Part I. A New Science for the Age of Exploration

Space exploration has transformed our understanding of the solar system. It has revealed a fascinating nested system of systems, so closely connected that an explosive event on the Sun produces measurable effects that span the entire solar system. Through judicious use of a number of operating missions, we have achieved system surveillance over parts of the heliosphere, and have been able to examine the causal linkages between its parts. In late 2003 we observed spectacular coronal mass ejections, power outages on the Earth, degradation of spacecraft solar panels and circuits, destruction of atmospheric ozone, inflation and ablation of planetary upper atmospheres, fatal damage to instrumentation in Mars orbit, auroral displays on Saturn, and, months later, radio disturbances at the edge of the solar system where it meets the interstellar medium. In short, we have observed that space contains weather and that it can affect us.

Classically, the structure and processes of our environment had been understood in terms of gravitation and pressure. Since space exploration began in 1957, we have learned that space is filled with matter and electromagnetic fields whose importance is belied by their invisibility. Unsheltered from the Sun's pervasive UV radiation, matter in space enters the fourth state: a conducting *plasma* of electrically charged electrons and ions, flowing and reacting to highly variable electromagnetic forces. Common human experience provides little experience or intuition about the behavior of such plasma atmospheres.

Owing to their conductivity, moving plasmas generate electrical currents and magnetic fields. Many exotic phenomena ensue, some of which resemble *turbulent* fluid flows, but impart so much energy to a subset of particles that they ionize many more atoms when they come in contact with cooler states of matter such as gases, semiconductor circuits, or living tissue. Magnetic field lines act to link their source plasmas into coherent cells, much as droplets of water are defined by surface tension. When such cells of plasma come into contact with each other, their magnetic fields may *reconnect*, creating a linkage between the two cells and coupling them to each other so that motions of one drive motions of the other. Electrical currents flow to generate the coupling forces, and electromotive forces are generated that *accelerate* charged particles, sometimes explosively as in solar flares.

The robotic exploration of our universe has clearly shown that electromagnetically driven processes act at the center of every stellar system. Our own solar system is driven by the Sun, a magnetically variable star. The Vision for Space Exploration will eventually free humankind from the gravitational forces that have held us through history. Space explorers will learn to live within the magnetically controlled space environment and, through our NASA exploration missions, every citizen will be able to see and experience these things.

Our program will help assure the assure the safety of the new generation of human and robotic explorers

At the same time we will pursue a deeper understanding of the fundamental physical processes that underlie the awesome phenomena of space

We will develop a predictive capability to address hazards to important technological assets closer to home and learn how fundamental space processes may affect the habitability of other distant environments beyond our own solar system

The Earth and Sun are linked together to form the system that has given origin and sustenance to our lives. The story of how this came to be, over the history of the solar system, is nothing less than a Creation Narrative. It is an aspect of the most compelling mystery faced by humankind. The physical processes and the evolutionary paths embedded in this combined system are studied in the Earth-Sun System division of NASA's Science Mission Directorate. We examine the Earth and Sun system today for insights into questions concerning how the system evolved so as to produce and sustain life, what will happen to this unique environment through the course of time, and how it will affect us.

With human space activity restricted to low Earth orbit since the mid-70's, we have been reconnoitering the solar system (and beyond) using robotic spacecraft and telescopes. In 2005, Voyager passed through the solar wind termination shock and into the heliosheath, nearing the outer edge of the solar system. Though we have not visited the inner boundary of the solar atmosphere, the Sun is bright enough to reveal a great deal about itself through remote imaging, spectroscopy, and polarimetry.

The first broad survey of the solar system is essentially complete and we are now beginning to revisit the planets, including Earth, for studies of greater depth. The region around the Earth remains an important astrophysical laboratory for the study of the physical processes that are of broad relevance to astrophysics. Moreover, these processes are by now known to have influenced the habitability of the Earth and are, therefore, relevant to the possible existence of life elsewhere in the solar system or universe. We have barely begun to scratch the surface of the history of our solar system over geologic time and have only recently determined that planets are commonplace around other stars. In at least one such case we can discern the signature of an atmosphere being ablated by a stellar wind. In another case, X-rays are emitted from a young star that is not fully ignited, showing that electromagnetic and plasma processes become active very early in the life of a planetary system.

[[[Figure Caption: These panels suggest the range of spatial scales relevant to SSSC observers and modelers. The left panel shows a simulation of an interplanetary disturbance approaching the Earth. The two images in the center show the Sun and it's corona (top) and a greatly expanded view of the disturbance reaching Earth; the Sun's diameter is about 100 times the Earth's. The images on the right show important physical features with size progressively decreasing from top to bottom: the interaction of the heliosphere with the interplanetary medium (several hundred AU), the orbits of the planets, a mass ejection over the solar limb, part of a sunspot, Earth's disturbed ionosphere, a model of reconnection, and an all-sky image of the aurora borealis (less than a kilometer in width).]]]

The United States is now embarking on an ambitious new journey of exploration to the Moon, Mars, and beyond. NASA has been challenged to establish a sustained presence on the Moon by the end of the next decade with the purpose of enabling Martian exploration thereafter. The will to achieve this Vision for Space Exploration presents the agency with great opportunity and sobering demands.

Success in this venture requires advanced understanding of the complex physical systems that link the variable star at the center of our solar system with the Earth and other planets. The harsh and dynamic conditions in space must be characterized and understood in some detail if robots and humans are to safely and productively travel and explore the Moon and Mars.

The biological effects of the energetic particle radiation environment outside of low-Earth orbit remain largely unknown. Astronauts aboard the International Space Station (ISS) accumulate significant radiation exposure and energetic particle events impact space station operations. Safe and productive travel outside Earth's protective magnetic cocoon, whether to the Moon or Mars, will require new predictive capability for solar particle events. Even well designed hardware is damaged or degraded by extreme conditions in space. And astronauts spending more than a few days in space will need a way to take shelter from episodic exposure to lethal doses of solar energetic particles.

Space weather and solar variability affect critical technologies used on Earth as well, for example satellite communications, navigation, remote sensing, and power distribution. Increasing reliance on vulnerable global systems demands active management in response to variations in the space environment. In many ways, our space weather approach resembles earlier steps taken by scientists to understand and predict weather in the Earth’s atmosphere. We too must observe and understand the detailed phenomena, generate theoretical models that can be validated and verified against observed reality, build data-assimilative predictive systems, and then develop operational decision support systems closely tailored to the needs of end-users and rigorously tested and improved over time. In this way and by these means, NASA’s Sun-Solar Systems connections program will bring sound science to serve society.

Space weather is in some ways analogous to the tropospheric weather that is so familiar to us, yet remains difficult to predict beyond a few days. In other ways it is fundamentally different. It is analogous in its nonlinear complexity, though across an even larger range of scales. Systems this large simply cannot be reduced to a linear combination of interacting parts, no matter how detailed the study of those parts. Space weather is fundamentally different in that electricity and magnetism are at least as important as the more familiar forces of gravity and pressure. Measuring, characterizing, and understanding these processes cannot be accomplished with images and common intuition. Localized measurements cannot merely be interpreted to generate a global picture. Conversely, the global picture does not provide insight into the small-scale physical processes of the system. For example, the magnetic reconnection that regulates much of the interaction between the solar wind and the Earth's magnetosphere cannot be observed remotely and it takes place in a rapidly moving location several Earth radii above the planet on a spatial scale of a few kilometers and temporal scale of several milliseconds.

Answering a specific science and/or exploration question often requires a narrowly focused mission to a particular location with a unique instrument. For example, measuring flows in the solar interior requires a long, continuous series of simultaneous velocity measurements at millions of locations on the solar disk. However, Sun – Solar System Connection science increasingly depends on combining multi-point *in situ* measurements with remote imaging.

Again, by analogy with meteorology, combining a network of distributed local observations with global measurements (a meteorological Great Observatory) enables the development and testing of predictive models that improve with time and experience.

Currently the SSSC Great Observatory includes satellites that (for example) hover near L1 – a million miles upstream in the solar wind, circle over the Sun's poles, orbit the Earth in various configurations, and have just reached the first boundary between the interstellar medium and the Sun's domain, the termination shock. As each set of scientific questions is answered, the SSSC Great Observatory evolves with the addition of new spacecraft. Solar-B will help understand the creation and destruction of solar surface magnetic fields, variations in solar luminosity, and the dynamics of the solar atmosphere. Soon the two STEREO spacecraft will drift away from Earth to provide the first stereoscopic views of the Sun and inner heliosphere. The Solar Dynamics Observatory (SDO) will image the Sun's interior, surface, and atmosphere from geosynchronous orbit. Observing the terrestrial response, the Radiation Belt Storm Probes will investigate the processes that accelerate particles to hazardous radiation levels, and the four Magnetospheric Multi-Scale (MMS) spacecraft will fly in tight formation to explore the multiple scales of reconnection, turbulence, and particle acceleration in the magnetosphere of the Earth. Solar Probe, if funded, will transform our understanding of the physical processes that control the heating of the solar corona, the acceleration of the solar wind, and the release of eruptive activity.

In this strategic roadmap for the Sun – Solar System Connection we explore the strategic planning consequences of a stated U.S. national objective for NASA: “Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational systems.” The resulting science and exploration objectives are explained in the next section. Implementation plans follow that span 30 years. The document concludes with an explanation of the links to other NASA activities.

New knowledge of this system enables safe and productive exploration. Exploration enables new scientific understanding. The knowledge has utility for society. Our high priority science and exploration objectives address each of these needs. The program is vital, compelling and urgent.