DID A MINOR GEOMAGNETIC STORM REALLY CAUSE THE LOSS OF 40 STARLINK SATELLITES?

F. Pitout[1], E. Astafyeva[2], R. Fleury[3], B. Maletckii[1] and J. He[1]

Abstract. On February 3, 2022, the SpaceX company launched 49 Starlink satellites into a parking orbit at 215 km altitude. That same day and the next, two weak geomagnetic storms yielded 40 satellites to prematurely reentry into the atmosphere. Weak mass coronal ejections whose effects may have been underestimated seem to be the cause of the loss. In this paper, we trace the sequence of events, from the Sun to the Earth, that led to this result. We use the tools of the Data Center for Plasma Physics (CDPP) and perform a diagnosis of the neutral and ionized upper atmosphere with ground and space instruments. Using the Drag Temperature Model (DTM), we show that the thermosphere mass density increased by 35% at 215 km during the storms. We also discuss thermosphere-ionosphere coupling during weak geomagnetic storms.

Keywords: geomagnetic storm, space weather, air drag, satellite orbits

1 Introduction

NOAA defines geomagnetic storms as "major disturbances of Earth's magnetosphere that occur when there is a very efficient exchange of energy from the solar wind into the space environment surrounding Earth." Storms are triggered when an solar event such as a Coronal Mass Ejection (CME), a Corotating Interaction Region (CIR), or a High Speed solar wind Stream (HSS) hits Earth's magnetosphere. The physical consequences are numerous: compression of the magnetosphere, intensification of magnetospheric currents systems, enhanced particle precipitation into the upper polar atmosphere, prompt penetrating electric field at low latitudes, etc.

To scale the strength of geomagnetic storms, one uses the Dst index and/or the Kp index. NOAA scales the storms according to the Kp index from G0 (minor) to G5 (extreme). Other authors came up with a slightly different classification. Loewe & Prlss (1997) use the Dst index to scale geomagnetic storms from "weak" to "great". Geomagnetic storms may impact ground-based or space-based infrastructure and human life or health in many different ways. In this paper, we shall focus on the consequences on the upper atmosphere (both neutral and ionized), air drag and satellite orbits.

On February 3, 2022 at 18:13 UTC, 49 Starlink satellites were dispatched into a parking orbit at 210x340 km. They should have reached their final orbit at about 500 km altitude but shortly after deployment, they were commanded to enter safe mode so as to limit the air drag due to an on-going storm. Despite the safe mode, 40 of them lost altitude in the course of the following days and reentered into the atmosphere where they burnt to ashes.

2 Observations

2.1 Heliophysical and geophysical context

In 2022, we are experiencing an increase of the solar activity with more sunspots, more filaments and prominences and more frequent extreme events (flares and CMEs). On January 29, 2022 at 23:36 UTC, a halo CME was

[1] Observatoire Midi-Pyrénées, Toulouse, France
[2] Institut de Physique du Globe, Paris, France
[3] Institut Mines-Télécom Atlantique, Brest, France

expelled, followed by another one on February 1 at 00:12 UTC. We have used CDPP's web based Propagation Tool (Rouillard et al. 2017) to estimate the arrival time of those two CMEs: February 2 for the first one and February 4 for the second.

Figure 1, generated with AMDA (Gnot et al. 2021), shows, from top to bottom, the solar wind bulk velocity, the solar wind density, the three GSE components of the IMF, and the Dst index, as functions of time.

The Storm Sudden Commencement, the moment when the magnetosphere gets compressed and the Chapman-Ferraro currents (electrical currents flowing at the magnetopause) intensifies, is seen around 23 UTC on February 1. A little more than 24h later, on February 3, a first storm develops as the ring current intensifies (negative bay of Dst index) and the Dst index reaches about -80 nT. On February 4, a second storm develops with a Dst reaching -70 nT. Both storms are classified as moderate according to Loewe & Prlss (1997), minor (G1) according to NOAA.

Let us emphasize that the Interplanetary Magnetic Field (IMF) provided by OMNI (3rd panel in 1 exhibit a negative B_z component down to almost -20nT. This strongly negative value enhance for sure the coupling between the solar wind and the magnetosphere and thus the energy deposition into the polar upper atmosphere.

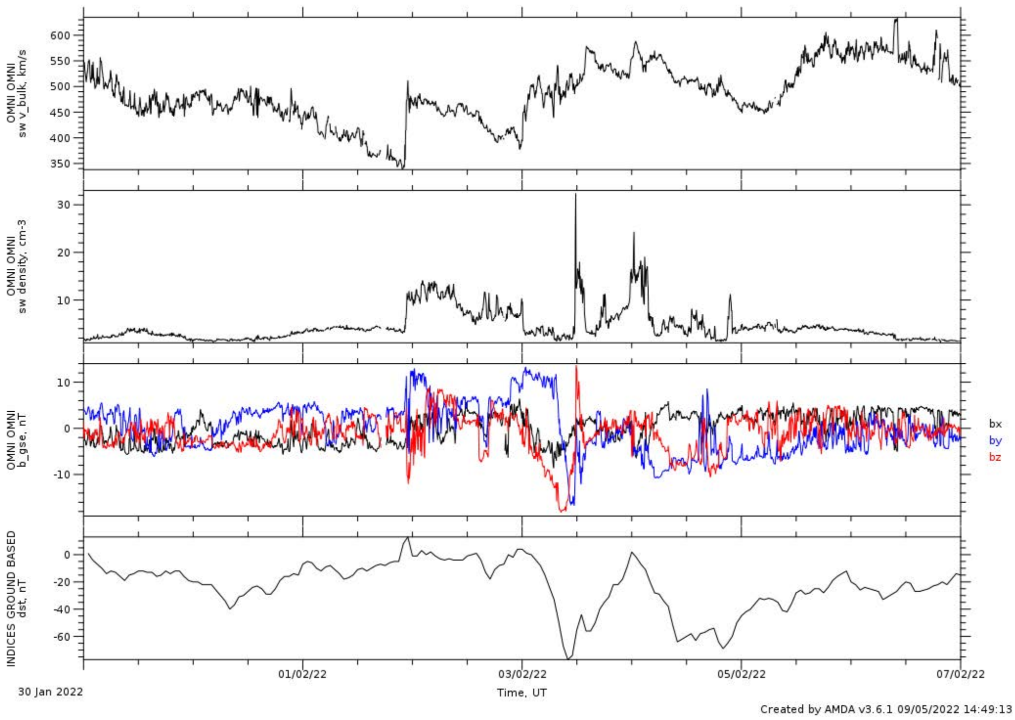

Fig. 1. Four panels show, from top to bottom, the solar wind bulk velocity, the solar wind density, the 3 GSE components of the IMF, and the Dst index as functions of universal time.

2.2 Thermospheric response

We have run several models of thermosphere to asses the density increase during the two days of the storms (February 3 and 4). Figure 2 shows the output of the Drag Temperature Model 2013 (Bruinsma 2015): the two panels show the air mass density at 215 km altitude on February 1 and 3, 2022 at 13:00 UT. February 1 is chosen as a quiet reference day. The modeled air mass density is significantly higher during the first geomagnetic storm: on the dayside, the mass density increased from about 1.85 to 2.5 g/cm^3, which correspond to an increase of 35% compared to the quiet reference day. These simulations are confirmed by space-borne measurements (not shown). Let us note that in the air drag is proportional to the air mass density (e.g., Vallado & Finkleman, 2014) so a 35% increase in the density means a 35% increase in the drag.

The mass density is not the only parameter impacted. In fact, the whole thermospheric composition may change as a consequence on the warming of the lower layers. Heavier atoms and molecules (in particular molecular nitrogen) may rise to higher altitude so that the O/N_2 ratio decreases. This occurs first where most energy is deposited into the atmosphere, that is at high latitudes, but the disturbances may propagate to lower latitudes through meridional neutral winds.

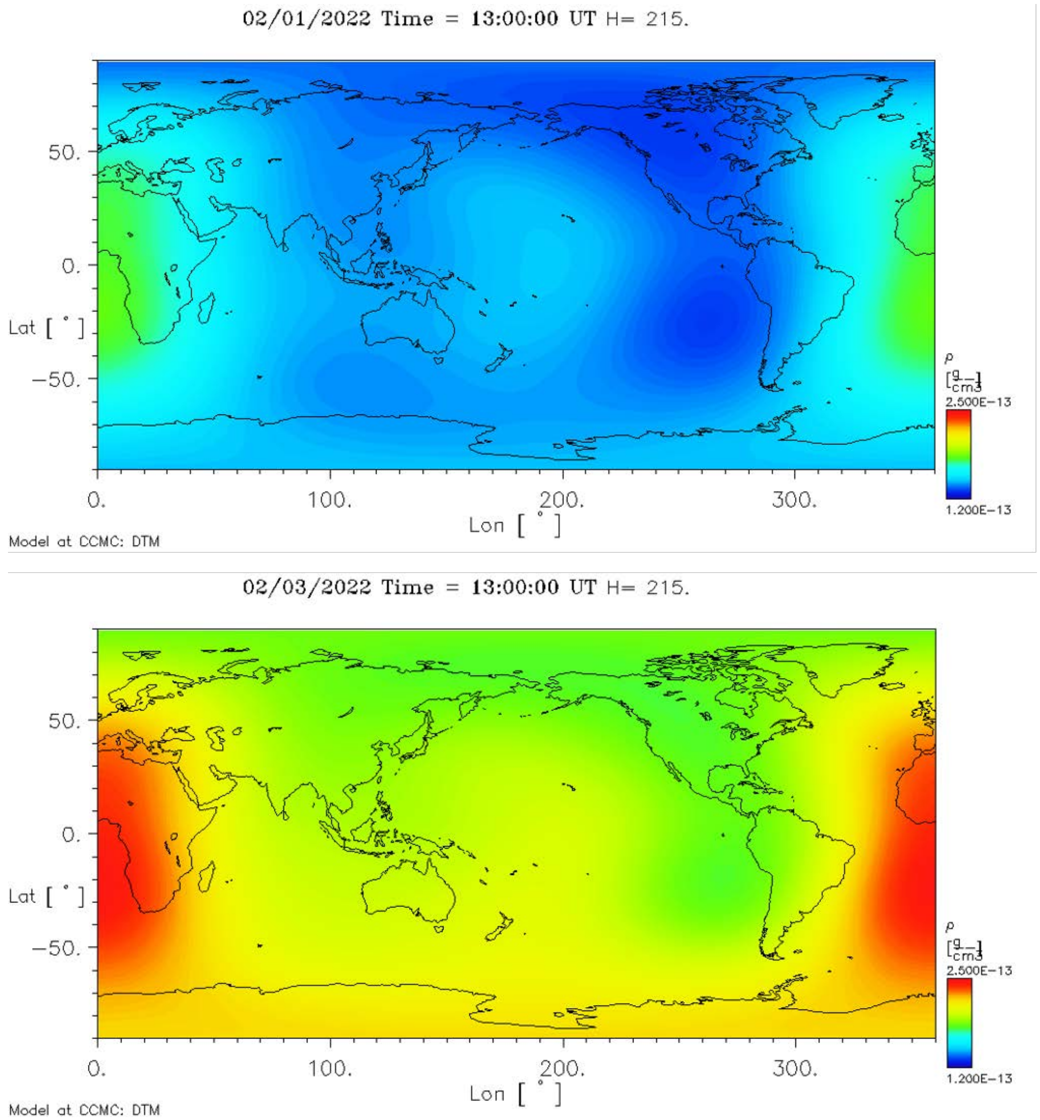

Fig. 2. Maps of air mass density at 215 km altitude provided by the Drag Temperature Model (DTM-2013) on February 1 at 13 UT (top) and February 3 same time (bottom)

2.3 Ionospheric response

As for the ionized part of the upper atmosphere, regions where the neutral density increases experience an increase of the Total Electron Content (TEC). When and where this occurs, it is called positive ionospheric storm. On February 3 and 4, 2022, innumerable GPS receivers measure strong TEC (not shown). However, some regions like Northern United States and Canada experienced a clear negative storm on February 3 while a positive storm occurred on February 4. Yet, according to its Dst, the second storm on February 4 was weaker than the first one on February 3. This is very likely a consequence of a composition change (Buonsanto 1999).

Indeed, figure 3 shows the relative abundance of H^+ and O^+ versus time measured on board the Ion Velocity Meter (IVM) instrument on board the ICON spacecraft (Immel et al. 2017). In quiet times, at the altitude of ICON (580 km), the ionosphere is dominated by light hydrogen ions at nigh and heavier molecular nitrogen ions during on the dayside. During the two storms, the relative abundance of O^+ remains quite high (up to

70%) even at night. This shows that the topside upper ionosphere is filled with heavier atoms and ions than usual.

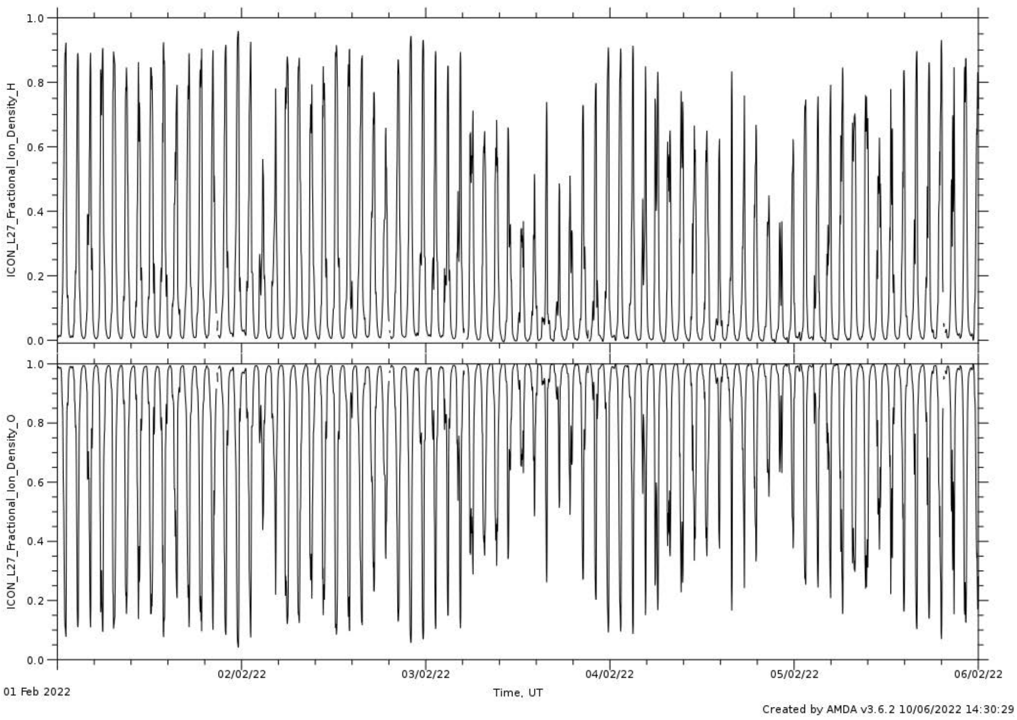

Fig. 3. Relative abundances of H^+ (top) and O^+ (bottom) at 580 km altitude measured at ICON

3 Discussion and concluding remarks

The response of the thermosphere-ionosphere coupled system to a geomagnetic storm is relatively well known. The energy deposited mostly at the two poles induces a series of disturbances that affect the local neutral and ionized upper atmosphere but also propagate to lower latitudes. In the end, the whole globe is impacted.

Here, our preliminary investigations show that the thermospheric mass density increased by 35%, which is not huge. The increase of O^+/H^+ ratio observed at ICON is indicative of composition changes in both the thermosphere and the ionosphere.

Eventually, we can wonder whether a 35% increase in the air drag is enough to cause the loss of the satellites. Of course, the parking orbit used by SpaceX to limit the cost and maximize the number of satellites launched at once is low. But then why did a previous launch, which also occurred during a storm of similar intensity succeed? In our case, two storms occur one after the other within less than two days and this could make a big difference. More investigations are surely needed to understand what really happened.

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