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PROBING MATTER WITH ELECTROMAGNETIC WAVES

Radio Observations of the Sun for Space Weather Purposes

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Abstract
This contribution illustrates how radio astronomical observations contribute to space weather research and operations. We will especially show how they indicate if solar energetic particles escape to the interplanetary space, and can be a hazard for the space environment of the Earth, or whether they remain confined in magnetic fields of the low corona. We argue that the utilisation of radio astronomical techniques would provide advantages for space weather warnings as compared to space-based methods, which are presently widely employed in forecasting approaches: (1) radio observations are carried out from the Earth over a large range of frequencies, which makes the equipment less vulnerable to space weather events than space borne observations; (2) relevant radio observations monitoring the whole Sun can be carried out with inexpensive equipment that can be purchased from shelve. The exploration of radio astronomical methods for space weather is the aim of the ORME project, which will be conducted in cooperation between Paris Observatory and the University of Orléans, with funding from the *Agence Nationale de la Recherche*.

Introduction
The Sun, and particularly its outer atmosphere, the corona, is a source of high-energy electromagnetic emissions (EUV, X-rays) and of energetic electrically charged particles. These emissions cannot be detected on the ground, because EUV and X-rays are absorbed in the Earth's atmosphere, while charged particles are reflected by the magnetic field into interplanetary space. But these shields of the Earth do not protect spacecraft above the absorbing atmospheric layers or outside the magnetic field of the Earth, and charged particles still can penetrate into the atmosphere in the polar regions.

Solar emissions in the above ranges can be strongly amplified during eruptive events: solar flares are transient enhancements of the electromagnetic spectrum, in particular EUV, X-rays and radio waves, while during coronal mass ejections (CMEs) matter is ejected together with the confining magnetic field. During these processes coronal plasma is heated, and charged particles are accelerated sometimes to orders of magnitude above their average energy of a few hundred eV in the million-degree-corona. When they escape from the corona, they are called solar energetic particles.

The term space weather comprises phenomena in the Earth's space environment that affect technology and human beings. The drivers are energetic photons, energetic charged particles or magnetic field configurations in regions that are not or not completely protected by the atmosphere or the magnetic field of the Earth. Prediction of the impact of solar disturbances would be of great potential importance if alerts could be emitted with a sufficient advance warning time and a low false alarm rate. As of today, it is not possible to predict that an eruptive solar event will occur within a given time lapse in the future. However, one can aim at using the first observable signatures of an eruptive event to predict the arrival near the Earth of solar energetic particles or a CME. The first signature of an eruptive event is electromagnetic radiation. This could provide advance warning times of about an hour for particles at 10 MeV, and of a day or more for CMEs. But it is not only the warning of an incoming event that is important. A reliable prediction that no major disturbance is expected in the near future is also a relevant piece of information. The present contribution aims at showing that radio observations are a valuable diagnostic tool for space weather purposes.

1. Radio observations of the Sun and Space Weather
1.1. Solar radio bursts
Radio observations of the Sun are routinely carried out from ground, at frequencies between 20 MHz – the ionospheric cutoff - and a few tens of GHz. Most observations are made with small antennas having the whole Sun in their field of

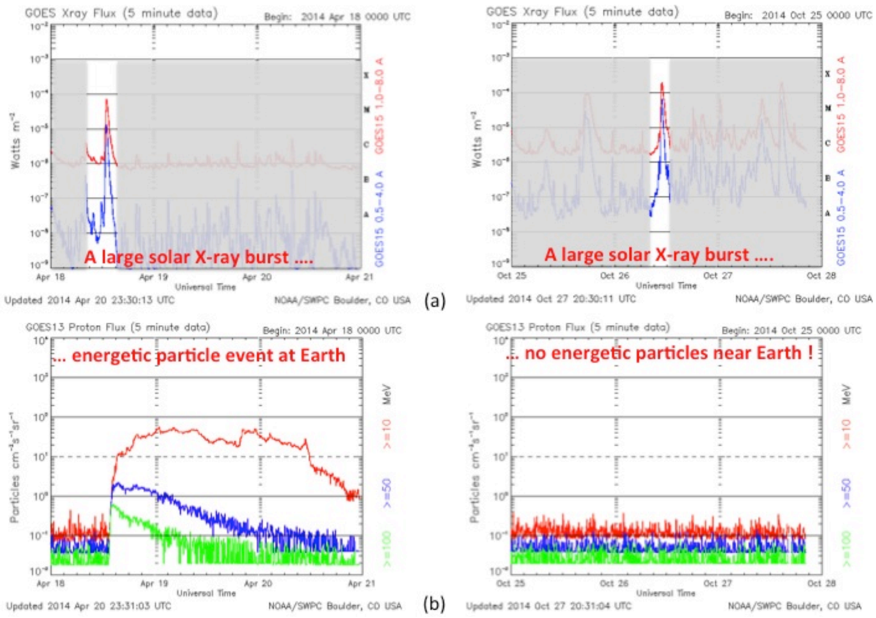

Figure 1: Time histories of the soft X-ray emission at the Sun (a) and of the energetic proton intensity measured at geostationary orbit (b) during two different three-day periods. The left column shows an X-ray burst associated with a strong solar energetic particle event on 18 April 2014. The right column shows a similarly strong X-ray burst on 26 October 2014, but no particle event was observed at Earth. Plots provided by NOAA (USA) via http://www.solarmonitor.org .

view. These instruments provide spectrographic observations characterising transient solar emissions, i.e. radio bursts. A few solar-dedicated imaging instruments are in operation, including the radioheliographs in Nançay (France, 150-450 MHz), Gauribidanur (India, 40-150 MHz), Siberia (6 GHz) and Nobeyama (Japan, 17 and 34 GHz). A radioheliograph operating beween 400 MHz and 15 GHz is in the commissioning phase in China. Additionally large general purpose telescopes like the *Very Large Array* (USA), the *Giant Metre Wave* Telescope (GMRT, India), the Low *Frequency Array* (LOFAR, Netherlands) or the *Murchison Widefield Array* (MWA, Australia) carry out occasional observations of the Sun.

Solar radio emission comes from the atmosphere of the Sun, overlying the photosphere that emits the visible light. Roughly speaking the height of the emission increases with decreasing frequency. The spectrum of solar radio bursts can roughly be divided into two regions: at microwaves (frequencies ν>1 GHz) the spectrum is broadband due to the dominance of gyro-synchrotron emission of near-relativistic electrons (energies 100 keV to several MeV). At frequencies below 1 GHz, the details of the radio spectrum offer unique diagnostics of key processes of eruptive solar activity, traced by energetic electrons (typically a few keV to a few tens of keV): electron beams that propagate through the corona and interplanetary space, shock waves, and confined energetic electron populations in coronal magnetic structures, especially in coronal mass ejections. By combining ground-based and space borne (ν<20 MHz) radio spectrography one can follow transient features like electron beams and shock waves from the Sun (frequency range 20-1000 MHz) to the Earth (emission at some tens of kHz). Radio bursts hence probe key features of space weather. This will be illustrated in the following for solar energetic particle events.

1.2. An illustration: solar energetic particle events

Protons and other particles that are transiently accelerated during solar eruptive events can reach the interplanetary space and the Earth. Very high energy particles or those which reach the Earth at high latitudes, propagating nearly parallel to the terrestrial magnetic field lines, are not repelled and can penetrate into the atmosphere. There they generate cascades of secondary particles by nuclear reactions with the atmospheric constituents. Solar energetic particle events are transient enhancements of the particle intensity, lasting between some hours and several days, associated with eruptive solar activity. The charged particles reach the Earth rapidly when there is a magnetic connection with the acceleration region. Protons with energy 10 MeV have an interplanetary travel time of about an hour.

Figure 1 shows two examples of major solar flares, traced by their soft X-ray emission (wavelengths 0.1-0.8 nm; Fig. 1a). The bottom panels (Fig. 1b) show simultaneous measurements of the energetic proton intensity at geostationary orbit, by the *Geosynchronous Orbiting Environmental Satellites* (GOES) operated by the National Oceanic and Atmospheric Administration (NOAA, USA). The three curves refer to three energy ranges: above 10 MeV (red), above 50 MeV

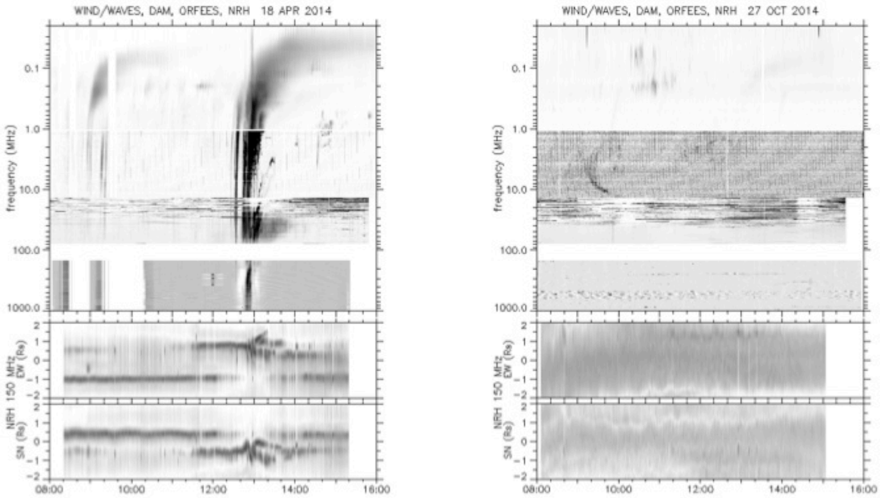

Figure 2: Radio observations at the times of the two X-ray bursts in Fig. 1. The two lower panels show the spatial evolution of the radio emission, projected onto the solar south-north and east-west directions. The upper panels display the dynamic spectrograms between some kHz and 1000 MHz (bright emission represented by dark shading). The left figure shows a prominent radio burst, while no such burst is seen in the right figure. Data from the Nançay radio observatory and from the WAVES experiment aboard the *Wind* spacecraft. Figures provided by http://radio-monitoring.obspm.fr/ .

(blue), and above 100 MeV (green). The left panel shows a conspicuous SEP event, with an enhancement of the proton intensity by up to 2-3 orders of magnitude over quiet-time values. The X-ray burst in the right panel is similarly strong, but no particle event is detected with it. This is the case although both solar events are located at a place from where the particles could reach the Earth along the interplanetary magnetic field. They do so in one event, but not in the other.

A warning system able to distinguish the two situations would be a valuable space weather service. X-ray emission clearly does not make the distinction. Figure 2 shows radio emissions from the corona during several hours around the two X-ray bursts of Fig. 1. The two bottom panels show the spatial evolution of the emission at 150 MHz, projected onto the solar south-north (bottom panel) and east-west directions. The other panels display the dynamic spectrum of the Sun between 1000 MHz and a few tens of kHz. The left panel shows a prominent radio burst covering the entire frequency spectrum. The emitters are energetic electrons. The bursts extending from hundreds of MHz to tens of kHz are produced by electron beams that propagate from the Sun to the vicinity of the Earth. They hence show that charged particles accelerated at the Sun do escape to the interplanetary space during this event. The spatial observations in the bottom panels show moving radio sources, indicative of a coronal mass ejection. In contrast, the second event (right panel) displays no such radio bursts, only quiet-Sun emission. The dark stripes in the spectrum between 20 and 80 MHz are most likely of ionospheric origin. The reason for the absence of radio emission is that electrons accelerated in the low corona during the flare do not escape to the overlying atmosphere and the interplanetary space, because they remain confined in closed magnetic structures of the low corona. There is no coronal mass ejection either which could accelerate particles higher up in the corona. This gives a consistent picture of two flares with comparable energy release as traced by the X-rays, but different conditions for the acceleration and propagation of energetic particles. The observation is consistent with earlier studies of our group [1, 2]. The radio emission is a valuable indicator that even a strong solar flare will not be accompanied by a solar particle event.

1.3. The Nançay Radio Observatory

The Nançay Radio Observatory, situated in central France, has a complementary set of instruments dedicated to solar observations: the Nançay Radioheliograph is unique as a dedicated imager of the corona at selected frequencies between 450 and 150 MHz, which corresponds roughly to a height range between 0.05 and 0.5 solar radii above the photosphere. Note that this is only a rough estimate, since the corona has no simple spherically symmetric structure. The Decametre Array makes spectrographic observations of the whole Sun between 10 and 80 MHz with unparalleled sensitivity. The ORFEES spectrograph, operating in the range 130-1000 MHz, entered operations in 2012 to complete the observational tools. It was built with financial support by the French Air Force. These three instruments provide a worldwide unique set of complementary observations of the Sun, which were illustrated at earlier French URSI meetings [3, 4]. While these instruments continue to play an important role in research, they are now also used to provide real-time data products for space weather services, especially for the space weather demonstrator project FEDOME of the Air Force.

Discussion

The use of radio diagnostics in space weather research and operations was widespread in the 1960s and 1970s, but has progressively decreased thereafter, mainly because soft X-ray patrol observations by the GOES satellites became readily available. In the meantime research on the relation between radio emission of eruptive solar activity and heliospheric consequences has been carried out notably in cooperation with the SoHO and STEREO missions. But systematic studies are necessary to establish empirical relationships usable in space weather forecasting. Data sets for doing this have been acquired in recent years using radio spectrographic and imaging observations in conjunction with coronography and EUV imaging from spacecraft, especially SoHO and STEREO.

A large part of the radio spectrum, ranging from frequencies between a few tens of GHz and about 10 MHz, can be observed from the Earth. This makes radio observations less vulnerable to space weather hazards than space borne techniques - a significant advantage especially in the presence of extreme solar events, which are the major unsettled threat in space weather. Radio spectrography can also be carried out by relatively simple instruments, which can be bought from shelve. For this reason it appears mandatory to evaluate methods for space weather forecasting that do not rely on space-borne detectors. The ORME project (*Outils radioastronomiques pour la météorologie de l'espace*) is a cooperation between Paris Observatory and the University of Orléans, which aims to exploit the large observational material collected in recent years through a systematic study of the relationship between solar radio bursts on the one hand, coronal mass ejections and solar energetic particles reaching the space environment of the Earth on the other. A particular effort will be dedicated to developing tools for the automated identification of space-weather relevant radio bursts in dynamic spectrograms. The characteristic shape in the frequency-time plane of the radio emission from electron beams, shock waves and CMEs will be used to develop algorithms. Interesting initial attempts were made in Australia [5, 6, 7]. The project is supported by the *Agence Nationale de la Recherche* (ANR).

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