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High flux solar protons in coronal mass ejection

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1. Abstract

There were six events between 1997 and October 2003 with proton peak flux from 12,900 to 31,700 pfu and they produced strong geomagnetic storms. The analysis shows that the five highest proton flux events correlate with (r=0.945) either the speed or (r=0.95) energy of the CME. The lowest flux event does not so correlate but exhibits prolonged (3.6-day) decay behavior for the 100 Mev protons (GOES data), as does the second-lowest flux event. This compares to the (average 1.7-day) decay typical of the higher flux events. An interpretation of shorter diffusion mean free path in the interplanetary transport equation for the lower flux events is consistent with the conjecture that the prolonged temporal decay is due to the extra scattering when the associated CME collides with the preceding halo CME. The Ulysses satellite uses full plasma and magnetic data to identify CME events. It also detected two CME events subsequent to the GOES flux signature of these two lower flux events. The subsequent time delay and Ulysses location is consistent with the diffusion interpretation. The waiting time distribution of high speed and halo CME events was also examined.

2. Introduction

Solar energetic particles SEP derive their energy from a solar magnetic source. LASCO revealed that coronal mass ejection CME events are rather common and average about 3 events per day. Recent study showed that coronal mass ejection CME collisions are an important aspect of SEP production (Gopalswamy 2002). The fast primary CME overtakes the preceding CME within a distance of about 20 solar radii. Thus SEP are accelerated from the preceding CME's matter. A recent review summarized the development of SEP event studies (Kallenrode 2003).

This project investigated, by statistical correlation, the high flux SEP events and the associated CME events that are posted by NOAA on the internet. The proton profiles captured by the GOES satellite have also been analyzed via the interplanetary transport diffusion mechanism.

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3. Data and Analysis

There were six events between 1997 and Oct 2003 with proton peak flux from 12,900 to 31,700 pfu and they produced strong geomagnetic storms.

The following proton peak flux data is available from the NOAA website.

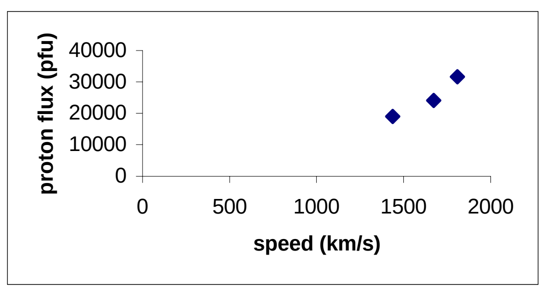
2000 July 15 proton flux 24000 pfu
2000 Nov 9 proton flux 14800 pfu
2001 Sept 25 proton flux 12900 pfu
2001 Nov 6 proton flux 31700 pfu
2001 Nov 24 proton flux 18900 pfu
2003 Oct 28 proton flux 29500 pfu

The CME data is available from the LASCO website.

Proton flux (pfu)	CME linear-fit speed km/s
31700	1810
24000	1674
18900	1437
14800	1738
12900	2402

The 29500 pfu event has been assigned a speed of about 2000 m/s by NOAA.

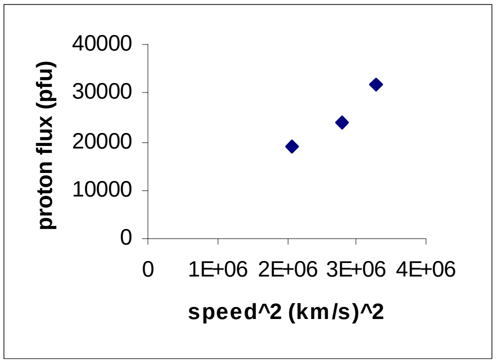
The flux versus CME speed graph for the three earliest high flux events is shown:



Proton flux versus speed graph

The correlation coefficient was 0.96 for 3 points. The CME speed intercept is about 950 km/s. This large intercept suggests that the actual function might instead be a second order polynomial.

The proton flux versus (speed)^2 , which is proportional to energy, graph is shown:



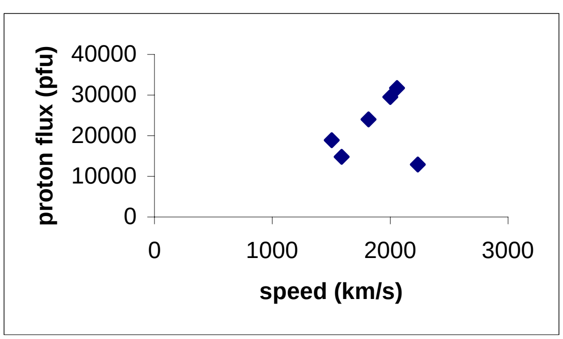
Proton flux versus speed^2 graph

The correlation coefficient was 0.97 for 3 points. The lowest flux event does not so correlate but exhibits prolonged (3.6-day) decay behavior for the 100 Mev protons (GOES data), as does the second-lowest flux event. This compares to the (1.7-day) decay typical of the higher flux events.

The addition of the most recent high flux Oct 28 2003 event is interesting. The preliminary data posted by NOAA put the 10 Mev proton flux peak at 29500 pfu and the CME speed at about 2000 m/s (NOAA-USAF). The addition of this event into the dataset and using the second order fit CME speed would give the data table:

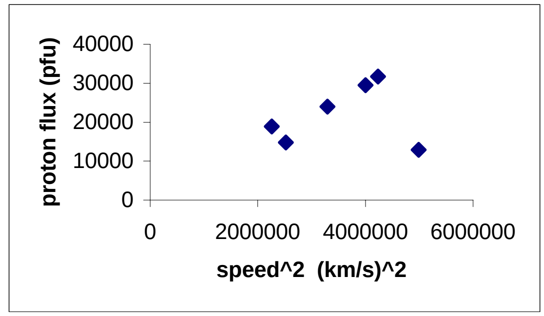
Proton flux (pfu)	CME speed km/s (2^{nd} order fit)
31700	2058
29500	2000
24000	1815
18900	1503
14800	1588
12900	2234

The graph is shown in the following:



Proton flux versus speed graph.

The correlation coefficient was 0.945 for 5 points, excluding the lowest flux, highest speed event.

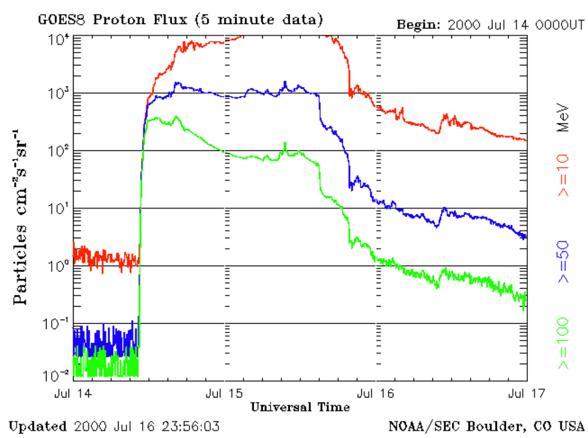


Proton flux versus speed^2 graph.

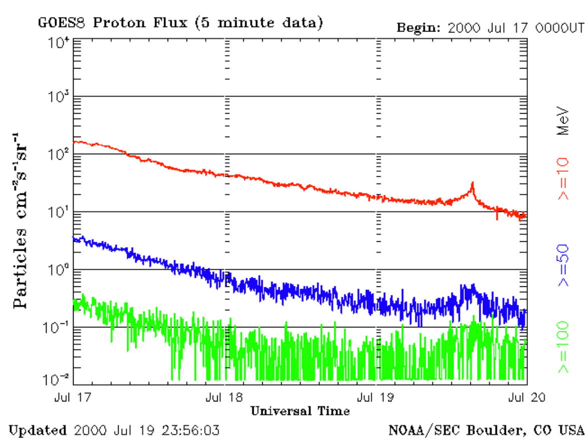
The correlation coefficient was 0.95 for 5 points, excluding the lowest flux event. The intercept corresponded to a speed of 685 km/s.

The proton data are shown in order of date.

GOES proton data for the 24000 pfu (high flux) event:

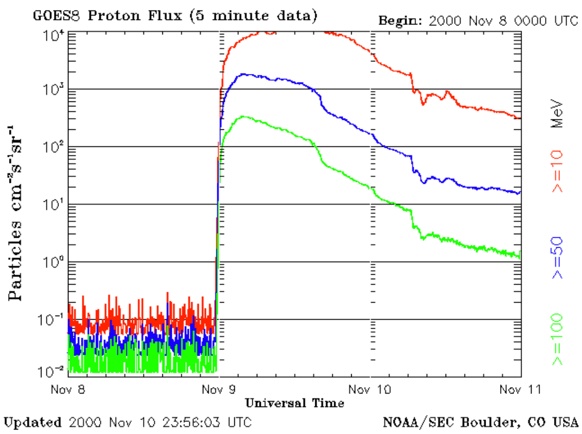


The high flux decay phase:

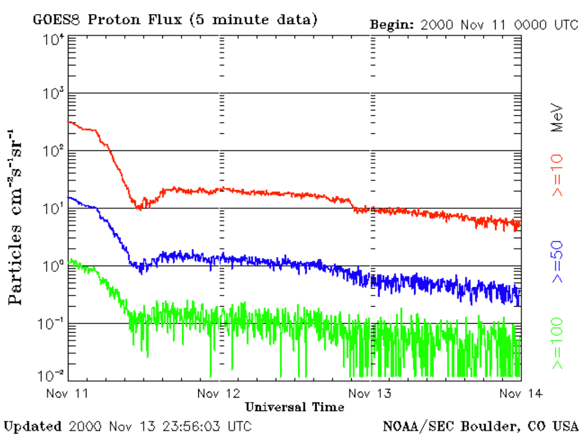


The proton flux leading edge jumped sharply. The 100 Mev proton had a broad (or double) peak for about one day, followed by a 2.5-day decay from the second peak or 3.5 day decay from the first peak. Guided by the 10 Mev data which does not show the early peak, we have taken 2.5 days as the decay interval.

GOES proton data for the 14800 pfu (low flux) event:

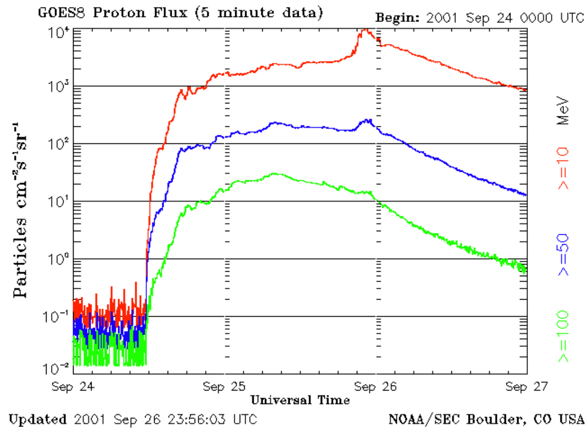


The low flux decay phase:

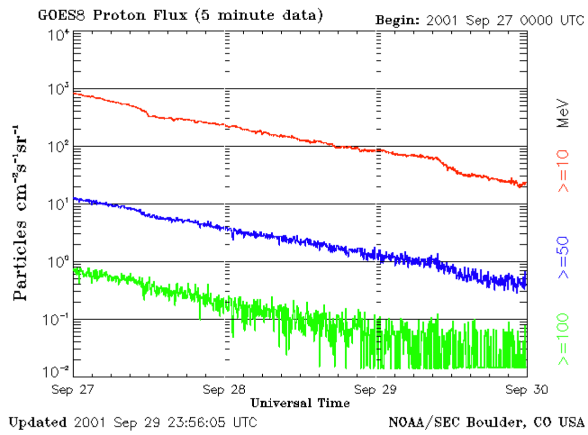


The proton flux leading edge jumped sharply. The 100 Mev proton had a small peak for about 0.5 day, followed by a 2-day decay and a small 1.5 day peak and decay, or a total of 3.5 days, on Nov 17 2000.

GOES proton data for the 12900 pfu (low flux) event:

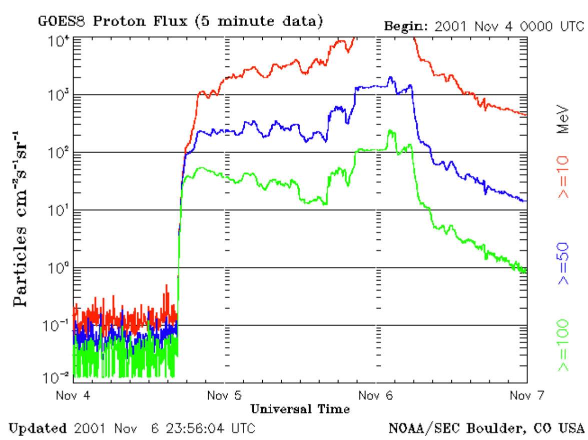


The low flux decay phase:

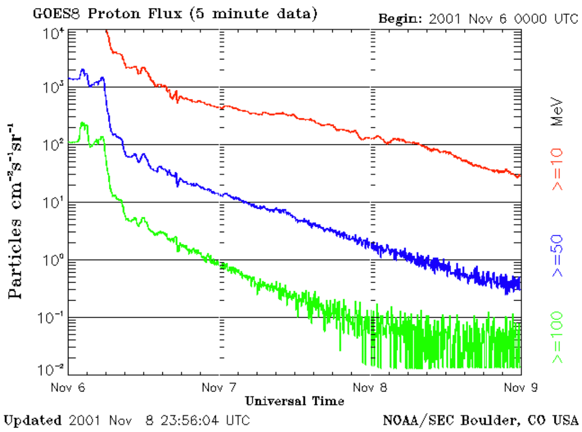


The proton flux leading edge increased gradually. The 100 Mev proton had a broad peak for about 1.5 days, followed by a 3.6-day decay.

GOES proton data for the 31700 pfu (high flux) event

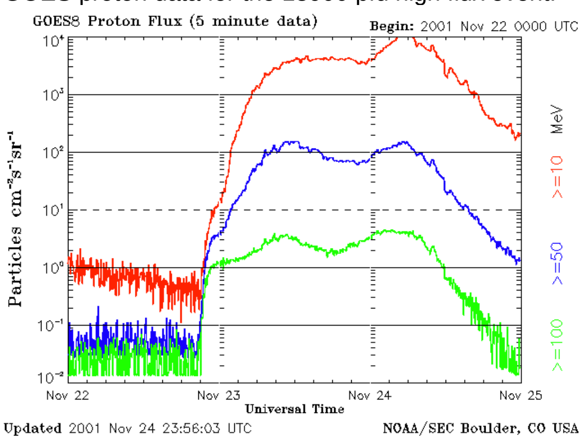


The high flux decay phase:

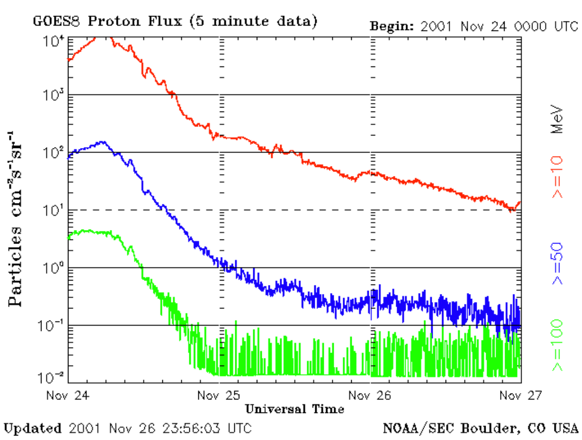


The proton flux leading edge jumped sharply. The 100 Mev proton had a broad peak for about 1.5 days, followed by a 1.8-day decay.

GOES proton data for the 18900 pfu high flux event:

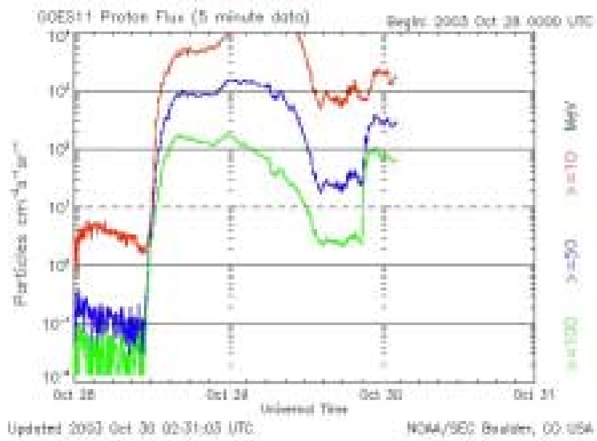


The high flux decay phase:

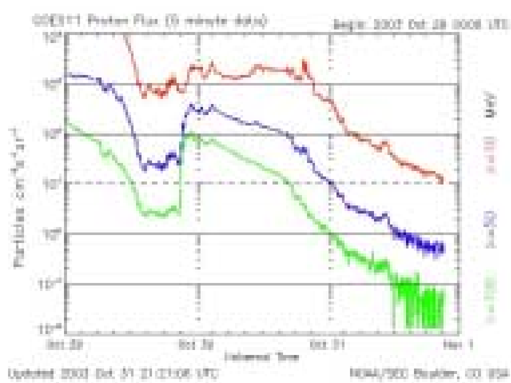


The proton flux leading edge increased gradually. The 100 Mev proton had a broad double-peak for about 1.5 days, followed by a 0.7-day decay.

GOES proton data for the 29500 high flux event , Oct 28, 2003



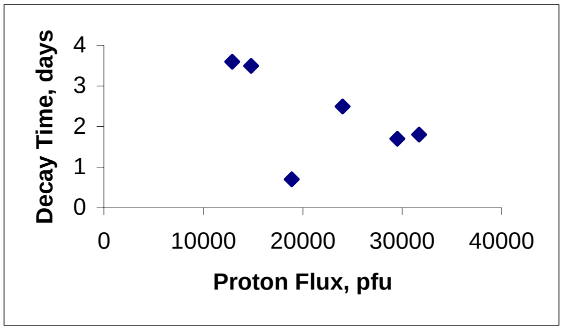
The high flux decay phase:



The 100 Mev proton flux had a broad double peak for 1.4 days followed by a 1.7 day decay.

A decay phase table is shown:

Proton flux (pfu)	Decay Time (days)
31700	1.8
29500	1.7
24000	2.5
18900	0.7
14800	3.5
12900	3.6



Proton flux decay time vs. Peak flux

The correlation coefficient for the five uppermost points, excluding the 18900 pfu event, is -0.99, which further suggests that the exceedingly rapid decay is unusual.

4. Discussion

The correlation between solar proton flux and energy per proton (or speed) is at least consistent with the concept of equipartition of energy. It appears, from the intercept, that the minimum speed for a high flux coronal mass ejection is about 700 km/s.

The average decay phase for the two lowest flux events (14800 pfu and 12900 pfu events) is about 3.6 days. The average decay phase for the remaining events (the five highest flux events) is about 1.7 days.

An interpretation of shorter diffusion mean free path in the interplanetary transport equation for the lower flux events is consistent with the conjecture that the prolonged temporal decay at low flux is due to the extra scattering when the associated CME collides with the preceding halo CME.

The 14800 pfu event was associated with a CME on 11/8/2000 at UT23:06 as listed on the NOAA website. The LASCO CME catalog listed a slow halo CME on 11/8/2000 at UT 04:50 at about 500 m/s.

The 12900 pfu event was associated with a CME event on 9/24/01 at UT 10:30 as listed on the NOAA website. The CME catalog listed a slow halo CME on 9/23/01 at UT 20:30 at about 550 m/s.

The Ulysses satellite uses full plasma and magnetic data to identify CME events (Reisenfeld 2003). It also detected two CME events subsequent to the GOES flux signature of these two lower flux events. Ulysses has a solar orbit of 80.2 degree, a perihelion of 1.34 AU, an aphelion of 5.4 AU, and a period of 6.2 years.

The Ulysses detectors indicated that a CME event started on Nov 9 2000 at UT 01:30 (DOY 314) and ended on the same day at UT 12:00. At the time Ulysses was near the southern polar pass region. NOAA listed the proton flux start time as Nov 8 at UT 23:50. This CME event could be associated with the 14800 pfu event.

The Ulysses detectors indicated that a CME event started on September 27 2001 at UT 12:30 (DOY 271) and ended on September 28 2001 at UT 14:50 (DOY 272). At the time Ulysses was near the northern polar pass. NOAA listed the proton flux start time as September 24 at UT 12:15. This CME event could be associated with the 12900 pfu event. The proton flux had a slow leading edge in contrast to the 14800 pfu event and was consistent with the longer propagation time revealed by the Ulysses detectors. The subsequent time delay and Ulysses location is consistent with the diffusion interpretation.

The Fokker Planck equation description of the convection and diffusion of solar cosmic rays could be used for the 14800 pfu and 12900 pfu events. The analytical solution showed that the number density as a function of time t scales as (t^{-n}) for large t for the following three cases (Fisk 1968). Let V be the solar wind speed, D = kr where k is the constant diffusion coefficient and r the radial distance, and the energy injection follows a power law E^{-u}.

Case 1:
n = 3 for simplified diffusion equation only

Case 2:
n = (3 + V/k) for the simpflied convection and diffusion equation

Case 3:
n = (1 + η) for the full Fokker Planck equation, that is, with energy loss in scattering, convection and diffusion
$\eta = (2+V/k)^2 + 16V(u-1)/3k$

The 12900 pfu event 100 Mev proton flux rate decayed as $t^{-4.4}$ and the 14800 pfu event 100 Mev proton flux rate decayed as $t^{-4.3}$. The corresponding n would be 3.4 and 3.3 with an average of 3.35.

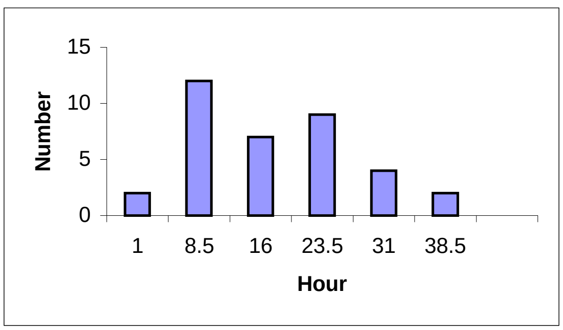
Using the numerical values in Fisk 1968 where V = 400 km/s, u= 4, D = kr = $2x10^{21}$ cm^2 sec^{-1} at r = 1 AU, the value n = 3.3 was obtained. Therefore we concluded that the 12900 pfu and 14800 pfu events were dominated by convection-diffusion mechanism in the 100 Mev range.

The 24000 pfu event 100 Mev proton flux rate decayed as $t^{-6.2}$ and the 31700 pfu event 100 Mev proton flux rate decayed as $t^{-7.4}$. These fast decay rates might suggest a focused transport mechanism (Kocharov 1996, 1998).

The 18900 pfu event 100 Mev proton flux rate decayed unusually rapidly, as (t^{-17}), after a double-peak feature. This is the data point which was excluded from the decay time vs. peak flux correlation above.

The 29500 pfu event 100 Mev proton flux rate decayed as (t^{-12}) with a double-peak feature. These large index values were the result of using the first peak starting time as t = 0. The index would be about –12 for the 18900 pfu event and about –6 for the 29500 pfu event if the second peak onset of uprise was used as t =0. An interpretation was proposed recently (Vainno 2003): the first peak feature was attributted to the SEP promptly escaping from the Sun before the Alfven waves grew significantly, and the delayed second peak started as the CME shock reached distances where the Alfven wave speed decreased.

The waiting time distribution of CME was recently reported by (Wheatland 2003), where several Poisson distributions were used in the data fitting. In this project, the halo CME waiting time distribution was examined. The halo CME dataset in the literature was used (Michalek 2002). There are 128 data points.



The waiting time distribution for halo CME events.

The distribution mode is at 8.5 hours suggesting that collision with a preceeding halo CME event is not uncommon.

6. Conclusion

The inclusion of the Oct 28, 2003 storm gave a straighter curve with a higher correlation coefficient than without it. The high coefficient suggests that it is a usual storm. The low flux event corresponds to convection-diffusion. The high flux events appear to have a high speed CME signature, with the latest Oct 2003 event fitting properly into the family. The very rapid decay time at 100 Mev for the 2001 Nov 22 event was unusual.

7. Acknowledgements

We thank Dr. Leon Johnson for discussion on this project, he and NASA/OSS Grant NAG-5-10142 for student support and for helpful discussion. We also thank Dr. Shermane Austin (NASA/MU-SPIN NCC 6-530) for helpful suggestions. DEC serves in the City University of New York NYC Space Science Research Alliance (NAG-5-10142). PJM and TDC serve in the City University of New York Queensborough Community College Physics Department.

The CME catalog used in this project is generated and maintained by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA.

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