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Space Weather

Charged particles and electromagnetic radiation stream from the Sun in all directions. The charged particles, also called the ‘solar wind’, travel at around 1,000,000 miles per hour---twenty thousand times the speed of a car on the highway---and near the Earth after about 4 days. Approaching the Earth, the particles squish the Earth’s magnetic field inwards, and then are deflected by the Earth’s magnetic field (like water is deflected by the prow of a boat). Not all of the particles pass by the Earth; a small fraction are deflected towards the North and South poles, where they enter the atmosphere and collide with oxygen and nitrogen atoms to give off light: the auroras, a.k.a. the Northern Lights.

The sun’s electromagnetic radiation is a different beast altogether. Comprised of gamma, X-ray, ultraviolet, visible, infrared, microwave, and radio waves, the radiation travels at the speed of light (670,000,000 miles per hour, or ten million times the speed of a car on the highway), and reaches the Earth in about 8 minutes. Unlike the solar wind, the sun’s radiation is not deflected by the Earth’s magnetic field. As a result, the Earth’s atmosphere is constantly bombarded with the different types of radiation. The atmosphere absorbs all of the more energetic and dangerous types of radiation, gamma and X-ray, and some of the ultraviolet radiation. All the other radiation reaches the Earth, providing the heat and light we use every day to survive.

These two sets of solar emissions---particles and radiation---comprise what scientists have dubbed ‘solar weather’. Ordinary solar weather is not a problem for humans; except for heat, visible sunlight, and suntans, most people don't even realize that solar weather exists.

Why It Matters

Extreme solar weather events provide the most cause for concern. Solar wind and solar radiation are affected by the sun's 11-year cycle of activity. At the beginning of each cycle, the sun is very inactive. In this period, a 'solar minimum', extreme solar weather events are less common, the solar wind is relatively harmless, bursts of radiation are uncommon, and the sun has fewer filaments and sunspots (filaments are like tentacles of solar matter that extend into space and occasionally collapse to with a huge explosion called a coronal mass ejection; sunspots are cooler patches on the sun that often burst, sending extreme solar wind and radiation towards the Earth). As time progresses, solar activity gradually intensifies. More filaments and sunspots are visible, particle and radiation bursts are more common, and generally the Earth is affected by more extreme solar weather events as the sun moves towards the 'solar maximum'. As more time passes, the sun's activity peaks, begins to decrease again, and slowly returns to the next solar minimum. It is not understood why the sun cycles every 11 years; scientists conjecture that the cycle is driven by complex oscillations in the sun's magnetic field.

Extreme solar weather events---that is, bursts of particles or radiation---fall roughly into five categories. All five categories of events occur more frequently as solar activity cycles towards the solar maximum, but extreme solar weather events can occur *at any time* in the solar cycle.

1. Protons. Poorly and cheaply engineered satellites are extremely vulnerable to doses of the protons contained in solar wind. Protons, in particular, can corrode satellite components, interfere with the circuitry on-board, and cause static electricity to build up within the satellite that can cause power surges and knock a satellite out of commission. These damaging impacts to spacecraft cost the satellite industry hundreds of millions of dollars each year. Proton bursts could potentially also kill space-walking astronauts (nobody has been killed yet), or any future space 'colonists' who are not forewarned and protected.

2. Geomagnetic storms. As described earlier, when the solar wind reaches the Earth's magnetic field, it squishes the field inwards and then deflects to either side of the Earth. Frequently, increased solar activity will result in the expulsion of a burst of charged particles from the sun's surface, a burst that greatly augments the force of the ordinary solar wind. When this extreme solar wind reaches the Earth's magnetic field, it squishes the field much further inwards before deflecting to the side. Moving a magnetic field produces an electric field, which can induce, essentially, direct electric current flows in power lines and power systems designed for alternating current. In particular, the most vulnerable part of the power grid is the transformer, a device used to convert one high voltage power line to several low voltage lines (you may have seen the green metal boxes that are often located at street intersections---these boxes often contain small transformers). When Geomagnetically-Induced Current (GIC) runs through the power system, it can overload several transformers at once, potentially crashing an entire power grid. During the last solar maximum, in 1989, a severe geomagnetic storm crashed the Norsk-Hydro power grid in Quebec, which blacked out virtually all of Quebec for nine

hours. Only lucky timing saved U.S. power grids from experiencing a comparable catastrophe.

Geomagnetic storms also cause a wide variety of other disruptions. Geomagnetic storms can induce current and cause corrosion in not just power lines, but long oil pipelines as well. Several forms of long-range radio communications are vulnerable to intense geomagnetic activity, including air traffic control, ship navigation systems, Voice of America, amateur radio, and several military systems (e.g. early warning, over-the-horizon radar, and submarine detection). Storms can also disrupt geologists' attempts to identify gas/oil/mineral deposits through the use of magnetic imaging. Storms can even throw off a pigeon's homing instinct, which bewilders hobbyists who hold annual pigeon races in England.

3. X-rays. By themselves, intense X-ray events are not a huge problem. They primarily disturb high frequency radio, causing fadeouts and disrupting communications in the 'daylight hemisphere' (the half of the Earth that happens to be facing the sun at the time of the event). X-ray events usually accompany other, more severe problems.

4. Radio waves. Bursts of radio waves from the sun can disrupt space shuttle and very high frequency communications in mid-latitudes.

5. Ultraviolet. Increased solar activity often leads to temporary increases in ultraviolet radiation from the sun. The problem is not more severe suntans. Instead, the UV radiation heats and expands the Earth's outer atmosphere. If the radiation is strong enough, the atmosphere expands past the orbit path of Low-Earth-Orbiting satellites. Those satellites then experience increased drag from the atmosphere, which will crash the

satellite if its orbit is not corrected. Skylab fell victim to this effect in 1973, crashing into the ocean and abruptly terminating a project that cost hundreds of millions of dollars.

The Role of Forecasts

Given the nature of the effects, solar weather forecasts are potentially useful mainly to power systems operators, satellite and communication system operators, NASA missions, a wide range of radio users, and a handful of other groups (e.g. military engineers, climate scientists, geologists, solar physicists). Most often, forecast users do not know or do not care about solar physics. They simply want to know when and what adjustments will be needed. Put differently, both the forecasts *and* the forecast delivery system must function properly to deliver a useful forecast.

Power Systems Operators

The remainder of this chapter focuses on one important aspect of solar weather forecasting: how electric utilities respond to geomagnetic storms. Geomagnetic storms are a good case study in solar weather because 1) like most solar weather events, geomagnetic storms are extremely complicated, 2) forecasting is just one of several methods we have for responding to the storms, and 3) the storms are catastrophes waiting to happen.

Most people have experienced blackouts caused by regular weather events. Electric utilities are long accustomed to dealing with such events; lightning bolts inevitably fry power equipment, and brisk winds frequently topple trees, which snap power lines as they fall. To counter these frequent disruptions, utilities build layers of redundancy into their supply system. A utility may coordinate its power lines such that a single neighborhood is fed by more than one line or a single region by more than a dozen lines. The more interconnected a power grid is, the more flexible system operators can be in diverting power from downed power lines while avoiding blackouts. Or, if a power supply temporarily goes out of service, because of weather or even just a scheduled maintenance, local utilities will arrange to buy power from nearby suppliers. Again, interconnectedness allows for flexibility in response to ordinary weather disturbances.

Ironically, this same interconnectedness transforms *solar* weather disturbances from infrequent nuisances into large-scale catastrophes. When a geomagnetic storm strikes an interconnected grid, the Geomagnetically-Induced Current (GIC) can strain not one transformer but fifteen or twenty connected transformers at once. These disturbances can propagate rapidly through the entire grid, causing erratic power supply and widespread blackouts. In the worst example, the 1989 Quebec example cited above, the entire province was blacked out 90 seconds after the storm began. Further, system-wide blackouts are a utility's worst nightmare; when power is restored, the simultaneously turning-on of thousands of computers, air conditioners, refrigerators, and lights causes a massive power spike that can overload the system and plunge the region back into blackout. A hundred years ago, people were not dependent on electric power in their daily lives. Today, our society shuts down when the power goes out.

Whereas electric utilities had previously dismissed geomagnetic storms as a small and manageable anomaly, the massive Quebec blackout awoke electric utilities to the dangers of geomagnetic storms. After that catastrophe, power system operators realized that once a burst of charged particles reached the Earth's magnetic field and the geomagnetic storm began, 90 seconds allowed no time for action. The power systems operators confronted the following options: 1) redesign their systems to handle GIC without advance warning, 2) develop a contingency plan to reduce the system whenever GIC flows above a certain threshold, 3) develop a reliable forecast system that can deliver useful geomagnetic storm predictions, days in advance, or 4) develop an early warning system that can deliver useful geomagnetic storm predictions, minutes in advance.

Redesign the System: This option has never been seriously considered. The costs of replacing huge chunks of the power grid are much greater than the expected benefits from reduced solar weather impacts.

Contingency Plan: The flow of GIC cannot be prevented in a cost-effective way, so immediately following the 1989 storm, a few utilities experimented with running their system in a way that always could accommodate some GIC. They tried simply to redirect power flow away from fully loaded transformers when storm conditions produced GIC above a certain threshold. These plans were quickly abandoned, however; some GIC impulses still happen too quickly for these plans to be effective, and furthermore one utility operated under their costly contingency plan for 10% of the 1991 calendar year, resulting in significant profit losses.

Forecasting System---Predict Storms Before They Leave the Sun: Sunspots are key to forecasting solar activity. Sunspots are darker and cooler regions on the sun where energy is stored in complex magnetic fields. Galileo discovered sunspots in 1613, but it was not until 1859 when, after forty years of recording daily the number of visible sunspots, an obscure German magistrate realized that the sun cycled every 11 years between having virtually no sunspots at all, having dozens of sunspots, and back.

Until very recently, space scientists believed that sunspots were often sources of extreme solar weather events. After slowly building in intensity, the magnetic fields of sunspots will burst forth with an explosion of radiation, particles, or both. These explosions are called 'solar flares', and they very often result in extreme solar weather conditions. Scientists at NASA and NOAA used a magnetograph to measure the strength and direction of the magnetic field around a sunspot. If the field lines are twisted and sheared, they are more likely to cross and flare with energy. Such solar flares are more common when sunspots group together, and when the groups are complex.

In 1993, scientists decided that extreme solar weather events are more strongly linked to solar explosions called Coronal Mass Ejections (CME), which occur when filaments of solar matter stretch into space and then collapse back onto the sun's surface. The collapse produces an explosion of particles and radiation that, if directed towards the Earth, can lead to solar weather disturbances. Filaments occur alongside sunspots during the more active part of the solar cycle, but they also form and collapse <u>independently</u> of sunspots [2]. At the solar minimum, an average of one CME occurs each week. At the solar maximum, around 20 CMEs occur each week [3].

In 1995, hoping to learn more about how a CME accelerates the solar wind, European and U.S. scientists joined forces and launched the first coronagraph into space. The coronagraph is essentially a tinkered-with telescope. Ordinary telescopes cannot see much in the solar corona---the hazy region surrounding the sun, where CMEs are best visible---because the sun's light is overpoweringly intense. The coronagraph has a lens with a blacked-out center, so that when it points directly at the sun, only the faint light from the solar corona is recorded.

The Space Environment Center (SEC), the main source of geomagnetic forecasts in the United States, has for several years used the coronagraph data and other measures of solar activity to attempt to forecast geomagnetic storms. The unpredictability of solar wind speed makes their task extremely difficult; nevertheless, they have made some progress. As an example, the chart below shows the evolution of SEC on-day forecasts of the Ap Index, a widely understood measure of planetary geomagnetic activity. Smaller biases, smaller Root Mean Squared Errors, and larger skill scores indicate better forecasts.

Table 1.1: Ap Index Forecasts

Year	Month	Bias (ME)	MSE	Accuracy (•MSE)	Skill
1994	7-9	2.84	33.7	5.8	.239
1994	10-12	2.38	109.2	10.5	.165
1995	1-3	1.93	90.9	9.5	-.284
1995	4-6	1.20	102.2	10.1	.252
1995	7-9	.41	54.8	7.4	.08
1995	10-12	2.72	72.5	8.5	.04
1996	1-3	-.33	33.7	5.8	-.10
1996	4-6	-.31	32.9	5.7	.31
1996	7-9	-.29	37.7	6.1	.07
1996	10-12	1.61	41.4	6.4	-.16
1997	1-3	.42	37.7	6.1	-.11
1997	4-6	.81	61.2	7.8	-.06
1997	7-9	?	?	?	?
1997	10-12	3.14	99.9	10	.05
1998	1-3	.12	33.1	5.8	.16
1998	4-6	-.30	234.2	15.3	.28

*All SEC data from the notes and technical memoranda of Kent A. Doggett [4]

A few conclusions can be drawn from this chart. Late 1995 and 1996 mark the last solar minimum, and the forecast accuracy is best (√MSE is smallest) during this interval. Yet the skill scores are higher in the active periods. This trend shows why one measure of the 'goodness' of a forecast cannot suffice. During periods of increased solar activity, the forecasts more consistently follow the general trends of geomagnetic activity (as seen in the skill scores) but are generally *less accurate* (as seen in the accuracy scores). The unfortunate implication is that during the most dangerous years in each solar cycle, the forecasts of geomagnetic activity will be the least accurate.

In the larger picture, in the (22nd) solar cycle that spanned from mid-1986 to early 1997, there were 3927 days and 432 geomagnetic storms (Ap index > 30). The SEC successfully forecasted 164 of these storms, and also forecast 234 storms that never actually happened (false alarms). In the chart below, these results are compared with a One way to evaluate these results is to compare them with a naïve baseline. In the chart below, the naïve forecast system predicts that there will be a storm every day. For the casual reader, P(X | Y) indicates the probability that event X occurred, given that Y occurred.

Statistic	**Naïve Baseline**	**SEC Forecasts**
P(forecast was made | there was a storm)	100%	38%
P(there was a storm | forecast was made)	11%	41%

Consider first the naive baseline---you predict a storm every day and act accordingly. The 100% means you will never miss a storm. The 11% means that, unfortunately, the vast majority of your predictions will be false alarms. As stated above in the *Contingency Plan* section, responding to a false alarm can be costly for a utility company, and responding to dozens of false alarms is a cure worse than the sickness.

Now consider the SEC forecasts. The 38% means you will be completely unprepared for about two-thirds of the storms. The 41% is more encouraging, because it means you will cut your false alarm costs dramatically. You still have huge false alarm costs, however, and for power companies, the SEC cure is still worse than the sickness. Thus, in the end, neither haphazard guessing nor the SEC forecasts are particularly useful to power companies. In both cases, many disturbances are avoided, but false alarm costs are discouragingly high and some blackouts continue to plague the power grid.

Early Warning System---Detect Storms After They've Left the Sun: In 1993, NASA began building a satellite that would detect extreme solar wind conditions before they reached Earth. This satellite, the Advanced Composition Explorer (ACE), was designed to orbit one million miles away from the Earth and in line with the sun. In this position, the satellite can detect Earthbound solar storms about an hour before the particles hit Earth's magnetic field. The satellite was fully operational by mid-1998, and since then its instruments have provided NASA and NOAA with a minute-by-minute description of the solar wind.

Using these descriptions effectively remained a significant hurdle. Power systems operators do not care about solar physics, and they cannot interpret the ACE data; the operators cannot prevent transformer damage (and potential blackouts) unless they are told which transformers are at risk. They need an understandable response plan.

In 1998, a company called Metatech succeeded in converting solar wind descriptions into understandable response plans. Drawing on 22 years of geomagnetic modeling research, Metatech scientists used ACE data and computer models to generate a map of projected magnetic disturbances. By overlaying the disturbance map with a map of a given region's power system, their computer models succeeded in forecasting GIC with a high degree of accuracy. The entire process, from satellite to power system operators, takes under twenty minutes. The operators then have about forty minutes to adjust the grid, redirect power flow, and prepare for the coming storm. Metatech scientist John Kappenman stated simply, when the next geomagnetic superstorm hits, "If the [satellite] data is available, the probability is very high that the forecasts will be effective."

If numerous tests and extremely good skill scores are any indication, Kappenman has reason to be proud of Metatech's computer models. However, excitement over the success of the ACE data and the Metatech computer models should be tempered by two sobering realities. First, no debilitating 'superstorm' has arisen since the 1989 Quebec geomagnetic storm, so the early warning system is like a trained soldier who has never seen a real battle. Second, Kappenman's qualification, "If the data is available," is much more worrisome than he lets on. The ACE satellite cannot provide consistent even close to 100% of the time. In summer, the satellite is operational 80% of the time. In winter, that number is much lower. If a storm struck while the satellite transmission was down, power system operators would have no warning and another superstorm could cause huge blackouts with seconds.

Conclusion

According to NOAA, "one credible electric power outage could result in a direct loss to US Gross Domestic Product of $3 - $6 billion; a recent estimate is that the use of good forecasts by the power industry could save the US $365 M per year, averaged over the solar cycle."[5] Long-range forecasts of geomagnetic storms will not be a practical reality in the near future. Short-range forecasts---one or two days---are accurate enough to provide power companies with useful advance notice that can save the companies money; at the same time, false alarms and missed storms are a major problem even for the best space weather forecasts. The NASA/NOAA/Metatech early warning system is the best option available for power companies who are concerned about geomagnetic storms. The warning system is imperfect, however, and both utilities and their customers should acknowledge the usefulness and limitations of our solar weather response systems.

Partial Bibliography

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