A large proton gradual event observed by ACE and STEREOs spacecraft

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Abstract: The aim of this project is to describe and determine the origin of the proton gradual event that took place on March 7th of 2011 by assembling energetic particle, solar wind plasma and interplanetary magnetic field observations made by ACE, STEREO-A and STEREO-B spacecraft. The data sets used have been obtained from the corresponding spacecraft data servers and have been plotted in a way that the solar-interplanetary scenario can be properly interpreted, and the possible passage of an interplanetary shock can be determined. The interpretation of this event has been compared with the official records concerning the beginning and end of the event and the characteristics of the interplanetary shocks detected by each one of the spacecraft.

Keywords: Solar energetic particle events; Coronal mass ejections, ACE, STEREOs, Interplanetary shock

I. INTRODUCTION

Solar Energetic Particle (SEP) events are flux enhancements of energetic particles, mainly protons, electrons and α-particles, released into the interplanetary medium. These events can last from a few hours (impulsive events) to a few days (gradual and mixed events)

The origin of SEP events is associated to solar flares and Coronal Mass Ejections (CME), which are violent manifestations of solar activity related to the solar magnetic field. Flares are eruptive solar events associated with a rapid release of energy in the corona. They are triggered by instabilities in the coronal magnetic field, which convert the magnetic energy into kinetic energy of particles and the emission of electromagnetic radiation ranging from γ-rays to radio bursts. CMEs are large emissions of plasma from the Sun's corona threaded with magnetic field lines, which propagate and expand in the interplanetary medium. Even though a SEP event can be associated to both a flare and CME, there is no cause-effect relation between them: a flare can occur without a CME and viceversa[4].

CMEs expand in the interplanetary medium and they can cause interplanetary shocks that are responsible for the acceleration of the energetic particles accompanying the CMEs, therefore originating gradual SEP events. Gradual SEP events are occur more frequently on periods of increased solar activity and are characterized by lasting from two to up to five days, having an element composition of particles similar to the element composition of the Sun's corona and reaching maximum particle intensities and levels of radiation much larger than in impulsive events. These particles, are injected into the interplanetary magnetic field lines and propagate along them following helicoidal orbits. SEP events are detected by the instruments and detectors on board the spacecraft orbiting around the Sun and Earth and cause an increase on the particle intensity profiles.

Gradual events show a wide variety of time-intensity profiles depending on the energy range considered, the strength and the direction of the interplanetary shock driven by the CME, the structure of the interplanetary magnetic field and the relative position between the spacecraft that detects the event and the heliolongitude of the solar activity responsible of originating the event. The aim of analysing the time profiles of the data obtained by the detection gradual SEP events is to understand the physical processes ocurring during the development of the CME and how shocks accelerate and inject particles into interplanetary space. By knowing how particles propagate and are accelerated, SEP events can be simulated and modelled in order to build tools to try predict them, since they represent a hazard to spacecraft components. Inside the Earth's magnetosphere, satellites and astronauts are only partially shielded against the radiation and there has been an interest in sending back astronauts to the Moon for extended periods of time and, eventually, to Mars . Thus having prediction of when these kind of events will take place and how intense will they be is needed to carry out such missions to avoid risking the proper functioning of the instruments and the life of the astronauts onboard the spacecraft.

The SEP event analysed in this project took place on March 7th, 2011. To describe the methodology, a brief description of the space missions and the instrumentation used to obtain the data will be given in section **II**.

The results and their discussion have been organized in three different sections.

In section **III** the solar activity that originated the event will be identified and the effects that it had on the Sun's Corona will be shown.

Then, the representation of the interplanetary scenario in section **IV** will show the direction of the flare and the positions of the spacecrafts relative to the Sun-Earth line and also to the flare.

Finally, in section **V** an analysis of the event will be made by studying it from the point of view of each one of the spacecrafts used to obtain the data for this project.

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II. INSTRUMENTATION

In order to study and understand the event it is needed to determine the solar origin and direction of the flare, the interplanetary scenario and the time-profiles of the proton intensities, solar wind velocity, density and kinetic temperature, and module and direction of the magnetic field. The data has been collected by different instrumentation on board of three spacecrafts: ACE, STEREO A and STEREO B. The fact that this event was observed by multiple spacecrafts is rare, since observations of SEP events are usually made by a single spacecraft.

A. Advanced Composition Explorer (ACE)

The main goal of the ACE mission, which is a near-Earth observatory orbiting around the L1 libration point, is to observe particles coming out of solar, interplanetary, interstellar and galactic sources and measure their elemental and isotopic composition.

In the study of this particular event the proton intensities, solar wind and interplanetary magnetic field properties have been measured with the following instruments:

- Low Energy Magnetic Spectrometer 120 (LEMS120) detector, which measures ions at 120°from the space spin axis in eight sectored energy channels.
- Solar Wind Electron, Proton and Alpha Monitor (SWEPAM) instrument, which provides real-time solar wind observations by measuring its plasma ion fluxes as a function of the energy and the direction.
- MAG experiment, which consists on a set of twin sensors that measure the local interplanetary magnetic magnitude and direction.

The data from the ACE spacecraft has been obtained using the Level 2 Data Server provided by the ACE Science Center[1] [2].

B. Solar TErrestrial RElations Observatory (STEREO)

The STEREO mission consists in two observatories, one of them orbiting ahead of Earth (STEREO-A) and the other one behind (STEREO-B) with the mission of obtaining 3D images of CMEs and making multi-point measurements of the solar wind, interplanetary magnetic field and SEPs .

The instruments used to obtain the data for this projects are the following:

- High Energy Telescope (HET), is designed to detect and measure protons and helium ions with an energy up to 100 MeV/nucleon.
- Low Energy Telescope (LET), which uses the same technique as HET but with the aim of detecting smaller and less energetic SEP events that HET would not be able to detect.
- Plasma and Suprathermal Ion Composition (PLASTIC) experiment, which provides measurements regarding the kinetic properties and composition of heavy ions.
- Magnetometers, to measure the module of the magnetic field components in RTN coordinates as well as the longitude and latitude.
- COR1 inner coronographs, which mask the solar disk in order to measure the brightness of the corona.

The data from the HET and LET detectors has been obtained from the SEP Instrument Suite database. Regarding the plasma and magnetic field properties, the data has been obtained from the level 2 STEREO IMPACT Magnetic Field and PLASTIC data server[5][6][7].

III. SOLAR ORIGIN OF THE SEP EVENT

On March 7 of 2011 an M3.7 class flare was measured by the X-Ray detector onboard the GOES satellite[3].

The flare, located at N30W48, started at 19:43 UT, reached its peak activity at 20:00 UT and a concomitant fast CME propagated between STEREO-A and Earth. The CME reached the Earth and both STEREO-A and STEREO-B as an interplanetary CME (ICME) that caused the detection of an increase in proton fluxes among other effects, as it will be discussed in section **V**.

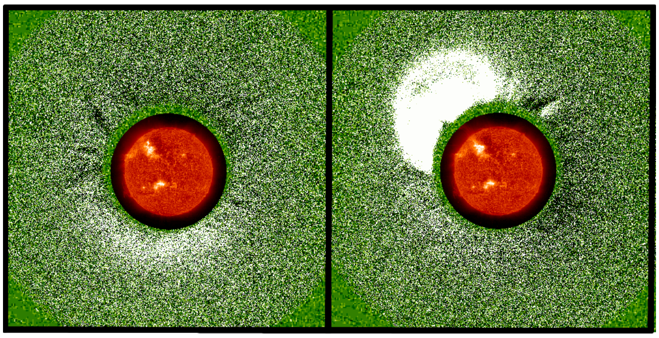

FIG. 1: CME associated with the event as seen by the white light coronograph COR1 on board of STEREO-A.

The left panel on FIG. 1 shows the solar corona at 19:45:18 UT, two minutes after the flare began. The picture at the right panel was taken at 20:05:18 UT, five minutes after the ejection reached its peak activity. In this panel the CME can clearly be seen.

IV. INTERPLANETARY SCENARIO

The interplanetary scenario of the event can be understood considering the heliolongitude of the flare and by averaging the positions of the STEREOs spacecrafts on March 7th and aproximating the position of the ACE spacecraft as being the same as the Earth.

On March 7th, STEREO-A was located at an heliocentric distance $R_{STEREO\text{-}A} \approx 0.96$ AU and had a separation angle with the Earth of 87.6°. On the other hand, STEREO-B had an heliocentric distance of $R_{STEREO\text{-}B} \approx 1.01$ AU and a separation angle with Earth of 94.9°.

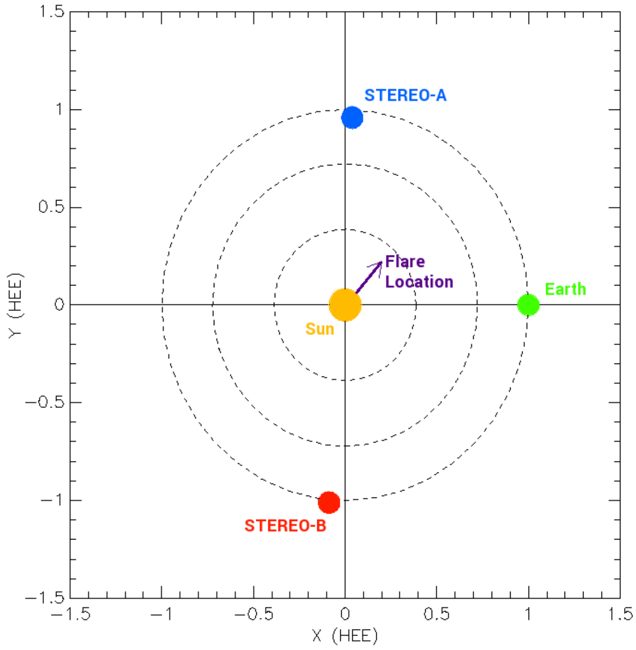

FIG. 2: Representation of the interplanetary scenario on March 7th 2011.

It is also useful to know the position of the spacecrafts relative to the position of the flare, which happened at the heliolongitude W48.

Spacecraft	Longitude from Earth	Longitude from the flare
ACE	W00	W48
STEREO-A	W88	E40
STEREO-B	E95	W143

TABLE I: Positions of the spacecrafts as seen from the Earth and as seen from the flare.

V. ANALYSIS OF THE EVENT

The data files containing the measurements collected by the instruments described in section **II**, had to be processed so that the proton intensities, kinetic properties of the plasma and magnetic field properties could be represented in stacked plots as a function of time expressed in Day Of the Year (DOY) units.

The behaviour of these variables shows the time the ICME reached each of the spacecrafts and can also determine if the ICME was propagating fast enough to cause a shock.

A. ACE Observations

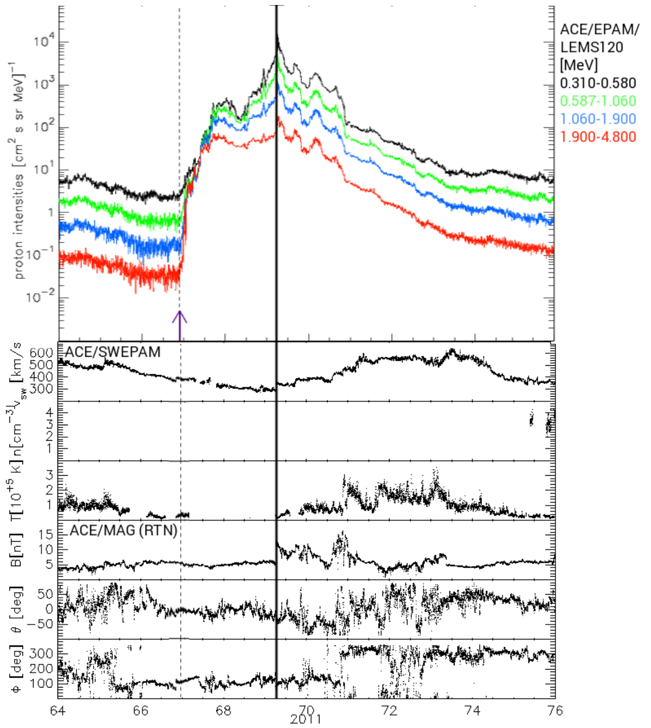

FIG. 3: Representation of the data collected by ACE as a function of time.

Out of the eight sectored energy channels that the LEMS120 instrument has, the data was only available for four of them. The sudden increase of the proton intensities shows that the ICME reached the near-Earth spacecraft on 66 DOY at 23:40 UT, as indicated by the arrow and dashed line across the plots. Thereafter, the intensity profiles increase until reaching a maximum on 69 DOY. After this peak, the proton influx decreases until almost reaching the same levels as the start of the event.

Regarding the solar wind and plasma properties, the velocity decreases and reaches a minimum when the proton intensities peak; while for the particle density and temperature, there is no data available for the most intense days of the event.

As for the magnetic field, it can be seen that it remains constant at the beginning of the event but once the proton intensities start reaching the maximum values, the magnetic field starts to fluctuate between 5 nT and 15 nT. After these fluctuations and when the proton intensities start to decrease, it goes back to the initial constant value.

The fact that the proton intensities peak at the same time that the solar wind velocity and magnetic field increase is due to the fact that an interplanetary shock reached the spacecraft, as indicated by the vertical line on 69 DOY.

B. STEREO-A Observations

The proton intensities are represented for a wide range of energies that spans from 1.8 MeV to 60 MeV using the measurements made by LET and HET telescopes. The arrow and dotted line mark the beginning of the event, when the ICME arrived at STEREO-A.

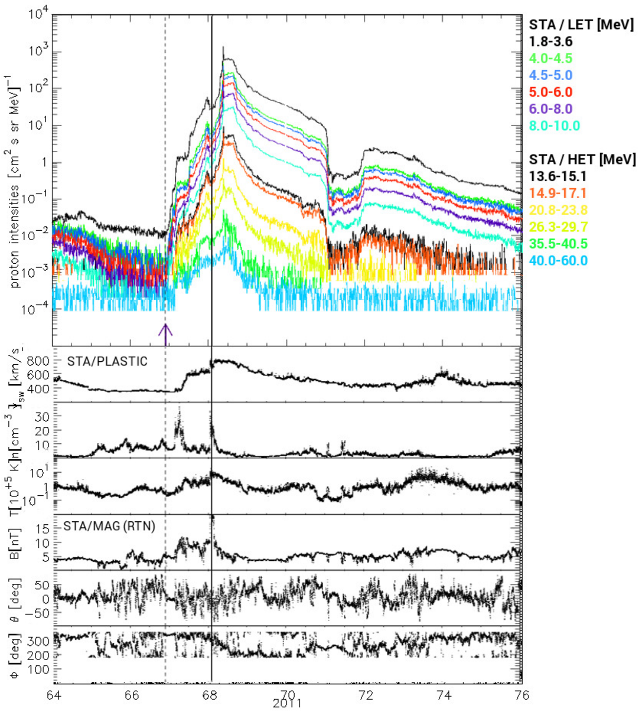

FIG. 4: Representation of the data collected by STEREO-A as a function of time.

The proton intensities increase until they reach a maximum during 68 DOY, and after that they begin to decrease. Between 71 and 72 DOY, the proton intensities profiles measured by LET and the least energetic channels of HET suddenly decrease an order of magnitude but they do not go back to the initial levels in the time span analysed. On the other hand, the profiles of the most energetic protons go back to the initial levels hours after peaking.

The solar wind velocity doubles its value after the start of the event and reaches a maximum of 800 km/s a day after the start of the event. The particle density peaks both at the start of the event and when the velocity reaches its maximum, while the temperature increases at the same time.

Regarding the magnetic field, it has a quite stable value except in between 67 and 68 DOY when its module fluctuates significantly until it peaks at the beginning of 68 DOY.

The solid vertical line on 68 DOY indicates that a shock reached the spacecraft. This shock associated to the ICME is responsible for making all the variables reach unusually large values.

Additionally, after the event had started and before the shock was detected, on 67 DOY it can be seen that the solar wind velocity starts to increase and the plasma properties and magnetic field peak. This behaviour could be due to a Corotating Interaction Region (CIR), which occur between fast and slow solar wind streams.

C. STEREO-B Measurements

The same energy channels from LET and HET used in STEREO-A have been used in STEREO-B. Once again, the arrow and dotted line point out the beginning of the event.

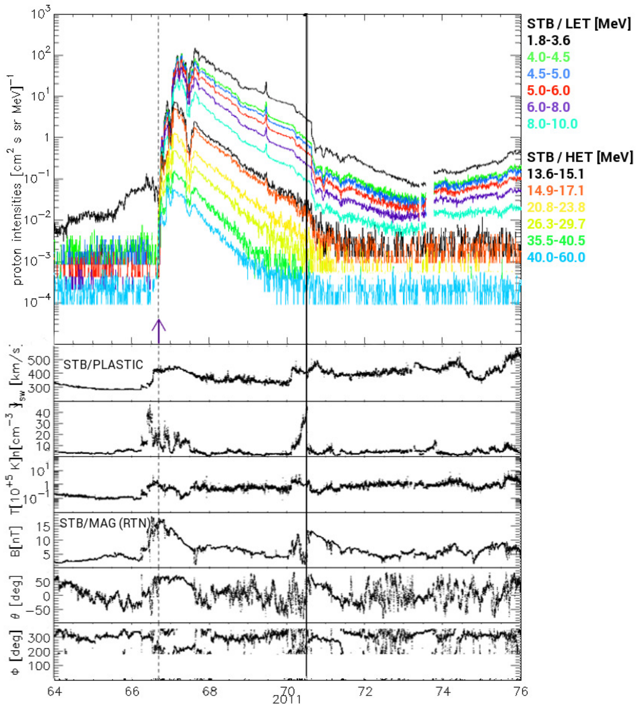

FIG. 5: Representation of the data collected by STEREO-B as a function of time.

The proton intensities suddenly increase, reach the maximum a few hours after the ICME arrived at STEREO-B and after that they start decreasing back to the original levels.

On 70 DOY, it can be seen that the solar wind velocity, particle density, temperature and magnetic field suddenly peak. Looking at the records, there is an interplanetary shock detected. Still, the fact that the proton intensities do not peak at the same time means that actually this shock is not associated to the event.

VI. CONCLUSIONS

- The N30W48 flare and a CME that were detected by the near-Earth mission ACE and both the STEREOs spacecrafts, as it can be seen by the increased proton intensities, solar wind velocity, particle density, kinetic temperature and module of the magnetic field.

- While the proton intensities profiles are similar for STEREO-A and ACE, the measurements made by STEREO-B show a profile in which the maximum of the lowest energy channel is 10^2 $[cm^2 \cdot s \cdot sr \cdot MeV]^{-1}$, compared to the value of 10^4 $[cm^2 \cdot s \cdot sr \cdot MeV]^{-1}$ measured by ACE and the value of 10^3 $[cm^2 \cdot s \cdot sr \cdot MeV]^{-1}$ measured by STEREO-A. Furthermore, the intensity decreases faster than in the other two observatories. This behaviour can be explained looking at FIG. 2: the direction in which the flare propagates is opposed to the position of STEREO-B, and therefore, less particles will reach the spacecraft.

- In some regions, the ICME associated to the event was traveling fast enough to produce an interplanetary shock that was detected on 68 DOY by STEREO-A and 69 DOY by ACE.

- The shock associated to this SEP event detected by STEREO-A can be found on the official records.

- The effects of the shock were observed as well by ACE but there are no official records of the detection of a shock. This could be due to the fact that since data concerning the density and temperature of the plasma is missing, it can't be properly classified.

- Regarding STEREO-B, the official records state that a shock was detected on 70 DOY, but it cannot be associated to the SEP event because the proton intensities do not peak as the other variables do.

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