conspicuous particle acceleration in flaring

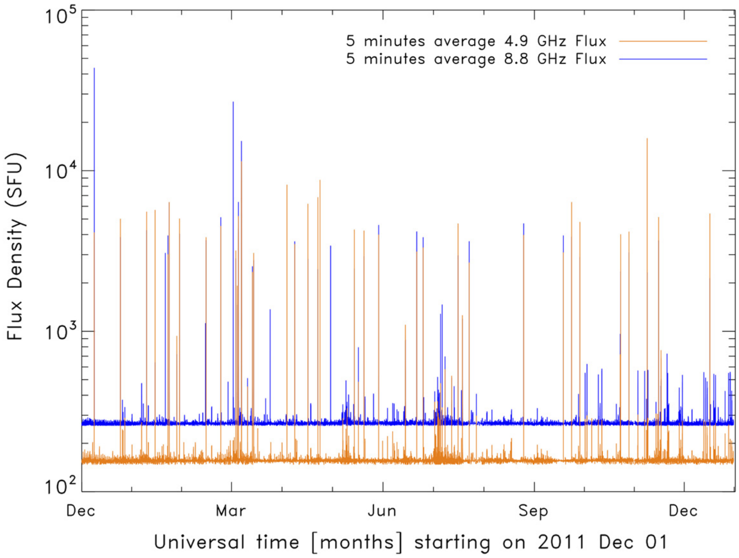

Fig. 4. Time profile of the whole Sun microwave emission during 13 months, composed from daily observations of the four RSTN observing stations of the US Air Force. From [13].

active regions, and may be missed by a prediction that relies only on non-thermal microwave bursts. The details of this study conducted in collaboration with the University of Málaga can be found in [13].

4. Discussion and conclusion

It has been known since the 1950s that solar radio bursts are closely related to interplanetary plasma disturbances and energetic particles (see [14] for a review). But the advent and easy availability of soft X-ray monitoring with the GOES satellites operated by NOAA has diminished the interest for this aspect of radio monitoring. The US Air Force is the only institution to provide 24-h monitoring of the Sun, using four stations around the Earth. These radio observations are conducted with rather simple patrol instruments, which monitor the whole Sun flux density using parabolic antennas with a typical size of 1 m. Such data are presently not provided in real time, but there is no technical obstacle to do so. If a reliable calibration and stable and reliable antenna operations can be achieved, microwave patrol observations appear to be a significant addition to our ability to forecast the occurrence of SEP events and the interplanetary travel times of CMEs. In addition to being easy to handle and relatively cheap, radio observations have the advantage that the instruments are protected by the Earth's atmosphere and magnetosphere against space weather hazards.

Acknowledgements

This work was supported by the ANR/ASTRID project ORME (*Observations radio astronomiques pour la météorologie de l'espace*, contract No. ANR-14-ASTR-0027), by the HESPERIA project, funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 637324, and by the “Centre National d'Etudes Spatiales” (CNES) (grant No. W-EEXP/10-01-01-05).

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