

Space Weather impacts on Aviation

PECASUS advisories for ICAO

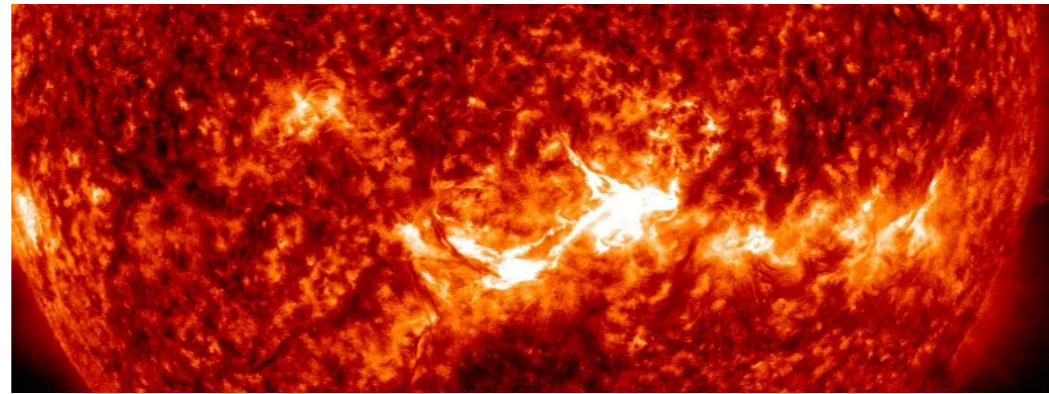
Course by the
Solar-Terrestrial Centre of Excellence



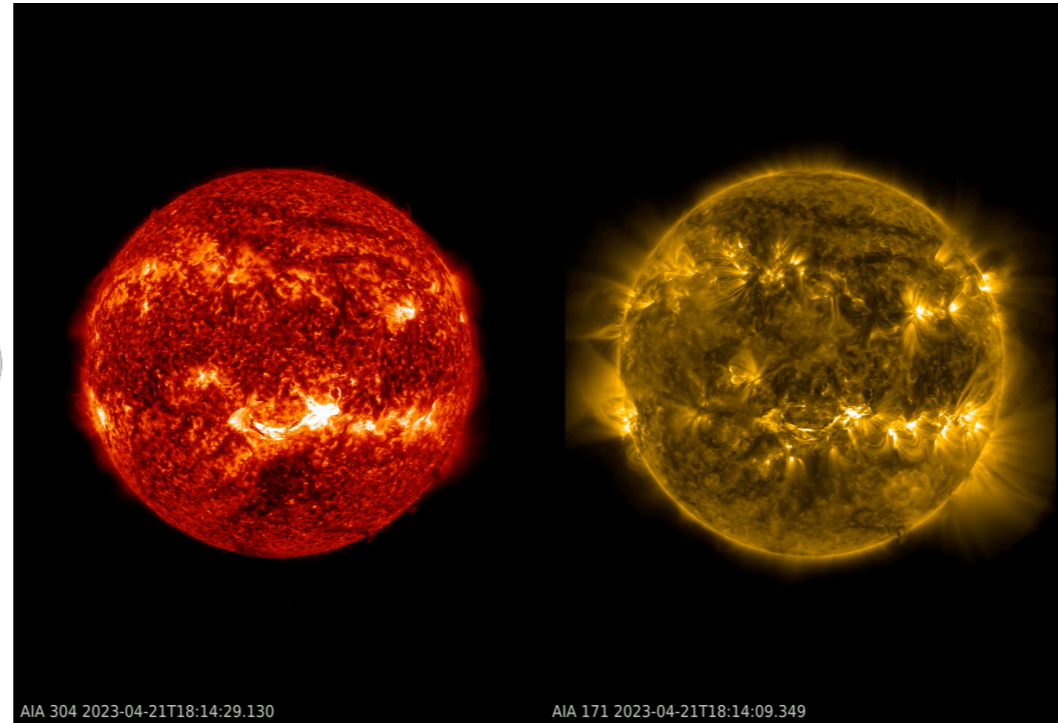
March 2024

Solar and heliospheric storms impacting aviation

CASE STUDY - April 21, 2023



Solar Observations



<https://www.jhelioviewer.org/>



Event on April 21, 2023 as seen by the SDO/AIA telescope in the 304Å and 171Å wavelengths.

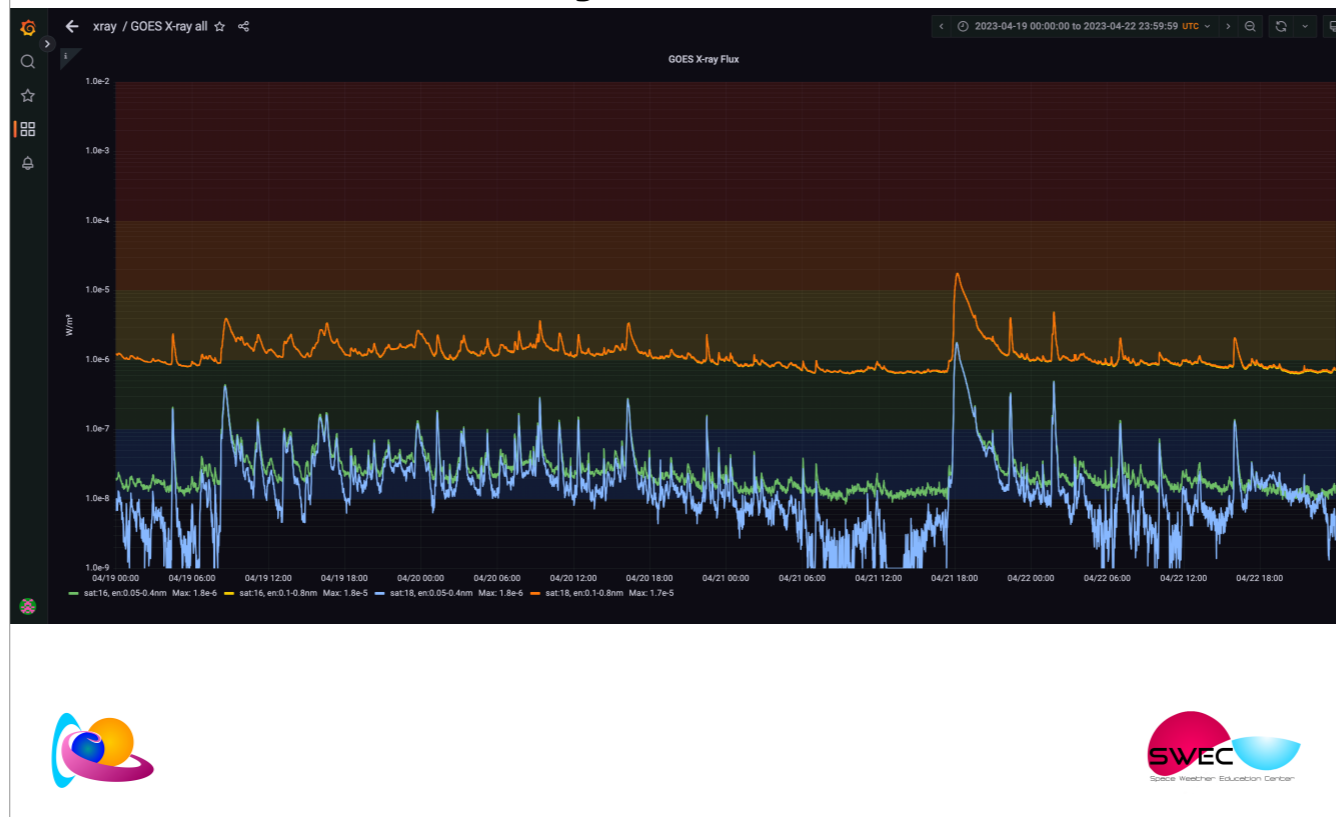
The red sun (304 Å) shows a brightening and an erupting filament, a magnetic structure above the solar surface that erupts and drags the plasma attached to it into space, forming a coronal mass ejection (CME).

The yellow sun (171Å) also shows a flash of light (solar flare) and plasma moving outwards.

The source region is at the center of the solar disk. Because the solar plasma moves outwards radially, we expect this CME to come to Earth.



GOES X-ray Flare Detection



The GOES X-ray flux shows an M-class flare of long duration which also indicates that a CME is associated to this event.

Solar Demon Flare Detection



Detector 24h operating status:

Last processed image:
 0 hours and 42 minutes ago (2023-04-27 12:36 UTC)

Last detected flare:
 1 hours and 3 minutes ago (2023-04-27 12:15 UTC)

Animations and brightness graph
[fixed brightness](#)
[adaptive brightness](#)

Navigation
 Please send me [back](#).

location of flare 11575

Flare 11575

Details for flare #: 11575

time	seq #	brightness	size	lat	lon	X,Y in R _⊙	dist. R _⊙	Blooming	Img ID
2023-04-21 17:54:00	1	10.2	68	-20.4	12.8	0.21, -0.27	0.34	0	2763782
2023-04-21 18:00:00	2	123.9	631	-20.3	13.0	0.21, -0.27	0.34	0	2763787
2023-04-21 18:03:00	3	178.2	824	-20.4	12.9	0.21, -0.27	0.34	0	2763788
2023-04-21 18:06:00	4	211.8	933	-20.6	12.7	0.21, -0.27	0.34	0	2763789
2023-04-21 18:09:00	5	238.9	999	-20.7	12.7	0.21, -0.27	0.34	0	2763790
2023-04-21 18:12:24	6	278.7	1085	-20.9	12.5	0.20, -0.28	0.34	0	2763791
2023-04-21 18:15:00	7	310.6	1103	-21.0	12.4	0.20, -0.28	0.34	0	2763792
2023-04-21 18:18:00	8	337.0	1126	-21.1	12.4	0.20, -0.28	0.35	0	2763793
2023-04-21 18:21:00	9	340.6	1149	-21.3	12.3	0.20, -0.28	0.35	0	2763802
2023-04-21 18:24:00	10	326.4	1176	-21.5	12.2	0.20, -0.29	0.35	0	2763803
2023-04-21 18:27:00	11	304.0	1198	-21.8	12.0	0.20, -0.29	0.35	0	2763804
2023-04-21 18:30:00	12	272.8	1157	-22.0	11.9	0.19, -0.30	0.35	0	2763805
2023-04-21 18:33:00	13	241.4	1075	-22.3	11.8	0.19, -0.30	0.36	0	2763806
2023-04-21 18:36:00	14	217.6	998	-22.6	11.7	0.19, -0.31	0.36	0	2763807
2023-04-21 18:39:00	15	198.4	921	-22.8	11.7	0.19, -0.31	0.36	0	2763808
2023-04-21 18:42:00	16	192.9	932	-23.0	11.7	0.19, -0.31	0.36	0	2763809

Solar Demon estimated flare class:

M1

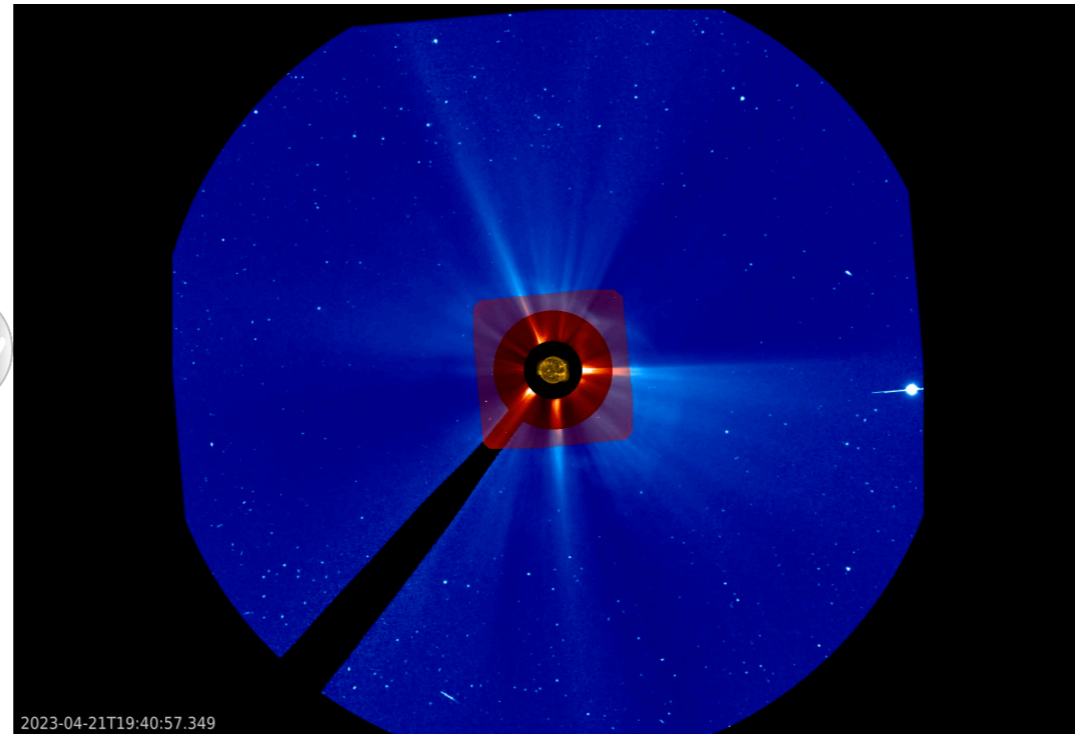


<https://www.sidc.be/solardemon/>



The automatic flare detection by Solar Demon also reported an M1 flare.

Coronagraph observations



2023-04-21T19:40:57.349



<https://www.jhelioviewer.org/>



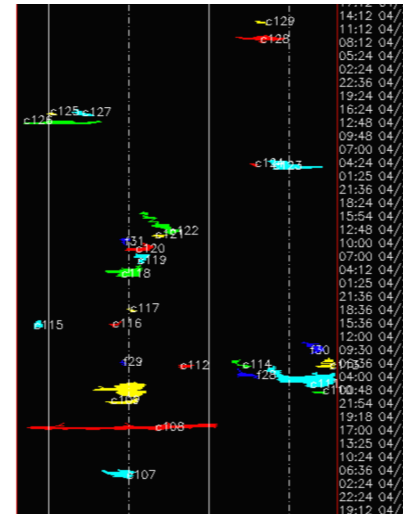
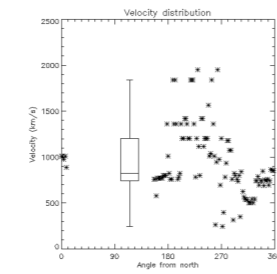
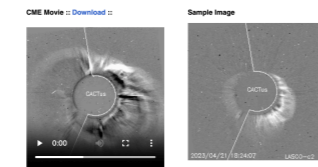
The filament eruption resulted in a halo CME, which means the plasma cloud can be seen expanding in all directions. A halo CME is either coming straight to Earth or away from us. In this case, it is coming towards us as the source region was on the Earth-facing side of the Sun at the time of eruption. We the forecaster sees this, a warning needs to be sent as soon as possible.

CACTus detection



Details and graphs for CME0108

CME | ID | dt0 | pa | da | dv | mindv | maxdv | halo? |
0108|2023/04/21 18:12| 01 | 263 | 212 | 0821 | 0375 | 0248 | 1838 | 111



```
14:12 04/25
11:12 04/25
08:12 04/25
05:24 04/25
02:24 04/25
22:36 04/24
19:24 04/24
16:24 04/24
12:48 04/24
09:48 04/24
07:00 04/24
04:24 04/24
01:25 04/24
21:36 04/23
18:24 04/23
15:54 04/23
12:48 04/23
10:00 04/23
07:00 04/23
04:12 04/23
01:25 04/23
21:36 04/22
18:36 04/22
15:36 04/22
12:00 04/22
09:30 04/22
06:36 04/22
04:00 04/22
00:48 04/22
21:54 04/21
19:18 04/21
17:00 04/21
13:25 04/21
10:24 04/21
06:36 04/21
02:24 04/21
22:24 04/20
19:12 04/20
```

A halo or partial-halo CME was detected with the following characteristics:

```
to dt0l pa l da l v l dv l minv l maxv |
2023-04-21T18:12:08.030 | 1.0 | 267 | 220 | 844 | 194 | 1838
```

to: onset time, earliest indication of liftoff
dt0: duration of liftoff (hours)
pa: principal angle, counterclockwise from North (degrees)
da: angular width of the CME (degrees),
v: median velocity (km/s)
dv: variation (1 sigma) of velocity over the width of the CME
mindv: lowest velocity detected within the CME
maxdv: highest velocity detected within the CME

```
#-----#
# Solar Influences Data analysis Center - RWC Belgium #
# Royal Observatory of Belgium #
# #
# Website http://www.sidc.be #
# E-mail sidc-support@oma.be #
# To unsubscribe http://www.sidc.be/registration/unsub.php #
# #
# Legal notices: #
# - Intellectual Property Rights: #
# http://www.astro.oma.be/common/internet/en/data-policy-en.pdf #
# - Liability Disclaimer: #
# http://www.astro.oma.be/common/internet/en/disclaimer-en.pdf #
# - Use and processing of your personal information: #
# http://www.astro.oma.be/common/internet/en/privacy-policy-en.pdf #
#-----#
```



<https://www.sidc.be/cactus/>



The CACTus tool automatically detects CME in coronagraph images.

The velocity distribution shows a large spread in velocity, ranging up to 1800 km/s.

The detected angular width shows that not the full CME was detected. It is in fact a full halo CME and not a partial one.

A halo CME alert was sent during the night, when the full coronagraph data was processed

PRESTO

#-----#

:Issued: 2023 Apr 21 2235 UTC

:Product: documentation at <http://www.sidc.be/products/presto>

#-----#

FAST WARNING 'PRESTO' MESSAGE from the SIDC (RWC-Belgium)

#-----#

A fast **full halo** coronal mass ejection (CME) was first observed in the LASCO/C2 chronograph imagery around 18 UTC on April 21st. The CME was driven by a **long-duration M-class flare** from NOAA AR 3283 (beta): an M1.7 flare with start time 17:44 UTC, peak time 18:12 UTC, end time 18:37 UTC on April 21st, and related **filament eruption** on the central meridian close to the disc centre. The estimated projected velocity of the CME is above 1100 km/s and preliminary analysis suggests an estimated **arrival at Earth on April 24th**. Due to the fast nature and location of the CME, moderate to major **geomagnetic storms** could be anticipated during the arrival with chances of reaching severe storm levels. The greater than 10 MeV GOES **proton flux might also be enhanced** in the next days due to particle acceleration at the CME front shock.

#-----#

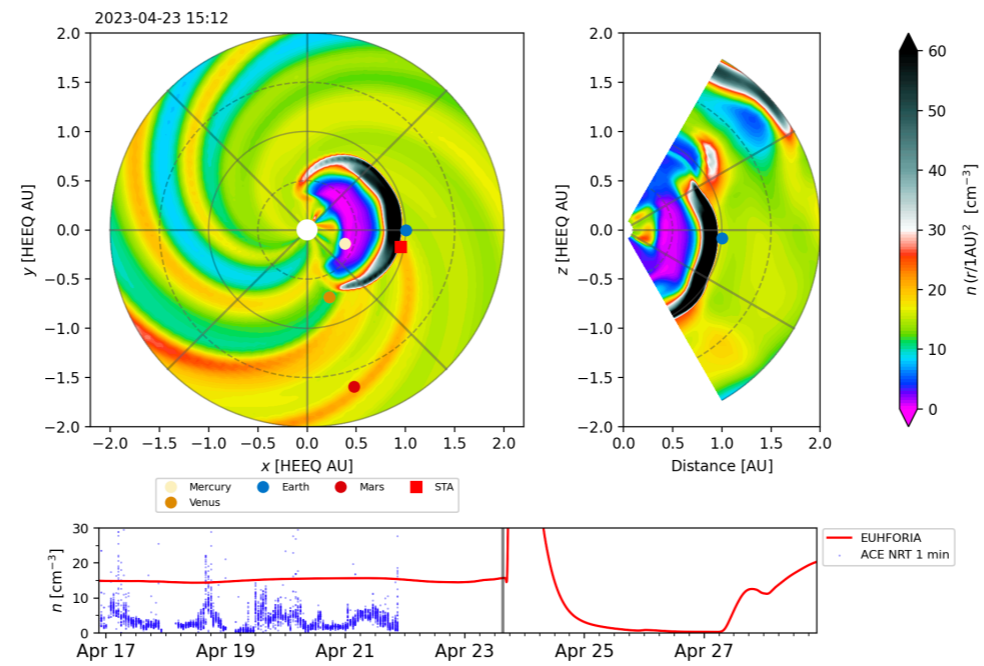


The forecaster sent out a PRESTO message after a first, quick analysis.

This is an SIDC fast warning message for an earth-directed CME manually created by the forecaster.

This presto was sent late in the evening. Our forecaster also work at night in case of important space weather.

EUHFORIA CME modeling



Next, the forecaster will run a model simulation to have a better estimate of the arrival time. This resulted in an arrival time prediction for late evening on April 23. This is slightly earlier than the first estimation, which was purely based in a projected (and thus underestimated speed).

The picture is the output of a simulation by EUHFORIA of the cloud propagation in the heliosphere. Left is a 'top' view of the sun (white dot) and the earth (blue dot). The black structure is the front of the magnetic cloud (purple) that reaches the earth. On the right is a side view of space. At the bottom, you see that the density curve goes through the roof at the time of arrival.

SIDC URSIGRAM 30422
 SIDC SOLAR BULLETIN 22 Apr 2023, 1234UT
 SIDC FORECAST (valid from 1230UT, 22 Apr 2023 until 24 Apr 2023)
 SOLAR FLARES : C-class flares expected, (probability >=50%)
 GEOMAGNETISM : Active conditions expected (A>=20 or K=4)
 SOLAR PROTONS : Warning condition (activity levels expected to increase, but no numeric forecast given)
 PREDICTIONS FOR 22 Apr 2023 10CM FLUX: 148 / AP: 010
 PREDICTIONS FOR 23 Apr 2023 10CM FLUX: 148 / AP: 018
 PREDICTIONS FOR 24 Apr 2023 10CM FLUX: 148 / AP: 065
 COMMENT: Solar flaring activity reached moderate levels in the past 24 hours with an isolated low M-class flaring from NOAA AR 3283 (beta), namely a long duration M1.7 flare, start time 17:44 UTC, peak time 18:12 UTC, end time 18:37 UTC on April 21st. This flaring activity was driven by a nearby filament eruption and no other significant flaring was observed from NOAA AR 3283. NOAA AR 3279 (alpha) was also triggered by the magnetic field reconfiguration during the previous eruptions and has produced multiple C-class flaring, the most significant one being a C4.8 flare, peak time 01:48 UTC on April 22nd. NOAA AR 3285 (beta) was numbered and has produced isolated low C-class flaring. NOAA AR 3282 (beta-gamma) remains the largest and most complex region on the visible solar disc, but has been quiet and inactive. The remaining active regions are relatively simple and have shown no significant flaring. The solar flaring activity is expected to be at low levels over the next 24 hours with chances for further isolated M-class flaring.

A fast full halo coronal mass ejection (CME) was first observed in the LASCO/C2 chronograph imagery at 18:12 UTC on April 21st. The CME was driven by a long-duration M-class flaring from NOAA AR 3283 and a related filament eruption on the central meridian close to the disc centre. The estimated projected velocity of the CME is close to 1100 km/s and current analysis suggests an estimated arrival at Earth late April 23rd to early April 24th. The nature and location of the CME suggest strong impact on Earth. No other Earth-directed CMEs have been detected in the available coronagraph imagery.

Over the past 24 hours the greater than 10 MeV GOES proton flux was at nominal levels and is expected to register gradual enhancements over the next 24 hours with the possibility of reaching minor radiation storm levels. The greater than 2 MeV electron flux has been below the 1000 pfu threshold and is expected to remain so. The 24h electron fluence was at nominal levels and is expected to remain so over the next 24 hours.

Over the past 24 hours the solar wind parameters (ACE and DSCOVR) were mainly at background slow solar wind levels with an indication of a sector boundary crossing in the evening of April 21st. The solar wind velocity varied around 400 km/s and is currently reaching 450 km/s. The interplanetary magnetic field was weak with a maximum value of 6.6 nT and a minimum Bz of -6.5 nT. The B field was switching orientation between the positive and the negative sector (directed away from and towards the Sun). The solar wind conditions are expected to remain mostly at background slow solar wind regime over the next 24 hours with possible slight enhancements later today pending a mild high speed stream arrival from a narrow patchy negative polarity coronal hole, which crossed the central meridian on April 18th. Strong solar wind disturbances are expected on April 24th with the anticipated arrival of the full halo CME related to the M1.7-flaring from NOAA 3283 (beta) and a nearby filament eruption around 18:00 UTC on April 21st. The CME-related shock might arrive late on April 23rd.

The geomagnetic conditions over the past 24 hours were globally quiet to unsettled and locally registered an isolated active period over Belgium in the interval of 21-22 UTC after prolonged periods of negative Bz. Quiet to unsettled geomagnetic conditions are expected over the next 24 hours with probable active periods pending an anticipated mild high speed stream arrival. Moderate to major geomagnetic storms might be expected in the night of April 23rd with chances for severe storm levels on April 24th due to an expected ICME arrival.

TODAY'S ESTIMATED ISN : 109, BASED ON 15 STATIONS.
 SOLAR INDICES FOR 21 Apr 2023
 WOLF NUMBER CATANIA : 136
 10CM SOLAR FLUX : 151
 AK CHAMBON LA FORET : 014
 AK WINGST : ///
 ESTIMATED AP : 012
 ESTIMATED ISN : 110, BASED ON 19 STATIONS.

NOTICEABLE EVENTS SUMMARY
 DAY BEGIN MAX END LOC XRAY OP 10CM Catania/NOAA RADIO_BURST_TYPES
 21 1744 1812 1844 S22W11 M1.7 2N 110 61/3283 II/3V/3IV/2

Daily bulletin of the day after the eruption.

Noticeable events summary also indicate that the filament eruption was associated with several types off radio bursts that can be linked to the CME.

SIDC **URSIGRAM** 30423
SIDC SOLAR BULLETIN 23 Apr 2023, 1230UT
SIDC FORECAST (valid from 1230UT, 23 Apr 2023 until 25 Apr 2023)
SOLAR FLARES : C-class flares expected, (probability >=50%)
GEOMAGNETISM : Major (ISES: Severe) magstorm expected (A>=100 or K>=7)
SOLAR PROTONS : Warning condition (activity levels expected to increase, but no numeric forecast given)
PREDICTIONS FOR 23 Apr 2023 10CM FLUX: 140 / AP: 030
PREDICTIONS FOR 24 Apr 2023 10CM FLUX: 140 / AP: 082
PREDICTIONS FOR 25 Apr 2023 10CM FLUX: 140 / AP: 021
COMMENT: Solar flaring activity at low levels over the past 24 hours with only isolated low C-class flaring. There are six numbered active regions on the visible solar disc. The largest and most complex one, NOAA AR 3282 (beta-gamma), has remained stable and inactive. The strongest activity was a C2.2 flare, peak time 06:40 UTC on April 23rd, produced by NOAA AR 3279 (beta). The rest of the active regions, including a newly formed unnumbered region near NOAA AR 3285 (beta), have been stable and inactive. The solar flaring activity is expected to be at low levels over the next 24 hours with low chances for isolated M-class flaring.

No Earth-directed coronal mass ejections (CMEs) have been detected in the available coronagraph imagery over the past 24 hours. The halo CME related to M-class flaring and filament eruption on April 21st is expected to arrive to Earth over the next 24 hours.

Over the past 24 hours the greater than 10 MeV GOES proton flux was elevated, remaining well below radiation storm levels. The greater than 10 MeV GOES proton flux is expected to remain enhanced over the next 24 hours with the chances of reaching minor radiation storm levels. The greater than 2 MeV electron flux has been below the 1000 pfu threshold and is expected to remain so. The 24h electron fluence was at nominal levels and is expected to remain so over the next 24 hours.

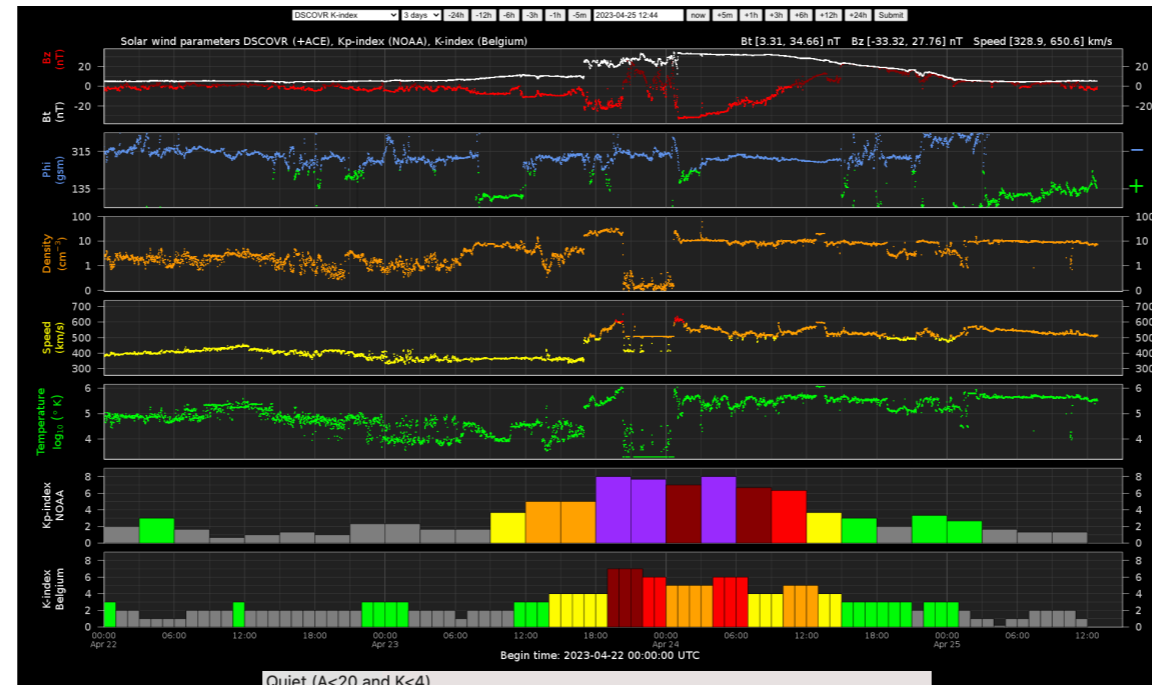
Over the past 24 hours the solar wind parameters (ACE and DSCOVR) were mainly at background slow solar wind levels until around 08:00 UTC on April 23rd when the beginning of an ongoing disturbance was first observed. It is too early to determine the nature of this disturbance, but it could be a precursor of the expected ICME arrival. The solar wind velocity varied from 329 km/s to 457 km/s. The interplanetary magnetic field reached a maximum value of 11.8 nT and a minimum Bz of -11.7 nT. The B field was mostly in the negative sector with some switch backs to the positive sector (directed away from the Sun). The solar wind conditions are expected to be significantly perturbed over the next 24 hours with an anticipated strong ICME arrival, related to the CME driven by M-flaring and filament eruption on April 21st.

The geomagnetic conditions over the past 24 hours were globally quiet and locally quiet to unsettled over Belgium. The geomagnetic conditions are expected to be significantly elevated over the next 24 hours with expected moderate to major geomagnetic storms and chances for severe storm levels due to an expected ICME arrival.



Ursigram (daily bulletin) for the next day, the day when the CME is expected to arrive late in the evening.
Some disturbance is already seen in the solar wind, but it is not clear yet whether it is the CME arriving. More data is needed to make that analysis.

CME arrival



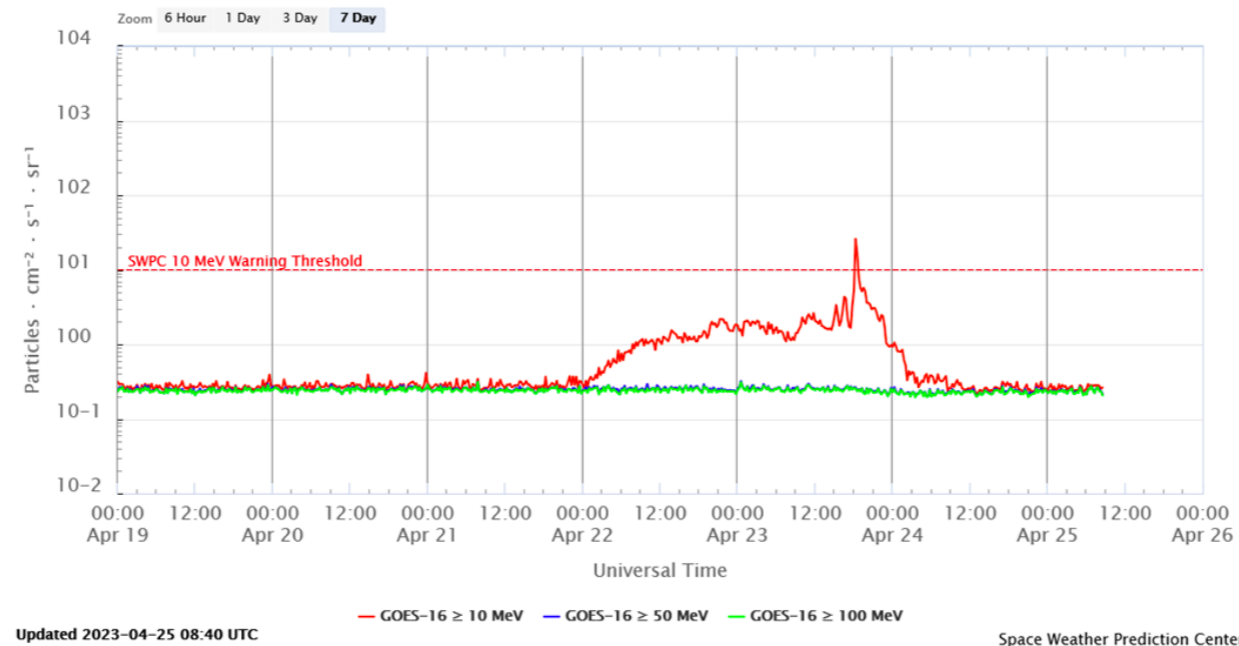
The satellite DSCOVR is at a point 1 hour upstream of the earth, which means that it takes the solar wind 1 hour to reach the Earth, 'saw' the cloud passing and measured a jump on **April 23, 17UT** as seen in the top panel of the graph below. The cloud induced a **severe geomagnetic storm on the planetary level** (purple rectangles in the 6th panel)) and a **moderate geomagnetic storm locally** in Belgium (dark red rectangles in the 7th panel).

These graphs show (from top to bottom): the outward component of the magnetic field, the total magnetic field, the direction of the magnetic field, the density of the solar wind, the velocity of the solar wind, the temperature of the solar wind, The planetary K-index and the Local K-index for Belgium.

Solar wind speed jumped from 360 to 475 km/s, then gradually further increased to values near 700 km/s by 21:00UTC. Bz, the north-south component of the interplanetary magnetic field, showed 2 prolonged periods of negative values: during the 17-20UTC interval, when its value was at a fairly stable -24 nT, and again on 24 April during the 01-09UTC interval when Bz evolved from -33 nT to -9 nT. The Bz value of -33 nT was the lowest since the 7 September 2017 storm (also -33 nT). For even more negative Bz, we have to go back all the way to the Solstice storm of 22 June 2015 when it reached values of -39 nT.

Proton Event

GOES Proton Flux (5-minute data)



Quiet
Proton event expected (10 pfu at >10 MeV)
Major proton event expected (100 pfu at >100 MeV)
Proton event in progress (>10 MeV)
Warning condition (activity levels expected to increase, but no numeric forecast given)



A shock was recorded in the solar wind parameters on 23 April at 17:00UTC (DSCOVR ; graph). It marked the **somewhat (a few hours) earlier-than-expected arrival of the interplanetary coronal mass ejection (ICME)**. The passage of the shock briefly drove the already enhanced greater than 10 MeV proton flux finally above the proton event threshold (10 pfu), with a maximum of 26 pfu recorded at 18:20UTC (graph underneath). This is called an Energetic Storm Particles event (ESP), and originates from the acceleration of charged particles by a fast, usually ICME-driven shock in interplanetary space (e.g. Ameri et al. 2023). The proton flux drops sharply after the **shock** passage, as was the case here.

```
#-----#
:Issued: 2023 Apr 23 1833 UTC
:Product: documentation at http://www.sidc.be/products/presto
#-----#
# FAST WARNING 'PRESTO' MESSAGE from the SIDC (RWC-Belgium) #
#-----#
A fast forward shock was observed in the solar wind at 17:00 UTC on April 23rd marking the expected arrival of a fast CME, which lifted off the solar surface on April 21st as a result of long duration M-class flaring triggered by a neighbouring filament eruption. The interplanetary magnetic field jumped from 9 nT to 26 nT with Bz reaching -24 nT. The solar wind velocity increased from 360 km/s to 480 km/s and the density jumped from 4.8 ppcc to 16.8 ppcc. The solar wind speed around 17:45 UTC has reached 527 km/s. The current geomagnetic conditions are active over Belgium and globally at minor storm levels. Moderate to major storms are expected in the upcoming hours with the ongoing ICME arrival. The greater than 10 MeV GOES proton flux has reached minor radiation storm levels and is expected to continue to increase, possibly reaching moderate radiation storm levels.
#-----#
```



Whenever a shock is observed in the solar wind, the forecaster is required to send out a presto message.

```
#-----#  
:Issued: 2023 Apr 23 2026 UTC  
:Product: documentation at http://www.sidc.be/products/presto  
#-----#  
# FAST WARNING 'PRESTO' MESSAGE from the SIDC (RWC-Belgium) #  
#-----#  
A major geomagnetic storm has been registered over Belgium due to an ongoing  
ICME arrival. The solar wind velocity has exceeded 610 km/s with interplanetary  
magnetic field values of 27 nT and a minimum BZ component of -25 nT. The solar  
wind density has exceeded 32 ppcc and the temperature is above 1 MK. The  
geomagnetic conditions are expected to remain at moderate to major storm levels in  
the upcoming hours. The greater than 10 MeV GOES proton flux remains enhanced,  
but has decreased to below minor storm radiation levels. Related to the storm there  
are ongoing strong ionospheric scintillations and post storm depressions, as well as  
some polar cap and auroral absorptions.  
#-----#
```



Another PRESTO sent by the forecaster, almost 2h later. This time the trigger for sending is the geomagnetic storm observed locally in Belgium.
At the end of this presto warning there is already a hint of the ionospheric effects that this eruption had.

:Issued: 2023 Apr 24 0909 UTC
:Product: documentation at <http://www.sidc.be/products/presto>
#-----#
FAST WARNING 'PRESTO' MESSAGE from the SIDC (RWC-Belgium) #
#-----#
The Corona Mass Ejection (CME) arrival first reported yesterday continues to cause a major geomagnetic storm. Although the solar wind velocity has now dropped to 500 km/s and the North-South component of the interplanetary magnetic field (Bz) has now increased to -10 nT, the Kp index has reached the **severe level** (Kp=8, G4). The geomagnetic conditions are expected to gradually decrease in the next several hours. Currently severe post storm depressions have been observed in various locations, and high auroral absorption.
#-----#



The next morning the forecaster sent yet another PRESTO, this time because the severe storm level (Kp =8) was reached. This were very busy days for the forecaster: many warning presto's were sent and in between the forecaster also had to take care of the daily bulletins, run models, check data, etc. In solar max it really can be a full time job just to monitor everything, especially when there are multiple eruption to track at the same time.

Impacts

25/04/2023 08:32 UTC

PECASUS DASHBOARD on 2023-04-23 20:00 UTC

GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2023-04-23 20:00	0.38	QUIET		0.41	QUIET
Phase Scintillation	0.4	0.7	2023-04-23 20:00	0.26	QUIET		1.06	SEVERE
Vertical TEC	125	175	2023-04-23 20:00	132.14	QUIET		132.14	MODERATE

RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FL ≤ 460	30	80	2023-04-23 20:00	0	QUIET		0	QUIET
Effective Dose FL > 460	/	80	2023-04-23 20:00	0	QUIET		0	QUIET

HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
Auroral Absorption (AA)	8	9	2023-04-23 20:00	8.0	MODERATE		8.0	MODERATE
Polar Cap Absorption (PCA)	2	5	2023-04-23 20:00	2.35	MODERATE		4.64	MODERATE
Shortwave Fadeout (SWF)	x1.0	x10.0	2023-04-23 20:00	< M5 flare	QUIET		< M5 flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2023-04-23 20:00	2	SEVERE		2	SEVERE

Sound alarm is triggered when MOD or SEV thresholds are exceeded or in case of data outages.



This case study is not finished because we did not discuss what is arguably the most important to users, and that is the impacts. There is a hint in the last lines of these presto's. This will be discussed in the lecture tomorrow. The PECASUS dashboard gives us a first glimpse as well. The colors red and orange give a clear visual indication that something is going on.