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Diagnostics radio de l'accélération et du transport de particules dans la couronne solaire à l'époque de Solar Orbiter
Radio diagnostics of particle acceleration and transport in the solar corona in the Solar Orbiter era

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Soleil - accélération de particules - émission de particules; Sun - particle acceleration - particle emission.

Résumé/Abstract
Nous présentons deux études d'électrons accélérées dans des éruptions solaires par des instruments au sol et dans l'espace (satellites Fermi et Solar Orbiter). Le premier cas est une éruption où des particules relativistes produisent un sursaut gamma surprenant, visible depuis l'orbite terrestre alors que l'éruption se situe sur la face cachée du Soleil; l'autre cas est une éjection de masse où des électrons sont détectés dans l'espace bien après le début de l'éruption. Dans les deux cas nous décrivons comment la spectro-imagerie à Nançay aide à révéler des processus complexes d'accélération et propagation des particules dans des structures magnétiques à grande échelle de la couronne solaire.

We present combined observations of energetic nucleons and electrons accelerated in solar flares, using case studies of two events: one where relativistic particles are accelerated and produce a surprising signature visible from Earth orbit, although the flare itself occurred behind the solar limb; a second one, where energetic electrons are observed in space, but well after the start of the flare. In both cases we illustrate how spectrographic imaging at the Nançay Radio Observatory sheds light on complex processes of acceleration and propagation of the energetic particles in large-scale coronal magnetic structures.

1 Introduction

Heliophysics benefits presently from two space missions that approach the Sun, Parker Solar Probe (NASA) and Solar Orbiter (ESA/NASA). Both carry energetic particle detectors and full-Sun radio spectrographs at frequencies below about 15 MHz. The observation of energetic particles accelerated near the Sun from a vantage point that is closer than the Earth reduces the distortion of the time profiles and other properties that is produced by propagation through the turbulent interplanetary medium. Solar Orbiter has in addition EUV and X-ray instruments for remote-sensing imaging and spectroscopy of the plasma of the solar atmosphere where at least part of the particles are accelerated, and of non-thermal electrons interacting in the low solar atmosphere.The question how particles are accelerated at and near the Sun and how they escape and fill the Heliosphere is one of the key science issues.

In the present contribution we attempt to illustrate how these instruments are complemented by ground-based radio observations in the frequency range 1 GHz to some tens of MHz, close to the ionospheric cutoff. The Nançay Radio Observatory operates whole-Sun radio spectrographs in the range 1000-144 MHz (ORFEES; [1]) and 80-20 MHz (Nançay Decameter Array NDA; [3]) and an imager in the range 450-150 MHz (Nançay Radioheliograph NRH; [2]). We present two case studies to illustrate how they further our understanding of particle acceleration and transport in eruptive solar activity.

2 Radio observations of solar flares with the Nançay Radioheliograph.

Solar flares are abrupt releases of energy stored in coronal magnetic field configurations. They manifest themselves in plasma heating and the acceleration of electrons and protons to energies far in excess of the thermal energy in the corona of order 100-200 eV. In extreme cases protons or heavy nuclei can be accelerated to GeV energies. The manner in which this is achieved is still poorly understood, especially because it is difficult to address the back-reaction of the energetic particles on the magnetic field configuration. More observations are also needed to disentangle the role of different candidate accelerators, which exist simultaneously during the major events where such high energies are achieved. It is still widespread to consider the flare as a point-like event in space and time, where small-scale processes such as magnetic reconnection energise the plasma and accelerate particles, whereas large-scale coronal shock waves driven by massive coronal mass ejections accelerate particles over large spatial scales and are responsible for the most energetic particles encountered in space or even in the solar corona.

Relativistic solar particles in the solar atmosphere can be observed through their gamma-ray emission. Such an event was observed on 2022 Sep 29 by the Large-Area Telescope (LAT) of the Fermi mission (NASA), which orbits the Earth. Pesce-Rollins and coworkers [4] analysed its time profile and found it to be highly reminiscent of a few impulsive gamma-ray events observed on the visible solar disk. However, this particular burst came from an active region behind the solar limb as seen from the Earth, but within the field of view of Solar Orbiter. In the standard picture of a flare that is restricted to the active region, gamma-ray emission would not be visible from this event. When combining the gamma-ray observations with X-ray imaging from Solar Orbiter and radio spectral imaging from the Nançay Observatory, we show that the radio images reveal a large-scale magnetic structure bridging the solar limb and connecting the occulted active region with the visible disk. The gamma-ray emitting particles could thus travel away from the parent active region to a favourable place for being observed by Fermi. In this presentation we will discuss these observations and a plausible picture of particle acceleration and particle transport.

In a second illustration, we will consider the evolution of non-thermal electrons in an erupting magnetic flux rope, which is part of a coronal mass ejection. During this event the particle detector aboard Solar Orbiter observed energetic electrons in space, at a heliocentric distance of 0.64 times the Sun-Earth distance, but several tens of minutes after the start of the flare. Combined imaging with the Nançay Radioheliograph and spectrography with ORFEES shows how the electrons are initially confined in the erupting closed magnetic structure, and released to the Heliosphere in discrete processes well after the flare start, probably as the structure reconnects with neighbouring magnetic field lines that are open to the Heliosphere.

3 Conclusion

After 5 years of maintenance work the Nançay Radioheliograph resumed scientific observations in November 2020. While work on the instrument is pursued to enhance the sustainability of the observations until the end of the Solar Orbiter mission, ongoing research by our group and others demonstrates its continued usefulness as the worldwide unique dedicated solar imager in the 150-450 MHz range. Together with the full-Sun radio spectrographs of the Nançay Observatory it adds a considerable scientific value to the observations of the Solar Orbiter mission, because it covers an essential height range in the corona on the way of energetic particles from acceleration regions low in the eruptive active regions to the high corona and interplanetary space probed by the space-borne radio and particle instruments. The physical phenomena that we illustrate in this presentation – propagation of particles along and trapping within large-scale magnetic structures – are basic ingredients that must be considered when the origin of energetic particle populations that fill the Heliosphere is to be understood.

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