Investigation of extreme solar storms based on satellite observations: The impact on early Earth studies

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Introduction

Coronal mass ejections (CME) and solar flares cause disturbances of the Earth’s upper atmosphere leading to increased exobase densities and temperatures. High-precision accelerometers on board of the GRACE mission are used to investigate the variation of the neutral density. We focus on the X17.2 Halloween flare in Oct./Nov. 2003 which had an intensity flux in the EUV range 2.5 times higher compared to moderate solar activity. Compared to solar-type stars of different ages, the conditions during the active flare correspond to the Sun at an age of 2.3 Gyr. Such extreme solar events can be used as proxies of the young Sun and may have an important impact on the investigation of the evolution of early Earth's atmosphere.

The Halloween period

During the spectacular Halloween period in late October/early November 2003, several X-class flares, more than 40 CMEs, 5 solar energetic particle events and two strong geomagnetic storms occurred. One extreme event was the X17.2 flare on October 28, 2003. The strong flare started at 09:51 UT with its maximum peak at 11:10 UT and was associated with a very fast halo CME. Due to the impressive velocity of more than 2200 km/s, this CME was one of the fastest ever recorded.

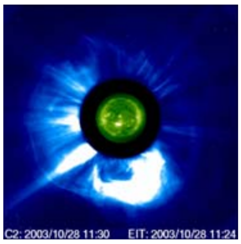

Fig.1: X17.2 flare on Oct. 28, 2003 recorded with EIT and the associated halo CME recorded with LASCO. (NASA/ESA)

In-situ measurements in the exobase by GRACE

In this study we solely focus on the along track acceleration of the GRACE spacecraft (S/C). After the calibration of the raw measurements, we further reduced the accelerations by the amount attributable to the solar radiation pressure. The neutral density ρ can than be deduced through the atmospheric drag equation.

$$F_d = m\, a_x = \frac{1}{2}\rho\, \mathrm{v}_i^2 C_d\, A_{ref}$$

The resulting atmospheric drag force, F_d, mainly depends on the shape and attitude of the S/C among other effects. Thus the drag coefficient, C_d, is treated as a highly variable quantity. The formalism underlying this study is an analytical expression of Sentman’s treatise (1961) of the drag coefficient, elaborated by K. Moe (2005). It incorporates the random thermal motion of the incident molecules, and assumes that all molecules are diffusely reemitted. The evaluations of the years 2003-2005 yielded a drag coefficient of 2.8-3.4. The main variation is caused by the elliptical satellite orbit. For this reason the determined neutral densities were normalized to an average S/C altitude of 490 km. Fig. 2 shows neutral densities from GRACE in a latitude-time plot during the Halloween period. Shortly before 12:00 UT we observe the first sudden rise in neutral density of approximately 60%. The major impact appears 19h hours later when the shock wave of the large CME disturbs the Earth magnetic field.

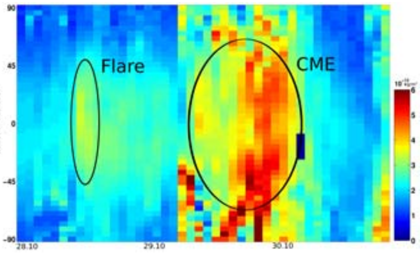

Fig. 2: Impact of the geomagnetic storm on the neutral densities determined from GRACE accelerations (normalized to 490 km, LT 16:19).

Additionally, we calculated total mass densities using the empirical thermosphere models NRLMSISE-00 and Jacchia-Bowman 2008 (JB08). Fig 3 illustrates the resulting neutral densities during the event. Especially the MSIS model shows clear deviations from the in-situ measurements before and after the event. In contrast to that, the JB08 model provides a considerable better correlation with GRACE densities. In addition, both models offer the possibility to calculate exospheric temperatures.

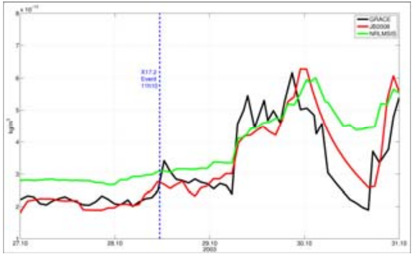

Fig. 3: Comparison of atmospheric densities from various sources during the Halloween period.

The JB08 model uses various solar indices (F10,M10,S10,Y10) as a proxy for solar EUV and FUV. These indices are given as daily and 81-day averaged values. For the analysis of the flare event we calculated factors by comparing the EUV flux with the corresponding solar index over a specific time. Thus we obtain indices which represent the peak intensity of the flare.

Based on these considerations, we have evaluated the JB08 model using the estimated peak indices. Assuming such a high solar radiation the total mass density rises to approximately 1.8x10^{-11} kg/m^3 and the exospheric temperature to about 1950 K during the flare event.

Analysis of the flare event

The Halloween X17.2 flare is used as a solar proxy to investigate the EUV radiation of the young Sun. This allows the exploration of the influence of the EUV radiation of the young Sun on Earth’s atmosphere by analyzing the solar EUV flare spectrum and measuring the response on atmospheric density and temperature.

The spectrum of this specific flare is presented in Fig. 4, recorded with the Coronal Diagnostic Spectrometer (CDS) shown in green, and with the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) shown in red. The black spectrum represents the intensity flux during moderate solar activity conditions. The intensity flux of the Halloween flare is 2.5 times higher compared to solar quiescence.

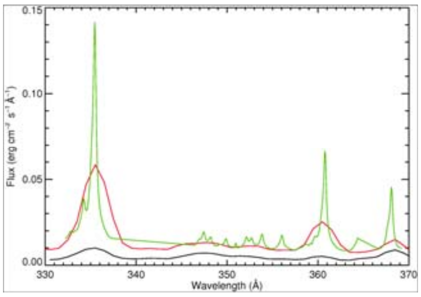

Fig. 4.: Flare Spectrum with CDS (green) and TIMED (red) and the over-plotted black spectrum of moderate solar activity.

Halloween flare compared to solar-like stars

To reconstruct the evolution and history of the young Sun, Ribas et al. (2005) analyzed a series of solar-like stars of different ages using multi-wavelength observations in the „Sun in Time“ program. According to these results the early Earth's atmosphere was exposed to a much higher level of solar radiation than nowadays. If the flare flux is compared to intensity-age power laws of Ribas et al. (2005) in the EUV range, this event corresponds to the conditions of a solar-like star at the age of 2.3 Gyr. The intensity fluxes of the flare event in different wavelength regimes fit in very well in Table 1, where they are compared to solar-like stars of different ages and our Sun today.

Wavelength (Å)	0.1 Gyr	0.3 Gyr	0.65Gyr	1.6 Gyr	2.3 Gyr	4.56 Gyr
100-360	187.2	69.4	22.7	7.7	**2.7**	2.05
360-920	45.6	15.2	7.0	2.85	**1.99**	1.00
920-1180	18.1	8.38	2.90	1.70	**1.64**	0.74
335 (Fe XVI)	36.6	9.7	2.6	-	**0.11**	-
361 (Fe XVI)	15.7	6.6	1.6	-	**0.06**	0.016
1304 (O I)	4.3	1.18	0.6	0.45	**0.20**	0.143
1335 (C II)	4.7	1.52	0.95	0.36	**0.28**	0.18
1400 (Si IV)	4.3	1.59	0.77	0.28	**0.18**	0.083
1550 (C IV)	9.1	2.21	1.02	0.40	**0.34**	0.146
1640 (He II)	6.0	0.99	0.56	-	**0.23**	0.04
1657 (C I)	4.1	0.97	0.78	0.47	**0.38**	0.202

Tab.1.: **Integrated fluxes of different solar-like stars of various wavelength ranges (Ribas et al., 2005) including several emission lines. The solar measurements of the flare event are marked in bold face.**

To probe the Earth's thermosphere under extreme solar EUV conditions, Tian et al. (2008) developed a multi-component hydrodynamic thermosphere model. For the altitude of 490 km neutral densities as well as exobase temperatures are given for EUV conditions during solar mean, solar maximum, 4x EUV and 10x EUV. Thus we can be roughly estimated that during flare conditions of 2.5x EUV the neutral density would be ~2x10^{-11} kg/m^3. Figure 5 illustrates the temperature at the exobase with increasing EUV fluxes. During the strong X17.2 flare (2.5x EUV) the exospheric temperatures is about 1800 K. Considering the electron impact processes, shown by Tian et al. the temperature would increase to about 2200 K.

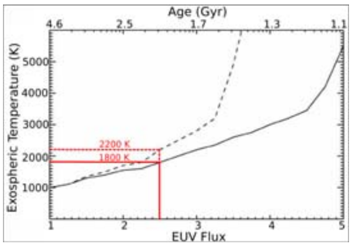

Fig. 5: Exobase temperatures under different solar EUV conditions and ages.

Summary / Discussion

- Our study indicates that extreme flare events and their atmosphere response can be used as a proxy for the young Sun (in the particular case: the Sun in an average activity range ~2.3 Gyr ago.
- More event studies of that kind will allow us to fill the gaps between data which are obtained from solar analogue stars with different ages.
- The rise in exobase temperature and expansion of the atmosphere is relevant for atmospheric escape and evolution studies.
- Our research also indicates that the upper atmosphere has a strong response to an enhanced particle energy input. Because the solar wind of the young Sun was also faster and denser, future studies will have to analyze such events too.

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