Multipoint observations of a sequence of events on the sun

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On 3rd November 2011 an X1.9 flare from NOAA 11339 was observed by STEREO-B and SDO at 20:16 (Flare 1), with a very weak associated CME (CME 1). It was followed by a second CME (CME 2) off the western limb of STEREO-B at 20:35 and a second flare (flare 2) just behind the western limb of SDO at 22:00. A larger CME (CME 3) occurred later at 22:20, with a speed of roughly 980km/s, from the backside of the sun. This was observed in STEREO-B and off the western limb of STEREO-A. An EIT wave is seen propagating from CME 3 on the sun, at a speed of 200km/s. It extends to an active region in the middle of the disk visible from STEREO-B, which later produces a fourth CME (CME 4).
A solar energetic particle (SEP) event of electrons is seen first by STEREO-A, then -B and ACE, after CME 3. An ion event is also seen by both STEREO spacecraft. Magnetic data shows an increase in total magnetic field at both STEREO spacecraft, arriving at STEREO-A first. The smooth rotation of the magnetic field visible in B_N in STEREO-B indicates the passage of a magnetic flux rope.

Introduction

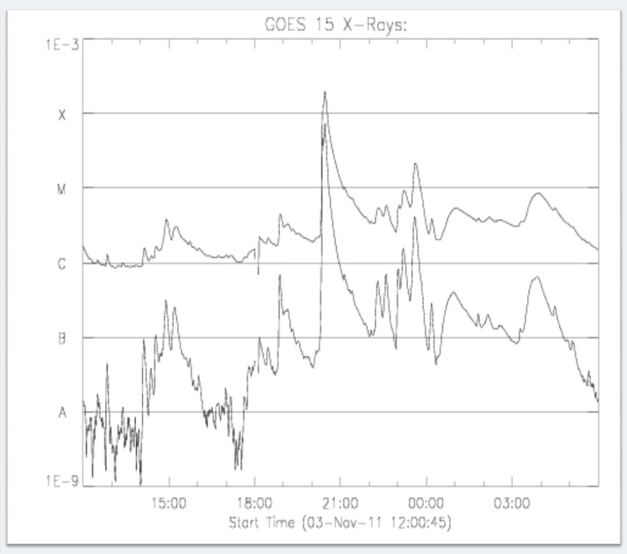
A solar energetic particle (SEP) event can be caused by the acceleration of particles by a flare or a shock, which each display a distinctive profile. Shock driven SEPs are more gradual,lasting several days, whereas flare driven SEPs tend to be impulsive, lasting a few hours (Cliver, 2008). The onset time of a SEP event depends on the source region of the particles, with earliest onset for spacecraft well connected to the source region and later for spacecraft with a poorer connection (Reames , 2010). SEP events have been observed arriving almost simultaneously at different spacecraft (Innes,EGU, 2011) and Liu et al (2011) have studied an event that included SEP events arriving at ACE and both STEREO spacecraft, though the shock and ICME were detected only at ACE.
A well connected SEP event will see a strong shock, resulting in an intensity profile that remains constant in time , where a less well connected event will encounter a shock that weakens with time, showing a decreasing intensity profile with time (Reames1996).
We study a sequence of events on the sun that show many unexpected characteristics, particularly in the timings of SEP event onset at ACE and both STEREO spacecraft.

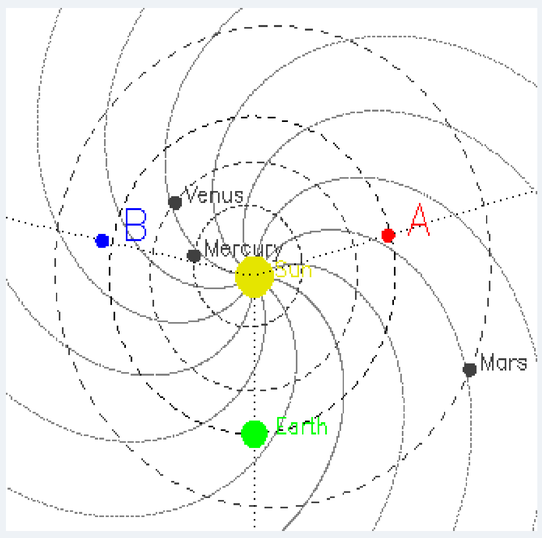
Sequence of Events

The sequence of events studied begins with an X1.9 flare that started at 20:16 on 3 November from active region 11339. The associated CME is very weak, and there doesn't appear to be an EIT wave connected with this flare.
Flare 2 occurred at roughly 22:00 , in view of STEREO-A. The location and timing suggest this may have been the source of energetic electrons arriving at STEREO-A , before STEREO-B .

Time	Event	Position
20:16 3 November	Flare 1 (X1.9)	11339. Near eastern limb of SDO, western limb of STEREO-B
20:35	CME1 (weak, associated with flare)	11339, visible off STEREO-A eastern limb
20:45	CME 2	Visible off STEREO-B western limb
22:00	Flare 2	Off SDO western limb 11333
22:20	CME 3	Backsided, off western limb of -A, near eastern limb of -B
22:22	Electron SEP onset	STEREO-A
22:35	Type II radio burst	STEREO-B
22:45	Ion SEP onset	STEREO-A
23:26	Electron SEP onset	STEREO-B, ACE
23:33	Ion SEP onset	STEREO-B
00:00 4 November	Ion SEP onset	ACE
00:25	CME 4	Middle of disk of STEREO-B
21:00 5 November	Magnetic field increase	STEREO-A
05:00 6 November	Magnetic field increase	STEREO-B

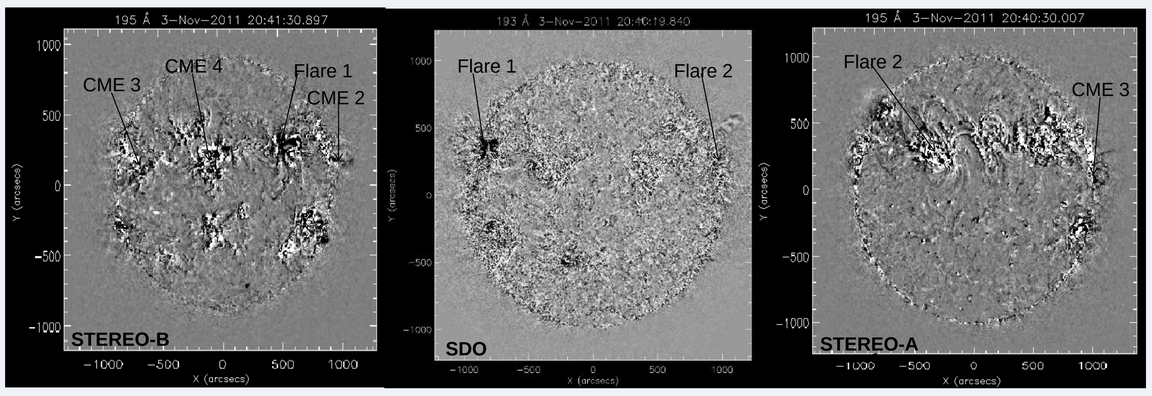
Timeline of events on the sun and onset times of in-situ measurements





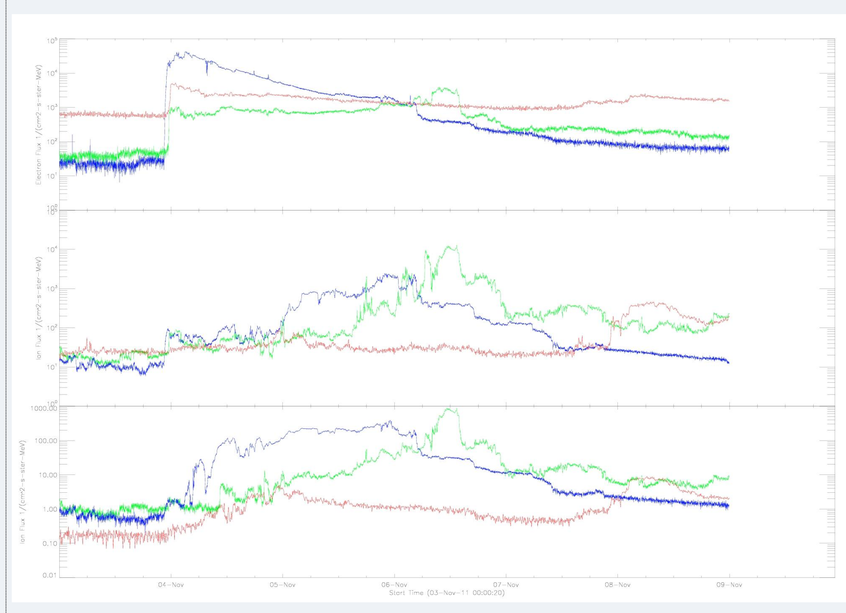
Positions of the STEREO spacecraft, Earth and the inner planets on 3 November 2011 as shown on the STEREO website

Height-time plots of CME 3 indicate an average speed of about 980km/s, and that the leading edge is decelerating. It has an associated EIT wave that propagates towards an active region near the centre of the disk on STEREO-B at a speed of approximately 200km/s. CME 4 then sets off from this active region, with an approximate speed of 380km/s, as measured from HT plots.



SEP events

Energetic electrons are detected at STEREO-A first at 22:22 and then simultaneously at ACE and STEREO-B roughly an hour later. The timing suggests that these cannot be caused by flare 1. The last event to occur on the sun before SEP onset was CME 3, which was directed towards STEREO-B. As the particles at STEREO-A arrive first, they are more likely to be due to flare 2. The intensity time profile of these SEPs show an almost constant profile with time at STEREO-B and a similar profile at ACE, after a small initial decrease. The gradual nature of the profile at –A, lasting several days, suggests that these SEPs were due to a CME rather than a flare.
The arrival of SEPs at ACE at the same time as STEREO-B is also unexpected, as there are no Earth-directed events at a suitable timing to explain this.



0.035-0.065 MeV electrons at STEREO-A /SEPT(blue), STEREO-B /SEPT(green) and 0.038-0.053 MeV electrons at ACE/EPAM (red)

0.137-0.623 MeV ions at STEREO-A /SEPT(blue), STEREO-B /SEPT(green) and 0.112-0.187 MeV ions at ACE/EPAM (red)

0.623 MeV-2.22MeV ions at STEREO-A/SEPT (blue), STEREO-B /SEPT(green) and 1.06-1.91 MeV ions at ACE/EPAM (red)

The STEREO spacecraft also show an increase in ion flux roughly 30 minutes after the electron flux increase, which peaks in STEREO-A at roughly 00:00 on Nov 6 and in STEREO-B at 12:00 the same day. Ions at ACE show a very gradual increase that is far less extensive, beginning at approximately 00:00 4 November on and peaking at 23:20.

Magnetic Storm

Magnetic field data show an increase in overall magnetic field first at STEREO-A at 21:00 on 5 November, which also implies the presence of a CME, travelling towards STEREO-A and occurring before CME 3.
The magnetic field increase starts on STEREO-B 9 hours later at 05:00 on 6 November. Assuming this is due to CME 3 gives a velocity of roughly 760km/s, verifying that CME 3 decelerates out to 1 AU. The smooth rotation of the magnetic field vector B_N indicates the passage of a magnetic flux rope at the same time as the increase in total magnetic field. After this, at 23:00 on 6 November, magnetic field increases again, corresponding to the passage of CME 4.
The magnetic field at ACE shows some signs of magnetic field increase, but this is much later on than seen in STEREO-A and -B, which suggests it is more likely to correspond to CME 4, which is directed more towards Earth than CME 3.

B_R at STEREO-A (blue),STEREO-B (green) and ACE (red)

B_T at STEREO-A (blue),STEREO-B (green) and ACE (red)

B_N at STEREO-A (blue),STEREO-B (green) and ACE (red)

B magnitude at STEREO-A (blue),STEREO-B (green) and ACE (red)

Summary

We have studied a complex series of events, 2 solar flares and several CMEs which display some unusual results.
• Flare 1 does not cause an SEP event, despite being an X1.9 flare and it has a very weak associated CME. This contrasts with the events studied by Liu et al (2011), which shows SEPs from a CME associated with a much less intense B7.4 flare.
• CME 3 causes expected results at STEREO-B, but at STEREO-A, the timing of the events implies it is not caused by the same CME. Flare 2 is the most likely source, but there are clear indications that a CME should be present, as this is a gradual SEP event and the magnetic field shows an increase.
• ACE and STEREO-B see a simultaneous onset of SEPs, though the ICME material is only clearly detected at STEREO-B. Liu et al (2011) show that SEPs can be detected, without the shock or ICME material, but the onset of particles at the same time at ACE and STEREO-B is still unexplained.