

Extreme Magnetic Storms: Their Characteristics and Possible Consequences for Humanity

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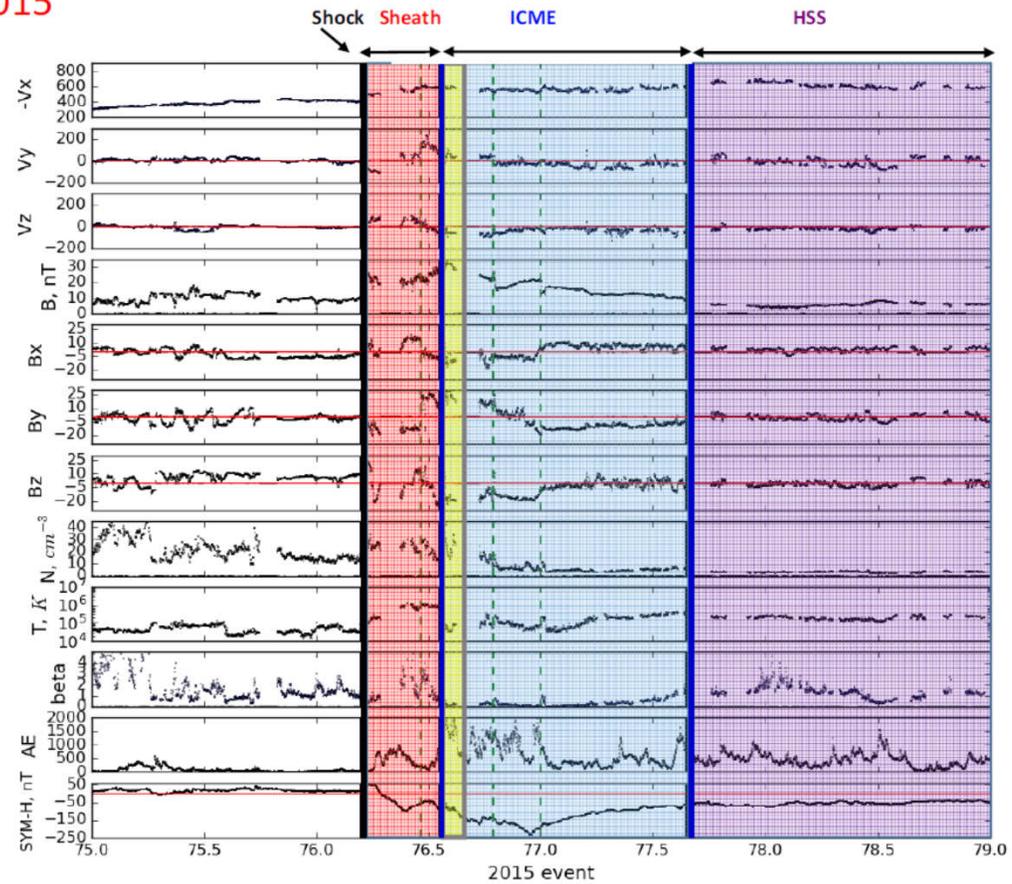
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17-18 March 2015 Triple Storm (Sheath, Coronal Loop, Magnetic Cloud)

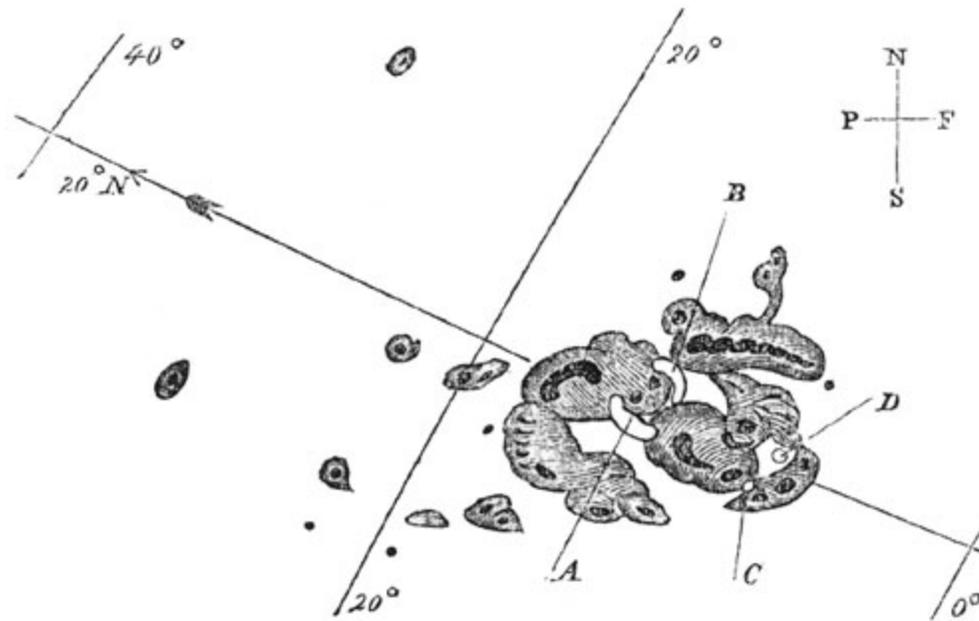
2015



Shock normal: 83°
MS Mach No. = 2.9

Super Magnetic Storms in the Past and Future

The September 1, 1859 “Carrington” Solar Flare



Famous hand drawn by R. Carrington: clearly what we now call an “active region”.

AR caused multiple flaring and continuous geomagnetic activity over a week duration

Carrington MNRS, 1859

“Description of a Singular Appearance seen in the Sun on September 1, 1859”

By R.C. Carrington, Esq. (*MNRS*, 20, 13, 1859)

“Mr. Carrington exhibited at the November meeting of the Society and pointed out that a moderate but very marked disturbance took place at about 11:20 am, September 1st, of short duration; and that towards four hours after midnight there commenced a great magnetic storm*,”

The CME took **17 hr 40 min** to go from the Sun to Earth.

*Carrington also gave us the average speed of the related CME/shock. Lord Kelvin was convinced that there was no connection between solar and geomagnetic activity.

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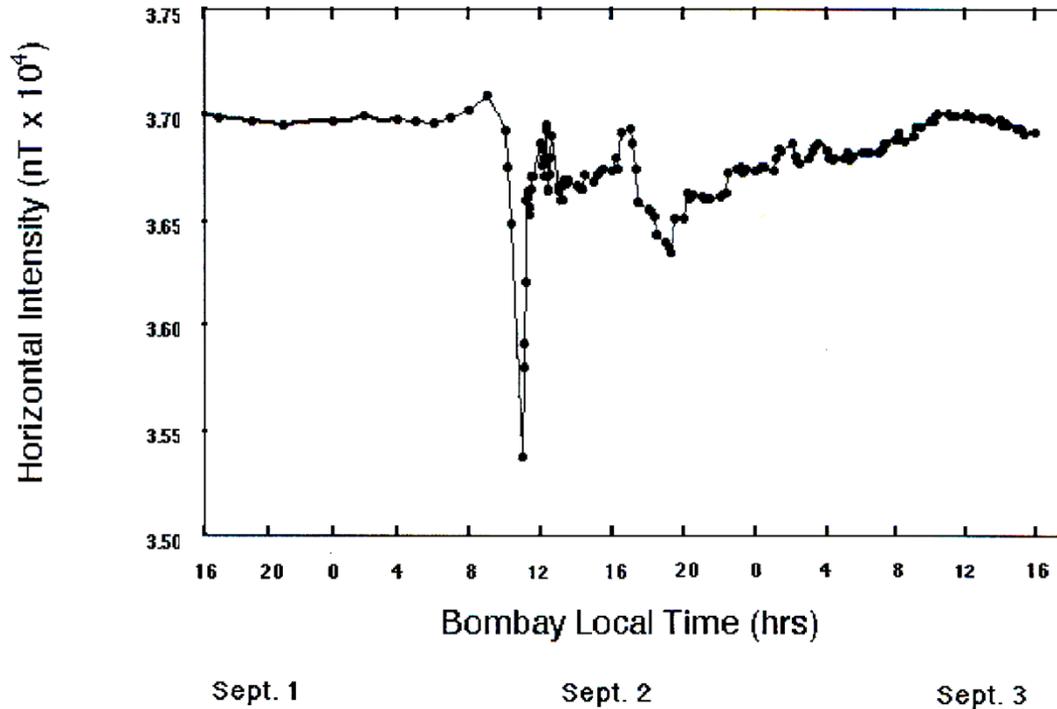
Auroras During the Magnetic Storm of 1-2 September 1859

D.S. Kimball* (*University of Alaska internal report*), 1960

“Red glows were reported as visible from within 23° of the geomagnetic equator in both north and south hemispheres during the display of September 1-2”

*Kimball was a colleague of Sydney Chapman. He was not a permanent employee of the University of Alaska, but came there for summers (from the east coast) to enjoy the Alaskan (summer) weather (S.-I. Akasofu, personal comm., 2001).

1859 Bombay Magnetic Storm



*Measurements taken from a Grubb magnetometer. The magnetometer was “high technology” at the time. The manual for calibration does not have a sketch of it, probably because the British wanted to keep it secret (a copy of the calibration information can be found at the Royal Society, London).

Tsurutani, Gonzalez, Lakhina and Alex, JGR, 2003

Modern day knowledge plus older observations allowed us to estimate the magnetic storm strength

From a plasmapause location of $L=1.3$ (auroral data: *Kimball, 1960*), we can estimate the magnetospheric electric field.

The electric potential (*Volland, 1973; Stern, 1975; Nishida, 1978*) for charged particles is:

$$\phi = -kR_E^2 / r - A(r / R_E)^2 \sin \psi + \mu M / (qr^3)$$

Where r and Ψ are radial distance and azimuthal angle measured counterclockwise from solar direction

M dipole moment, q and μ - particle charge and magnetic moment.

The magnetospheric electric field is estimated to be ~ 20 mV/m.

The interplanetary electric field has been estimated to have been ~ 160 to 200 mV/m*.

*will return to this number later

Extreme Magnetic Storm of September 1-2, 1859

Dst is estimated to be ~ -1760 nT, consistent with the Colaba 11 am response of $\Delta H = -1600 \pm 10$ nT.

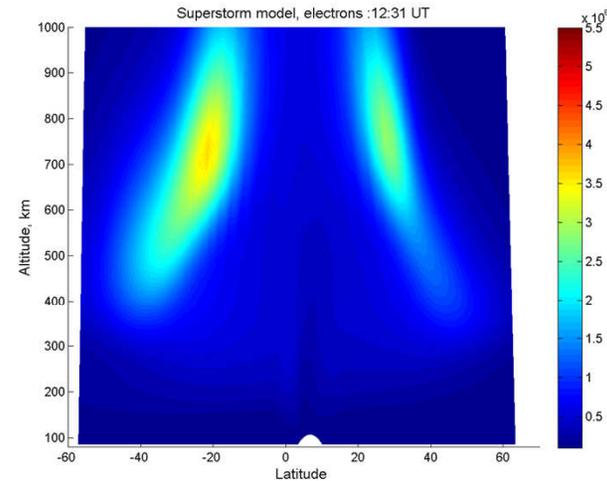
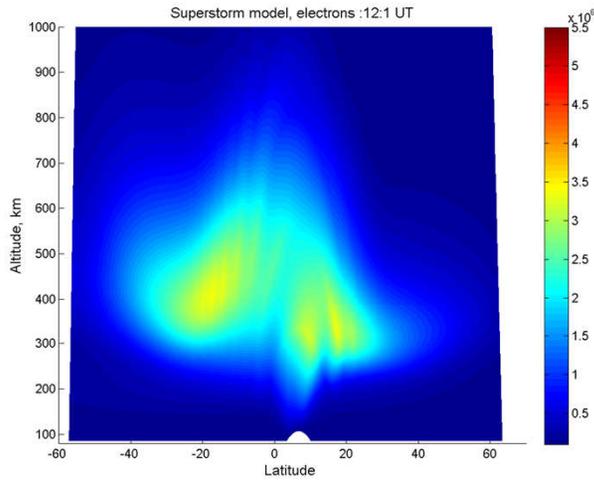
The storm was the most intense in recorded history. Auroras were seen at Hawaii and Santiago, Chile.

The Carrington storm was larger than anything that we have experienced in our lifetimes*.

*In comparison, the 1989 storm which knocked out the Hydro Quebec electrical grid was “only” Dst = -589 nT.

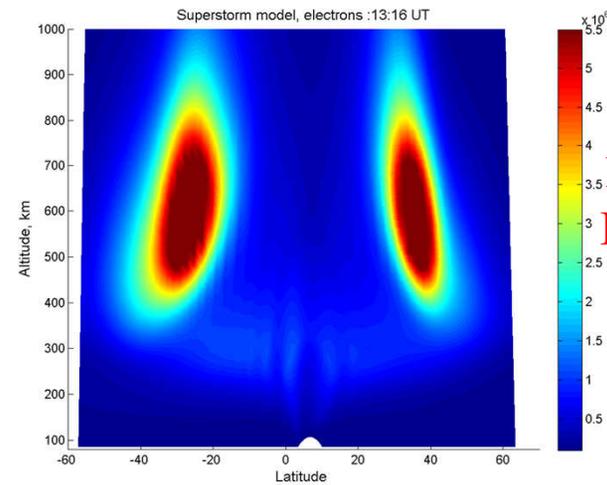
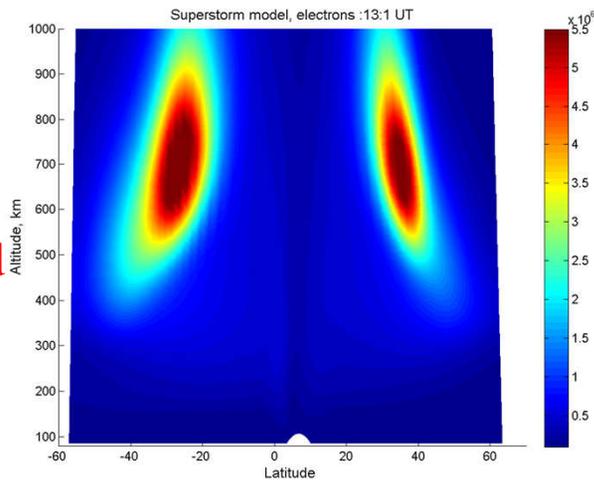
NRL SAMI2 Model* Application: O⁺ Ion Uplift* During the 1859 Carrington Magnetic Storm

Quiet



30 min after
PPEF applied

1 hr after
PPEF applied



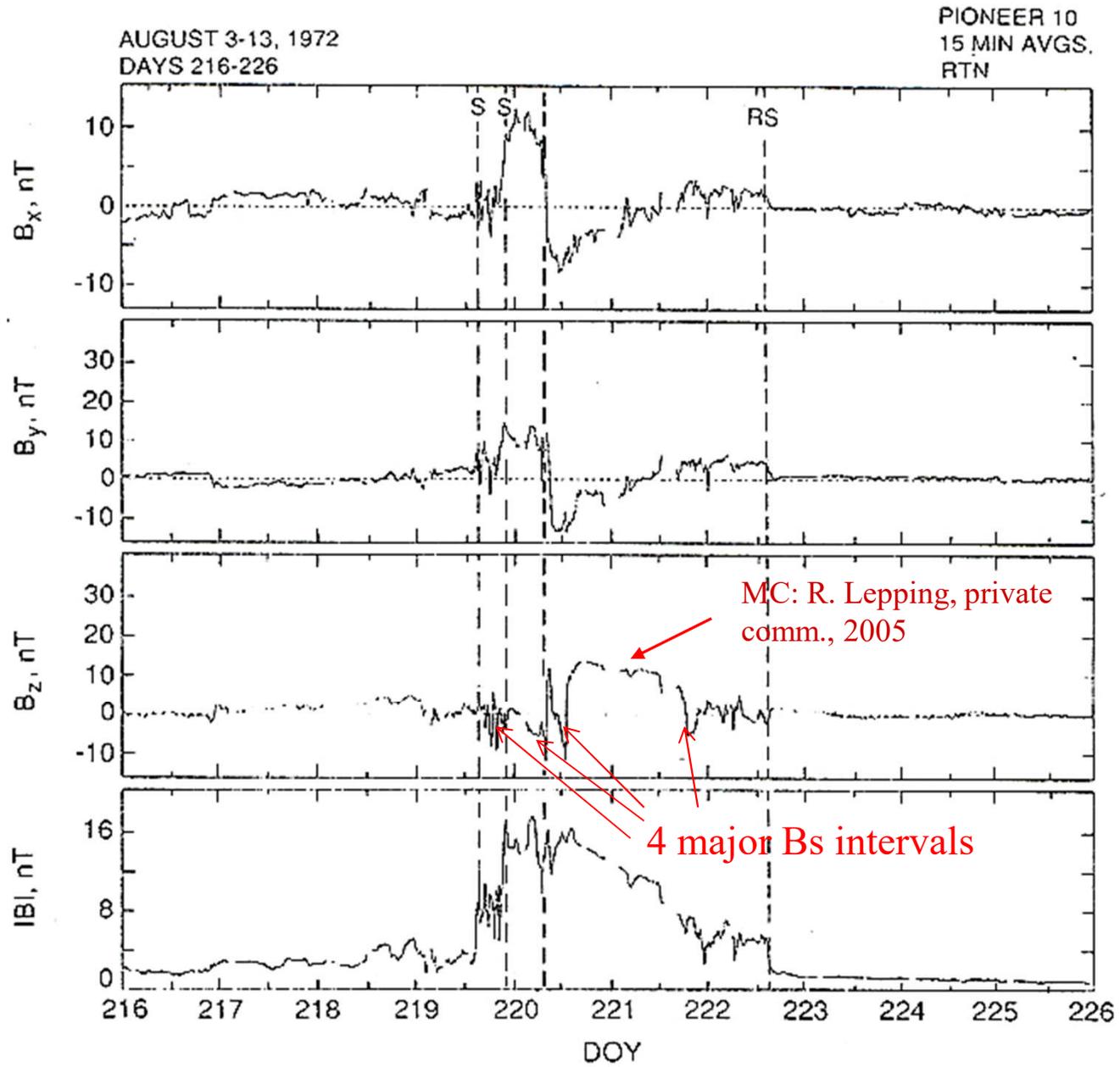
15 min after
PPEF terminated

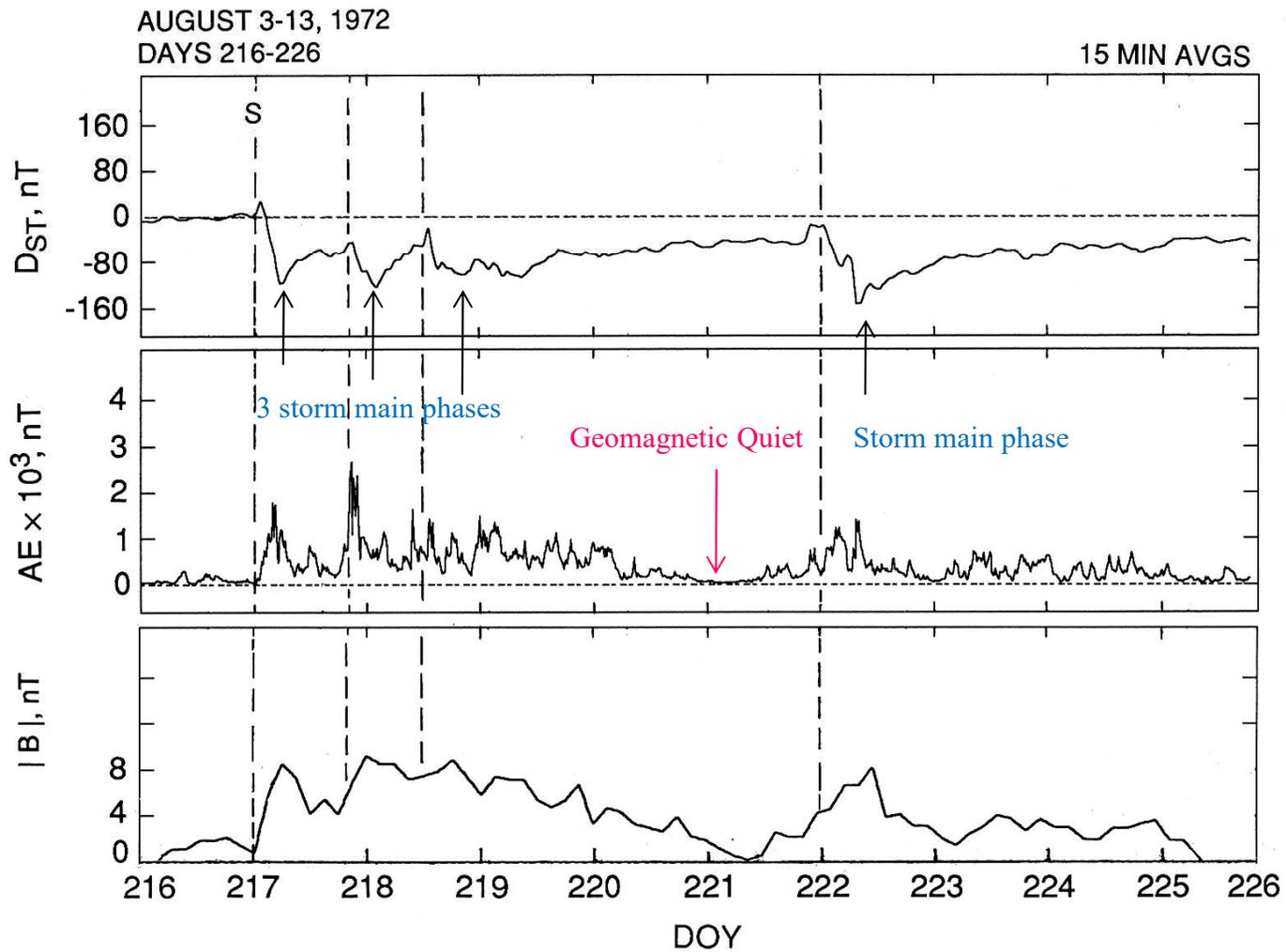
At altitudes of ~ 700 to 1000 km the O^+ densities will be 300 X quiet time neutral densities.

This will increase drag substantially for LEO satellites.

THE AUGUST 1972 SUPER FLARE/ICME

- The ICME took only 14 hours to reach the Earth ($V_{sw} = 2850$ km/s. *Vaisberg and Zastenker, 1976; Zastenker et al., 1978*). The 1859 ICME took 17 hrs to reach 1 AU.





Removal of the radial and corotational delays indicate that the Pioneer 10 Bz features and geomagnetic activity at Earth line-up very nicely.

Since the August 1972 Event Could Have Been
More Intense than the Carrington Event Was That
the Biggest Possible Storm?

Starting with one simple assumption, one can go quite far with basic plasma physics

Assume that a maximum CME speed at the Sun is 3,000 km/s.

Assume that the interplanetary deceleration is a minimum, 10%.

Shock Speed

$$V_s = \rho_2 / (\rho_2 - \rho_1) [V_2 - V_1] \cdot n + V_1 \quad (\text{Rankine-Hugoniot})$$

Where 1 indicates upstream values (from the shock) and 2 indicates downstream values. n is the shock normal. Here, the reference frame is the Earth.

The largest speed occurs for a perpendicular shock where the shock normal and all velocities are aligned (along the Sun-Earth line).

$$V_{\text{shock}} = 3480 \text{ km/s}$$

$$M_A = 63$$

$$M_{\text{MS}} = 45$$

Maximum Interplanetary Magnetic and Electric Fields

- $B_{MC} \approx 0.047 V_{sw(MC)}$ (empirical result: Gonzalez et al. 1998; Tsurutani et al. 1999)*.
- $B_{max} = 127 \text{ nT}$ at 1 AU.

$$E = - (V_{sw} \times B)/c$$

- $E_{IPmax} = 340 \text{ mV/m}$ at 1 AU.

*Of course, extreme events were not included in these statistical studies.

Magnetospheric Compression

$$k\rho V_{sw}^2 = (2fB)^2/8\pi \quad (\text{Sibeck et al. 1991})$$

where $f^2/k = 1.77$ for low solar wind ram pressures and 2.25 for high solar wind ram pressures*.

$P_{\text{downstream}} = 244 \text{ nPa}$, an increase in pressure by ~ 240 times.

The magnetopause will be moved inward to $5.0 R_e$.

*however none as high as assumed here.

Sudden Impulse (SI⁺) Intensity

- $\Delta H = k \times \alpha \times f \times \Delta P^{0.5*}$ (Siscoe et al. 1968; Araki et al. 1993)
- $\Delta H = 234 \text{ nT}$

*Again, the empirical relationship did not have extreme events like this included.

$$dB_{\text{mag}}/dt^*$$

- $dB_{\text{mag}}/dt = 30 \text{ nT/s}$
- $\text{Curl } E = 30 \text{ mV/km}^2$

*Important for calculating relativistic electron acceleration and location

SUMMARY OF THE MAXIMUM POSSIBLE MAGNETIC STORM

- Shock transit time from Sun to Earth: **12.0 hrs** (August 1972 event: 14.6 hrs; Carrington event: 17.6 hrs).
- $M_{ms} = 45$ (the largest to date is 9.4)
- Magnetopause compression: **5.0 R_e** . The lowest ever detected was 5.2 R_e for the August 1972 storm.
- $SI^+_{max} = 234 \text{ nT}$. For 24 March 1991 event, $SI^+ = 202 \text{ nT}$
- IP $E_{max} = 340 \text{ mV/m}$. (Carrington event estimated at 160 to 200 mV/m).
- $SYM-H_{max} = -3500 \text{ nT}^*$ (the Carrington event was estimated to be -1760 nT)
- ***Vasyliunas (2010)** has estimated saturation to occur at -2500 nT

CONCLUSIONS

- Storms larger than the Carrington event can occur under ideal conditions. Perhaps as high as 2 x larger? (Vasyliunas, 2010 suggests saturation at SYM-H \sim -2500 nT).
- Intense shocks (not seen to date) could lead to exceptionally high fluxes and energies of “solar flare” particles.
- The $\text{dB}_{\text{mag}}/\text{dt}$ in the magnetosphere is 6 x larger than the 1991 event and should create an intense new relativistic electron radiation belt.

- The magnetopause inward motion will expose many Earth-orbiting satellites to the extremely intense solar flare radiation.
- Storm-time ionospheric electric fields should cause major uplift of the dayside ionosphere with substantial ion-neutral drag. This additional drag on low-orbiting satellites (due to collisions with both ions and neutrals) will degrade orbits considerably.
- Power grid failures can be expected.
- Telecommunication networks will go down.

FINAL COMMENT

All of the various extreme event features should be thought as independent variables. The possible limitation on storm SYM-H value will not affect other extreme event features such as: flare energetic particles, storm sudden impulses, new radiation belt production, and dayside superfountain effect

THANK YOU FOR YOUR ATTENTION

THE END

