Extreme Space Weather: Lessons Learned
(topic given by S. Sharma)

Bruce T. Tsurutani

Jet Propulsion Laboratory, California Institute of Technology,
Pasadena CA

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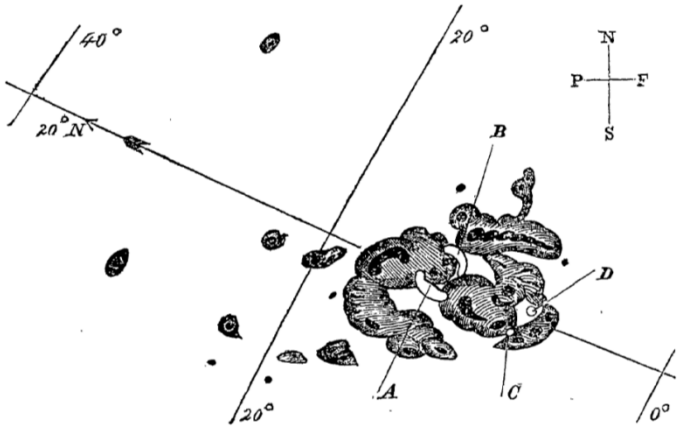
Carrington, R.C., Description of a single appearance seen in the Sun on September 1, 1859, *Mon. Not. R. Astro. Soc.*, *XX*, 13, 1859



"...and that towards four hours after midnight there commenced a great magnetic storm, which subsequent accounts established to have been considerable in the southern and in the northern hemisphere. While the contemporary occurrence may deserve noting, he would not have supposed that he even leans towards hastily connecting them. One swallow does not make a summer".

Why Did Carrington Make This Negative Statement about the Connection between the Solar Flare and the Magnetic Storm at Earth?

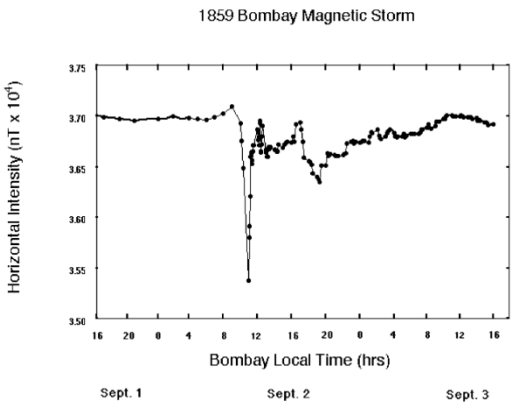
Is seeing a flash of light on the Sun worthy of a paper? Especially with no confirmation from you own laboratory? Luckily Hodgson saw it at the same time. What about a later magnetic storm? Is that solid science?

So for Carrington to publish and remain in good standing as an amateur astronomer he had to add this disclaimer about the storm.

Moral: This piece of evidence for extreme space weather was at the fringes of science. But it turned out to be very useful.

The seminal auroral description of
D.S. Kimball (Univ. Alaska, 1960) was unpublished.
Without the above "internal report", the following paper would not have been published:

Tsurutani, Gonzalez, Lakhina and Alex, The extreme magnetic storm of 1-2 September 1859, JGR, 2003



Estimated Dst ~ -1760 nT

Carrington and Kimball were amateurs. The finding the magnetic recordings of the Colaba India magnetometer was an accident. I was in Mumbai talking to Prof. Gurbax Lakhina about joint works on plasma waves.

Moral: Amateurs (Carrington, Kimball) have been important for the development of space weather knowledge. Trained international scientists (Volland-Germany, Stern- US, Nishida-Japan) working on abstract problems (magnetospheric potential expressions) have been very useful as well.

The First Systematic Group Study of Space Weather From the Sun to Interplanetary Space to the Earth: Mid-1980s

Major resistance from solar physicists. They were totally uninterested in what happens at Earth. They also argued that they “there were many solar flares and so few magnetic storms, thus the connection could not be important”.

From fellow scientists: “not real science” (sort of true—not hard science).

Three papers were published anyway (small collaboration of experts on solar, solar wind and magnetosphere. The analyses were done in our “spare time”.

- Tsurutani, Gonzalez, Tang, Akasofu and Smith, Origin of Interplanetary southward nterplanetary magnetic fields responsible for major magnetic storms near solar maximum (1978-1979), JGR, 1988
- Gonzalez, Gonzalez, Tsurutani, Smith, Tang and Akasofu, Solar wind-magnetosphere coupling during intense magnetic storms (1978-1979), JGR 1989
- Tang, Tsurutani, Gonzalez, Akasofu and Smith, Solar sources of interplanetary southward Bz events responsible for major magnetic storms (1978-1979), JGR, 1989

Contrary to the standard view at the time, we started with storms at the Earth and worked backwards. This proved to be a successful approach.

“The Magnetosphere Saturates at Dst ~ -300 to -400 nT”

This was a consequence of the storm intensities in the late 1950s and early 1960s. This was an interval of solar maximum when the sunspot number was the highest of the last century. This general thought was reinforced by the Halloween storms in 2003 (I will discuss later).

Theoretical articles were written on “polar cap potential saturation”, explaining the cutoff of Dst.

Observations and theory were then in “good agreement”. Everyone could feel comfortable.

Then came the 1989 Hydro-Quebec magnetic storm!

Allen, Sauer, Frank and Reiff (*EOS*, 1989) Dst = -589 nT

Lakhina and Tsurutani (Geo. Letts., 2014) SYM-H = -710 nT.

Copper busses rated for 2,000 amperes. New Jersey nuclear power plant transformer.

Moral: agreement between theory and observations is good, but don’t accept it blindly. One should also always be open to new possible interpretations/explanations.

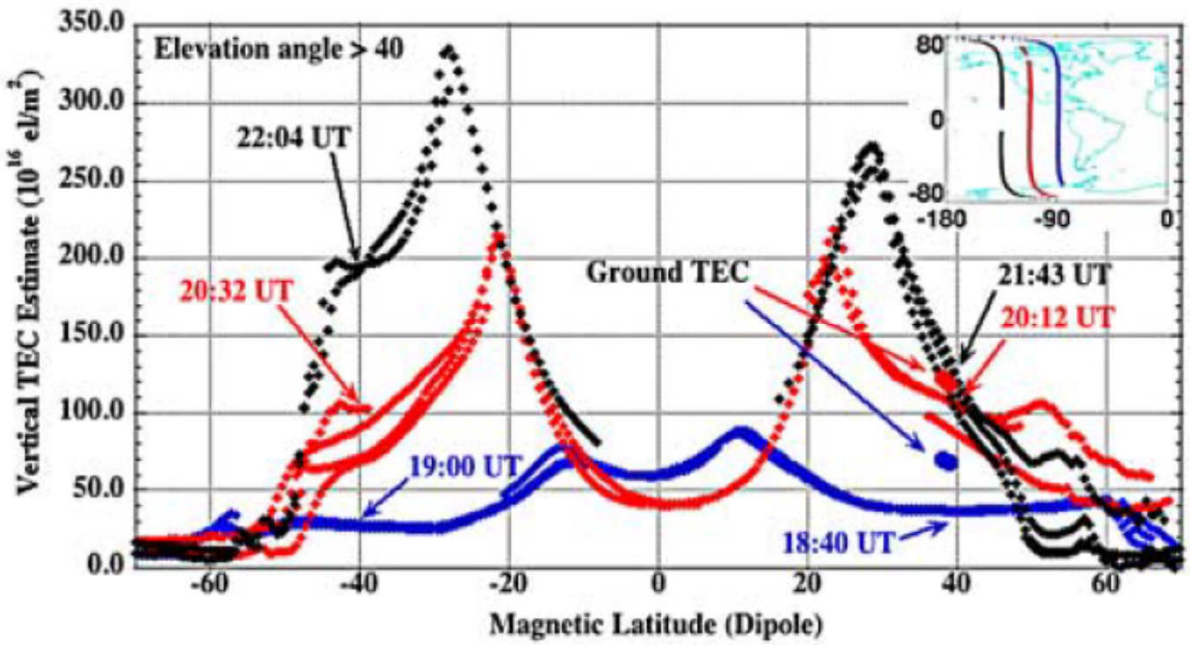
Prompt Penetration Electric Fields into the Ionosphere:

(Published by Nishida, 1968 and Kelley et al. 1979 for substorms, but essentially ignored)

Theory then says that PPEFs could only exist in the dayside ionosphere for at most 15 to 30 min (substorm durations), but afterwards the fields would be shielded out. So PPEFs would not happen during magnetic storms.

When observations were first noticed where PPEFs could explain these observations, we were told (by theoretical people): “Observationalists should not try to understand the physical bases for the observations”.

October 30 (Halloween Storm), 2003



The CHAMP satellite observations clearly demonstrated uplift of the dayside ionosphere by PPEF fields. This uplifted ionospheric ions could be a hazard for low orbiting spacecraft.

Mannucci, Tsurutani, Iijima, Komjathy, Saito, Gonzalez, Guarnieri, Kozyra and Skoug, GRL, 2005

Now PPEF uplift of the dayside ionosphere during magnetic storms is well accepted (but this took the ionospheric scientific community ~10 years to agree to this).

Theory is still not well understood.

Moral: “Conventional wisdom and attitudes” can be a hindrance.

Now everyone is Focussed on Extreme Solar Flares/Magnetic Storms Because These Are What Cause All Extreme Space Weather

Is this the right conclusion?

What is the intensity of the largest solar flare on record?

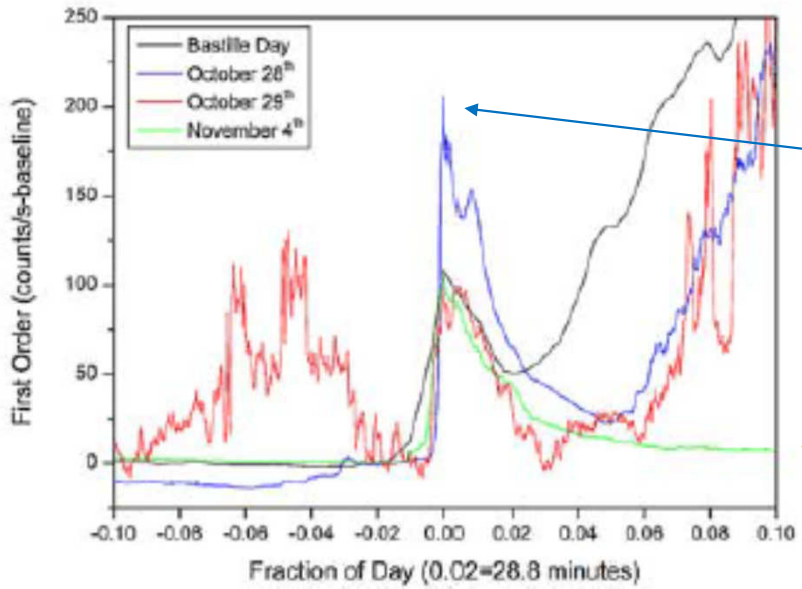
All of the NOAA x-ray detectors were saturated by the Oct 28 and Nov 4 solar flares. These were rated at X-17 and X-28, so Nov 4 is the all time record? The SOHO-SEM EUV broadband detector was saturated as well.

Because the detectors were saturated people “extrapolated” their flare data profiles to find the peaks.

SOHO-SEM also had a “narrow band channel” but I was told that “it should be contaminated by relativistic electrons, so don’t bother looking at that”.

October 28, 2003, the Largest Solar EUV Flare in Recorded History

Tsurutani et al. GRL, 2005



Oct 28 flare is twice the peak intensity of Nov 4 Flare in EUV flux.

Nov 4 flare was rated as X28 by NOAA

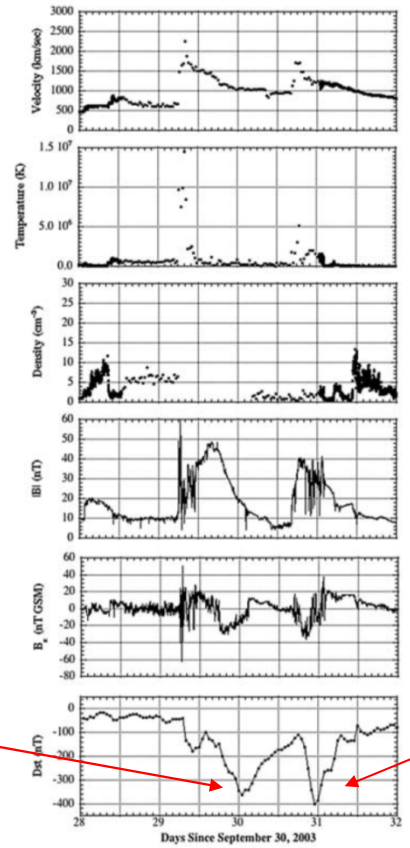
However the New Zealanders Thomson, Rodger and Dowden (GRL, 2004) rate the Oct 28 flare as X45 ±5.

Since the Oct 28 was a limb event, the X-rays would have been absorbed going through the solar atmosphere. Thus is ~X-50 about right? One needs to do some calculations.

Moral: One should question the “experts” and understand their reasoning before accepting the explanation. Don’t take at face value.

Did the October 28 2003 solar flare produce the biggest/fastest ICME and the largest magnetic storm?

The answers are “no” and “no” to the questions



Mannucci et al. GRL, 2005

Magnetic storm associated with 28 Oct flare

Magnetic storm associated with 29 Oct flare

But….we did not view the event from front-on! Thus, is this still an open question?

Prof. Shibata is the leading solar physicist in Japan.

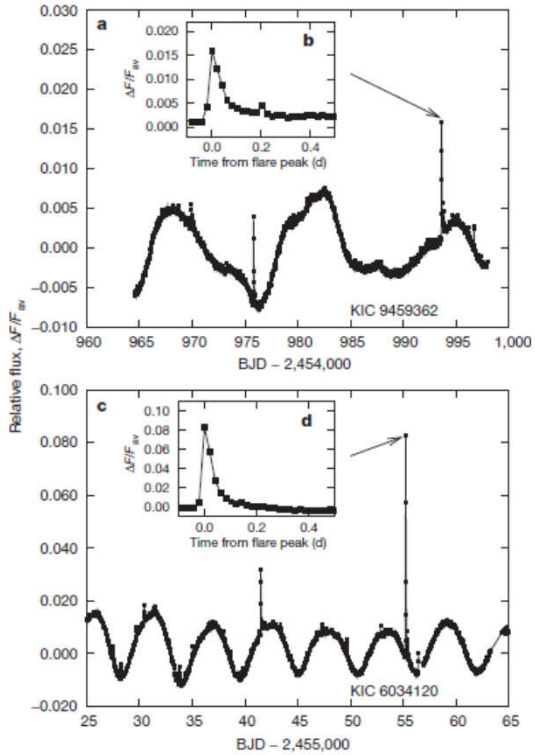
He is thus free to look at new ways to think of extreme events. It is wonderful to see that he has this attitude!

He is starting a new field in Japan.

Superflares on Solar Type Stars

Shibata is using Kyoto University undergraduates to study the U.S. Kepler dataset.

Maehara, Shibayama, Notsu, Notsu, Nagao, Kusaba, Honda, Nogami and Shibata, *Nature*, 2012



Shibata had strong resistance from referees with this paper.
One referee suggested that his events were “hot Jupiter” stars. The same person also demanded that Shibata remove reference to the Sun and flare effects on Earth or he would not be allowed to publish.

Can Super-CME Shocks Create Super Solar Cosmic Ray Fluxes?

Miyake, Masuda and Nakamura, *Nat. Comm*. 2013

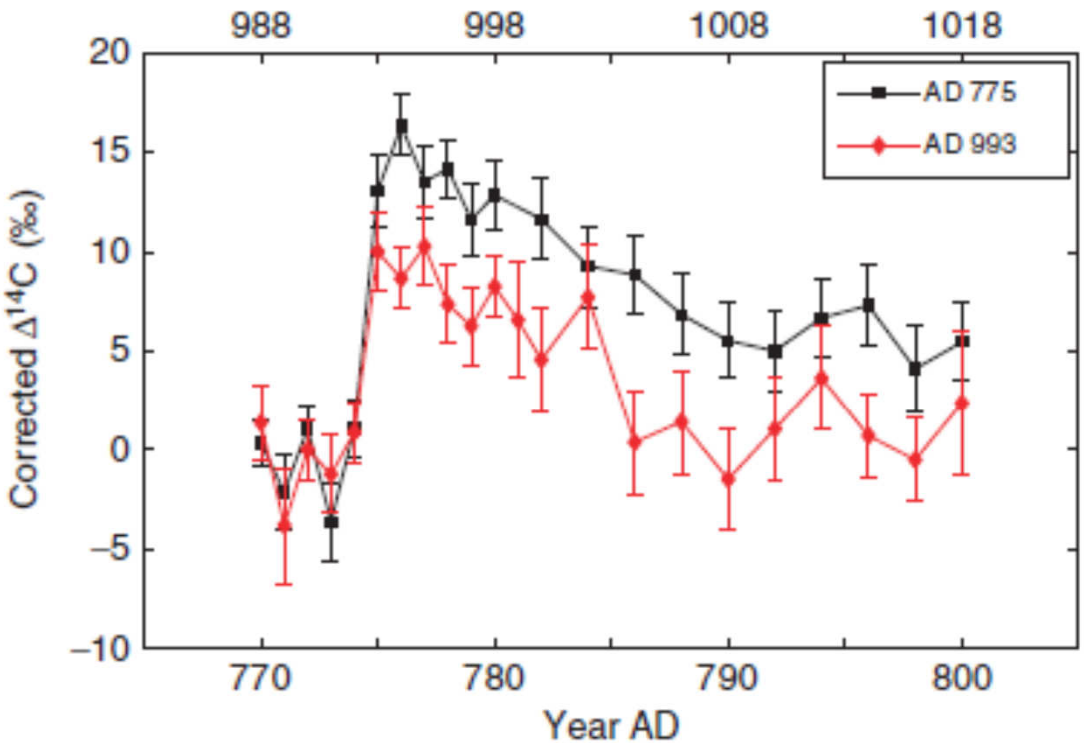


Figure 2 | Comparison of the AD 775 and the AD 993 peaks. Squares

What Other Important Maxima Are There?

Maxima in magnetospheric compression

Maximum in magnetospheric electric field

Maximum in Dst/SYM-H

They may all be independent of each other?

Tsurutani and Lakhina, GRL 2014

Tmin =12 hrs (min propagation time of a CME)

SI^+ max =234 nT

Mach No. = 45 (maximum shock Mach number– never seen in space yet)

dB/dt ~30 nT/s

Emag = 1.9 V/m

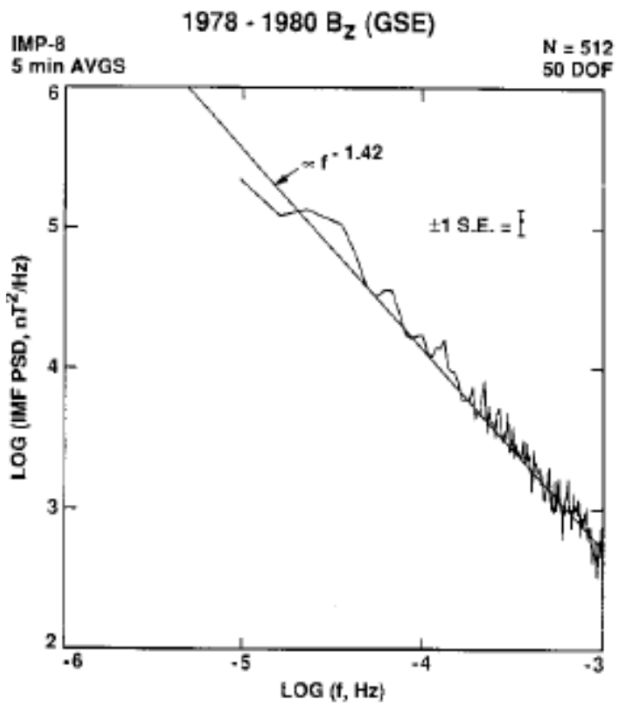
Dst ~ -2500 nT (if saturated, -3500 nT if not; this would be double the size of the Carrington storm)

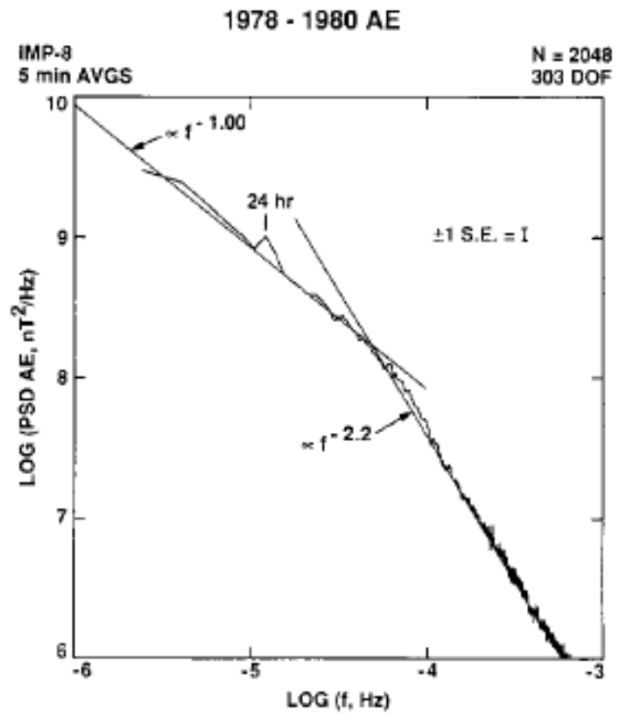
But……

Should We Try to Focus on Extreme Magnetic Storms for Power Outages? Predictions?

The strongest ionospheric currents may be related to substorms.
But there are many substorms that occur within a magnetic storm.

Tsurutani, Sugiura, Iyemori, Goldstein, Gonzalez, Akasofu, Smith, GRL, 1990



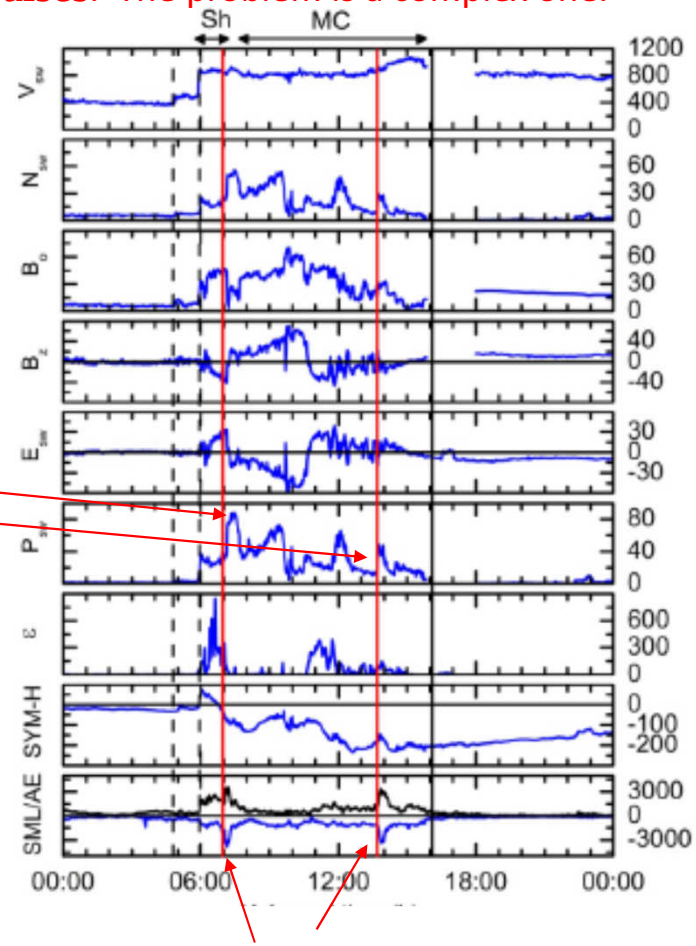


Does this imply that the magnetosphere is chaotic? And we need to understand Chaos to predict intense ionospheric currents?

Answer: Maybe, but perhaps not always. Our current thought is some supersubstorms are triggered by solar wind pressure pulses. The problem is a complex one.

Tsurutani, Hajra, Echer, Gjerloev, SWSC, 2014

Solar wind pressure pulses



Supersubstorms

Moral: Look deeper. Don’t be satisfied with initial “correlations”

Do We Have All the Data That We Need?

Answer: No.

Richard Horne of the British Antarctic Survey, Cambridge England has said that the aerospace industry is reluctant to give out information on single event upsets/electronic failures onboard their satellites because of insurance issues.

SUMMARY

- Knowledge about extreme space weather is getting help from an international community and amateurs alike.
- It is being advanced by highly interested and motivated scientists.
- It is not mainstream science. Should it be? Sometimes mainstream scientists have been a hindrance in the past.
- Publications in scientific journals are often difficult. Only “hard” science articles see print. Is that the way it should be?

FURTHER COMMENTS

I don’t think that national panel studies are the solution for making progress. Very few on the panel may be knowledgeable for any specific question, if anyone at all!

An example is the 2013 (British) Royal Academy of Engineering report on “Extreme Space Weather: Impacts on Engineered Systems and Infrastructure”. I consider to be the best report to date. I asked them if they would like to have our comments, which they did. Lakhina and I sent them 7 pages of comments which could be used for their next update. It is not that they did not have space plasma people on their extensive panel, they did. However to cover all of the topics is nearly impossible.

Method of Funding?

Theory and modeling are useful but one needs to be careful. To do modeling you need to put in all of the physics that is needed. And one doesn't always know that beforehand. Also how would one put in nonlinearities or saturation in the physical systems when one might not know if they are there or not?

In my opinion throwing lots of money at the problems is not the right solution.

Thank You For Your Attention