Space Weather: Big & Small - A Continuous Risk

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Abstract

"Space Weather" is the term used to describe the relentless barrage of particles that bathe the Earth and other planetary bodies of the solar system that originate in the steady evolution, and catastrophic breakdown, of magnetic structures on the Sun. The Sun literally generates the weather that populates and pervades the solar system. In our society, growing in technical dependence, the constant drip of space weather can impact ground-based infrastructure, drains satellite systems in space, presents a radiation hazard to robotic and human explorers while also protecting us from relativistic cosmic rays that penetrate from deep space, that beyond our solar system.

Keywords: Sun, Earth, Sun-Earth Connection, Space Weather, Flare, CME, Solar Wind, Economics

1. Introduction

We live in the atmosphere of the Sun. "Space Weather" is the term used to describe the relentless barrage of particles that bathe the Earth and other planetary bodies of the solar system that originate in the steady evolution, and catastrophic breakdown, of magnetic structures on the Sun. In the increasingly technological society in which we live, the impacts of the Sun are being felt more and more by members of the public and an ever-growing number of infrastructure communities in the private sector. Space weather is relentless and poses constant risk - just like its equivalent in our atmosphere.

Space weather has a range of impacts on our atmosphere that manifest themselves across the scale from raw natural beauty, as aurorae [1], to the destruction of critical public infrastructure [2]. The day-to-day drip drip drip of the Sun on our atmosphere costs the U.S. government and private sectors upwards of \$ 10bn per year [3] and it is one of the only "natural disasters" that the re-insurance industry will not cover [4]. For example, the economic impact of a "black swan event," like the Carrington Flare of 1859, on society would be in the many trillions of Dollars, in the first couple of years alone [5]. While our planet's magnetic field is critical as a shield in protecting us from the majority of solar variability - the characterization, monitoring, and modeling of the Sun's magnetic field is the critical driver of the Sun-Earth system, and also poses the most significant challenge to progress.

1.1. Space Weather: The Early Years

Early investigations of solar magnetism and extreme flavors of solar activity relied heavily on correlated impacts on our atmosphere [6]. Indeed, many investigations into what would eventually be dubbed space weather, were rooted in the practical aspects of military need during World War II. Both the Axis and Allied powers deployed observational techniques that were very advanced at the time to provide forewarning of ionospheric distortions that would significantly impact battlefield tactics through local and global radio communications [7, 8] - empirical connections of Sun and the Earth were the norm. In those days the primary means of identifying solar "storms" was the detection of events on the Sun's East limb using a device called a coronagraph - a device invented by French astrophysicist Bernard Lyot [9] to create artificial total eclipses by blocking the light from the disk of the Sun. A coronagraph reveals the Sun's corona - a cloud of gas surrounding the Sun that is one million times fainter than the Sun's disk - and chromospheric protuberances called "prominences"

Following World War II, our knowledge of the Sun-Earth system advanced with the dawn of the rocket, space, and satellite age, much as terrestrial meteorology did. V2 rocket-borne spectroscopic measurement of the Sun's corona and its subsequent identification as being consistent with the presence a million Kelvin cloud of highly charged particles [10, 11], the prediction of the "solar wind" [12] and its eventual detection by the Russian Luna 1 satellite and subsequent Mariner mission measurements [13]. The observational environment outside of the turbulence and (photon) absorption of our atmosphere provided by the Orbiting Solar Observatory (OSO) fleet and then Skylab identified a new relevant feature in the space weather lexicon - the "coronal mass ejection" or CME [14, 15].

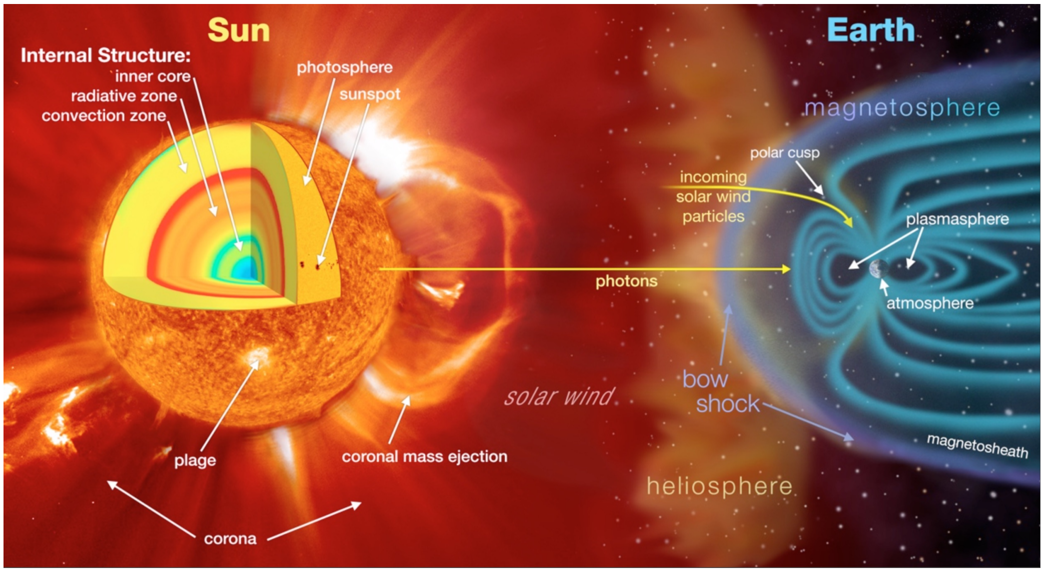

Figure 1: The Sun and its atmosphere consist of several zones, or layers, from the inner core to the outer corona. Beyond the corona is the solar wind, which is an outward expansion of coronal plasma that fills the solar system. Controlled by the Earths magnetic field, the magnetosphere acts as a shield protecting our planet from solar wind. The shape of the Earth's magnetosphere is the direct result of being impacted by solar wind - compressed on the sunward side and elongated on the night-side creating a feature known as the magnetotail. The relentless magnetic activity of the Sun directly influences the near-Earth environment. Image credit: NASA Goddard Space Flight Center

2. The Space Weather "Problem"

The space weather problem can be decomposed into two separate, but linked, issues: "top-down" and "bottom-up." The former is the response of the Earth to driving from the Sun and solar variability. The latter is the forcing of the Earth's troposphere on the near-space environment. So the Sun's magnetic weather and the Earth's weather affect space weather, although unequally. When solar activity is low the latter poses the greatest risk as a non-negligible driver of the ionosphere and thermosphere, but generally speaking the Sun is the principal driver of the system. Thus, characterizing the Sun's magnetism and its variability is the single biggest impact on the predictability of space weather. In the following sections we'll look at these two perspectives of the problem.

2.1. Top-Down Space Weather

We know now that CMEs are very often intimately related to flares and prominence eruptions, but not uniquely [16]. They flow into a solar system that has plasma flows dictated by the Sun's magnetic field, the solar wind structure and the energization of the corona. Characterizing, and predicting that relentlessly evolving environment is the essence of Space Weather forecasting, or "SWx". The forecasting challenge has two flavors.

Once an eruptive event has occurred (noting that it takes 8 minutes for the changes from the event to be seen at the Earth due to the 93 million miles of light travel time) we are in a race against time to estimate the path of the disturbance through the solar system including the determination of the disturbance's intersection with the orbit of Earth, estimating the arrival time at Earth; estimating the magnitude of the interplanetary shock (CMEs can travel faster than the background medium); and estimating the magnetic polarization of the disturbance - since an anti-parallel magnetic field in the disturbance will couple directly into the Earth's protective magnetosphere. This sounds a lot like hurricane forecasting, but for a couple of critical differences - we really don't know a great deal about the mechanisms driving and populating the solar wind (the background state on which the disturbance travels) and we have no observational baseline to estimate the disturbance polarization, other than a couple of sentinel spacecraft a few tens of minutes upstream of the Sun-Earth line at the Lagrange "L1" point of gravitational balance between the Sun and the Earth. Since numerical models form the primary forecasting tool, there is wide acknowledgement of fundamental limitations in predictive skill on the event-by-event basis. This "after the horse has bolted" approach is the current paradigm of SWx.

The alternate, predictive, approach to SWx doesn't really exist! To the vast majority of the SWx community, in addition to the broader solar research community, solar flares and CMEs are as "intrinsically unpredictable," as Earthquakes are. This paradigm is neither acceptable, or true. The future of human exploration of the solar system, the protection of critical infrastructure in space, and in the troposphere requires the development of considerable predictive skill in SWx, for solar events and terrestrial impacts.

Solar magnetism is the root cause of space weather. In fact, solar magnetism drives the bulk of our star's variability across scales and so characterizing that evolving magnetism on timescales from seconds to millennia is sometimes cast in the similar "weather" and "climate" paradigms as our investigations of the Earth's atmosphere. The vast scale of the Sun and the massive Sun-Earth distance make the SWx problem, or those relating to the root of the space weather problem at the Sun, is a profound remote sensing challenge - a challenge where we capture photons and particles 93 million miles away to infer the physics of the fundamental processes that propelled them to us.

Of most critical importance to the SWx enterprise is the characterization of the Sun's magnetism throughout the solar atmosphere. By exploiting quantum mechanical effects and measuring polarized radiation we can get a bearing on the Sun's vector magnetic field as it becomes visible after building up in the Sun's opaque interior by an as yet process called the "solar dynamo".

Solar magnetism displays a host of variational timescales of which the enigmatic 11-year sunspot cycle is most prominent. Sunspots are a manifestation of intense magnetic field concentrations and are the hosts to flares, "Coronal Mass Ejections" (CMEs), and the most dynamic of prominences - in other words, the majority of the most dangerous space weather events. The other, more stealthy, and mysterious constituent of the space weather zoo is also rooted in varying magnetism - the coronal hole. Discovered once systematic, or synoptic, coronal observations of the solar disk were visible from orbit [17] they are literally "holes" in the corona. It was subsequently discovered that coronal holes were the outward extensions of spatially extended regions of unipolar magnetic field [18] and the source of the "fast solar wind" [19].

It is worthy to note the differences between flares and CMEs. As highlighted by Gosling [16] the two are often associated with each other, but they can occur in isolation in addition to occurring together - why is not yet known. A flare is defined as a sudden, rapid, and intense variation in brightness. A solar flare occurs when magnetic energy that has built up in the solar atmosphere is suddenly released. Radiation is emitted across virtually the entire electromagnetic spectrum, from radio waves at the long wavelength end, through optical emission to x-rays and gamma rays at the short wavelength end. A CME is a huge bubble of plasma threaded with magnetic field that gets ejected from the Sun over the course of several hours, then taking tens of hours to transit the Sun-Earth distance - for reference, a flare timescale is minutes and the radiation starts to hit us in 8 minutes.

The solar wind has two primary states, "slow" (200 - 500km/s) and "fast" ($>$ 500km/s). The former is really a continuum of slow states, where differences in slow wind parcels are most easily quantified through differences of plasma composition in the parcels [20] that result from the different magnetically confined regions of the Sun's corona from which that plasma originates [21]. Slow wind can arise from quiescent and active regions on the Sun. The physical origins of the slow solar wind, its gradual acceleration, and its compositional contrast pose challenges to our community. The simpler, in principle, state is the fast wind, coming from the relatively simple coronal hole environment, but the rapid acceleration and starkly different compositional signature similarly pose physical challenges. A simple delineation between slow and fast wind, beyond their - measured velocities - is that the latter is "cooler" with a compositional signature consistent with a plasma of <1MK, and the former with a range of consistent root plasma temperatures that can greatly exceed 1MK [22]. These two states vary and mix in the three-dimensional magnetic system that is the heliosphere on pathways that are themselves set by the magnetic field configurations at the center of the system.

Establishing the "solar wind roadmap," the state of the background plasma environment into which a flare, CME, or prominence is launched poses as much of a challenge to our community as the disturbances themselves. In a sense though, it is more critical, because any scientist knows about the impact of poor initial conditions... Can you imagine the chances of successfully forecasting the characteristics of a hurricane when you have no more than 50% accuracy on any of the background environmental variables? That wouldn't be acceptable, would it? There are many "decision points" in the contemporary SWx challenge. Operational practice leans heavily on past experience that results from the analysis of high-heritage observational tools.

We must rise to these challenges! The SWx capability required to protect future human explorers in the solar system, in addition to critical ground- and space-based infrastructure is being conceived through the recent National Space Weather Strategy. This strategy is devised to reduce and/or eliminate the shortcomings of the physical challenges and forecasting decision points. Observational tools to reduce risk on the background solar wind, CME directionality, CME and prominence magnetic polarization, etc are all critically wedded to information technology, data assimilation, and the array of numerical modeling techniques that have been extensively developed over past decades in the solar-terrestrial physics community. A truly critical need for future space weather understanding (and increased forecast skill) is the full characterization of the Sun's global magnetic field distribution - we must begin to study the Sun's atmosphere as a weather system, exploiting the observational tools, and methods developed by the meteorological community. Early investigations of (truly) global solar phenomena point to strong analogs between our atmosphere and the Suns [23] and offer insight into the gross predictability of solar activity that belongs to persistent longitudinal patterns in solar magnetism.

2.2. Bottom-Up Space Weather

On the terrestrial side of SWx, observational platforms are being deployed to explore the magnetosphere, radiation belts, and now the ionosphere with the GOLD [24] and ICON [25] missions. Those missions, their data, and the numerical models derived from them are going to critical provide insight into the "top-down" (from the Sun) and "bottom-up" (from the troposphere) impacts on the ionospheric interface between magnetically and thermodynamically controlled environments. As is often the case, some of the most interesting physical phenomena and challenging measurements to characterize occur at boundaries of physical domains. Conquering the physics of the ionosphere will be necessary to improve forecast skill of that region beyond a few hours. Application of high-skill, long duration ionospheric forecasts have a reach beyond the academic environment, into commercial and the military sectors where warfighters critically depend on their field communication devices.

Another interesting, and very relevant, side-note to the terrestrial side of the space weather problem comes from the changes in the Earth's magnetic field itself [26] and how the they will change the coupling of our planet's magnetism with that of the Sun.

3. Space Weather - Looking To the Future

Following the 2006 launch of the twin STEREO satellites [27] and SDO [28] in 2010, a new picture of global solar magnetism is developing. Spatial and temporal relationships in the pattern of how the Sun's magnetic field emerges have revealed that the Sun undergoes quasi-annual episodes of significantly enhanced activity of an amplitude equivalent to the more familiar solar magnetic cycle [29, 30, 23]. These well-studied strongly-longitudnal magnetic flux emergence processes [31, 32, 33], appear to be driven by magneto-Rossby modes on the global scale [34, 35, 36, 37, 38] which then drive significant increases in the production rate of flares and CMEs.

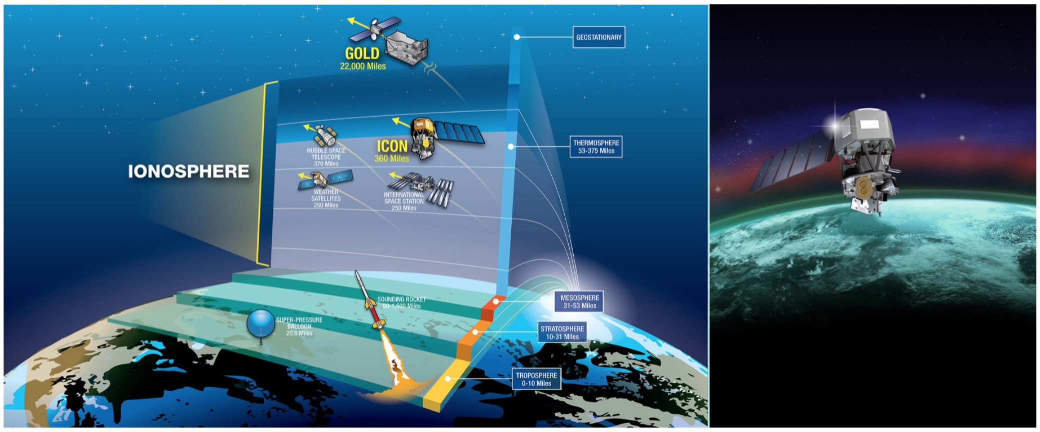

Figure 2: Left: The Earth's ionosphere, stretching from roughly 50 to 400 miles above the surface, is an electrified layer of the upper atmosphere, generated by extreme ultraviolet radiation from the Sun. It is the boundary between tropospheric weather and that driven by the SUn into the magnetosphere. Understanding the ionosphere's variability is a second fron in the SWx puzzle. It is a puzzle requiring us to detangle the interaction between the neutral and ionized portions of the atmosphere. Measuring airglow helps, occurring when atoms and molecules in the upper atmosphere are excited by sunlight, emit light in order to shed their excess energy. The phenomenon is similar to that which produces aurorae, although those are driven by high-energy particles originating from the solar wind. Airglow carries information on the upper atmospheres temperature, density, and composition. Vast, high-altitude winds sweep through the ionosphere, pushing its contents around the globe and airglows subtle dance follows their lead, highlighting global patterns that are likely critical to predicting the behavior of this region hours to days in advance. Credit: NASA Goddard Space Flight Center

Using these whole atmosphere observations we could compare periods of enhanced solar activity with the occurrence of most destructive of solar storms. We observed patterns indicating strong longitudinal dependence. Active solar longitudes persist for many solar rotations [23] with periodic surges of the timescale of 11-ish months [30]. Therefore, monitoring, understanding and forecasting the origin of these active longitudes is of vital importance in the context of short and long-term forecasting for the geospace and heliospheric environment, in addition to the protection of vital space and ground infrastructure. From our current, limited, vantage point we will not gain insight into these processes and, as a result, solar storms will remain high-frequency intrinsically unpredictable events, i.e., *exactly* where terrestrial meteorology was half a century ago with respect to the predictability of extreme weather events at the dawn of the space age and prior to global observations of our planet's atmosphere.

Unfortunately, the loss of one of the STEREO spacecraft pair in late 2014, in addition to the fact that the STEREO orbits are continuously drifting relative to the Sun-Earth line, has limited our ability to study the Sun in this fashion and really get a bearing on our star's magnetic weather and its driving impact on space weather.

3.1. Heliospheric Meteorology - A solution Path

Significant predictive skill for tropospheric weather was accelerated by the dawn of the satellite age through our ability to study the entire atmosphere from the vantage point of low Earth orbit [39, 40]. The identification and characterization of global-scale drivers of local-scale weather and developing predictability for the former led to more success in forecasting the latter. SWx research is at the same status as terrestrial meteorology was at the dawn of the space age - 70 years ago - because the SWx enterprise is limited by the single "local-time" perspective. Our observational baseline is focused only on the Sun-Earth line and our knowledge of the global solar atmosphere from where the bulk of our issues stem is, to be frank, naive. A conceptual mission to look at the Sun's weather and space weather from a meteorological perspective has been drawn up [41] and dubbed, simply, the Heliospheric Meteorology Mission (HMM).

3.2. Solar Polar Orbiter - A Discovery Path

The preliminary HMM configuration would look like a string of pearls around the Sun in the ecliptic plane. However, the growing realization that our inability to observe the Sun's polar regions and characterize the evolution of plasma flows and magnetism at high solar latitudes is also limiting our understanding of the processes that govern the production of the Sun's magnetism. There is a growing body of literature [29] pointing to 55° latitude as the potential origin of the Sun's dynamo and, hence, as the source of all space weather. To address this issue *continuous* observations of the high latitude solar atmosphere are required. Taking the HMM concept, and sequentially launching four or six of the *same* smallsats into highly inclined orbits or solar polar orbits would provide 4-π observations of the Sun.

Naturally, deploying advanced coronagraphs as part of an extended HMM concept, like those capable of measuring magnetic fields in the corona [42] may provide unique perspectives on (and solutions to) the "B_z challenge" of measuring and forecasting the magnetic orientation/polarization of solar disturbances *long* (potentially tens of hours) before they reach the Earth. The present paradigm is a very short warning (∼20 minutes) from upstream monitors at the L1 point.

4. Conclusion

Space weather is a 24/7/365 phenomenon, covering the gamut from raw natural beauty to cataclysmic impact that would set civilization back decades. In the coming decades, society's increased dependence on technology will drive the need for high-skill, accurate, space weather forecasts of the coupled Sun-Earth system like never before.

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