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THE ORIGIN OF SEP EVENTS: NEW RESEARCH COLLABORATION AND NETWORK ON SPACE WEATHER

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Abstract: *A new project on the solar energetic particles (SEPs) and their solar origins (flares and coronal mass ejections) is described here. The main aim of this project is to answer the question – whether the SEPs observed in situ are driven by flares, by CMEs or both accelerators contribute to an extent which varies from event to event – by deducing a quantitative measure of the flare vs. CME contribution, duration and efficiency. New observations (SONG/Koronas-F, Relec/Vernov) and new approaches of analysis will be utilized (e.g., magnetic topology of active regions using 3D extrapolation techniques of detailed case studies together with statistical analysis of the phenomena). In addition, the identification of the uncertainty limits of SEP injection, onset time and testing the validity of assumptions often taken for granted (association procedures, solar activity longitudinal effects, correlation analysis, etc.) are planned. The project outcomes have the capacity to contribute to other research fields for improvement of modeling schemes and forecasting methods of space weather events.*

ПРОИЗХОД НА СЛЪНЧЕВИ ЕНЕРГЕТИЧНИ ЧАСТИЦИ: НОВО НАУЧНО СЪТРУДНИЧЕСТВО И МРЕЖА НА ТЕМА КОСМИЧЕСКО ВРЕМЕ

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Ключови думи: *слънчеви енергетични частици, космическо време*

Резюме: *Тук е представен новият проект по слънчеви енергетични частици и техния слънчев произход (избухвания и коронално изнасяне на маса). Целта на проекта е да се отговори на въпроса – дали наблюдаваните in situ частици са породени от избухвания, от коронална маса, или и двата източника влияят в степен, която варира между отделните събития – като се изведат количествени характеристики за приноса от всеки източник, тяхната продължителност и ефективност. Нови наблюдения (SONG/Koronas-F, Relec/Vernov) и нови методики за анализ на данни ще бъдат използвани (напр. магнитна топология на активни области чрез триизмерни екстраполации на избрани случаи, заедно със статистическите изследвания на всички събития). В допълнение се планува да се определят неточностите при инжекцията на частици в междупланетното пространство, тяхното начало във времето, както и приложимостта на широко приетите приближения (като процедури за асоциация, ефекти на местоположението на слънчевите събития, корелационен анализ и др.). Резултатите от проекта имат потенциал да допринесат и в други гранични научни сфери с цел подобряване моделите и схемите за прогнозиране на явленията на космическо време.*

Introduction

Our increasingly technological civilization is ever more vulnerable to disturbances known as 'space weather' which can not only endanger astronauts and space-borne instrumentation but can also disrupt ground-based communications and power supply, and can even lead to harmful effects on the human physiological state. The forecasting of such effects is at present one of the main challenges in the field of solar-terrestrial physics. The possibility of early warning of these potentially harmful solar events is invaluable for preventing or at least mitigating the effects of such adverse space weather conditions. Solar energetic particle (SEP), solar flare and coronal mass ejection (CME) events are signatures of the active Sun and the main space weather drivers [1].

At present there is no reliable method for prediction of when, where and how intensive each of these eruptive phenomena will become. The current challenge and ultimate goal of the space weather studies is the successful forecasting and timely mitigation of the negative effects in various aspects of human society, especially the large storms. Among these is the health hazard in terms of the elevated radiation doses which astronauts outside the protective magnetosphere can obtain and to a lesser extend also aircraft crew on polar flights. On other hand, there are social and economical damages to be prevented or minimized, such as service interruption, partial damage or loss of different technological systems, both space born and ground based. Of special interest are the prevention of black-outs due to large-scale networks failure, decreasing the operational costs and increasing longevity for satellite and ground-based systems. In addition, the high energy part of the SEPs can reach the surface (known as ground level enhancements, GLEs) and be detected by neutron monitors. Finally, the elevated radiation dose by SEP effects is rated among the main obstacles for the manned space travel (NASA report No. IG-16-003). In overall, there is the need to increase the space weather awareness by information exchange and active cooperation between scientific, engineering, governmental and general public communities.

The evolution of SEP fluxes is of considerable interest to heliophysics, since it allows us to study processes of particle acceleration, probe interplanetary magnetic fields, and understand the origins of particle radiation that pose significant risks for space exploration.

Solar energetic particles (SEPs) are electron, proton and ion populations with energies in the range of tens of keV to a few GeV. SEP events were initially categorized into two categories, 'impulsive' versus 'gradual' events, according to the timescales of their intensity profiles, their associated element/ion abundances, ionization states and accompanied phenomena [2]. In overall, the impulsive SEP events are attributed to particle acceleration due to magnetic reconnection process of solar flares, whereas the gradual SEP events are due to CME-driven shocks. Since observations from various new spacecrafts showed that there are a number of SEP events that exhibit characteristics of both impulsive and gradual events, identifying the distinction between flare and coronal/interplanetary shocks acceleration is difficult. At present, there is no clear answer on the origin of SEP events. Although multiple observations have shown that many 'mixed' in properties SEP events exists, the widely adopted terminology is still in use today [3].

In order to be able to forecast the SEP events, one needs to understand how to identify and separate unambiguously the different physical processes of particle acceleration that often occur simultaneously. The source of origin of solar energetic particles is one of the fundamental non-solved problems of space weather.

There exists a causality effect between the solar flare/CMEs (regarded as the SEP origin) and the non-thermal particles. Both flares and CMEs are known to be able to accelerate particles to high energies, which in turn can reach Earth traveling around the interplanetary (IP) field lines. The identification of the particular accelerator, however, is not an easy task. The difficulty is due to several reasons, e.g., an overall uncertainty of the time of SEP escape from the solar corona (error margins are usually not given); there are multiple flare/CME candidates prior the particle injection as well as during the course of the SEP event. The standard practice is to choose the 'best candidate' in terms of strongest flare and fastest and widest CME; however this procedure is a gross over-simplification.

The implications of knowing the SEP origin are multiple. There is direct effect for modelling, as well as for improving the forecasting techniques and their predicting capabilities. Flare and CME models for particle acceleration are both strongly supported by observational data. An intrinsic part of the problem is that solar flares and CMEs are related and frequently overlaid (in time/energy) phenomena. Despite the need for correct identification of flare/CME as the SEP origin, the association of the particle event with its origin is usually done based on temporal studies. Usually, a single flare-CME pair is selected as the SEP origin. Namely, the strongest in X-ray emission solar flare and fastest in projected speed CME that occur prior the particle enhancement (at 1AU) are selected as the most probable SEP origin. This procedure is usually straightforward to apply in 'quiet' times, however during active periods (around solar maximum) multiple flare/CME pairs can be present and identification becomes subjective. The presence of several flare/CME candidates prior the SEP onset (and its time-shifted injection point) indicates that there is a multiple influence on the resultant particle flux.

The fact that during large SEP events (with duration of several days) several flare/CME events take place is usually never examined. The potential subsequent contribution by multiple flares/CME has not being quantified before. The 'rule of thumb'-type criteria employed to select the 'best' candidate or flare-CME pair, described above, could be erroneous. Occasionally, different authors provide a different SEP origin association, however the differences are not compared in details. In overall, no decisive dominance is obtained when performing correlation studies between the peak particle intensity and the flare class vs. the CME projected speed, with correlation coefficients about 0.6 in either case. This is especially true when one consider large number of events [4], or use statistical uncertainty estimation [5]. In summary, the reliability of the SEP origin evaluation needs to be assessed in a quantitative manner and uncertainty ranges need to be given. During the project we plan to address all these issues.

In order to unravel the connection between the SEP and their accelerator we aim to focus on new and not explored before observations, both in situ and remote-sensing, which are available to the team. With the aid of multi-wavelength emission observations and new techniques for analysis, we aim to explore in detail the topic of the SEP origin. We will identify a number of SEP events and we will perform two different tests for their origin: by means of statistical approach and via detailed single case studies. In addition, we will focus in identifying early eruptive signatures of flares/CMEs and their SEP-predictive capability will be quantified. At present we have unprecedented space observations monitoring flare and CME activity, however the CME parameters are not well integrated into the forecasting schemes. Finally, we will summarize our findings into a set of guidelines to be used for improvement of theoretical and forecasting models.

Description of the project

The main objective of the project is to address in details the long-standing question of the origin of the SEP events. Two main candidates are known to be able to accelerate particles in space plasmas: magnetic reconnection process (electric field acceleration) during solar flares and shock waves (single or multiple shock front encounters, wave–particle interactions) driven ahead of CMEs. The goal of the present project is to identify the individual contribution of flares vs. CMEs to the resultant flux of energetic particles observed close to Earth by means of observations.

There are three working hypotheses that our team will address, as summarized below. We aim to evaluate which scenario is true for the majority of the SEP events.

1: The dominant SEP acceleration is either flare or CME. We will investigate if the other accelerator provides any effect on the particle flux and under which conditions.

2: Both accelerators play a role that varies in time and space during the course of the particle event. In such case we aim to isolate, quantify and study the effect by each accelerator (where possible) as a function of time, space and energy. We will also study to which extent the multiple accelerators (multiple flares and CMEs) influence the peak particle flux and SEP total duration, compared to an isolated accelerator.

3: We will test (by applying the exclusion principle) whether the injection and transport effects are the dominant factor which shape the SEP events observed in situ, irrespective on the acceleration processes and drivers.

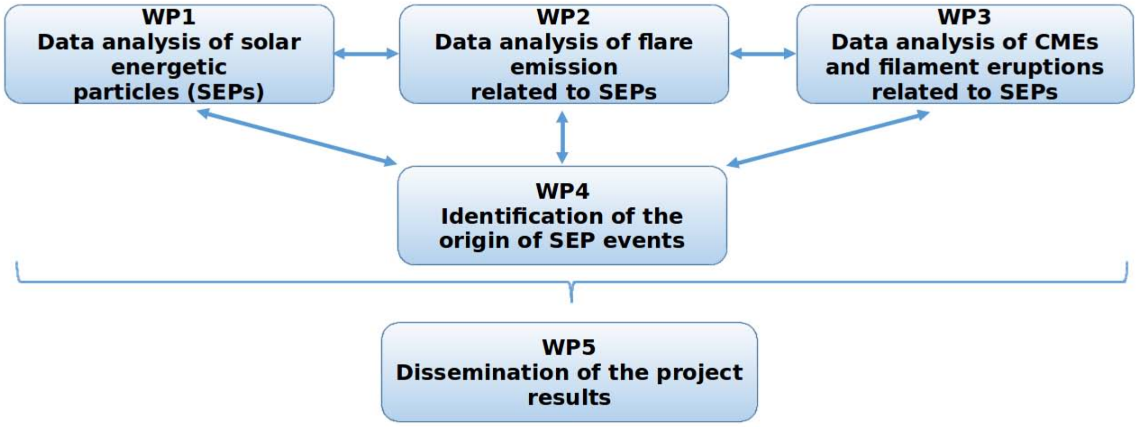

Fig. 1. Work flow structure of the SEPorigin project in terms of work packages (WPs) and their interaction

Data

The basic scientific method to be utilized during this project ('SEPorigin') is analysis of observational data, both, from new instruments and from well-known but unexplored in full data sources. The project will utilize particle and electromagnetic data from several new instruments. These are the Russian spacecraft **CORONAS-F** [6] and **Vernov** [7,8].

Flare observations are provided by GOES, SDO and SOHO and their data will be used in the project. For the observations of eruptive filaments we will use ground-based data (from the Bulgarian National observatory Rozhen) and space-born missions (SDO, SOHO, Hinode, STEREO). We will analyse full-vector SDO/HMI magnetograms using techniques developed by the project team participants (in collaborations). The links to solar dedicated satellite data are listed below:

GOES: http://www.swpc.noaa.gov/products/goes-x-ray-flux
Hinode: https://www.nasa.gov/mission_pages/hinode/index.html
SOHO: http://sohowww.nascom.nasa.gov/
SDO: http://sdo.gsfc.nasa.gov/
STEREO: http://stereo.gsfc.nasa.gov/

Work organization

The project is divided into five main directives (work packages: WPs) which will serve to its accomplishment. The research structure is given in Fig. 1.

WP1: Data analysis of solar energetic particles

This WP will provide the selection and identification of all SEP events to be considered in the project. Two directions for the SEP analysis will be followed: analysis of a large sample of proton events observed by SOHO/ERNE in multiple energy channels (namely, the development of a new proton catalog) and detailed single event analysis (by analysis of SEP data provided by multiple instruments and energy coverage stimulated and coordinated by data analysis and results in other WPs).

WP2: Data analysis of flare emission related to SEP events

The main target of this WP is to prepare observational data of solar flares, to separate the events by active region of their origination, and to estimate parameters of the magnetic field of the different active regions. Multi-wavelength observations together with 3D-magnetic field extrapolations will be considered here.

WP3: Data analysis of CMEs and filament eruptions related to SEP events

Several approaches will be explored, namely, the influence of the reported differences of various CME parameters on the deduction of the SEP origin. The analysis will continue with using de-projected CME speeds for selected events and comparison with the widely used on-sky projected speeds. Further, the team will evaluate if the presence of eruptive prominences increases the chance a SEP event to be detected or not and what is the energy distribution of such SEP events. Finally, the effect of multiple CMEs and their interaction on the resultant in-situ SEP fluxed will be addressed [9,10].

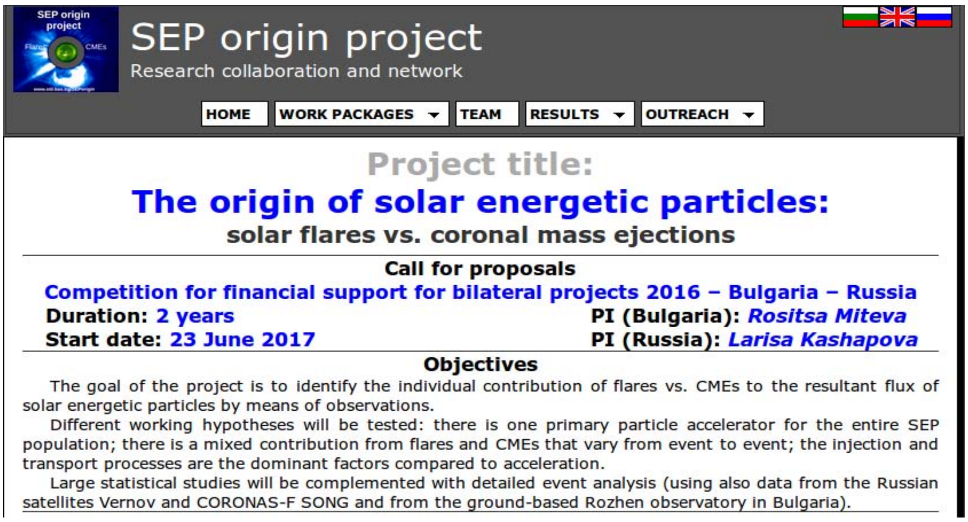

Fig. 2. Example view from the home page of the project web-site: http://newserver.stil.bas.bg/SEPorigin

WP4: Identification the origin on SEP events

This work package will combine all results obtained in the previous WPs (1, 2, and 3) in order to complete the project objective.

We will probe, test and finally identify the physical relationship of flares and CMEs to the SEP events (by inspection of the profiles and their temporal, spatial and spectral evolution). Timing relationships will be scrutinized and the validity of broadly adopted approximations will be tested. This will be accomplished by detail evaluation of well-observed case studies and comprehensive evaluation of SEP origin over two solar cycles (as statistical work).

Two novel approaches in the SEP origin evaluation will be explored here: the influence of the active region topology (using 3D magnetic field extrapolations) and the timing and spectral analysis of radio emission signatures in cm and m wavelengths (used as proxy for the particle escape from the solar corona, e.g., type III radio bursts). The occurrence, duration and efficiency of the particle accelerator can be also tested using gamma, X-ray and radio emission signatures (multi-frequency for the flare, and white light and radio emission for CMEs).

WP5: Dissemination of the project results

Scientific dissemination includes publications of the project results in scientific journals, conference participations of the project members, as well as the organization, participation and discussion of work progress in project meetings.

Dissemination to the general public is planned to be performed via direct communications by members of the research teams presenting popular talks (to schools, general public); writing popular publications (newspapers, social media); preparation of exhibitions; participations at science events; publication of free-of-charge flyers, information materials, etc.

In addition indirect contact will be established via the project dedicated web-site: http://newserver.stil.bas.bg/SEPorigin. Detailed information on the project objectives, team members and published results will be given there. The main content of the web-site will be dedicated to the scientific community with a section designed for the general public as well. We plan to support the website in three languages: English (as default language), Russian and Bulgarian. An example view on the developed web-site can be seen in Fig. 2.

Perspectives

The project success is based on the mutual collaboration between Bulgarian and Russian experts in different space weather topics. The novelty in this respect is that the two teams will gather for the first time establishing a new scientific network.

The foundation set by the project will allow exchanging data and expertise between the partner organizations thus improving the individual team member qualifications with a focus on young researchers and PhD students who will be part of the project.

We aim to achieve improved understanding on the physical link between SEP events and their accelerator by exploring the observational data to their limit. In addition, we plan to evaluate the SEP origin in quantitative way and to provide the uncertainty boundaries of our results.

During the project we foresee to obtain the following results:

1) We will test new hypothesis considering the peculiarity of the magnetic topology on the SEP origins and make a conclusion about the efficiency of using such factors in forecasting methods.

2) We will produce new scientific products. Among them is the new SEP proton catalogue in multiple energy channels by SOHO/ERNE instrument over two solar cycles (e.g., 1997–2016, with further extension if data is publicly released). In addition, we will analyse and present detailed case studies (temporal, spatial and spectral comparison) for selected SEP events and their solar origin using data from the new Russian space missions (CORONA-F, Vernov).

The project will translate the main findings into a set of guidelines and recommendation dedicated for improvement the numerical modelling efforts and forecasting schemes. The potential for practical application of the project is by providing a quantitative indication of which flare/CME parameters have the major influence on the SEP flux and its evolution.

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