An international roadmap to advance scientific understanding of space weather, commissioned by COSPAR and ILWS

By Karel Schrijver, Lockheed Martin Advanced Technology Center, Palo Alto, CA, USA,
On behalf of the COSPAR/ILWS study team: Carolus J. Schrijver, Kirsti Kauristie, Alan D. Aylward, Clezio M. Denardini, Sarah E. Gibson, Alexi Glover, Nat Gopalswamy, Manuel Grande, Mike Hapgood, Daniel Heynderickx, Norbert Jakowski, Vladimir V. Kalegaev, Giovanni Lapenta, Jon A. Linker, Siqing Liu, Cristina H. Mandrini, Ian R. Mann, Tsutomu Nagatsuma, Dibyendu Nandi, Takahiro Obara, T. Paul O'Brien, Terrance Onsager, Hermann J. Opgenoorth, Michael Terkildsen, Cesar E. Valladares, Nicole Vilmer.

Publication: Schrijver et al., Advances in Space Research 55, 2745 (2015)

[paragraph numbers correspond to slide numbers]

[1] The Sun not only sends us the visible and infrared light that warms the Earth to a comfortable home for all its life forms, but also hazardous ultraviolet and X-rays, a magnetized solar wind, and energetic particles moving at near-light speed. The visible and infrared output of the Sun are remarkably stable over time. In X-rays, however, the entire Sun can brighten 10,000-fold or more within minutes. The solar wind is gusty, with speeds ranging over at least a factor of four, while the direction of the magnetic field can rapidly change to any value depending on what the Sun ejected and how this evolved on its way to Earth. Energetic particle fluxes can intensify strongly for minutes to many hours. All that variability powers space weather, which is as diverse as terrestrial weather in its manifestations (where we think of heat waves and frost, storms and windless days, snow, rain, or sleet, and thunder and lightning), but with rather less familiar temperatures of millions of degrees, winds of thousands of kilometers per second, densities of near ultra-vacuum, all subject to forces and waves in an electro-magnetic field that reaches throughout the solar system.

It is this variability that drives space weather, that includes geomagnetic disturbances, radiation storms, radio blackouts, and satellite drag, to name but a few of the phenomena. Increasingly, studies uncover that space weather has substantial impact on our technological infrastructure, and therefore on society, increasingly quantified in terms of frequency and cost of impact during moderate to severe storms and hypothesized for century-level extremes. We have also seen space weather situational awareness reach operational maturity in some aspects, and that space weather information is valued by society (as reflected in the tens of thousands of subscribers to alerts). Yet, we have also learned that reliable, actionable forecasts require significant advances in the Sun-to-Earth sciences; it is these knowledge gaps on which this presentation focuses. I would like to point out explicitly here that I use the terms “Sun-Earth connections”, “space weather science”, and “heliophysics” largely interchangeably, using them all to describe those scientific investigations of our local cosmos that have societal relevance.

[2] With our modern technologies, we need to be aware of the weather around us all the time. But weather – which is in essence the changeability of environmental conditions – is not limited to terrestrial weather.

[3] Nowadays, we routinely observe solar weather, including many eruptions into the heliosphere that travel from the Sun to the orbiting planets. We are beginning to learn how to track and model the solar wind and the magnetized coronal mass ejections that run through it. And our sensors and computers are increasingly providing us with a better understanding, and a more comprehensive view, of the impact of these storms on the Earth's magnetic field, that is buffeted and stressed at any time, but particularly when solar storms hit it with a magnetic orientation most conducive to efficient coupling.

[4] The first hints of solar magnetism were discovered in large solar flares in 1859, along with associated geomagnetic variability, seen by Richard Carrington and, independently, Richard Hodgson, who reported on it in back to back papers in the proceedings of the British Royal Astronomical Society. Nowadays, we can easily see some of space weather's signatures, such as the auroral lights seen from the International Space Station, and appreciate that these are globe-spanning events.

[5] It is the growing awareness of the importance of space weather that prompted the leadership of COSPAR (a body representing scientists from around the world) and the International Living With a Star steering committee (in which international space agencies seek to shape partnerships in understanding of space weather) to commission a roadmap. The core charge of that was to map out a path towards better understanding of space weather, specifically where impacts on technological infrastructure are concerned. The international team, chaired by Kirsti Kauristie and myself, comprised expertise in science, engineering, and impacts, and had connections to scientific groups, space agencies, and space weather forecasters.

[6] The team's charge was to identify high-priority challenges in research, that would lead to a demonstrable improvement in timely and reliable space weather information, focused on the civilian side, but involving stakeholders from around the world. The team worked its way through various impact pathways, seeking to identify strengths and weaknesses in the Sun-to-Earth knowledge chain. We identified steps that could be taken on short, intermediate, and decadal time scales, favoring use of known technologies and aware of affordability throughout.

[7] The team worked its way through the Sun-to-society system, from what leaves the Sun, to how society responds to threats and impacts. We readily realized that one complexity lies in the fact that we are dealing with a highly coupled system of nonlinear effects, meaning that events do not occur in isolation, but depend on what came before, that is, a system full of hysteresis or pre-conditioning.

[8] We made recommendations for the space research community, for the interaction between stakeholder groups, and for collaboration between agencies and governmental entities. Condensed to their core they may look obvious, but there is much detail in the recommendations in the full roadmap. All emphasize the importance of a collaborative international approach:

For the space sciences community: We should build on the existing Sun-Earth system observatory. To that end, the roadmap identifies critical capabilities that are assumed to exist, and that should not be lost even if new instrumentation is deployed. New instrumentation should focus on understanding what leaves the Sun and how geomagnetic disturbances couple into induced currents on Earth – more on that later. And we should complete environmental knowledge: quantify the conditions to expect, including their probabilities, from benign to extreme.

For all stakeholders, it is important the uncover technologies' susceptibility to space weather, because only that can help design the best research and engineering plans to protect society. To be affordable, we need to focus resources, sometimes locally (say, to understand the ionosphere in the auroral or equatorial zones), sometimes from distributed platforms but targeting a specific observable or process (such as improving our understanding of magnetic instabilities by enabling 3D solar observing and by many-point in-situ measurements throughout the inner magnetosphere). And we have to achieve that in an affordable manor, that is we need to look at novel solutions using state-of-the art technologies (including smallsats and cubesats in our plans) and with a much-different risk approach, in which the system observatory weighs far more heavily than its single components.

As to bridging communities: We need to enable trust between partners, remove the walls of proprietary information, competition sensitiveness, fear of increased oversight or liability insurance: the goal has to unequivocally be the advancement of mutual benefit, not attributing responsibility. Hence, we need a trusted broker environment, which we may find examples for in the world of health research.

We need to create some form of curation of information on space weather: there is an abundance of information, but finding trustworthy sources is a challenge. Try googling "space.weather" and sifting to over 73 million hits as of this week!

We need to keep evolving our priorities. We recommend a 5-year cycle for roadmaps such as ours. When we update the roadmap, we can fold in where we advance and where not in space weather issues. And we should learn from other communities, such as those involved in making weather and earthquake predictions

[9] The team reached these recommendations by developing three largely complementary pathways by which space weather can impact society: (I) First, there is the pathway by which solar eruptions drive geomagnetic disturbances (or GMDs) and associated geomagnetically induced currents (or GICs), for which more than 1-day forecasts are needed of the incoming CME magnetic field and the anticipated disturbances in the Earth's magnetic field and the ionosphere. (II) Second, there is the need to improve environmental specifications and near-real-time conditions related to energetic particles in Earth's radiation belts, both in space and at stratospheric altitudes where airplanes travel. (III) Third, there is a need to enable short-term forecast of flares and solar energetic particles (or SEPs) and ionospheric conditions, including all-clear forecasts.

[10] These pathways reflect assessments of impact, need, feasibility, likelihood of near-term progress, and a logical progression of understanding.

[11] Together, these pathways cover not only the various types of impacts, but also the needs of users that range from environmental knowledge for system design and anomaly resolution, to near-real time information and short-term forecasts to support real-time decisions, and to 1-2 day forecasts for operations from power grid and GNSS navigation to near-Earth space walks and planetary exploration.

[12] To improve 12-24 hour forecasts of geomagnetic storm times and strengths, the roadmap recommends four highest-priority deployments of instrumentation: First, we need to focus on understanding what leaves the Sun in magnetic terms

during a coronal mass ejection, so that forecasts can be made beyond the 1-hour interval between the last upwind sentinels (SoHO, ACE, and DSCOVR) and Earth. To know the magnetic field that leaves the Sun, we shall need to image the low solar corona in 3D, using two-perspective or binocular imaging. Second, we shall need to invest in understanding how the field in the magnetosphere responds to external driving, and under what conditions that leads to strong induced currents at Earth's surface that threaten the power grids. This will require a swarm of observatories within a few Earth radii from the ground, and improved coordination between ground-based networks. Third, we shall need to cover more of the solar surface to measure the magnetic foundation of the heliosphere, so that computer models can show how a mass ejection evolves as it moves into the heliosphere and towards Earth; this will require multiple perspectives well away from the Sun-Earth line, ideally looking at the Sun from three to five angles. And finally, we shall need to learn to describe the state of the full magnetosphere-ionosphere system, with help from the existing observatories, the above-added resources, and additionally space- and ground-based auroral imaging to better map the induced electrical currents.

[13] For advanced understanding and forecasting of the radiation belts we shall need the above in Pathway I, plus advanced computer models of the radiation belts, driven with input from sensors in key parts of the Earth's radiation belts.

[14] For better forecasts of flares and solar energetic particles, we need the above in Pathways I and II, augmented by in-situ particle sensors in the heliosphere between Sun and Earth, to better understand how energetic particles move from Sun to Earth along the solar-wind magnetic field. Existing resources, plus the coming ESA Solar Orbiter and NASA Solar Probe Plus, are stepping stones towards more comprehensive measurements of the vast space between Sun and Earth; equipping future planetary and heliospheric spacecraft with particle sensors should be routinely considered to aid in supporting this challenge.

[15] In summary, the roadmap makes explicit recommendations for needed activities of the stakeholder communities and for critically needed instrumentation that must be deployed, without which the goals of understanding and reliable forecasting of space weather are unlikely to be met. We articulated mission concepts but we do not imply that these are the only or the best solutions; they are meant to demonstrate that technological means exist, and that the required instrumentation is feasible technically and financially. But the magnitude of the challenge we face for space weather is such that we recommend an international approach, involving agencies that sponsor space-based and ground-based research, and engaging researchers and engineers from around the world.

[Time permitting: 16] Our primary conclusions are: (1) space weather and its impacts are there all the time and not only during the infrequent most severe storms, as is the case for terrestrial weather; (2) that there are several key areas where significant scientific investments are needed before understanding reaches a sufficient level for reliable, actionable forecasts; (3) and, fortunately, that major advances are possible with moderate investments in critical observations and models, best achieved through international coordination and collaboration, basically enhancing what already exists as a powerful distributed observatory for the Sun-Earth system.