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PRESENTATION OF THE PROJECT "AN INVESTIGATION OF THE EARLY STAGES OF SOLAR ERUPTIONS – FROM REMOTE OBSERVATIONS TO ENERGETIC PARTICLES"

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Abstract: *Coronal mass ejections (CMEs), one of the most energetic manifestations of solar activity, are complex events, which combine multiple related phenomena occurring on the solar surface, in the extended solar atmosphere (corona), as well as in interplanetary space. We present here an outline of a new collaborative project between scientists from the Bulgarian Academy of Sciences (BAS), Bulgaria and the University of Graz, Austria. The goal of the this research project is to answer the following questions: 1) What are the properties of erupting filaments, CMEs, and CME-driven shock waves near the Sun, and of associated solar energetic particle (SEP) fluxes in interplanetary space? 2) How are these properties related to the coronal acceleration of SEPs? To achieve the scientific goals of this project, we will use remote solar observations with high spatial and temporal resolution to characterize the early stages of coronal eruption events in a systematic way – studying the pre-eruptive behavior of filaments and flares during energy build-up, the kinematics and morphology of CMEs and compressive shock waves, and the signatures of high energy non-thermal particles in both remote and in situ observations.*

ПРЕДСТАВЯНЕ НА ПРОЕКТ "ИЗСЛЕДВАНЕ НА РАННИТЕ СТАДИИ НА СЛЪНЧЕВИТЕ ИЗРИГВАНИЯ – ОТ ДИСТАНЦИОННИ НАБЛЮДЕНИЯ КЪМ ВИСОКОЕНЕРГЕТИЧНИ ЧАСТИЦИ"

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Ключови думи: *Коронални изхвърляния на маса, слънчеви високоенергетични частици, коронални ударни вълни, еруптивни влакна*

Резюме: *Короналните изхвърляния на маса (Coronal Mass Ejections – CME), едно от най-енергетичните проявления на слънчевата активност, са комплексни събития, съпътствани от множество свързани феномени върху слънчевата повърхност, в слънчевата атмосфера (короната), както и в междупланетното пространство. Тук представяме нов съвместен проект между учени от Българската академия на науките (БАН), България, и Университет "Карл-Франц", Грац, Австрия. Целта на представения проект е да отговори на следните въпроси: 1) Какви са свойствата на еруптивните протуберанси, короналните изхвърляния на маса и ударните вълни предизвикани от тях в близост до слънцето (в слънчевата корона), както и на произтичащите от тях потоци високоенергетични частици в междупланетното пространство? 2) Как са свързани тези свойства с ускорението на слънчеви високоенергетични частици в короната? За да изпълним научните цели на този проект, ще използваме дистанционни слънчеви наблюдения с висока времева и пространствена разделителна способност, за да изследваме най-ранните етапи на слънчевите изригвания по систематичен начин – като проучим пред-еруптивното поведение на протуберанси и избухвания в*

бяла светлина през периода на натрупване на енергия, а също кинематиката и морфологията на CME и компресивни ударни вълни, и свойствата на свързаните високоенергетични заредени частици в дистанционни и in situ наблюдения.

Introduction

Coronal mass ejections (CMEs) are impulsive eruptions of plasma and magnetic fields from the Sun that propagate in the heliosphere, and one of the main phenomena that affect space weather in the Solar system. They can influence the interplanetary environment over vast longitudinal and radial ranges by injecting fast solar wind plasma, increased magnetic flux, and highly energetic ions and electrons. Modeling studies suggest that these major solar eruptions are part of stellar activity in general, and they help determine the structure and dynamics of astrospheres. Our research project aims to investigate the connection between CME onset, early-stage dynamics, and the acceleration of highly energetic ions in solar eruptive events.

If they reach speeds in the solar corona higher than the local fast magnetosonic speeds, CMEs may drive magnetized shocks of varying strength and speeds. It has been suggested that high-energy charged particles, called solar energetic particles (SEPs), may be accelerated out of the coronal plasma population and may gain most of their energy (up to several hundred MeV) at such eruption-driven shocks relatively close to the Sun, within 10 Rsun [1]. In fact, observational studies show that such shocks and compressions capable of producing SEPs can form as low as 1.2 Rsun due to the rapid expansion and acceleration of the CMEs, but then subside higher in the corona (beyond 2–3 Rsun), where the CME acceleration slows [2].

Characterizing and predicting the early-stage acceleration and heliospheric propagation of CMEs and SEPs is of considerable interest to heliophysics. CMEs disturb the interplanetary conditions and can drive strong geomagnetic storms at Earth if they reach the terrestrial environment. SEPs probe the magnetic conditions in the solar system, but also present a significant radiation damage risk to astronauts and spacecraft situated beyond low-earth orbit. The period between onset of a solar eruption and arrival of SEP fluxes of harmful energies to 1 Astronomical Unit (AU) is generally on the order of several hours, which is often very short time to warn astronauts and spacecraft operators. Thus, an important applied goal of heliospheric research is developing a capability to estimate and forecast interplanetary SEP fluxes and CME events as early as possible after their onset.

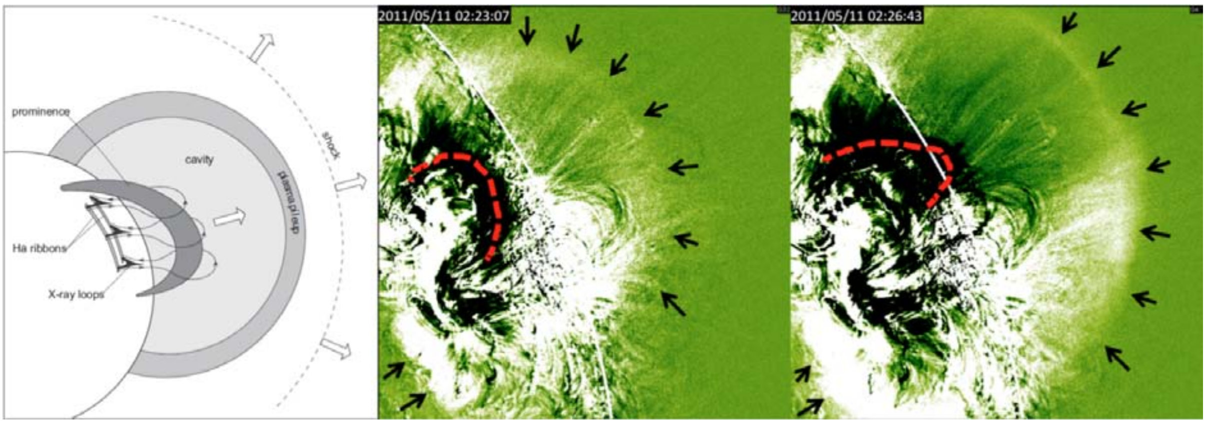

Fig. 1. A diagram of a canonical solar eruption from [6] showing the prominence lift-off, driving the plasma pile-up and shock wave. The pile-up and shock are shown separated. (Center and Right) Two snapshots from a solar eruption imaged by SDO/AIA, with the EUV wave brightening outlined by arrows, and the erupting prominence marked with a red dashed line. The flare emission is seen as bright EUV emission below the prominence. Adapted from [7].

Eruptive filaments (also known as eruptive prominences or EP) are often associated with CMEs and play an important role in their initiation. A common pattern of typical filament eruptions consists of: pre-eruption activation, followed by an initial slow-rise phase, during which the filament gradually ascends; then an abrupt transition to a fast-rise phase of acceleration, and a final gradual evolution characterised by little change of speed or morphology. In many events, the impulsive acceleration of the eruptive structure occurs closely synchronized with the energy release and particle acceleration in the associated flare [3]. While the detailed mechanisms responsible for the triggering and driving of the eruption are not fully understood [4], the specific characteristics of the eruptions may well provide early diagnostics of CME triggers and behavior. Thus, detailed knowledge of the early evolution of CMEs and accompanying phenomena (flares, shocks) is essential for better understanding of their role in accelerating SEPs.

The initial properties of eruption drivers – such as orientation and initial velocity – may influence significantly their interaction with the corona, whether and where shocks may form, and how energetic particles are produced. While it is known that large SEP events correlate with fast interplanetary CMEs, and modeling has shown that flux rope overexpansion should cause the formation of coronal shock waves, it is not presently known to what extent the speed profiles of eruptions lower in the corona influence particle acceleration, or how much overexpansion is necessary to drive strong enough coronal shocks that produce significant SEP fluxes.

Eruption-driven coronal shocks and compressive waves are most readily observed in EUV as “EUV waves” [5] – broad, large-scale, arc-shaped regions of brighter EUV emission that propagate along the solar surface (when seen on the disk), or along the limb and away from the solar surface (when seen off limb). The left panel of Fig. 1 shows a diagram of a canonical CME onset, including an eruptive prominence, plasma pile-up, and leading shock wave. The middle and right panels in Fig. 1, adapted from [7], show two observations of an eruption onset near the western solar limb, separated by ~3 minutes, with the EP outlined by red dashed line and the driven compressive wave as a bright feature pointed out by arrows. Individual EUV waves have been studied in detail recently, thanks to the significant improvement in the spatial and temporal resolution of space-based, multi-wavelength remote observation missions, such as the extreme ultraviolet imagers (EUVI; [8]) on the two Solar-Terrestrial Relations Observatory (STEREO) spacecraft and the Atmospheric Imaging Assembly (AIA; [9]) on the Solar Dynamic Observatory (SDO) spacecraft.

Planned Work

Several previous observational case studies have made the connection between erupting filaments and EUV waves [10]. They have shown that EPs indeed can drive shocks low in the corona, based on kinematics and shock stand off models. However, these studies have not explored this connection for multiple events, or from the point of view of particle acceleration. We propose to investigate the connection in detail. Furthermore, a strong connection between EUV waves and shock waves has been established by observations showing temporal and spatial overlap of EUV waves and metric type II radio emission, indicative of a coronal shock. Recent analysis of the temporal relation between EUV wave evolution and in situ particle flux onset for a large sample of cycle 23 events has shown a general consistency with wave/shock acceleration for protons [11], but the question remains at which stage of the eruption SEP acceleration is strongest. This is one of the goals of the present project.

From a modeling perspective, early-stage acceleration of SEPs by CME compressions/shocks is possible. Previous studies of coronal SEP acceleration in single events have successfully used realistic 3D numerical CME simulation results in the corona to drive particle acceleration models [12,13]. These studies explored the time-dependent CME evolution in the corona and effects of post-shock compression structures on particle acceleration, and found that CMEs can accelerate protons to energies exceeding several hundred MeV within 20 solar radii. However, the detailed acceleration efficiency of a larger sample of CMEs has not been explored. We will address this using a recently developed an analytic model for early-stage SEP acceleration, based on diffusive shock acceleration (DSA) theory, driven mostly by detailed remote CME observations [14]. We will apply this model to selected events in our list with enough data to drive the model. This will allow us to directly characterize the overall acceleration efficiency of these CME-driven coronal shock waves.

The goal of the research work is to answer the following questions: 1) What are the properties of erupting filaments, CMEs, and CME-driven shock waves near the Sun, and of associated SEP fluxes in interplanetary space? 2) How are these properties related to the coronal acceleration of SEPs? To achieve the scientific goal of this project, we will use remote solar observations with high spatial and temporal resolution to characterize the early stages of coronal eruption events in a systematic way – studying the pre-eruptive behavior of filaments and flares during energy build-up, the kinematics and morphology of CMEs and compressive shock waves, and the signatures of high energy non-thermal particles in both remote and in situ observations. Below we describe briefly the various activities of our project.

Event and Data Selection

As a first step, we will select the CMEs for our analysis, identify eruptive filaments associated with onset of the events, pick the relevant EUV, X-ray, radio, and in situ observations. In previous work, the Bulgarian team has identified close to 50 solar flares with onsets and peaks (as indicated by soft X-rays – SXR) in freely available RHESSI data over the last years. Such observations point to times and locations of SEP acceleration. The Graz team has identified a set of about 50 CMEs associated with EUV waves that are observed on-disk with SDO and from quasi-quadrature (limb view) from one of the two STEREO satellites. This unique combination of data allows detailed analysis of the intial CME/flux rope evolution for Earth directed events. These CME events will be cross-checked for associated SEPs. Using both these event samples as a starting point, we will determine a list of suitable events according to available other key observations, also based on the two teams' prior work. Developing a larger list of events will allow us to perform both single-case and statistical studies. We will select a sub-sample with sufficient multi-wavelength coverage, presence of EUV waves, and in situ observations, for the single-case studies. The necessary data will be downloaded and prepared for analysis.

Analysis of CME Eruptive Prominences and Flux Ropes

We will determine the relevant morphological and dynamic parameters of EPs and flux ropes in our event sample, such as: type, size, orientation of the filament or flux rope, time-dependent position, speed, and acceleration; timescales of activation and acceleration, amount of overexpansion, whether it activates overlying loops or not. We will use freely available SDO/AIA, STEREO/SECCHI, and SOHO/LASCO data.

EUV Wave Analysis

We will characterize the parameters of CME-driven coronal waves in the event list: onset time relative to the CME eruptions, time-dependent radius, starting velocity and acceleration, thickness/intensity of the wave sheath, stand-off distance from the driver, whether the wave is dome-like, change in sheath temperature and density, interaction with a model coronal magnetic field. The list of relevant parameters may change in the process. We will use freely available SDO/AIA, STEREO/EUVI, and SOHO/LASCO observations – separately, as well as in concert, where available. Where possible, we will augment our analysis with results from existing EUV wave catalogs, such as CoRPITA and CASHeW.

Analysis of remote signatures of SEPs

We will investigate the electromagnetic signatures of accelerated particles in hard X-rays (HXR) and in radio produced during the events, and quantify their properties (occurrence, location, spectrum and temporal evolution). We will select emission parameters to be utilized as additional input parameters. In addition, we will compare observed in situ SEP fluxes with HXR emission signatures (as evidence for particles and their spectra accelerated toward the Sun). Namely, we will perform a detailed analysis of all well-observed SEP-related flares in HXRs using RHESSI data. We will perform a correlation between the deduced HXR photon flux and spectral index and the particle event fluxes. We will compare the results with similar diagnostics using freely available GOES soft X-ray and ground-based radio observations.

Analysis of In Situ SEP observations

We will analyze in situ observations of SEP (proton) fluxes during the event periods, determine whether they are related to the appropriate solar eruption event, and characterize their parameters: onset time, rise time, maximum flux, energy spectrum. Since we are only interested in the coronal acceleration capability of SEPs, we will focus on the rise phase up to a day after the onset of the eruption. In addition, we will control carefully for SEP events that may be produced entirely in flares. We will use freely available proton data from SOHO/ERNE and GOES. Where possible, we will also use results from web-based catalogs such as SEPServer (http://server.sepserver.eu/).

Modeling of SEP Shock Acceleration

We will prepare, run and analyze data-driven analytic particle acceleration models, to be driven and constrained by our analyzed observations. The model to be used has been recently developed and enables a novel approach to characterizing early stage coronal SEP fluxes. It solves for the particle distributions based on an analytic solution of DSA theory, taking into account shock evolution and injection speeds, and produces time-dependent fluxes for each shock-crossing magnetic field line. The model domain is currently limited by the extent of the observations to ~2 solar radii. To keep the investigation focused on the influence of coronal dynamics on particle acceleration, we will simulate only protons as a representative SEP species.

Summary

Carrying out this project now is important and timely, as it will contribute significantly to advancing research on the topic of early-stage solar eruption evolution and energetic particle acceleration. By making the needed connection between the observational parameters of the onset of eruptive filaments and flux ropes, EUV waves/shocks, and SEP acceleration efficiency, the results of this project will enhance our understanding of arguably the most important and consequential stages of solar eruption, which have not been studied in such detail in multi-wavelength analyses previously. This work will be relevant and necessary for interpreting observations from the upcoming NASA and ESA space missions Solar Probe Plus and Solar Orbiter, which will study activity in the solar corona with unprecedented detail at a proximity to the Sun never studied before. Identification of remotely observable coronal eruption parameters that control early particle acceleration will allow us in future work to develop predictive tools that will improve the current state of solar event forecasting. In addition, the project will produce a significant and consistently analyzed event sample, which may be used as a catalog in upcoming studies of solar eruptions, and may serve to identify additional predictive parameters of these eruptions in the future.

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