HIGH ENERGY PARTICLE ACCELERATION BY SOLAR FLARES AND FAST CORONAL MASS EJECTIONS

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ABSTRACT

The Sun is the most powerful particle accelerator in the solar system, able to accelerate ions up to tens of GeV and electrons up to hundreds of MeV. The acceleration to energies >~10 MeV by flares and fast CMEs appears to occur within ~30 solar radii. Hard X-/gamma-ray continuum and gamma-ray line/energetic neutron are the most direct signatures of energetic electrons and ions, respectively, near the Sun. Some of the energetic particles escape, but scattering and energy changes in propagating to ~1 AU blur out our view of the acceleration process. Solar Orbiter located at ~ 0.2 AU, co-rotating with the active regions, could detect for the first time neutrons down to ~ MeV energies, provide far more sensitive X-/gamma-ray measurements, pristine energetic particle observations, and observations of fast CMEs and their shocks before they have evolved significantly. Also close to the Sun the Parker spiral field is nearly radial so the regions which produced the energetic particles are always well-observed by the remote sensing instruments. A coordinated set of in situ and remote-sensing instruments, such as proposed for the Particle Accleration Solar Orbiter (PASO) mission in the NASA Roadmap, could provide a great leap forward in our understanding of the fundamental process of particle acceleration in nature.

SCIENTIFIC OBJECTIVES

The Sun is the most powerful particle accelerator in the solar system, able to accelerate ions and electrons well into the energy range of galactic cosmic rays. Gamma-ray observations show that large solar flares accelerate ions up to 10s of GeV and electrons to 100s of MeV (Mandzhavidze et al 1997). At altitudes of ~2-30 Rs, shocks driven by fast CMEs appear to accelerate particles to similar energies (Kahler 1994); the escaping particles produce the large gradual solar energetic particle (LSEP) events observed at 1 AU. The ions and electrons above tens of MeV in LSEPs can pose a serious hazard for manned space travel.

Large solar flares and CMEs are also the most powerful explosions in the solar system. Solar flares release up to ~10^{32}-10^{33} ergs in a period of ~10-1000 s. A substantial fraction of this energy is channeled into energetic >~10 keV electrons and possibly ~ MeV ions, implying that the particle acceleration process is intimately related to the flare energy release process. Fast CMEs release a comparable amount of energy in ejecting up to 10^{15}-10^{16} g of coronal material into the interplanetary medium (IPM). The shock wave driven by the fast CME appears to accelerate particles over a wide range of longitude of the Sun's corona.

The time-averaged energy input of all flares, down to the very smallest ones, may be important for coronal heating. Flare accelerated particles directly heat the solar atmosphere through collisions. Parker (1988) proposed that solar magnetic field lines, twisted up by the photospheric motions of their footpoints, relax by reconnection to produce nanoflares (>~10^{23} ergs) that heat the corona. Weaker flares occur more frequently, and tend to accelerate electrons to lower energies (Lin 1997). Averaged over all flares/microflares above detection threshold at 1 AU (~10^{29} ergs), the >8 keV electrons deposit >~10^{26} ergs/s into the active corona near solar maximum (Feffer 1996). Smaller (~10^{25} ergs) flare-like energy releases are observed in soft X-rays/EUV to occur ~once per 3s in the quiet chromospheric network, with radio signatures that suggest electron acceleration (Krucker et al 1997).

Flares also provide fresh hot coronal plasma through chromospheric evaporation; this might be the primary way mass is supplied to the corona (Brown et al (2000). Microflares may also generate Alfven waves (Axford & McKenzie 1992) and/or fast shocks (Lee & Wu 2000) to heat the corona and accelerate solar wind ions.

Energetic particles are produced in a variety of other transient solar events. Solar type III radio bursts show that impulsive electron acceleration occurs high in the corona: the escaping particles are detected at 1 AU in impulsive SEP events. These are rich in ~1-100 keV electrons, ~0.01- 1 MeV/nuc ^{3}He, and heavy ions (Fe), suggestive of ion acceleration by gyroresonant interactions with plasma waves driven by electron beams, as found in the Earth's aurora (Temerin and Roth 1991). The electron spectrum often extends down to below ~1 keV, implying acceleration high in the corona. Type III storms last for days and have thousands of individual fast drift bursts. They occur ~50% of the time

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near solar maximum, and weaker storms almost certainly occur even more frequently. These bursts originate at altitudes of 1.5-2.5 Rs and often precede CMEs. The merging of escaping electrons from the numerous storm bursts may be the source of the ~1-100 keV superhalo component (Lin 1997) of solar wind electrons.

The ESA Solar Orbiter (SO) mission can uniquely address the fundamental physics of particle acceleration to high energies in flares and fast CMEs, by providing comprehensive measurements of the accelerated particles and related phenomena, both at the Sun and in the inner heliosphere. SO will achieve a near-synchronous orbital speed i.e., about equal to the solar rotation rate, at the perihelion of ~0.2 AU. This allows continuous observation of particle acceleration from a flare active region and/or CME-related solar feature for periods of ~10 days.

SOLAR ORBITER MEASUREMENT STRATEGY

The most direct signatures of energetic electrons and ions close to the Sun are the hard X-ray/gamma-ray continuum and gamma-ray line/energetic neutron, respectively, produced through electron bremsstrahlung and energetic ion collisions with the solar atmosphere. For hard X-ray/gamma-ray imaging instruments, Solar Orbiter at perihelion would provide ~25 times the sensitivity and 5 times the linear spatial resolution of the same instruments from 1 AU. For neutrons the gain in sensitivity would be far greater, a factor of ~1000, since neutrons decay in flight (e-folding decay time of 1000s). In fact, neutrons below ~10 MeV and down to <~1 MeV would only be detectable by getting this close.

Low energy neutrons can be produced by ions of energies as low as a few tenths of MeV/nucleon; thus such observations can provide direct evidence for the acceleration of low energy ions in small flares. Since much of the energy released in flares appears to be contained in accelerated electrons of ~tens of keV or less energy and ions of <~1 MeV, the low energy hard X-ray and neutron measurements also bear on the mechanism for the transient release of energy by the Sun. The high sensitivity provided by the near-Sun SO trajectory allows microflares and possibly smaller energy releases, as well as releases high in the corona where the ambient density is low, to be detected.

Furthermore, the near-Sun SO trajectory is crucial for obtaining nearly pristine observations of the accelerated particles which escape. Scattering and energy changes (particularly important for slow moving ions) in interplanetary propagation of escaping particles to ~1 AU erases most of the information about the acceleration process. The strongly diverging magnetic field near the Sun, within ~0.2 AU, however, focusses the SEPs to minimize scattering so the propagation should be nearly adiabatic and information about the acceleration mechanism itself should still be intact. SO hard X-ray imaging observations could locate the acceleration regions, while comparisons of the timing and energy spectra measurements from the SO X-ray/gamma-ray/neutron measurements with the in situ SO particle measurements to low energies will give the distance and the column depth along the field line. In addition, SO radio observations provide the plasma density along the path, and SO measurements at different energies can detect the presence of electric potentials.

At this orbital distance the Parker spiral interplanetary field is nearly radial, which means that the same regions at the Sun which accelerate the escaping particles directly detected by Solar Orbiter's in situ instrumentation will always be well observed by its remote sensing X-ray/gamma-ray/neutron and EUV/optical instruments. In addition, the CMEs and their associated shock waves can be tracked in the upper corona and inner heliosphere through their type II radio emission, and then observed by SO's in situ plasma and field instrumentation before they have evolved significantly.

INSTRUMENTATION

Solar Orbiter's strawman payload already includes EUV and optical imaging instruments which can provide the necessary thermal context measurements at the Sun. Energetic particle, solar wind plasma, fields, low-frequency radio,and neutron measurements are already in the strawman payload, although these should be optimized for studying particle acceleration. What needs to be added are hard X-ray imaging spectroscopy and gamma-ray spectroscopy. Gamma-ray imaging would be very highly desirable, but may not be possible with the limited resources available.

For SO a Fourier transform imager of the same type as the Hard X-ray Telescope (HXT) (Kosugi et al 1991) successfully flown on the Yohkoh spacecraft could be implemented with relatively minimal resources. Table I gives the specifications for a Spectrometer/Telescope for Imaging X-ray (STIX), which employs a set of 64 subcollimators, each of which consists of a pair of widely separated x-ray opaque grids with an x-ray detector element located behind the rear grid (Figure 1). Front and rear grid pairs have identical pitch and orientation, whose choice determines the spatial frequency to be measured. As was demonstrated by Yohkoh HXT, the relative count rates of a pair of subcollimators, one of whose grids is displaced by ¼ of its pitch, can be used to accurately measure both the real and imaginary parts of one Fourier component of the angular distribution of the source. With 64 subcollimators the imaging system then measures 32 different Fourier components. This data can then be

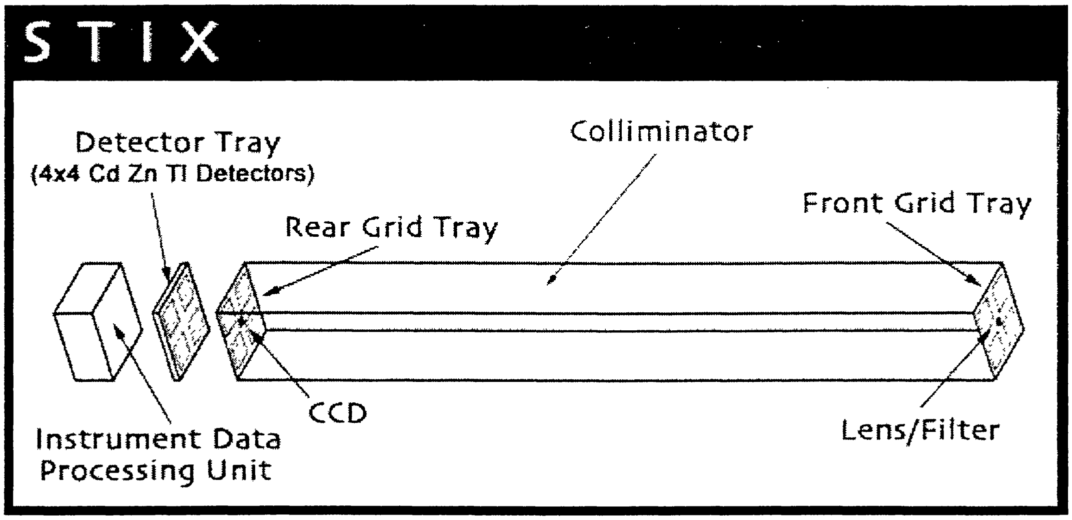

Figure 1: Schematic of the Spectrometer/Telescope for Imaging X-rays (STIX).

used to reconstruct the source image, using well-established techniques used by radio astronomy, Yohkoh HXT and HESSI.

The front and rear grid assemblies are both constructed as a unit by stacking sets of etched tungsten sheets up to a thickness of 1 mm. Grid pitch values range from 35 microns to 2 mm. At a separation of 1.4 m, the corresponding spatial resolution of the individual subcollimators (defined as one half of the ratio of grid pitch to separation), is 2.5 arcseconds to 5 arcminutes. At 0.2 AU, however, the former is equivalent to 0.5 arcseconds at 1 AU. The grid fabrication and alignment requirements needed to achieve this are significantly less demanding than those already achieved on HESSI.

The FWHM imaging field of view, given by the ratio of the subcollimator diameter (1cm) to separation is 24 arcminutes, which even at 0.2 AU is sufficient to fully encompass an active region. It should be noted that the field of view for spectroscopy is 4 times larger, so that full sun sensitivity to is retained even at 0.2 AU.

Coalignment with other telescopes on board and on the ground is established by the use of a 1.5 cm lens/narrow-band filter in the front tray which focuses a white-light image onto a 2-dimensional CCD on the rear tray. Occasional transmission of such an image establishes the co-alignment with respect to other on-board telescopes and s/c aspect.

Since the detector spatial resolution need only match the ~cm dimension of the subcollimator, detectors can be optimized for their spectral resolution. This enables the imaging to be done as a function of energy, resulting in an instrument which functions as an imaging spectrometer. Such a detector system consists of a set of four identical CdZnTe solid state detectors each of which is divided into sixteen 1 cm square elements, 2mm thick. Operating at room temperature, they provide a total of 64 detector elements, each of which provides from ~1-15 keV resolution over the range ~3 to 150 keV. The overall effective area of the system for imaging is about 16 cm2, which at 0.2 AU is equivalent to about 4 times that of HESSI.

Table 1: Hard X-ray/Gamma-ray Instrument Parameters

	Spectrometer/Telescope for Imaging X-rays (STIX)	Gamma-ray Spectrometer (GS)
Energy range	~3 – 150 keV	~0.1 – 20 MeV
Spectral resolution	~1 – 15 keV	$\Delta E/E$ ~ 10%
Spatial resolution	~2.5 arcsec	----
Field of View	~24 arcmin	Full Sun
Mass	~5 kg	~4 kg
Volume	~12cm x 12cm x 150cm	~8cm x 8 cm x 20 cm
Power	~4 W	~3 W
Data Rate	~200 bps average	~100 bps average

The instrument data processing unit digitizes and accumulates the detector output into time and energy bins. The timing and energy-selection of theses bins is adaptable and is optimized in realtime by an internal processor, using an algorithm which takes into account the parameters of individual flares. Data for each image can be compressed to less than 100 byte of telemetry for each energy band. This could be stored in a burst memory for a flare and read out at a constant rate.

The estimated mass of STIX as described is estimated at 5 kg, consisting of 0.25 kg for the grids, 1 kg each for collimator structure, detectors and electronics, and 50% contingency. Power requirements are estimated to be ~4 watts.

In summary, an instrument such as STIX uses proven techniques to provide hard-x-ray imaging spectroscopy with unprecedented spatial resolution and sensitivity within the resources of the Solar Orbiter.

Gamma-ray line and continuum (~0.1-20 MeV) observations are highly complementary to neutron observations for providing information on energetic ions at the Sun. A Gamma ray Spectrometer (GS) at ~0.2 AU, using a standard 7.5 cm diam x 7.5 cm bismuth germanate (BGO) scintillation detector (~4 kg with housing, PMT, and electronics) would provide higher effective area for solar gamma-ray observations than any gamma-ray instruments ever flown at 1 AU. It may be possible to combine this detector with the energetic particle instrument to save on mass. Alternatively, recent developments in CdZTe could provide much better spectral resolution for gamma-ray line spectroscopy at the cost of smaller detectors.

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