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## FINAL REPORT ON NASA GRANT NAG5-4183

## "STUDIES OF SOLAR FLARE AND INTERPLANETARY PARTICLE ACCELERATION AND COORDINATION OF GROUND-BASED SOLAR OBSERVATIONS IN SUPPORT OF U.S. AND INTERNATIONAL SPACE MISSIONS"

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## I. Studies of Hard X-ray Solar Flares and Interplanetary Protons

A primary focus of the P.I. has been to conduct studies of particular types of hard X-ray evolution in solar flares and their associations with high energy interplanetary protons observed near Earth. Previously, two large investigations were conducted that revealed strong associations between episodes of progressive spectral hardening seen in solar events and interplanetary proton events (Kiplinger, 1995). An algorithm was developed for predicting interplanetary protons that is more accurate than those currently in use when hard X-ray spectra are available. The basic research on a third study of the remaining independent subset of HXRBS events randomly not selected by the original studies was completed. This third study involves independent analyses of the data by two analysts. The results echo the success of the earlier studies. Of 405 flares analyzed, 12 events were predicted to have associated interplanetary protons at the SESC level. Of these, five events appear to be directly associated with SESC proton events, six other events had lower level associated proton events, and there was only one false alarm with no protons. Another study by Garcia and Kiplinger (1995) established that progressively hardening hard X-ray flares associated with interplanetary proton events are intrinsically cooler and not extremely intense in soft X-rays unless a "contaminating" large impulsive flare accompanies the hardening flare.

From the beginning of this grant until mid-April 1998, only three SESC qualified proton events occurred. The first one occurred on 20 Oct. 1995, and proved to be of considerable interest with regard to progressive hardening events. It is an excellent example of a purely progressive hardening solar flare and an interplanetary proton event. It was imaged by Yohkoh in both soft and hard X-rays and by a Russian interferometer in microwaves (5 GHz in Irkutsk). There is clear evidence for a coronal mass ejection occurring near the region, as well as large moving loops and soft x-ray enhancements prior to the hard X-ray/microwave event. Timing of the arrival of energetic electrons and protons at Earth shows that the particles were created simultaneously with the episodes of hardening X-rays and microwaves - - not at the earlier onset of loop motions and soft X-ray flux increases.

Kiplinger (1995) had previously reported that the progressive hardening seen in hard X-rays is also apparent in microwaves in another example. This current work has found additional examples of associations of interplanetary protons with progressively hardening microwave spectra. The potential for progressively hardening microwave spectra to predict (now-cast) interplanetary proton events is important since we are on the horizon of having continuous microwave surveillance of solar activity. Although it is not yet known how often "ordinary", non-proton-associated flares may or may not display spectral hardening (needed for effective

prediction algorithms), such investigations were initiated during the course of this grant by new studies of total fluxes as measured by prototype radio spectrometers known as the Solar Radio Burst Locator (SRBL) telescopes. These telescopes are being installed worldwide by the U.S. Air Force. Examinations of SRBL observations obtained mainly during solar minimum suggest strong promise for SRBL microwave spectral evolution observations (above the turnover frequencies) to act as a surrogate for hard X-ray observations in predicting interplanetary protons. This work is continuing with some support from NASA grant (NAG5-4477).

## II. Development and Deployment of the SOONSPOT Solar Digital Archive System

These services to the community described here and in Section III have evolved as an outgrowth of the Max'91 program that was jointly funded by NSF and NASA to support coordinated solar observations during the past solar maximum (~1989-1994). Prior to this grant, the P.I., in conjunction with his role as coordinator of the Max'91 program, created the SOON Solar Patrol On Tape (SOONSPOT) solar image archival system. This system employs four U.S. Air Force SOON observatories located around the world in the collection of solar images and archival of the data on tape. In the absence of flares, each site records H-alpha full disk and large scale white light images every 30 minutes and large scale H-alpha images of active regions or other features every five minutes. If the weather at all four sites is clear, the system records a digital image, in FITS format, about every 45 seconds at solar minimum (about 800 images per day). Although the system began partial operation in 1994, the system was significantly refined by the P.I. with support of this grant -- refinements that are now crucially important for the successful operation of SOONSPOT at solar maximum.

SOONSPOT successfully collected data during solar minimum, but the effort required Air Force observers to wait up to two hours for data archival each day. During solar maximum, data collection rates can increase by a full order of magnitude (i.e. 8,000 images/day) because solar flares are imaged every 30 seconds. It was discovered that the initial SOONSPOT implementation would not allow simultaneous data archival and collection. Thus, solar maximum conditions would overwhelm capabilities of the system and the observers. Close collaborations between the P.I. and Air Force field technicians led to a radically new and more efficient means of archiving the data. SOONSPOT now uses large disk drives that can hold many days of data (up to 3.2 gigabytes of data, or about 12,000 images) which can be written to a single 8-mm Exabyte tape - even while the system is collecting new data. The new tapes can be read on either PC or Unix platforms, and there is sufficient information for each image that renders the data to be compliant with the "SOLARSOFT" software that is rapidly being adopted by much of the solar physics community.

Original data tapes reside at the NOAA Space Environment Center in Boulder, CO and at the Lockheed Martin Solar and Astrophysical Laboratory in Palo Alto, CA. The P.I. also has taken steps to insure that copies of the new, CPIO formatted data are available at the SOHO Experimenters' Analysis Facility at Goddard S.F.C. All data lies in the public domain and is available to scientists worldwide. Working with Lockheed programmers, the P.I. developed a convenient cataloging program (in IDL) to manage this massive image database. The catalog, maintained at Lockheed M.S.A.L., is available via a web page which can be found at:

[www.lmsal.com/SXT/soonsearch.html](http://www.lmsal.com/SXT/soonsearch.html).

A longstanding problem recently resolved with regard to SOONSPOT is that inevitable changes in command within the Air Force, combined with SOONSPOT's informal existence, caused confusion for new commanders. Accordingly, the P.I. drafted a formal Memorandum of Understanding (M.O.U.) that resolves the roles of the institutions most involved. It was slightly modified by the Air Force in the Spring of 1998, and was then signed by Lt. Col. William C. Kellar of the 55<sup>th</sup> Space Weather Squadron, Dr. Ernie Hilder of the NOAA Space Environment Center and Mr. Larry Nelson, director of the Contracts and Grants office of the University of Colorado. This much needed document should help secure SOONSPOT data coverage until the SOON upgrade occurs around the year 2001.

Although SOONSPOT data normally serve as backups or augmentations to other space and ground-based observations, notable exceptions include student research. In 1997, a University of Denver graduate student, Randall Meisner, completed his Master's thesis on the evolution of a major active region. SOONSPOT data formed the cornerstone of his investigations with the inspection and analyses of more than 6000 SOONSPOT images of the region over approximately 10 days of its appearance on the Sun. The thesis is entitled "The Delta-Spot Growth and Formation of NOAA Active Region 7978 and its Relation to Non-linear Numerical Simulation Models." Another work which capitalized on SOONSPOT data was a senior physics research project at the University of Colorado by Mr. Pete Zink (who also was an NSF R.E.U. student) entitled "An Investigation of Chromospheric Waves." Despite the fact that the study spanned the few flares observed during solar minimum, two examples were found in which SOONSPOT revealed moving waves (Moreton waves) and remote brightenings. These effects in H-alpha moved away from flaring sites and were seen simultaneously with waves seen by the Extreme Ultraviolet Telescope on SOHO or in He 10830A observations respectively.

### III. Coordination of Solar Observations

The P.I. has aided in coordination of ground and space-based instrumentation for several observing efforts and campaigns since the Max'91 program concluded. The infrastructure for conducting worldwide solar observing campaigns was maintained into solar minimum in anticipation of the launch of the SOHO mission, the continued operation of the YOHKOH satellite, and anticipated major observing campaigns planned by the Inter-Agency Consulting Group of international space agencies. This communications infrastructure has evolved through utilization of electronic list servers, gopher services and development hypertext pages on the world wide web. The main web page supporting coordinated ground based solar observations is located at: <http://sec.noaa.gov/solcoord/solcoord.html>

The campaign observations specifically supported by means of web listings and notices and/or daily messages sent via email include:

\* Shuttle launched SPARTAN 201 missions of 13-14 Sep., 1994, 8-10 Sep., 1995 and 20-21 Nov., 1997 (unfortunately SPARTAN failed on this mission).

- \* the SYNOP (Synoptic) Coronal Observing Campaign (10-24 October 1994),
- \* Solar eclipses of 4 Nov., 1994 and 24 Oct. 1995
- \* the Prominence and Coronal Observing Program (1-5 November 1994),
- \* X-Ray Bright Point and Filament campaigns, 15-23 September, 1995, 8-13 April, 1996 and 27-31 May, 1996
- \* the Meudon-Yohkoh Chromospheric Campaign of 19-26 Oct., 1995
- \* Rocket flight of the Multi-spectral Solar Telescope Array, 25 October 1995
- \* the Flare Genesis long-duration balloon payload in January 1996
- \* SOHO Polar Plumes Mini-Campaign on 7 Mar., 1996
- \* the SOHO - Meudon/Ground Based campaign, 3-10 June, 1996
- \* SOHO, Yohkoh and Meudon observations of Filaments 20 - 29 Sep., 1996
- \* the IACG3 (Interagency Consulting Group) CME onset campaigns, 4-13 Oct., 28 Oct - 3 Nov., and 11-20 Nov. 1996
- \* VLA, SOHO and YOHKOH observations of Filaments, 22-26 Jan., 1997, 21-28 Feb., 1997 and 22-26 Jan., 1998
- \* Coordinated Filament Observations - Pic du Midi, SOHO, Yohkoh and Themis, 27 May - 06 June, 1997
- \* Rocket flights of HRTS on 30 Sep. 1997 and SERTS on 18 Nov., 1997
- \* Instigated re-discovery of the SOHO satellite after loss of signal using bi-static radar between Arecibo and Goldstone, 23 July, 1998.

Observing summaries compiled from various observatories for many of these efforts are maintained on the Coordinated Solar Observations home page under the NOAA Space Environment Center's page (<http://www.sel.noaa.gov/solcoord/solcoord.html/>)

#### IV. The High-Speed Ha Camera System: Data Analyses and Observations

Work with the High-Speed H-alpha camera system was de-emphasized due to the emphasis on interplanetary protons and conditions of low solar activity at solar minimum.

The high-speed digital camera system was developed to explore temporal relationships of rapid

fluctuations in hard X-rays and flashes in H-alpha intensities ( at -1.3A in the blue wing). In 1994, the camera was upgraded to measure linear polarization in H-alpha at high cadences. The system can measure linear polarization with a cadence of 0.5 seconds and achieve a polarization sensitivity of 0.1% in approximately 20 seconds. Also in 1994, a serial-to-parallel buffered converter was constructed that allowed local downloading of the data for the first time. At solar minimum, the camera was generally not operated. However, it did observe its first X-class flare near the limb in August of 1998.

#### Publications:

"Hard X-Ray Spectroscopy for Proton Flare Prediction", Garcia, H. A., Farnik, F. and Kiplinger, A. L. 1998, in the Proceedings of the S.P.I.E. "Missions to the Sun II", Vol. 3442, C. Korendy, ed., 210.

"The Solar Minimum Active Region 7978, Its X2.6/1B Flare, CME, and Interplanetary Shock Propagation of 9 July 1996." Dryer, M. et al. 1998, Solar Physics, 181, 159.

"Fire Under Fire: Proton Predictions at Perihelion." Kiplinger, A. L., Tsurutani, B. T., 1996, In the proceedings of the first US-Russian Scientific Workshop on Fire, 1996, O. Vaisberg and B. T. Tsurutani, eds., 273.

"Low-Temperature Soft X-ray Flares, Spectrally Hardening Hard X-ray Flares, and Energetic Interplanetary Protons." Garcia, H. A. and Kiplinger, A. L. 1995, in Solar Drivers of Interplanetary and Terrestrial Disturbances, the proceedings of the 16th NSO/Sacramento Peak International Workshop, Sunspot New Mexico, Oct. 16-20, 1995.

"Comparative Studies of Hard X-ray Spectral Evolution in Solar Flares with High-energy Proton Events Observed at Earth." Kiplinger, A. L. 1995, ApJ, 453, 973.

"Max'91 and Beyond." Kiplinger, A. L. 1994, in Proceedings of the Third SOHO Workshop on Solar Dynamic Phenomena and Solar Wind Consequences, Estes Park, Colorado, USA, September 26-29, 1994, pp. 331.