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Title: The Extreme Space Weather Events in the 18-20th Centuries: Reconstructions from Contemporary Observational Reports and East Asian Historical Documents

Abstract

Apart from its long-term intrinsic variability, the Sun can frequently cause significant short-term influences on the space surrounding the Earth; these variable conditions are called “space weather”. The most extreme space-weather event in observational history is arguably considered to be the Carrington event in 1859. Extreme events with such intensity are considered a significant threat for a modern civilization increasingly dependent on an advanced technological infrastructure. At the same time, such high-impact low-frequency events are not easily analyzed with the existing scientific databases, due to their limited chronological coverage.

However, it is known that the equatorward boundaries of the auroral oval have a fairly good empirical correlation with the storm intensity measured by the Dst index. Considering that we have historical auroral reports for more than 2 millennia, we can possibly extend quantitative datasets of extreme-space weather events backwards in time on the basis of the historical auroral reports, with the aid of archaeomagnetic field data.

Therefore, this thesis examines extreme space-weather events after the 18th century using auroral reports in the Western observational records and the East Asian historical documents, and evaluates their intensity on the basis of their reconstructed equatorward extension. This thesis also examines contemporary sunspot drawings to evaluate the level of solar activity at that time and identify the source active regions

Firstly, in Chapter 2 (Hayakawa et al., 2016b, *PASJ*, 68, 99), this thesis examines East Asian auroral reports around the Carrington event to provide an important exemplar for the scientific analyses of such historical documents. Indeed, analyses of such historical records lets us reconstruct the equatorward extension of auroral visibility down to ≈ 23° magnetic latitude (MLAT) in East Asia at that time. The survey result is comparable to the known observational data in other geographical sectors.

Secondly, in Chapters 3 and 4 (Hayakawa et al., 2018d, *ApJ*, 862, 15; Hayakawa et al., 2019a, *MNRAS*, 484, 4083), this thesis reconstructs the equatorward boundaries of the auroral oval during the extreme space-weather events with “outstanding auroras” in 1872 February and 1909 September, and compares them with geomagnetic measurements at that time. The 1872 February storm has its

reconstructed equatorward boundary of the auroral oval at ≈24.2° ILAT and is associated with an incompletely recorded extreme geomagnetic disturbance at Bombay. The 1909 September storm has its reconstructed equatorward boundary of the auroral oval at 31.6° ILAT. Comparison with the reconstructed Dst time series (with a minimum value of −595 nT) contextualizes these auroral reports mostly with the main phase of the magnetic storm and explains the enhanced auroral visibility in East Asia, and the timing of large telegraph disturbances, even down to extremely low MLATs. Moreover, analyzing the contemporary observations of the solar surface and geomagnetic measurements, it is estimated that the flare intensity of this space-weather event was ≥ X10 in the soft X-ray class.

Thirdly, this thesis extends its survey beyond the coverage of systematic magnetic measurements and investigates the extreme space-weather events in September 1770 and February 1730 (Hayakawa et al., 2017e, *ApJL*, 850, L31; Hayakawa et al., 2018c, *A&A*, 616, A177). The equatorward extensions of auroral visibility in 1770 September and 1730 February have been reconstructed as being ≈ 18.8° MLAT and 25.8° MLAT, respectively. The equatorward boundary of the auroral oval in 1730 February has been conservatively estimated as being ≈ 34.2° ILAT. Also examined is the solar surface in 1770 September on the basis of a contemporary sunspot drawing, which shows an anomalously large sunspot active region (up to ≈ 6000 msh), and is the association with long-lasting low latitude aurorae that existed for more than a week.

On the basis of the results, in Chapters 7 and 8 (Hayakawa et al., 2018f, *ApJ*, 869, 57; Hayakawa et al., 2019f, *Space Weather*), the Carrington event has been subjected to detailed considerations in terms of the equatorward boundary of the auroral oval based on contemporary observational reports, and comparisons with other extreme space-weather events of comparable scale. These results show that the Carrington event is one of the most extreme space-weather events within observational history – comparable to the extreme storms in 1872 and 1921 – but is not likely to be unique.

Finally, this thesis also applies the equation implicit in Figure 3 of Yokoyama et al. (1998) to the historical storms in 1770, 1730, and 1582, and compares the results with the extreme storms with magnetic measurements. The results presented in this thesis open a new door to compare the intensity of extreme space-weather events before the onset of systematic magnetic measurements and indicate the possibility of examining historical space-weather events over a much longer time span.