**Final Report on NAG5-10892: "Hard X-ray Spectroscopic, Microwave and H-alpha Linear Polarization Studies with Hard X-Ray Observations from HESSI"**

**From: Dr, Alan L. Kiplinger**
**To: Whom it may concern**
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Dr. Kiplinger has been pursuing a three year grant under NASA's Sun-Earth Connection Guest Investigator Program in support of the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). An objective of these efforts is to combine X-ray and other data on solar flares, coronal mass ejections and interplanetary particle events in order to obtain a more comprehensive recognition of signatures, and understanding of interplanetary proton events. Thus, part of these efforts are to investigate if signatures seen in hard X-rays and microwaves can lead to better predictions of interplanetary proton events that can be dangerous to astronauts and spacecraft. The original proposal was written in May, 2000 and it discusses a three-pronged approach for data comparisons with three new types of instrumentation observing at X-ray, microwave and optical wavelengths.

The major impetus behind this work and the proposal is that the P.I. discovered a strong correlation between a particular type of hard X-ray signature seen in spectral evolutions and interplanetary proton events (Kiplinger, 1995). The basic signature is that hard X-ray flux peaks either exhibit spectra that soften on their decays (i.e. show fewer and fewer high energy X-rays with time) or they harden during decays (i.e. high energy X-rays decay significantly slower that lower energy X-rays). This signature is called "progressive hardening". Studies were conducted over an eight-year period of data from the Hard X-Ray Burst Spectrometer (HXRBS) of the Solar maximum mission. Out of the 750 well observed flares studied, 41 flares had major associated proton events. Of these, 29 events were "predicted" on the basis of progressive hardening for a hit rate of 71%. The 152 largest flares had a hit rate of 82%.

The first wavelength range covered by the new instrumentation is hard X-rays. The new instrumentation is the Hard X-Ray Spectrometer (HXRS) built by the Czech Republic, launched in March of 2000 and which flew piggyback on DOE's Multispectral Thermal Imager mission. It consists of two 25mm diameter NaI scintillators operating in the ~3-240 keV range. It was intended to test the concept of continually monitoring hard X-ray progressive hardening at geosynchronous orbit for the operational purpose of predicting proton events. One detector was heavily magnetically shielded in order to reduce the severe particle environment that exists in that orbit. The prototype HXRS was actually flown in a 575 km sun-synchronous orbit at 97 degrees inclination. This orbit also exhibits a very harsh particle environment due to frequent passes through high latitude radiation belts and the SAA. In addition, there are very strong background variations seen in all channels as the instrument orbits over the poles. The magnetic shield was found to only reduce the particle fluxes by a factor of ~2, thus it does not effectively render clean observations in either orbit. The P.I., with assistance from Richard Schwartz of SDAC at

Goddard S.F.C., successfully integrated the HXRS into the SPEX program of the SolarSoft software tree and flares were spectroscopically analyzed with those procedures.

In its first year of observations (2000), 27 large flares were observed of which one had an associated proton event. It was only partially observed and the strong particle effects described above limited detection of any progressive hardening in any event. The total effective area of HXRS is only 10 $cm^2$ which is seven times smaller than that of HXRBS. This effective area of HXRS appears to be insufficient to adequately detect progressive hardening in weaker events. This is especially true when one takes the large background fluctuations caused by electrons into account. It was an unexpected surprise in March, 2003 when HXRS suddenly stopped sending data -- it could not be revived. With the delayed launch of RHESSI due to the "shakeup" at the testing facility, there is only ~1 year of overlap between HXRS and RHESSI.

The second wavelength range covered by new instrumentation is microwave. The instrumentation is the Solar Radio Burst Locator (SRBL). The inclusion of microwave observations stem from the fact that both hard X-rays and microwaves sample much of the same population of high energy electrons; thus, microwaves can serve as a surrogate for hard X-ray observations and potentially detect progressive spectral hardening. A problem with geosynchrotron microwaves emitted in strong magnetic fields is that they become optically thick (opaque) and the true nature of the source is masked. However, at sufficiently high frequencies, the source becomes optically thin (transparent) and the entire source of emitting electrons can be seen and measured. Sufficiently high means: above the turnover frequency where the microwave spectrum turns downward (i.e. fluxes decrease with increasing frequency). The P.I. has noted in many flares that when progressive spectral hardening is seen in hard X-rays, it is also seen on decays of microwave bursts above the turnover frequency. Thus microwave observations above the turnover frequency have the potential to aid in predicting interplanetary proton events.

The SRBL instrument was designed by Dr, Gordon Hurford (who designed the principal and many detailed aspects of RHESSI) to utilize a small 2m microwave dish to measure solar radio fluxes as well as determine source positions in efforts to augment solar monitoring and forecasting. SRBL typically observes more than 100 frequencies from 1 – 18 gHz in addition to monitoring lower frequencies in order to match RSTN frequencies. Its development was funded by the U.S.A.F. and was intended for world-wide deployment and continuous coverage. The P.I. saw this as an opportunity for continuous surveillance of progressive spectral hardening – at least when spectral coverage extends beyond the turnover frequency. After years of development and SRBL had met its requirements, the U.S.A.F. cancelled the program in 2003. Only the prototype at Owens Valley Radio Observatory and the first production instrument, now at Holloman, New Mexico are in operation. With stealth technology aircraft and numerous radar facilities, the Holloman site has proven to be a very poor site for a sensitive, wide-band solar microwave telescope. Conversely, the original prototype at Owens Valley works well in that benign environment. Only one flare observed by SRBL in 2000 was associated with an SESC qualified proton event. There were none in 2001 and the only one in 2002 was not seen by

RHESSI. The data only exists in raw form and no flare lists from SRBL data are available after 2002.

However, a significantly better, yet similar instrument exists. This instrument is the Owens Valley Solar Array (OVSA). It covers the same microwave frequency frequencies as SRBL with essentially the same detectors. It began limited operation in 1999, but since 2001 it has had a complement of three small 2 meter dishes that form 7 baselines with two large 35 meter dishes. Thus it has much more sensitivity that SRBL. Moreover, as part of a graduate student's work, all of the data from 2001 – 2003 has been cataloged, carefully calibrated, reduced and placed on-line in a convenient form for analysis with IDL. These data and catalogs have only existed since 2004 when this grant nominally ended. With regard to associations with major proton events, OVSA observed three in 2001 – one had a high turnover frequency, one shows some evidence for spectral hardening but the third flare (04 November, 2001) shows rather clear evidence for progressive hardening on flux peaks. Also associated with this flare was also a halo CME, an X1 soft X-ray flare and strong proton fluxes observed at Earth. RHESSI had not been launched. In 2002, OVSA observed two proton associated events, one of which had good overlap with RHESSI coverage. Another, similar event observed in 2003 holds considerable promise for progressive hardening. More detailed analyses of these events, and perhaps some to be found in the 2004 catalog that is being produced, is now an ongoing process. Perhaps the proof of concept originally conceived for SRBL data may be accomplished from OVSA data.

The third wavelength to be considered is optical and in particular H-alpha. Originally, the emphasis was to have been on polarization observations with the High Speed H-alpha Camera/Polar meter located on the Boulder Campus. At the very beginning of this grant, it was suggested that the work should concentrate more on the hard X-ray and microwave aspects of the proposed work rather than on the optical aspects. On the other hand, in 2003, RESSI P.I Bob Lin and Brian Dennis both expressed interest in additional H-alpha support from the P.I. Some Hi Speed Camera data has been obtained but it has been limited.

Another approach to H-alpha observations has been utilization of the U.S.A.F.'s Solar Optical Observing Network (SOON). Since 1994, the P.I. has been collecting world-wide H-alpha observations from SOON. The system is named "SOONSPOT" where the "SPOT" stands for Solar Patrol On Tape. In 2004, the SOON system employed 3 U.S. Air Force SOON observatories located in New Mexico, Australia and Italy. Each site records full disk Ha images every 30 minutes and large scale H-alpha images of active regions or other features every five minutes (or 30s during flares). Originally, Exabyte recorders were installed at the five SOON telescopes around the world. Data has been being received in Boulder and at Lockheed's LMSAL who constructed and maintained the online catalog. Lockheed's involvement ceased in 2001 and tapes began accumulating in Boulder. A goal has been to support RHESSI and the general scientific community with this data by continuing this archival process. Using undergraduate student support, SOONSPOT data for flares observed by RHESSI in 2002 and 2003 was transferred to hard disk for more convenient access than tapes provide. Over time the Exabyte drives have been becoming less and less reliable. It is for this reason that new data will be recorded on DVD's instead of tapes. A DVD burner was recently installed at Holloman, New Mexico and data has been successfully read at Boulder. This will make data retrieval and cataloging far more convenient due to the random access of the DVD medium. In 2004, a new Memorandum of Understanding was approved and signed by the U.S. Air Force, the NOAA Space Environment Center and the University of Colorado to continue the SOONSPOT archival program.

The P.I. has also continued work and support on another solar optical telescope operated by the U.S. Air Force. It is known as the Improved Solar Optical Observing Network (ISOON). ISOON records images with 2048x2048 pixels instead of 512x512 pixels per image as recorded by SOON and SOONSPOT. ISOON is a vast improvement over the older SOON and was intended to replace it. However, only one ISOON telescope is in operation at NSO Sacramento Peak. ISOON does support full disk imaging and it records precise full disk images in H-alpha every sixty seconds. From 21 April 2003 to 22 May 2003, the P.I. volunteered to participate in remote observing and operation of the ISOON telescope. A remote control computer was set up on the P. I.'s desk at the NOAA/Space Environment Center in a test required by the U.S.A.F. After the ISOON telescope and the remote control test were proven to be successful, it was quite unexpected that the system that was to replace SOON in 2003 was instead cancelled by the U.S.A.F. Ironically, the SOON system with its Microvax computers is now slated to be operated until 2013. The single ISOON telescope in New Mexico is likely to remain in operation on weekdays as long as funds prevail.

The P.I. recognized the patrol potential of the ISOON telescope in detecting the elusive phenomena of "flare waves" which accompany either major solar flares or CME's and often proton events. Accordingly, he worked with scientists and programmers at NSO's Sacramento Peak Observatory in developing a means to observe not only the brightness of the hydrogen on the Sun, but to also measure its motion via Doppler measurements and to fold that data into the massive datastream. The P.I. proposed taking smaller (1024x1024) +/- 0.6A images every minute along with the normal, larger on-band images. This patrol mode was successful and is now the default mode of operation. Several wave events of differing types have been seen.

One such event as shown in Figure 1 (courtesy of Don Neidig) is associated with an X11 flare from region 486 on 29 October, 2003. In the image, one sees not only the flare itself in the lower right hand corner, but also a series of large diffuse light and dark bands. The light bands show the Sun's chromosphere moving upward and the dark bands show it moving downward. It should be noted that the classic Moreton wave usually appears as a single propagating wave front, not as a wave train. This flare was a very powerful gamma ray line flare that allowed the RHESSI satellite to obtain some of its best gamma ray imaging to date. There were associated protons.


Figure 1. Bands of a new type of "flare wave" discovered by the new patrol mode of the ISOON telescope. The broad dark and light bands represent a wave train moving away from the flare at 1100 km/s. The physical cause and exact nature of the wave is not yet understood.

Another intriguing wave event is one associated with a flare that was seen 2002 Dec. 19 although it was only an M class flare. There was an associated coronal mass ejection and a modest interplanetary proton event. Figure 3 shows an enhanced ISOON H-alpha image of most of the sun before the flare. There are two large active regions above and below the equator. The area from the center to the bottom center of the upper region was the site of the flare as seen by the enhanced bright areas shown in Figure 4. The flare waves appear here as two streaks of enhanced brightenings extending downwards and towards the left of the flare site and situated across the equator. In all there were a total of four such waves of sequentially brightening patches that occurred over a twenty minute period following the start of the flare. These streaks of brightening which left the flare site at 600-800 km/s are remarkable since they appear to be so different from the classic Moreton flare wave. The Moreton waves proceed from major flares and appear as moving, expanding circular arches subtending tens of degrees. Conversely, these wave disturbances appear to be focused and only subtend narrow angles. Thus a Moreton wave is reminiscent of a wave produced by someone throwing a large stone into a pond, while these waves are reminiscent of someone skipping stones across a pond at different times and in different directions. It is also most curious that the brightenings which occur along any given propagating disturbance are (essentially) all from regions of the same magnetic polarity. Note that propagating arcs of bright points have been seen in SOONSPOT data. Kiplinger is a co-author on a new paper by Balasubramaniam et al. (2005) to be published in the Astrophysical Journal. The authors speculate that the disturbances represent the footpoints of magnetic field lines which extend high into the corona. These coronal loops are then energized as the eruption tears away from the sun.

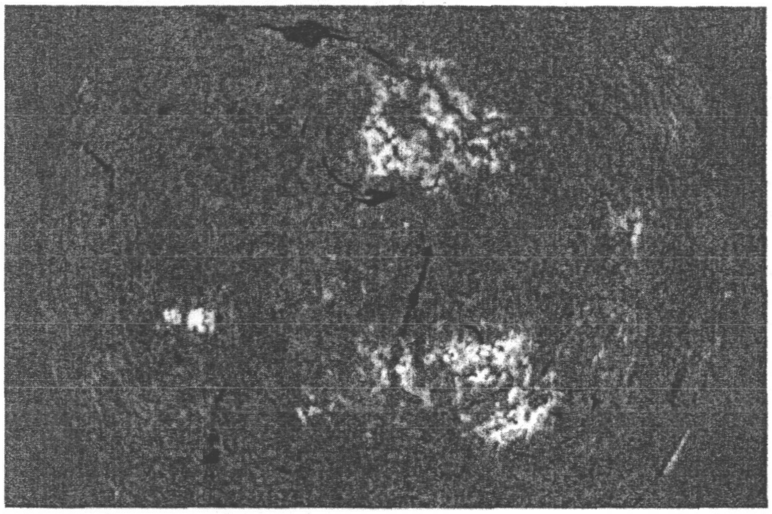

Figure 2. Two bright large active regions as seen in the light of H-alpha before the flare/wave event of 2002 December 19. The upper region was the site of the flare.

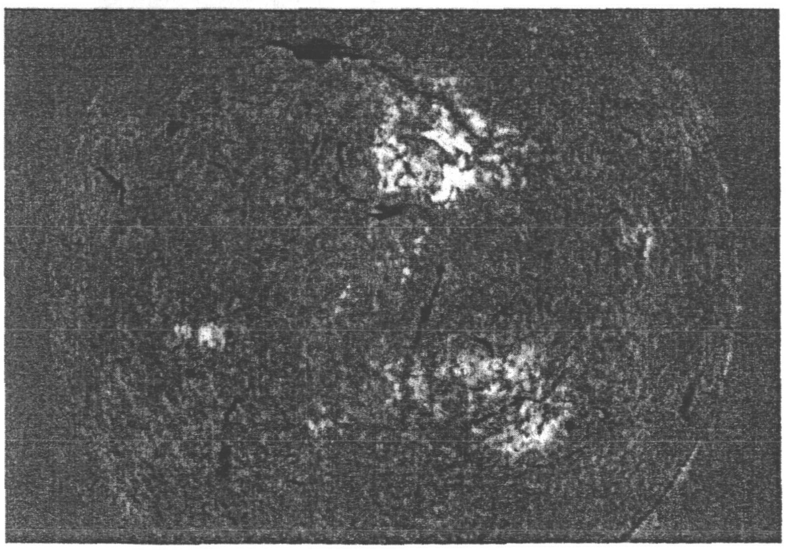

Figure 3. The flare near maximum seen as bright areas in the upper active region (compare with Fig.2). Downward and to the left around the center of the sun are streaks of propagating bright patches which seem to represent a new type of flare wave.

In late October and early November 2003 the Sun provided one of the most active periods of solar activity since spacecraft have been in space. On the same hemisphere of the sun, there were three large active regions that produced more than 100 major solar flares, the largest recorded flare as seen in X-rays, very large interplanetary particle events, the most energetic coronal mass ejection on record, and geomagnetic storms. One of the active regions is known as region 486 and can be proclaimed as the most powerful of regions during this solar cycle. Two of its solar flares saturated NOAA's soft X-ray detectors that are used to classify solar flares. The P.I. carefully reconstructed the soft X-ray light curves of these giant flares by matching curves of a similar but smaller flare from region 486. The largest flares saturated the 1-8A detectors at a level of ~X18.4 but the corrected data indicates fluxes 66% larger at X30.6 – easily making this the largest ever seen since X-ray observations began in the mid-1960's. Temperature calibrations from this corrected data indicate that soft X-ray plasmas heated to 38 million K and that on the rise to maximum it was warming massive quantities of flaring plasma at a rate of 300,000 Kelvins per second.

This was indeed a most remarkable period of activity when the Sun – Earth Connection really hit home. As noted by scientists from the TRACE satellite, one Japanese spacecraft was lost completely and more than 25 other research satellites had to placed in safe hold conditions or suffered instrument losses. Astronauts on the International Space station were ordered into aft sections five times in order to receive more protection from proton storms. Power grid operators modified routing operations and reduced output of nuclear power plants in order to avoid damage from the numerous geomagnetic storms. Global positioning systems (GPS) had problems including a deep ocean drilling ship. We were fortunate that the great flare and CME pictured above occurred when it did and not five days earlier. Had that occurred, Earth would have taken the full blast of the CME and interplanetary particle storms – we would have had some **real** problems. In the paper being prepared, Kiplinger has found that intrinsic characteristics of these great flares are not fundamentally different from previous large events, but rather, they are just bigger.

The results on these flares were first presented at the 2004 AAS meeting in Denver. Howard Garcia calibrated the reconstructed fluxes and emission measures for the two flares with his algorithms. Recently, a new algorithm by Stephan White (White, Thomas and Schwartz, 2005) proposes updated expressions for determining these quantities that take into account coronal rather than photospheric abundances. The P.I. has just received these new algorithms from White and currently plans to include these results in the paper with all due respects to Howard Garcia – especially in light of his recent tragic passing. The authorship is likely to be Kiplinger, Garcia and White (2005, to be submitted).

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