The High-Energy Sun at High Sensitivity:
a NuSTAR Solar Guest Investigation Program

A concept paper submitted to the Space Studies Board Heliophysics Decadal Survey

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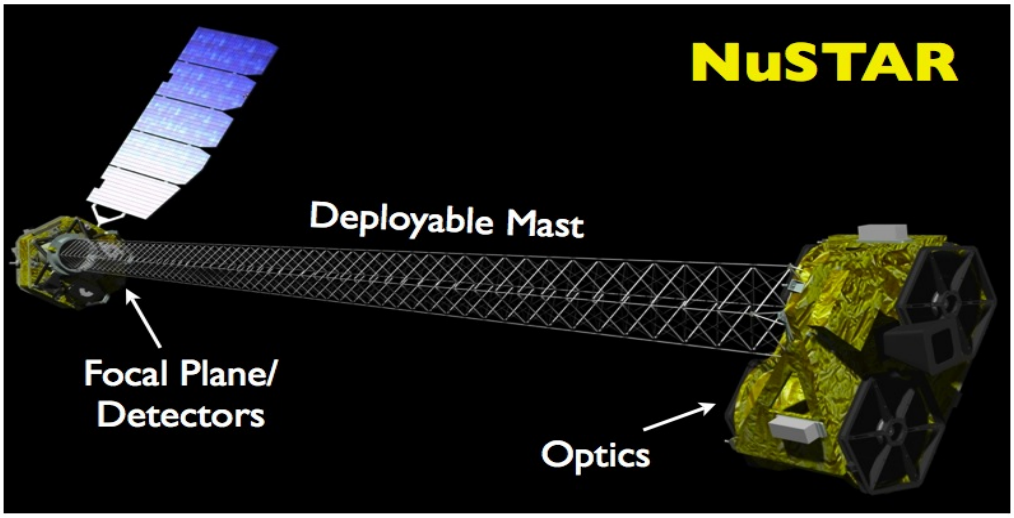

Figure 1: Artist's conception of the NuSTAR spacecraft

Introduction and Overview

Understanding the origin, propagation and fate of non-thermal electrons is an important topic in solar and space physics: it is these particles that present a danger for interplanetary probes and astronauts, and also these particles that carry diagnostic information that can teach us about acceleration processes elsewhere in the heliosphere and throughout the universe. Such non-thermal electrons can be detected via their X-ray or gamma-ray emission, their radio emission, or directly in situ in interplanetary space. To date, the state of the art in solar hard x-ray imaging has been the *Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI),* a NASA Small Explorer satellite launched in 2002, which uses an indirect imaging method (rotating modulation collimators) for hard x-ray imaging. This technique can provide high angular resolution, but it is limited in dynamic range and in sensitivity to small events, due to high background. High-energy imaging of the active Sun is technically easiest in the soft x-ray band (see, for example, the detailed and dynamic images returned by the soft x-ray imager on *Hinode,* as well as the corresponding telescopes on *Yohkoh* and *GOES),* but these x-rays are generally emitted by lower-energy thermal plasmas.

The purpose of this paper is to draw the attention of the solar community to a new mission that can address these topics with a sensitivity far superior to any previous detector. The *Nuclear Spectroscopic Telescope Array (NuSTAR;* Harrison et al. 2010*)* is another Small Explorer, currently being prepared for launch in February 2012, and aligned with NASA's Astrophysics Division. *NuSTAR* is a true hard x-ray telescope, using grazing-incidence optics with multilayer reflective coatings to make true images with 7.5" FWHM angular resolution over the 5-80 keV energy band. *NuSTAR*'s primary science goals concern supernovae, black holes, and pulsars, but, unlike virtually every other high-energy astrophysics mission to date, it is capable of being pointed at the Sun, a plan which has the support of the *NuSTAR* PI, Project Scientist, and science team. *NuSTAR's* effective area at 10 keV is over ten times that of *RHESSI* (800 cm^2 versus 60 cm^2), but, even more importantly, its background is four orders of magnitude lower, thanks to the use of focusing optics. Overall, *NuSTAR* will be able to observe solar hard x-ray sources **200 times fainter** than our current capabilities allow. This sensitivity will open the door to brand new observations, such as the coronal hard x-rays related to type III radio bursts, and will allow comparison of the non-thermal characteristics of flares over eight orders of magnitude, from the brightest X flares seen by *RHESSI* to the faintest nanoflares visible to *NuSTAR* at a level about 200 times fainter than GOES class A1. Since flares increase in number as flux decreases (at least to the limit we can now observe), *NuSTAR's* high sensitivity also means that a large database of hundreds of (nano- and micro-) flares can be accumulated in days or weeks, as opposed to the years required to accumulate a library of C, M, and X flares.

During *NuSTAR's* primary science mission, in the years 2012 and 2013, approximately two weeks of the fully-allocated observing plan will be dedicated to solar observations. These will be planned by the *NuSTAR* solar science team (the authors of this concept paper, pending final approval by the *NuSTAR* Science Steering Committee). But we consider it important for *NuSTAR* solar science to be explicitly supported during the extended mission of the satellite, which we trust will be long and valuable (there are no spacecraft expendables). We propose here that the SSB recommend to NASA the establishment of a solar Guest Investigator (GI) program for *NuSTAR* as long as its extended mission is approved by the Astrophysics Senior Review. A formal GI program would:

1. Assure the participation of the wider solar community, with the inclusion of new ideas and science payoffs not anticipated by the *NuSTAR* solar science team,
2. Support dedicated observing campaigns at other wavelengths to exploit the full potential of the hard x-ray observations in a broader context, and
3. Make sure that solar GI proposals are not disadvantaged by competing against astrophysics proposals in panels composed of astrophysicists who may not be knowledgeable about the solar measurements.

Examples of *NuSTAR* Solar Science

1) Active region microflares

non-thermal emission from active-region microflares is most easily detected at photon energies around 10 keV (Benz & Grigis 2002, Krucker et al. 2002), an energy perfectly suited to NuSTAR. The smallest RHESSI microflares with statistics sufficient to analyze the photon spectrum (i.e. with about 1000 counts) contain about 10^{27} ergs in non-thermal electrons. Assuming that the spectral shape of smaller flares is similar, the enhanced sensitivity of NuSTAR will measure the energy spectra of microflares with energies down to 5×10^{24} ergs. This energy is about 8 orders of magnitude smaller than the largest flare seen, and lies in the so-called nanoflare range. NuSTAR will extend the current hard X-ray (HXR) microflare distribution to lower energies by at least two orders of magnitude, and provide new information on active-region microflares. Further, it will permit comparison of active-region nanooflares with the quiet-region network flares discussed in the next section.

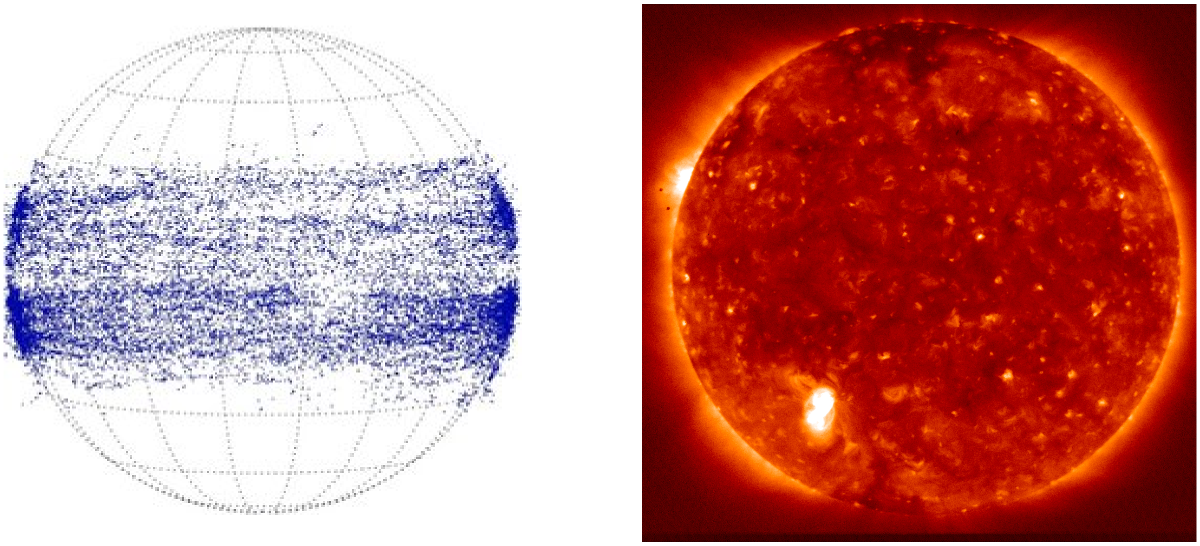

Figure 2. Left: map of hard x-ray microflares associated with active regions observed by RHESSI *(Christe et al. 2008). Right: soft x-ray bright spots in a* Hinode *image of the solar disk (NASA image).* NuSTAR *will have the sensitivity to see if the latter events have a hard x-ray component.*

2) Non-thermal electrons in the quiet corona

The high sensitivity of *NuSTAR* will allow a search for HXR counterparts of network flares seen in the quiet corona outside of active regions (Krucker et al. 1997, Berghmans et al. 1998, Krucker & Benz 2000). From soft X-ray (SXR) and extreme ultraviolet (EUV) observations, the thermal energy content is estimated to be up to 10^{26} ergs (Krucker & Benz 1998, Parnell & Jupp 2000, Aschwanden et al. 2000). Radio observations have revealed the existence of non-thermal electrons in at least some network flares (Krucker et al. 1997), suggesting that network flares are heated in a fashion similar to regular flares occurring in active-regions. If network flares are indeed smaller versions of regular flares, the thermal heating seen in EUV and SXR is provided by non-thermal electrons. With the sensitivity of *NuSTAR* allowing us to observe non-thermal events with energies down to $5\mathrm{x}10^{24}$ ergs, non-thermal bremsstrahlung of these electrons should be easily detected with *NuSTAR*.

EUV observations from EIT and TRACE predict about 2 to 250 network flares per minute above 10^{25} ergs in a field of view of 600×600 arcsec. While *NuSTAR* will not resolve the spatial structure of network flares, it will allow the separation of source locations, and simultaneous EUV observations taken by *SDO*/AIA, *STEREO*/EUVI and *Hinode* could help to resolve ambiguities. Spectral analysis will provide averaged values for the energy in non-thermal electrons in these events even when they overlap.

3) Tracing electron beams in the solar corona

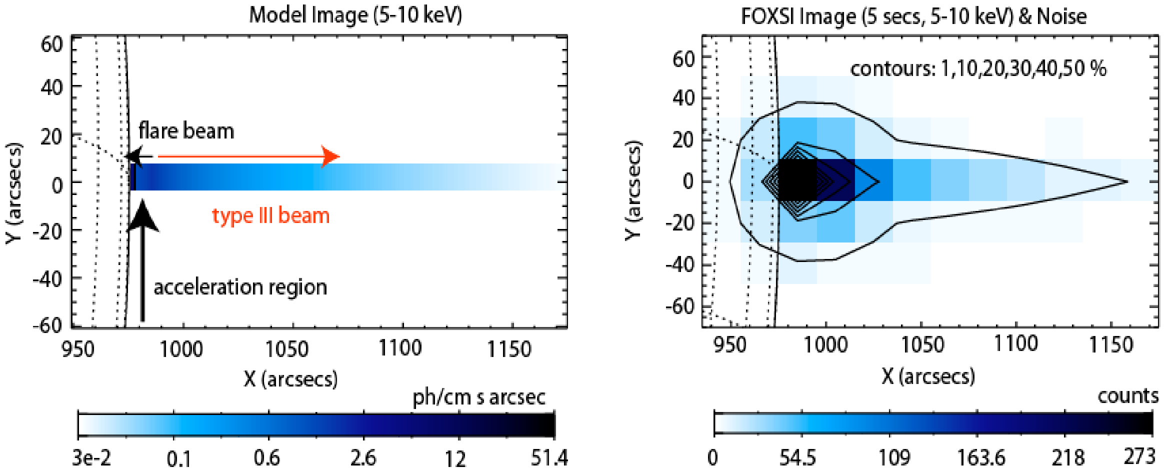

Figure 3: Simulated image of the electron beam associated with a type III burst, calculated for the FOXSI sounding rocket by Pascal Saint-Hilaire and Säm Krucker (adapted from Saint-Hilaire et al. 2009). NuSTAR will have over 5 times the effective area of the FOXSI rocket, and images to higher energies.

With the sensitivity of *NuSTAR*, it will be possible to detect HXR emission from electrons that produce coherent radio bursts seen at meter and centimeter wavelengths (e.g. Bastian, Benz, & Gary 1998). The best understood of these bursts are type III bursts, which are produced by electron beams in the corona. Although these beams generally travel outwards towards low densities, they also radiate in X-rays albeit at a much lower rate than downward moving flare beams. The X-ray observation of a type III beam is therefore difficult for two reasons: the relatively small fluxes and the large dynamic range necessary since such bursts are often associated with flares. Assuming that the electron beam consists of 10^{33} electrons above 5 keV (consistent with in-situ electron measurements near 1 AU, Lin 1973) and propagate away from the Sun beginning from a density of 5×10^{9} cm^{-3} (corresponding to a plasma frequency of 600 MHz), *NuSTAR* will detected about 250 counts per second. Therefore *NuSTAR* will make the first HXR observations of a type III-producing beam. The hard X-ray emission will outline where the electrons are accelerated and along which path they escape from the Sun. More importantly, the *NuSTAR* spectra will permit determination of the energy distribution of the emitting electrons close to their source in the low corona. Radio measurements do not constrain the electron content of type III bursts because the emission is coherent. Joint radio and hard x-ray measurements of type III bursts will allow the electron content of these events to be calculated for the first time, and permit comparison of the low-coronal spectrum and intensity with the energy distributions that have been measured for decades at two sites: in situ at 1 AU, after what we believe to be extensive energy redistribution in the course of beam propagation, and at flare footpoints, by which time there may also be reacceleration, Coulomb losses, and other effects in the flare loops.

4) Non-thermal electrons associated with coronal mass ejections

For flares occurring 20 or more degrees behind the solar limb, not only the HXR footpoints but also the main thermal and non-thermal HXR emission from the corona are occulted, and flare-related emission from the high corona (>200 arcsec above the flare site) can be seen (Hudson 1978, Kane et al. 1992, Hudson et al. 2001, Krucker et al. 2007a). *RHESSI* provided the first high-resolution imaging spectroscopy of HXR emission from such events, revealing large sources (with sizes >200 arcsec) that expand and move outwards. The upward motion of the hard X-ray source is slower than the speed of the CME front, but similar to the speed of the filament seen behind the CME front. This suggests that energetic electrons are being advected outwards in magnetic flux tubes related to the CME. This is also the scenario for the expanding loops observed in microwave images by Hudson et al. (2001) in conjunction with an event far beyond the west limb. Multi-spacecraft observations (Kane et al. 1992) have already shown that such HXR emissions from the high corona could occur during the impulsive phase of the flare, simultaneously with the HXR footpoint emissions.

Krucker et al. (2007a) found evidence that all fast ($v > 1500$ km s^{-1}) farside CMEs that originate from flares occulted by 20° to 45° may show related HXR emissions from the high corona. With the sensitivity of *NuSTAR*, hard X-ray emission from the much more frequently occurring slower CMEs should be detectable. Hence, even with only a few days of observations, several occulted CME should be seen. Since these sources are extended, *NuSTAR* imaging provides appropriate spatial resolution.

5) The quiet Sun

NuSTAR will make a giant improvement in our understanding of the hard X-ray spectrum of the quiet Sun. Several mechanisms outside the normal plasma physics of flares and solar magnetic activity could contribute; specifically we note cosmic-ray effects (both extrasolar and solar-system), as seen for example in the Fermi observations of inverse Compton scattering of sunlight from cosmic-ray electrons (Orlando et al. 2009). The current (RHESSI) limits on hard x-ray flux from the quiet Sun (Hannah et al., 2010) are somewhat improved over those derived earlier (Churazov et al. 2008), but *NuSTAR*'s sensitivity will suddenly drop these numbers into the domain of the albedo source from the diffuse cosmic x-ray background – the Sun will actually appear darker against the bright cosmic background, shining primarily with Compton back-scattered cosmic x-ray light. We also note the possibility of axion emission from the solar core, which could produce an X-ray signal via Primakoff conversion in the solar magnetic field (Carlson & Tseng 1996).

6) The earliest stages of flares

NuSTAR's high sensitivity will give an unprecedented look at particle acceleration in the precursor period to small, medium, and large flares when active regions are observed on the disk or at the limb. By comparing these observations with other wavelengths – such as EUV observations, which often saturate when flares reach their impulsive phase – it may be possible to identify the onset of particle acceleration and the rate and method of its expansion.

Scope of the proposed program

Based on the size of the qualified community, we might expect to receive 15-30 proposals per year for a *NuSTAR* GI program, once the capabilities of the instrument become well known thanks to the guaranteed solar observations during the primary mission. We expect to be limited more by the amount of observatory time available to be dedicated to solar observing than by the availability of good proposals. Let us say, then, that between 5 and 10 proposals should be funded each year. There may be only time for a few individual pointings on the order of a day or two, but each of these may observe a variety of phenomena, and solar GI awardees would be chosen and funded based on their proposed exploitation of the data, not just for novel observing strategies, although those may be considered as well. Consistent with the policy for all *NuSTAR* observations, no data would be proprietary, so multiple uses could be made of each pointing, and multiple investigators funded. Individual awards should be large enough to fund the acquisition and analysis of simultaneous ground-based and other space-based observations, and/or directly relevant theory and modeling efforts, as well as the analysis of *NuSTAR* data. We suggest that approximately $500K per year should be available to fund the 5-10 selected proposals, of which 1-3 could be two-year proposals to be funded out of that total, if exceptional reasons warranted it. The management of the GI program should be negotiated among the Heliophysics Divsion, the Astrophysics Division, and the *NuSTAR* Science Steering Committee. It could be administered as a panel of solar specialists within the context of the regular *NuSTAR* GI competition, with the only difference being the source of funding for accepted solar proposals, or it could be administered separately by the Heliophysics division, with a different procedure and deadline, with *NuSTAR* team members brought in for technical support of the review. In the latter scenario, the total time available for *NuSTAR* solar observations would have to be negotiated among the parties ahead of time.

Conclusion

NuSTAR's 200-fold advance in hard x-ray sensitivity over current capabilities will open up entirely new parameter spaces for the study of particle acceleration at the Sun. Because the Sun produces ever more microflares at lower and lower luminosity in the range where we can now observe it, extrapolation leads us to expect that even short observations at these sensitivities will return a wealth of interesting events; and, if not, that will imply the discovery of a surpising and informative threshold effect for particle acceleration. The few weeks of *NuSTAR* solar pointings may therefore provide a science return approaching that of a dedicated mission. We believe the best way to assure this and harness the ingenuity of the solar community is the dedicated solar GI program outlined here.

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