Senior Review 2003 Proposal for the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) Mission

Robert Lin, Principal Investigator and presenter, University of California, Berkeley (UCB)

Brian Dennis, Project Scientist; Richard Schwartz, Goddard Space Flight Center

Manfred Bester, Mission Operations Manager, UCB

Nahide Craig, E/PO Manager, UCB

David Smith, Sam Krucker, Jim McTiernan, Martin Fivian, Gordon Hurford, Hugh Hudson, UCB

Table of Contents

Executive Summary

1. Science
- **1.a. Introduction**
- **1.b. Electron Acceleration and Energy Release in Solar Flares**
- **1.c. Ion Acceleration and Gamma-ray Line Emission**
- **1.d. Thermal Energy Release in Flares**
- **1.e. Flare/CME Associations**
- **1. f. Microflares and the Quiet Sun**
- **1.g. Solar Energetic Particles (SEPs)**
- **1.h. Other RHESSI Science**
- **1.i. Context Observations and Collaborations**
- **1.j. RHESSI Scientific Effectiveness**
- **1.k. Proposed Extended Mission Program**
- **1.l. Minimal and Optimal Scenarios**

2.a. Technical
- **2.a.1 Observatory Status**
- **2.a.2. Instrument Status**
- **2.a.3. Mission Operations and Data Analysis**
- **2.a.4. RHESSI Contributions to a Distributed Environment for Accessing and Integrating SEC Data**
- **2.a.5. References**

2.b. Budget

3. Education and Public Outreach

Appendix A. Budget

Appendix B. Acronyms

Executive Summary

RHESSI, the sixth NASA Small Explorer (SMEX) mission, is designed to investigate particle acceleration and energy release in solar flares, through imaging and spectroscopy of hard X-ray/gamma-ray continua emitted by energetic electrons, and of gamma-ray lines produced by energetic ions. The single instrument consists of an imager, made up of nine bi-grid rotating modulation collimators (RMCs), in front of a spectrometer with nine cryogenically-cooled germanium detectors (GeDs), one behind each RMC. It provides the first high resolution hard X-ray imaging spectroscopy, the first high-resolution gamma-ray line spectroscopy, and the first imaging above 100 keV including the first imaging of gamma-ray lines. The spatial resolution is as fine as 2.3 arcsec with a full-Sun 1° field of view, and the spectral resolution is ~1-10 keV FWHM over the energy range from soft X-rays (3 keV) to gamma-rays (17 MeV).

RHESSI was launched on February 5, 2002, and has been operating successfully since. Over 8000 flares with detectable emission above 12 keV (>~600 above 25 keV) have been observed since then, including one gamma-ray line flare. Even more microflares have been detected above 3 keV. All the data has been made immediately available to the scientific community, together with the analysis software.

Some of the new results include:

* The first hard X-ray imaging spectroscopy of flares from thermal to non-thermal energies.

*The first flare high resolution X-ray spectroscopy that resolves the thermal-nonthermal energy transition, showing that the non-thermal power law extends down to <~10 keV and implying an energy content in the accelerated electrons at least several times greater than previous >~20 keV estimates.

* The discovery that flare non-thermal X-ray spectra often have a relatively sharp downward break, usually in the range ~30-50 keV for small flares but as high as >100 keV in large flares.

* The first high resolution flare gamma-ray line spectrum, measuring red-shifts of a fraction of a percent, implying directivity of the energetic ions as well as non-radial magnetic fields.

* The first imaging of flare gamma-ray lines, showing that the centroids of the energetic ion and electron sources are separated by ~20 arcsec.

* The first detection of continuous glow from the Sun at 3-15 keV energies, with frequent microflaring. The microflares have non-thermal power-law spectra indicating substantial energy in accelerated electrons.

* The detection of a non-thermal coronal source with a double-power law spectrum during the onset of a large flare. This source requires a significant energy release into the corona prior to the impulsive phase.

* The detection of 3-15 keV X-ray emission from solar type III radio bursts, sometimes with no obvious relation to flares.

*The discovery of strong polarization in a cosmic gamma-ray burst, implying strong coherent magnetic fields in the source.

RHESSI is presently in its prime mission - two years of operation (to March ‘04) with a third year of data analysis (to March ’05). We request funding for an extended mission of at least another three years (to end of FY ’07).

There are compelling scientific reasons for a mission extension of at least three years, through FY’07. The RHESSI mission was planned for launch in July 2000, near the predicted peak of the ~11-year solar activity cycle, but was delayed nineteen months by a vibration test catastrophe and many launch vehicle delays. By launch, the flare rate had decreased and it continues to fall, so to obtain the same number of >25 keV hard X-ray flares as in a 2000 launch two-year prime mission will require at least a ~3 year extended mission.

More important, since large flares and large Solar Energetic Particle (SEP) events often occur in the descending phase of the solar cycle, the extended mission will allow RHESSI to capture ~6-8 gamma-ray line flares and 9-12 SEP events, on average. A major scientific objective is to observe a gamma-ray line flare accompanied by an associated large SEP event (like the August 1972 flares), so the flare-accelerated ion composition and spectra (also electrons) inferred from gamma-ray measurements by RHESSI could be compared to those measured for SEPs by ACE, Wind, SOHO, Ulysses, and STEREO (after 2005). RHESSI’s imaging of the energetic ion and electron populations at the Sun could be compared with STEREO and Ulysses measurements at widely separated longitudes/latitudes. This will clarify the relationship between SEP acceleration by shocks driven by fast CMEs and by flares.

RHESSI has >14-500 times more effective area than any previous solar intrument at energies from ~3 to 15 keV. It will be able to probe down to smaller and smaller microflares as solar activity declines, to address the question of their contribution to coronal heating. RHESSI imaging spectroscopy of the quiet Sun (when no obvious microflares are seen) will reveal insights on the nature of the quiet Sun emission, non-thermal or thermal, that might be related to unresolved microflares of even smaller size.

In summary, we believe an extended mission through FY ’07 is needed to achieve the baseline mission originally proposed, and to take advantage of the capabilities of RHESSI and of new missions such as STEREO and Solar B. RHESSI was designed with no expendables and we expect that it will continue to operate well for many years to come.

1. Science

1.a. Introduction

The processes of particle acceleration and impulsive energy release occur in active cosmic plasmas at diverse sites throughout the universe, ranging from planetary magnetospheres to active galactic nuclei. The understanding of these processes is a major Sun-Earth Connections (SEC) objective (Table 1) and also a major astrophysics objective. The Sun constitutes an unparalleled laboratory for investigating these processes. Its proximity allows measurements over the entire electromagnetic spectrum to be made on physically relevant scales. Furthermore, the system as a whole can be studied, and the escaping energetic particles and plasma can be sampled directly.

The primary scientific objective of the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) mission is to investigate particle acceleration and explosive energy release in the magnetized plasmas at the Sun. The Sun is the most energetic particle accelerator in the solar system, accelerating ions up to tens of GeV and electrons to tens of MeV in solar flares and in fast Coronal Mass Ejections (CMEs). Solar flares are the most powerful explosions, releasing up to 10^{32}-10^{33} ergs in ~10-1000s. The flare-accelerated ~10-100 keV electrons (and sometimes >~1 MeV/nucleon ions) appear to contain a significant fraction, ~10-50%, of this energy, indicating that the particle acceleration and energy release processes are intimately linked. How the Sun releases this energy, presumably stored in the magnetic fields of the corona, and how it rapidly accelerates electrons and ions with such high efficiency, and to such high energies, is presently unknown.

High-energy emissions are the most direct signature of the acceleration of electrons, protons and heavier ions in solar flares. Bursts of bremsstrahlung hard X-rays emitted by accelerated electrons colliding with the ambient solar atmosphere, are the most common signature of the impulsive phase of a solar flare (Figure 1). Hot (multi-million ºK) thermal flare plasmas also emit bremsstrahlung X-rays. In large flares, collisions of accelerated ions with the atmosphere result in a complex spectrum of narrow and broad gamma-ray lines (Figure 2). RHESSI provides, for the first time, high resolution imaging and spectroscopy of all these emissions, from soft X-rays (3 keV) to gamma-rays (17 MeV).

Experimental Details

A detailed description of the RHESSI mission and instrument is given in the first six papers of November 2002 issue of Solar Physics, v. 210, p. 3-124. At hard X-ray and gamma-ray energies, unlike soft X-rays, EUV, and longer wavelength emissions, focusing optics are not feasible. The only viable method of obtaining arcsec-class images in hard X-rays and gamma-rays within the SMEX constraints is with Fourier-transform imaging, similar to that used in the pioneering Hinotori rotating modulation collimator (Makashima et al., 1977) and Yohkoh Hard X-ray Telescope (HXT) (Kosugi et al., 1991).

The RHESSI instrument (Figure 3 and Table 2) 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 of ~2 arcsec and imaging up to gamma-ray energies (Figure 4a). Behind each RMC is a segmented germanium detector (GeD) to detect photons from 3 keV to 17 MeV. The GeDs are cooled to ~75 K by a space-qualified long-life mechanical cryocooler, to achieve the highest spectral resolution (Figure 4b) of any presently available gamma-ray detector.

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 ($>10^7$) of flare intensities to be handled without instrument saturation.

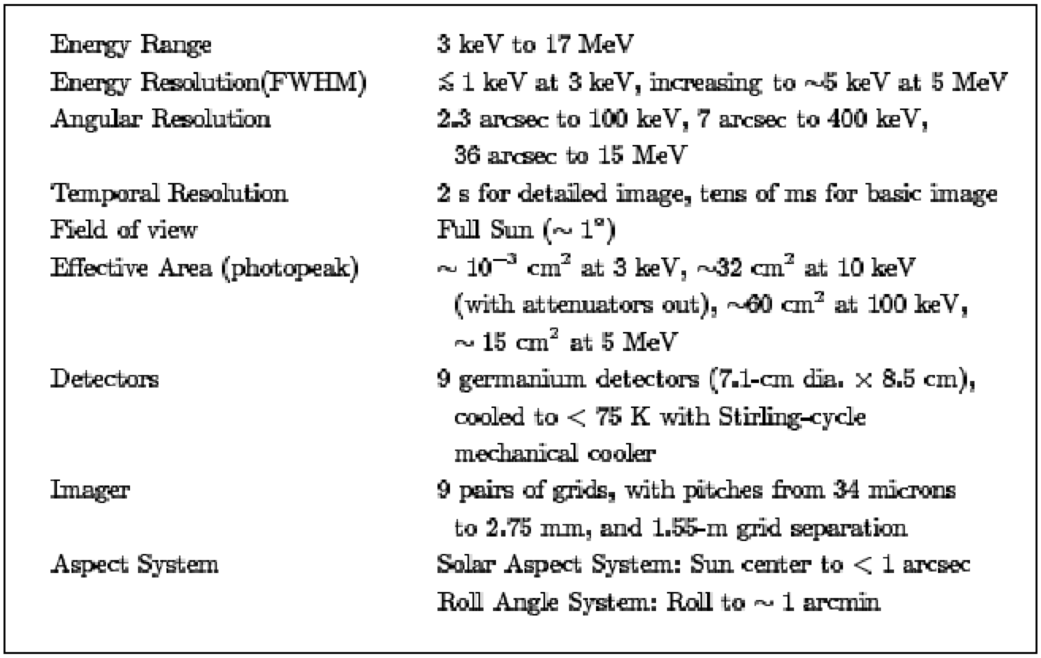
The spin-stabilized (~15 rpm) spacecraft is Sun-pointing to within ~0.2° and operates autonomously, with the data for every photon stored in a solid-state memory (sized to handle the largest flare) and telemetered to the ground. The mission is operated from Berkeley using a dedicated 11-m antenna for telemetry reception and command uplinks. All the data are made immediately available to the scientific community, together with the analysis software (Schwartz et al., 2002).

RHESSI was launched on February 5, 2002, into a nearly circular, 38° inclination, 600-km altitude orbit and began continuous observations a week later. Over 8000 flares with detectable emission above 12 keV (>~600 above 25 keV) have been observed since then, including a gamma-ray line flare. Even more microflares have been detected above 3 keV.

The RHESSI observations have tremendous potential because: 1) they combine high spatial and high spectral resolution; 2) they span an enormous energy range from soft X-rays (~3 keV) emitted by hot thermal plasmas, through hard X-ray/gamma-ray continuum emitted by accelerated electrons, to gamma-ray lines emitted by accelerated ions; 3) information on every detected photon is 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. Early results are contained in the last 15 papers in the November 2002 issue of Solar Physics, v. 210, p.215-456. A issue of ApJ Letters (in preparation) is devoted to the gamma-ray line flare of 23 July 2002 .

Sun-Earth Connection Science Objectives	Sun-Earth Connection Research Focus Areas	RHESSI contribution
Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.	- Understand the transport of energy and matter within the Sun, the solar atmosphere, and into the solar wind. - Determine the evolution of the heliosphere and its interaction with the galaxy. - Understand the response of magnetospheres and atmospheres to external and internal drivers.	a) Observe energy release and particle acceleration in flares, heating and transport of flare plasma, and flare/CME & flare/ SEP connection b) Observe microflares contribution to coronal heating c) Trace coronal/interplanetary magnetic field topology with energetic electrons/X-ray emission/type III radio burst. d) Measure flare X-ray input for ionization of Earth's atmosphere
Explore the fundamental physical processes of plasma systems in the solar system.	- Discover how magnetic fields are created and develop and how charged particles are accelerated. -Understand coupling across multiple scale lengths and its generality in plasma systems.	a) Observe particle acceleration and energy release in flares, likely due to reconnection of magnetic fields. b) Observe diverse acceleration in type III electrons, flares, microflares, cosmic gamma-ray bursts, Crab nebula, Earth's magnetosphere c) Study flare/CME & flare/ SEP connection
Define the origins and societal impacts of variability in the Sun-Earth Connection.	- Develop the capability to predict solar activity and the evolution of solar disturbances as they propagate in the heliosphere and affect the Earth -Develop the capability to specify and predict changes to the Earth's radiation environment, ionosphere, & upper atmosphere.	(a) Enhance understanding of flare particle acceleration and energy release, and flare/CME & flare/ SEP connection, leading eventually to predictive capability (b) Accurate measurement of energetic flare emissions incident on Earth's upper atmosphere (c) Study of new radiation belts created from solar energetic particles through their gamma-ray emission

Table 1. *RHESSI contribution (right column) to achieving Sun-Earth Connection (SEC) Science Objectives and Research Focus Areas*



Energy Range	3 keV to 17 MeV
Energy Resolution(FWHM)	$\lesssim 1$ keV at 3 keV, increasing to ~5 keV at 5 MeV
Angular Resolution	2.3 arcsec to 100 keV, 7 arcsec to 400 keV, 36 arcsec to 15 MeV
Temporal Resolution	2 s for detailed image, tens of ms for basic image
Field of view	Full Sun (~ 1°)
Effective Area (photopeak)	$\sim 10^{-3}$ cm^2 at 3 keV, ~32 cm^2 at 10 keV (with attenuators out), ~60 cm^2 at 100 keV, ~ 15 cm^2 at 5 MeV
Detectors	9 germanium detectors (7.1-cm dia. × 8.5 cm), cooled to < 75 K with Stirling-cycle mechanical cooler
Imager	9 pairs of grids, with pitches from 34 microns to 2.75 mm, and 1.55-m grid separation
Aspect System	Solar Aspect System: Sun center to < 1 arcsec Roll Angle System: Roll to ~ 1 arcmin

Table 2. *RHESSI Instrument Characteristics*

Table 3 summarizes these results. Here we describe the research in more detail, including areas not yet in papers.

1.b. Electron Acceleration and Energy Release in Solar Flares

The Flare of February 20, 2002

Figure 5 shows one of the first examples of RHESSI imaging spectroscopy, for the 20 Feb '02 flare. Images are shown in 2 keV bands from 12 to 26 keV, and then broader bands up to 80 keV. The image evolves from an elongated single source at low energies to two footpoints at high energies. Figure 6 shows high-resolution (~1 keV FWHM) X-ray spectra for the flare, showing the thermal (~10 million K) component dominating at low energies, with a power-law component dominating at high energies.

If the electrons producing the power-law X-rays have energies, $E_{e,}$ much greater than the average thermal energy, kT, of the ambient gas, then essentially all of the electron energy will be lost to Coulomb collisions, with only a tiny fraction $\sim 10^{-5}$ lost to bremsstrahlung. For this non-thermal situation, it was found that to produce the hard X-ray fluxes of many flares, the energy in accelerated >20 keV electrons must be comparable to the total flare radiative and mechanical output (Lin and Hudson 1976). Thus, the acceleration of electrons to tens of keV may be the most direct consequence of the basic flare-energy release process. Earlier solar hard X-ray instruments flown in space had relatively poor energy resolution (Figure 4b); most were designed with a thick entrance window to eliminate photons below ~20 or 25 keV to avoid pile-up and saturation from low energy thermal photons (Kane and Anderson, 1970). Thus, previous estimates of the total energy in electrons referred to electrons above 20 or 25 keV. RHESSI is the first space experiment capable of accurately measuring the flare spectrum from thermal to non-thermal energies. As Figure 6 shows, the non-thermal power-law spectrum extends down to ~10 keV, implying that the energy contained in the electrons is at least several times greater than estimated previously. In fact, since we are now interested in the energy loss of electrons for which E_e is only several times kT, the Coulomb losses need to be evaluated more carefully. This has been addressed by Emslie et al (2003).

The precise RHESSI observations (Figure 6) clearly show that the non-thermal spectrum is a double-power-law, with a relatively sharp downward break at ~40 keV; a similar break was first seen in the high resolution flare spectrum obtained by a balloon-borne germanium instrument (Lin et al 1981). What is the cause of this break? Several possible interpretations have been suggested: a break in the parent electron spectrum due to the acceleration process; it could result from the fact that the higher energy electrons can penetrate to the neutral chromosphere while the lower energy electrons stop in the fully ionized corona where their Coulomb energy loss rate is ~3 times higher (Brown et al 2002); or it might be due to beam-plasma return current effects (Gordovskyy and Zharkova, 2003); or some as yet unknown process. More detailed analysis will be required to get to the origin of this break.

Density Model of the Flaring Chromosphere

As an example of the type of analysis that can be carried out with the precision RHESSI measurements, Brown et al (2002) and Aschwanden et al (2002) were able to obtain chromospheric density and height measurements in a solar flare. Thanks to the high energy resolution and angular resolution, very accurate altitude measurements of HXR footpoints as a function of energy were obtained (Figure 7). Since the range of an electron depends on its energy, these measurements implied a chromospheric density model which (1) corroborates the extended (spicular) chromosphere models inferred from sub-mm radio observations, and (2) refutes standard hydrostatic models.

The X4.8 Flare of July 23, 2002

The most powerful flare and the first gamma-ray line flare (the only one to date) observed by RHESSI is the X4.8 flare of 23 July 2002 located at S13E72. It has yielded a harvest of revolutionary results for RHESSI, which have been submitted for a special issue of Astrophysical Journal Letters (see Table 3b).

The flare hard X-ray and gamma-ray emission (Figure 8) divide naturally into an rise phase (~0018 to ~0027UT) dominated by a coronal hard X-ray source that appears to be non-thermal, a main impulsive phase (~0027 to ~0043 UT) with continuum and gamma-ray line emission extending up to >~7 MeV, and a decay phase (>~0043UT) dominated by a superhot (~40 million° K) thermal hard X-ray source.

During the rise the hard X-ray emission above 10 keV is concentrated in a coronal source with no counterpart observed in TRACE 195 A, SoHO MDI visible or Halpha images (Lin et al 2003). The hard X-ray spectrum above ~10 keV fits a double-power-law spectral shape (Holman et al 2003).

Assuming thick target emission from energetic electrons colliding with a cold ambient medium (E_e>>kT), the energy deposited by the electrons above ~10 keV, integrated over time from the rise to ~0026UT, is $>\sim 4\times10^{32}$ ergs. But by fitting the observed spectrum to a thermal component plus a power-law non-thermal component and choosing the highest possible low-energy cutoff to the non-thermal electron spectrum that is consistent with the X-ray data (~20 keV), Holman et al find a lower limit to the total energy input in accelerated electrons of~2×10^{31} ergs. Thus, very substantial energy release and acceleration of electrons occurs high in the corona prior to the impulsive phase.

At the beginning of the impulsive phase, ~0027UT, there is an abrupt change in the character of the hard X-ray emission, to strong footpoint emission (Krucker et al 2003) together with a (super)hot thermal source in the corona (Figure 9). Three footpoints are observed - a north, a south, and a middle footpoint - each with a chromospheric counterpart observed in Hα and TRACE. Their spectra, although still double-power-laws, are much harder than for the rise phase coronal source.

During the first (and most intense) burst, the north footpoint rapidly moves northeast, roughly parallel to the magnetic neutral line, while the south footpoint stays relatively stationary, so the separation between them increases with time (Figure 10). These X-ray fluxes and spectra of two footpoints show the same temporal variations, suggesting that they are at opposite ends of the same magnetic loop. The motions generally are most rapid when the X-ray flux is largest, as might be expected if magnetic reconnection is forming the loops connecting the footpoints.

Of particular interest for flare energy release are the recent simulations of collisionless reconnection in 3D that indicate electron acceleration is a major consequence of the process (Drake et al 2003), and the observation by the Wind spacecraft of electrons accelerated to hundreds of keV energy in the magnetic reconnection ion diffusion region in the distant magnetotail (Oieroset et al, 2002).

Flare-associated Coronal Hard X-ray Sources

Stereoscopic (multi-spacecraft) observations of large solar flares during the last solar cycle had indicated the existence of such sources at heights up to 160000 km in the corona. However, since suitable imaging observations were not available at that time, very little was known about the physical characteristics of these sources. With the launch of RHESSI it has become possible to study these flare associated coronal hard X-ray sources in detail. Preliminary analysis shows the following: (1) Gradual hard X-ray sources are present in the corona at heights up to 27,000 km above the photosphere even in relatively small solar flares. (2) Impulsive hard X-ray sources in large flares occur at coronal heights up to 50000 km and have non-thermal photon spectra. (3) In the early decay phase of some flares the coronal source seems to drift upwards in the corona at a speed of about 15 km/s. The total energy in energetic electrons is surprisingly large, and as with the 23 July flare, substantial energy release and acceleration of electrons occurs in the corona.

Future work

High spectral resolution measurements of the solar flare hard X-ray spectrum can be directly inverted to obtain the detailed spectrum of the parent X-ray-producing electrons (Johns and Lin 1992). The quality of the RHESSI spectroscopic data has triggered new theoretical work to optimize the inversion process (Piana et al, 2003). This has shown promise in revealing details of the parent electron spectrum.

RHESSI, however, provides imaging spectroscopy -- the photon spectrum is obtained in each spatial element (Figure 9), as a function of time. The long-term goal of RHESSI is to obtain $N(E,\mathbf{r},t)$, the X-ray producing electron number density, as a function of energy (E), position ($\mathbf{r}$), and time (t). With information from context observations on the ambient density, temperature, magnetic field strength and topology, the electron loss processes can be directly evaluated. By using a spatially dependent continuity equation, including loss processes, the spatially and temporally resolved accelerated electron source distribution, $F(E,\mathbf{r},t)$, can be inferred. Then, detailed quantitative models of the acceleration, energy release, and energy propagation processes can be constructed and tested. The complications of the coupled problems of deconvolving the Fourier transform image and of inverting the spectrum (see Alexander and Metcalf 1999) means that we are just at the beginning of this process, with much work ahead.

Core-Halo and Albedo studies

Schmahl and Hurford (2002) have developed Fourier techniques that provide a robust way of determining the spatial scales of hard X-ray flares observed with RHESSI. In a preliminary study, unpixelized forward-fitting was used to show that, in addition to the 'core' structures that the other RHESSI imaging algorithms find, there are often 'halo' structures with sizes up to ~40". These 'halos' contain from 10 to 25% of the total flux in the 12-25 keV band, and may be the result of albedo emission--Compton scattering of the primary hard X-rays from the photosphere. If so, it would provide a direct indication of the height of the core x-ray emission. This can be tested by determining the energy and longitude dependence of the halo properties, and by determining the photon spectrum of the halo emission for comparison with theoretical calculations of albedo emission. These studies will also provide determinations of the dependence of core sizes on photon energy for comparison with models of downward magnetic convergence expected in beam models.

Harmonics

Although the angular response of the RHESSI RMC's has a quasi-triangular profile, all RHESSI imaging to date has been based on a sinusoidal approximation to this response. The other harmonics in the modulation profiles provide additional imaging information equivalent to grids with 1/2 and 1/3 of the pitch, albeit with reduced sensitivity. For stronger flares, analysis software upgrades to use this information will not only improve image quality (by providing information on additional Fourier components), but also improve angular resolution by up to a factor of 3.

X-ray Polarization

The hard X-ray emission from any bremsstrahlung source will be polarized if the distribution of electrons is anisotropic. Although designed primarily as a hard X-ray imager and spectrometer, RHESSI is also capable of measuring the polarization of hard X-rays (20-100 keV) from solar flares. This capability arises from the inclusion of a small beryllium (Be) scattering element that is strategically located within the cryostat that houses the array of nine GeDs. 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. Low energy photons from the Sun have a direct path to the Be and have a high probability of Compton scattering into a rear segment of a GeD. The azimuthal distribution of these scattered photons carries with it a signature of the linear polarization of the incident flux.

Sensitivity estimates, based on Monte Carlo simulations and in-flight background measurements, indicate that a 20-100 keV polarization sensitivity of less than a few percent can be achieved for X-class flares (McConnell et al., 2002). Although there are still some concerns regarding residual systematics, preliminary analysis of solar flare data from 23-July-2002 indicate a 20-40 keV polarization of 27%. Analysis is still in progress.

Polarization at higher energies (~0.15- 2 MeV) can be detected by RHESSI through scattering from one GeD to another. This method was used to show that a cosmic gamma-ray burst was highly polarized (Coburn and Boggs, 2003), but solar flares have lower polarization and that is thus, harder to detect.

1.c. Ion Acceleration and Gamma-ray Line Emission

RHESSI has provided the first direct information on the location and spatial characteristics of the accelerated ions in a flare, by imaging the gamma-ray line emission produced by collisions of the energetic (tens of MeV) ions with the ambient solar atmosphere (Hurford et al. 2003). The two rotating modulation collimators (35 & 180 arcsec resolution) with the thickest (2 & 3 cm, respectively) tungsten grids were used to obtain images in the following three energy bands, all for the same time interval: (i) the narrow deuterium line at 2.223 MeV formed by thermalization and capture of neutrons produced in the collisions, (ii) the 3.25-6.5 MeV band that includes the prompt de-excitation lines of C and O, and (iii) the 0.3-0.5 and 0.7-1.4 MeV bands that are dominated by electron-bremsstrahlung, all for the same time interval.

The centroid of the 2.223 MeV image (Figure 11) was found to be displaced by ~20(±6) arcsec (~15,000 km) from that of the 300-500 keV band (and from the 50-100 keV X-ray continuum emission), implying a difference in acceleration and/or propagation between the accelerated electron and ion populations near the Sun. If the acceleration process is indeed common, as suggested by the similarity (within ~5 s) of the time profiles of the prompt gamma-ray line emission and the bremsstrahlung X-ray/gamma-ray continuum emission, it would suggest that electric fields are involved.

The de-excitation lines, which come from ambient nuclei stimulated by accelerated protons and alpha particles, were measured for the first time with high spectral resolution (Figure 12) (Smith et al. 2003). They were discovered to be significantly redshifted, by fractions of a percent, even though the flare was nearly on the solar limb. These redshifts imply that the magnetic loop containing the ions must have been strongly tilted from radial, toward the solar surface.

Also resolved for the first time in this flare was the positron-annihilation line which was discovered to be unexpectedly broad (8.1 keV; Share et al. 2003). This width implies annihilation in either a hot medium of about 600,000K or a cold medium very close to 6,000K. The quiet solar atmosphere contains little material at either temperature; thus this line is a very sensitive measure of some very unusual conditions associated with flares.

Future Work

More detailed studies of this flare are still ahead. Preliminary estimates of the energy contained in the accelerated ions range from ~10^{31} to 10^{32} ergs (depending on the low energy cutoff), but more analysis is required. The narrow de-excitation lines studied to date are produced by accelerated protons and alphas colliding with heavy nuclei in the ambient solar atmosphere. The reverse process, accelerated heavy nuclei colliding with ambient hydrogen and helium, produces broad lines, which have yet to be analyzed. Studies of temporal variations in the ion acceleration and its relationship to the electron acceleration are under way.

The imaging of the bremsstrahlung continuum at >0.3 MeV needs to be compared with the microwave emission, since for the first time we have images of the same energy electrons that produce the gyrosynchrotron radio emission.

Further high-resolution observations of the annihilation and de-excitation lines, and imaging of these lines and the neutron capture line in other flares, will be vital to put these discoveries in context, and will undoubtedly lead to new discoveries as well.

1.d. Thermal Energy Release in Flares

One of the fundamental questions for flares is how much of the energy released in a flare is involved in direct plasma heating and how much in accelerating electrons that subsequently lose their energy to produce secondary plasma heating. RHESSI is the first instrument to provide imaging spectroscopy across the transition between the thermal emission at low energies and the nonthermal bremsstrahlung at higher energies with the same high-resolution detectors, allowing us to separate the highest temperatures (>10 MK) plasmas present during the flare from flare-accelerated electrons that (along with the ions) carry the bulk of the nonthermal energy.

In addition, RHESSI's high sensitivity and ~1-keV (FWHM) energy resolution allow the intensity and mean energy of the iron-line complex at ~6.7 keV to be measured and imaged as a function of time. This line complex is due mostly to the 1s-2p transitions in He-like and H-like iron, Fe XXV and Fe XXVI, respectively, and to associated satellite lines. Another weaker emission feature at ~8 keV made up of He-like nickel and more highly excited Fe XXV lines is also evident in the more intense flares.

Detailed calculations of emission line intensities as a function of temperature, with provision for different element abundance sets (e.g. photospheric or coronal), are given by the atomic codes MEKAL/SPEX (Mewe et al. 1995) and CHIANTI (Dere et al. 1997). These codes also include thermal continuum intensities. They are being used to interpret the RHESSI spectral observations in terms of the plasma temperature and emission measure. The centroid energy and width of the iron-line complex at ~6.7-keV, the intensity of the Fe/Ni line complex at ~8 keV, and the line-to-continuum ratios are all functions of the plasma temperature and can be used to limit the range of possible plasma parameters.

Near-coincident flare observations with the RESIK instrument on the Russian Coronas-F mission (similar to the Bragg Crystal Spectrometer on Yohkoh) are providing detailed line and continuum spectra in various soft X-ray energy bands between 2 and 7 keV. These provide additional information on the heated plasma that, when combined with the RHESSI data, make it possible to obtain the differential emission measure (DEM) as a function of temperature. An exponentially falling DEM with temperature has been found to give consistent results for four flares observed with RESIK (Phillips et al. 2003). A similar DEM is being used to interpret RHESSI higher energy spectra. Thus, the temperature and emission measure of the thermal plasma can be determined in a consistent manner assuming only the abundance of iron and the thermal origin of the emission.

The recent activation of the new GOES Soft X-ray Imager (SXI) offers additional opportunities for quantifying the flare's thermal emission. This instrument is providing invaluable broad-band whole-Sun images observations with higher cadence (~1 minute) than SOHO/EIT and with comparable angular resolution to RHESSI. Like the Yohkoh SXT images obtained prior to the RHESSI launch, SXI detects flaring plasma without the strong temperature selectivity of EIT or TRACE. It images solar plasma over a broad temperature range from as low as 2 MK to greater than 50 MK, thus giving a more comprehensive measure of the thermal flare energy than is available from any other instrument.

Preliminary results of these investigations will be presented at the AAS/SPD meeting in June (Dennis et al., 2003; Hudson et al., 2003).

1.e. Flare/CME Associations

Given the geoeffectiveness of CMEs, the effort to understand and eventually to predict these powerful solar events has become a major activity of the SEC program. Observations with TRACE, Yohkoh/SXT, and SOHO/EIT and UVCS have revealed the early stages of CMEs, while LASCO images show the CMEs propagating out into interplanetary space. Instruments on ACE, Wind, and SOHO detect the CME and its shock at ~ 1AU.

Despite these observations, little is understood about the early initiation of a CME and its connection to the very large energy release of the often-associated flares. RHESSI has provided observations of several such associated flares in which 10^{32} ergs or more appear in the nonthermal electrons alone on time scales of minutes during the period of CME initiation and acceleration. The flare/CME event on 21 April 2002 is the best observed example of such an association, with two workshops and a special session at the Fall AGU meeting devoted to it and other events during the period of intense storm activity from 14 – 23 April 2002.

The first hard X-ray emission on 21 April 2002 was detected with RHESSI some 5 minutes before any brightening was observed in the TRACE 19.5-nm images (Gallagher et al. 2002). This time delay is presumably because the early hot plasma was at a higher temperature than the ~1.5 MK sensitive range of the TRACE passband. The hard X-ray emission continued to rise for the following hour, at the same time that a wave-like propagation appeared to move through the TRACE field at a mean velocity of ~120 km/s. This has been interpreted by Gallagher et al. (2003) as the first evidence for the CME.

Thanks in part to the early warning made by the RHESSI-funded Max Millennium flare forecasters, UVCS recorded the passage of the CME through its slit that was fortuitously placed 1.63 solar radii off the limb. LASCO obtained four images of the CME as it passed through its C2 and C3 fields. Gallagher et al. (2003) combined these CME observations to show that from the CME initiation in near coincidence with the start of the associated flare, the leading edge accelerated to a maximum velocity of over 2500 km/s in less than 2 hours. The maximum rate of acceleration was as high as 1500 m/s^2 and this occurred when hard X-ray emission was seen with RHESSI. The flare released some 10^{32} ergs during its rise phase over the same time period that the CME was being accelerated. An intense SEP event was seen at the Earth.

RHESSI recorded several impulsive peaks in the hard X-ray emission to energies well in excess of 100 keV, with clearly nonthermal emission from points along the ribbons seen in the TRACE images. Curiously, with its 2-arcsecond angular resolution, RHESSI was able to show that the impulsive brightenings did not always match brightenings seen with TRACE in either time or location.

With its high sensitivity to X-rays below 10 keV, RHESSI was able to follow the decay phase of this event for over 12 hours. The RHESSI images (Figure 13) show a bright X-ray source, some 30" in extent, moving out above the limb with a velocity that was initially about 10 km/s, but decreased to about 2 km/s after 2 hours, and then maintained that value for another 10 hours. Images made at different energies showed that the higher energy emissions (6 – 12 keV) consistently came from slightly higher altitude than the lower energies (3 – 6 keV). This result provides support for the basic Kopp and Pneuman flare model in which energy is released at higher and higher altitudes in the corona as the flare progresses, energizing larger and larger magnetic loops (Gallagher et al. 2002).

The 23 July 2002 (Lin et al. 2003) flare was considerably more energetic than that on 21 April and produced emission detectable with RHESSI into the MeV range, including many nuclear gamma-ray lines, as discussed earlier. A fast (2180 km/s) CME was also recorded in association with this flare but no SEP event was seen at the Earth above the elevated background from the July 20 CME, that was itself accompanied by a flare but not observed with RHESSI.

CMEs sometimes occur without flares and vice-versa, but the largest flares tend to be associated with fast and powerful CMEs. Thus, no full understanding of either phenomenon will be possible until we understand how they are related. 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, and the existing large fleet of spacecraft with a wide range of instruments is poised to make such observations during the waning phases of this solar cycle.

1. f. Microflares and the Quiet Sun

The Sun releases energy in transient outbursts, ranging from major flares down to microflares and even nanoflares, with the frequency of the releases increasing as the energy released decreases (see discussion in Aschwanden et al 2000). For flares, the energy releases often appear to be dominated by accelerated 10s of keV electrons and sometimes MeV/nucleon ions. Hard X-ray microflares, tiny bursts with 10^{27} to 10^{28} ergs in >20-keV electrons, were discovered to occur on average once every ~6~minutes near solar maximum (Lin et al., 1984), leading to speculation that the energy released in accelerated electrons, summed over HXR bursts of all sizes, might contribute significantly to the heating of the active corona.

Using the BATSE SPEC detectors on the Compton Gamma-Ray Observatory, whose thresholds were occasionally set as low as 8~keV, Lin et al (2001) found that only one third of all non-thermal (hard spectra unlikely to be thermal) events detected above 8 keV are observed above 25~keV. Additionally, the generally steep HXR spectra (power-law fits with exponent of 3-7) reveal that most of the flare energy is in the non-thermal electrons at the lowest energy. Furthermore, the similarity of frequency vs. energy release distribution of these >8keV bursts to that of active region transient brightenings (ARTBs) seen in soft X-rays by the Yohkoh SXT instrument (Shimizu, 1995) suggests that these accelerated electrons may provide the energy for ARTBs.

The excellent sensitivity, spectral and spatial resolution provided by RHESSI allows for the first time the detailed study of the locations and the spectra of solar microflares down to 3 keV. As discussed above, previous solar hard X-ray instruments had entrance windows that absorb emission below ~15-25 keV to avoid pile-up and saturation from the intense thermal emissions in large flares. The RHESSI instrument accommodates medium and large flares by automatically inserting shutters in front of detectors to absorb low energy photons and avoid saturation. Compared to the most sensitive previous instrument from 3 to 15 keV, the Hard X-ray Imaging Spectrometer (HXIS) on SMM, RHESSI with the shutters out (Figure 4c) has an effective area 14 to 500 times larger. Thus, RHESSI can probe the Sun in the 3-15 keV energy range with unprecedented sensitivity to provide new information on low level energy releases and quiet Sun emissions, whether they result in heating of >~5 x 10^6 K thermal plasmas or in the acceleration of low energy electrons.

The first RHESSI results on active region microflares (Figure 14) show soft (power law exponents between 4 and 7) non-thermal spectra down to low (<~7 keV) energies (Benz & Grigis 2002, Krucker et al. 2002). If a 25 keV cutoff energy is assumed, the total energy in non-thermal electrons in microflares is underestimated by at least a factor of ~10, in some events up to a factor of ~2000. Furthermore, the smaller the event, the steeper the spectrum appears to be. Thus there may be a systematic underestimate of the energy in small events relative to large events, and the frequency distribution of microflares may well be steeper than previously reported (Crosby et al. 1994), i.e. microflare heating might contribute more to coronal heating than previously thought. A detailed statistical study is underway.

As the total solar emission in this energy range declines, it will be possible to see even smaller events than during the first years of the mission, possibly down to the micro/nanoflares where perhaps most of the non-thermal energy is released.

Towards solar minimum, it will also be possible to study the emission of the 'quiet' Sun (when no obvious microflares are seen) by time averaging RHESSI observations over many hours. Such imaging spectroscopy of the quiet Sun in the 3-15 keV range may reveal insights on the possible non-thermal nature of the quiet Sun emission that could be related to unresolved micro/nanoflares of even smaller size.

1.g. Solar Energetic Particles (SEPs)

SEP events observed in the interplanetary medium (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). Impulsive events (Lin, 1985) are dominated by non-relativistic electrons, ~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 the entire Sun). Impulsive electron events are observed to be emitted over a cone of ~40-60º of solar longitude, and they are often closely associated with type III radio bursts, and sometimes with small flares, usually too small to detect gamma-ray lines. The associated energetic ion emission is generally weak and limited to low energies (<~1 MeV/nucleon), but typically 3He-rich (Reames et al. 1985) and heavy ion-rich (Fe, Mg, Si, S). Surprisingly, gamma-ray de-excitation line measurements show that the energetic ions in *large* flares are often also 3He-rich [Mandzhavidze et al., 1999] and Fe-rich [Murphy et al., 1991].

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}). They extend over >100º in longitude and are usually associated with large flares (sometimes absent) and fast, wide 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. Recent ACE observations, for example, show significant enrichments of 3He and Fe in some *gradual* events, more than can be easily explained as acceleration of remnant 3He and Fe in the IPM from previous impulsive events.

RHESSI and Gradual SEP Events

A major scientific goal is to compare SEP composition, spectrum, number, and angular distributions measured with the Wind, ACE, SOHO, Ulysses, and STEREO (after 2005) energetic particle instruments, with abundances, spectra, and angular distributions inferred from RHESSI spectroscopic observations of gamma-ray lines produced by the energetic ions at the Sun. In a large gamma-ray line flare/SEP event, the detailed abundance patterns of H, He, C, N, O, Ne, Mg, Si, Fe, (and electrons from a few keV to MeV energies) can be compared. No such direct comparison has ever been made for the same event.

In addition, RHESSI's imaging provides information on the location and extent of the energetic ion and electron populations at the Sun for comparison with the IPM energetic particle measurements, especially with the two STEREO spacecraft (after 2005) and Ulysses sampling a range of longitudes/latitudes. In previous solar cycles, large gamma-ray/SEP events (such as August 1972) have occurred on the descending phase of the solar cycle, which we are entering now.

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. SEPs also penetrate deep into the atmosphere over the Earth's magnetic polar regions and produce increased ionization, lowering the ionosphere and disrupting radio communications.

Recent SAMPEX observations indicate that SEPs in the polar regions may penetrate to lower latitudes to form new radiation belts at lower latitudes if the magnetosphere is then perturbed by the passage of an interplanetary shock.

RHESSI and Impulsive SEP Events

Most of the flare hard X-ray emissions observed by RHESSI come from energetic electrons colliding with the dense lower solar atmosphere. In an initial survey of more than 600 HXR events detected by RHESSI (Rauscher et al. 2002) about 70% were accompanied by interplanetary type III bursts seen by WIND/WAVES. The impulsive-event electrons that escape through the relatively low density corona and IPM to produce the type III radio bursts will also produce bremsstrahlung hard X-rays, albeit at much lower fluxes.

The energy spectra of the impulsive-event/type III electrons observed in the IPM are power-laws, often extending down to ~1 keV before a turnover, indicating a high coronal origin (Lin et al. 1996). With RHESSI's high sensitivity down to 3 keV, very weak HXR events are sometimes observed which are simultaneous with the type III burst but either do not have the usual intense flare HXR emission or the flare HXR emission is seen at a later time (Figure 15). We tentatively identify this weak emission as the X–ray signature of the escaping type-III electrons.

Soft X-ray jets discovered by Yohkoh (Shibata et al. 1992) may be the channels in which some type III bursts propagate (Kundu et al. 1995). Studies combining RHESSI's imaging with imaging from TRACE, GOES SXI, SOHO/EIT, SOHO/MDI and radio imaging at metric wavelengths from the Nancay Radioheliograph, etc., will reveal the magnetic structure of these events and the conditions for energetic electrons escape.

These escaping electrons can be used to unambiguously trace magnetic field lines, through imaging by RHESSI of the X-rays they produce, and radio tracking of the type-III emission they produce from the Sun to 1 AU. Detection of the electrons themselves is possible with the Wind 3D Plasma and Energetic Particle experiment, which provides unique coverage of these ~keV to few tens of keV electrons.

Analysis of the observed velocity dispersion at onset of these electrons gives the field-line length and solar release time of the detected electron beam. Furthermore, the observed spectrum of the escaping electrons can be compared with the spectrum of the electrons at the Sun inferred from the RHESSI X-ray measurements, to study the physics of the escape process. ACE and Wind ion observations can identify SEP events that are highly enriched in 3He. The tracking described above can identify the solar source regions, to see what conditions lead to the strong elemental and isotopic enhancements seen in 3He-rich events.

Since these impulsive events occur frequently, these techniques can also be used for tracing the magnetic connection back to the Sun of structures such as CMEs and magnetic clouds (Larson et al 2000).

An ACE/RHESSI/Wind Workshop on Solar Energetic Particle Acceleration and Transport will be held October 6-8, 2003, to explore the acceleration and transport of solar energetic electrons and ions.

1.h. Other RHESSI Science

Scientific use of the Solar Aspect Sensor

RHESSI imaging requires real-time knowledge of the location of the solar limb, which accordingly is measured frequently and with high precision. Typically we get on the order of 100 samples per second at high precision, so the number of measures in the current database already approaches 3 x 10^9. The rms error for an individual measurement of the limb is less than one arcsecond after applying a linear fit through the measured pixels at the limb. Simulations showed that the limb positions can be fitted with an accuracy of better than 50 arcsec assuming a perfect knowledge of the measured limb profile. Thus, a careful estimate of the point spread function (PSF) will significantly improve the measured location of the limb.

This provides a vast database for studies of phenomena at the limb visible in white light. These in principle include sunspots, plage, flares, "white light prominences", the limb-darkening function of the photosphere, convection, oscillations (p-modes if not g-modes), the figure of the Sun (e.g., its oblateness), and secular (or cyclic) changes of the radius. None of this material has been developed scientifically yet, but the database exists its quality has been verified to be at the design specifications or better. The data far exceed in quantity and in "seeing" quality any previously obtained measurements, and anticipate a planned French satellite mission, PICARD. This satellite is scheduled for launch in 2005 and is explicitly devoted to this kind of observation as a primary science objective. We expect that the RHESSI data will greatly improve upon Dicke's classical ground-based limb observations as input to relativity theory.

Non-Solar Astrophysics

The thin walls of RHESSI's cryostat expose the germanium detectors to photons over 30 keV from the entire sky, and a wealth of non-solar science is already being done. RHESSI provides the largest effective area, high spectral resolution (~ keV) measurements for all sky observations. In its first year of operation, RHESSI has made the first-ever measurement of polarization in a cosmic gamma-ray burst (Coburn and Boggs 2003). Surprisingly, the polarization was between 50% and 100% over the energy range ~0.15-2 MeV, implying that the emission mechanism is synchrotron radiation in a region with a nearly uniform field. RHESSI is able to measure polarization because photons in this energy range Compton scatter in one detector and are stopped in another. Since every energy loss is timed to a microsecond, coincident events in two detectors can be identified. The direction of the scatter depends on the plane of the photon's electric field. This technique is also applicable to solar flare X-rays and gamma-rays but the level of polarization is much lower and therefore much harder to detect.

RHESSI also resolved a major dispute in nuclear astrophysics by measuring the width of the gamma-ray line from the decay of 26Al in the inner Galaxy (Smith 2003), helped localize several gamma-ray bursts, enabling follow-up observations of their afterglows (Hurley 2002), and observed two extremely rare bright outbursts from the black-hole binary Cyg X-1.

Over the coming years, as the software is developed, RHESSI will be used as an all-sky monitor in the hard X-ray range, using the mutual occultation of the detectors as the spacecraft spins to image the sky (McConnell et al. 2003). Further studies of Galactic nuclear lines will map 26Al, using occultation by the Earth and perhaps make the first measurement of radiation from 60Fe.

By pointing just a few degrees away from the Sun, RHESSI will, once a year, produce hard X-ray maps of the Crab nebula with all the power and resolution of its RMC imaging. Since the nebula has shown significant variability on this timescale at other wavelengths (Hester et al. 2002), repetition of this observation over several years should multiply the scientific return several-fold.

Since RHESSI returns every photon with a precise arrival time, we can separately study the emission from not only the Crab's pulsar but many pulsars of different periods, with their X-rays arriving from many directions at once, simply by re-"folding" the data at their different pulse periods. Thus we will study both rotation-powered and accreting pulsars, watching their spectra, luminosity and pulsation periods evolve with time.

RHESSI has proven to be a sensitive detector of both cosmic gamma-ray bursts and soft gamma repeaters (magnetars). RHESSI's detection rate is about one burst per week. This makes the mission a valuable member of the 3rd interplanetary network, an ensemble of six missions (Ulysses, Mars Odyssey, Wind, HETE-II, RHESSI and INTEGRAL) which monitor the entire sky for bursts and localize them to ~arcminute accuracy by triangulation. Furthermore, with its high sensitivity and high spectral resolution, RHESSI is providing the best gamma-ray burst spectra ever obtained. Further polarization measurements of gamma-ray bursts will be made, confirming the initial discovery and searching for variability in this phenomenon from burst to burst.

Finally, RHESSI stands ready, as the most sensitive all-sky gamma-ray instrument in space, to make the first measurements of the shock break-out event in a nearby supernova or the positron-annihilation flash expected to occur at the onset of a classical nova.

Terrestrial Studies

RHESSI's unshielded detectors also allow it to study gamma-ray emissions from the Earth's atmosphere. Mysterious, millisecond-long flashes of gamma rays have been observed from the Earth by a single mission, the Burst and Transient Source Experiment BATSE on the Compton Gamma-Ray Observatory (Fishman et al. 1994), and dubbed Terrestrial Gamma Flashes (TGFs). TGFs have been correlated with large-area thunderstorms, and are possibly related to other recently-discovered high-altitude phenomena such as sprites and elves (Fishman et al. 1994; Lehtinen, Bell and Inan 1999). It has also been suggested, however, that they are showers from interactions of ultra-high-energy tau neutrinos with the Earth's crust (Fargion 2002). In either case, the direct emission mechanism is probably bremsstrahlung from relativistic electrons. Such events were rare in BATSE (on the order of one per month). RHESSI is well-equipped to see them, and has a greater energy range and much higher energy resolution than BATSE. In order to generate a set of events large enough to distinguish between the two models, however, several years of operation will be necessary.

Atmospheric gamma-ray events of longer duration (minutes to hours) are the sign of precipitation of relativistic electrons from the Earth's radiation belts -- electrons which, while trapped, present a danger to unmanned satellites. Recently, high-altitude balloons have discovered gamma rays from a class of events that precipitate MeV electrons preferentially, and which may be the dominant loss mechanism for this component of the outer belt (Millan et al. 2002). One mechanism that has been suggested for these events is scattering from electromagnetic ion cyclotron waves (Lorentzen et al. 2000). RHESSI, particularly with an extended mission, has the potential for detecting more of these events. By correlating them with context observations from the ground and other spacecraft, we may not only discover the primary loss mechanism for these electrons, but also learn about the causes and rate of their energization and trapping. RHESSI's sensitive X-ray and gamma-ray response and auxiliary particle detector will also make it a useful source of context information for other missions studying magnetospheric phenomena.

The RHESSI GeDs are probably the best detectors ever flown for directly detecting relativistic electrons precipitating from the trapped radiation belts. These large (7.1 cm diameter and 8.5 cm long) detectors will easily stop electrons up to 17 MeV, the energy limit of the electronics.

RHESSI demonstrated its capability for detecting gamma-ray lines from impact of SEPs on the Earth’s atmosphere during the 21 April 2002 event. De-excitation lines from 14N and from spallation products such as 12C were detected with the polar region in view, even though the proton intensity was 10 - 100 times weaker than previously detected gamma-ray events observed by SMM and Yohkoh (Share et al 2002). Comparison of gamma-ray line ratios provides information on the spectrum of the incident protons.

Recent SAMPEX observations indicate that the SEPs in the polar regions may penetrate to lower latitudes to form new radiation belts if the magnetosphere is then perturbed by the passage of a interplanetary shock. RHESSI, at a maximum L of ~2.5 will be able to diagnose the formation of such new belts through the gamma-ray line emission of the energetic ions, possibly with better sensitivity than SAMPEX.

With RHESSI's excellent spectral resolution, it may even be possible for it to detect the 7Be line at 429 keV produced by spallation of atmospheric N during intense solar energetic particle events. This would confirm the SEP origin for the exceptionally high concentration of 7Be in the upper atmosphere detected by the LDEF satellite in late 1989.

1.i. Context Observations and Collaborations

The Max Millennium Program

Co-temporal and co-spatial data from other space and ground based observatories is crucial to a comprehensive physical interpretation of RHESSI data. For this reason, the RHESSI budget fully supports the Max Millennium Program, whose most visible component is observing target selection. This is accomplished through the experienced international cadre of Max Millennium Chief Observers (MM_COs), centered at Big Bear Solar Observatory, communicating through the Max Millennium Message of the Day. This mechanism has been very effective and is appreciated widely -- for example, see http://sohowww.nascom.nasa.gov/hotshots/2002_04_26/, which documents the comprehensive space and ground-based coverage of the spectacular X flare of April 21, 2002, guided by the MM_COs. Table 4 is a (partial) list of collaborating observatories.

The Max Millennium Program implements many RHESSI functions through a web page at Montana State University: http://solar.physics.montana.edu/max_millennium/. This page furnishes convenient links to the RHESSI data archives and those of other space missions and ground-based observatories. Also linked are education, outreach, and press pages; majordomo lists for scientific and operational communications to the international flare community in support of RHESSI; hypermail archives of all past messages, an e-print archive to promote rapid dissemination of results; a page of descriptions of RHESSI data analysis projects to keep both the scientific community and the PI team well informed on work in progress, and a page of links about the Sun today.

RHESSI Collaborations

Instrument	Area of Research	Leading collaborators
Space-based Observatories		
SOHO		Zarro, Gallagher - GSFC
EIT	EUV images	Gurman - GSFC
MDI	Magnetograms	Gallagher - GSFC
UVCS	EUV spectra	Raymond - SAO
SUMER	Spectra	Curdt – Max-Planck
CDS	EUV spectra and images	Gallagher - GSFC
LASCO	CME images	Lawrence – GSFC
TRACE	UV & EUV images	Metcalf, - LMSAL Gallagher – GSFC
ACE	SEPs	von Rosenvinge – GSFC
WIND - Waves	Radio spectrograms	Krucker – UCB
Coronas-F		
RESIK		Phillips – GSFC
IRIS		Kocharov – IOFFE, Russia
MTI - HXRS	Hard X-ray spectra	Farnik, Kasparova – Ondrejov,
SXI on GOES-12	Soft X-ray images	Hill – NOAA/SEC
Ground-based Observatories		
Big Bear Solar Observatory	H-alpha, magnetograms	Wang – NJIT
Phoenix	Radio spectrograms	Benz – ETH Zurich
Nançay, France	Radio heliograph	Vilmer – Meudon

BIMA	Millimeter images	White - UMD
Owens Valley Solar Array	Microwave spectra	Gary – NJIT
Nobeyama, Japan	Microwave images	Shimojo - NRO
Kanzelhöhe, Austria	H-alpha images	Veronig – Graz, Austria
VLA	Radio images	Bastian – NRAO White – UMD Willson - Tufts
Solar Radio Burst Locator	Microwave spectra	Dougherty - Caltech
Marshall Magnetograph	Magnetograms	Hagyard – MSFC
GONG	Magnetograms	Leibacher – NOAO

TRACE & SOHO

Of particular importance for interpretation of RHESSI observations is the magnetic topology during flares. Here we depend crucially on the high quality context observations in the EUV, provided by TRACE and - at lower resolution – SOHO/EIT, as well as the availability of ground and space-based magnetograms. Almost every possible interpretation of flare phenomena observed with REHSSI requires a spatial model of the magnetic topology that RHESSI cannot observe, but which can be inferred from TRACE pre-flare and post-flare images.

TRACE can respond to targets of opportunity of particular importance to RHESSI science within a day. For weekend operations, the TRACE FOT have agreed to send special pointing commands to the spacecraft if the target is deemed of particular importance.

High Cadence Flare Observations

Since RHESSI time-tags every photon to a microsecond and telemeters this information to the ground, RHESSI's temporal resolution is only limited by photons statistics. We have arranged for high cadence observations in Hαby BBSO and other ground observatories, and in EUV bands by TRACE. We hope to arrange for high cadence observations by the SXI soft X-ray imager on GOES. Some results have already been obtained by BBSO, where several RHESSI events were observed successfully with camera systems at cadences of 30ms and 10ms (Ji et al. 2003a, 2003b). For microflare studies BBSO now has full-Sun high-cadence observations. This is an area of great potential which we hope to exploit in the future.

Radio- Hard X-ray studies

Accelerated electrons produce radio emission through the gyrosynchrotron process and thus radio observations help to address the issues of particle acceleration and energy release. All the major radio telescopes capable of observing the Sun with good spatial resolution have pursued major campaigns in conjunction with RHESSI. The Very Large Array has carried out at least 24 separate solar observations coordinated with RHESSI since April 2002. These have addressed a range of science from the study of decimetric emission from within the acceleration regions themselves to the imaging of the coronal structures in which the accelerated electrons propagate.

The Owens Valley Solar Array (OVSA) and the Nobeyama Radioheliograph (NoRH) carry out daily observations and make their data, including detailed event analyses, available to RHESSI observers via the web. The radio spectra from OVSA can be used to infer magnetic field strengths in the flare regions that RHESSI observes, while NoRH data at 17 and 34 GHz can be used to measure spatially-resolved energy distributions for the radio—emitting electrons. Planned for the future is the first joint application of X-ray and microwave imaging spectroscopy diagnostics (using RHESSI and OVSA data) for the quantitative study of thermal and nonthermal electron populations in flares.

At low radio frequencies sensitive to phenomena in the outer corona such as CMEs, both the Nancay Radioheliograph in France and the Giant Meterwave Radio Telescope in India have carried out campaigns for the RHESSI targets. At millimeter wavelengths the Berkeley-Illinois-Maryland Array (BIMA) has observed the Sun in conjunction with RHESSI on 27 days since launch. Millimeter data are the most sensitive means for detecting the highest energy electrons. Metric and decimetric radio spectrographs at Potsdam and Zurich provide high time and frequency resolution observations for comparison with RHESSI.

1. j. RHESSI Scientific Effectiveness

RHESSI has revitalized interest in solar flare research with its freely accessible database and the extensive suite of analysis software. RHESSI results have been presented at two press conferences besides the one at launch. One featured the first RHESSI X-ray movie of a flare recorded on Feb. 20, just 15 days after launch; it was presented in association with the Sun-Earth Day on 20 March 2002. The second featured the RHESSI movie of the X-flare on 21 April 2002; it resulted in a RHESSI/TRACE overlay image in the New York Times Science Section on 7 June 2002. RHESSI results for that flare have also been featured in the SEC workshop and AGU session on the solar storms that were well observed by most SEC missions.

One of our major goals has been to involve as many solar physicists as possible in fully exploiting the great scientific potential of the RHESSI observations. To this end, two prelaunch RHESSI data analysis workshops were held that attracted over 30 people each, and two post-launch science workshops had ~50 attendees each. A special two-day session at the Houston COSPAR meeting in October, 2002, on Energy Release and Particle Acceleration in Solar Flares and Related Phenomena featured early RHESSI results and attracted an audience of ~100 people. Many of these presentations have now been refereed and accepted for publication in Advances in Space Research. As of this writing, there are 76 RHESSI publications (42 in refereed journals, 32 in 2002) A total of 99 (including in press) are listed in the on-line bibliography:
http://www.lmsal.com/~aschwand/publications/hessi.html

They include 11 instrument and software papers and 15 early-results papers published in the November 2002 issue of Solar Physics. This was also published as a book dedicated to Reuven Ramaty. A complete issue of the Astrophysical Journal Letters is now in preparation with 17 papers on the different aspects of the gamma-ray line flare recorded on 23 July 2002.

The large number of presentations made by RHESSI team members (92 in 2002 and 26 so far in 2003 with 8 more already planned, many of them by invitation) indicates the great interest in RHESSI results. RHESSI-specific workshops, the next in Glasgow in June, 2003, followed by one near Goddard, also in June. Several joint workshops with other missions are planned in the next two years. The first will be with ACE and Wind in October, 2003, and one with TRACE and SOHO is planned for 2004. Special sessions at the June 2003 SPD meeting and the Paris COSPAR meeting in 2004 are also planned to cover RHESSI-related flare physics.

1. k. Proposed Extended Mission Program

We believe there are compelling scientific reasons for a mission extension of at least three years, through FY'07. The RHESSI mission was originally planned for launch in July 2000, near the predicted peak of the ~11-year solar activity cycle. During environmental testing of the integrated spacecraft at the Jet Propulsion Laboratory in March 2000 (while on schedule), a malfunction in the shake table subjected RHESSI to a vibration level of >25 G rather than the requested 2G, resulting in extensive damage to both the instrument and spacecraft. The instrument and spacecraft were repaired, re-integrated, and re-tested in time for a launch at the end of 2000. A problem was then discovered on the Pegasus-XL launch vehicle, and fixing that problem delayed the launch first to March 2001, and then to June 2001. One week before this planned RHESSI launch, NASA attempted a test flight of the prototype X-43 aerospace plane. The modified Pegasus first stage used for launch failed and the X-43 had to be destroyed. This led to a series of further delays while the cause of the failure was investigated. On February 5, 2002, nineteen months late, RHESSI was finally successfully launched by the Pegasus-XL.

By then, the flare rate had decreased (Figure 16), and the number of >25 keV flares predicted to be observed by RHESSI in a nominal two-year prime mission had dropped by about a factor of two. The actual rate of >25 keV flares observed since launch is consistent with the prediction. Because the flare rate continues to fall, obtaining the same number of flares as in the RHESSI 2000-launch prime mission will require at least a ~3 year extended mission, to 2007.

The expected number of much rarer >300 keV gamma-ray flares had dropped even more (again as expected) with the delayed launch.

From the science point of view, perhaps the most remarkable new results from RHESSI are the gamma-ray line observations of the flare of 23 July 2002. They raise a myriad of new questions, which can only be answered by more observations. If RHESSI had launched in July 2000 as planned, it would likely have detected at least a half dozen gamma-ray line flares in its prime mission; we have captured one gamma-ray line flare in 14 months. Analysis of that flare has emphasized the need for detailed observations of the flare magnetic structure, such as will be provided by the Solar B mission (launch 2006?).

It is well known that isolated large flares and large SEP events often occur in the descending phase of the 11-year solar cycle. Based on the Solar Maximum Mission (SMM) Gamma-Ray Spectrometer (GRS) observations in the 1980s (cycle 21), reduced by about 30% to take into account the weaker overall activity of the present cycle 23, we estimate that RHESSI should detect about two gamma-ray line flares per year, on average, over the next 4 years.

Although a fast (2180km/s) and wide CME accompanied the 23 July 2002 flare, surprisingly no solar energetic particle (SEP) event was detected. It is interesting to note that 2.223 MeV gamma-ray line emission has been observed from a behind the limb flare with accompanying large SEP event (Vestrand and Forrest 1993).

A major scientific objective for RHESSI is to observe a gamma-ray line flare accompanied by an associated large SEP event (like the August 1972 flares). Then, the SEP ion and electron spectra and ion composition measured by ACE, Wind, SOHO, Ulysses, STEREO, etc. could be compared to those inferred from X-ray/gamma-ray measurements by RHESSI. This could resolve many questions on the relationship between SEP acceleration by shocks driven by fast CMEs and by flares. Sampling a range of longitudes in the IPM with the two STEREO spacecraft after 2005 would be useful for comparisons with RHESSI's information on the location and extent of the energetic ion and electron populations at the Sun. Based on the >10 MeV SEP proton events measured by GOES over the last two cycles, we estimate that there will be about 3-4 such SEP events per year over the next four years.

As mentioned previously, RHESSI has >14 to 500 times more effective area than any previous solar instrument at energies from ~3 to 15 keV. As the total solar background declines, it will be possible to see even smaller events than during the first two years of the mission. Thus it may be possible to extend statistical studies down to the size where the hypothesis that the energy deposited by non-thermal electrons, integrated over all micro/nanoflares, is significant for coronal heating. Towards solar minimum, it will also be possible to study the emission of the quiet Sun (when no obvious microflares are seen) by time averaging RHESSI observations over several hours or more. Since the solar emission is modulated by the grids, instrumental background (not modulated) can be removed (effectively doing on-source-off source background subtraction). Preliminary analysis indicates that sources two orders of magnitude below background can be detected and imaged. The imaging spectroscopy of the quiet Sun in the 3-15 keV range will reveal insights on the possible non-thermal (or thermal) nature of the quiet Sun emission, that could be related to unresolved microflares of even smaller size.

In summary, we believe an extended mission through FY '07 is needed to take advantage of the capabilities of RHESSI and of new missions such as STEREO and Solar B. RHESSI was designed with no expendables and we expect that it will continue to operate well for many years.

1.l. Minimal and Optimal Scenarios

The present level of funding and effort is set by the originally proposed RHESSI budget for the prime mission: two years of operation (to March '04) with a third year of data analysis (to March '05). The guideline budget for Mission Operations (MO) after the prime mission (~$400K/yr) is about the minimum required for "bare-bones mission operation and science operations". With the expected drop in solar activity and consequent lower data volume per day, however, we can reduce the number of Wallops ground station passes, resulting in a decrease in the "in-kind NASA cost attributions" (see budget). For the rare intervals when the Sun is very active, we will request extra passes as needed.

The guideline Data Analysis (DA) cost for the extended mission (beginning ~3/05) is barely enough for "bare-bones data handling, including low-level processing and basic archiving" and "minimal science data analysis" as described in the "Call for Proposals". To maximize the science return from RHESSI, however, will require significantly more data analysis effort. As mentioned previously, the power of the RHESSI data is that it provides quantitative spectral, spatial, and temporal information; however, the analysis effort required is significant, and we are only just beginning to explore the full scientific potential of the observations. The required effort may well be peaking at the time of the extended mission. Thus, we request under the Optimal Scenario that there be significant additional Guest Investigator funds, ~$1 million/year, for continued RHESSI scientific data analysis.

2. a. Technical

2.a.1 Observatory Status

RHESSI was launched on February 5, 2002. The Pegasus XL launch vehicle was dropped from the Orbital Carrier Aircraft (OCA), operating out of KSC. The achieved orbit at payload separation was 600.24 x 586.85 km at 38.02 deg, very close to the 600 km circular target orbit. The first contact with the spacecraft was established via the Berkeley Ground Station on orbit 2, about 85 min after payload separation. During this first contact the flight control team verified that the spacecraft was healthy, power positive with all solar arrays deployed, and pointed within 10 deg of the Sun. All temperatures were nominal. Within the first week on orbit, the spacecraft was completely configured and tested. Milestones accomplished during this week include IDPU turned-on, cryocooler ramp-up to 76 W, then down to 50 W, configuration and partitioning of the solid-state recorder (SSR), and power-up of the Particle Detector, Imager and Spectrometer. The spacecraft was spun-up to a preliminary rate of 14 rpm and spin balanced with the on-board Inertia Adjustment Devices (IADs).

RHESSI observed its first solar flare on February 12, 2002, only 7 days after launch. During the following weeks, the spacecraft was spun up to its nominal rate of 15 rpm. Subsequently the detection algorithms for the SAA and the outer electron belts were fine-tuned. The attenuators were exercised and, after careful testing, were configured to move autonomously in and out of the field of view, depending upon detected photon rates. The thresholds for the GEDs were adjusted to optimize sensitivity and background noise levels. The first X-class flare was observed on April 21, 2002, and instrument commissioning was completed at L+50 days. Minimum science was achieved on October 31, 2002, about 9 months after launch.

2.a.2. Instrument Status

Spectrometer

RHESSI's spectrometer, consisting of nine cryogenically-cooled germanium detectors, has been performing well since the early part of the mission and is extremely stable. There has been no noticeable change in gain or electronic noise since the initial turn-on of the detectors. One detector (#2), which had shown an unusual sensitivity to vibration before launch, became noisy during the second week of operation, so its high voltage was decreased. It has been operating stably since then as a unsegmented detector with its energy threshold at 20 keV instead of 3 keV, with electronic resolution of 8 keV FWHM instead of 1 keV. This is still good for imaging and for continuum spectroscopy above 20 keV, but not for high resolution gamma-ray line spectroscopy. No other detector has shown any similar tendency, either pre- or post-launch.

Radiation damage over the first year was within 20% of the level predicted before launch (Figure 17). We are thus confident that our prediction for at least four years of operation is reliable. At the end of four years, the contribution of radiation damage to the full width at half maximum (FWHM) of gamma-ray lines will be approximately 0.4%. This is still about a factor of three narrower than most of the nuclear de-excitation lines from flares, and an order of magnitude better than the resolution of previous scintillation detectors. This small effect can be easily connected in the analysis. At hard X-ray energies, our resolution (1 keV FWHM in the front segments) is entirely dominated by the performance of the electronics, and will be unaffected by radiation damage.

We have the ability to anneal the detectors by heating them to 100C for two to three days, removing almost all of the accumulated radiation damage; however, based on the predictions above, we do not expect to have to do this before the end of a three year extension.

The RHESSI spectrometer maintains the nine germanium detectors at approximately 74K with a Sunpower M77B Stirling-cycle mechanical cryocooler. The cooler was originally manufactured in 1994, and accumulated 11,000 hours of operating time before its counterbalance was replaced in 2000. The cooler ran for another 1000 hours through the final qualification and checkout process of the RHESSI spectrometer, and has now accumulated over 10,000 hours on orbit with no anomalies.

While operating on orbit, the cryocooler thermal performance has remained at or near nominal, maintaining the detectors at temperature, while exhibiting a slow increase in operating power from its initial value of 52W. This power trend, at a rate of approximately 15mW per day, shows short-term variations due to the orbital fraction of daylight, but has overall maintained a steady slope. At the current rate, the cooler, which has a maximum power rating of 100W, should not exceed 80W before June 2007. The cooler has also shown a small increase in vibration during this time, but this has been reduced back to near original levels by adjusting the phase of the cryocooler counter-balancer. There has been no impact on spectrometer resolution.

Solar Aspect System (SAS)

The SAS is used to provide information on the pointing of the imager with respect to the Sun center. The concept of redundant measurements of solar limbs led to a very good calibration of the instrument in an early stage of the mission. Since May 2002, the SAS provides pointing measurements with an accuracy of typically 0.2 arcsec (rms) in the rotating frame. This is well below the requirement of 0.4 arcsec. Furthermore, the quality of the pointing measurements is not affected by the complicated dynamics of the S/C, which has an off-pointing of up to 12 arcmin and a typical coning angle of 6 arcmin.

The high quality of the SAS data allowed a simplification of the fit of the limb positions without using any knowledge of the PSF of the instrument. Therefore, the online reconstruction of the aspect solution has no significant contribution to the computing time of the ground-based analysis.

During the first few month, the sensitivity of the SAS decreased rapidly. After one year into the mission, the decay has flatten to a stable level with an overall loss in sensitivity of the order of 30 %. This lowered, but stable sensitivity has no effect on the overall accuracy of the instrument.

Roll Angle System (RAS)

RHESSI has two redundant systems to provide the roll angle of the imager as a necessary ingredient for image reconstruction, the CCD-based Roll Angle System (RAS) (Fivian et al 2002) and the Photomultiplier Tube Roll Aspect System (PMTRAS) (Hurford and Curtis, 2002). Since launch the PMTRAS has been the source of roll aspect for RHESSI image reconstruction. This system has performed well, typically providing roll aspect with an accuracy of ~0.1 arcminutes rms, a factor of 10 better than required and supports image placement to ~1 arcsecond. No measurable degradation in PMTRAS performance has been noted to date. Initial data analysis issues, related to star misidentification, are being resolved by the generation of a mission-long roll-aspect database.

For the RAS, however, the rate of false triggers (due to the Earth albedo) is higher than expected. To calculate the roll angle to the required level of accuracy, sophisticated filtering, averaging and smoothing of the measured star events are needed. The complex calibration process required for this has been accomplished. The RAS data are presently being used to fill the PMTRAS data gaps in the roll angle database. These data gaps are in the order of 2 % for the total time of the mission up until now.

Unlike the PMTRAS, which only measures the roll angle, the RAS can measure the polar angle for stars with an accuracy of better than 10 arcsec. Thus, RAS can be used to determine the pointing of the RHESSI imager when the Sun is not in the field of view of the SAS. This capability can be used to image non-solar source such as the Crab nebula.

2.a.3. Mission Operations and Data Analysis

In 1999, a multi-mission operations facility was established at Berkeley to support the RHESSI and FAST missions. The joint facility, which now also supports CHIPS operations, includes the Mission Operations Center (MOC), the Science Operations Center (SOC), the Berkeley Ground Station (BGS) and the Flight Dynamics Center (FDC). 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. The facility is staffed during normal working hours and performs automated pass supports, spacecraft and instrument state-of-health checking, and generation of all mission planning products in a “lights-out” mode.

Ground Stations

The primary ground station for the RHESSI mission is the Berkeley Ground Station. Wallops Flight Facility serves as secondary command and control 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 a MOU with our German collaborator (Dr. Gottfried Mann at the Astrophysical Institute in Potsdam). On average, RHESSI is supported 6 times per day by the BGS, and 4 times at Wallops, allowing recovery of an average data volume of 13.5 Gbits/day. Passes at Santiago and Weilheim are requested during times of increased solar activity or as contingency supports. Total data recovery efficiency generally falls between 95% and 99% (e.g. 98.6% during March of 2003). The following table summarizes all RHESSI passes for the entire mission.

Ground Station	Passes Supported as of 24-Apr-2003
Berkeley	2,340
Wallops	1,635
Santiago	328
Weilheim	131

The Berkeley Ground Station consists of a pedestal with a three-axis drive system, an 11-m parabolic reflector and S-band RF systems. 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. The system was rebuilt by the manufacturer, EMP Systems, and both azimuth and elevation gearboxes were retrofit with an improved bearing design. The BGS returned to service on July 25, 2002 and has since supported 1,600 RHESSI and 340 CHIPS passes. During the downtime, RHESSI was supported by the Wallops, Santiago and Weilheim ground stations with 10 passes per day on average.

Mission Operations Center

The RHESSI Mission Operations Center comprises a secure, state-of-the-art 600 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. During the first year of RHESSI operations the automation procedures have been refined to improve overall reliability. Operational software (SatTrack, ITOS, MPS, and SERS) and hardware are kept up-to-date to ensure continued operational status. Various equipment upgrades have been implemented to increase performance. The AC power in the entire MOC is protected by uninterruptible power supplies, which in turn are backed up by a Diesel generator.

Operations

RHESSI 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 NASA/OIG web site, quality checked and archived locally in a fully automated mode. Pass supports via the BGS 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 14.2 rpm to its nominal spin rate of 15 rpm. The FOT works closely with project scientists to determine 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 have been developed that allow FOT members, subsystem engineers and instrument scientists to monitor spacecraft and instrument performance remotely.

A contract on a time-and-materials basis is in place with the spacecraft provider, Spectrum Astro, to allow for sustaining engineering support. This contract was invoked to provide flight software patches for the ACS system to allow for off-pointing observations of X-ray sources passing near the Sun, such as the Crab nebula and the Galactic Center. Other software patches for the IDPU were provided by SSL engineers to optimize the data acquisition and shutter control algorithms on the spacecraft. 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 FOT members, subsystem engineers, instrument scientists, the PI and the spacecraft contractor. Only three anomalies occurred to date. Each of these events led to a reset of the spacecraft CPU or IDPU, and each event is understood and will be prevented in the future. The first two events were spacecraft CPU resets caused by a watchdog timer that tripped during verification of command loads that were large, but within the allowed size limits. The FOT recovered the spacecraft within two or three orbits each time. No data were lost since the IDPU continued to record data throughout these events. The third reset was an IDPU reset, caused by an operator who inadvertently sent a raw reset command. This command has now been embedded in a procedure and blocked from raw execution. In this case the FOT recovered the spacecraft within 24 hours. Two potential problems related to the spacecraft CPU are known, namely a VxWorks sine function bug that could impact ACS functions during infrequent off-pointing observations, and a potential RAD6000 EEPROM bit-flip problem. The latter is monitored by reading out the checksum once per week.

Science Operation

RHESSI data in the form of telemetry packets are received in the Science Operations Center (SOC) after every ground station contact. An automated IDL script is used for level-0 processing. The telemetry packets are checked for errors, time sorted and output into files with FITS binary table formatting. There are typically 1 to 2 files per orbit, with a maximum size of 100 Mbytes per file. Information about the packets contained in the level-0 files and the relation between the spacecraft clock and UT is written to database files, which are distributed with the RHESSI software package. The level-0 files are mirrored to GSFC and ETHZ, in addition to being stored online at SSL. The original files received from the ground station are archived on CD-ROM in addition to being stored online at SSL. As of late April 2003, there is approximately 1 Tbyte of level-0 data, an average of approximately 1.8 Gbyte of data per day.

In addition to creating the level-0 data files, the IDL procedure also generates quick-look data that are made available in graphical form and in FITS files. At present, the quick-look data files contain the RHESSI Observing Summary, and Flare List. The observing summary contains the following information: spin-averaged count rates, in 9 energy bands summed over all detectors, the modulation variance in the count rate in collimators 8 and 9, spacecraft position, and various data flags,(e.g., SAA passage, flare, particle event, etc..). Aspect data, such as spacecraft pointing, roll period, and roll angle are also included. Quick-look plots are available for each orbit, consisting of count rate, monitor rate and particle rate plots.

The flare list contains the following information for each flare: an ID number, start_time, end_time peak_time, background accumulation time range, highest energy band of observed data, peak, total and background count rates, total counts, and position on the Sun. A full-mission flare list is distributed with the RHESSI software package. There are currently approximately 8000 flares in the flare list. 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 of the data, the level-0 data, quick-look files and plots, and SOH data are available from the RHESSI Data Center website: http://rhessidatacenter.ssl.berkeley.edu.

Science Operations are monitored by the RHESSI "Tohban", following the example of Yohkoh. The Tohban for each week is appointed at the weekly operations meeting. He or she surveys the real-time data for the ground station contacts via the RHESSI status web page (http://hessi.ssl.berkeley.edu/ground_systems/hessi_spacecraft_status.html), and confirms that key SOH parameters, such as the fill level of the spacecraft memory, the monitor rates, the various temperatures, the accelerometer readout, and cryocooler power are within their operational specifications. (This is in addition to the monitoring of the system by the flight operations team.) The Tohban consults with the flight operations team about any science-related issues, and alerts the flight operations team if there is a need to replay data from the spacecraft memory, e.g., if there is noisy data. Also, the Tohban will communicate if necessary with ground-based observers (e.g. via Max

Millennium) with regard to observing campaign activities.

2.a.4. RHESSI Contributions to a Distributed Environment for Accessing and Integrating SEC Data

Since the beginning of the project we have recognized the importance of integrating RHESSI data with other data sets. As a result, several team members play a leading role in generic data modeling, web services and virtual observatory activities (Csillaghy et al. 2000). These efforts are focused on both maintaining and expanding current capabilities using evolutionary methods and facilitating future revolutionary techniques.

As a first step towards supporting a distributed environment for accessing and integrating Sun-Earth Connection (SEC) data, we have constructed the RHESSI Synoptic Data Archive (hereafter referred to as the Synoptic archive). The Synoptic archive is a database of observations obtained during RHESSI-observed flare times from cooperating space- and ground-based observatories. The observations span a wide range of wavelengths including soft X-rays (GOES), EUV (SOHO/EIT & TRACE), H-alpha (BBSO), radio (OVSA, Phoenix), and optical magnetograms (SOHO/MDI). The Synoptic archive is maintained at the Goddard Solar Data Analysis Center (SDAC), where it is updated daily and made accessible to the solar- and space-physics research community via the Web-based Max Millennium catalog and transparently through the distributed Solar Software (SSW). Team members have also played a leading role in integrating the new GOES-12 Solar X-ray Imager (SXI) observations into both the SSW environment and the RHESSI environment for joint analysis.

In the domain of data modeling, members of the RHESSI team are playing a leading role in the definition of a global schema that describes solar observations in a generic way. In this context, a schema is a set of definitions connecting a dataset and the metadata abstractions used to facilitate data processing on a remote server. The global schema consists of elements from several sub-schemata, such as a flare schema, an active-region schema, a schema for whole-Sun observations, etc. We are designing an object-relational schema for solar flares that will allow queries that combine both generic attributes, such as time interval and active region, with instrument-specific parameters such as energy or wavelength range. Thus, complex queries over several catalogs are possible. For instance, we can search for events observed by several instruments, or by only one instrument, we can compare flare locations, and so on.

In the domain of standardization of the global data model, we are undertaking an implementation of the schema into both a relational database system and an XML Schema (in fact both definitions are interchangeable in several database systems). We are currently investigating the format of the XML schema, as several choices are possible. We can either match our developments with a similar ongoing effort for the NSO Holdings (Hill, Csillaghy et al. 2002) or we could match our developments with the astrophysics standard VOTable of the Virtual Observatory Alliance (Williams et al. 2002), or we can do both. Although doing both would be better, technical considerations may lead us in one or the other direction.

In the domain of web services, we are considering providing a Web Service Data Language (WSDL) description of several entry points in RHESSI data. Through WSDL it is possible to create custom data products on demand by passing instructions to our SSW/IDL software running on a server. In a first phase, we plan to develop web services for the RHESSI flare list and for the RHESSI file database. In a second phase, we will investigate the possibility of making the RHESSI images, light curves, and spectra available over a web service. We have developed a web service for the GOES flare list as a prototype. This exercise has shown that the development time needed for such an application is relatively low. In parallel we are investigating a Simple Object Access Protocol (SOAP) interface to read SOAP messages in the IDL data analysis environment and transform them into IDL data structures.

The effort described above will facilitate the integration of RHESSI data into a solar virtual observatory. One of the RHESSI software team members (Csillaghy) is a Co-I on the European Grid of Solar Observations (EGSO, Bentley et al. 2002), the European version of the Virtual Solar Observatory, which also has NASA/GSFC and NSO participation. Furthermore, the RHESSI data will be easily integrated into the US-funded Virtual Solar Observatory (Martens et al. 2002) since this project is also based on the same web services approach.

RHESSI Data Access and Archiving

RHESSI differs from many imagers in that, instead of transmitting a pre-selected subset of images, the telemetry includes all of the information about each detected photon. Thus, the data analyst can make tradeoffs among time resolution, spectral range and resolution, spatial resolution, image quality, etc., on the ground. These decisions can be made on a case-by-case basis to match the unique characteristics of the event under study and the relevant scientific objective. A key driver of our data analysis approach is the preservation of this flexibility so as to extract the maximum scientific return from the observations. This means that all detailed scientific analysis will use the same primary database with the most current calibration information.

This approach for RHESSI data reduction and analysis has been implemented by ensuring that (1) the complete data output of the RHESSI mission is made available promptly to the scientific community, without restriction; and (2) a fully documented analysis package, supported by a range of platforms, is available to the scientific community, with the same toolbox of software used by the PI team. A promptly-generated catalog of summary data products is distributed with the RHESSI data base, to serve as a multi-parameter index and overview of the data base and to provide data products to users not requiring custom analyses.

The data analysis software is also freely available and can be conveniently downloaded as part of the Solar Software (SSW) tree. The extensive RHESSI software package, mostly written in the IDL programming language, contains all procedures necessary to read the data FITS files, prepare and plot light curves, images, and spectra, and output the results for further customized analysis. Furthermore, the joint analysis of many different observations of the same events by other observatories is greatly facilitated, since most other solar space missions and many ground-based observatories also have their analysis software in this same SSW tree. A convenient interface is provided to allow easy comparison of RHESSI images and light curves with similar products from SOHO, TRACE, GOES, Big Bear, etc. The analysis procedures can all be invoked from the IDL command line, or a more user-friendly graphical user interface is also available for basic analysis tasks. All the software is fully compatible with both the Unix and Windows operating systems. The SSW system allows for rapid bug fixes and software upgrades that can be downloaded to each user's own computer at any time from a central server, at least four of which exist at the following locations: Berkeley, Goddard, ETH at Zurich, and Nobeyama.

Since arrival time, recording detector, and energy information are available for each individual photon, the data analyst can make a wide variety of science-driven trade offs that wouldn't otherwise be possible. Specifically, the analyst can select the time resolution and cadence, the energy range and resolution, and the spatial resolution, image quality, and field of view. Tradeoffs can be made in response to the nature of the flare and the specific scientific objectives of the analysis. The main limitation is in the processor speed and the time it takes to carry out the various analysis tasks. The online quick-look light curves in .png format allow for a more rapid evaluation of the available observations of specific time intervals prior to carrying out more detailed and time-consuming analysis.

Data Analysis Workshops and Websites

In an effort to familiarize as many interested scientists as possible with analyzing RHESSI observations, we have held an ongoing series of hands-on workshops. These provide a combination of presentations by software developers and hands-on experience for potential users of RHESSI software. Two data analysis workshops were held before launch, one at Goddard and one at Berkeley, and one just after launch at ETH in Zurich. They provided training to about thirty scientists at each workshop in accessing RHESSI data and in the use of the image reconstruction and spectral analysis software. This not only represented an additional channel by which to reach potential users of RHESSI observations, it also provided useful feedback to the software development team. The workshops were an integral part of our documentation strategy and provided the impetus for the creation for many of the documents found on the RHESSI Data Center website – http://hesperia.gsfc.nasa.gov/rhessidatacenter/.

On-line documents are available on this site for all the software, from beginner guides to the detailed manuals required by program developers. We believe the workshops have been highly successful and have enabled many scientists to conduct scientific analysis of the RHESSI data that may otherwise have been intimidated by the unfamiliar nature of the observational technique and the data analysis methods.

Other useful RHESSI websites are listed in Table 5.

Table 5: RHESSI Web Resources

Home Pages:	
Berkeley	http://hessi.ssl.berkeley.edu/
Goddard	http://hesperia.gsfc.nasa.gov/hessi/
ETH Zurich	http://www.hessi.ethz.ch/
Paul Scherrer Institut	http://hessi.web.psi.ch/
Spacecraft Status	http://soleil.ssl.berkeley.edu/ground_systems/hessi_spacecraft_status.html
Observation times on GOES	http://sprg.ssl.berkeley.edu/~hhudson/goes_hessi_plots/
Long-term state-of-health plots	http://hesperia.gsfc.nasa.gov/hessidata/metadata/hsi_1day_sohdata/
Flare catalog	http://hesperia.gsfc.nasa.gov/ssw/hessi/dbase/hessi_flare_list.txt
Quicklook Data: - Light Curves	http://hesperia.gsfc.nasa.gov/hessidata/metadata/
Light Curves + GOES & WIND	http://sprg.ssl.berkeley.edu/~krucker/hessi_plots/
Images and Spectra	http://www.hedc.ethz.ch/www/quick_dp_search.html
Accessing RHESSI data	http://hesperia.gsfc.nasa.gov/ssw/hessi/doc/hessi_data_access.htm
Data Center -GSFC	http://hesperia.gsfc.nasa.gov/rhessidatacenter/
HE Data Center - Zurich	http://www.hedc.ethz.ch/
Data Analysis Projects	http://solar.physics.montana.edu/rhessi/projects/default_page.pl

Synoptic Data Archive	http://orpheus.nascom.nasa.gov/~zarro/synop/show_synop.html
Active Region Monitor - ARM	http://www.bbso.njit.edu/arm/latest/
Publication List	http://www.lmsal.com/~aschwand/publications/hessi.html
Solar Physics Special Issue	http://www.kluweronline.com/article.asp?J=5172&I=72
Gamma-ray-line flare papers	http://sprg.ssl.berkeley.edu/~hhudson/rhessi/
Max Millennium Program of Solar Flare Research	http://solar.physics.montana.edu/max_millennium/
Education &Public Outreach – UCB GSFC	http://cse.ssl.berkeley.edu/hessi_epo/ http://hesperia.gsfc.nasa.gov/hessi/outreach.htm
Solar Flare Theory	http://hesperia.gsfc.nasa.gov/sftheory/index.htm

Science Workshops

More recently, a series of general workshops, held approximately annually, has been initiated. These workshops are aimed at bringing scientists together in small teams to explore topics in solar flare physics with the emphasis on areas that can be addressed with the RHESSI mission. At each workshop, the participants are organized into working groups, led by motivational team leaders, with each team aimed at addressing specific problems in high-energy solar flare physics. The first general workshop with over 50 participants was held in Berkeley in October 2002. The second general workshop will be held following the Solar Physics Division Meeting in Lanham, MD in June 2003, and the third is planned for Meudon, France, in the spring of 2004. We expect the goals of the general workshop series to evolve from a primarily "data analysis" mode in the early stages to a more "scientific results" oriented focus later in the series. Proceedings will be published summarizing the scientific results of the workshop series.

In between these general workshops, participants are encouraged to hold and/or attend smaller more topical workshops. The first of these focused on "Distribution Functions of Energetic Flare particles" will be held in Glasgow, Scotland, in June 2003. A second such workshop to be held in Taos, NM, in October 2003 will focus on joint observations with RHESSI, ACE, and Wind. These workshops allow participants to interact in small-group discussions of problems of common interest, built upon and motivated by the research activities of group members. Computer and network facilities are provided at each workshop to enable participants to perform hands-on data analysis, using both RHESSI data and data from supporting instrumentation. The results from the topical workshops will be reported at the general workshops and used for review, assessment and planning of ongoing studies in identified areas.

Smaller workshops are organized by RHESSI collaborators. For example, Nobeyama Solar Radio Observatory will have a data-analysis workshop this July for domestic solar researchers using NoRH and RHESSI data.

2.a.5. References

Alexander, D. and Metcalf, T. R., ApJ, **489**, 422, 1997

Aschwanden, M. J. et al., ApJ 535, 1047, 2000

Aschwanden, M.J. et al., Solar Physics **210**, 193, 2002

Bentley, R.D and the EGSO Consortium, ESA SP-506, **2**, 2002

Benz, A. O. and Grigis, P. C., Solar Physics **210**, 431, 2002

Brown, J. C. et al., Solar Physics **210**, 373, 2002

Cane, H. V., et al., JGR, **107**, pp. SSH 14-1, CiteID 1315, 2002

Coburn, W., and Boggs, S., Nature, in press 2003

Crosby, N. B., et al., Solar Physics, 143, 275, 1993

Csillaghy, A. and Benz, A. O., Solar Physics, **188**, 203, 1999

Csillaghy, A., Zarro, D.M., Freeland, S., IEEE Signal Processing Magazine, **18**, No 2, 2001

Dennis, B.R., et al., "Thermal and Nonthermal Contributions to the Flare X-ray Flux," AAS/SPD meeting, June 2003.

Dennis, B.R., et al., COSPAR Colloquia Series, Adv. Space Res., 2003, in press.

Dere, K. P.; Landi, E.; Mason, H. E.; Monsignori Fossi, B. C.; Young, P. R., A & A Supplement series, **125**, 149-173, 1997.

Drake, J. F. et al., Science, **299**, 873., 2003

Emslie, A. G., ApJ Letters, in press 2003

Emslie, A. G. et al., ApJ Letters, in press 2003

Fargion, D., ApJ, **570**, 909, 2002

Fishman, G. J. et al., Science, **264**, 1313, 1994

Fivian, Henneck, Mchedlishvili and Zehnder, Solar Physics, **210**, Nos. 1-2, 27-100, 2002

Fivian, M., et al., COSPAR Colloquia Series, Adv. Space Res., 2003, in press.

Gallagher, et al., Solar Physics, **210**, Nos. 1-2, 341-356, 2002

Gallagher, P. T., Lawrence, G. R. and Dennis, B. R., ApJ **588**, 53, 2003

Gopalswamy, N. et al., ApJ, **572**, 103., 2002

Gordovsky, M. and Zharkova, V.V., National Astronomy Meeting (NAM), Dublin, Ireland, 2003

Hester, et al., ApJ, **577**, 49 2002

Hill, F. et al., Proceedings of the SPIE, **4846**, 35-42, 2002.

Holman, G. D. et al., ApJ Letters, in press, 2003

Hudson, H.S., et al., AAS/SPD meeting, June 2003

Hurford, G.H. and Curtis, D., Solar Physics **210**, 101, 2002

Hurford, G. J. et al., ApJ Letters, in press 2003

Hurley, K., BAAS, **201**, 69.01, 2002

Ji, H. et al., Ap.J., Submitted 2003a

Ji, H. et al., Ap.J., Submitted 2003b

Johns, C. M. and Lin, R. P., Solar Physics **137**, 121, 1992

Kahler, S., ApJ**, 428**, 837, 1994

Kane, S. R. and Anderson, K. A., ApJ, **162**, 1003, 1970

Klein, K.-L. et al., Astronomy and Astrophysics, 373, 1073, 2001

Kosugi, T. et al., Solar Physics, **136**, 17., 1991

Krucker, S., et al., Solar Physics, **210**, Nos. 1-2, 445, 2002

Krucker, S. et al., ApJ Letters, in press, 2003

Kundu, et al., PASJ, **44**, 173, 1995

Larson, D. et al., AGU, Spring Mtg, abstract #SH61A-09, 2001

Lehtinen, N. G., Bell, T. F, & Inan, U. S., JGR, **104**, 24699, 1999

Lin, R. P. and Hudson, H. S., Solar Physics, **50**, 153, 1976

Lin, R. P. et al., ApJ Letters, **251**, L109, 1981

Lin, R. P. et al., ApJ **283**, 421, 1984

Lin, R. P., Solar Physics, **100**, 5371985

Lin, R. P., Reviews of Geophysics, **25**, 676, 1987

Lin, R.P., EOS Trans. AGU, **75**, #40, 457, 1994

Lin, R. P. et al., GRL, **23**, 1211 1996

Lin, R. P., et al., ApJ, **557**, 125., 2001

Lin, R. P. et al., ApJ Letters, in press 2003

Lorentzen, K. R. et al., JGR, **105**, 5831, 2000

Makashima, K. et al., in New Instrumentation for Space Astronomy,K. A. van der Hucht and G. Vaiana eds., New York: Pergamon Press, 1977

Mandzhavidze, N., et al., ApJ, **518**, 918, 1999

Martens, P. C. H., et al., AAS Mtg., 201, #141.03, 2002

McConnell, et al., Solar Physics, **210**, Nos. 1-2, 125-142, 2002

McConnell, M.L., et al., BAAS, **35**, 22.20, 2003

Mewe, R., et al., J. High Energy Astrophysics Science Archive Research Center (HESARC), NASA GSFC, **6**, 16, 1995.

Millan, R. M., et al., GRL, **29**, 47, 2002.

Murphy, R. J. et al, ApJ, **371**, 793., 1991

Oieroset, M. et al., Physical Review Letters, **89**, id. 195001, 2002

Phillips, K.J.H., et al., ApJ Letters, **589**, 2003 June 1, in press.

Piana, M. et al, ApJ Letters, in press., 2003

Rauscher, E., et al., AGU Fall Mtg., abstract #SH52A-0482 , 2002

Reames, D. V., et al., ApJ, **292**, 7161985

Reames, D.V., et al., ApJ, **466**, 473 1996

Saint-Hilaire, P., et al., Solar Physics, **210**, Issue 1, 143-164, 2002.

Saint-Hilaire, P. and Benz, A.O., Solar Physics, **210**, Nos. 1-2, 287-306, 2002

Schmahl, E.J. and Hurford, G.J., Solar Physics, **210**, Nos. 1-2, 273-286, 2002

Schwartz, R. A. et al., Solar Physics, **210**, 165, 2002

Share, G.H. et al., Solar Physics, **210**, Nos. 1-2, 357-372 2002

Share, G. H. et al., ApJ Letters, in press., 2003

Shibata, K. et al., PASJ, **44**, 173, 1992

Shimizu, T., PASJ **47**, 251, 1995

Smith, D. M., ApJ Letters, in press, 2003

Smith, D. M. et al., ApJ Letters, in press, 2003

Vestrand, W.T. and Forrest, D.J., ApJ, **409**, 69, 1993

Williams, R., ASP Conference Proceedings, **281**, 29, 2002

Zehnder, A. et al., COSPAR Colloquia Series, Adv. Space Res., 2003, in press.

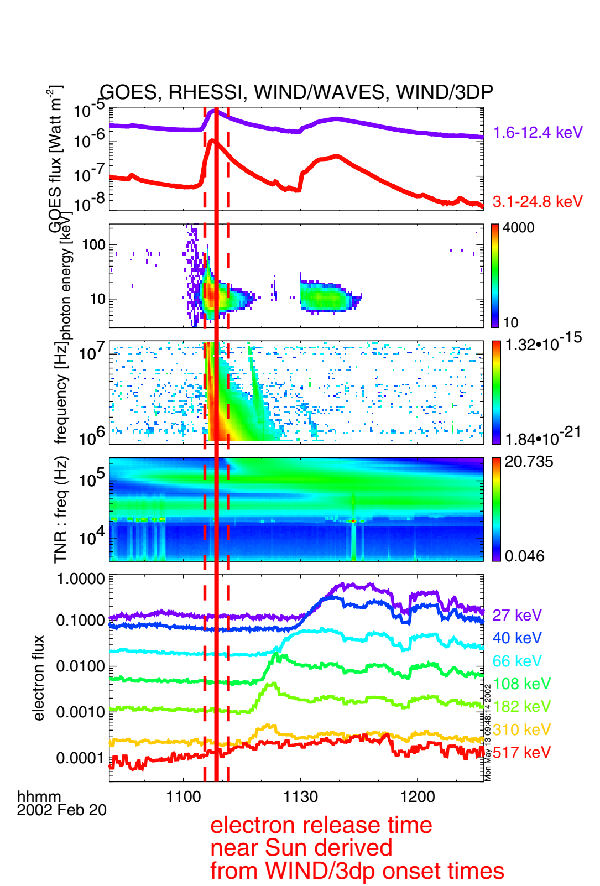


FIGURE 1:
X-ray, radio, and in-situ observations of energetic electrons: From top to bottom the panels show: GOES light curve, RHESSI x-ray spectrogram, WIND/WAVES radio spectrograms, and in-situ electron observations from WIND/3DP.

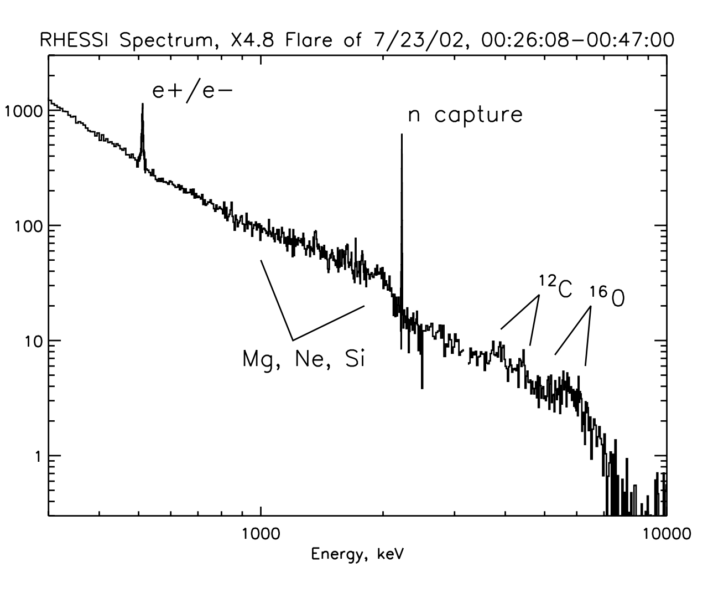


FIGURE 2
X-ray/gamma-ray spectrum of the July 23 gamma ray flare.

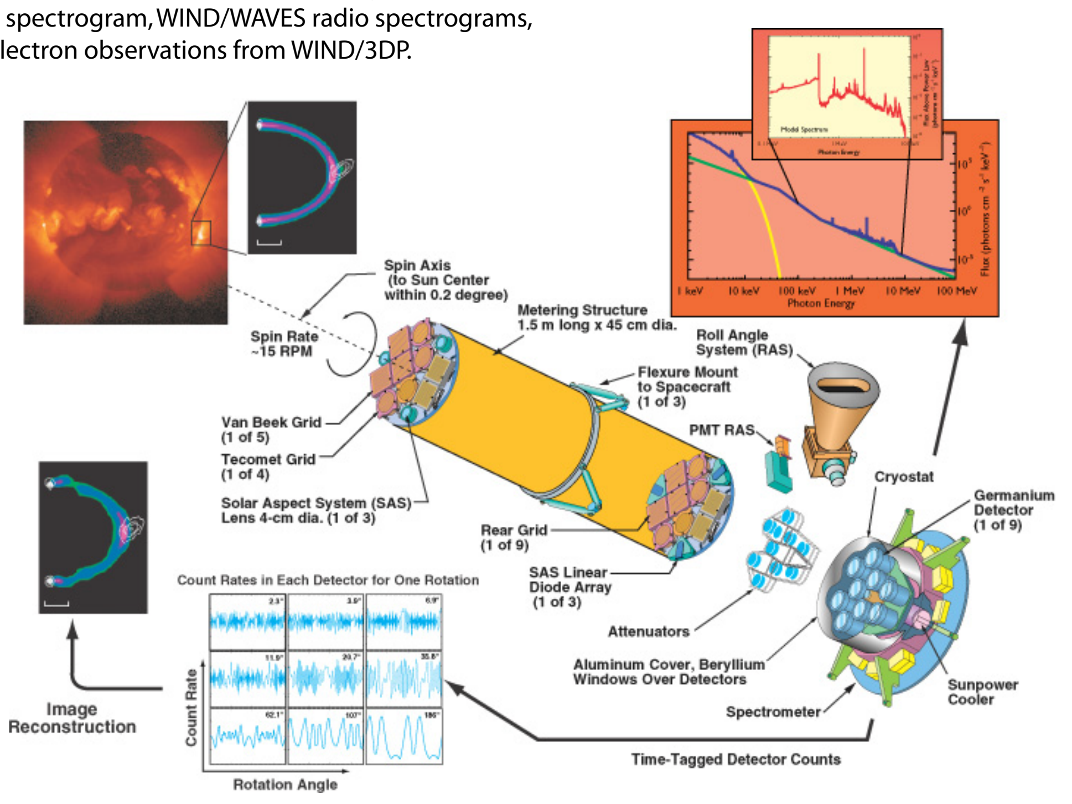


FIGURE 3:
Schematic of the RHESSI instrument illustrating the imaging spectroscopy. X-rays and gamma-rays from the Sun (upper left) pass through the slits of the front and rear grids of each of the nine grid pairs to reach the germanium detector. As the spacecraft rotates the detector count rates are temporally modulated (lower left). These modulations can be analyzed to reconstruct the image. The germanium detectors are cryogenically cooled to provide high spectral resolution capable of resolving narrow gamma-ray lines and steep solar continuum spectra (upper right). The attenuators are inserted automatically when the count rate approaches saturation. The SAS and RAS provide solar pointing and roll aspect information.

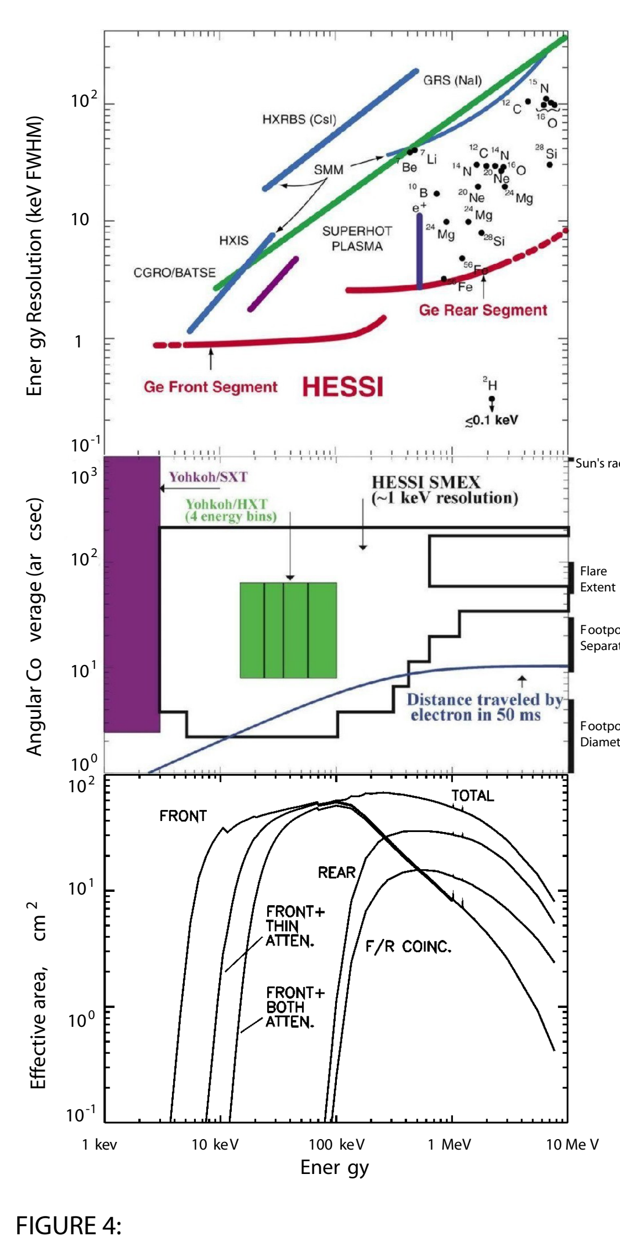


FIGURE 4:
a) RHESSI's FWHM energy resolution (lower curves), compared with previous instruments (upper lines). The dots are the expected FWHM widths of the predicted gamma-ray lines, and the vertical line the range of widths (temperature and density dependent) for the positron annihilation line. The short diagonal line shows the resolution to resolve the steep "superhot thermal" emission.

b) RHESSI's angular resolution versus energy, compared to Yohkoh SXT (left) and HXT (center). RHESSI has ~1-10 keV energy resolution over this energy range and can image up to 17 MeV, while HXT had four broad energy channels from 15 to 100 keV.

c) RHESSI's effective (photopeak) area as a function of energy for solar X-rays/gamma-rays. The three curves to the left show the effect on the front segment response (summed over all nine detectors) of no attenuators, thin attenuator, or both thick and thin attenuator inserted over the detectors. The curves to the right show the effective area for the rear segment, and for photons that leave energy in both the front and rear segment of the detectors (F/R coincidence).

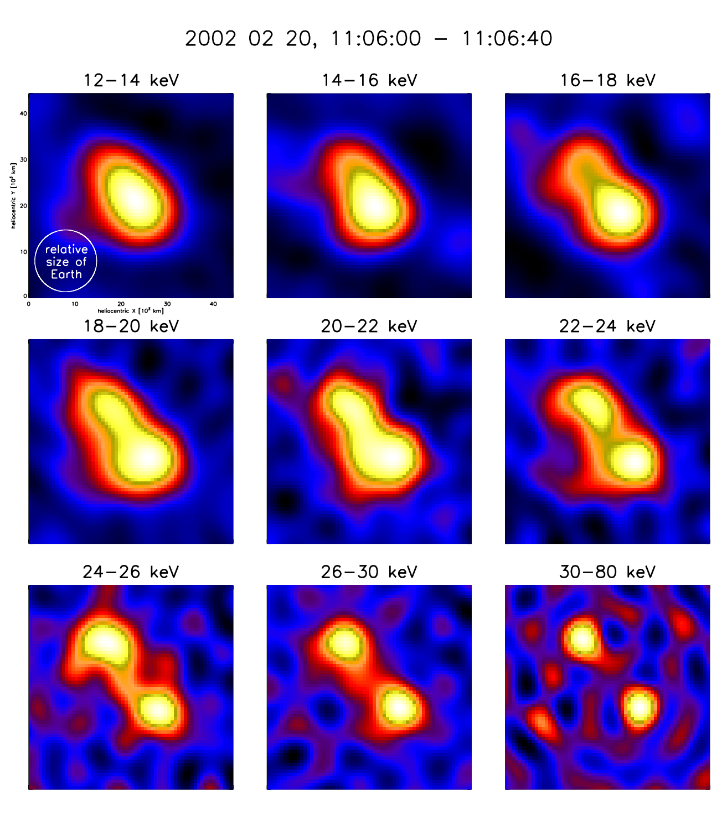


Figure 5:
Imaging spectroscopy of the February 20, 2002 flare. Images (64"x64") at different energies are shown. The spatial resolution is 8".

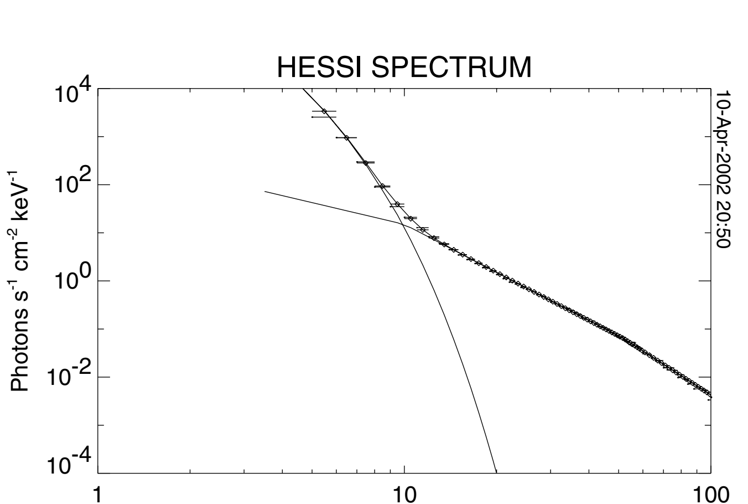


FIGURE 6:
RHESSI X-ray spectrum of the February 20, 2002 flare (cf. Fig. 1 and 4). A thermal and a broken power law are fitted to the observed spectrum.

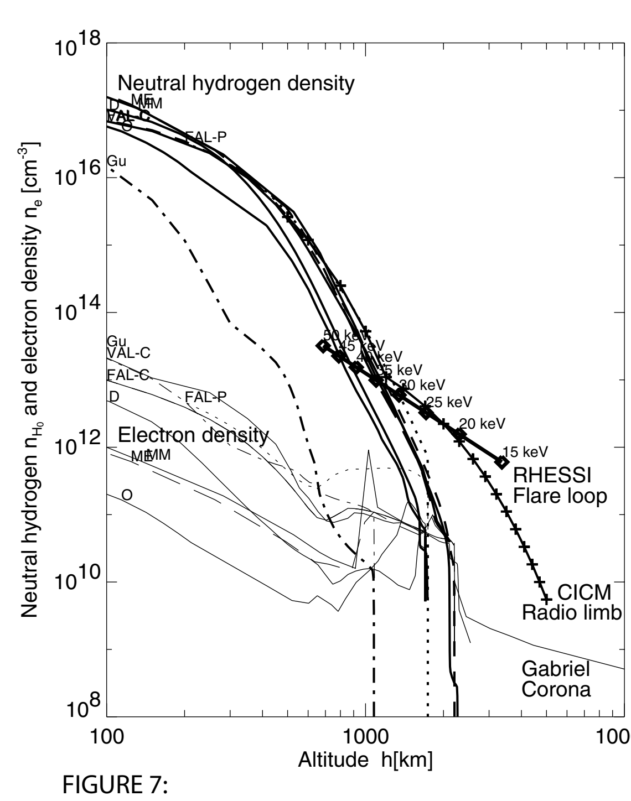


FIGURE 7:
A compilation of chromospheric and coronal density models and derived values from RHESSI observations (from Aschwanden et al. 2002).

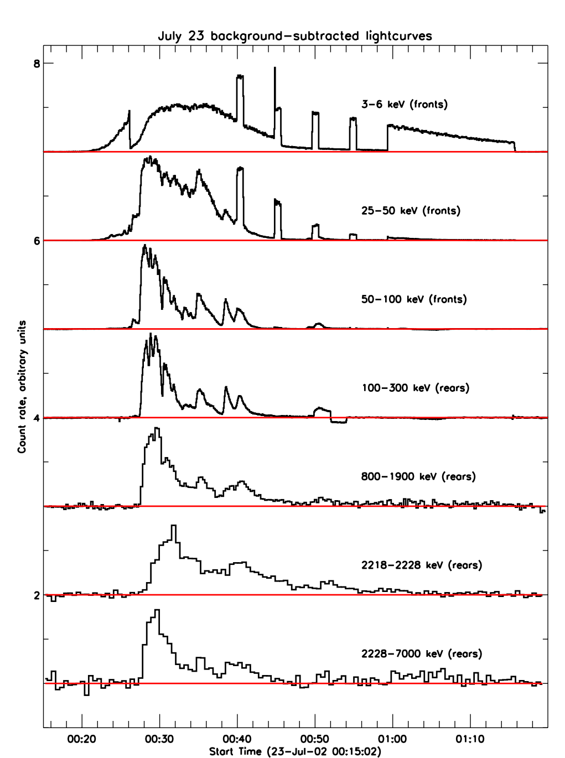


FIGURE 8:
Background-subtraced light curves for the July 23, 2002 gamma-ray flare at 7 different energies.

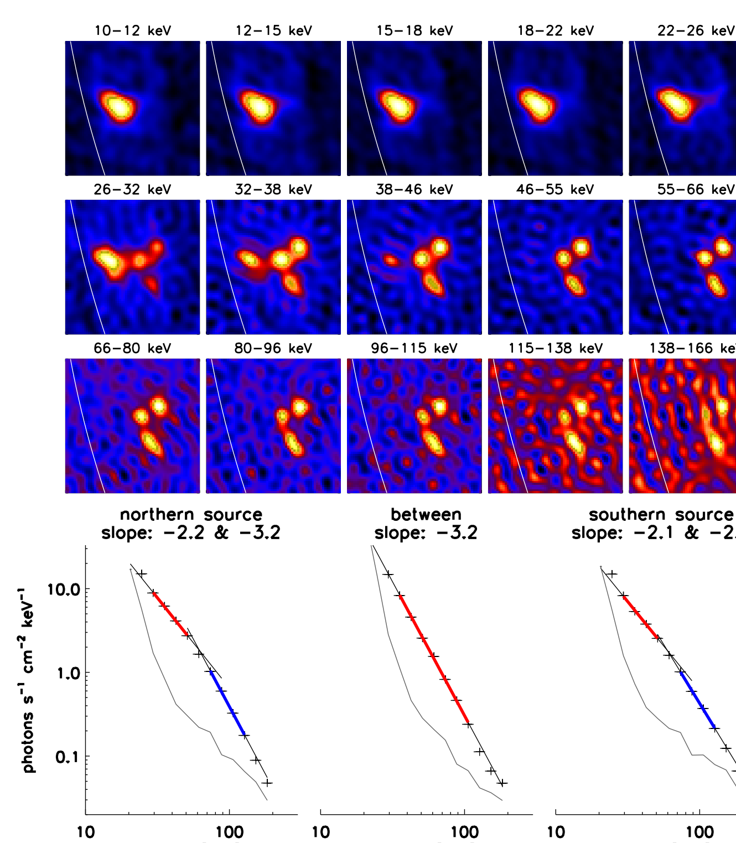


FIGURE 9:
Imaging of the July 23, 2002, X4.8 solar flare in 15 energy bands, from 2 keV wide bins at 10 keV, to 28 keV wide bins (for enough counts to image) at 138 keV, illustrating the changes in sources as a function of energy, from a single dominant elongated source at energies below ~30 keV to three sources above ~40 keV. The images are 64 arcseconds on a side; the thin white line marks the limb of the Sun. Bottom: The energy spectra of the three dominant sources at energies above ~40 keV, showing that the spectra are similar for the north and south sources but quite different for the source in between. The gray lines indicate background.

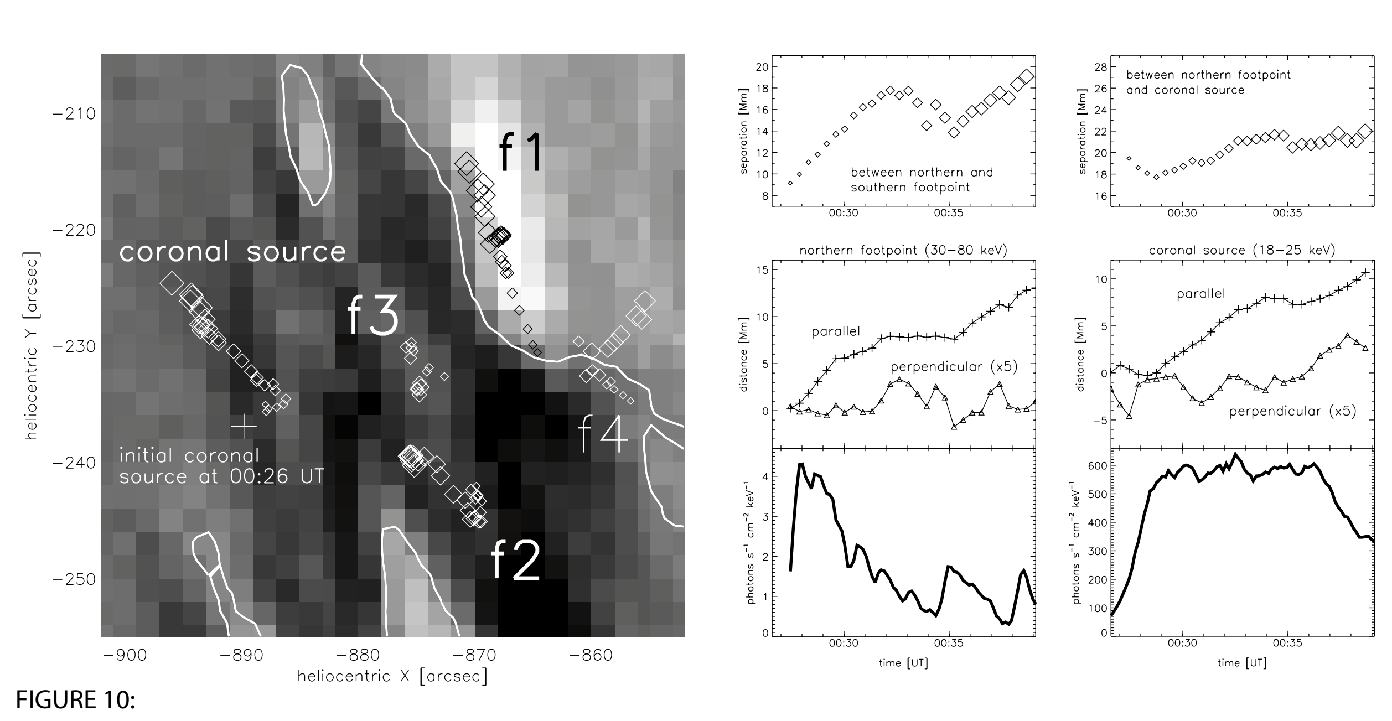


FIGURE 10:
Left: Temporal evolution of centroids of HXR sources f1, f2, f3, and f4 (30-80 keV) and the coronal sources (18-25 keV) taken from 27 s integrated images. The size of the diamonds represent time (00:26:55UT - 00:39:07UT). The gray-scale image is a SOHO MDI magnetogram. The apparent neutral line is shown in white. Right: Relative separation in time of the two main footpoints f1 and f2. Below: Source motion of f1 (right) and the coronal source (left). The source motion parallel (crosses) and perpendicular (triangles, multiplied by 5) to the main direction of motion and the total flux are shown.

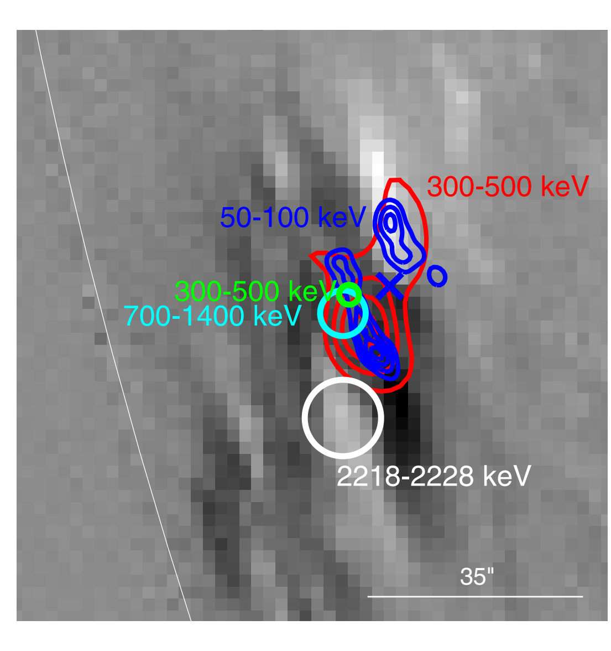


FIGURE 11:
Location of the gamma-ray source. The circles represent the 1-sigma errors for the energies given. All these images are made with identical imaging parameters. The FWHM angular resolution is shown in the lower right. Blue contours show the high resolution 50-100 keV map at 3" resolution and the red contours represents the 300-500 keV map with 8" resolution. The blue X shows the centroid of the 50-100 keV emission made with the same lower resolution as the gamma-ray maps. The background image is a SOHO/MDI magnetogram.

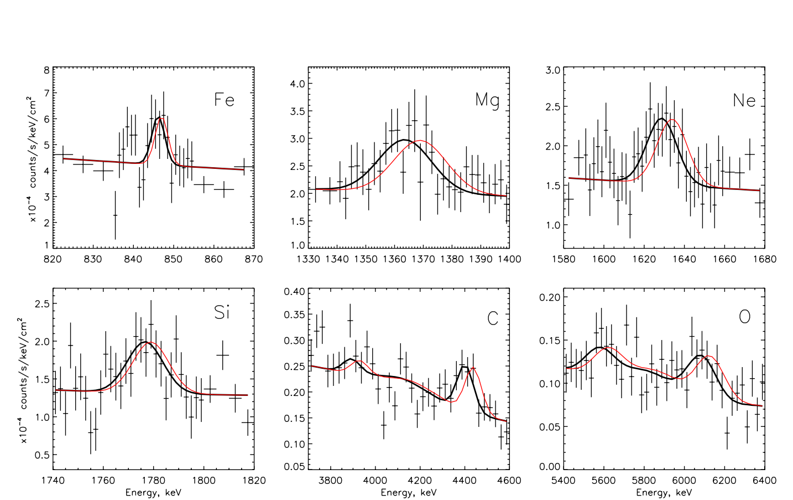


FIGURE 12:
RHESSI background-subtracted count spectra from 00:27:20UT to 00:43:20UT on 23 July, 2002. Each panel is labeled with the element primarily responsible for the line shown. The carbon and oxygen lines also show the secondary peak from escape of a 511 keV positron-annihilation photon, which also contains information on the line shape. The heavy cube shown in each panel a Gaussian fit plus the underlying bremsstrahlung continuum and broad lines, convolved with the instrument response. The lighter line is the same fit forced to zero redshift for comparison. The error bars are from Poisson statistics.

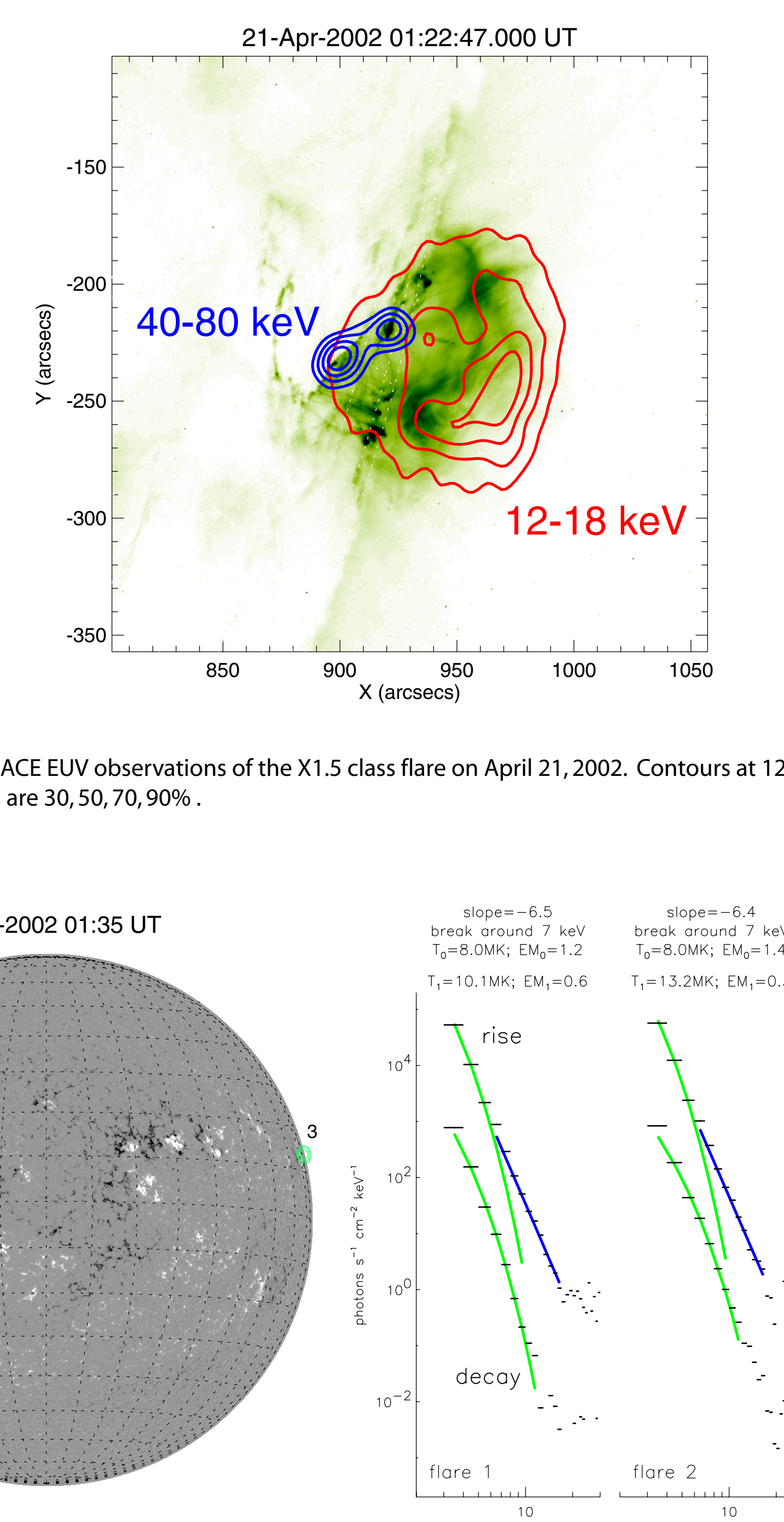


FIGURE 13: RHESSI and TRACE EUV observations of the X1.5 class flare on April 21, 2002. Contours at 12-18 keV and 40-80 keV are shown. Contour levels are 30, 50, 70, 90% .

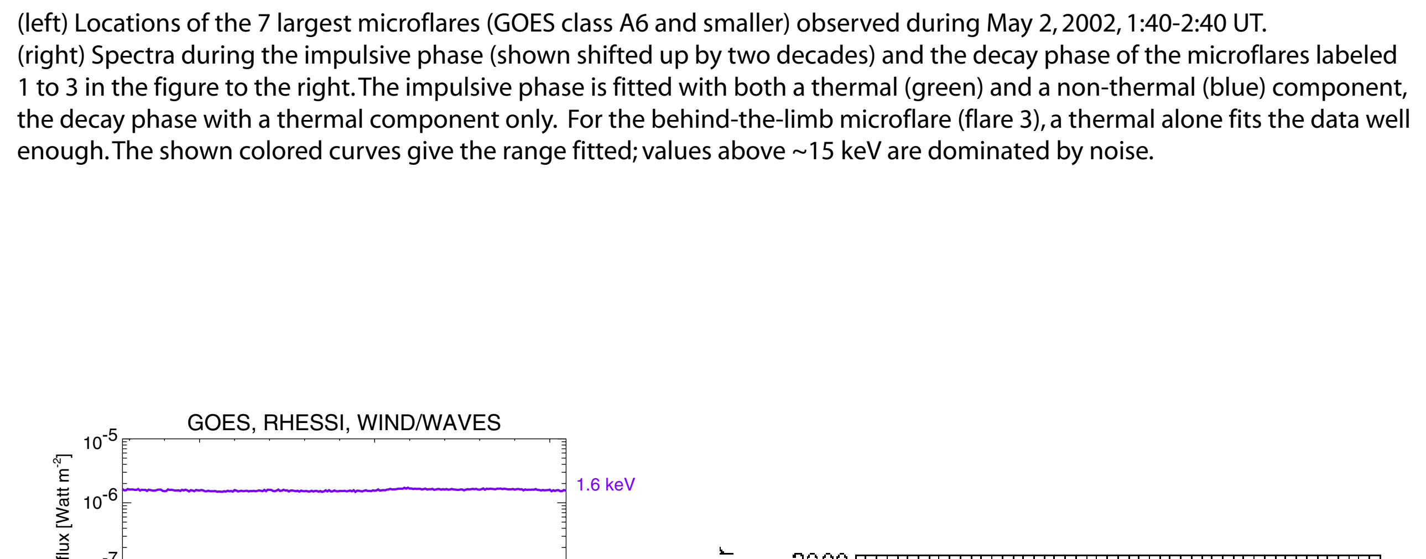


FIGURE 14:
(left) Locations of the 7 largest microflares (GOES class A6 and smaller) observed during May 2, 2002, 1:40-2:40 UT.
(right) Spectra during the impulsive phase (shown shifted up by two decades) and the decay phase of the microflares labeled 1 to 3 in the figure to the right. The impulsive phase is fitted with both a thermal (green) and a non-thermal (blue) component, the decay phase with a thermal component only. For the behind-the-limb microflare (flare 3), a thermal alone fits the data well enough. The shown colored curves give the range fitted; values above ~15 keV are dominated by noise.

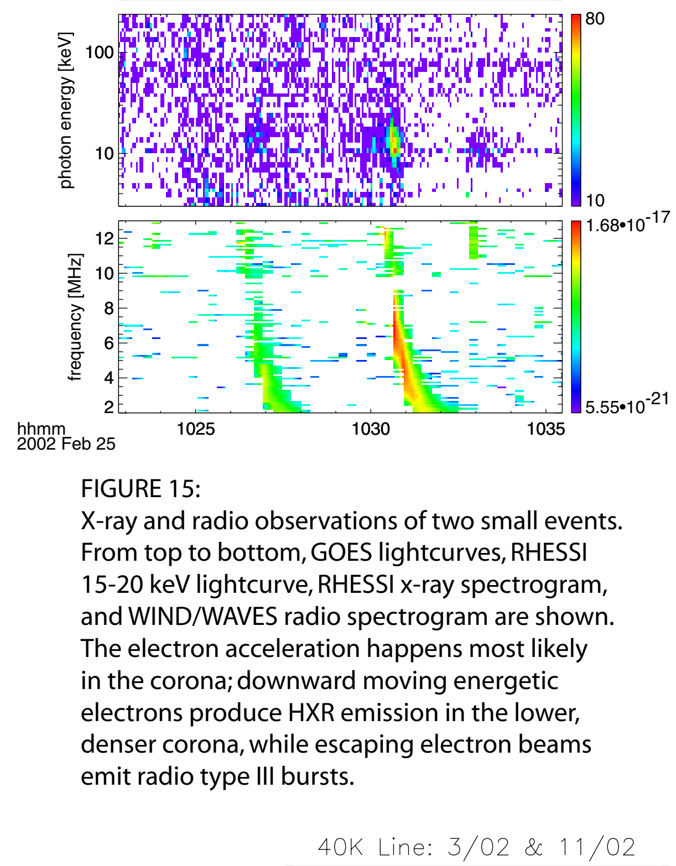


FIGURE 15:
X-ray and radio observations of two small events. From top to bottom, GOES lightcurves, RHESSI 15-20 keV lightcurve, RHESSI x-ray spectrogram, and WIND/WAVES radio spectrogram are shown. The electron acceleration happens most likely in the corona; downward moving energetic electrons produce HXR emission in the lower, denser corona, while escaping electron beams emit radio type III bursts.

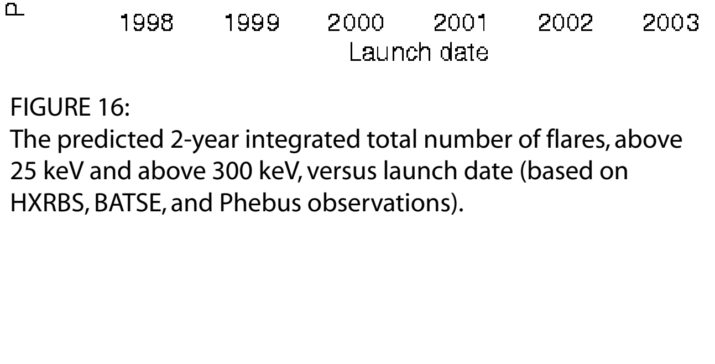


FIGURE 16:
The predicted 2-year integrated total number of flares, above 25 keV and above 300 keV, versus launch date (based on HXRBS, BATSE, and Phebus observations).

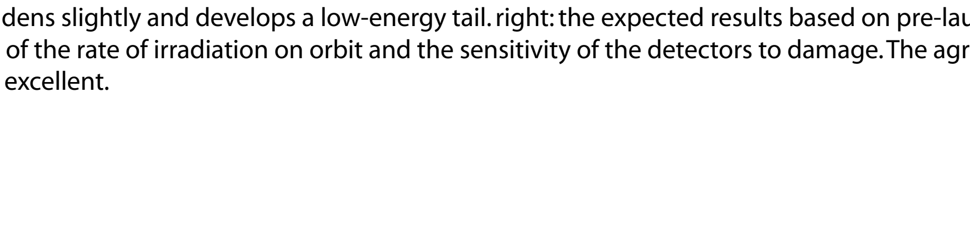
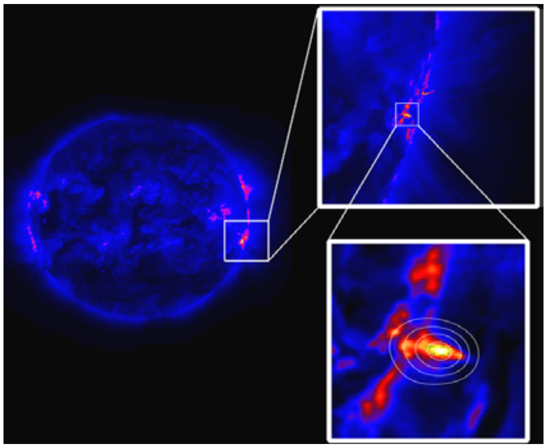


FIGURE 17:
Results of radiation damage in the RHESSI spectrometer. left: the evolution in the shape of the background line from natural radioactive potassium. The heavy curve is the line shape after 9 months of operation; the line broadens slightly and develops a low-energy tail. right: the expected results based on pre-launch estimate of the rate of irradiation on orbit and the sensitivity of the detectors to damage. The agreement is clearly excellent.

3. RHESSI E/PO at UC Berkeley and Goddard Space flight Center:

RHESSI's educational and public outreach efforts have supported teachers, science museum educators, and scientists in the design of classroom materials that are connected intellectually to RHESSI science and appropriate for Middle and High School National Science Education Standards. Having E/PO partners both in Berkeley and GSFC has allowed for much wider dissemination locally and nationally. RHESSI E/PO materials have been presented in professional development workshops at every National Science Teachers Association Conference since 1999, as well as in poster format at various AGU, AAS, HEAD, YOHKOH, and OSS E/PO conferences.



RHESSI Litho April 21 2002 X-ray Flare

RHESSI E/PO at UCB:
http://cse.ssl.berkeley.edu/hessi_epo

RHESSI E/PO at UCB focuses on outreach to middle and high school teachers, their students, and the public. In formal education, the pre-college program includes the training of lead teachers from urban and rural school districts in the larger Bay Area. Collaboration with NASA's Sun-Earth Connection Education Forum (SECEF) provides an effective multiplier effect for local RHESSI-based education efforts at UCB and at GSFC. The resources have been developed through partnerships between NASA scientists and educators. The classroom activities are well aligned with National Science Education Standards. *Sunspots* -an inquiry based resource emphasizes mathematical connections through measurement, graphing, and analysis of satellite and student-acquired data. This resource incorporates background information, including the importance of the Sun in ancient cultures, a historical account of sunspots observations, and current NASA solar research. In addition, it includes guidance for safe sunspot viewing and an interactive Java research tool that allows students to analyze possible correlations between sunspots and X-ray active regions on the Sun from visible light and Yohkoh images. The *Sunspots* Teacher Guide and accompanying CD-ROM resource was used in five San Francisco Unified School Districts middle schools for a three-week summer course as a testbed before being released to NASA's Space Science Education Resource Directory as an exemplary educational resource.

Students at "Solar Camp" building RHESSI

As part of the museum partnership with the Lawrence Hall of Science, two summer camps were held for a week with the topic of "Solar Camp". Students concentrated on a project in solar science, were introduced to the RHESSI mission, made RHESSI spacecraft models, visited the 11m dish, and had a guided tour of RHESSI MOC and SOC.

We have also developed another educational resource material, *X-ray Candles: Solar Flares on Your Birthday*. This resource allows students to discover the solar cycle by analyzing X-ray flare data and graphing the percentage of high energy flares over time. *X-ray Candles* was selected to be featured on an episode of the Emmy-winning broadcast program, NASA Connect. The program was produced by NASA Connect, titled *Having a Solar Blast*, and distributed to 120,000 educators through NASA CORE.

The EPO program consists of dissemination of RHESSI web and hardcopy resources within the SEGway program's national partnership of science museums plus SEGway's collaboration with UC

Berkeley's outreach programs, such as the Interactive University Project for middle school science teachers.

Informal Education: RHESSI's participation in the widely observed Live@Exploratorium webcast of the 1999 total solar eclipse from Turkey was a successful implementation of scientist and public interface. More than 3,000 people came to observe this remote event at the Exploratorium, and it became a model for SECEF to use natural events such as total solar eclipses as a hook for public outreach.

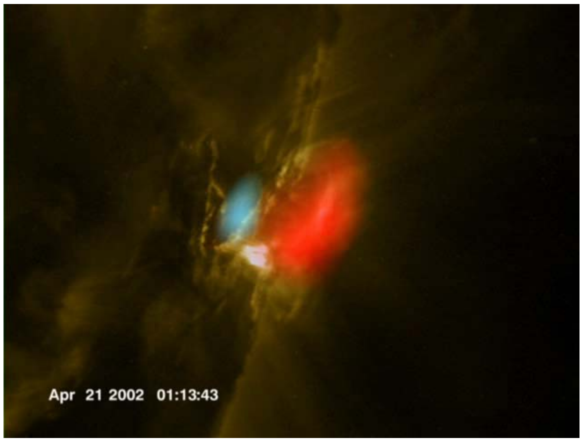
Scientist Participation in the Exploratorium Museum for the Eclipse

RHESSI also participates annually in "CAL DAY" where about 30,000 students and members of the general public visit UC Berkeley's Open house. People are invited to visit SSL for a lecture and a popular guided tour of the RHESSI MOC and SOC, presented by the EPO lead Dr. N. Craig, and Mission Operation Scientist Dr. M. Bester.
During the RHESSI launch of February, 2002, the EPO program planned TV and Media coverage at SSL, and also a special Launch Day Event at the Chabot Space and Science Center.

CAL Day at the RHESSI MOC w/ Dr.Bester

RHESSI E/PO also participated in *Sun-Earth Day* activities, organized by SECEF in Spring 2002 and 2003, by visiting class-rooms and giving talks about the new knowledge obtained on solar flares and by participating in the public events at the Chabot Space and Science Center.
In addition, RHESSI EPO both at Berkeley and Goddard supported the traveling Space Weather exhibit at the Lawrence Hall of Science, at Berkeley and at the Maryland Science Center.

E/PO at Goddard Space Flight Center:
http://hesperia.gsfc.nasa.gov/HESSI/outreach.htm
The GSFC EPO effort includes teacher workshops modeled after an ongoing GSFC summer teacher program where teachers work with scientists in the Solar Physics Branch for eight weeks each summer. These workshops are in collaboration with the SUNBEAMS (Students United with NASA Becoming Enthusiastic About Math and Science) program. Teachers develop educational materials motivated by RHESSI science and technology. The summer teachers' workshop phase of the SUNBEAMS program is followed by each teacher bringing their class to GSFC for a full week of total immersion in hands-on, inquiry-based, cooperative-learning activities. GSFC scientists, engineers, and technicians stay involved with the teachers through visits to their classrooms, guest lectures, and by providing a continuing flow of RHESSI information.



RHESSI X-ray Flare of April 2002 in two channels superimposed on a TRACE image.

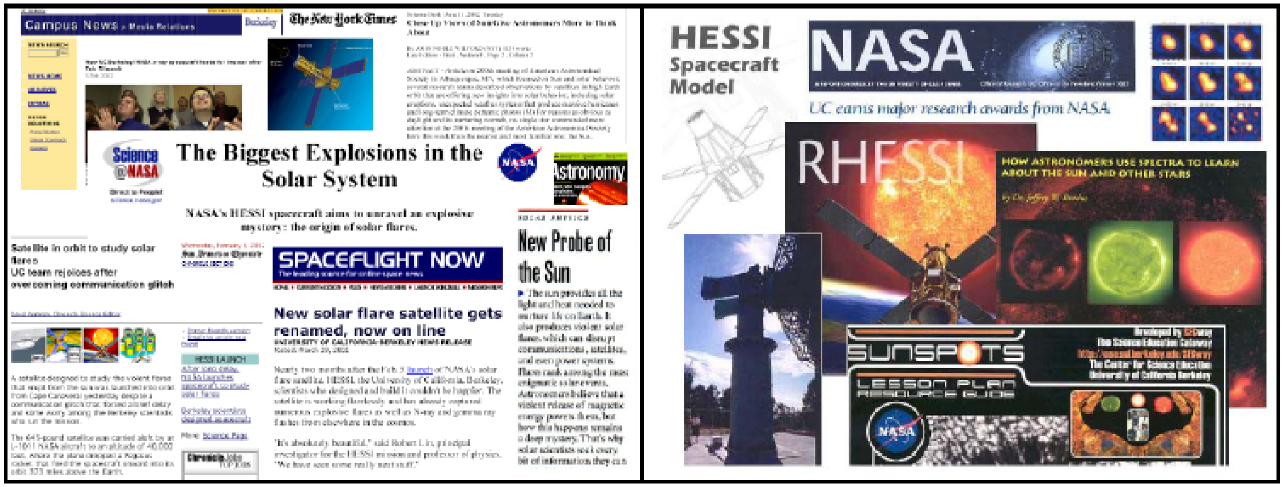
RHESSI PRODUCTS

RHESSI EPO has created a variety of educational products which include web-based resources, posters, lithographs, a paper spacecraft model booklet, a sunspot resource guide and CD-ROM, RHESSI cards, RHESSI decals, a book cover, and RHESSI websites (at GSFC & UCB) with continual updates. A Science@NASA article was prepared with the collaboration of RHESSI scientists and the EPO program prior to the June 24 launch date. The RHESSI satellite, mission science, and a RHESSI-EPO-developed solar flare activity was featured in the *Having a Solar Blast* episode of NASA Connect, which has been broadcast on NASA TV and PBS stations. Through NASA Connect, the *Having a Solar Blast* video was released to 120,000 educators. The Goddard group produced and distributes 10,000 RHESSI book-covers with an exercise for students and teachers illustrating how RHESSI can image solar flares with the RHESSI-like grid optics. The Goddard Group also produced and distributed 10,000 RHESSI Spacecraft Booklets for middle school students that guides them through the process of building a paper model of RHESSI by working as teams of "scientists" and "engineers". 10,000 copies of the *Discover the Solar Cycle* RHESSI lithographs created by the Berkeley group were distributed through the National Science Conferences as well as National Math Teachers' Conferences with workshops. After RHESSI launch the litho was updated with the April 21st, 2002 observation of an X-class flare and 5,000 additional copies were printed and distributed.

E/PO Plans for the Extended Mission

The EPO program is cognizant of the general and specific requirements of the Office of Space Science's Education and Outreach Programs. The EPO program is fully committed to the continuation of building on the infrastructure of RHESSI and the partnerships of UC Berkeley's other SEC EPO missions, such as STEREO/IMPACT and the newly approved THEMIS where Dr. N. Craig is also the lead EPO. Our aim is to make use of the existing RHESSI resources, using our partnership with science museums, SECEF, and the Broker/Facilitator Network to insure the continuation of the national-scale effort. Beyond further outreach efforts for the general public and educators, the EPO team would like to develop two new educational resources using the RHESSI flare data with illustrations of what the RHESSI Team has learned about the solar flares. One will be at the appropriate level for the educated public and the other for middle and high school students. We plan to continue to participate in professional development opportunities for teachers. The Goddard E/PO plans to continue cooperating with the Challenger Center and the SUNBEAMS Program.

The Sunbeams Summer program at GSFC



Left: *A collage of some of the RHESSI related launch and science press coverage in print and electronic media.*
Right: *A collage of the RHESSI E/PO science and education materials.*

Date 2002	**RHESSI Presentations, Events & Activities**
Jan.	Keynote address at a University of Minnesota symposium on science outreach
	RHESSI Poster at YOHKOH 10 Anniversary Mt. Kona, Hawaii
	RHESSI science and an informal lecture on the SUNBEAMS at Middle Tennessee State University
Febr.	RHESSI Launch event at UCB/SSL - Media - Papers
	Talks to four classes at Clemente Middle School in Germantown, MD
March	Judge at the Montgomery County Science Fair
	Workshop at NOBCChE Meeting w/ Teacher Professional Development Program. New Orleans, LA
April	Take Our Daughters to Work Day at NASA/GSFC
	Gave a talk on RHESSI to Native Americans from Bay Mills Tribal College
June	RHESSI Poster presentation at OSS Conference- Chicago, IL
July	Jodie Sanders -Space Science evaluation of SUNBEAMS
August	Reviewed a book on Aurora for young students
Sept.	Bay Area Earth Science Institute Presentation
	RHESSI EPO evaluation interview by Leslie College
Oct.	Linking Girls to the Land Eco-Expo
	Demos @ Journey through the Universe organized by the Challenger Center
	RHESSI Presentation at California Science Teachers Association
Mar.‘ 03	GEMS workshop
	Workshop at NSTA- Philadelphia, PA

Appendix A

Title	Authors	Pages
Standard budget in mandatory format		?

Appendix B
Acronym List

AAS/SPD	American Astronomical Society
ACS	Attitude Control System
ACE	Advanced Composition Explorer
AGU	American Geophysical Union
ARTBs	Active Region Transient Brightenings
ATS	Absolute Time Sequence
AU	Astronomical Unit
BATSE	Burst and Transient Source Experiment
BBSO	Big Bear Solar Observatory
BGS	Berkeley Ground Station
CCD	Charged Coupled Device
CD-ROM	Compact Disk, Read-Only Memory
CHIANTI	An Atomic Database for Spectroscopic Diagnostics of Astrophysical Plasmas
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer
CME	Coronal Mass Ejections
CORE	Central Operation of Resources for Educators
COSPAR	Committee on Space Research
CPU	Central Processing Unit
DA	Data Analysis
DEM	Differential Emission Measure
EGSO	European Grid of Solar Observations
EIT	Extreme Ultraviolet Imaging Telescope
EP/O	Education and Public Outreach
ETHZ	Swiss Federal Institute of Technology in Zurich
EUV	Extreme Ultra-Violet
FAST	Fast Auroral SnapshoT Explorer
FDC	Flight Dynamics Center
FITS	Flexible Image Transport System
FOT	Flight Operations Team
FWHM	Full Width at Half Maximum
GDS	Ground Data System
GeD	Germanium Detector
GEMS	Great Explorations in Math and Sciences
GOES	Geostationary Operational Environmental Satellite
GRS	Gamma-Ray Spectrometer
GSFC	Goddard Space Flight Center
G/T	A Receiving System Figure of Merit

HEAD	High Energy Astrophysics Division
HETE-II	High-Energy Transient Experiment II
HXIS	Hard X-Ray Imaging Spectrometer
HXT	Hard X-Ray Telescope
HXR	Hard X-Ray
IADs	Inertia Adjustment Devices
IDL	Interactive Data Language (a data analysis commercial program)
IDPU	Instrument Data Processing Unit
IMPACT	The In-situ Measurements of Particles and CME Transients investigation on STEREO
INTEGRAL	International Gamma-Ray Laboratory
IPM	Interplanetary Medium
ITOS	Integrated Test and Operations System
KSC	Kennedy Space Center
LASCO	Large Angle and Spectrometric COronagraph
LSEP	Large Solar Energetic Particle
MM_Cos	Max Millennium Chief Observers
MEKAL/SPEX	An Atomic Database for Spectroscopic Diagnostics of Astrophysical Plasmas
MDI	Michelson Doppler Imager
MO	Mission Operations
MOC	Mission Operations Center
MOU	Memorandum of Understanding
MPS	Mission Planning System
NASA	National Aeronautics and Space Administrations
NOBCChE	National Organization for the Professional Advancement of Black Chemists and Chemical Engineers
NoRH	Nobeyama Radioheliograph
NSO	National Solar Observatory
NSTA	National Science Teachers Association
OCA	Orbital Carrier Aircraft
OIG	Orbital Information Group
OSS	Office of Space Science
OVSA	Owens Valley Solar Array
PICARD	French Satellite Mission named for Jean PICARD
PMTRAS	Photomultiplier Tube Roll Aspect System
PSF	Point spread function
PSLA	Project Service Level Agreement
RESIK	The Bragg bent crystal spectrometer aboard Russian CORONAS-F Solar Observatory
RHCP/LHCP	Right Hand and Left Hand Circular Polarization
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
RAD6000 EEPROM	Processor Memory
RAS	Roll Angle System

RMCs	Rotating Modulation Collimators
SAA	South Atlantic Anomaly
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SAS	Solar Aspect System
SatTrack	Satellite Tracking System
SDAC	Solar Data Analysis Center
SEC	Sun-Earth Connections
SECEF	Sun-Earth Connection Education Forum
SEGway	Science Education Gateway, aUCB-led education and public outreach program
SERS	Spacecraft Emergency Response System
SEP	Solar Energetic Particle
SMEX	Small Explorer
SMM	Solar Maximum Mission
SOAP	Simple Object Access Protocol
SOC	Science Operations Center
SOH	State-Of-Health
SOHO	Solar and Heliospheric Observatory
SPEC	Spectroscopy Detector
SSL	Space Science Laboratory
SSW	Solar Software
STEREO	Solar-TErrestrial RElations Observatory
SUNBEAMS	Students United with NASA Becoming Enthusiastic About Math and Science
SXI	Soft X-Ray Imager
SXT	Soft X-Ray Telescope
TGFs	Terrestrial Gamma Flashes
TRACE	Transient Region and Coronal Explorer
UCB	University of California at Berkeley
UT	Universal Time
UVCS	Ultraviolet Coronagraph Spectrometer
VOTable	Data exchange standard for the National Virtual Observatory
XML	Extensible Markup Language
WSDL	Web Service Data Language