SPACE WEATHER: SCIENTIFIC FORECASTING

I. Summary

A consortium of six research universities, New Jersey Institute of Technology (NJIT), University of Maryland (UMd), University of New Hampshire (UNH), California Institute of Technology (Caltech), University of Alabama in Huntsville (UAH), and University of Michigan (UMich), plus two industrial laboratories (Bell Laboratories/Lucent Technologies and Raytheon) and a government laboratory (Naval Research Laboratory), are proposing a comprehensive, singular suite of solar-terrestrial measurements and modeling that will significantly advance the state of knowledge of the nature of space weather. Space weather, as defined in the FY 2001 MURI Topic #29, can significantly, and negatively, impact DoD operations as well as civilian telecommunication facilities and the electric power grid. Our team has very strong observational capabilities, with dedicated state-of-art solar optical and radio telescopes and networks ideal for space weather studies. Our unique observational resources will be combined with measurements from additional instruments (associated with consortium members and other groups) that are flying in the heliosphere and in the earth's magnetosphere. The data to be acquired will be analyzed, synthesized, and modeled by consortium members who are well-known space plasma theorists. The central theme of our proposal is to use our solar data, along with space-based solar and heliospheric data to understand and forecast the initiation of space weather events, follow their propagation and development in the heliosphere, and predict their likely impact on the near-earth environment.

We propose to utilize NJIT's extensive optical and radio observing facilities at Big Bear Solar Observatory (BBSO) and the Solar Array at Owens Valley Radio Observatory (OVSA), which include our various magnetographs, our global Hα network, and the OVSA and Solar Radio Burst Locator (SRBL) instruments for microwave imaging spectroscopy. We also propose to extend our ground-based observations of the sun to 24-h coverage in two key areas – microwave radio spectroscopy and optical vector magnetograpy – with world-wide networks. For in-situ and remote heliospheric observations, we will continue to rely on spacecraft data from SOHO, Wind, Ulysses, and ACE.

Using the expertise of our team, we will emphasize: (1) the 3-D magnetic structure before and after major events from observation and modeling, (2) the physical cause of, and correlations among, different types of solar activity (flares, filament eruptions, and Coronal Mass Ejections (CMEs), (3) prediction and/or forecasting of solar activity, (4) real-time prediction of properties and dynamics of magnetic clouds resulting from CMEs, (5) study of coronal and IP shock waves and energetic particles, to understand and, perhaps, forecast >10 MeV proton (solar energetic particle, or so-called "SEP") events, and (6) prediction of likelihood and magnitude of geomagnetic storms. As an independent check of the particular models of filament eruptions, we will also include a laboratory component to simulate filament eruptions. The laboratory "data" will be closely compared with the results of observations and models. The above components will enable us to understand the underlying physics of CMEs, and will provide tools to predict geomagnetic disturbances and SEP events.

Education of PhD students is an important part of this proposed work. We anticipate that at least 7 PhD students will have major involvement in the project across the 6 universities.

II. The Science Team

1) From NJIT, which operates BBSO, the Solar Array at OVRO and a dedicated global Hα network, the members are Philip Goode, Director, BBSO, Distinguished Professor of Physics; Haimin Wang, Associate Director, BBSO, Professor of Physics; and Dale Gary, Director, OVSA, Associate Professor of Physics.

2) Paul Bellan, Professor of Applied Physics at Caltech does laboratory modeling and theory of filament destabilization.

3) Terry Forbes, Research Professor at UNH does MHD Modeling of filament eruptions, flares, and magnetic reconnection.

4) Mukul Kundu, Professor of Astronomy at UMd, and Stephen White, Research Scientist at UMd, do radio observations, modeling, and interpretation of radio data from mm to m wavelengths.

5) S.T. Wu, Director, CSPAR, Distinguished Professor, UAH, does modeling of CMEs and the solar wind.

6) Thomas Zurbuchen, Research Scientist at UMich, combines space-based experiment and theory in heliospheric research.

7) James Chen and Simon Plunkett, Research Physicists at Naval Research Lab. Chen does CME modeling, magnetic cloud modeling, and the prediction of geomagnetic storms; and Simon Plunkett is Associate Research Scientist with USRA working on the LASCO (and SECCHI) coronographs for NRL.

8) Louis J.Lanzerotti, Distinguished Member of Technical Staff, Bell Laboratories/Lucent Technologies, with expertise in heliospheric research.

9) Michael Reiner, Research Scientist, Raytheon Corp., with expertise in solar and heliospheric radio physics.

10) Other domestic partners: We are negotiating with additional domestic partners in key areas. Some of these depend on resolution of potential conflicts of interest.

11) International Partners: our current partners include Kanzelhohe Solar Observatory in Austria, Beijing Observatory and Yunnan Observatory in China. We are currently negotiating with other possible partners for radio and magnetograph sites. We plan to coordinate with Space Weather efforts in France through close cooperation with Monique Pick, Observatoire de Paris, (Meudon/Nancay).

We have formed an external advisory committee to provide oversight to our proposed project. The current members are Dr. Art Poland NASA/GSFC, Dr. Ernest H. Hildner, NOAA and Dr. B.C. Low, HAO. We propose that the committee would critique our plans and efforts to the benefit of the project.

III. Instruments

1. Hα Network

Based on our successful experience in making high-resolution full-disk Hα observations at BBSO, and the urgent need to monitor the evolution of the solar chromosphere continuously during the solar maximum, we have deployed a network for Hα full-disk observations after upgrading and coordinating existing facilities at BBSO in California, Kanzelhohe Solar Observatory (KSO) in Austria, and Yunnan Observatory (YO) in China. Each of these observatories has over 300 sunny days a year, good seeing conditions, experienced observing staffs, and well-established Hα telescope systems. With this network, our upgrades allow us to monitor solar chromospheric activity with $1''$ pixel resolution and one minute cadence round-the-clock for most of the year, with the best available data quality. The network is in full operation.

2. Vector Magnetograph Network

BBSO and Huairou Observing Station (HSO) of Beijing Observatory have collaborated in round-the-clock vector magnetograph observations since 1988. The night gap for this two-station network ranges betwen 4 and 8 hours, depending on the season. Both stations have cadence of about 5 minutes and spatial resolution of about 1 arcsec. We plan to add a third partner, KSO in Austria, which would give us global coverage. Their system will be patterned after that at BBSO. A potential fourth partner is the Crimean Astrophysical Observatory which has a long history of measuring magnetic fields.

3. Radio Network

We are building a small (2 m) radio telescope, called the Solar Radio SpectroPolarimeter (SRSP), for obtaining 1-18 GHz radio spectra of solar bursts. The telescope is based on a similar system being deployed by the US Air Force called the aforementioned SRBL (see the web page at http://srblserver.caltech.edu/). The telescope that we are building, the SRSP, will be more sensitive to weak bursts and will record in two polarizations. Thus, it is complementary to the Air Force SRBL system, and its ability to record both circular polarizations makes it superior as a key indicator of emission mechanisms that may be important for studies of space weather.

As an equipment procurement associated with this proposal, we propose to build two additional SRSP dishes to be placed in strategic locations, at existing radio sites, one in Europe and one in the Asia/Pacific region, to provide continuous 24-hour coverage of solar bursts.

4. Space Data

The combination of surface data discussed above with the direct imaging of CMEs from the LASCO/NRL team is an important aspect of the proposal. STEREO, when it becomes available late in the target period, will extend and improve on LASCO. In addition, EIT will provide EUV imaging of eruptions in the low corona. MDI will provide continuous monitoring of photospheric longitudinal magnetic fields of the whole sun.

Data from Wind, Ulysses, and ACE will be used, including magnetometer and particle detector data. These data provide in-situ measurements of the structure of magnetic clouds and particle properties. Data from the radio instruments on Ulysses and Wind will also be utilized for remote sensing of solar eruptive events, of propagating coronal and interplanetary shocks, and the heliospheric magnetic structure.

Although the data will provide a solid foundation for the proposed research, the final achievement will also heavily rely on theoretic modeling based on the data.

IV. Scientific Objectives

Our scientific objectives are to observe and forecast the initiation of space weather events, follow their propagation and development in the heliosphere, and predict their likely impact on the near-earth environment. We divide these objectives into two related parts: study of geo-effective CMEs and studies of SEP events.

IV.A Study of Geo-effective CMEs

1. We will use the data from the Hα network to provide real-time reports of all flux emergences, filament disappearances and flares. When a major event occurs, the morphology (such as the extent of flux emergence, the filament helicity) will be used as boundary conditions for the models, to predict the magnetic field orientation in CMEs as they propagate in heliosphere. The predictions will include the speed of the CME and the magnetic structure of the consequent magnetic clouds. The predictions will be verified by the in-situ magnetic cloud data observed by ACE and Wind at 1 AU. The large number of events will provide a useful tool to sort out which kind of flare/filament eruptions may have associated geo-effective events. The result, combining with models, will certainly be used as a forecast tool. The software that we develop will be coordinated with the ISOON team for use in their planned network coverage of the sun in Hα.

2. We will use combined, high-resolution vector magnetograph data from BBSO and HSO (and, subsequently, from a third station) to observe the magnetic structure of solar active regions almost continuously. With the observed vector magnetic fields as boundary conditions, we propose to carry out force-free extrapolations to obtain the 3-D magnetic configuration before and after major events, which produce geo-effective CMEs. Based on the results of studying many events, we will develop tools to predict eruptions from continuous monitoring of magnetic fields. At the same time, we will learn the underlying physics of the events. One of the most important factors is to establish the possible connection between the filaments and the orientation of the out-of-plane magnetic field component B_z at the Earth's bow shock, when the associated material reaches the Earth. It is well-established that a southward B_z produces large magnetic storms while a northward B_z is much less geo-effective. For the former, we will use real-time space weather data (B_y and B_z) as input to estimate the duration and magnitude of southward interplanetary magnetic field upstream of the space weather monitor.

Different models will be tested and compared with observations. These include the "erupting flux" model (Chen), the "MHD" model (Wu) and the "hybrid" model (Forbes). Our modeling will focus on the vector B field at the surface and B field at 1 AU, and the CME trajectories. For Wu's model, we will test the streamer and flux-rope for the initiation of a CME. There the observed vector magnetic field will be used as boundary conditions which yields a quantitative description of the flux-rope, such as the length of the flux-rope and strength of the field. In this way, the critical field strength could be determined for the eruption to destablize the streamer to launch a CME. Chen's model assumes that the magnetic field underlying a CME is a magnetic flux rope. The equations of motion for the model are obtained by integrating the standard MHD equations over a flux rope of toroidal geometry. It is assumed, for simplicity, that the flux rope is a section of a torus, but the minor radius is allowed to vary from the footpoints to the apex. The initial-value solutions give the dynamics of a flux rope from its initial configuration. Forbes' work will concentrate on the developing improved initial and boundary conditions for use in the numerical codes. Boundary conditions for flare and CME models will be constrained by the observations of the photospheric magnetic field. One of our principal goals will be to test numerical models which use different initial conditions that are consistent with the observed plasma structures, in order to determine whether the subsequent evolution of the coronal magnetic field is consistent with the observed dynamics of CMEs and flares.

As a test of how filament eruptions occur, Prof. Bellan (Caltech) will use pulse power experimental techniques to create laboratory scale filaments which replicate the complex three-dimensional topological dynamics occuring on the sun. We intend to use the observational results to guide the laboratory studies and vice-versa. Also, the output of the theoretical modeling of filaments and CMEs will be tested in the laboratory where possible.

3. More subtle characteristics of radio phenomena, such as spatial characteristics of interacting magnetic loops, will be studied with the multi-frequency imaging data from OVSA, to shed light on the development of instabilities in the solar atmosphere that lead to interplanetary events. The goal is to understand these interactions, and recognize the important pre-event geometries that signal the likelihood of activity.

4. We will compare the 1-18 GHz spectral characteristics of solar bursts with the lower frequency radio events that are observed from ground-based and spaced-based observatories. We will link solar radio events near the surface with type II/IV events seen in ground-based metric spectrographs in Europe and the Asia/Pacific region, and with low-frequency type II and type III radio emissions observed from onboard the Wind and Ulysses spacecraft. We will also follow, into interplanetary space, those events that are observed with the radio spectrograph on the Wind spacecraft. We will seek signatures in such events, as well as magnetic geometries predicted by our heliospheric modeling, that are predictive of highly geo-effective CMEs and interplanetary shocks. The Maryland researchers - Kundu and White are experienced in relating radio outbursts to proton events, so they will play critical roles in items 3 and 4 as listed above.

IV.B Study of SEP Events

1. SEPs must be accelerated by interaction of CMEs with coronal and IP magnetic fields. Observations of the evolution of solar surface vector fields and 3-D modeling will enable us to study the acceleration processes of flare particles, and investigate the role of such particles in SEP events. The SEP are likely accelerated by shock waves, but do seed particles from a flare play a role? How does the magnetic geometry affect the formation and acceleration properties of the shock? We will develop MHD and particle models to investigate these questions. The results from the models will be compared with observations from in-situ particle instruments on ACE, Ulysses and Wind, as well as radio observations.

2. The microwave spectral data will pertain to the high-energy component of solar flares, and diagnostics of the energy release region such as magnetic field and plasma parameters. We will use the microwave spectroscopic data to do a correlation analysis of microwave spectral characteristics with other characteristics such as optical, hard X-ray, and heliospheric (SEP) events. Successful correlation of robust characteristics in the radio spectra (e.g. spectral hardening through the burst) with later production of interplanetary protons, will allow us to forecast when such damaging radiation may occur near the Earth. We anticipate that with a world-wide network we will be able to issue a warning minutes to hours ahead of the arrival of these particles.

As the end-product of the proposed research, we will have a model to predict the onset of solar flares, CMEs and SEPs, the propagation and orientation of magnetic clouds, and the occurrence of geomagnetic storms.