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Mr. Chairmen, Ranking Minority members, and members of the Subcommittees, I want to thank you for the opportunity to testify today at this hearing on "Surveying the Space Weather Landscape". My name is Sarah Gibson and I am a Senior Scientist at the National Center for Atmospheric Research and a co-chair of the National Academy of Sciences Committee on Solar and Space Physics. The views presented here are my own, and are based on my professional experience in the field of Heliophysics, the science at the heart of Space Weather.

The particular intent of this testimony is to provide context for your discussion of space weather legislation, and to argue for moving forward with said legislation as soon as possible. I work in Boulder, Colorado, which is a nexus of space-weather research and operations[1]. I was pleased to see that my state's Senator Gardner co-sponsored the Senate space weather bill that passed last year (S.141), along with Senators Booker and Wicker, and that now the House space weather bill (H.R.3086) has been introduced by Colorado's Mr. Perlmutter, along with Ms. Johnson and Mr. Bridenstine. Space weather is fundamentally an issue of safety and protection of life and property, and as such, it is no surprise that it crosses party lines.

In brief, the points I wish to make today are as follows:

- **Space weather has broad and potentially devastating impacts on the Nation.**
- **Fundamental scientific questions, central to space weather, remain unanswered.**
- **Space-weather research and operations are observationally starved.**
- **The path forward requires strategic actions that emphasize efficiency and agility.**
- **Legislation is needed now.**

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[1] Just a few examples of institutes participating in space weather activities in the Boulder area include: NCAR's High Altitude Observatory, the Space Weather Prediction Center at NOAA, the USGS geomagnetism program, the National Solar Observatory, the recently formed Space Weather Technology, Research and Education Center at the University of Colorado, the Atmospheric and Space Technology Research Associates, the Boulder offices of the Southwest Research Institute and Northwest Research Associates, and aerospace companies including Ball Aerospace and Sierra Nevada Corporation.

1. Space weather has broad and potentially devastating impacts on the Nation.

We are living inside the atmosphere of our star, the Sun. That atmosphere continually expands outwards as the solar wind, passing the Earth in an unceasing stream of charged particles. It is variable in nature, and, on a regular basis, dense, fast, and strongly magnetized gusts buffet the Earth. Luckily, the Earth's atmosphere and its own magnetic field act as shields that protect us and our technology from direct exposure to this solar wind. However, the Earth's magnetic shield is neither static, rigid, nor indestructible, and the strongest solar wind gusts can and do frequently break through.

When they do, interactions between the magnetic fields in the solar wind and those of the Earth result in one of the most common forms of space weather: geomagnetic activity. Until the last century or so this meant only that humans were treated to the spectacle of beautiful auroras. With the advent of technology, however, new vulnerabilities emerged.

In 1859, Richard Carrington was observing a particularly complicated group of sunspots projected from his telescope onto a screen, when he saw two brilliant spots of white light appear and brighten on top of the otherwise dark sunspots. This was unusual -- only the very brightest solar flares are visible in this manner -- but what made this astronomical observation particularly significant was that Carrington subsequently connected the solar flare to the strong geomagnetic activity observed the following day, when the storm reached the Earth. The storm was so strong that auroras were seen as far equatorward as Cuba and El Salvador, and -- marking the first recorded impact of space weather on our nascent technology -- fires were sparked along telegraph lines.

Now, with our increasingly technological society, our vulnerability to this type of space weather is much higher. Geomagnetic activity induces ground currents that interfere with our power grids (Knipp, 2015). In the event of a "Carrington-level" storm, cascading transformer failures, power outages, and disruptions of global supply chains could cost the U. S. tens of billions of dollars per day (Oughton et al., 2017), with long-term global costs potentially reaching trillions of dollars (Schulte in den Baumen et al., 2014; see also National Research Council, 2008).

Geomagnetically-induced ground currents represent just one of several hazards associated with space weather. A variety of ionospheric disturbances may also occur, affecting global navigation and communications. This introduces wide-ranging costs and risks: a particularly trenchant example occured in 1967, when space weather disrupted radar and radio communication in a manner that was initially interpreted by the U. S. military as a possibly hostile act by the Soviet Union (Knipp et al., 2016).

Disturbances of the upper atmosphere also pose difficulties for the International Space Station and other satellites in low-altitude orbit (Oliveiros et al., 2017). The atmospheric drag on such assets change in unexpected ways, impacting calculations of satellite trajectories that are critical for avoiding collisions. Radiation storms also often occur with large solar storms, posing a danger to both astronaut health and satellite function. The threat is highest away from the Earth's protective shields, and deep-space missions -- for example to the moon or other planets -- must be prepared for hazardous levels of radiation.

As with terrestrial weather, space weather can range in severity -- from minor squalls occurring multiple times per year, to larger storms that strike once or twice per 11-year solar cycle, to 100-year Carrington-level storms, and, possibly, to storms surpassing anything experienced in modern times (particularly with regards to radiation hazards) (Schrijver and Beer, 2014). There are costs even for the smallest of these events: for example, an assessment of insurance claims attributable to variations in the power grid suggests that the impacts of non-extreme geomagnetic activity may be as large as 10 billion dollars per year for the U.S. alone (Schrijver et al., 2014).

Space weather and associated economic and societal impacts run the gamut from frequent and small (yet still costly) events, to rare (but potentially globally-disastrous) superstorms.

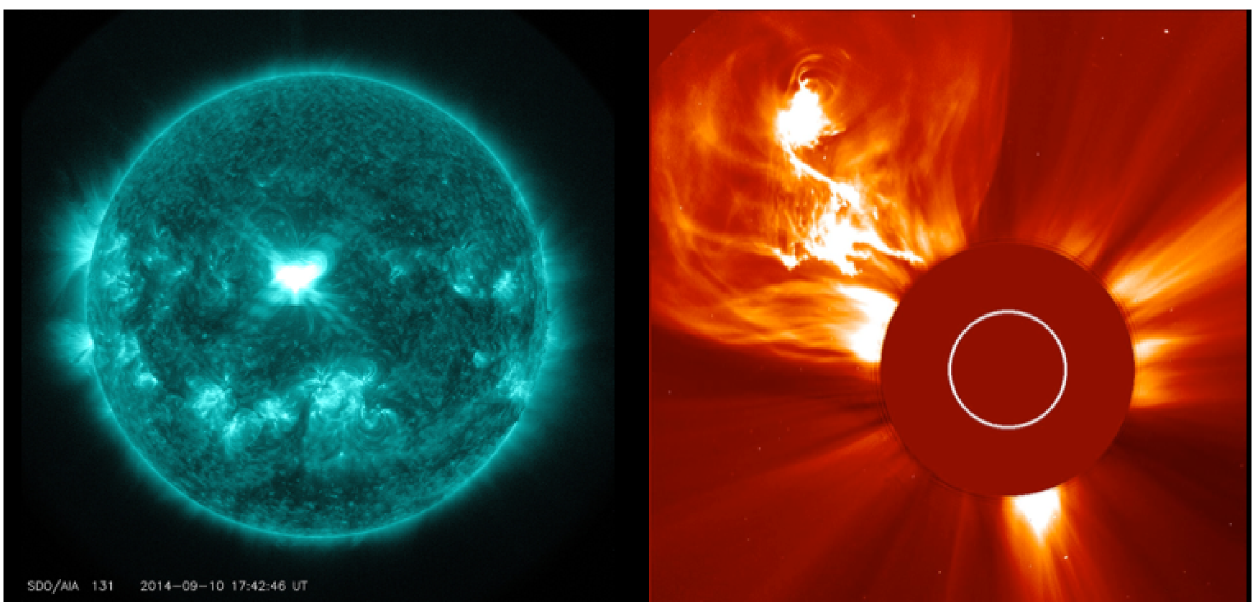

Figure 1. (Left) An X1.6 class solar flare flashes in the middle of the Sun and is observed by the Solar Dynamics Observatory Atmospheric Imaging Assembly (SDO/AIA). (Right) The Solar and Heliospheric Observatory Large Angle and Spectrometric Coronagraph (SOHO/LASCO) observes a coronal mass ejection (CME) as a bright tangled structure exploding out into the solar wind. The white circle indicates the size and position of the solar disk, which is blocked so that the Sun's outer atmosphere, or corona, can be seen (thus, the coronagraph mimics a solar eclipse). **(***Image credits: NASA/ESA***)**

2. Fundamental scientific questions, central to space weather, remain unanswered.

The ultimate source of space weather is the Sun. Flares and coronal mass ejections (CMEs) (Figure 1) are both manifestations of a solar eruption. The flare is the flash of light released as the eruption is triggered; it drives radio blackouts at the Earth almost immediately. The CME is the subsequent launch of mass outward into the solar wind; it can lead to geomagnetic activity a day or two later. Both contribute to ionospheric disturbances, satellite tracking problems, and radiation storms.

Ultimately, we would like to be able to predict solar eruptions before they happen. We know that they occur in regions that are magnetically-energized (for example, complex groups of sunspots) and some progress has been made in identifying observational signatures of this energization. However, we still do not know what triggers the eruptions, which significantly limits our capability for prediction.

So, in general, we wait until an eruption occurs, and then hope to provide warning at least in advance of any geomagnetic activity. Unfortunately, we do not know with certainty how severe the space weather impacts at the Earth will be. The likelihood that a CME will break the Earth's magnetic shield depends on the CME's magnetic strength and orientation. To know this, we have to quantify the original 3D magnetic configuration at the Sun, and then understand how it erupts and how the resulting CME interacts with the solar wind as it travels from Sun to Earth. If we get the magnetic orientation backwards, we run the risk of false positives that trigger unnecessary mitigative steps in preparation for an event that turns out to be minor.

Even if we were able to predict the solar storm in advance, and even if we were able to specify the magnetic structure of the CME as it reaches the Earth, we would still be limited in our ability to forecast when, where, and how strongly ground currents, upper atmospheric disturbances, and radiation storms would occur. Fundamental physical processes such as magnetic reconnection and particle acceleration -- both of which are areas of active research -- must be taken into consideration, along with complex interactions between the Earth's upper atmosphere, space environment, and solar wind.

In the words of the recent international Committee on Space Research (COSPAR) Space Weather Road Map (Schrijver et al., 2015), "*The domain of space weather is vast – extending from deep within the Sun to far outside the planetary orbits – and the physics complex – including couplings between various types of physical processes that link scales and domains from the microscopic to large parts of the solar system*."

Accurately forecasting space weather requires an understanding of all the links in the physical chain from Sun to Earth. At present, there are multiple conceptual gaps along that chain. Many are in fact the very same key science challenges, from Sun to Earth, that were identified in our field's last Decadal Survey (*Solar and Space Physics: A Science for a Technological Society,* National Research Council, 2013). **The gaps in our understanding lie at the bleeding edge of fundamental scientific research in Heliophysics, and represent problems that must be tackled if we wish to advance beyond our current forecasting capability.**

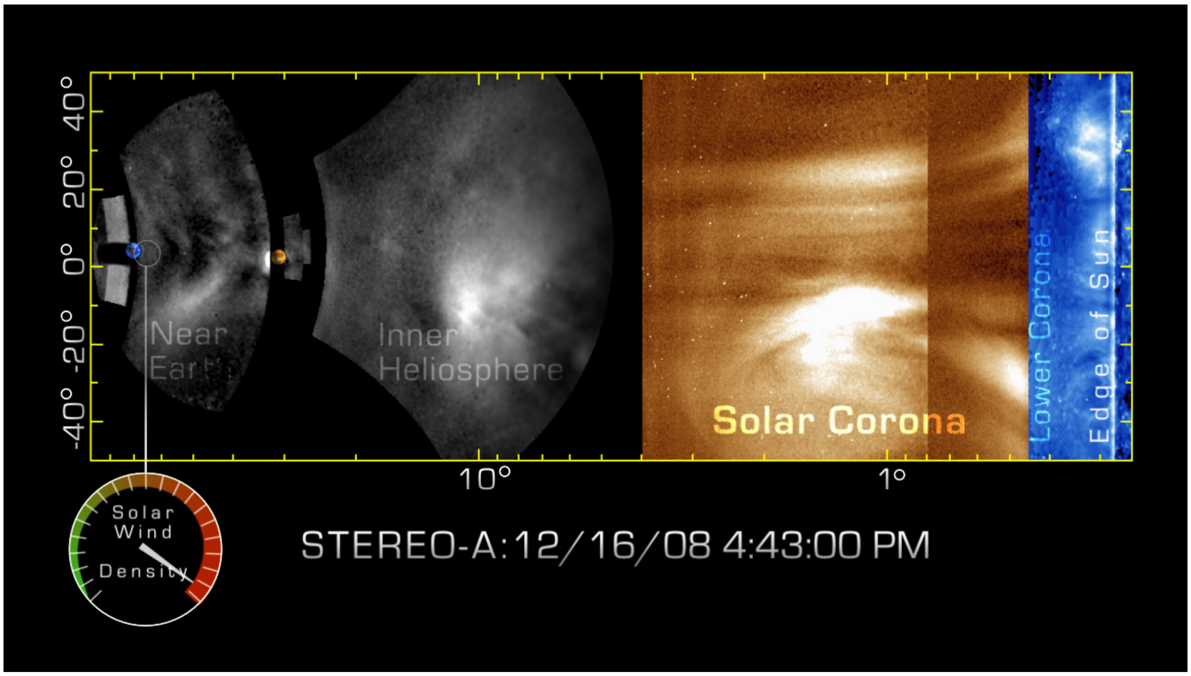

Figure 2. Taking a side view, instruments on board NASA's STEREO-A spacecraft track a CME as it evolves between Sun (on the right of the image) and Earth (the blue dot to the left), and connect image data directly to measurements at Earth at the time of impact. The images at the right are obtained near the Sun and deformed to enable tracking the CME structure through space The gauge on the left shows solar wind density measured by NASA's WIND spacecraft spiking as the CME passes the Earth.
Credit: NASA/Goddard Space Flight Center/SwRI/STEREO/WIND; DeForest et al., 2013; https://svs.gsfc.nasa.gov/vis/a010000/a010800/a010809/index.html.

3. Space-weather research and operations are observationally starved.

Our best bet for filling the gaps in our scientific understanding of the space-weather chain is through observations[2]. For example, the question of how the CME changes en route from Sun to Earth is one that could be addressed by directly observing its progress, as shown in Figure 2.

[2] "*If the matter is one that can be settled by observation, make the observation yourself. Aristotle could have avoided the mistake of thinking that women have fewer teeth than men, by the simple device of asking Mrs. Aristotle to keep her mouth open while he counted.*" -- Bertrand Russell

These observations were taken by one of NASA's two STEREO spacecraft, which precede and follow the Earth in its orbit around the Sun. The views from STEREO are thus complementary to those from the Earth, but are continuously changing. At the time of this event, STEREO had a side-angle view of the Sun-Earth line that was particularly appropriate for space-weather monitoring.

This raises an important point. The observational needs for solving fundamental scientific questions are not necessarily the same as those for day-to-day forecasting (i.e., space-weather operations). If we want to figure out the physical processes acting on a CME as it moves through the solar wind, it does not necessarily matter if the CME we observe is aimed at the Earth, but we do require high- resolution, spatially-continuous observations. If we are making space-weather operational forecasts, we could greatly benefit from the side-angle view of the Sun-Earth line, but we also require near-real-time, consistent and reliable observations. The example shown in Figure 2 is compelling, but offers only a fleeting glimpse of what is needed, and does not fully satisfy either type of needs. Moreover, it represents just one example of the broad range of observations from Sun to Earth required for progress in both space-weather research and operations.

Observations are not only needed to fill gaps in fundamental research, but also in applied research. An example of this is found in the benchmarking activities that are currently being undertaken to quantify the potential severity of space-weather hazards[3]. Comprehensive observations are needed to make these assessments, which in some cases are not currently available. For example, assessing geo-electric field benchmarks requires characterizing both geomagnetism and ground conductivity, but gaps in observational coverage prevent accurate estimates across much of the continental United States (Love et al., 2016).

In terms of operations, there are a few, critical, measurements that we know we need: for example, the SOHO/LASCO coronagraph observations of CMEs (e.g., Figure 1, right) represent the first definite sign of an approaching storm, and can be used to estimate arrival time and, to some extent, the size of the storm. Measurements just upstream of the Earth, e,g,, at the L1 Lagrange point[4] between the Sun and Earth, act as the "canary in the coal mine" and provide a much more accurate characterization of how big the storm will be, with however only about an hour (or less) of warning. It is no wonder that these two measurements in particular are

[3] https://www.ofcm.gov/publications/spacewx/DRAFT_SWx_Phase_1_Benchmarks.pdf

[4] The Lagrange points referred to here are locations where a spacecraft can maintain its position relative to the Sun and Earth, and so obtain essentially continuous observations from one (reasonably) stable vantage. Of particular interest to space-weather are the L1 point, which lies along the Sun-Earth line and so samples the solar wind in advance of its hitting the Earth; and the L4 and L5 points, which give views from either side of the Sun-Earth line and so enable the imaging of Earth-directed CMEs (similar to the view shown in Figure 2).

emphasized as essential in the Space Weather Action Plan (SWAP)[5], and that there is concern regarding their future availability. Beyond this, various solar observations (including from ground-based telescopes) along with measurements of the Earth's upper atmosphere and space environment are routinely ingested into space-weather operational models, and ground magnetometer networks and neutron monitors are used for situational awareness of the geomagnetic and radiative environment.

But could we have a better, earlier forecast of storm strength if, for example, we had a continuous side-angle view of CMEs as they move along the Sun-Earth line? Or if we did a better job of measuring the magnetic field of the CME before it left the Sun (Tomczyk et al, 2016)? In truth, it is not yet clear exactly what the optimal set of observations are for forecasting and monitoring space weather.

To summarize: the gaps in our fundamental scientific understanding motivate new, cutting-edge observations of the sort presented in our Decadal Survey. The usefulness of these new observations for operational forecasts can then be assessed through applied research, potentially identifying new targeted observations needed to achieve specific operational goals. This represents one important aspect of a Research-to-Operations/Operations-to-Research (R2O-O2R) feedback loop (a similar argument can be made with regards to the development of the computer models used in space-weather forecasting). **The goal is an operationally relevant, scientifically sound approach to space-weather forecasting; however, currently the observations that support both the research and operations elements of space weather are insufficient and/or at risk.**

4. The path forward requires strategic actions that emphasize efficiency and agility.

A key motivation for the National Space Weather Strategy, stated both in its current form[6] and in the recent call for its update[7], is the improvement of government coordination. Laying out roles and responsibility for the different government agencies enables strategic coordination, and through this, a more efficient use of national resources.

Further efficiency comes from leveraging opportunities that arise outside of U.S. government agencies, in particular from the international, commercial, and academic sectors. An example of the benefit of international collaboration specific to the space-weather arena is the LASCO

[5] Space Weather Action Plan (https://www.sworm.gov/publications/2015/swap_final__20151028.pdf), Section 5.3 "Establish and Sustain a Baseline Observational Capability for Space-Weather Operations"
[6] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/final_nationalspaceweatherstrategy_20151028.pdf
[7] https://www.federalregister.gov/documents/2018/04/20/2018-08336/developing-an-update-to-the-national-space-weather-strategy

coronagraph, so critical to operations. LASCO is an instrument on board the SOHO satellite, a collaboration between NASA and the European Space Agency (ESA). Currently, ESA is considering a mission at the L5 Lagrange point trailing the Earth, which would provide a view of CMEs on the Sun-Earth line, highly complementary to U.S. assets at the Earth and upstream L1 point. Commercial opportunities have similarly benefited space weather activities. An example is NASA's GOLD mission to study the cause of dense, unpredictable bubbles of charged gas that appear over the equator and tropics in the Earth's upper atmosphere, sometimes causing communications breakdowns. GOLD is a hosted payload aboard a commercial communications satellite (SES-14). Ground-based observations relevant to space-weather science are also obtained in collaboration with the international, commercial and academic communities.

These communities have also played, and can continue to play, the absolutely essential role of disruptor. A classic example from the commercial arena is the technological development of small satellites. Both the academic and commercial communities act as an extended work force for the national space-weather enterprise -- analyzing agency observations, helping to build modeling frameworks and operational tools, and playing key roles in R2O/O2R development. International space-weather research and operations is also a growth area around the world, and open exchange of ideas and observations across borders promotes best practices and creative approaches. The sheer diversity of players introduces an organic, unpredictable element to the process. Where will the next good idea emerge? By being open to new ideas, and promoting a broad range of interactions, we maximize the benefit to the Nation.

Space weather affects life and property, so an efficient, coordinated public policy is needed and warranted to ensure that the Nation is safe. Beyond this, we need an agile approach that leverages external opportunities and is open to innovation.

5. Legislation is needed now.

We are an increasingly technological society, and space weather cannot be ignored. Space-weather scientific research and operations is a growing, but still young field -- it is often stated that our current space-weather forecast capabilities are akin to terrestrial-weather forecast capabilities of several decades ago. The problems we face are complex and multidisciplinary, but with coordinated and targeted actions, we stand to make significant progress. I am reminded of the words of the Solar and Space Physics Decadal Survey "DRIVE" initiative: "*Relatively low-cost activities that maximize the scientific return of ongoing projects and enable new ones are both essential and cost-effective*."[8]

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[8]National Research Council (2013); Chapter 4

The various coordinating activities of the Space Weather Operations, Research, and Mitigation (SWORM) Task Force have given us a clear path forward. The actions that have been outlined in the Space Weather Action Plan represent the first steps along that path. To make certain that we continue onwards to where we need to go, we now need legislation. I believe that H.R. 3086 provides a good framework for progress. In particular, it strikes a good balance between promoting coordinated actions of government agencies to act as a bulwark protecting the Nation, and maintaining a (necessarily) open-ended approach to ensure that good ideas and opportunities from outside the government are considered and pursued.

If we delay action, we run multiple risks. The obvious one is that we will be woefully unprepared when a superstorm hits. Another all-too-obvious risk is that LASCO, the sentinel coronagraph monitoring CMEs from the SOHO satellite -- along with related assets sitting at the upstream L1 point -- could fail before they are replaced, leading to substantial backslide in our current monitoring and forecasting skill. Beyond this, the impacts of even moderate space weather are costly, and every day we wait to improve upon our scientific understanding and operational capabilities, we waste time and money.

Finally, I am speaking as an individual, but in preparation for this hearing I have spoken to many people in my field, and attempted to “take the temperature” of the community. The overwhelming impression I gathered from this exercise is that the space-weather community feels that we must keep the momentum going. I personally feel that there is a very real risk of “dropping the ball” if we do not move forward with legislation soon. **Space weather is an urgent national issue, and it is time to take legislative action.**

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