2005 Sun-Solar System Connections (S^3C)

Senior Review Proposal

for the

Reuven Ramaty

High Energy Solar Spectroscopic Imager (RHESSI)

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Table of Contents

1 Executive Summary

The RHESSI Small Explorer mission is designed to investigate particle acceleration and energy release in solar flares through imaging and spectroscopy of hard X-ray (HXR)/gamma-ray continua emitted by energetic electrons, and of gamma-ray lines produced by energetic ions. The single RHESSI instrument provides ground-breaking imaging and spectroscopy measurements from soft X-ray (3 keV) to gamma-rays (17 MeV).

RHESSI was launched on February 5, 2002, and has been operating successfully since. Over 12,000 flares with detectable emission above 12 keV (>~1500 above 25 keV) have been observed since then, including 14 gamma-ray line flares. All the data has been made immediately available to the scientific community since launch, together with the analysis software.

RHESSI provides unique observations of high energy processes close to the Sun that address the key goals of the S^3C Great Observatory: understanding the fundamental processes of particle acceleration and energy release in solar eruptions, both flares and CMEs. The resulting photon emissions and accelerated particles directly affect our Home in Space, and are especially important for our Journey Outward.

In the ~2 years since the last Senior Review, analysis of RHESSI observations has resulted in over 200 publications, and many press releases, popular articles, and awards. Some of the new results include:

The first ever flare imaging in a gamma-ray line showing that flare-accelerated ions are separated from the accelerated electrons by ~15,000 km.

The first measurements resolving the solar flare positron-electron annihilation line (0.511 MeV), showing typical widths of ~5 - 8 keV FWHM during the impulsive phase, but sometimes abruptly narrowing to ~1-keV FWHM, the narrowest seen in any astrophysical source, during the decay.

Comparisons of energetic proton spectra inferred from gamma-ray lines with spectra of solar energetic protons measured near 1 AU, showing the same power-law index for magnetically well-connected flares.

The first detection of HXR polarization, ~18% (~6σ) at 20-40 keV energies, in the 23 July 02 flare, indicating beaming of the accelerated electrons.

The first measurements of HXR microflares showing that they typically have non-thermal power-law components and are associated with active regions.

The first inversions of HXR flare spectra showing that the parent X-ray-producing electrons may have a low energy cutoff.

The first HXR imaging showing evidence for magnetic reconnection and the formation of a current sheet high in the corona.

Pioneering measurements of solar radius and solar oblateness with the Solar Aspect System (SAS), at the milli-arcsec level.

The first measurements of terrestrial gamma-ray flashes (TGFs) showing that the spectrum typically extends above ~10-20 MeV, and that TGFs occur ~10 times more often than previously thought.

The best measurements of the brightest cosmic gamma-ray burst ever detected (from a magnetar, a neutron star with the strongest magnetic fields in the universe) showing a hot (kT~175 keV) black-body spectrum.

Several workshops have been held to train researchers, especially students and post-docs, on the RHESSI data analysis. Many topical workshops have been held to facilitate the joint analysis of data with other S^3C missions. Over a dozen Ph.D. students and numerous post-docs worldwide are doing research on the RHESSI data.

The spacecraft and instrument continue to operate nominally. The GeDs show the effects of radiation damage as predicted, and we plan to anneal them to bring them back to nominal performance, most likely in the next year. Since the mission was designed with no expendables and the orbit decay has been minimal, RHESSI should be able to operate for years to come.

The years 2006 - 2008 span solar minimum and the beginning of the next activity cycle. The X-17 flare in September 2005 is a reminder that large events occur even during solar minimum, when conditions are simpler. Solar-B, STEREO, and GLAST (planned launches in 2006-7) bring unique new observations that are highly complementary to RHESSI for study of solar flares, CMEs, and solar energetic particles. In addition, RHESSI's uniquely high sensitivity at 3-15 keV energies will enable studies of micro/nanoflares and quiet Sun thermal and non-thermal emissions to much lower levels than ever before. The best SAS measurements of solar radius and oblateness will be obtained then, and RHESSI will continue to provide unique measurements of terrestrial gamma-ray flashes (TGFs) and astrophysical transients.

We and the ACE, SOHO, TRACE, and Wind teams propose a Solar Eruptions Events GI program to maximize the science return by supporting studies (not possible under the in-guide funding) that integrate the remarkable new observations of solar explosions, eruptions and their energetic consequences obtained by the S3C Great Observatory in this solar maximum.

2 Science

As indicated by the many new results, the past two years have been tremendously productive scientifically for the RHESSI mission. RHESSI has provided (and continues to provide) an enormously rich data set. Besides the pioneering HXR and gamma-ray imaging spectroscopy measurements of solar flares, RHESSI observations are able to extend into the soft X-ray and HXR ranges with very high sensitivity to study magnetic reconnection, current sheet formation, and the initiation of CMEs high into the corona. The RHESSI measurements of energetic electrons and ions at the Sun can be compared to those solar energetic particles (SEPs), both ions and electrons, measured in situ near 1 AU to try to understand the connection from the Sun to the heliosphere. The uniquely high sensitivity of RHESSI from 3-15 keV allows the exploration and study of the thermal and non-thermal aspects of microflares and the quiet Sun, likely important for understanding the heating of the active corona. The ability to measure and image the Fe and Fe/Ni lines provides an additional powerful diagnostic of thermal plasmas, needed to help separate the thermal and non-thermal continuum and obtain accurate energy estimates. Remarkably, the Solar Aspect System (SAS) makes measurements of the solar limb accurate enough to study solar oblateness!

In fact we are just beginning to tap the potential of the RHESSI data. The RHESSI observations can provide powerful diagnostics because (1) they combine high spatial and high spectral resolution and excellent precision; (2) they span an enormous energy range from soft X-rays (~3 keV) emitted by hot thermal plasmas, through the hard X-ray/gamma-ray continuum emitted by accelerated electrons, to gamma-ray lines emitted by accelerated ions; (3) data for every energy deposition are brought to the ground so there is unlimited flexibility in the data analysis; and 4) the X-ray and gamma-ray emission processes are quantitatively well-understood.

As indicated in sections 2.1.2.1-4, we have been developing the tools for mining the information contained in the RHESSI data. Sophisticated mathematical methods are being developed to invert the HXR spectrum to obtain the parent X-ray-producing electron population (2.1.2.1). To do this, the contribution (up to ~30 %) to the observed spectrum from scattered photons (albedo) must be subtracted. RHESSI's Fourier-transform imaging technique can be used to measure large area, low surface brightness emission such as the albedo (2.1.2.3). By measuring the size of the albedo patch, we can obtain information on the height of the HXR source, and the ratio of the intensity of the albedo to the HXR source intensity gives information on the directivity of the HXRs and therefore the directivity of the parent electrons. Information on the electron directivity can also be obtained through measurements of the HXR polarization (2.1.2.4), which RHESSI can also measure. Because RHESSI images as well, we plan to jointly optimize the spectral and spatial inversion techniques to maximize the scientifically useful information obtained (2.1.2.2).

Similarly for the gamma-ray measurements, much more information can be obtained by careful analysis of the spectrum – both the lines and the continuum. The shapes of the narrow lines will provide information on the directivity and alpha/proton ratios. With the recent development of software to obtain visibilities, it is likely that the gamma-ray line imaging can be extended to the positron annihilation line, bringing with it much better angular resolution, and perhaps imaging of the prompt de-excitation lines, both the broad lines from accelerated heavy ions and the narrow lines from accelerated protons and alphas.

To tap the real power of the RHESSI requires the integration of its data with that of the other S^3C Great Observatory missions. To understand what is special about the flare and CME-related particle acceleration and energy release regions identified by RHESSI, we need good magnetic field models based on accurate photospheric (and chromospheric if available) measurements. We need information on the magnetic topology, waves, shocks, and ambient conditions in the corona obtained by instruments on TRACE, and SOHO, and on Solar-B and STEREO when they are launched. To understand the Sun's connection to the heliosphere will require ACE, Wind, STEREO, and other spacecraft measuring energetic particles, radio emission, magnetic fields, and the solar wind. Then we will want to understand what conditions lead to these eruptive events. Thus, there is a lot of work to do over the next two years, but it is clear the rewards will be worth it. The in-guide funding, however, is not sufficient for this integration, so the RHESSI team, together with the TRACE, SOHO, ACE, and Wind teams, are proposing a Solar Eruptive Events GI Program (see section 2.2.7).

For those who are unfamiliar with RHESSI we provide here a brief description of the instrument and mission. A detailed description of the RHESSI mission, instrument, and software is given in the first six papers of the Nov. 2002 issue of Solar Physics (vol. 210, p. 3-124). At HXR and gamma-ray energies, the only viable method of obtaining arcsec-class images within the SMEX constraints is with Fourier-transform imaging. The RHESSI instrument has an imager made up of nine Rotating Modulation Collimators (RMCs), each consisting of a pair of widely separated grids mounted on a rotating spacecraft, to achieve angular resolution as fine as ~2 arcsec and imaging up to gamma-ray energies. Behind each RMC is a segmented germanium detector (GeD) to detect photons from 3 keV to 17 MeV. The GeDs are cooled to ~85 K by a space-qualified long-life mechanical cryocooler, to achieve the high spectral resolution (~1 to 10 keV FWHM).

As the spacecraft rotates, the RMCs convert the spatial information from the source into temporal modulation of the photon counting rates of the GeDs. Pointing information is provided by the Solar Aspect System (SAS) and redundant Roll Angle Systems (RASs). An automated shutter system allows a wide dynamic range (>107) of flare intensities to be handled without instrument saturation. The spin-stabilized (~15 rpm) spacecraft is Sun-pointing to within ~0.2º and operates autonomously, with the energy and time of arrival for every photon stored in a solid-state memory (sized to handle the largest flare) and telemetered to the ground.

RHESSI was launched on February 5, 2002, into a nearly circular, 38º inclination, 600-km altitude orbit and began continuous observations a week later. Over 12000 flares with detectable emission above 12 keV (>~1500 above 25 keV) have been observed since then, including 23 above 300 keV and 14 gamma-ray line flares. Many more microflares have been detected above 3 keV.

2.1 Accomplishments

To date, there have been over 260 publications using RHESSI data. They cover a very wide range of topics so we are only able to highlight some of the areas of current research.

2.1.1 Particle Acceleration and Energy Release in Large Flares

Here we list RHESSI's major scientific accomplishments in understanding particle acceleration in solar flares. More detail is provided in subsequent sections on specific topics where major advances have been made and more are expected as we continue to analyze the extensive data set, refine our knowledge of the instrument, and develop more advanced data analysis techniques.

- RHESSI's first observation of a gamma-ray line flare, the X4.8 on 23 July 2002 located at S13E72, yielded a harvest of revolutionary results on energy release and particle acceleration in large flares (see special issue of the Astrophysical Journal Letters, vol. 595, L69-L138, 2003). Some of the highlights are as follows:
  - RHESSI has found unpredicted nonthermal coronal hard X-ray sources in flare pre-impulsive phases (section 2.1.2.7). One such source required about half of the total accelerated electron energy for the entire flare! RHESSI's measurements of the Fe and Fe/Ni lines at ~6.7 and 8 keV (section 2.1.7) provide an independent constraint on the thermal plasma that suggests the accelerated electron spectrum extends well below 20 keV, implying even more energy.
  - RHESSI has provided stronger evidence that magnetic reconnection is responsible for the energy release in the flare impulsive phase. The fluxes and spectra of the hard X-ray footpoints observed during the impulsive phase showed the same temporal variations to within seconds, indicating that they are at opposite ends of newly formed magnetic loops. The speed of the footpoint motions, a measure of the rate of reconnection, was roughly proportional to the HXR flux, which measures energy release (section 2.1.2.5). A superhot thermal source, seen throughout the impulsive phase, started near the location of the pre-impulsive phase coronal non-thermal source, and moved in the same direction as the footpoints. This source was always positioned high above the loops joining the footpoints, as expected for the reconnection region itself. Similar behavior has been seen in other large flares, but not always.
  - RHESSI has provided the first ever flare imaging in a gamma-ray line (the neutron-capture line at 2.223 MeV), showing that flare-accelerated ions are separated from the accelerated electrons by ~15,000 km. More recently, the 2.223 MeV line imaging of the 28 October 2003 flare showed two sources, very likely the footpoints of a loop. The loop length is about the same as observed for the HXR footpoints; however, the two loops are separated by ~10,000 km (section 2.1.3.1).
  - RHESSI has provided the first ever high resolution spectroscopy of flare gamma-ray lines, detecting mass-dependent redshifts of ~0.1 - 1%, consistent with downward going energetic parent ions, but inconsistent with radial magnetic field lines (section 2.1.3.5).
  - RHESSI has detected HXR polarization for the first time, ~18% at 20-40 keV energies, suggesting beaming of the accelerated electrons. RHESSI has also obtained polarization upper limits at 0.15 – 2 MeV energies (section 2.1.2.4).
- RHESSI's spectral measurements show that flares in general produce double power-law HXR spectra with a relatively sharp downward break at a few tens to >~100 keV, implying a similar sharp feature in the parent electron spectrum. Thus, any theory for electron acceleration in flares must be able to explain these sharp features. RHESSI's excellent spectral

resolution and sensitivity enable the inversion of the observed flare HXR spectra to determine model-independent parent electron spectra (section 2.1.2.1) vs. time, key diagnostics of the energy release and particle acceleration mechanisms. For the 23 July flare the inversion indicated the likely presence of a low energy cutoff. This finding has spawned new ground-breaking work on inversion techniques and albedo correction (section 2.1.2.3).

- RHESSI has discovered a new class of hot, thermal "above-the-loop-top" X-ray sources. These sources detach from the hot flare loops during the impulsive phase and either fade out or propagate away from the Sun. One has been associated with a flare-related CME (section 2.1.8).
- RHESSI has resolved the solar positron-electron annihilation line (0.511 MeV) for the first time, showing typical widths of ~5 - 8 keV FWHM during the impulsive phase, but sometimes abruptly narrowing to ~1-keV FWHM, the narrowest seen anywhere in astrophysics, during the decay. These widths imply transition region temperatures of ~3 - 5 x 10^5 K, changing to photospheric temperatures (section 2.1.3.2).
- RHESSI measurements for 11 gamma-ray line flares show a close linear correlation of the fluences of the 2.223 MeV line produced by >~30 MeV ions with the >300 keV continuum fluences from electron bremsstrahlung, suggesting that ion and electron acceleration to MeV energies are closely related.
- RHESSI measurements of the prompt gamma-ray lines of Fe, Si, Ne, C, and O indicate changes in flare ambient composition in time through the flare (section 2.1.3.4).

2.1.2 Hard X-rays

2.1.2.1 HXR Spectral Interpretation

Hard X-ray spectroscopy is a vital tool for the study of high energy processes at the Sun, yielding direct information on fast electron populations in flares. Most earlier X-ray detectors had rather poor energy resolution, and as a result, solar flare hard X-ray spectra were typically fitted with an assumed isothermal or single or double power-law photon spectrum. RHESSI's high resolution spectra allow the thermal component at low energies to be clearly distinguished from the nonthermal component at higher energies. The nonthermal component is now routinely fitted with calculations of the bremsstrahlung from model electron distributions and, when appropriate, the thermal component can be fitted with multithermal models. Line emission is often visible in RHESSI spectra at ~6.7 keV and ~8 keV (section 2.1.7).

The clear distinction between the thermal and nonthermal components has allowed the minimum energy content in accelerated electrons to be calculated for many flares (Holman et al. 2003; Emslie et al. 2004; 2005, section 2.1.9). Knowledge of the full spectrum of accelerated electrons and the total energy these electrons carry requires knowledge of the electron distribution at low energies. The radiation from electrons at these energies is usually masked by radiation from thermal plasma. In some flares observed by RHESSI, however, the electron distribution must contain a low-energy cutoff or substantially flatten below energies of ~10 keV, or the radiation from the nonthermal electrons would exceed the flux observed at lower energies. Using a combination of RHESSI light curves, images, and spectra, Sui, Holman & Dennis (2005) have argued that the nonthermal electron spectra in the 15 April 2002 flare must have a cutoff (or substantially flatten) at energies around 24 keV.

Johns and Lin (1992) showed that it was possible, in principle, to invert optically thin bremsstrahlung HXR spectra directly to obtain the detailed parent HXR-producing electron spectra with no *a priori* assumptions. Such inversions, however, are inherently ill-posed, in that the recovered electron spectrum is highly sensitive to even small levels of noise in the photon spectral data. The RHESSI spectrometer, with its excellent spectral resolution (~1 keV FWHM for HXRs) and sensitivity, provides the most precise measurements of solar flare HXR continuum spectra ever (possibly the best in astrophysics). These observations have spurred the development of mathematical techniques to optimize the spectral inversion, calibration techniques to achieve extremely high precision, and theory and analysis of related effects such as albedo (section 2.1.2.3).

The original matrix inversion technique of Johns and Lin (1992) employs binning of the photon spectra into energy bins sufficiently wide to reduce the resulting uncertainties in the recovered electron spectrum. More recently, inversion techniques based on Tikhonov regularization (e.g., Piana et al. 2003, Massone et al. 2003) have been further developed and implemented. (Computational codes related to the above data analysis techniques have been made available to the solar community via SolarSoft.) Brown et al. (2005) show that both binned-matrix inversion and Tikhonov regularization techniques are robust in the sense that they can reliably recover a wide range of spectral features. Moreover, while they may smooth out very sharp features in the spectrum, they do not introduce artificial features that are absent in the real electron spectrum.

One of the most intriguing results from application of such inversion techniques to RHESSI data is the finding that a number of events, including the 23 July 02 gamma-ray flare, appear to show a local maximum ("hump") in the recovered electron spectrum (Piana et al. 2003, Kontar and Brown 2005). Such a feature would have significant implications, discriminating between competing electron acceleration and flare energy release models and affecting total energetics of the flare. The observed solar flare HXR spectrum, however, includes both direct emission from the source and albedo - HXRs scattered from the solar atmosphere below the source. After applying corrections for albedo developed by Kontar (2005), Kasparova et al. (2005) showed that low-energy cut-offs in electron spectra are no longer required for most of the events they studied (except for 23 July 02). We note here that for some flares, RHESSI can directly measure the albedo component (section 2.1.2.3) to provide information on the height of the HXR source and its directivity.

The derived X-ray-producing electron spectra and their variations with time are the result of the modification of the accelerated electron spectrum by energy loss, propagation, and escape processes. If those processes are known (or can be assumed), then a continuity equation can be solved to obtain the accelerated electron source spectrum (see, for example, Lin and Johns, 1993), the key signature of the acceleration mechanism.

Brown, J.C., Emslie, A.G., Holman, G.D., Johns-Krull, C.M., Kontar, E.P., Lin, R.P., Massone, A.M., & Piana, M. 2005, ApJ, in preparation
Emslie, A.G. 2003, Ap.J., 595, L119.
Holman, G. D., Sui, L., Schwartz, R. A., and Emslie, A. G., 2003, ApJ, 595, L97.
Johns, C.M. & Lin, R.P. 1992, Solar Phys., 137, 121.
Kasparova, J., Karlicky, M., Kontar, E.P., Schwartz, R.A., & Dennis, B.R., 2005, Solar Phys., in press.
Kontar, E.P. & Brown, J.C. 2005, Advances in Space Research, in press.
Kontar, E.P., Emslie, A.G., Piana, M., Massone, A.M., & Brown, J.C., 2005, Solar Phys., 226, 317.
Kontar, E.P., Piana, M., Massone, A.M., Emslie, A.G., & Brown, J.C. 2004, Solar Phys., 225, 293.
Lin, R.P., & Johns, C.M., 1993, ApJ. Lett. 417, L53.
Massone, A.M., Emslie, A.G., Kontar, E.P., Piana, M., Prato, M., & Brown, J.C., 2004, ApJ, 613, 1233.
Massone, A.M., Piana, M., Conway, A., & Eves, B. 2003, A&A, 405, 325.
Piana, M., Massone, A.M., Kontar, E.P., Emslie, A.G., Brown, J.C., & Schwartz, R.A. 2003, ApJ, 595, L127.
Sui, L., Holman, G. D., and Dennis, B. R. 2005, ApJ, 626, 1102.

2.1.2.2 Imaging Spectroscopy

RHESSI's ability to image sources in different energy bands is exemplified in Figure 2.1.2-1. It has provided the heretofore unavailable capability to obtain high resolution X-ray spectra as a function of position. Previous spectral analyses were constrained by the implicit but problematic assumption that the X-ray spectra (and by implication the electron energy distribution) was the same at all footpoint and looptop locations in the flare. Early RHESSI work (e.g. Sui et al. 2002, Emslie et al. 2003) showed that, not surprisingly, the spectra of high-altitude coronal sources and low-altitude footpoint sources were different in form and that fundamentally new information could be obtained by analyzing each source separately.

Determination of the photon spectrum as a function of space and time leads, through standard spectral fitting and/or inversion procedures (see Section 2.1.2.1) to the determination of the electron spectrum as a function of space and time. This in turn can be used (Emslie et al. 2001) to determine empirically the energy redistribution processes affecting the bremsstrahlung-emitting electrons. In addition to obtaining distinct spectra for each source component, additional insights can be gained by exploiting the new ability to study the spectral variations in location, size, and shape within individual source components. An early example of this approach is provided by Aschwanden et al. (2002), who used the energy dependence of source height to infer relevant properties of the chromosphere within flaring loops.

Since RHESSI imaging spectroscopy is based on quantitative comparison of maps made at different energies, it is dependent on the quality of images. The quality and potential of images are improving as a result of both improvements in our understanding of the instrument calibration and with the development of new software tools. For example, new software tools have significantly reduced the effects of pileup in the modulated count rates which had been a serious constraint for intense events. Newly available tools such as visibility analysis provide new and highly sensitive techniques for studying the energy dependence of source size and shape. With this improved capability, the time is now propitious to pursue imaging spectroscopy studies over a wider range of events.

Aschwanden, M.J., Brown, J.C., and Kontar, E.P. 2002 Solar Physics, 210, 383.
Emslie, A.G., Kontar, E.P., Krucker, S., and Lin, R.P. 2003, Ap. J., 595, L107.
Emslie, A. G., Barrett, R. K., and Brown, J. C. 2001 ApJ, 557, 921-929.

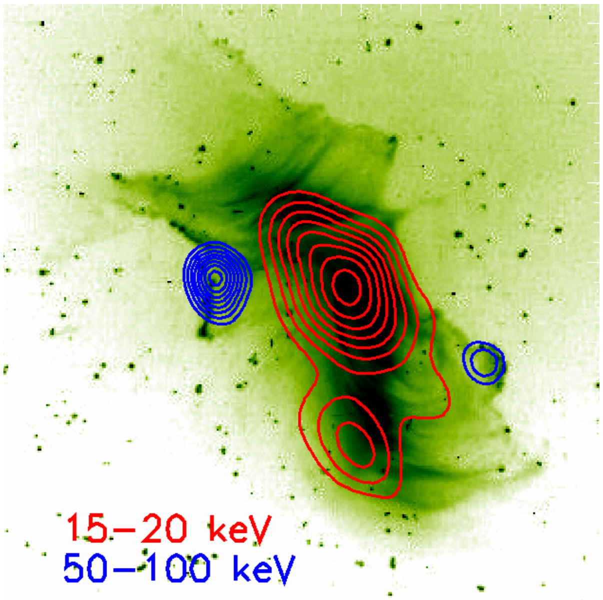

Figure 2.1.2-1. Composite image of the X10 flare on 29 Oct. 2003 at 20:52 UT showing the TRACE 195-Å image in green and the RHESSI contours in two energy ranges. There is a clear distinction between the thermal loop tops and the nonthermal hard X-ray footpoints (Krucker, 2003).

Krucker, S., 2003, http://plasma2.ssl.berkeley.edu/~krucker/hessi/oct2003.html

Sui, L, Holman, G. D., Dennis, B. R., Krucker, S., Schwartz, R. A., and Tolbert, K. 2002, Solar Physics, 210, 245.

2.1.2.3 HXR Albedo Measurements

The RHESSI telescope produces hard X-ray images by Fourier imaging techniques that are capable of determining the sizes and shapes of sources with spatial scales in the range ~2 - 180". Applying Forward Fitting techniques in the Fourier domain to RHESSI modulation profiles from simple flares, we have identified extended features of low intensity whose size scale (~40") greatly exceeds the flare core sizes (~6 - 14") (Schmahl and Hurford, 2002, 2003). The surface brightness of these 'halos' is typically a factor of ~100 weaker than that of the core, so they are difficult to image with other methods. Nevertheless these 'halos' contain a significant fraction (10 - 30%) of the total flux. Our interpretation for these extended sources is that they are albedo patches caused by Compton back-scattering. The albedo flux can be as large as 25 - 50% of the primary X-rays in the 12 - 25 keV band (Alexander & Brown, 2002, Bai and Ramaty, 1978), compatible with our observations.

The spatial distribution of albedo X-rays depends on the height and extent of the source X-rays, so examination of the albedo sources can provide information about the height of the flare source. The center-to-limb dependence and location of the centroid of the albedo patch depends on the X-ray directivity, which can, therefore, be quantified. The spectrum of the albedo differs from that of the primary source, since the effective reflectivity is an increasing function of energy from ~6 to ~40 keV, so the total spectrum of a flare is distorted by the albedo (see section 2.1.2.1). These dependencies of albedo can be inferred with our improved software, which is capable of analyzing more complex sources (e.g. double vs. single) than were possible earlier in the RHESSI mission. Continued analysis of albedo patches can yield a rich trove of information about the directivity of the HXR flux and the degree of pitch-angle anisotropy, and can provide corrections for the effects of the albedo on the total spectrum.

Alexander, C., and Brown, J., Solar Phys. 210, 407, 2002.

Bai, T. and Ramaty, R., Ap. J., 705, 1978.

Schmahl, E.J., and Hurford, G.J., Solar Phys. 210, 273, 2002.

Schmahl, E.J., and Hurford, G.J., Adv. Spa. Res. 32, No. 12, 2477, 2003.

2.1.2.4 Hard X-ray Polarization in Solar Flares

Efforts have been made to study electron beaming in solar flares using statistical measurements of the hard X-ray directivity and using stereoscopic observations (as reviewed in McConnell et al. 2003). Statistical studies are based on a large sample of solar flares that may not provide sufficient insight into singular events. Stereoscopic observations are prone to cross-calibration issues. These difficulties suggest the need for a diagnostic technique that can measure time-dependent anisotropies for individual flares, such as X-ray polarization.

RHESSI has proven itself to be a valuable polarimeter. Since the GeDs are segmented, with both a front and rear active volume, low energy photons (below about 100 keV) can reach a rear segment of a GeD only indirectly, by scattering (Smith et al. 2002). For polarization measurements at low energies (20 - 100 keV), a small block of passive Be (strategically located within the GeD array) is used to scatter photons into the rear segments of adjacent GeDs (McConnell et al. 2003). Low energy photons from the Sun (collimated to a 1° FOV) have a direct path to the Be and have a high probability of Compton scattering into a rear segment of a GeD. The polarization of solar flare HXRs can be determined by a careful analysis of the counting rates in the GeDs that are closest to the Be scattering block, to determine any favored direction of scattering. In principle, the capability of RHESSI to simultaneously image the hard X-ray emission represents a major advantage over previous efforts to measure hard X-ray polarization, in that photospherically backscattered photons (albedo) may be directly imaged by RHESSI as a constraint on the contribution of such backscattered photons to the primary signal.

Analysis of data from this low energy polarimetry mode has indicated a 20-40 keV polarization level of 18 (±3)% from the solar flare of 23-July-2002 (Figure 2.1.2.4-1; McConnell et al. 2005). The polarization angle of 80° (as measured from solar west) implies that the polarization vector for this event was at an angle of ~65° with respect to the solar radial direction. This result is contrary to most theoretical models of nonthermal solar flare polarization that predict a predominantly radial polarization direction, because this is the projection of the plane containing the local vertical and the line of sight on the solar disk. Emslie, Bradsher & McConnell (2005) have shown, however, that the polarization angle can be significantly non-radial if the flaring loop is tilted with respect to the local vertical. Their theoretical models predict a polarization direction and magnitude that is broadly consistent with the July 23 observations if the electron distribution is significantly beamed (width ~30°) and injected along a loop tilted from the vertical at an angle consistent with the tilt suggested by observed redshifts in gamma-ray lines (Smith et al. 2003) for this same event.

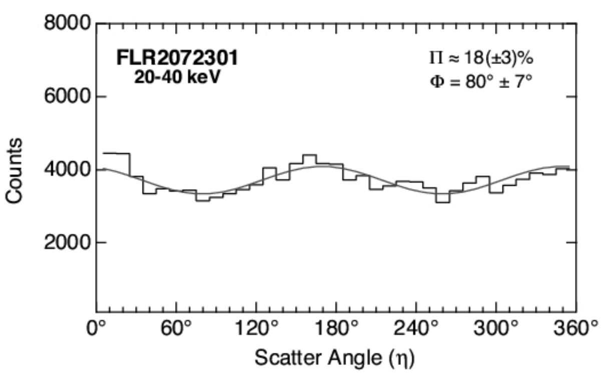

Figure 2.1.2.4-1. The 20-40 keV polarization result for the X4.8 solar flare on 23 July 2002. Minima in the count rate curve indicate the direction of linear polarization of the incoming photon beam.

Analysis of data from three other solar flares (the X1.5 event of 21-Apr-2002, the X3.9 event of 3-Nov-2003 and the X2.5 event of 10-Nov-2004) has found no evidence for polarization (McConnell et al. 2005). A systematic analysis of all significant solar flare events in the RHESSI database is currently underway.

At energies above ~150 keV, polarization can be detected by analyzing photons scattering between adjacent GeDs. Those can be identified since the two GeDs will have time-coincident energy depositions. Upper limits of ~20 % have been obtained for the 23 July 02 flare using this technique (Boggs et al, 2005).

Boggs, S., Coburn, W., and Kalemci., E., ApJ., 2005, submitted.
Emslie, A. G., Bradsher, H., & McConnell, M. L., et al., 2005, Solar Phys., in preparation.
McConnell, M. L., et al., 2003, Solar Phys., 210, 125.
McConnell, M. L., et al., 2005, Solar Phys., in preparation.
Share, G. H. and Murphy, R.J.: 1997, Ap. J., 485, 409.
Share, G. H., et al., 2002, Ap. J., 573, 464
Smith, D.M. et al. 2003, Ap.J., 595, L81

2.1.2.5 Ribbons and Footpoints

The ribbons (chromospheric; a basically thermal signature of a flare) and the footpoints (hard X-ray; basically nonthermal) show the anchor points of flaring coronal magnetic loops. The RHESSI footpoint observations (e.g. Krucker et al., 2003; Grigis and Benz 2005) confirm and greatly extend the association of footpoint geometry and energy release. The speed of the footpoint motions, a measure of the rate of reconnection, is roughly proportional to the HXR flux, which measures energy release. Typical inferred reconnection rates are ~10^{18} Maxwells s^{-1} with v x B electric fields of a few kV m^{-1}. This reflects the fact that the coronal magnetic field both *stores* the energy (as $B^2/8\pi$) and also *guides* the energy release from its source to its sink in the form of energy loss by collisions of nonthermal electrons. Thus, the spatial and temporal development of the ribbons, in a sense, maps coronal magnetic reconnection in flare/CME events, a key to understanding the basic loss of equilibrium.

The RHESSI observations show that the hard X-ray footpoints do not fill the entire ribbon areas, even during the impulsive phase. The more-localized footpoint sources instead move along/within the ribbons with time, in patterns that are systematic but not yet understood. One working hypothesis is that this ribbon/footpoint discrepancy is related to the "soft-hard-soft" pattern of temporal evolution (e.g., Hudson and Farnik, 2002), and hence is a fundamental property of the ill-understood acceleration mechanism. The compact footpoints, in this picture, would be showing us just the hardest spectrum, and the ribbon regions not visible in hard X-rays would have softer spectra, down to the limit of ordinary thermal conduction.

The footpoints show the behavior of the lower atmosphere in a solar flare. We do not presently understand this behavior, which includes such different observables as submillimeter emission and gamma-ray line emission, as observed by RHESSI (see section 2.1.3.2)

Grigis, P.C. and Benz, A.O., ApJ 625, L143 (2005).
Hudson, H., and Farnik, F., ESA SP-506, 569 (2002).
Krucker, S., Hurford, G.J., and Lin, R.P., ApJ 595, L103 (2003).

2.1.2.6 White-light Flares

The "white-light" signature appears during flare penetration into the deepest and most energetic layers. RHESSI and TRACE provide the best-ever data for directly linking the hard X-ray footpoints with the bulk of the flare's radiated energy. A preliminary survey of joint RHESSI/TRACE events has been carried out by Hudson et al. (2005). The complete sample of events with high cadence (<10 s in white light) and full coverage by both RHESSI and TRACE consists of 11 events, ranging in GOES class from C1.6 to M9.1, through 2004. In all cases, both white light and hard X-ray emissions were detected. The results show that:

- All events exhibit correlated hard X-ray and white-light emission
- The observations show small scales in space (unresolved at the TRACE 0.5 arcsec pixel size) and time (unresolved at the RHESSI 4-s rotation period).

These findings may have profound significance for the interpretation of RHESSI observations, namely that the flare energy is *highly intermittent in space and in time*. The essence of the speculation is that the optical/UV observations show essentially the whole radiated power of the flare, and the strong association with the RHESSI hard X-ray sources implies that these scales apply to the impulsive-phase acceleration mechanism.

With Solar-B, the optical resolution will improve by a factor ~5. Furthermore, our existing data show that with improved resolution comes an improved ability to see weaker flares. We therefore anticipate being able to extend the range of white-light flare studies to events below C1 (RHESSI and TRACE have already detected a C1.6 event). The quest for the smallest scales and most rapid variations has a clear objective, namely the constraints these scales set on the properties of high-energy particle acceleration and propagation, a fundamental property of the flare energy release. RHESSI observations of microflares have already hinted at a strong nonthermal component even in these much smaller energy releases (Krucker & Lin, 2002).

Hudson, H.S., Wolfson, C.J., and Metcalf, T.R., Solar Phys., submitted, 2005.

2.1.2.7 Coronal HXR Sources

RHESSI has shown that the corona itself, as viewed above the limb, supports a surprisingly rich variety of hard X-ray sources, both impulsive-phase and gradual. Perhaps the most famous source type is the "Masuda flare", an above-the-looptop impulsive-phase event observed with *Yohkoh* (Masuda et al., 1994). RHESSI has not found a clear example of this, but has found related intermediate-energy (3-30 keV) predominantly thermal sources described in section 2.1.1.

The RHESSI gradual coronal sources appear to have three classes. A distinctive event type observed in a few limb-occulted flares prior to RHESSI (Frost & Dennis 1971) appears to have a RHESSI counterpart visible even for disk events. The coronal emission is faint but the events have temporal and spectral properties consistent with the earlier observations, in particular a gradually hardening spectrum. Perhaps surprisingly, such sources have strong footpoints (cf. Qiu et al. 2004) as well as their coronal structure. These "extended events" tend to correlate well with type I and type IV radio emission and with strong heliospheric effects such as CMEs and particle events

In another important development, RHESSI has found novel coronal hard X-ray sources during the pre-impulsive phase of large solar flares. For the 23 July 2002 flare, no counterpart was observed in TRACE 195 Å, SoHO MDI visible, or H-alpha images (Lin et al. 2003a, b). This source had a double-power-law spectral shape and required at least ~10^{31} ergs in accelerated electrons above ~20 keV, about half of the total accelerated electron energy for the entire flare (Holman et al. 2003). This finding is supported by radio observations (White et al. 2003). Hence, the deposited energy of the HXR producing electrons is very large in these events too, even larger than during the impulsive phase. We currently do not understand the physics of these newly-discovered sources and especially do not understand the energy partition.

Finally, the RHESSI observation of "collisionally thick" loop flares represents still another category of coronal source (Veronig & Brown, 2004). Here the classical picture of a loop flare with coronal acceleration seems to be fulfilled, and the inference from the RHESSI images (which have no obvious footpoints) is that a loop of finite extent underwent an energy release, but that the loop was too dense to allow particle precipitation to the chromosphere.

We expect a dramatic increase in our understanding of coronal hard X-ray sources with the advent of Solar-B and STEREO. With STEREO observations, we will often be able to tie down a limb-flare location unambiguously. There also may be improved knowledge of the magnetic structure. This will greatly enhance our understanding of the event geometry. Solar-B will also be making coronal observations with its high-resolution soft X-ray telescope and with its EUV imaging spectrograph. For CME-related events, we will have the opportunity to locate the coronal hard X-ray sources (with their information about the acceleration and the energy release) in the evolving magnetic structure of the eruption for the first time.

Masuda, S., Kosugi, T., Hara, H., Tsuneta, S., Ogawara, Y., Nature, 371, 495 (1994).
Lin, R.P. and 12 coauthors, ApJL, 595, L69 (2003a).
Lin, R.P. Krucker, S., Holman, G. D., Sui, L., Hurford, G. J., and Schwartz, R. A., Proc. 28th Int. Cosmic Ray Conf., p. 3207 (2003b).
Qiu, J., Lee, J., and Gary, D. E., ApJ 603, 335 (2004).
Veronig, A.M., and Brown, J.C., ApJ. 603, L117 (2004).
White, S.M., Krucker, Sam, Shibasaki, K., Yokoyama, T., Shimojo, M., and Kundu, M.R., ApJL, 595, L111 (2003).

2.1.3 Gamma-Rays

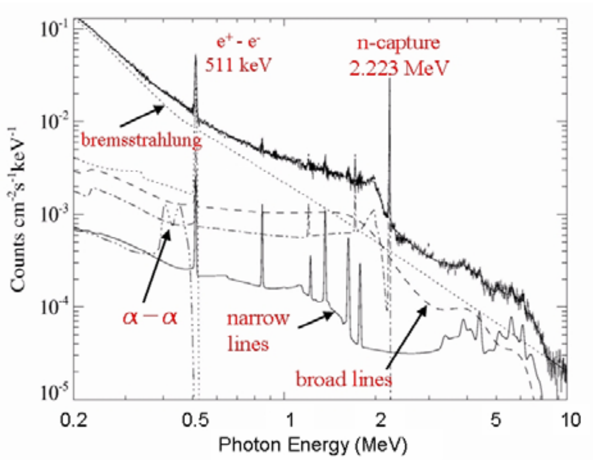

Figure 2.1.3-1. RHESSI gamma-ray spectrum for the 2003 October 28 X17 flare showing all the different contributions to the measured count rate spectrum.

Gamma rays are produced when electrons and ions above several hundred keV interact with the solar atmosphere. The gamma-ray spectrum observed from 200 keV to 8.5 MeV by RHESSI during the decay phase of the 2003 October 28 flare is plotted in Figure 2.1.3-1. The spectrum reveals several distinct components. The electron bremsstrahlung shown by the dotted curve appears to harden between 400-500 keV, and may reflect a comparable hardening of the primary electron spectrum. The most distinct line features are the narrow 511-keV annihilation line and 2.223-MeV neutron capture line. Several moderately Doppler-broadened lines from proton and alpha-particle collisions on ambient C, O, Ne, Mg, Si, and Fe are shown by the solid line. The dashed line combines the spectrum from highly Doppler-broadened lines produced by heavy-ion interactions with ambient H and He and a nuclear continuum. The presence of a high α/p ratio can be inferred from the Li and Be fusion lines (marked α-α in the figure) between 400 and 500 keV.

2.1.3.1 Gamma-ray Imaging

Gamma-ray imaging provides the only available observational technique for studying the spatial distribution of accelerated ions near the Sun. RHESSI is the only instrument available for acquiring such images. The first gamma-ray image of a solar flare was obtained using the intense neutron-capture line at 2.2 MeV in the X4.8 flare of 2002 July 23 (Hurford et al., 2003). It showed that the centroid of the gamma-ray source was displaced from that of electron-bremsstrahlung continuum by 20 arcseconds, a displacement which implies a spatial distinction in the acceleration and/or transport between high-energy electrons and ions near the Sun. Further analysis of the same event has confirmed the separation with improved statistical confidence. This observation remains unexplained although Emslie et al. (2004) attributed the displacement to different size scales of the loops on which electrons and ions were accelerated.

Since that event, four more flares have been observed with neutron-capture line fluxes sufficient for imaging. The largest of these events occurred on 2003 October 28. It was the first multi-component source imaged at gamma-ray energies, showing a double source at 2.2 MeV with components matching the ribbons of the EUV arcade (Figure 2.2.1-2) (Hurford et al, 2005). The locations of these gamma-ray footpoints were displaced by a significant distance (14 arcseconds) from the corresponding electron-bremsstrahlung footpoints. In this case, however, the geometry does not support the Emslie et al. explanation. Instead the displacement was consistent with the sense of electron-ion drift due to the gradient and curvature of the loop arcade, but the estimated drift rates are far too low.

Future work in this area will be directed along three lines. First improved analysis techniques based on visibilities will improve the statistical significance of the results. Second, improved background- and continuum-subtraction techniques (also visibility-based) represent a promising avenue to permit imaging in the 511 keV line. The significance of this is that RHESSI can image such lower energy photons with significantly better angular resolution as the finer and thinner grids give usable modulation at this energy.. Third, observations of additional events in the next solar maximum will permit a more systematic (as opposed to a case-by-case) understanding of the geometry of ion acceleration and transport near the Sun.

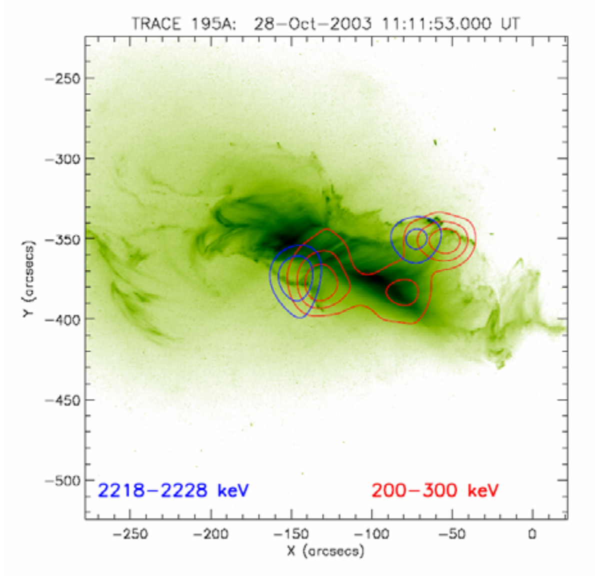

Figure 2.1.3-2. Imaging of the 2.223 MeV neutron-capture line (blue contours) and the HXR electron bremsstrahlung (red contours) of the flare on October 28, 2003. The underlying image is from TRACE at 195 Å. The X-ray and γ-ray imaging shown here used exactly the same selection of detector arrays and imaging procedure. Note the apparent loop-top source in the hard X-ray contours.

Emslie, A. G.; Miller, J. A.; Brown, J. C., 2004, ApJ. Letters, 602, L69-L72

Hurford, G. J., Schwartz, R. A., Krucker, S., Lin, R. P., Smith, D. M., and Vilmer, N., 2003, ApJ. Letters, 595, L77-L80.

Hurford, G. J., et al., 2005, ApJ. Lett., in preparation.

2.1.3.2 Positron-electron Annihilation Line Spectroscopy

RHESSI has spectrally resolved the narrow-line profile of the strong solar positron-electron annihilation line (0.511 MeV) for the first time (Share et al. 2003, 2004). This line and the associated continuum just below it provide information on the temperature, density, and ionization state deep in the solar atmosphere where there are few other measurements. The positrons are emitted from radioactive nuclei (e.g. ^{11}C and positive pions) following their production in flare-accelerated particle interactions. Measurements of the line in five flares reveal that the flare effects penetrate to photospheric densities. Figure 2.1.3-3 shows the line at two different times during the 2003 Oct. 28 flare. The line width is highly variable with the FWHM changing from ~6 keV to ~1 keV in the span of 2-3 minutes (Share et al. 2004, 2005). This suggests that the environment for the annihilating positrons changed from a plasma at transition-region temperatures to essentially a near photospheric plasma.

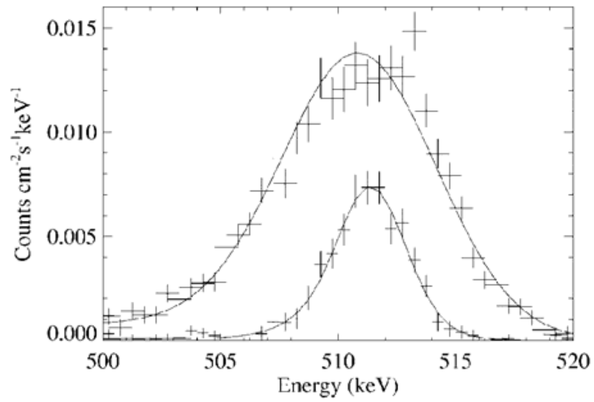

Figure 2.1.3–3. Count spectra of the solar 511 keV annihilation line (instrumentally broadened) for two times during the 2003 Oct. 28 flare when the line was broad (11:06 – 11:16 UT) and narrow (11:18 – 11:30 UT). The solid curves are the best fitting models including a Gaussian line and positronium continuum.

TRACE and SOHO/MDI provide evidence that the footpoint sources penetrated into sunspot umbral regions at the time of the line narrowing (Schrijver et al .2005).

These measurements have been made using just rear detector elements. Future studies will include measurements using the higher-resolution front detectors and flares observed during solar minimum such as those on 2005 January 20 and September 10. Protons with energies ≥ 300 MeV may be responsible for >50% of the positrons produced in some events through pion production. In late 2007, NASA plans to launch GLAST, the most sensitive instrument for detecting pion production in flares. Coordinated observations with RHESSI will then be possible.

Schrijver et al, in preparation, 2005

Share et al., 2003, ApJ, 595, L85.

Share et al., 2004, ApJ, 615, L169.

2.1.3.3 Surprisingly Hard Flare-Accelerated Ion Spectra

During Solar Cycles 21 and 22, gamma-ray observations made by spectrometers on SMM, Yohkoh, and CGRO indicated that flare-accelerated ions could be represented as power laws with indices ranging from ~ -3 to –5. In contrast, four of the best-studied RHESSI flares had indices ranging from ~2.2 to 3.5. The hardness of the flare spectra is well determined from diagnostic line ratios, e.g. Ne/O line ratios, and it is also reflected in the relative weakness of these lines compared to the continuum. The hardest spectrum of particles at the Sun was measured during the 2005 January 20 solar flare. Only the annihilation and neutron-capture lines, and strong nuclear continuum produced by high energy ions were observed in this flare in addition to a very hard bremsstrahlung spectrum. The inferred solar ion spectrum was remarkably similar to the spectrum of the solar energetic particles observed in situ at 1 AU. These particles reached Earth extremely promptly, raising new questions about the relationship between the acceleration of particles impacting the Sun and those reaching 1 AU (see section 2.1.4).

2.1.3.4 Variable FIP Effect Deep in the Solar Atmosphere

Gamma-ray spectroscopy has made the surprising discovery that the overabundance of low first-ionization potential (FIP) elements extends to chromospheric depths in flares (Ramaty et al. 1995). RHESSI has observed an even more surprising characteristic - the low FIP/high FIP ratio can be highly variable in flares. This has been determined by comparing the flux in Fe, Mg, and Si low-FIP de-excitation lines with the flux in Ne, C, and O high-FIP lines. Figure 2.1.3-4 shows striking increases in the FIP ratio during the October 28 and November 2 flares suggesting that the ambient material changed from a photospheric composition to a coronal composition within minutes. The change during the October 28 flare occurred at the same time that Compton scattering of the annihilation-line decreased suggesting the same change from photospheric to chromospheric densities.

Ramaty et al., 1995, ApJ, L193.

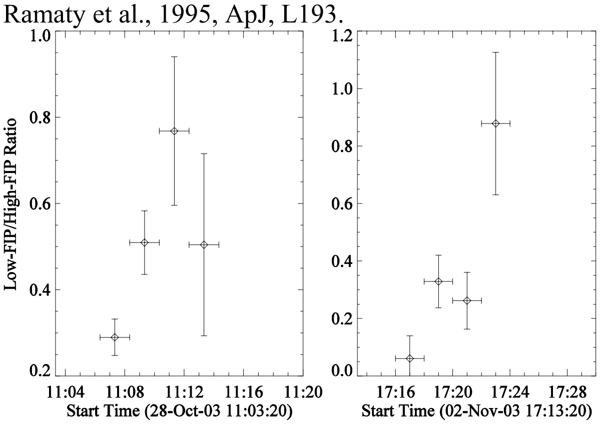

Figure 2.1.3-4. Variation in low-FIP/High-FIP line ratio observed in the 2003 October 28 and November 2 flares.

2.1.3.5 Evidence for Tilted Magnetic Loops

RHESSI's high spectral resolution allows detailed studies of the nuclear de-excitation line shapes. Smith et al. (2003). found that the energies of these lines had redshifts that were significantly larger than what was expected for a broad downward distribution of accelerated particles. Together with RHESSI observations of the neutron-capture line (Murphy et al. 2003) and α-He fusion lines (Share et al. 2003), this suggests that the magnetic loop confining the flare-accelerated particles was tilted towards the Earth. This is consistent with the X-ray polarization measurement discussed in section 2.1.2.4. In contrast, the redshift of the lines observed in the October 28 flare was surprisingly consistent with fields normal to the solar surface.

Smith, et al. 2003, ApJ, 595, L81
Murphy, et al. 2003, ApJ, 595, L93
Share, et al. 2003, ApJ, 595, L89

2.1.3.6 Solar Nuclear Lines Outside of Flares

.A RHESSI guest investigator program is currently in progress to search for the 847 and 1238 keV lines from radioactive ^{56}Co (half life 78.8 days) produced in the solar atmosphere by (p,n) reactions with ^{56}Fe (Ramaty & Mandzhavidze 2000) during the extremely large flares in October-November 2003. The initial brightness of the prompt ^{56}Fe de-excitation lines during flares can constrain the total "dose" of accelerated protons and the atmospheric Fe content. The location of active region 10486 producing the flares can be observed every two weeks as it crosses the solar disk. We estimate that RHESSI can observe a flux as low as 1.5 x 10^{-4} photons cm^{-2} s^{-1} at 3-sigma significance. This is close to theoretical estimates. The rate of fading of the flux, if faster than the natural decay, will reveal the rate at which chromospheric material is convected deeper into the Sun -- something that can only be done with this radioactive tracer.

RHESSI is also being used to search for the 2.2 MeV line from neutron capture from the quiet Sun, to see whether ion acceleration to high energies takes place at low levels in microflares or the quiet corona. The spectrum for 21 months of observing was summed, and a 3-sigma upper limit of 4.8 x 10^{-5} ph cm^{-2} s^{-1} has been placed on the 2.2 MeV line, a value slightly better than was obtained with 9 years of data from SMM (Harris et al. 1992). During this period, the average GOES level was slightly higher than C1. The X4.8 flare of 23 July, 2003, one of the best line flares observed by RHESSI and typical large flare with respect to production of the neutron capture line, had a flux about 5000 times the long-term limit. But the GOES soft X-ray flux during this flare was only about 500 times the long-term average, suggesting that, for a given amount of thermal energy, quiet-time processes are at least an order of magnitude less efficient than a typical large flare in accelerating high-energy ions.

Harris, M. J. et al. 1992, Sol. Phys. 142, 171
Ramaty, R., and Mandzhavidze, N. 2000, IAU Symposium 195, 123

2.1.4 Solar Energetic Particles (SEPs) in the Interplanetary Medium (IPM) and at the Sun

A major scientific question for S^3C is how the SEPs observed in situ in the interplanetary medium (IPM) near 1 AU are related to energetic particles at the Sun. Combining RHESSI observations with in-situ measurements of the energetic electrons and ions that reach ~1 AU gives a unique diagnostic tool to study the origin and transport of SEPs. RHESSI accurately locates where energetic electrons and ions lose their energy at the Sun, and its high-resolution spectral measurements provide information on the spectra of the parent electrons and ions, and on the ion composition.

The SEP events in the IPM have been classified as impulsive or gradual, so-called because of the temporal behavior of the associated flare soft X-ray burst (Lin 1987, 1994). Gradual SEP events (tens per year at solar max) are generally large (hence also called LSEP) events dominated by protons, with "normal" solar abundance and charge states typical of quiet 1-2 x 10^6 K corona, (e.g. Fe^{+13}), although new observations show that departures from this are not uncommon. Recent ACE observations show significant enrichments of ^{3}He and Fe in some *gradual* events, more than can be easily explained as acceleration of remnant ^{3}He and Fe in the IPM from previous impulsive events. Gradual events extend over >100º in longitude and are usually associated with large flares (sometimes absent) and fast, wide Coronal Mass Ejections (CME's).

The SEPs in gradual events are generally believed to be accelerated at altitudes of a few to ~tens of solar radii by the fast shocks driven by the CMEs (Kahler, 1999, Reames 1996), but acceleration processes in the high corona (Klein et al 2003, Cane 2002), or acceleration due to interactions between CMEs (Golpaswamy 2002), or flare acceleration processes have also been proposed. The most intense LSEP events are important for space weather since the fluence of protons energetic enough (>~50 MeV) to penetrate the walls of manned spacecraft can be high enough to significantly degrade solar panels and electronic components on unmanned spacecraft, and to result in a harmful or even fatal radiation dose to astronauts.

For the LSEP event of 21 April 02, RHESSI observed the associated flare (Gallagher et al, 2002), but no gamma-ray line emission was detected, suggesting an absence of significant flare acceleration of energetic (>~10 MeV) ions. The flare and CME initiation were closely related, with the impulsive flare HXR emission occurring first (section 2.1.8).

RHESSI's first gamma-ray line flare, 23 July 02, was accompanied by a very fast (2180 km/s) and wide CME. No SEPs were detected by the ACE or Wind near the Earth, as expected since the flare was located near the east limb of the Sun. However, no SEPs were detected by the Mars Global Surveyor (MGS) spacecraft located on the opposite side of the solar system very close to the nominal Parker spiral field from the flare, even though two previous SEP events (July 16 and 19) were detected from the same active region. Thus, even a fast and wide CME may not always accelerate SEPs.

For the 28 Oct and 2 Nov 03 events, Figure 2.1.4-1 shows preliminary comparisons of the spectra of energetic protons at the Sun, inferred from the observed fluences of the 0.511 MeV positron annihilation line, the 2.223 MeV neutron-capture line, the 4.443MeV carbon line, and the 1.63 MeV Neon line (Ramaty and Murphy 1987); with the spectra for the energetic protons observed near 1 AU (using ACE, GOES 10, and SAMPEX spacecraft to provide full energy coverage), integrating over the entire event to obtain the fluences (Mewaldt et al 2005). The observed spectra are consistent with a double power-law with a downward break, both for protons in the IPM and for those at the Sun. For 28 Oct, where the flare is located at E08 solar longitude, the two spectra are different; but for 2 Nov, where the flare at W58 is magnetically well-connected, the spectra are consistent with being the same.

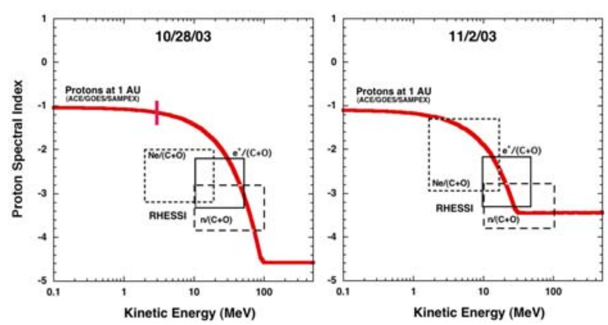

Figure 2.1.4-1. Comparison of the power law indices of energetic proton spectra measured by ACE, SAMPEX, GOES in situ near 1 AU (red lines) with power law indices of protons at the Sun, inferred from RHESSI gamma-ray line fluences, for the 28 Oct. 2003 and 2 Nov. 2003 events. The spectra appear to be a downward-breaking double power laws.

The most intense ground level (>~500 MeV) LSEP event since the February 1956 accompanied the large solar flare and coronal mass ejection on 20 Jan 05. The energetic protons that arrived in the Earth's vicinity less than 15 minutes after the first sign of the magnetically well-connected (W61) flare, suggesting that the particles were either accelerated by the flare itself or by the accompanying CME at unusually low altitude in the solar corona. The observed proton spectrum at 1AU is extremely hard and essentially identical to that inferred from the gamma-ray line emission observed by RHESSI (Figure 2.1.4-2). Such hard and prompt LSEP events represent a serious threat to astronauts during EVA's and on the lunar surface.

Thus, in the two magnetically well-connected LSEP events, the spectral slope of the energetic protons producing the gamma-ray lines was found to be the same as that of the SEP protons observed at 1 AU. This suggests that the gamma-ray producing and energetic protons observed in-situ at 1 AU may have the same source (in well-connected events), contrary to the current paradigm that the gamma-ray producing protons are accelerated by a different process (flares) from the SEP protons (fast CMEs). These two events had quite different spectral slopes, so this agreement is unlikely to be a coincidence. The imaging of the gamma-ray line emission shows that the energetic ions at the Sun are located in relatively compact regions in these flares.

Detailed analysis of the full gamma-ray spectrum, lines and continuum, will provide information on the spectrum of energetic alpha particles and the composition of the energetic heavy ions (that produce broad lines), which can then be compared to the observed composition of the SEPs after transport effects are taken into account.

2.1.5 Interplanetary Electron Events, HXR bursts, and Type III radio bursts

Impulsive solar particle events (Lin, 1985) are dominated by non-relativistic electrons at ~1 to 10s of keV (but sometimes down to ~0.1 keV, or up to 100s of keV). They are the most commonly observed solar events at 1 AU (>~1000/year near solar maximum over entire Sun), and are often closely associated with interplanetary type III radio bursts, and sometimes with small flares. The associated energetic ion emission is generally weak and limited to low energies (<~1 MeV/nucleon), but typically ^{3}He-rich (Reames et al. 1985) and heavy ion-rich (Fe, Mg, Si, S). Surprisingly, previous gamma-ray de-excitation line measurements suggest that the energetic ions in *large* flares are often also ^{3}He-rich [Mandzhavidze et al., 1999] and Fe-rich [Murphy et al., 1991].

RHESSI's excellent sensitivity enables the study of the relationship between the X-ray-producing electrons at the Sun and those in impulsive electron events detected by the WIND/3DP instrument near 1 AU. For the 16 events observed above 50 keV, where velocity dispersion analysis of the electron onsets at 1 AU shows that the release time at the Sun coincides with a RHESSI HXR burst, the HXR power-law spectral index and the electron spectral index (both measured above 50 keV) observed in-situ show a clear correlation (Figure 2.1.5-1), suggesting a common acceleration mechanism (Krucker, Kontar, & Lin 2005). Furthermore, the X-ray source structures of these events all look similar, showing hot loops with HXR footpoints plus an additional HXR source separated from the loop by about 15", suggesting a simple magnetic reconnection model with newly emerging flux tubes that reconnect with previously open field lines, so-called interchange reconnection, with HXR emission at the footpoints (thick target model). The observed correlation, however, does not agree with a simple thick-target model, but may require an energy dependent escape mechanism (with high-energy electrons escaping more easily).

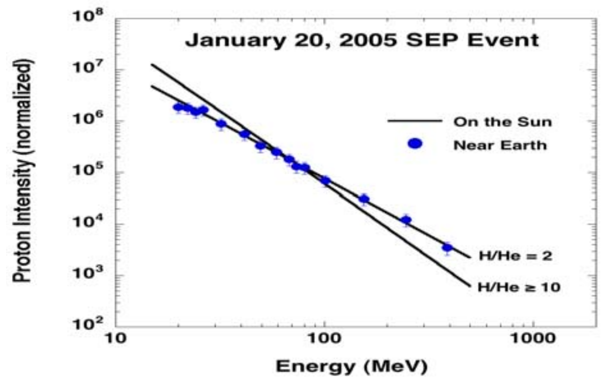

Figure 2.1.5-2. Comparison of the spectrum of protons at the Sun, inferred from RHESSI gamma-ray line fluences (lines) with the spectrum measured by ACE, SAMPEX, GOES in situ near 1 AU (points).

From WIND/3DP observations in the previous solar minimum, we expect to see about 12 impulsive electron events per year in 2006 and 2007, with most seen only below 15 keV. For part of this time, STEREO/STE electron observations will be available with much higher sensitivity from 2 to 30 keV, providing three longitudinally separated spectral measurements. Solar minimum conditions with little thermal emission from the corona, together with RHESSI's sensitivity (~100 times more sensitive at 10 keV than any previous instruments) gives us the best chance to detect HXR emission of impulsive electron events at low energies. HXR emission from escaping electrons that produce type III radio bursts could possibly be detected, especially for partially occulted events (cf. Christe et al., 2005).

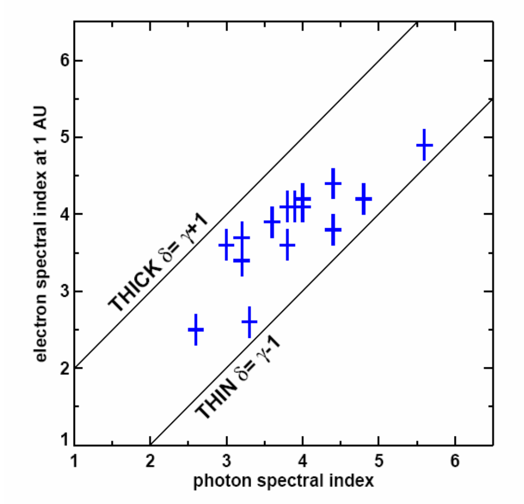

Figure 2.1.5-1. The HXR photon spectral index (>50 keV) observed by RHESSI plotted versus the spectral index of electrons in impulsive events observed in-situ by WIND/3DP. The correlation suggests a common acceleration mechanism, but neither simple thick- or thin-target models fit.

Krucker, S. and Lin, R. P., ESA Special Publications series, SP-560, Editors, F. Favata, G.A.J. Hussain, B. Battrick, p. 101 (2005)

Christe, S, Krucker, S, & Lin, R.P., 2005, in preparation.

Krucker, S, Kontar, E.D., & Lin, R.P., 2005, in preparation.

2.1.6 Microflares and Coronal X-rays

One possibility for heating the solar atmosphere is via very small flares (microflares, like ordinary flares but weaker, or Parker's "nanoflares") occurring quasi-continuously over the solar disk. The viability of this mechanism depends on the integrated energy of these events and on their ubiquity, particularly in the absence of sunspots. Their integrated energy depends on two factors: their frequency and the low-energy cutoff to the steep nonthermal electron spectrum, which RHESSI has shown dominates the energetics of the weakest events (Krucker et al., 2002). It follows then that the determination of the integrated coronal heating contribution of microflares requires both high sensitivity (to detect the smallest events) and the ability to characterize nonthermal spectra down to a few keV. Furthermore, it is necessary to know whether such events are specifically associated with active regions or have a ubiquitous presence on the solar disk. RHESSI is uniquely positioned to fulfill these requirements.

RHESSI has three significant advantages for such studies over previous missions. The first is its ***imaging*** capability that allows it to associate individual microflares with active regions (see figure 2.1.6-1). There is a strong preference for the microflares in this figure to occur in active regions. The second advantage is its ***spectral coverage*** down to 3 keV with an exceptionally ***high sensitivity*** (about 100 times that of any previous solar instrument at ~10 keV) to enable evaluation of the occurrence frequency of much smaller events than heretofore possible. The third advantage is its ***high spectral resolution*** (~1 keV FWHM) to enable the separation and characterization of thermal and nonthermal emission to lower energies than previously feasible.

RHESSI results obtained to date (Benz and Grigis 2002, Krucker et al. 2002, Qui et al., Liu et al. 2004, Battaglia et al. 2005) have shown that microflares have relatively steep power-law (viz. nonthermal) spectra extending down to below 10 keV in some cases. This has extended the low energy cutoff well below that available with previous instruments, a result which has significantly raised estimates of their integrated energy. Ongoing work has also extended the frequency distribution of individual microflares below previous limits so that detailed spectral analyses are yielding initial energy estimates down to $\sim 10^{26}$ erg from the soft X-ray observations. Tiny events of this magnitude may be surprisingly frequent, especially when compared to earlier statistics (e.g. Crosby, Aschwanden, and Dennis 1993) based on measurements at higher energies. Spatially, RHESSI microflares with sufficient statistics for imaging have been found to be located in active regions (Figure 2.1.6-1). In the future, correlative microflare studies during the solar minimum are planned in concert with Solar B and STEREO observations. This will allow multifaceted perspective on individual events to establish whether microflares are indeed just smaller versions of large flares or whether they form a separate class of events. In such work, Solar B/EIS will provide observations of plasma flows, while Solar B/SOT, STEREO/XRT and STEREO/EUVI will provide 3-dimensonal-event geometry. RHESSI's role is to provide HXR diagnostics and quantitative measurements of the energy content in non-thermal electrons.

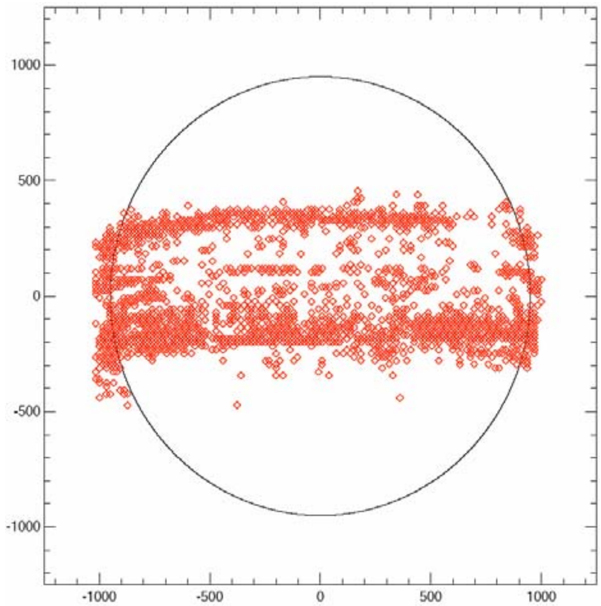

Figure 2.1.6-1: Locations for some 3500 microflares observed by RHESSI from January to June 2004.

Qiu, J., Liu, C., Gary, D. E., Nita, G. M., Wang, H., ApJ 612, 530, 2004

Liu, C.; Qiu, J.; Gary, D. E.; Krucker, S.; Wang, H., ApJ 604, 442, 2004

Battaglia, M.; Grigis, P. C.; Benz, A. O., Astron. and Astrophys. 439, 737, 2005

Krucker,S., Benz A.O, Bastian, T.S, Acton, L.W., ApJ 488, 499, 1997.

Krucker, S., Christe, S., Lin, R.P., Hurford, G.J., and Schwartz, R.A.; Solar Phys. 210, 445-456, 2002

Neupert, W., Ann. Rev. Aston. Astophys. 7, 121-148, 1969.

2.1.7 Soft X-ray results

The low-energy end of RHESSI's spectral coverage (3 - 20 keV) contains considerable diagnostic information about the hottest part of the solar flare plasma (>~6 MK). The spectrum measured by RHESSI in this energy range includes continuum emission (the sum of free--free and free--bound) and two broad features at ~6.7 keV and ~8.0 keV (fig. 2.1.7-1). The latter are made up of many unresolved resonance and satellite lines of highly ionized Fe and, to a much smaller extent, Ni ions. The shape and intensity of the continuum spectrum provides information on the emission measure and the temperature, or temperature distribution, of the hot plasma. The line-to-continuum ratio or the equivalent width of the broad Fe-line complexes are functions of both temperature and the abundance of Fe in the plasma. The intensity ratio of the Fe and Fe/Ni complexes is a function of temperature alone since nearly all of the component atomic lines that make up both peaks are from Fe. Thus, it should be possible to obtain an accurate measure of the iron abundance in the hot plasma, a parameter that is important for identifying the origin of the plasma, either heated in situ in the corona (Feldman et al. 2004) or evaporated from the chromosphere. The continuum and Fe features constrain the temperature distribution of the thermal plasma and help to separate it from the nonthermal component of the X-ray spectrum. In this way, we can obtain more accurate estimates of the thermal energy of the plasma and the total energy in nonthermal electrons that produce the power-law hard X-ray continuum.

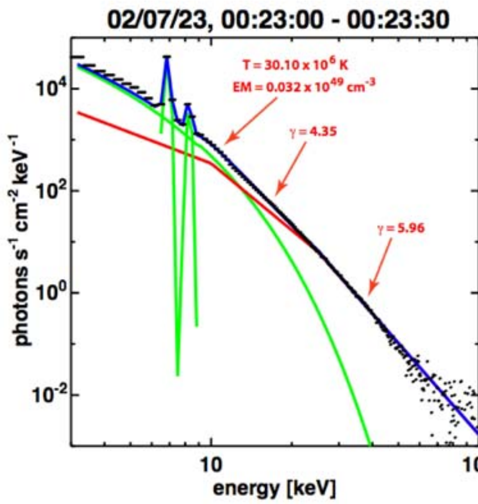

Figure 2.1.7-1: RHESSI spectral fit showing the decomposition of a low-energy spectrum into thermal and nonthermal (power-law) components. The two broad features at 6.7 and 8 keV make clearly distinguishable contributions in each of the three RHESSI attenuation states allowing their intensities to be determined throughout each flare at temperatures >~15 MK.

The operation of the RHESSI attenuators during the periods of intense flare X-ray emission (necessary to limit detector saturation and pulse pile-up) makes the absolute sensitivity in the different attenuator states difficult to determine accurately. The very steeply increasing attenuation below ~10 keV and the instrumental background lines in this energy range make it more difficult to isolate the solar features. Nevertheless, Dennis et al. (2005) reported that the temperature dependence of the equivalent width of the Fe-line feature at ~6.7 keV agreed with predictions based on the latest CHIANTI version 5.1 for one flare for an iron abundance close to four times photospheric, a value previously reported for flare plasma. Caspi et al. (2005) have reported that the ratios of the peak intensities of the two features generally follow the predicted shape of the dependency on temperature but, surprisingly, different curves are obtained for different flares. It is not clear what causes these differences from flare to flare; they may be caused by contributions from the instrumental background lines or they could be an effect of the multi-temperature nature of the source.

Phillips et al. (2005) have reported on variations of the 6.7 keV equivalent width with temperature during the decay (to avoid complications of the more intense fluxes and nonthermal effects present during the impulsive phase) of some 30 flares ranging from GOES class C3 to X5. They find that, at least in the middle attenuator state and for an iron abundance of four times photospheric, the measured equivalent widths follows the predicted dependency on temperature but with an offset of a few MK towards higher temperatures. They suggest that this offset may be caused by (a) the non-isothermal nature of the flare plasma and/or (b) instrumental effects related to the calibration of the sensitivity at low energies, and/or (c) errors in atomic rates used in theoretical He-like Fe ion fractions.

Clearly. much work remains to be done to fully exploit this feature-rich part of RHESSI's spectral coverage. A spare flight detector is being used at Berkeley with flight-spare grids and attenuators to investigate the possible background spectral lines. A better assessment of the multi-temperature nature of the plasma will be obtained by independent differential emission measure analyses using RHESSI data along with observations from other instruments at lower X-ray energies (GOES and RESIK on Coronas-F), at EUV wavelengths (EIT, TRACE), and in the radio domain. In addition, detailed comparisons are being made with spectra obtained in the same energy range below ~10 keV with the X-ray Solar Monitor (XSM) on the European SMART-1 mission and the Solar X-ray Spectrometer (SOXS) on the Indian geostationary satellite, GSAT-2; both of which use silicon PIN detectors with sub-keV energy resolution from ~2 – 10 keV.

Caspi, A. and Lin, R. P., 2005, Eos Trans AGU, 86(18), Jt. Assem. Suppl., Abstract SP41C-05.
Dennis, B. R., Phillips, K. J. H., Sylwester, J., Sylwester, B., Schwartz, R. A., and Tolbert, A. K., 2005, Adv. Space Res., 35, in press.
Feldman, U., Dammasch, I., Landi, E. and Doschek, G. A., 2004, ApJ., 609:439-451.

2.1.8 RHESSI X-ray measurements and correlations with CMEs

Given the geoeffectiveness of CMEs, the effort to understand and eventually to predict these powerful solar events has become a major activity of the S^3C program. As we know, CMEs sometimes occur without flares and vice-versa, but the largest flares tend to be associated with fast and powerful CMEs. Most models of these events include an intimate magnetic connection between the initiation and early acceleration of the CME and the energy release in the associated flare. It appears that the total energy released in the associated flare is comparable in magnitude to the eventual kinetic energy of the CME (see Section 2.1.9). Thus, it is imperative that all aspects of both the flare and the CME be studied if we are going to make progress in understanding these complex eruptive events to the point of being able to predict their occurrence and their effects on the Earth and in interplanetary space. What magnetic configuration is needed to initiate the energy release, and what magnetic reorientation is needed to produce such large releases of energy over such a short time? Clearly, more events must be observed with the existing large fleet of spacecraft and its wide range of instruments, soon to be augmented with Stereo and Solar-B. The few events observed during solar minimum may be of particular importance since they will tend to occur when only one active region is present on the solar disk and there should be no ambiguity about the location of their origin.

RHESSI contributes to this effort in two ways by measuring both the thermal and nonthermal flare emissions. The hard X-ray emissions provide information about the site of the intense flare energy release. We can use this information effectively with STEREO 3D reconstructions. RHESSI has observed many CME-associated flares in which as much as 10^{32} ergs or more appear in the nonthermal electrons alone, on time scales of minutes, exactly during the period of rapid CME acceleration and energization (e.g., Gallagher et al. 2002).

RHESSI furthermore has discovered a new class of hot thermal, "above-the-loop-top" X-ray sources. Typically, these sources detach from the hot flare loops during the impulsive phase and either fade out or propagate away from the Sun as the flare progresses (Sui & Holman 2003; Sui, Holman, & Dennis 2004; Sui 2005; Veronig et al. 2005). The centroid of this above-the-loop-top source is lower in altitude at higher energies, indicating that it is hotter at lower heights in the corona. The centroid of the loop tops, on the other hand, is higher in altitude at higher energies. These observations localize the impulsive energy release between the loop tops and the coronal X-ray source, consistent with the standard model invoking a current sheet where magnetic reconnection takes place.

In the 2002 April 15 flare, the coronal X-ray source changed its motion within about one minute from being approximately stationary to moving outward at about 300 km s^{-1}. This speed was found to be consistent with that of an associated CME observed later with LASCO. Several weak X-ray sources were later observed along the line of motion of the original coronal source, indicating the continued presence of a current sheet below the CME and the presence of instabilities within the current sheet.

A number of thermal X-ray flare loops show apparent outward expansion at speeds ranging from a few km s^{-1} to tens of km s^{-1}. The X-ray loops in the 2002 April 21 flare initially expanded outward at about 10 km/s and then, after about two hours, slowed to 1.7 km/s (Gallagher et al. 2002). In another flare with multiple X-ray peaks, the X-ray flux was found to be correlated with the speed of outward expansion (Sui, Holman, & Dennis 2004). This confirms earlier observations that have been one of the definitive clues to the standard large-scale reconnection models.

An unexpected new result is that many flare X-ray loops appear to *contract downward* early in the impulsive phase of flares before they expand outward (Sui & Holman 2003; Sui, Holman, & Dennis 2004; Sui 2005; Veronig et al. 2005; Holman et al. 2005, in preparation). This is an evolutionary feature that **was not predicted** by existing flare models and may be associated with the initial formation of the current sheet. Veronig et al. (2005) argue that the collapsing magnetic trap resulting from magnetic reconnection above the flare loops may explain this behavior. This new early-phase phenomenon may hold key information regarding the manner in which the structure approaches its trigger point, obviously an important consideration for event prediction. Alternatively it may require that we change the standard model. The forthcoming observations in conjunction with EIS (Solar-B) in particular may be decisive in determining how such a change would look, because of its ability to determine coronal flow fields spectroscopically.

Gallagher,P.T., Dennis,B.R., Krucker,S., Schwartz,R.A., and Tolbert,K. 2002, Solar Physics, 210, 341-356.

Sui,L., Holman, G.D., and Dennis,B.R. 2004, ApJ, 612, 546-556.

Sui,L. & Holman, G. D. 2003, ApJ., 596, L251.

Sui,L. 2005, PhD Thesis, NASA/GSFC, Techn. Mem. NASA/TM-2005-212776.

Veronig, A. M., Karlick´y, M., Vrˇsnak, B., Temmer, M., Magdaleni´c, J., Dennis, B. R., Otruba, W., and P¨otzi, W., 2005, Astron. and Astrophys., in press.

2.1.9 Flare Energetics

A solar flare/CME event is basically a process in which stored magnetic energy is converted into various forms that propagate in the solar atmosphere and through interplanetary space. Ultimately, all of the energy released appears either as energy associated with the mass ejection, or as enhanced radiative output. The dominant term of the CME energy appears to be the kinetic energy, which can be estimated from LASCO images. We have direct measurements of the total radiative output for only a few flares, notably the one on October 28, 2003, from the Total Irradiance Monitor on the SORCE spacecraft (Woods et al. 2004). While such measurements are the most accurate for estimating the total energy released in an event, information about the nature of the energy release process can be acquired only through analysis of the partition of energy amongst various components such as energetic particles and thermal plasma that are present as the flare proceeds.

Emslie et al. (2004, 2005) studied the partitioning of energy in two well-observed solar flare/CME events (April 21, 2002 and July 23, 2002), using RHESSI data in conjunction with data from a variety of other missions, such as ACE, SOHO, and GOES. Since the energy in accelerated particles is found to be such a large fraction of the total flare energy, the RHESSI data were crucial to this endeavor. The RHESSI hard X-ray spectra were used to deduce the energy transported by energetic electrons and the gamma-ray spectra provided similar information for ions. RHESSI softer X-ray images and spectra provided the temperature, emission measure, and volume (but unknown filling factor) needed to estimate the energy content of the hotter plasma. This study yielded the following results:

- Flare radiant energy and CME mechanical energy have the same order of magnitude.
- The soft X-ray flare (GOES and RHESSI) contains only about 1% of the total radiant energy
- The impulsive-phase radiation may dominate
- SEP particles (as well as the impulsive-phase acceleration) have a substantial energy component

Dennis et al. (2005) conducted further analysis of some 30 flares with associated CME's that came from the three regions that produced the sustained activity during October-November, 2003. They found a general correlation over two decades between the flare energies obtained by scaling the GOES soft X-ray luminosities and the corresponding CME kinetic energies obtained from LASCO images by Gopalswamy et al. (2005). St.-Hilaire and Benz (2005) carried out a flare energetics study for medium-sized events, finding similar thermal/non-thermal partition. Work continues on detailed energetics analysis for more well-observed eruptive events to verify this result for other active regions and over a broader range of flare sizes down to the microflare domain.

The new observations from SORCE (Woods et al., 2004) have proven to be a key factor in our new ability to characterize the partition of energy, because now we have a handle on the nature of the total flare radiation. These results will improve with time as filtering is developed to reduce the TIM background fluctuations. In the meanwhile, it is imperative to extend the overlap period between SORCE and RHESSI, since only RHESSI can characterize the non-thermal energy release in these events.

Dennis, B. R., Holman, G. D., Haga, L., and Hudson, H. S., 2005, Eos Trans. AGU, 86(18), Joint Assem. Suppl., Abstract SP21A-01.

Emslie, A. E. and 14 co-authors, 2005, JGR, 109, A10, A10104.

Emslie, A. E., Dennis, B. R., Holman, G. D., and Hudson, H., 2005, JGR, in press.

Gopalswamy, N., Yashiro, S., Liu, Y., Michalek, G., Vourlidas, A., Kaiser, M. L., and Howard, R. A., 2005, JGR, vol. 110, A09S15.

Saint-Hilaire, P. and Benz, A. O., 2005, Astron. & Astrophys., in press.

Woods et al., GRL 31, L10802, 2004

2.1.10 Solar radius measurements

The RHESSI system for precise aspect determination includes a Solar Aspect System (SAS) with a simple design but remarkable properties. Essentially it follows the idea of Dicke's "Solar oblateness telescope" (Dicke and Goldenberg, 1967) in having sensors on a rotating telescope continually scanning the limb of the Sun. The data have exceptional quantity – about 7×10^9 data points thus far – and quality. The preliminary data reduction (Fivian et al., 2004) showed that the rms error for a single one of these measurements had a precision better than 50 milli-arc seconds (mas), whereas the known oblateness of the Sun is on the order of 10 ± 1 mas. Thus, in principle, only a small fraction of the data – say one minute's worth – achieves the precision of the best previous observations. In practice, of course, systematic errors rapidly dominate the observed error. Figure 2.1.10-1 shows a sum over 50 orbits of radius measurements. The measurements have been averaged in 1° bins in position angle along the circumference of the solar disk. A modulation consistent with the solar oblateness can readily be seen, along with excesses due mainly to facular brightness. There are also artifacts present as well as noise at a level of about 2 mas per angular bin (rms). This result is preliminary and not yet corrected for systematic errors.

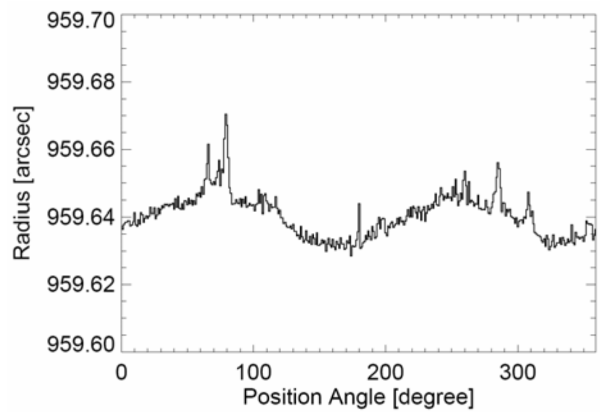

Figure 2.1.10-1. The binned radius measurements as function of position angle along the circumference of the solar disk show a modulation which is consistent with the solar oblateness. The excesses in the signal are mainly due to faculae.

We believe that the RHESSI mode of observation, with multiple sensors on a rotating platform, will lead to a high degree of control of systematic errors. The Sun itself is used, in a statistical sense, as a standard candle for photometric calibration. Extending the RHESSI mission into solar minimum will allow acquisition of valuable calibration data. Longer periods of quiet Sun provides a database for determining flat-field and dark-level calibrations and for gaining knowledge of the point-spread function. A comparable long-term study of the solar radius and shape using such an instrument in space has never previously been possible.

The measurement of solar oblateness, and higher-order shape components of the solar limb (including time-dependent shape changes due to p-modes or even possibly g-modes) interests research communities outside RHESSI's primary area of solar high-energy astrophysics. The data also prominently show the effects of solar activity, notably the sunspots and faculae near the limb in the preliminary data reduction (Fivian et al., 2004). This novel means for tracking solar activity will be especially interesting over longer time scales. We expect to be able to use the data on solar activity to study diverse aspects of solar activity: spots, faculae and polar faculae, flares, and possibly coronal holes.

For the global properties of the Sun, the RHESSI radius measurements are, in a sense, analogous to the 1980 - 1989 SMM/ACRIM measurements of the total solar irradiance ("solar constant"). RHESSI is making a first systematic observation of the solar shape, another basic astrophysical parameter and one of substantial importance for heliospheric physics as well. Thus continuity of measurement and the attainment of overlaps among different instruments have paramount importance. We therefore hope that RHESSI data will continue until SDO and PICARD (both expected in 2008) have been in operation for a reasonable period of time.

The reduced solar activity during solar minimum means that unwanted solar "noise" sources such as sunspots and faculae will dramatically decrease. This period will therefore provide the primary data for the RHESSI radius measurements, which we have already shown to have excellent precision. We expect to tackle several new scientific problems:

- Does the shape of the Sun vary significantly along the solar cycle?
- Does the limb darkening function vary along the solar cycle?
- What is the behavior of polar faculae at solar minimum?
- Do sunspot umbrae differ across the cycle?
- Can we detect the solar g-modes?

Most of these new objectives relate to the heart of the solar cycle, namely the sources of the variation in the solar interior. We list the g-modes as well; this is a speculative entry but one of such vital significance that it is worth mentioning. With long lifetimes (quality factor Q >> 1) the signal-to-noise ratio for g-modes should increase linearly with time. As is well known, the g-mode frequencies, if observable, would give direct helioseismic information about the solar radiative core.

Dicke, R. H., and Goldenberg, H. M.: Phys. Rev. Lett. 18, 313, 1967.
Fivian, M., Hudson, H., and Lin, R.: ESA Conference Proceedings SPM-11, to be published, 2005.

2.1.11 Terrestrial Gamma-ray Flashes (TGFs)

In July 2005, we developed an analysis technique to recover the signal of Terrestrial Gamma-ray Flashes (TGFs) from RHESSI data (Smith et al. 2005). These mysterious, millisecond bursts, associated with lightning, have only been observed by one other instrument, BATSE on CGRO (Fishman et al. 1994). A big surprise of the RHESSI observations was that the photon energies typically extend up to 10-20 MeV, energies as high as seen for black holes. This provided support for theoretical predictions for a mechanism called relativistic runaway breakdown. A second surprise was that RHESSI showed that TGFs are far more frequent than previously thought. Over 500 RHESSI TGFs have been identified, and are being correlated with radio data from lightning (Cummer et al. 2005), particle measurements from other satellites, and other data. The radio results show that strokes with remarkably small charge tranfers can still create gamma-ray flashes. Detailed simulations have already been performed to show that the runaway breakdown process can produce the RHESSI spectrum and that the altitude of particle acceleration corresponds to thundercloud tops (about 15-18 km) (Dwyer and Smith 2005).

The primary goals of this project are to identify the site and cause of the breakdown and to determine if the TGF process is basic to the initiation of ordinary lightning. We are studying whether TGFs contribute high-energy electrons to the inner belt, or affect atmospheric processes through their ionization of the ambient gas. We are also looking for correlations with exotic thunderstorm phenomena such as sprites and blue jets. RHESSI's TGFs have generated a great deal of press attention and interest within the field of atmospheric electricity, and there will be a special TGF session at the 2005 Fall AGU meeting stimulated by these results.

Cummer, S. A. et al. 2005, GRL, 32, CiteID L08811
Dwyer, J. R. and Smith, D. M. 2005, GRL, in press
Fishman, G. J. et al. 1994, Science, 264, 1313
Smith, D. M. et al. 2005, Science, 307, 1085

2.1.12 Astrophysics Results

2.1.12.1 Nuclear Astrophysics

RHESSI data from the first two years of the mission produced two major breakthroughs in the study of radioactive nuclides in the Galaxy. Three isotopes are of particular interest: ^{26}Al and ^{60}Fe, both with lifetimes on the order of a million years, reveal the current rate of nucleosynthesis in the Galaxy. Since they are produced by different mechanisms in different environments, the difference in their intensities and Galactic distribution can separately constrain both the frequency and the physics of the supernovae, novae, and stellar winds which can produce them.

The ^{26}Al line at 1809 keV is the brightest of these lines and has been studied for about twenty years. RHESSI's main contribution to its study was the measurement of its Doppler width (Smith 2003). RHESSI finds the line width to be 0.9 (+1.1, -0.9) keV, consistent with broadening due to Galactic rotation, and in contradiction to an earlier width measurement of 5.4 (+1.4, -1.3) keV made by the GRIS balloon instrument (Naya et al. 1996). The issue was critical to resolve because the GRIS result was not easily explainable, it being very difficult to keep the aluminum moving that quickly for its whole life, even by putting it into grains. The RHESSI result not only resolved that problem, but also has implications for the production mechanism of cosmic rays, since fast-moving grains figure in some scenarios of the cosmic-ray source material.

The lines at 1.1 and 1.3 MeV from ^{60}Fe, expected to originate in supernovae, were finally discovered by

RHESSI after years of upper limits and expectation by the high-energy astrophysics community (Smith 2004). A recent reanalysis and the inclusion of more data has increased the statistical significance of the detection from 2.6 to over 5 sigma. The $^{26}Al/^{60}Fe$ ratio is one of the best ways to constrain models of nucleosynthesis in supernovae. The ^{60}Fe isotope is also of great current interest due to its recent discovery in a thin layer of iron crust on rocks from the ocean floor (Knie et al. 2004). This layer implies an extremely nearby supernova (order of 100 parsecs or less) about 3 Myr ago. The RHESSI detection was recently confirmed by data from the European INTEGRAL spacecraft (Harris et al. 2005).

After the RHESSI detectors are annealed, the rear-segment resolution will become adequate to effectively study these very narrow nuclear lines again, increasing the significance of the results and allowing more detailed comparison with INTEGRAL data, which are accumulated over a much narrower field of view. Extra flux in the RHESSI observation would imply a diffuse, high-latitude component to the radioactivity, perhaps from very local sources.

RHESSI is the only instrument currently active which is capable of making sensitive searches for a phenomenon predicted but never yet seen: the several-hour flash of positron-annihilation radiation expected from the decay of 13N produced in classical novae (thermonuclear explosions on the surface of a white dwarf). A sufficiently nearby novae (less than about 1 kpc distant) generally occurs once every few years, but we have not yet had one during the RHESSI mission. This observation, when made, will constrain both models of nucleosynthesis and models of the explosion mechanism. Further, it will establish beyond question, for the first time, the starting time of a nova -- improving our interpretation of the optical lightcurves of all recorded novae of that class, not just the one observed by RHESSI. RHESSI's sensitivity to these events is approximately a factor of 2.5 better than the previous experiments which have searched for this annihilation flash: BATSE on the Compton Gamma-Ray Observatory (Hernanz et al. 2000), and TGRS on Wind (Harris et al. 1999, 2000).

Harris, M. J. et al. 1999, ApJ, 522, 424
Harris, M. J. et al. 2000, ApJ, 542, 1057
Harris, M. J. et al. 2005, A&A, 433, 49
Hernanz, M. et al. 2000, Proc. 5th Compton Symposium, AIPC, 510, 82
Knie, K. et al. 2004, PRL 83, 18
Naya, J. et al. 1996, Nature, 384, 44
Smith, D. M. 2003, ApJ 589, L55
Smith, D. M. 2004, Proc. 5th INTEGRAL Workshop, p. 45

2.1.12.2 Gamma-Ray Bursts (GRB's)

RHESSI is in a unique position for gamma-ray burst astrophysics. With its all-sky view, RHESSI observes many GRB's with high spectral resolution, time resolution, and potential sensitivity to polarization (Coburn & Boggs, Nature, 2003). RHESSI is a critical complement to Swift GRB studies by providing high-energy spectroscopy (which Swift can not do above ~100 keV), constraining the overall spectral parameters and fluence. These capabilities are critical for verifying the recent papers claiming GRBs can be used (through their spectral and fluence parameters) as "standard candles" for studying cosmology to higher redshifts than supernovae. In addition, RHESSI GRB data was used in the past year to set a new constraint on Lorentz invariance, constraining models of quantum gravity (Boggs et al., ApJ, 2004).

On December 27, 2004 the known soft gamma-ray repeater SGR 1806-20 underwent a cataclysmic giant flare, expelling in less than half a second the equivalent energy output of the Sun in 250,000 years. This was the brightest gamma-ray event observed in over 30 years of monitoring the high energy sky. At the time, SGR 1806-20 happened to be 5 degrees off the solar limb, allowing RHESSI to uniquely capture and study this transient, unique event. A series of letters were published in Nature, led-off by a full article on the RHESSI analysis and results (Hurley et al., 2005). Again, with its all-sky monitoring, RHESSI can continue to follow outbursts from this source and other SGRs.

Boggs, S.E. et al. 2005, ApJ., 611, L77-L80.
Boggs, S., Coburn, W., and Kalemci, E., 2005, ApJ, submitted.
Coburn, W. and Boggs, S E. 2003, Nature, 423, 415-417.
Hurley et al., 2005, Nature, 434, 1098.

2.1.12.3 Accreting X-ray binary A0535+26

In May 2005, the accreting X-ray binary A0535+26 went into outburst while tens of degrees from the solar limb. Swift was able to follow this source briefly, but not for most of the outburst due to solar pointing constraints. This also prevented any other instrument but RHESSI from observing it. A0535+26 has cyclotron absorption lines in the spectrum – a direct measure of the neutron star magnetic fields - and reached a remarkable brightness 5 times that of the Crab Nebula during this outburst. RHESSI was able to take advantage of its off-pointing capabilities to follow this source for several weeks during this rare outburst (the last outburst was in 1994). The RHESSI data set provides a unique opportunity to study cyclotron lines with very high spectral resolution. Analysis is in process.

2.1.12.4 Imaging the Crab Nebula

In June of 2003 and 2004, RHESSI observed the Crab Nebula within the field of view of its RMC imaging system (this requires a few degrees of offpointing). The Crab Nebula is by far the brightest extended X-ray source beyond the solar system, and it is the prototype for the study of young supernova remnants. Comparison of the RHESSI images with the arcsecond images in soft x-rays produced by Chandra will address the acceleration and propagation of high-energy particles in the Nebula.

The Chandra images show a jet, an inner ring (interpreted as a shock), and a larger torus. To date, every new waveband opened on the Crab has shown an image with new or highly altered features. The Crab imaging, which requires extensive new software to derive aspect information, is being funded by a Guest Investigator grant from the former Structure and Evolution of the Universe division.

Further Crab pointings of a few days per year are planned if the Sun is quiet at the appropriate time, to look for variations such as those seen in soft X-rays by Chandra.

2.2 SCIENCE OBJECTIVES for 2007 - 8 and 2009 - 10

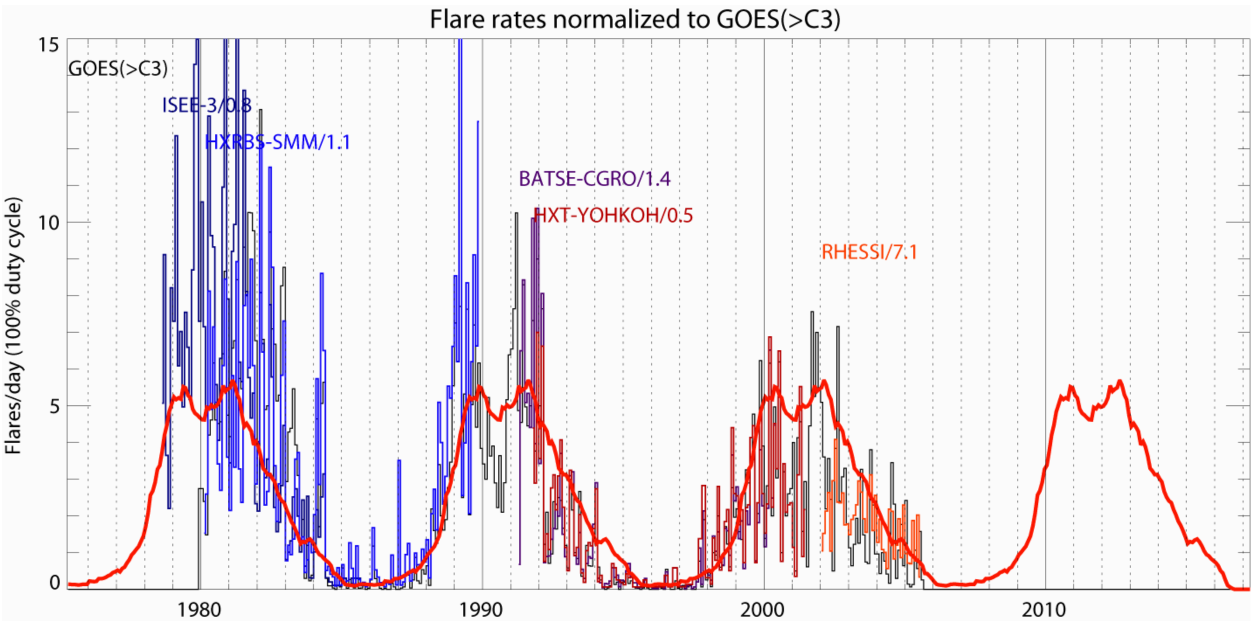

Figure 2.2-1. Predicted rates of X-ray flares for the next solar cycle based on the rates from the three previous cycles as measured with the indicated instruments. The measured rates have been normalized to the rate of GOES-class C3 and higher by dividing by the indicated factors for each instrument.

Solar minimum is predicted for 2006-7, with a significant upturn in activity expected for 2008 (Figure 2.2-1). Large flares, fast CMEs , and SEP events still occur but are less frequent near solar minimum. Such events are important because of simpler conditions in the coronal and solar wind. In 2006, STEREO and SOLAR-B will be launched to join the S^{3}C Great Observatory. RHESSI is the ideal high-energy complement to the high-resolution optical imager and vector magnetograph, soft X-ray imaging, and EUV imaging spectroscopy of SOLAR-B, and the 3-D imaging in EUV and white light coronagraphy of STEREO for studying flares and CME initiation (section 2.2.2). STEREO's highly sensitive energetic electron and ion measurements, separated in longitude, are perfect for comparisons with RHESSI's sensitive measurements of energetic particles at the Sun near solar minimum when the background is low (section 2.2.3). Solar minimum will also enable RHESSI to make deep searches for microflares (2.2.4) and quiet-Sun nonthermal emissions (2.2.5).

As pointed out earlier, much work remains to be done to develop methods and software to mine the information in the rich RHESSI data set. In addition we propose a GI program to integrate the remarkable new observations of solar eruptions and their energetic consequences obtained by the S^{3}C Great Observatory in the last solar maximum (2.2.7). As always RHESSI will contribute unique measurements for study of Terrestrial Gamma-ray Flashes (2.2.5) and cosmic gamma-ray bursts and other high energy astrophysical phenomena (2.2.6).

In 2009-10, solar activity will be steeply rising towards its peak, and RHESSI's high energy measurements will be essential to the S^3C Great Observatory.

2.2.1 Flare Rates and Energetic Events

Since the choice of which RHESSI science objectives will be pursued depends on the level of solar activity, we first present our best estimates of predicted flare rates through the next solar maximum. From the rate of >25 keV HXR flares for the last three solar cycles shown in figure 2.2-1, we use as a prediction for the next cycle the average rate (solid red curve) for each month of the cycle assuming a 10.5-year period. For the solar minimum period (2006-7), we expect ~0.2 HXR flares per day, for a total of ~75 above 25 keV or ~500 above 12 keV, assuming a 50% duty cycle. The activity is likely to be more intense for short periods with long intervals of virtually no activity at all – a so-called spotless Sun. Activity is expected to pick up rapidly in 2008 with the flare rate more than doubling in that year as we rise toward the next solar maximum. During the solar minimum period from January 1986 - January 1988, the SMM Gamma-Ray Spectrometer (GRS) observed 5 gamma-ray flares with detectable flux above 300 keV, with four coming from a single active region. We should detect a similar number during the two-year minimum period. Several large SEP events should be detected as well.

The flare rate does not predict the occurrence of some major phenomena very well, however. Huge SEP events are well known to occur away from solar maximum. In the past minimum, for example, the X-class flare of July 1996 resulted in the first detection of a flare-generated helioseismic wave. In the recent late-phase activity of 2003 and 2005, further examples have been found. RHESSI HXR and gamma-ray line imaging of such a flare could determine whether high energy particles are the energy (and momentum) source for the wave, which has unique potential for sounding sub-surface active-region structure that may have implications for event prediction.

Finally, we note that the July 1996 region (and its flares and CMEs) resulted in many important studies simply because this "test particle" activity dropped into a greatly simplified solar-minimum coronal structure.

2.2.2 RHESSI Flare Studies with SOLAR-B, STEREO, and GOES N

Comparing STEREO and SOLAR B observations with the RHESSI data set will greatly enhance the scientific return for all three missions. SOLAR-B, to be launched in August 2006, carries a high-resolution optical telescope (SOT), an EUV imaging spectrograph (EIS), and a soft X-ray telescope (XRT), perfect complements to RHESSI's high-energy observations for studies of solar activity. SOLAR-B/SOT will provide the first stable time-series observations of the solar vector magnetic field, at the highest possible angular resolution. Together with SOLAR-B/XRT soft X-ray imaging and SOLAR-B/EIS EUV imaging and spectroscopy, this will certainly give the best information to date regarding the pre-event physical conditions in the solar corona. In some manner not yet understood, these conditions change gradually to a "trigger point", at which time an instability or loss of equilibrium occurs (e.g., Forbes 2000). Arguably the best signs of the initiation are the non-thermal effects, as observed by RHESSI, even in the weakest microflares. The combination of RHESSI and SOLAR-B observations thus will provide our best and most objective determination of the trigger conditions.

RHESSI can identify the coronal regions, both pre-flare and during the impulsive phase, that appear to be the sites of flare energy release, magnetic reconnection, and electron (and ion) acceleration. XRT will provide the high cadence high resolution imaging of these high temperature regions (not presently available). RHESSI footpoint motions (Krucker et al., 2003) give a clear indication of the reconnection process in the evolution of the coronal magnetic field. EIS imaging spectroscopy can provide the key measurements of flows and turbulence in these regions to clarify the energy release and particle acceleration processes.

STEREO/EUVI will provide 3-dimensional observations of flare loops seen in EUV. Although RHESSI HXR observations only provide 2-dimensional information, HXR footpoints occur at high density in the chromosphere. Hence, the HXR footpoints can be relatively easily compared with the 3-dimensional geometry obtained from STEREO. Furthermore, SOLAR-B/XRT and RHESSI will provide thermal flare energy estimates, SOLAR-B/EIS will give flow measurements, and vector-magnetograms by SOLAR-B/SOT will be needed to for accurate modeling of the coronal field. This will allow the spatial and temporal evolution during a flare to be modeled and different models to be tested. RHESSI will provide both thermal and non-thermal electron diagnostics.

STEREO observation will provide different view angles of partially occulted flares seen by RHESSI. For one of the two STEREO spacecraft, the flare will not be occulted, thus providing information about the magnetic structure. This will greatly enhance our understanding of the event geometry. EUV ribbons will give us the likely location of the occulted HXR footpoints. The CME geometry seen with STEREO coronagraphs COR 1/2 can be compared with the HXR coronal source location. RHESSI observations show that about 10% of all flares are partially occulted. However, relatively large flares are needed to get good counting statistics so it is expected that only a few good candidates will occur until the flare rate increases leading up to the next solar maximum.

The Gamma Ray Large Area Space Telescope (GLAST) (late 2007 launch) provides a unique opportunity to make simultaneous nuclear-line and very-high energy (several GeV) gamma-ray observations, extending RHESSI measurements of the accelerated-particle spectrum to >1 GeV. GLAST will also detect neutral pions produced in the same reactions as the positive pions that yield positrons responsible for the annihilation line observed by RHESSI. The high-energy protons can penetrate below the photosphere and may be responsible for the helioseismic waves and recent near-IR observations (Section 2.1.3.2). Joint high-sensitivity RHESSI and GLAST measurements also may detect gamma-rays from delayed CME shock-accelerated particles that may impact the solar atmosphere after the impulsive phase of a flare. Delayed annihilation and neutron-capture line emissions have been detected by RHESSI following the impulsive HXR phase of the 10 September 2005 flare.

Very soon, perhaps as early as the end of 2005, a new GOES spacecraft will be launched (GOES-N). This spacecraft will carry the next generation of the Solar X-ray Imager (SXI), with much better spatial resolution that the SXI currently in operation, roughly like the Yohkoh/SXT half resolution images. After launch there will be a checkout period of several months during which the much improved SXI instrument will be imaging the X-ray Sun. Eventually, the GOES spacecraft will be turned off until needed, but the months of overlapping coverage with RHESSI will be invaluable for joint studies. Topics of interest include cross-calibrations of the instruments and complementary observations of solar activity. It was most unfortunate that the Yohkoh spacecraft failed just before the launch of RHESSI. With the launch of the new SXI instrument, much of the joint science planned with SXT can be recovered.

Forbes, T., JGR 105, 23,253 (2000)

Krucker, S., Hurford, G.J., and Lin, R.P., ApJ 595, L103 (2003)

2.2.3 In situ Particle Observations and HXR Emission

For the large flares/SEP events that occur in 2007-8, RHESSI's gamma-ray line measurements of the spectrum of energetic protons and its imaging of the ion source at the Sun can be compared to the ACE, Wind, and STEREO multi-point SEP spectral measurements spread in longitude, while Ulysses will be measuring SEPs while crossing the ecliptic plane at ~1.5 AU distance. These comparisons could determine whether solar flares directly contribute to SEPs at 1 AU when the flare is magnetically well connected, as suggested by the 2 Nov 03 and 20 Jan 05 events (Section 2.1.4).

Most of the impulsive electron events detected at 1 AU during solar minimum will be seen only below ~15 keV. The excellent sensitivity of RHESSI in the 3-15 keV energy range will give us by far the best chance ever (with two orders of magnitude better sensitivity) to see related HXRs from these events, possibly even the thin-target emission from the escaping electron beams that produce type III radio bursts. Solar minimum conditions with little thermal emission from the corona are optimal for these observations. STEREO will provide 3-dimensional event geometry of the solar source region of the escaping electrons and STEREO/WAVES will track escaping electrons by their radio emission. Although the RHESSI observations are only 2-dimensional images, the relatively simple source structure in X-rays (footpoints) will make it possible to put the X-ray emission in the 3-dimensional geometry.

The STEREO IMPACT suite SupraThermal Electron (STE) instrument will provide ~50 times greater sensitivity for measurements of impulsive electron events from ~2 to 30 keV. The two STEREO spacecraft will provide these *in situ* measurements at widely separated solar longitudes. By tracking the electrons from the solar source HXR emission imaged by RHESSI, through the interplanetary medium through the Type III radio emission, to the in situ detection by the STEREO spacecraft we can trace and study the magnetic connectivity from the Sun to the Earth.

2.2.4 Microflares

Combined microflare observation of RHESSI, STEREO, and SOLAR B will allow detailed studies of single microflare events to see if microflares are indeed just smaller version of large flares or whether they possibly are a separate type of event. So far RHESSI microflares are observed to originate from active regions. SOLAR-B/EIS will provide observations of plasma flows, while SOLAR B/SOT and STEREO/EUVI will provide "3D" estimates of flare volumes giving better energy estimates. SOLAR-B/XRT is sensitive in the RHESSI microflare temperature range (~5-10 MK) providing independent energy estimates. RHESSI observations will be an essential part of these studies since it is the only instrument that can provide HXR diagnostics and give quantitative measurements of the energy content in non-thermal electrons and hotter (>15 MK) thermal plasmas. The energetics of small-scale energy release in the solar atmosphere (microflares, “blinkers”, flaring bright points, and many other manifestations) may have a strong relationship to the coronal heating problem. SOLAR-B provides unparalleled diagnostic power for such transients, ideally complemented by RHESSI’s sensitivity to higher temperature plasma and to non-thermal electron acceleration effects.

2.2.5 X-ray flux from the quiet Sun

Although several interesting mechanisms predict HXR emission from the quiet Sun, prior to RHESSI no instrument had sufficient sensitivity to explore it. One of the early pleasant surprises from RHESSI was the finding that the non-flaring Sun was usually a source of hard X-ray emission (Krucker et al., 2002). RHESSI imaging immediately identified the sources with active regions. This suggested that some continuous X-ray emission might be associated with strong sunspot-associated magnetic fields. However the question remains as to whether there is continuous quiet-Sun hard X-ray emission that is not associated with active regions, but with the diffuse hot corona.

Microwave observations (e.g. Krucker et al. 1997) have shown the quasi-continuous presence of small ‘network flares’. While observations of individual events are problematic, their integrated emission should be detectable. Such emission would have significant implications for coronal heating. There are several other potential mechanisms for continuous quiet-Sun hard X-ray emission: Parker’s nanoflares, double layers, or non-thermal wave heating to temperatures beyond those observable with SXI or Yohkoh/SXT. More exotic mechanisms such as albedo emission secondary to the galactic cosmic rays (Seckel et al., 1991) or even “axions” (Zioutas et al., 2004) are also possibilities. The RHESSI capability of defining the non-thermal spectrum and spatial characteristics of such emission will provide definitive diagnostics.

With its shutters open, RHESSI has much greater sensitivity than any previous instrument in the 5-15 keV range. To apply this great sensitivity to the quiet Sun, it is essential to eliminate background contributions. Furthermore, since widely-distributed, weak hard X-ray sources do not lend themselves to efficient imaging with rotating modulation collimators, it is necessary to use a technique that correctly sums the individual sources. We will use two techniques for determining the presence and spectrum of quiet Sun emission, *irrespective of its spatial distribution*. (In each case, conventional RMC imaging can then be used to infer its spatial properties.) Each technique is 2 to 3 orders of magnitude more sensitive than the previous upper limits (Neupert, 1969 and references therein).

The first approach relies on statistical analysis of changes in observed count rates as RHESSI enters or leaves eclipse. This is relatively straightforward although background *trends* need to be carefully handled. The second technique requires RHESSI to offpoint from the Sun by about 0.4 to 0.8 degrees. In this case, the 1-degree field of view of the individual grids in 6 of the 9 subcollimators modulates the integrated solar emission. (In effect, it chops the background signal at 0.5 Hz with a predetermined phase.) The remaining 3 grids act as controls in that no modulation is expected because of their larger fields of view. These procedures have been tested with a limited data set on a few very quiet days. Since the results of such quiet-Sun observations are expected to be statistically-limited, we require observations on a large number of days in solar minimum, the only time that a spotless Sun is likely to be observed.

Krucker, S., Benz A. O., Bastian, T. S., Acton, L. W., ApJ 488, 499-505, 1997.
Krucker, S., Christe, S., Lin, R.P., Hurford, G.J., and Schwartz, R.A.; Solar Phys. 210, 445-456, 2002.
Neupert, W., Ann.Rev.Aston.Astophys. 7, 121-148, 1969.
Seckel, D., Stanev, T., and Gaisser, T., K.: ApJ 382, 652, 1991.
Zioutas, K., et al.: ApJ 607, 575, 2004.

2.2.6 Terrestrial Gamma-ray Flashes

In 2005, over ten collaborative research projects began which correlate RHESSI TGF data to radio atmospherics from lightning, optical emission from sprites and elves seen with ISUAL on FORMOSAT-2, relativistic electrons seen with SAMPEX, and even infra-sound from sprites. RHESSI TGF times and locations are now made publicly available in near realtime. RHESSI is the only observatory currently detecting TGFs and releasing TGF data to the community, so it is critical to the progress of this young field over the next several years.

2.2.7 Astrophysical Objectives

2.2.7.1 Gamma-Ray Bursts

There is a strong possibility that GRBs can be used as high-redshift standard candles (like type Ia supernova) to determine a cosmic distance scale. However, this can only be done if the full spectrum and fluence of each GRB is measured. This requires extending the spectrum to well above the Swift maximum energy of 150 keV. Currently, the only instruments that are able to make such high-energy spectral measurements are HETE-2 and RHESSI. HETE-2 observations are due to end at the end of September, 2005. Thus, until GLAST is launched in 2007 with a BATSE-like instrument that can detect the burst to GeV energies, RHESSI will be alone in its ability to make these critical high-energy spectral measurements.

2.2.7.2 Imaging the Crab Nebula

The inner features of the Crab Nebula are extremely dynamic, showing significant variations from season to season in the optical (HST) and soft x-ray (Chandra) bands (Hester, J. J. et al. 2002). Since the highest energy emission might be expected to be dominated by freshly shock-accelerated particles, this variation could be greatest in RHESSI's hard x-ray band. We therefore plan to revisit the Crab for about one week annually at the Sun's closest approach in June.

Hester, J. J. et al. 2002, ApJ 577, L49

2.2.8 Proposed Solar Eruptive Events GI Program

In the recent solar maximum, an enormous range of remarkable new observations of solar explosions and eruptions and their energetic consequences has become available from ACE, RHESSI, SoHO, TRACE, Wind, and other missions of the S^3C Great Observatory. The buildup, initiation, evolution, and consequences of explosive and eruptive events are topics of particular relevance to NASA's future in this era of the Vision for Space Exploration and the Living With a Star initiative. In FY 2007 and 2008, STEREO and SOLAR-B will add more qualitatively new observations. Each of these missions contributes fundamental new insights, but a global integration and analysis of these observations will provide the real pay-off in our understanding of these phenomena. Since the in-guide funding levels of the individual missions are inadequate to cover such integrated studies, the science teams of many of the S^3C Great Observatory missions (including, alphabetically, ACE, RHESSI, SOHO, SOLAR-B, STEREO, TRACE, and Wind) propose that NASA allocate **$1.5 million/year** in Guest Investigator (GI) funds in the coming years to stimulate rapid advancement of our understanding of the buildup, initiation, evolution, and consequences of explosive and eruptive events. A multi-mission GI program would stimulate analysis of data from joint observing campaigns as well as stimulate coordination between instrument and analysis teams. Multi-disciplinary science workshops, focused on specific aspects of these tasks, will provide additional stimulus to discover new processes, phenomena, and correlations in archival and newly-obtained data.

2.3 Impact, Productivity, and Vitality of Science Team

RHESSI scientific results have been presented at innumerable scientific meetings and published in over 250 papers listed at the following web site:

http://www.lmsal.com/~aschwand/publications/hessi.html

Many of then are available electronically in the E-Print archive at the Max Millennium web site -

http://solar.physics.montana.edu/max_millennium/

Various awards have been given to members of the RHESSI team in recognition of their contribution to the success of this mission. PI, Bob Lin, received the AAS/SPD Hale prize. Mission Scientist, Brian Dennis, received the GSFC Lindsay Award and NASA Outstanding Leadership Medal. The RHESSI data analysis team received a NASA Group Achievement Award. A senior NRC resident research associate, Ken Phillips, received a AAS Popular Writing Award for an article that included RHESSI results.

The most newsworthy results have been broadcast to the general public through over ten press releases from NASA, UC Berkeley, and UC Santa Cruz covering such topics as magnetic reconnection powering solar flares, the connection between flares and CME's, the first gamma-ray image of a solar flare, particle acceleration in the large flare on Jan. 20, 2005, the brightest gamma-ray burst ever recorded on Dec. 27, 2004, and terrestrial gamma-ray flashes. In addition, popular articles with RHESSI results have appeared in many newspapers and magazines including Astronomy Now, Discover Magazine, National Geographic, New Scientist, Science News, and Sky and Telescope.

RHESSI personnel have initiated, organized, and attended many scientific meetings and special sessions in the last three years including five special RHESSI science workshops attended by about 50 scientists, three special data analysis workshops in Glasgow, Scotland, two joint science workshops, one in conjunction with ACE and Wind, the other with SOHO and TRACE. A series of workshops is being held at the International Space Science Institute in Berne, Switzerland to study the RHESSI spectral inversion problem, with the first held in September 2005. RHESSI team members have organized special sessions on high-energy solar physics topics at every meeting of the AAS/SPD since launch and at the two COSPAR General Assemblies, the first in Houston in 2002 and the second in Paris in 2004 with proceedings of both published in Advances in Space Research (vol. 32/10 and 35/10, respectively). In addition, the RHESSI team has held a series of workshops to educate the scientific community on how to use the RHESSI data analysis software in order to obtain the best possible images and spectra, with the most recent being at UCB in Oct. 2004. Finally, members of the RHESSI team are organizing the 2006 SPD Summer School in high energy solar physics to be held in

Durham, NH, in June 2006, with funding from NASA and NSF to cover the costs of up to 40 students and 10 lecturers.

2.3.1 Science Nuggets

In early 2005, at the initiative of graduate student Steven Christe, we began a biweekly series of RHESSI "science nuggets"

(http://sprg.ssl.berkeley.edu/~tohban/nuggets/)

aimed at a technically literate audience. These follow the five-year run of Yohkoh science nuggets

(http://solar.physics.montana.edu/nuggets/)

that began early in the Web age. Each nugget contains about a page of text and a small number of figures. The idea is to present the results in an informal manner, with lots of links for the curious to follow, and with no pretense at literary rigor. On the other hand, most of the nuggets thus far are based on published work.

3 TECHNICAL STATUS

3.1 Observatory

RHESSI was launched on February 5, 2002, into a circular orbit with an altitude of 600 km and an inclination of 38°, and the first solar flare was observed on February 12, 2002.The observatory continues to function very well after more than 3.5 years of operations in its present 578 x 557 km orbit. All of its subsystems are fully operational. The solar array power output has declined by only 1.1% since launch, the battery voltage has been stable for the past 2 years, the absolute battery pressure has been stable for the past 3 years, and the differential pressure has been relatively stable for the past 1.5 years. The average spacecraft temperature has increased by only ~1° C since launch. The S-band transceiver still generates a stable output power of 4.9 W with clean BPSK modulation at 4.0 Mbps, and the receiver shows no signs of deterioration in performance. The attitude control system is stable and the command and data handling subsystem shows no signs of degradation.

The CPU experienced six resets since launch. Three of these resets occurred as a result of the very large solar flare in October of 2003, two were caused by watchdog timeouts during ATS loading, and one had an unknown cause. The IDPU never reset autonomously, but was reset once by ground command. On two occasions ATS loads with faulty checksums were erroneously accepted by the spacecraft. However, these ATS loads were subsequently reloaded and verified flawlessly prior to their on-board execution.

Overall, there is no reason to believe that the spacecraft will not continue to function very well over the next three years. The solar arrays have shown minimal degradation and are projected to be capable of providing adequate power for the next three years and beyond. The battery showed some degradation early in the mission, but has been stable for the past two years and is projected to provide adequate power storage for the next years. The telecommunications subsystem has been stable since launch, and all other subsystems and sensors are functioning nominally.

3.2 Instruments

3.2.1 Spectrometer and Cryocooler

The RHESSI germanium spectrometer and its cryocooler are working well. The cooling performance declined slowly until February 5, 2004. At that time, the cryostat was vented to space using a one-shot valve installed for that purpose. Since then, the cold-plate temperature has decreased slightly to <~85 K with the cryocooler power holding steady at ~65 W. There are no indications of any degradation of cryocooler performance. The gradual increase in the spectrometer temperatures during the early mission appears to have been due to condensation of contaminants inside the spectrometer cryostat, and that is now released to space. As of now, cooling does not appear to present any limitation on the mission lifetime. Furthermore, the microphonics have also diminished and are not degrading the detector energy resolution.

All nine RHESSI detectors are segmented and functioning. The detectors have suffered radiation damage from trapped and cosmic ray protons at very close to the rate predicted before launch. This only affects the measurements of narrow gamma-ray lines, and has no effect on the performance at soft or hard X-ray energies, to which the vast majority of flares are restricted. At gamma-ray energies, the result is a loss of energy resolution (now approximately 8.1 keV FWHM at 2.2 MeV versus 4.4 keV early in the mission) and a loss of active detector volume (about 15%, with larger changes in some detectors than others).

Three of the detectors, (#2, 5, and 6) occasionally demonstrate transient noise and current spikes so that their operating voltages have been gradually lowered. (Radiation damage may be responsible for this, but it allows the detectors to remain segmented and operable at lower voltages than would have been possible at launch). If this need to lower the voltage continues at the current rate, detectors 2 and 5 will be inoperable early in 2006, and this may finally trigger the decision to anneal. Annealing will bring all detectors to their original operating condition

3.2.2 Detector Annealing

The capability to remove nearly all the effects of radiation damage by annealing the detectors for several days at high temperature was designed into the RHESSI instrument. Not only will this reverse the ill effects on detector resolution and active volume, it will also vent to space accumulated water ice and other volatiles in the cryostat. This will improve both the reliability of the detectors and the performance of the cryocooler.

In this procedure, the cryocooler is run at low power (≥40 W to keep its own components cool) while Zener diodes heat the cold plate on which all nine detectors are mounted to raise their temperature to between 85 and 100° C. Cooling the detectors back down from the annealing temperature to their operating temperature of ~85 K is estimated to take 160-180 hrs based on the flight cool-down curve immediately following launch.

While this annealing process carries some inherent risk as with any first-time operation in space, we have demonstrated on a RHESSI spare detector in the lab that even seven such annealing thermal cycles have no ill effects. Furthermore, germanium detectors have been annealed in space on many occasions before. The germanium detector on Mars Odyssey has also been annealed successfully, and the 19 detectors on the SPI spectrometer of the European INTEGRAL mission have been annealed successfully five times to date. In principle, INTEGRAL's anneal is riskier than RHESSI's, since its detectors are sealed in pressurized modules whereas RHESSI's detectors are unsealed and in a cryostat that is now vented to space so that any contaminants can escape with each anneal cycle. Despite these precedents, we are choosing to be very conservative and delaying the first on-orbit anneal until it is necessary for the primary science. As long as all nine front segments are still working well and returning good hard X-ray flare science, we do not plan to anneal.

3.2.3 Imager

The RHESSI imager subsystem consists of nine rotating modulation collimators, each of which has a pair of widely separated grids. A metering structure maintains the relative twist alignment of the nine grid pairs. The imaging subsystem is inherently stable and has shown no evidence of change in grid alignment. Improved analysis techniques are refining the calibration of the grid parameters and locations (now known to submicron accuracy), the results of which are built into the software package and are applicable to all data acquired since launch.

3.2.4 Aspect System

There are three parts to the RHESSI aspect system -: the Solar Aspect System (SAS) to provide absolute pitch and yaw aspect with subarcsecond accuracy relative to Sun center; and two redundant side-looking star scanners, a CCD-based Roll Aspect System (RAS) and a Photomultiplier-Tube-based Roll Aspect System (PMTRAS), either of which provide the required knowledge of spacecraft roll angle.

The SAS consists of a set of 3 identical lens/sensor subsystems each of which focuses a narrow-bandwidth image of the solar disk onto a linear CCD array. No anomalies in its operation have been observed. During the first few months of the mission, the sensitivity of the SAS decreased, but it has now stabilized at ~60% of the original value, a level which provides an order of magnitude of sensitivity margin with no compromise in accuracy. The SAS also continues to provide accurate radius measurements (to 50 mas) for the study of global solar applications as discussed in section 2.1.10.

The PMT-RAS continues to provide the roll aspect knowledge upon which most of the solar imaging is based. Its response has remained stable since launch, easily meeting its 1 arcminute roll-angle requirement with a large margin in sensitivity.

The CCD-based Roll Angle System (CCD-RAS) has also proven to be stable and able to meet the 1 arcminute roll-angle requirement. CCD-RAS data are used to fill occasional gaps in the PMT-RAS coverage. In addition, by measuring the polar angle as well as the roll angle, the CCD-RAS can provide full aspect information with 10 arcseconds accuracy for non-solar targets such as the Crab nebula and the pulsar A0535+26.

3.3 RHESSI Software & Data Access

3.3.1 Software

One of the unique characteristics of RHESSI is that the telemetered data contains detailed information on each detected photon. This provides unprecedented flexibility in that decisions and tradeoffs associated with time resolution, energy resolution, imaging resolution and field of view, etc, can be made *ex post facto* to enable the analyst to make these decisions in the manner best suited to the scientific objectives and to the characteristics of the event under study. The RHESSI software fully supports this flexibility.

The basic RHESSI software package is fully developed and robust. Software workshop are held periodically to acquaint students and post-docs with both basic and advanced topics in data analysis. Imaging and spectroscopy analysis is now sufficiently robust that, in addition to the light curves that have been available since soon after launch, quicklook images and spectra now are automatically generated and posted online in near real time.

On going software (and calibration) developments are primarily directed in two directions. The first is to expand the boundaries over which RHESSI data can be well analyzed. For example, improved pile-up and deadtime corrections now support data analysis at exceptionally high count rates from intense flares; improved understanding of the low energy response supports the use of the 6 keV Fe-line complex for isolating the thermal component of flares; a specialized approach to superimposed epoch analysis (data 'stacking') now supports efficient analyses of very long time integrations; the off-axis instrument response has been extended to support observations well-away from the imaging axis for both non-solar and special purpose solar applications; a new demodulation algorithm to support high time resolution light curves is now in general use.

The second broad area of software development is the creation, display and analysis of 'visibilities'. A visibility is a calibrated, 'instrument-independent' intermediate data product that measures a single Fourier component of the source image. It is mathematically equivalent to the output of a single baseline of a radio interferometer. The option of using visibilities opens up new capabilities that were not anticipated when RHESSI was designed. For example, they improve spectral line imaging (e.g. the Fe line feature at 6.7 keV or the positron annihilation line at 511 kev) by cleanly removing the background and continuum contributions; they allow for the isolation and characterization of the albedo contribution to the observed X-ray flux; they support isolation of spatial changes on sub-second time scales (e.g. for footpoint simultaneity studies); accurate determination of source sizes, and additional improvements to high-rate dead-time and pileup corrections; and they provide a mechanism for separating the electron-bremsstrahlung and ion roles in continuum gamma-ray imaging.

One of the advantages of RHESSI"s photon-oriented database is that on-going improvements to the software and instrument calibration can be fully applied to all the data since the beginning of the mission.

3.3.1 Data sharing and accessibility

As discussed in section 3.3.3, the RHESSI observing summary, quick-look lightcurves, images and spectra, level-0 data files, and documentation are available through the RHESSI Data Center. In common with many other solar missions, analysis and display software (with both graphical and command-line interfaces) are fully integrated into SolarSoft. The same data and software resources are equally available to all RHESSI users. As discussed in section 2.3, a series of workshops has also been held to acquaint the scientific community with the best ways to access and analyze RHESSI data.

To achieve the full scientific potential of RHESSI data and to support the convenient integration of RHESSI data into studies initiated at other wavelength regimes, it is essential to have convenient access both to the data and to relevant software resources. Two steps have been taken to ensure this. First, the RHESSI software package includes flexible tools for accessing and integrating multiple data sets (for example by overlaying images). Coalignment is simplified since the absolute positions of RHESSI images are inherently known to arcsecond accuracy.

Second, we have established a comprehensive RHESSI Synoptic Data Archive at the GSFC Solar Data Analysis Center (SDAC) that allows quick and easy access to a broad range of observations for all the RHESSI flares. The archive contains image, spectral, and lightcurve data from a wide range of sources stored in standard formats for direct comparison with RHESSI data. The sources include SOHO (EIT 195 Å images and MDI magnetograms and white light images), TRACE EUV, UV, and white light images; Big Bear, Kanzelhohe, and Kiepenheuer Hα full-disk images; GOES-12 SXI full-Sun images and GOES 6-12 two-channel light curves with 3 s time resolution; Phoenix, OVSA, Nobeyama, and Nancay radio images & spectra.

Plans to enhance the Synoptic archive include:

- Increasing the cadence and time coverage of complementary data to encompass pre- and post-flare phases of RHESSI-observed events.
- Adding data from the following new missions as they become available after launch: STEREO SECCHI EUV and COR coronagraph images; Solar-B EIS imaging spectra, FPP vector magnetograms, and XRT coronal soft X-ray images; SOLIS FDP He 10830 and VSM longitudinal magnetograms, CORONAS-F/RESIK Bragg Crystal Spectrometer soft X-ray spectra. To this end we are partnering with pertinent STEREO and Solar-B PI teams to develop a database system that will integrate with the Synoptic archive. For example, we are collaborating on defining a common set of standard FITS keywords to form the basis of metadata to permit efficient joint searching of RHESSI and complementary datasets. In the case of STEREO, we are working on integrating the World Coordinate System (WCS) into the IDL mapping software to enable direct overlay of STEREO and RHESSI images.
- Evolving away from a centralized data archive to a distributed system that is incorporated into the Virtual Solar Observatory (VSO). A key challenge to integrating with the VSO is to link the IDL-based RHESSI data analysis system into the Web-based VSO. We have had success with using IDL sockets to connect with remote HTTP (and FTP) servers and

downloading data directly into the RHESSI analysis system. By programming IDL sockets to generate and process SOAP/XML requests, we will extend this capability to access the VSO.

3.4 Ground System

In 1999, a multi-mission operations facility was established at SSL to support the RHESSI and FAST missions. The joint facility, which now also supports CHIPS operations and was recently expanded in preparation for THEMIS mission support, includes the Mission Operations Center (MOC), the Science Operations Center (SOC), the Flight Dynamics Center (FDC), and the Berkeley Ground Station (BGS). A high degree of integration and automation combined with flexible system architecture provides a very reliable and cost effective state-of-the-art environment to perform all functions required to operate multiple spacecraft simultaneously.

3.4.1 Ground Stations

The primary ground station for the RHESSI mission is the Berkeley Ground Station (BGS) while the Wallops Ground Station (WGS) serves as a secondary data acquisition and command station. Additional ground stations at Santiago, Chile, and Weilheim, Germany, provide telemetry-only services. Passes at Wallops and Santiago are arranged via a PSLA, and those at Weilheim are provided on a best effort basis, outlined in an MOU. On average, RHESSI is supported 6 times per day by BGS with a mission total of nearly 7,000 passes. WGS supports typically 4 passes per day with a mission total of about 5,000 passes. The average daily data volume recovered at these two stations amounts to 13.5 Gbits. Passes at Santiago and Weilheim are requested during times of increased solar activity or as contingency. Overall telemetry recovery efficiency is generally ~99%.

The BGS consists of an 11-m parabolic reflector mounted on a pedestal with a three-axis drive system, and an S-band RF system. The figure of merit (G/T) for each of the receive channels (RHCP/LHCP) is typically 24.0 dB/K. Since its original installation in 1999, the system has been equipped with redundant control systems, RF exciters, front-end processors and 100 GBytes of local disk storage. Also, the control software has been refined. The system performs automated self-tests every 6 hours to detect any degradation in performance.

On June 9, 2002 a weakness in the gearbox design led to a failure of a bearing in the elevation gear train. Following a gearbox retrofit by the manufacturer in July 2002, the system has supported more than 7,000 passes for RHESSI, FAST and CHIPS with a total track time of 65,000 min. In October 2005 the system was re-inspected, and all gears were found to be in excellent working order.

The antenna pedestal requires some re-engineering work to reduce the risk from high winds. The system is equipped with a lock-down mechanism for the cross-elevation axis. This lock-down mechanism is designed to protect the gears of the cross-elevation drive system during high-wind conditions. However, the implementation of this mechanism which consists of two motors, four clutches, four worm gears, bellows and limit switches is unreliable and unusable in its current form. Repeated attempts by the antenna manufacturer to fix this system have failed. UCB will redesign and fabricate components in-house this year to reduce the risk.

3.4.2 Mission Operations Center

The RHESSI Mission Operations Center is part of a secure, shared state-of-the-art 900 ft^2 facility with a network of workstations for flight dynamics, spacecraft command and control, mission planning, command load generation and data trending. All mission critical workstations and servers are protected by redundant firewalls. In mid 2005 the ITOS command and control workstations for RHESSI (and FAST) were replaced with more modern Sun workstations, and match those that were installed for THEMIS. Operational software (SatTrack, ITOS, MPS, and SERS) is kept up-to-date and procedures are constantly refined to further improve reliability and data quality. New, sophisticated routing software for telemetry and command frames was installed and tested to support true multi-spacecraft operations. This enhancement to the MOC was implemented for THEMIS, but also improves management of data flows for the other missions. The facility, typically staffed during normal working hours only, performs automated pass supports, spacecraft and instrument state-of-health checks, and generation of all ephemeris and planning products in a lights-out mode. The AC power to the entire MOC and the BGS are protected by uninterruptible power supplies, which are backed up by a Diesel generator.

3.4.2.1 Normal Operations

RHESSI normal operations comprise mission planning functions, command load generation, real-time pass supports, spacecraft state-of-health monitoring, data trending, instrument configuration, and science data recovery and archiving. Generation of all ephemeris and mission planning products is based on two-line element sets that are downloaded from the Space-Track.org web site, quality checked and archived locally in a fully automated mode. BGS pass supports are scheduled autonomously, while those at other ground stations are scheduled interactively via email exchanges between the FOT and the respective scheduling offices. Spacecraft ATS loads cover 48 or 72 hours and are built by the FOT and uploaded to the spacecraft multiple times per week. Every six weeks, the spacecraft is re-spun from about 14.5 rpm to its nominal spin rate of 15 rpm. The FOT works closely with project scientists to determine the optimal instrument configuration, depending upon current solar activity.

During off-hours, on-call FOT members carry two-way pagers to receive yellow or red limit alerts, or notifications regarding any ground system anomalies. Required response times are 60 minutes or less. A number of web based tools were developed to allow FOT members, subsystem engineers and instrument scientists to monitor spacecraft and instrument performance remotely. In addition, a secure Web camera with pan/tilt/zoom capabilities was installed to observe subsystems remotely within the facility.

Several times per year the Sun passes near astronomical targets of interest, such as the Crab nebula. To allow for observations of such targets, the spacecraft is off-pointed from the Sun by up to 10°. While the RHESSI attitude control system was not originally designed to support such a mode, a number of flight software refinements and associated procedures were developed in collaboration with Spectrum Astro, the spacecraft bus provider, and then tested and refined to allow for this additional capability. Other software patches for the IDPU were provided by SSL engineers in order to optimize the data acquisition and shutter control algorithms. All flight software patches were carefully tested and verified on simulators prior to upload to the spacecraft.

Any spacecraft anomaly is assessed and resolved by an experienced team, consisting of operations team members, subsystem engineers, instrument scientists, the PI and the spacecraft contractor. Two potential problems related to the spacecraft CPU are known, namely a VxWorks sine function bug that could impact ACS functions during the infrequent off-pointing observations, and a potential RAD6000 EEPROM bit-flip problem which is monitored by reading out the checksum once per week. A contract on a time-and-materials basis is in place with Spectrum Astro to allow for sustaining engineering support.

3.4.2.2 Impact of Other Missions

Since RHESSI is operated from a multi-mission facility, its resources are shared with other missions. On one hand, this approach provides redundancy and reduces overall operations costs, but it also has the potential for conflicts and risks. The primary competitor for personnel resources is the THEMIS mission, to be launched in October of 2006. To mitigate associated risks, the composition of the multi-mission flight operations team has been carefully selected to provide sufficient resources to support RHESSI and THEMIS operations in parallel. The flight control team was increased from five to nine FTEs. Additionally, three new team members were hired to support flight dynamics, ground systems software development and database management. A number of students supplement the multi-mission team and assist full-time staff with data processing, data archiving and Web tool development.

The operations facility itself was expanded from 600 to 900 ft^2 to allow for installation of additional workstations. The Berkeley Ground Station will be able to handle the increased loading since THEMIS requires only five passes per day during normal operations for the entire constellation combined. Scheduling conflicts, in particular during the very active on-orbit check-out and constellation deployment phase, can be resolved by shifting conflicting RHESSI passes from Berkeley to the Weilheim ground station.

3.4.3 Science Operations Center

The RHESSI Science Operations Center (SOC) is located at SSL. Currently, it consists of 3 RAID servers, with ~4.6 Tbytes of data capacity, and 8 processors. RHESSI data in the form of telemetry packets are received in the SOC after every ground-station contact. They are processed by an automated IDL script to yield the level-0 data archive, which is the starting point for most RHESSI analyses. Level-0 files are mirrored at GSFC and ETH, in addition to being stored online at SSL. The original files received from the ground station are archived on CD-ROM. As of late August 2005, there are approximately 33000 level-0 data files, containing 2.24 Tbytes of data, for an average of approximately 1.8 Gbyte of data per day.

Other automated IDL procedures generate quick-look data containing the RHESSI Observing Summary, flare list, quick-look light curves, images and spectra. Instrument state-of-health (SOH) data are available in the telemetry packets, and long-term trend plots of SOH data are updated daily in the SOC. All user-documentation, current software, level-0 data, quick-look files and plots, and SOH data are available through the RHESSI Data Center website at UCB,

http://rhessidatacenter.ssl.berkeley.edu

and a mirrored version at Goddard

http://hesperia.gsfc.nasa.gov/rhessidatacenter/

4 Education/Public Outreach

RHESSI's education and public outreach (E/PO) efforts have supported teachers, science museum educators, and scientists in the design of educational programs that are connected intellectually to RHESSI science and are accessible for students and the general public. RHESSI E/PO materials have been presented in professional development workshops at every National Conference of the National Science Teachers Association (NSTA) since 1999. RHESSI's E/PO program has also been presented at various conferences of the AGU, AAS, HEAD, YOHKOH, SACNAS, AISES, ASP, and the OSS E/PO program.

4.1 *Accomplishments of the UCB E/PO Program: Formal Education*

RHESSI Lithograph

RHESSI detected a powerful Gamma Ray Burst (GRB) in late 2002. In 2003, the E/PO team at the University of California at Berkeley (UCB) developed a lithograph called "Serendipity: RHESSI Spies a Gamma-Ray Burst" to highlight this special observation and the new knowledge about GRBs that it generated. The front side of the lithograh features artwork from the Science Visualization Lab at the Goddard Space Flight Center (GSFC) showing the RHESSI spacecraft observing the Sun as the GRB goes off. The reverse side contains a brief discussion of GRBs and how they are thought to be the results of hypernova explosions of super massive stars before their cores collapse to form black holes. The lithograph was submitted for official NASA Educational Product Review in 2004 and was well received by the review panel and recommended for broad distribution with no revisions. The lithograph has since been distributed through teacher workshops and at national conferences of both scientists and teachers, such as the annual meetings of the American Astronomical Society (AAS) and the NSTA. It is also available in PDF format on the UCB RHESSI E/PO Website.

Student Observation Network

In FY04, the UCB RHESSI E/PO team worked with RHESSI scientists at UCB's Space Sciences Laboratory (SSL) and GSFC, and the Sun-Earth Connection Education Forum (SECEF) to integrate RHESSI data into the Tracking a Solar Storm module of NASA's Student Observation Network (SON, http://son.nasa.gov). SON is a program that provides teachers with hands-on activities for the classroom and a website for students and teachers to use for comparing their own observations with those of actual NASA satellite missions. Quick plots of RHESSI light curves, images, and spectrograms are all included in the website. The UCB RHESSI E/PO team wrote tutorial pages so that the data could be understood and used by students.

Exploring Magnetism – Educators' Guide

The RHESSI E/PO team contributed to development of a teacher's guide, 'Exploring Magnetism' for grades 6-9. The guide was submitted to the NASA Educational Product Review in FY04, was given high marks, and is recommended for distribution in teacher workshops. The guide was presented at the annual IGES Earth and Space Science products workshop, which brings together NASA educators from NASA Educator Resource Centers (ERC) and the Aerospace Education Services Program (AESP) from across the nation to be trained on the newest and best reviewed NASA educational products. It is currently distributed in teacher workshops given by ERC and AESP personnel, and by members of the RHESSI E/PO team; it is also available on the Web in HTML and PDF formats at the following location:

http://cse.ssl.berkeley.edu/ExploringMagnetism

Exploring Magnetism in Solar Flares

In FY05, RHESSI E/PO developed a teachers' guide for grades 8-12 in the Exploring Magnetism series focusing on Solar Flares. This guide features 4 activities about magnetism on the Sun's surface leading to sunspots and Solar Flares. Students learn about these concepts by doing hands-on experiments, watching a lecture, reading an essay, using real data from the RHESSI spacecraft to make measurements of an actual Solar Flare event, and holding a mock science conference to discuss their findings. The concept for this guide was developed with GSFC RHESSI scientist, Gordon Holman, who also provided the data used in the guide. The guide was developed with and reviewed by several classroom educators. It was also pilot tested by a California middle school teacher. The guide was submitted for NASA Educational Product Review in FY05 and was given high marks. It has been recommended for distribution in teacher workshops with minor revisions. Revisions are currently underway and when completed the guide will be sent in for the new NASA Communications Review so that it can be distributed by NASA. Following that review we will do a print run of the guide and present it at the annual IGES Earth and Space Science products workshop. The guide will be used in teacher professional development workshops across the country. The guide is also available online in HTML and PDF formats.

(http://cse.ssl.berkeley.edu/ExploringMagnetism/SolarFlares)

Teacher PD Workshops - Pipeline Diversity

Space science is a topic that excites and interests students like no other in the science curriculum. However, many teachers are reluctant to teach the subject due to a lack of strong instructional materials and little confidence in their content knowledge. The RHESSI E/PO team provides multiple opportunities for teacher professional development throughout the year. Workshops are held in a variety of formats and venues. We give short 1-4 hour workshops at conferences of organizations such as the NSTA, the California Science Teachers Association (CSTA), and the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS). We also hold 1-2 day workshops at SSL for teachers in northern California, and educators from across the nation who are traveling to the UCB Lawrence Hall of Science (LHS) for training in the Great Explorations in Math and Science (GEMS) program. In many of our workshops, RHESSI educational materials are presented along with other NASA educational materials in the SEC theme. The costs, planning, and logistics of the workshops are often shared with other SEGway missions and SECEF. In FY03, RHESSI was the primary mission for four workshops and was a secondary mission for seven. In FY04, RHESSI was the primary mission again for four workshops and was a secondary mission for another four. With an average of 20 teachers attending each workshop, and assuming each teacher works with about 100 students on average, then we are reaching approximately 20,000 students per year. For the extended mission, we will continue to distribute RHESSI materials through teacher workshops and will increase the frequency of workshops. The main goal of training these teachers is to provide useful, interesting, and teacher-friendly guides and lesson plans such that the teachers will take the excitement about earth and space science back to the classroom where they will inspire their students to continue studying science, technology, engineering, and/or mathematics (STEM) topics, giving them the basis to go on to a career in a STEM field.

Our E/PO team, N. Craig and B. Méndez, have given workshops and invited talks in the following conferences which directly serve the teacher and educators of underserved and diverse communities:

SACNAS (Society of Advancement of Chicanos and Native Americans) conference Oct 03 and Oct 04; AISES (American Indian Science and Engineer Society) teacher workshop in Nov 04; NEVADA Middle school Teachers through the GEMS program Jun 05 (underserved rural groups) and the Bay Mills Tribal College Space/Earth Science Teacher workshop Aug 05.

4.2 Informal Education

SEC Public Events and RHESSI Web Site

The UCB E/PO team has participated in Sun-Earth Day events organized by SECEF. We have contributed the RHESSI GRB Lithographs and RHESSI Discover the Solar Cycle Flyers to Sun-Earth Day folders that are distributed to thousands of educators each year. We have also participated in events at local museums programmed around the Sun-Earth Day theme of the year. In FY04, we participated as roving scientists at the Exploratorium in San Francisco and LHS in Berkeley during their live web cast of the Venus Transit. In FY05, we were again roving scientists for the Ancient Observatories: Timeless Knowledge events at the Exploratorium. The first was a live web cast from Chaco Canyon during the Winter Solstice and the second was a live web cast from Chichén Itzá during the Spring '05 Equinox. The UCB RHESSI E/PO website is updated regularly with news and events related to the RHESSI mission and with new classroom lessons. During FY04 the website was also updated with a new section for RHESSI images and movies.

http://cse.ssl.berkeley.edu/hessi_epo

Evaluation

Cornerstone Evaluation Associates, Inc. has been evaluating education programs for 12 years and is a client-centered research firm specializing in program evaluation in the areas of education, human services, health care, government, the arts, business, and web site assessment. They provide cost-effective technical expertise in collecting, managing, and interpreting a wide range of quantitative and qualitative data specific to their clients' programs. They use this critical information to assist their clients in making data-driven decisions that ensure the quality and effectiveness of their programs and projects. Dr. Allyson Walker of Cornerstone is the evaluator of our THEMIS and WISE Missions, and her previous work is being leveraged for this proposal. Due to the limited budget of this proposal, the E/PO team will use the teacher workshop evaluation questionnaires Cornerstone has developed for THEMIS for each of the workshops/seminars, and Dr. Walker will analyze the questionnaires and provide a final report.

Cost

Dr. Craig will be compensated minimally for coordinating and managing the administrative elements of the E/PO program. Dr. Méndez will receive 2 months salary/year for updating and maintaining the RHESSI E/PO web pages, and for planning and conducting 2-3 teacher workshops per year that will include RHESSI E/PO in the agenda. Materials costs for teacher workshops held at SSL and at National Conventions will be leveraged from SEGway and CSE@SSL programs. Travel costs for Dr. Méndez to present one workshop at a national science teachers' conference (NSTA, SACNAS, CSTA) and one at AGU (local) will be covered by this E/PO program. These workshops may also contain content about our other SEC Mission E/PO programs and we will be leveraging from their resources.

Plans for FY06 and FY07

The RHESSI Mission E/PO program participates in the existing space science teacher professional development programs that take place at SSL at UCB. These 1-day and 2-day workshops are free to educators and teach inquiry-based science with activities about magnetism, solar science, and lectures about the Sun, flares and the solar cycle. The workshops take place throughout the year and often they are planned to coincide with training workshops put on by UCB's LHS GEMS project. NASA materials are handed out for free to the teachers including GEMS teachers' guides, lithographs, posters, and other learning tools. Continuing Education Units are offered for attendance at the two-day workshops through Cal State East Bay.

The E/PO program is well aligned with Science Mission Directorate goals of enhancing the National formal science education system and to contribute to the public's broad understanding of science, mathematics and technology. We will continue to offer our programs for FY08 through FY10 using the RHESSI specific materials and other related SEC Mission resources developed either at SSL or by the EPO programs of other SEC mission.

4.3 E/PO Plans at Goddard

In order to increase the impact of our very limited EPO funds (~$10,000 per year), we have chosen to partner with other S^3C missions that have a Goddard presence - SOHO, Polar, Geotail, and Wind – and with the Sun Earth Connection Education Forum (SECEF) at Goddard. The upcoming STEREO and SDO missions have agreed to join this partnership as they enter their MO&DA phases. We plan to develop cross-mission themes and EPO programs and products from the individual instrument teams. By working across missions, we eliminate duplication of effort, leverage award-winning resources already in operation, and increase the impact of limited EPO funds for any one individual mission. In addition, our approach ensures a sustainable EPO program that emphasizes overall S^3C science understanding and how each mission contributes to this integrated picture. In this manner, as older missions fade, new missions (data, science results, and funding) can take their place and add their chapters to the ever growing story of S^3C science.

This consortium of missions will support the SECEF award-winning EPO programs that meet both science and pedagogy standards and are reviewed by NASA. SECEF will incorporate our mission science results into its larger programs as outlined in the table below.

We will continue to support the Goddard SUNBEAMS program (Students United with NASA Becoming Enthusiastic About Math and Science) with mission materials and the mentoring of sixth-grade teachers from the District of Columbia Public School System.

We will use SECEF's well-developed network of end users to enhance the reach and impact of these programs. These end users include museums and science centers; national parks; Girl Scouts USA; Amateur Astronomers (e.g. Astronomical League, AAVSO), and numerous minority and professional groups such as AGU, AAS, La Raza, World Hope, National Society of Black Engineers.

The educational products and programs produced by this consortium will be reviewed annually for science accuracy and currency, and for pedagogy. This will be done as part of the SECEF annual review process through its membership in the NASA Space Science Education Support Network. We will leverage these existing NASA evaluation programs to ensure that our education products and programs are engaging, effective, and appropriate for the target audiences.

SECEF Program	How it will be used	Impact each year
Sun Earth Day 2006 and beyond	Use mission data to highlight the Sun and eclipses	10s of Millions
Student Observation Network (SON)	Develop learning modules based on mission science	>10,000 students
Space Weather Center	Build a museum kiosk on solar phenomena	>10,000 museum goers >100 teachers in exhibit-based workshops

5 Appendices

5.1 Budget

The RHESSI budget, submitted on a separate spreadsheet, includes as in-kind funding the current RHESSI GI program in FY 06 and FY 07 awarded after the last Senior Review.

We, together with the ACE, SoHO, TRACE, and Wind missions, are requesting a Solar Eruptive Events GI program in this Senior Review at a total of $1.5 million/year (see section 2.2.7). All of the GIs would be selected by NASA Headquarters, but we are showing this total amount in the "Breakdown for Optimal Budget" in Table V of the spreadsheet.

We are also showing in this optimal budget a constant level of funding for the Science Center Functions and Science Data Analysis, increased from the current level only by inflation of 3%/year.

5.2 Acronym List

AAS	American Astronomical Society
ACS	Attitude Control System
AESP	Aerospace Education Services Program.
AGU	American Geophysical Union
AISES	American Indian Science and Engineer Society
ATS	Absolute Time Sequence
AU	Astronomical Unit
BGS	Berkeley Ground Station
CD-ROM	Compact Disk – Read Only Memory
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer
CSE@SSL	Center for Science Education at Space Sciences Laboratory
CSTA	California Science teachers Association
ERC	Educator Resource Center
EEPROM	electrically erasable programmable read-only memory
ETH	Eidgenossische Technische Hochschule, Zurich, Switzeerland
EVA	Extra-Vehicular Activity
FAST	Fast Auroral SnapshoT
FDC	Flight Dynamics Center
FIP	First Ionization Potential
FITS	Flexible Image Transport System
FOT	Flight Operations Team
FoV	Field of View
FWHM	Full Width at Half Maximum
GDS	Ground Data System
Ge	Germanium
GED	Germanium Detector
GEMS	Great Explorations in Math and Science
GSFC	Goddard Space Flight Center
GRB	Gamma Ray Burst
HEAD	High Energy Astrophysics Division
IDL	Interactive Data Language
IDPU	Instrument Data Processing Unit
IGES	Institute for Global Environmental Strategies
IPM	Interplanetary Medium
ITOS	Integrated Test and Operations System
KSC	Kennedy Space Center
LHCP	Left-Handed Circular Polarization
LHS	Lawrence Hall of Science
mas	milli-arcsecond

MOC	Mission Operations Center
MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NSTA	National Science Teacher Association
OCA	Orbital Carrier Aircraft
OIG	Orbital Information Group
PD	Professional Development
PMTRAS	Photomultiplier Roll Angle System
PSLA	Project Service Level Agreement
RAS	Roll Angle System
RF	Radio Frequency
RHCP	Right-Handed Circular Polarization
RHESSI	Reuven **R**amaty **H**igh **E**nergy **S**olar **S**pectroscopic **I**mager
SAA	South Atlantic Anomaly
SACNAS	Society for Advancement of Chicanos and Native Americans in Science
SAS	Solar Aspect System
SECEF	Sun Earth Connection Education Forum
SEGway	Science Education Gateway
SEP	Solar Energetic Particles
SERS	Spacecraft Emergency Response System
SOC	Science Operations Center
SOH	State-Of-Health
SSL	Space Science Laboratory
STEM	Science, technology, engineering, and mathematics
THEMIS	Time History of Events and Macroscale Interactions during Substorms
UCB	University of California at Berkeley
UT	Universal Time
WGS	Wallops Ground Station
WISE	Wide Field Infrared Survey Explorer
Yohkoh	Name of a Japanese Satellite observing the Sun