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SCAR Lecture – Space Weather and Its Effects

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Introduction

Antarctica is not only observed in its own right. It is also a platform for the scientific observation of the effects on the Earth of emanations from the Sun, which produce 'weather' in space that can harm electrically based technologies. These interactions are the focus of SCAR's ICESTAR project, a bipolar research effort to ascertain the extent to which solar-terrestrial interactions are conjugate (i.e. occur simultaneously) in the northern and southern hemispheres, and are predictable.

Notes to Accompany Slides

1. Auroral arcs: visible manifestations of solar-terrestrial phenomena and the weather in space that can produce deleterious effects on technologies.
2. SCAR Lecture, XXXI Antarctic Treaty Consultative Meeting, Kiev, June 2008.
3. Schematic outline of the Earth in space from a first-year college physics textbook at the time of the International Geophysical Year (IGY 1957-58). The Earth's magnetic field extends into the void of space, with no indication of the major space-related discoveries – of the Earth's radiation belts, the solar wind, and other space phenomena – that would be found as a result of the IGY and its aftermath. The magnetic field of Earth has its north and south poles located in the geographic polar regions. Prior to the IGY it was known that "cosmic rays", high energy charged particles from the Milky Way galaxy (and from elsewhere in the universe), were incident on Earth. Measurements made in Antarctic regions during the expeditions of those such as Mawson and of Byrd helped to establish the fact that these "rays" were indeed charged, and not neutral, particles.
4. However, the space around Earth must not be "empty" (except for the cosmic rays); these contemporary news clippings indicate that some important impacts of space-associated phenomena on human technologies exist.
5. Indeed, as the discoveries from the IGY and from the last five decades of space and polar research have shown, the space around Earth, and from the Sun to Earth (the solar-terrestrial environment), is a very complex and dynamic environment filled with low density ionized

gases – plasmas. Dynamic processes on the Sun in the form of sunspots and solar flares and solar mass ejections produce not only the solar wind (an expansion of the hot (million degree) upper atmosphere of the Sun that fills the entire solar system) but also large disturbances in the solar wind flow. The solar wind and the disturbances associated with it encounter Earth's magnetic field and form it into the "magnetosphere" – a shape analogous to that of a comet (albeit invisible to the naked eye), with a long "tail" that extends to hundreds of Earth diameters in the anti-solar direction. Inside the magnetosphere is another complex plasma environment that can change dramatically in form and intensity depending upon the level of the disturbances encountered from the solar wind. The charged particles in Earth's magnetosphere range in energy from a few electron volts to many millions of electron volts. In the latter category are the Van Allen radiation belts which were discovered as a result of the Explorer 1 satellite launch in the IGY. These belts of trapped high energy particles can change substantially in intensity and in spatial configuration under the influence of the solar wind flow. Under normal solar wind conditions, the Sun-facing boundary of the magnetosphere is at a distance of about ten Earth radii above Earth's surface; this distance has been measured to come as close as four to five Earth radii under very disturbed solar wind conditions (communications satellites in the geosynchronous orbit are located at a distance of about five Earth radii above the surface). Under such disturbed conditions, the radiation belts are greatly enhanced in intensity, and large auroral displays occur in the polar regions, where charged particles from the Sun and in the solar wind can be "funneled" down magnetic field lines to Earth's upper atmosphere. Under the most severely disturbed conditions, aurora have been observed at such low latitudes as Rome and Hawaii and Cuba, for example.

6. A central scientific objective of research in the polar regions is to study the "conjugate" nature of aurora and other manifestations of solar-produced phenomena. The conjugacy, and non-conjugacy, of upper atmosphere polar phenomena provides critical information on the state of disturbance of the magnetosphere, the connections of Earth's magnetic field lines to the solar wind flow, polar asymmetries in this connection, and the boundary of the magnetosphere. Magnetic field lines from the polar regions pass through the outer regions of the magnetosphere and so give information on conditions near the geosynchronous orbit and beyond, including near the magnetosphere boundary. All of these facts are among the central organizing scientific motivations for the SCAR ICESTAR Program. All such measurements, including importantly when polar region data are included in models of Earth's space environment, contribute to an understanding of the weather in space and therefore to the understanding and prediction of the effects of space weather on human technologies.

7. It is important to have an historical perspective of the effects of space weather on technologies. We will see that as human technologies – largely electrically-based technologies – have increased in types and in sophistication over the last more than 150 years, the level of sophistication of understanding of the solar-terrestrial environment has also had to increase commensurately in order to mitigate against solar-produced technology outages and failures. Nevertheless, it remains the case that the solar-terrestrial environment still can produce surprises for the successful operation of new technologies.

8. Soon after the installation and operation of the first electrical technology – the electrical telegraph that revolutionized communications – unexplained disturbances were observed in the lines of many of the telegraph systems. One of the earliest records of these disturbances, and attempts at understanding them, was by the chief engineer of the Midland Railway company in England, Mr. W. H. Barlow. Barlow recorded the spontaneous currents (measured by galvanometers hooked to the lines) on spare telegraph lines, and noted that when aurora were seen the spontaneous currents were also observed and were enhanced in intensity. We now know that these spontaneous deflections of the galvanometer needles arise from electrical currents induced in the Earth by fluctuating magnetic fields at Earth's surface. These induced Earth (often called "telluric") currents seek the lowest resistance path – the telegraph wires. The fluctuating magnetic fields at Earth's surface are produced by fluctuating electrical currents in Earth's ionosphere. These ionosphere currents on the dayside of Earth are caused originally by ultra violet radiation from the Sun, and become enhanced at all local times by charged particles both from the radiation belts and directly from the Sun itself at higher latitudes that strike the upper atmosphere and increase the ionization of the ionosphere.

9. The first visual observation of a solar flare from a sunspot region was made in 1859 by the English solar astronomer Richard Carrington, who had a personal program each day of recording visible features on the solar surface as seen from his observatory in Redhill. The solar flare observed by Carrington appeared over a large sunspot region as a more than five minute brightening of the region. Such visible eye brightenings are known today as "white light flares". Carrington numbered his drawings by the number of the solar rotation (one solar rotation is approximately 27 days) and solar rotations to this day are called "Carrington Rotations" and follow sequentially from his original numbering scheme (this 1859 white light flare occurred in rotation #80 from the beginning of his observations).

10. Within 15 hours or so following Carrington's observation of the solar flare huge auroral displays were reported around the world, and telegraph lines in eastern North America and in Europe were disrupted and even rendered unusable for substantial lengths of time. The electrical currents induced in the Earth and that flowed in the telegraph lines were sometimes large enough so that telegraph signals could be sent without using the telegraph system batteries to supply the currents. This sequence of events (white light flare, large aurora displays, telegraph disturbances) was not recognized immediately at the time, of course, but only in the course of time as researchers and lay persons began to report and publish their observations of various aspects of the events that they had observed. However, it was not readily acknowledged that the Sun could cause such auroral and telegraph disturbances, and great debate existed in the science and engineering communities for several decades as to the underlying causes of the effects measured in those days, as well as during subsequent, albeit smaller, events in the later 19th century. Many argued that there was no readily-explained connection between the two heavenly bodies. Following this 1859 event, much practical research was conducted by telegraph engineers for the remainder of the 19th century to understand and mitigate the effects of the Earth currents. While telegraph systems are now a by-gone electrical technology, those communications technologies that followed it were not immune to solar-produced disturbances in Earth's space environment.

11. The first effects of weather in space on electric power systems was during a large solar-produced event in 1940. At the same time, disturbances were also seen on telephone lines, where data from a U.S. phone line from Minneapolis to Fargo are shown. The physical cause of the disturbances on these two additional electrical technologies is the same as for the telegraph: greatly enhanced electrical currents flowing in the Earth (produced by a solar event) seek the least resistant path – the wires of the power systems and of the telephone lines. Joint meetings of power system and telephone system engineers were organized to study this event and to discuss mitigation strategies.

12. Shortly after its laying in the mid-1050s, the first trans-Atlantic telephone cable was disrupted by a large magnetic storm that also caused a complete outage of the power system in Toronto, Canada. The power outage was so dramatic and received such public attention that it was written about in the popular press, the *New Yorker* magazine. This event occurred almost two solar cycles after the 1940 occurrence, which had largely been forgotten by researchers and company managements. Again, the cause was greatly enhanced electrical currents flowing in the Earth.

13. Long-distance wireless communications, initiated by Marconi with his first trans-Atlantic transmissions of December 1901, significantly enhanced the bandwidth available for sending signals long distance, and obviated the need for laying long lengths of wire across ocean depths. Wireless transmissions also meant that Earth currents could be ignored. However, it was soon found that wireless signals were also disturbed when aurora were seen, as well as at other times, as Marconi himself acknowledged in a 1928 talk and paper. The underlying cause of these disruptions of wireless signals is known to be changing electrical currents in the ionosphere, the same currents that can produce the magnetic field variations at Earth's surface that induce the electrical Earth currents that enter the wires and then disrupt telephone, telegraph, and power systems.

14. The new technology of radar, introduced in the Second World War as a means of identifying and tracking enemy airplanes, was found to be disrupted by large solar disturbances. Reporting after the War, researchers showed that large bursts of solar flare energy at radio frequencies could completely swamp the radar receivers, rendering them useless. This was the discovery of solar radio bursts, a still very active area of research into the physics of the solar corona, and is an example of a direct and totally unexpected solar effect on a technology. Solar radio bursts remain today of important concern for their potentially disruptive effects on military radar, satellite and ground antennas, GPS receivers, and wireless cell site transmissions.

15. The past history of the effects of solar-produced disturbances in the Earth's space environment permit us to evaluate the effects in contemporary technologies and to see the role that polar research plays in understanding the weather in space that can disrupt technologies.

16. News headlines of the last two decades indicate on a time plot of sunspot numbers some effects on various technologies of solar-produced disruptions and outages.

17. These effects of space weather on technologies all arise from the complex solar-terrestrial plasma physics environment.

18. The solar surface varies from a nearly featureless quiescent state near solar minimum (left-most upper picture of the sun taken in ultraviolet emissions) to a very active and disturbed state near solar maximum (right hand ultraviolet picture).

19. Fluctuations in ionosphere currents and in Earth's magnetic field caused by disturbances in Earth's space environment that are triggered by solar events can produce deleterious effects in many technologies, some of which are listed. A very large solar disturbance in March 1989 caused, via greatly enhanced and fluctuating ionosphere currents, a complete black-out of power in Quebec for many hours, and produced such enhanced Earth currents in the northeast U.S. that a power transformer at a nuclear power station in New Jersey was burned out.

20. Early, pre-IGY, Antarctic expeditions all were interested in investigating aurora and associated phenomena such as variations in Earth's magnetic field, VLF waves, and the radio wave-reflecting medium – the ionosphere. Much of the interest was driven not only by scientific curiosity but also by practical motivations of the need for reliable polar communications wherever and whenever feasible. Fluctuating ionosphere currents were an object of investigation during the IGY, where Dr. Paul Siple led the U.S. winter-over team at the Amundsen-Scott South Pole station. An example of a sounding of the height of the ionosphere is illustrated by the ionogram from the IGY South Pole investigators.

21. Studies of upper atmosphere, ionosphere, and space investigations in the Antarctic are carried out using many techniques. Since the south geomagnetic pole and the latitudes where aurora can be measured all occur largely over the Antarctic continent, both manned and remote unmanned stations can be used for studies of the spatial and temporal scales of the solar-produced effects. An example of an unmanned station, one of the "Automatic Geophysical Observatories" (AGOs), in the U.S. Antarctic program is shown together with a logistical re-supply aircraft. These stations now operate year-round on solar (in austral summer) and wind power and support a wide range of low power instruments: magnetometers, riometers, VLF receivers, imaging photometers.

22. Earth's magnetic field and its variations have been carried out in Antarctic regions since the earliest expeditions. For example, the Ross expedition made measurements in 1840 of a large magnetic disturbance on Kerguelen Island that was later shown be recorded simultaneously at Toronto, Canada – a major leap in understanding at that time. Several contemporary magnetometer sites in the Antarctic are shown. Data from these and other Antarctic sites are now used extensively to construct sophisticated models of disturbances produced in Earth's space environment by solar events.

23. Measurements of the ionosphere and of its disturbances are now made in conjugate polar regions by the Super Dual Auroral Radar Network (SuperDARN) system. One of the antennas of one of the installations of this system is shown from Syowa Station, Antarctica. Such measurements provide a global perspective of the state of Earth's space environment and of space weather that can affect technologies.

24. Discovery of the trapped Van Allen radiation around Earth meant that Earth's space environment was not benign for any technologies (and humans) that might fly in it. The effects of this radiation on electronic components and spacecraft sub-systems are multi-fold, as listed. The radiation belts extend along magnetic field lines to Earth's upper atmosphere – the ionosphere, and the outer-most radiation regions map into the polar regions. The new NASA program, Radiation Belt Storm Probes, is designed to study in detail, using two spacecraft, the temporal and spatial structures and variations of the trapped radiation.

25. Loss of the trapped radiation into the upper atmosphere can disturb the ionosphere and can be measured across Antarctica using imaging riometer systems; one antenna system located at an AGO site is shown here. These riometers measure the changes in the reception of radio noise from the Milky Way galaxy, changes that can be inverted to give information on the ionosphere densities overhead. By making measurements in conjugate regions of riometer and auroral emissions (schematic diagram of conjugate studies between Syowa Station in the Antarctic and Iceland), changes in the trapped radiation belts can be monitored. Such measurements are an integral part of the SCAR ICESTAR program.

26. High altitude circumpolar balloons can be used for measuring the x-rays produced by radiation belt electrons that are lost and strike the upper atmosphere. The Antarctic is especially advantageous for such long-duration balloon flights for numerous reasons, including the range of geomagnetic latitudes that can be covered and the ability to track the balloons over a land mass without political boundaries. Balloon launches from McMurdo and from SANAE IV Antarctic stations are shown. The balloon data (upper data panel) show a large enhancement of electron-produced x-rays in the high atmosphere at the time when instruments on a geosynchronous-orbit spacecraft measure a sudden decrease in electrons. The electrons at geosynchronous orbit are lost to the atmosphere, producing the x-rays measured by the balloon instruments. This set of data illustrates the ability to monitor the space radiation environment using Antarctic platforms such as balloons.

27. Space radiation is important for the safety and security of trans-polar airline flights, which have become increasingly more frequent in the post-cold war era. The importance arises from both the episodic production at the Sun of high energy particles that can increase radiation dosages and from the disruptions of communications that can occur due to ionosphere disturbances when the magnetosphere is perturbed. In this figure, these data are measurements of high energy solar-produced particles made with an instrument on an airliner flying over the U.S. from Los Angeles to New York in October 2003, the first such aircraft-based measurement. When such solar events occur their intensities are larger at the higher latitudes; polar-flying aircraft are then diverted to lower latitude flight paths to reduce radiation dosages, thereby increasing flight times and airline company costs.

28. The news story from October 2003 shows that airline communications were disrupted at the higher latitudes, and so flight diversions occurred due to the ionosphere black-out of communications. The total cost of the disruption in the flight routes of this one carrier during the January 2006 solar event was about a quarter-million dollars. Similar communications disruptions exist for aircraft flying across the Antarctic continent during solar events.

29. Enhanced and disturbed electrical currents in the ionosphere can seriously disrupt navigation systems, such as the experimental Wide Area Augmentation System (WAAS) currently under study in the U.S. The data show that the WAAS coverage over the U.S. (upper plot) was essentially rendered inoperable during intervals of a large magnetic and ionospheric storm (lower plot) produced by a large solar event in October 2003.

30. As noted earlier, solar radio bursts can completely disrupt navigation receivers on Earth. A solar radio burst in December 2006 was the largest such event ever recorded. It occurred when the western hemisphere was in daylight, and so GPS receivers in the U.S. took the full interference hit of the greatly enhanced radio noise that struck them. GPS receiver outages occurred across the continental U.S. and into the Arctic region of Alaska. The WAAS system was seriously degraded due to the solar radio noise interference, a degradation that had a source quite different than the ionosphere-produced degradation of the previous slide.

31. The effects of the solar-terrestrial environment on human technologies has increased in importance and in the attention devoted to the subject as the number and types of technologies has increased from the early electrical telegraph ---

32. To the studies of the height of the ionosphere and its effects on Antarctic communications in the IGY ---

33. To the vast number of technologies that are today affected by the complex plasma physics system that the Earth and its human population and technologies are embedded within.

34. And research in the Antarctic has an essential role to contribute to understanding the weather in space around Earth that can affect so many contemporary technologies.

35. Thank you! [*slides will be available in due course on the SCAR web site*]