New estimation of non-thermal electrons energetics in
the giant solar flare on 28 October 2003 based on Mars
Odyssey observations

B.A. Nizamova,b,∗, I.V. Zimovetsc,d,e, D.V. Golovinc, A.B. Saninc,
M.L. Litvakc, V.I. Tretyakovc, I.G. Mitrofanovc, A.S. Kozyrevc

aSternberg Astronomical Institute of Lomonosov Moscow State University, Universitetsky
pr. 13, Moscow 119234, Russia
bFaculty of Physics, M.V.Lomonosov Moscow State University, Leninskie Gory, Moscow
119991 Russia
cSpace Research Institute (IKI) of the Russian Academy of Sciences, Profsoyuznaya str.
84/32, Moscow 117997, Russia
dState Key Laboratory of Space Weather, National Space Science Center (NSSC) of the
Chinese Academy of Sciences, No.1 Nanertiao, Zhongguancun, Haidian District, Beijing
100190, China
eInternational Space Science Institute – Beijing (ISSI-BJ), No.1 Nanertiao,
Zhongguancun, Haidian District, Beijing 100190, China

Abstract

A new estimation of the total number and energy of non-thermal electrons
produced in the giant (> X17) solar flare on 2003 October 28 is presented
based on the analysis of observations of hard X-ray (HXR) emission by the
High Energy Neutron Detector (HEND) onboard the Mars Odyssey space-
craft orbiting around the Mars. This is done to complement the estim a-
tion of non-thermal electron energy (E > 5.6 × 1031 ergs) by Emslie et al.
(2012) based on the Reuven Ramaty High-Energy Solar Spectroscopic Im-
ager (RHESSI) data, which missed the peak of the flare impulsive phase.

We used different models to make this estimation, including the widespread
thick and warm target models. We found that, depending on the model
used and the low-energy cutoff (Ec) of non-thermal electrons, the estimate
of their total energy in the entire flare can vary from 1.6 × 1032 to 5.7 × 1033
ergs. The lowest estimate, 1.6 × 1032 ergs, obtained within the thick target
model and fixed Ec = 46 keV, is consistent (within the factor of 2) with the
estimate of Emslie et al. (2012). In this case, non-thermal electrons acceler-
ated in the peak of the flare impulsive phase missed by RHESSI contained

∗Corresponding author
Email address: nizamov@physics.msu.ru (B.A. Nizamov)
approximately 40% of the total energy of non-thermal electrons of the entire flare. The highest value, $5.7 \times 10^{34}$ ergs, obtained with the thick target model and fixed $E_c = 10$ keV, which is comparable to the estimate by [Kane et al. (2005)] for another giant flare on 2003 November 4, looks abnormally high, since it exceeds the total non-potential magnetic energy of the parent active region ($2.9 \times 10^{33}$ ergs) estimated by [Emslie et al. (2012)]. Our estimates also show that the total number and energetics of the HXR-producing electrons in the flare region is a few times larger than of the population of energetic electrons impulsively injected into the interplanetary space from the Sun.

Keywords: Solar flares, hard X-rays, energetic electrons

1. Introduction

Major solar flares have always been an object of intensive investigation. Apart from the fact that they demonstrate a huge variety of physical processes and interactions between them, there are two reasons which make such events worth considering. First, strong solar flares can severely impact the Earth causing geomagnetic storms and affecting technical facilities including spacecraft, airplanes and ground infrastructure. A good illustration of this point is the so-called Halloween storm which was caused by a series of strong solar flares in October-November 2003. A special issue of the Journal of Geophysical Research (volume 110, issue A9) was dedicated to this phenomenon (see, e.g., [Gopalswamy et al., 2005] for an overview). Also, the ”Solar Extreme Events-2003” collaboration organized in Russia presented the detailed investigation of these extreme phenomena in a special volume of the Cosmic Research journal (see [Veselovsky et al., 2004]; [Panasyuk et al., 2004]).

Second, large solar flares serve as natural benchmarks indicating the highest energy which can be released in such an event. This is interesting from the point of view of solar-stellar relation. [Maehara et al., 2012] and [Shibayama et al., 2013] report on the so-called superflares on G-type dwarfs. Their estimations of the total energy released in a superflare reach $10^{36}$ ergs. The stars they analyzed are close to the Sun in their fundamental parameters, but they are mostly very young and fast rotating objects. A natural question is whether the difference in energies between solar and stellar flares is only quantitative or also qualitative. To understand this, it is important to understand what is the energy limit for solar flares.

In the last three solar cycles, there occurred a number of exceptional, or ”giant” flares. By ”giant” one calls extremely powerful flares, in which X-ray detectors onboard the Geostationary Operational Environmental Satellites (GOES) are in the saturated state (e.g., [Kane et al., 1995]; [Struminsky, 2013]).
In the 22nd solar cycle, the level of the GOES saturation corresponded to an X12 class flare. A series of giant flares greater than X12 took place on 1, 4, 6, 11 and 15 on June 1991. During the next (23rd) cycle, when the level of the GOES saturation was increased to around X17, there took place a series of powerful flares in October-November 2003 mentioned above. Kane et al. (2005) observed the most extreme event on November 4 with Ulysses and estimated the total energetics of non-thermal (> 20 keV) electrons produced in the flare to be \( \approx 1.3 \times 10^{34} \) ergs that is extremely high for the solar flares ever observed (see also Kane et al. (1995). Bieber et al. (2003), Klassen et al. (2005), Miroshnichenko et al. (2003) and Simnett (2005) discuss the timings of energetic particles in, probably, the second largest of the October-November 2003 events, i.e. the October 28 event, but did not estimate the total energetics of non-thermal electrons accelerated in the flare region. Mewaldt et al. (2005) estimated the total energetics of non-thermal interplanetary particles (including electrons, protons and ions) to be \( \approx 6 \times 10^{31} \) ergs. Kuznetsov et al. (2005), Grechnev et al. (2005) and Kurt et al. (2010) observed this event with CORONAS-F. Kopp et al. (2005) detected this flare with the Total Irradiance Monitor. Gros et al. (2004) and Kiener et al. (2006) investigated gamma radiation of this flare by the gamma-ray spectrometer SPI/INTEGRAL. Su et al. (2006) compared the EUV observations of the event made by TRACE and hard X-ray (HXR) observations by the Anti-Coincidence System ACS/INTEGRAL. Struminsky (2013) compared electromagnetic emissions of this and other giant flares of the 23rd solar cycle. It is shown that the peak fluxes of HXR and microwave emissions of the October 28 flare were even higher than of the November 4 flare. This indicates that the energetics of non-thermal electrons in the first flare (probably, having the lower X-ray class) could be even higher than in the second one. Nonetheless, the energetics of electrons accelerated in the October 28 flare was not estimated in the aforementioned papers.

It has been done by Emslie et al. (2012) with the RHESSI (Lin et al. 2002) HXR data, and the lower estimate to be \( 5.6 \times 10^{31} \) ergs that is more than two orders of magnitude less than the estimate for the November 4 flare given by Kane et al. (2005). However, it should be emphasized that the October 28 event was only partially observed by RHESSI, which apparently missed the maximum of the flare HXR impulsive phase because of the passage through the South Atlantic Anomaly (SAA; see Fig. 1). But this event was fully observed by the High Energy Neutron Detector (HEND), a part of the gamma-ray spectrometer GRS on board of the Mars Odyssey spacecraft (Boynton et al. 2004). This instrument observed the event from the Mars orbit nearly at the same angle as RHESSI (see Fig. 2), and it provides HXR spectral information in the range 87–1014 keV for the whole time of the flare.
This event is the most powerful of all listed by Livshits et al. (2017) in their catalog of solar flares detected by HEND in 2001-2016. The goal of this work is to use these HXR data to infer the total amount and energy of non-thermal electrons accelerated in the course of this extreme flare. This will help to refine the estimate given by Emslie et al. (2012) and compare it with the estimate given by Kane et al. (2005) for the November 4 flare.

The paper is organized as follows. In Section 2 the observations and the data are described. In Section 3 we discuss the models of propagation and bremsstrahlung of non-thermal electrons in the solar flare region and then apply them to infer the total amount of accelerated electrons and their energy. We also present simple estimation of amount and energetics of interplanetary energetic electrons. Discussion and conclusions are given in Sections 4 and 5 respectively.

2. Observations and data reduction

2.1. Mars Odyssey/HEND observations

HEND instrument onboard 2001 Mars Odyssey spacecraft is described by Boynton et al. (2004). It consists of a set of $^3$He proportional counters and a scintillation block with two detectors. We used the data from the outer (CsI) scintillator. It provides the HXR count rates in 16 energy channels with the time resolution of around 20 sec. This detector was not pre-calibrated to before the flight, and we used the calibration described in Livshits et al. (2017). The energy boundaries are reliable only for channels 3–14 which cover the range of 87–1014 keV.

2001 Mars Odyssey is in a polar Sun-synchronous orbit, therefore it is continuously exposed to the sunlight. However a given flare observed from near Earth may not be observed by HEND due to relative locations of Earth, Mars and the flaring site on the solar surface. Moreover, sometimes the Sun as observed by HEND is obscured by the spacecraft, and in such cases the measurements are not reliable. We checked the observation conditions for the time interval from 2003 October 28 11:00 to 11:35 UT, when the flare took place, with the SPICE package Acton (1996). The positions of Earth, Mars and the location of the flare on the solar surface are shown schematically in Fig. 2. One can see that the flare was observed from Mars at the same small angle as from Earth (Earth and Mars were located almost symmetrically with respect to the line connecting the center of the Sun and the flare site). This allows us not to consider the possible effects of anisotropy of HXR emission in this event (e.g., Kane et al. 1988; Kudryavtsev and Charikov 2012). The analysis of the spacecraft orientation
showed that the Sun was seen directly from the position of HEND within the
time of the flare.

In general, HEND data reduction was the same as in Livshits et al. (2017).
Here we briefly outline the procedure. First, the background was subtracted.
The background level was estimated from the signal before the flare and ex-
trapolated up to the end of the HXR burst according to the linear law. The
adequacy of the background level obtained was estimated visually because
the flare was well pronounced in all the channels and the background showed
linear behavior before and after the flare. The raw count rate and the back-
ground are shown in panel $a$ of Fig. 6. Next, the count rates were converted
to the photon fluxes using the response matrices obtained from the calibra-
tion procedure and the data on the detector shape and the discriminator
coefficients.

As was mentioned before, RHESSI observed the flare only partially, start-
ing from 11:06:15 UT (see Fig. 1). These data can be used to check the
correctness of the HEND data. We broke the time range from 11:06:15 to
11:29:30 UT, when RHESSI was observing the flare, into 20 sec intervals
which is equal to the time cadence of HEND. In each of these intervals we
approximated the RHESSI spectrum by a broken power law in the range
50–400 keV. Such energy range was chosen in order to be sure that the con-
tribution of the thermal component is negligible. Then the model photon
spectra were summed within the boundaries of the HEND energy channels.
These quantities were compared with the photon fluxes derived from the
HEND data.

This comparison revealed that HEND suffered from saturation during
this powerful flare: HXR fluxes measured by HEND are lower than fluxes
measured by RHESSI and the difference is larger for larger flux. This effect
is caused by the fact that the HEND electronics has a finite time resolution.
When a time interval between two photons detection is too short they are
registered as one photon with the energy equal to the sum of the energies of
the incident photons. This is known as the pile-up effect. Fig. 3 illustrates
the problem: in the left column, we show the ratio of the RHESSI flux to
that of HEND for the HEND channels 3, 5, 7, 9. The curves fitted are of the
form $R(x) = a + be^{(x-c)/d}$, where $a, b, c, d$ are the parameters fitted for each
channel. For the higher energy channels the saturation curve approaches a
straight line. In the right column we show the HEND and RHESSI fluxes for
the same HEND channels. One can see that the response of HEND continues
to vary even at the high level of saturation. Therefore, we decided to use
the curves shown in Fig. 3 to correct the HEND fluxes via multiplication
of the flux $F$ in the given channel by $R(F)$. The saturation curves for the
channels 12, 13, 14 show somewhat irregular behavior and we excluded these
channels from the analysis, the resulting energy range being 87–511 keV. The corrected normalization coefficient and the power law index as functions of time are shown in panels b and c of Fig. 6 respectively. In panel c we also show the two power law indexes of RHESSI spectra.

The model curve of the form \( I(E) = A(E/E_0)^{-\phi} \) was fitted to the corrected flux data giving us the HXR spectrum for each time instance. In Fig. 4 we show several examples of HEND and RHESSI spectra at various time instances.

The flare under consideration was observed by Konus/Wind [Aptekar et al. (1995)]. We compared HXR spectra in the 170-500 keV range made with HEND and Konus/Wind for several time intervals within 11:01:12-11:02:57 UT, when the Konus/Wind spectral data are available, and found consistency between these spectra within a factor of 2 (private communication with A. Lysenko, Ioffe Institute, St. Petersburg, Russia). This gives us additional confidence that our calibration of the HEND data is quite adequate.

2.2. RHESSI observations

The parameters of non-thermal electrons can be derived from the RHESSI HXR spectra using \textit{thick2} model. We used RHESSI data from the detector 4 from 11:06:14 to 11:29:24 UT (when the RHESSI data are available). This time interval was divided into subintervals of 20 sec length. The spectrum was then approximated by the combination of an isothermal and a non-thermal components \((v_{th} + \textit{thick2})\) in the range from 15 to 300 keV. The lower boundary was chosen so that the isothermal approximation gave an acceptable fit. The flare under consideration was exceptionally strong and the pile-up effect could not be fully corrected by the standard RHESSI software. This is evident in Fig. 5 where the fragments of the spectra are shown for the time intervals 11:07:34–11:07:54 and 11:11:34–11:11:54 UT together with the residuals. Our fitting strategy is illustrated in these figures as well. Namely, we did not try to achieve \(\chi^2 \approx 1\). Instead, we first fitted the non-thermal component in the range 50–300 keV then the thermal component in the range 15–25 keV. This resulted in good fits at all energies except for the region of the spurious bump. Note that at 11:07:34 UT the pile-up effect is not well pronounced and the fit is quite good. We also performed this data reduction following another strategy, namely fitting both components simultaneously within the whole 15–300 keV energy range, but setting the break energy sufficiently high in order not to fit the spurious bump by a low energy spectral break. In this case we failed again to obtain good quality fits in the whole spectral range. However the total non-thermal electron number and energy practically did not change.
We used these fits in two ways. First, to compare the number and the energy of non-thermal electrons derived from other models and HEND data. Second, to obtain the temperature of the hot plasma which is a parameter of the warm target model. For the time interval from 10:50:00 to 11:05:15 UT we used the temperatures from GOES. From 11:05:39 to 11:15:06 UT the GOES 0.5–4.0 Å channel was saturated and we used the temperatures from RHESSI starting from 11:06:15 UT. The evolution of the temperature with time is shown in panel d of Fig. 6. One can see that when GOES was not saturated the temperature derived from the RHESSI data is sufficiently higher than that derived from the GOES data.

3. Estimation of number and energetics of non-thermal electrons

3.1. Non-thermal electrons in the flare region on the Sun

The HXR spectrum allows one to calculate the instantaneous flux of non-thermal electrons being accelerated in the course of the flare. Different approaches are possible. First, one can accept the thick target model developed by Brown (1971); Syrovatskii and Shmeleva (1972). In this case one has to introduce the lower energy cutoff $E_c$ of the electron source. Since HEND data provide no idea about its value (which is usually less than 50 keV in solar flares) we perform the calculations for several cutoff energies from 10 to 46 keV. Second, one can use the warm target model by Kontar et al. (2015), which does not introduce the cutoff energy artificially, because the electron spectrum appears to be suppressed at low energies due to the model properties. The effective cutoff energy in this model is shown to be $(\delta + 2)kT$, where $k$ is the Boltzmann constant, $\delta$ is the power law index of accelerated electrons in the source and $T$ is the temperature of the target. Thus, in this case one needs information on the flaring plasma temperature. We utilize this approach either by using the GOES data to determine the temperature of the soft X-ray (SXR) emitting plasma when the RHESSI data were not available or using RHESSI spectral fits as described in Sec. 2. Finally, one can deduce the properties of the accelerated electrons from RHESSI data with the OSPEX package by fitting the thick2 model. We follow this approach in order to compare our calculations in a more simple thick target model. Emslie et al. (2012) estimated the total energy of non-thermal electrons in this flare using RHESSI data and thus obtained the lower limit of this quantity (see Introduction). We will refer to their results later.

In the framework of the thick target model, one needs the HXR spectrum and some guess about the electrons’ low energy cutoff $E_c$ in order to obtain the total amount of accelerated electrons and their energy. In the literature different values of $E_c$ are adopted, usually from 10 to 30 keV. We used...
RHESSI data to estimate $E_c$ at the time it exited SAA, the value obtained is $45.9 \pm 6.2$ keV. Thus, we performed the calculation for four values of $E_c$: 10, 20, 30 and 46 keV. We used the formulas from Syrovatskii and Shmeleva (1972):

$$\Phi(E > E_1, t) = 1.02 \times 10^{34} \frac{\gamma_1^2}{E_1 B(\gamma_1, \frac{1}{2})} \frac{I(\varepsilon_1 < \varepsilon < \varepsilon_2)}{1 - \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^{\gamma_1}} \text{[sec}^{-1}]$$  (1)

for the number of electrons and

$$F(E > E_1, t) = 1.02 \times 10^{34} \frac{\gamma_1(\gamma_1 + 2)}{B(\gamma_1, \frac{1}{2})} \frac{I(\varepsilon_1 < \varepsilon < \varepsilon_2)}{1 - \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^{\gamma_1}} \text{[keV sec}^{-1}]$$  (2)

for the energy. In these formulas, $\varepsilon_1$ and $\varepsilon_2$ are the boundaries of the HXR spectrum, $\gamma_1 = \varphi - 1$ is the power law index of the electrons in the target, $\varphi$ being the power law index of the HXR spectrum, $I$ is the total (energy integrated) HXR flux. We set $\varepsilon_1 = E_1 = E_c$ (i.e. we extrapolate the spectrum down to $E_c$), $\varepsilon_2 = \infty$.

The warm target model introduced by Kontar et al. (2015) is believed to avoid the difficulty of unknown $E_c$. Due to the electron thermalization taken into account in this model, the spectrum at the low energy end becomes suppressed without introducing cutoff. The beam cross-section integrated flux reads in this model:

$$AF_0(E_0) = -2K \frac{d}{dE} \left[ \frac{1}{E} \left( \frac{E}{kT} - 1 \right) G\left(\frac{E}{kT}\right) \langle nVF\rangle(E) \right]_{E=E_0}$$  (3)

where $K = 2\pi e^4 \Lambda$, $\Lambda$ is the Coulomb logarithm,

$$G(u) = \frac{\text{erf}(u) - u\text{erf}'(u)}{2u^2},$$  (4)

$\text{erf}$ is the error function. Further, $\langle nVF \rangle$ is the source integrated electron spectrum:

$$\langle nVF \rangle = \frac{\int_V n(r, t) F(E, r, t) dV}{\int_V n(r, t) dV}$$  (5)

which in case of the power law spectrum of the form $I(E) = A(E/E_0)^{-\varphi}$ is equal to

$$\langle nVF \rangle = 6.66 \times 10^{37} B(\varphi - \frac{3}{2}, \frac{1}{2})A(2\varphi - 3)(\varphi - 1)E_0^{\varphi} E^{1-\varphi}, [\text{cm}^{-2}\text{s}^{-1}\text{keV}^{-1}]$$  (6)
In (3), $T$ is the temperature of the target. We estimated it from the GOES and RHESSI data (see Sec. 2). Then integration of (3) over energies with the weight 1 or the electron energy $E$ gives the total electron flux and energy flux respectively.

Finally, we make a remark about the non-thermal electron parameter derivation from RHESSI data. Here, one needs only to fit the certain model to the spectrum to obtain the parameters sought. As was stated in Sec. 2, the spectrum of the flare in question was distorted due to the pile-up effect. For this reason, accurate determination of the electron parameters was difficult. At the same time, this is not a problem for the calculations described above because in this case one only needs the HXR spectrum (at relatively high energies) which is fitted by a power law model quite reliably. But in such calculations the problem of unknown $E_c$ cannot be solved.

The results of our calculations are presented in Table 1. Each row corresponds to a certain model: warm target; thick target with $E_c = 10, 20, 30, 46$ keV; and RHESSI spectral fit. The calculations in the warm and thick target models are performed for the two time intervals: 1) the interval when the RHESSI data are available and 2) the whole time of the flare. The comparison of the results obtained with the HEND data with those obtained purely from the RHESSI data as well as the results of Emslie et al. (2012) is given in Sec. 4. The time evolution of the number and energy of non-thermal electrons is shown in panels e and f of Fig. 6 respectively for all the models used.

3.2. Interplanetary energetic electrons

Mewaldt et al. (2005) estimated the total energy of solar energetic particles (SEP) in the range from 0.01 to 1000 MeV/nucleon to be $\approx 5.8 \times 10^{31}$ ergs in the 2003 October 28 SEP event. Emslie et al. (2012) gave similar value of $\approx 4.3 \times 10^{31}$ ergs. These estimates have been done for the entire SEP population (including electrons, protons and ions) and for the total duration of the SEP event of more than 30 hours. It was inferred that energetic electrons contain not more than 18% of the total estimated energy of SEP, i.e. not more than $\approx 1.0 \times 10^{31}$ ergs.

Klassen et al. (2005) showed that there were at least two populations of energetic electrons injected in the interplanetary medium during this SEP event: impulsive and gradual. Impulsive electrons were accelerated/injected in the flare impulsive phase and they were detected for around 25 min that is similar to the duration of the flare impulsive phase observed in the HXR range. Gradual electrons started to accelerate and release approximately 20 min after the onset of the impulsive electron acceleration, and this process lasted more than 5 hours. Though details of acceleration/injection processes
in this event are not known, the timing analysis indicates that the impulsive electrons could be accelerated during the flare impulsive phase in the flaring region, while the gradual electrons were accelerated later, and the site of their acceleration is not clear. Thus, it makes sense to compare total numbers and energetics of impulsive electrons in the interplanetary medium and non-thermal electrons in the flare region. We will also estimate the same parameters for gradual electrons.

We follow the same simplified approach as Lin and Hudson (1976) to estimate total number

\[ N(E > E_0) \approx \Delta t V \int_{E_0}^{\infty} I(E)4\pi v^{-1}dE \]  

(7)

and total energy

\[ \epsilon(E > E_0) \approx \Delta t V \int_{E_0}^{\infty} I(E)4\pi E v^{-1}dE \]  

(8)

of energetic electrons with energies above some threshold level \( E_0 \) injected into the interplanetary space. Here \( \Delta t \) is the duration of the energetic electrons detection. For impulsive electrons (denoted by i-superscript) we take \( \Delta t_i = 25 \) min and for gradual electrons \( \Delta t_g = 5 \) hours. \( V \sim 10^{40} \) cm\(^3\) is the volume filled by the energetic electrons, \( v \) and \( E \) is their velocity and energy respectively. According to Klassen et al. (2005) the peak intensity spectra of impulsive and gradual electrons in this event can be fitted by combinations of two power-law functions \( I_{1,2}^{i,g}(E) = A_{1,2}^{i,g} \times (E/E_{1,2}^{i,g})^{-\delta_{1,2}^{i,g}} \) [cm\(^{-2}\)sec\(^{-1}\)ster\(^{-1}\)MeV\(^{-1}\)], the first one is for the energies below around \( E_{2,g} \) = 66 keV and the second one is for the energies above \( E_{2,g}^{i,g} \). The numerical parameters of these functions for impulsive electrons are as follows: \( A_1^i \approx 5 \times 10^7 \), \( A_2^i \approx 6 \times 10^8 \), \( \delta_1^i \approx 1.9 \), \( \delta_2^i \approx 6.2 \), and \( E_1^i = 8.9 \) keV; and for gradual electrons: \( A_1^g \approx 2 \times 10^6 \), \( A_2^g \approx 7 \times 10^5 \), \( \delta_1^g \approx 1.3 \), \( \delta_2^g \approx 2.2 \), and \( E_1^g = 27 \) keV. Here we multiplied coefficients \( A_{1,2}^{i,g} \) from Klassen et al. (2005) by \( 10^6 \) to take the error in their paper into account (the ordinate axis dimensionality in their Fig.3 should be \( \text{[cm}^{-2}\text{sec}^{-1}\text{ster}^{-1}\text{MeV}^{-1}\]); see, e.g., Simnett (2005; Mewaldt et al. 2005). Since \( E_0 \) is not known, we will make estimations for several different values \( E_0^1 = 0.1 \), \( E_0^2 = 1 \), \( E_0^3 = 10 \), \( E_0^4 = 20 \), \( E_0^5 = 30 \), and \( E_0^6 = 46 \) keV. \( E_0^1 \) corresponds to the boarder energy between the Maxwellian-distributed solar wind electrons and power-law-distributed energetic electrons (see, e.g., Lin 1985).

Calculating the integrals in the formulas (7) and (8), we get the values for \( N(E > E_0^{1,2,3,4,5,6}) \) and \( \epsilon(E > E_0^{1,2,3,4,5,6}) \) summarized in Table 2. We need to note that these are the upper estimates because they were obtained using
the peak spectra, i.e. the spectra calculated for the peak intensity in each energy channel of the particle detector (see \textcite{Klassen:2005}).

4. Discussion

\textcite{Emslie:2012} estimated the energetics of 38 solar flares in various channels of energy release. The non-thermal electron energy was estimated from RHESSI HXR observations. Regarding the flare on 2003 October 28 the authors give the lower estimate $E > 5.6 \times 10^{31}$ ergs due to the fact that only a part of the flare was observed by RHESSI and they adopted the highest value of $E_c$ which gave an acceptable spectral fit. Our lowest energy estimation derived from the HEND data within the time interval of RHESSI observations is $1.0 \times 10^{32}$ ergs for the low-energy cutoff $E_c = 46$ keV. However, \textcite{Emslie:2012} point out that their estimations are the lower limits in the sense that they adopted the highest $E_c$ which provided acceptable fit and the actual energy of non-thermal electrons can be up to one order of magnitude higher. Thus, regarding the accuracy of our estimations based on the HEND data, we argue that they are consistent within a factor of two with the analysis based on forward fitting of RHESSI spectra; this provides the grounds to consider our results valid. Our own calculations using RHESSI data differ from that of \textcite{Emslie:2012} within a factor of three. Again, as stated by \textcite{Emslie:2012}, it is the uncertainty of $E_c$ which hinders accurate and reliable estimation of the non-thermal electron energy. Since our estimation in case of $E_c = 46$ keV is quite close to that obtained from forward fitting, we argue that the value we obtained for the full time of the flare ($1.6 \times 10^{32}$ ergs) is the lower estimate of the total non-thermal electron energy released in the 2003 October 28 flare. In such case, the energy content of non-thermal electrons produced around the peak of the flare impulsive phase, missed by RHESSI, is $\approx 40\%$ of the total energy of non-thermal electrons produced during the entire flare.

Warm target model gives significantly higher estimates of the number and energy of non-thermal electrons. The effective cutoff energy in this model is $(\delta + 2)kT$ where $\delta$ is the power law index of the HXR source integrated electron spectrum and $T$ is the target temperature. In our calculations, this effective cutoff never exceeds 12 keV, and indeed the results of this model are close to the results of thick target model with $E_c = 10$ keV. However, the total energy in this case exceeds \textcite{Emslie:2012} estimate of the total non-potential, i.e. free magnetic energy contained in the flare region $\approx 2.9 \times 10^{33}$ ergs, and, by this reason, seems unrealistic.

\textcite{Kopp:2005} obtained the total radiated energy of the October 28 flare between 3 and $9 \times 10^{32}$ ergs from the observations with the Total Ir-
radiance Monitor. This is consistent with the estimate of the free magnetic energy in the flare region by Emslie et al. (2012). It is clear that the free magnetic energy should be larger than the energy of non-thermal electrons, and the last one should be a fraction of the total radiated energy of the flare. This points that the total energy of non-thermal electrons should be not more than a few times of $10^{32}$ ergs. This is consistent with our estimations for $E_c = 30$ and $E_c = 46$ keV within the thick target model.

It is interesting to compare our results with the results for another giant flare on 2003 November 4, whose X-ray class might be even higher than that of the 28 October flare (e.g., Kiplinger and Garcia 2004; Brodrick et al. 2005). Kane et al. (2005) give the estimate of $\sim 3 \times 10^{41}$ electrons above 20 keV, which carried the energy between $4 \times 10^{33}$ and $3 \times 10^{34}$ ergs that is several times larger than our result for $E_c = 20$ keV (i.e. $1.1 \times 10^{33}$ ergs). Obviously, for these two giant flares there is at least rough scaling between thermal and non-thermal energy, i.e. the total non-thermal electron energy in the more powerful flare is larger, suggesting the same low-energy threshold of non-thermal electrons. Unfortunately, HEND did not observe the November 4 flare since it was in the safe mode because of strong bombardment by SEP caused by the October 28–29 flares.

Finally, we obtained the upper limit estimates of the total number and energetics of the impulsive and gradual interplanetary non-thermal electrons in the 2003 October 28-29 SEP event based on the peak intensity spectra measured in the Sun-Earth Lagrangian point L1 and presented by Klassen et al. (2005). Our estimates show that the amount and energetics of the impulsive interplanetary electrons (followed by the gradual ones) is several times less than the corresponding values of the HXR-emitting non-thermal electrons with the same low-energy cutoff. This does not contradict the possibility that the same acceleration process in the flare impulsive phase is responsible for both the HXR-emitting not-thermal electrons and population of impulsive electrons escaped into the interplanetary medium from the solar corona. However, our estimate gives much larger percentage of the escaped electrons than usually observed in well-magnetically connected impulsive SEP events (e.g., Krucker et al. 2007). This may be due to that our estimate of the interplanetary electrons is overstated, and also because the situation in a giant event may differ from the situation in weaker impulsive events. The first possibility seems more reasonable, since our estimate for the gradual population of energetic interplanetary electrons exceeds by two orders of magnitude the estimate given by Mewaldt et al. (2005) for the entire SEP population in this event.

Aulanier et al. (2013) used numerical MHD simulations and historical data on sunspots to derive the maximum possible energy of a solar flare.
Taking into account the limitations and uncertainties of their method they put the upper limit of \(~6 \times 10^{33}\) ergs. At the same time, flares with energies of up to \(~10^{36}\) ergs are observed on the Sun-type stars. Even our largest energy estimation resulting from the thick target model and fixed \(E_c = 10\) keV gives an energy \((\approx 5.7 \times 10^{33}\) ergs) slightly lower than the limit of [Aulanier et al. (2013)], which means that purely HXR observations (and non-thermal electron energetics derived from them) of this particular flare cannot remove the energetic gap between the strongest solar flares and flares on the Sun-type stars. Probably some other dynamo mechanism should operate on stars with superflares (see, e.g., [Katsova et al. 2018; Brandenburg and Giampapa 2018]), but this topic is outside the scope of the present work.

5. Conclusion

In this work we estimated the total amount and energy of the non-thermal electrons accelerated in the giant (>X17) solar flare on 2003 October 28. We used the HXR observations by the Mars Odyssey/HEND which covered the full time of the flare and the viewing angle was practically the same as from the Earth. We obtained the estimates for the thick target model with several values of the lower cutoff energy and for the warm target model. The results were compared with those derived from the RHESSI observations of a portion of this flare. We conclude that the result consistent with the RHESSI observations (and with other energy estimations made by other authors) is that of the thick target model with \(E_c = 46\) keV, the results being \(1.5 \times 10^{39}\) electrons and \(1.6 \times 10^{32}\) ergs. The estimate obtained from the warm target model is close to that of the thick target model with \(E_c = 10\) keV, namely \(1.1 \times 10^{41}\) electrons and \(3.9 \times 10^{33}\) ergs. Previously, it was not known to what extent the non-thermal energy derived for this flare from the RHESSI data is underestimated due to the partial time coverage. Our results point that RHESSI ‘missed’ \(\approx 40\%\) of this energy.

We also estimated the upper limits of the number and energy of the interplanetary energetic particles originating from this event. Our estimates are \(5.1 \times 10^{38}\) electrons and \(4.8 \times 10^{31}\) ergs for the impulsive injection, and \(6.6 \times 10^{39}\) electrons and \(1.3 \times 10^{33}\) ergs for the gradual injection in this SEP event.

Our observations with HEND of the whole flare complement those made with RHESSI by [Emslie et al. (2012)] for a part of the flare. The result we obtained can be considered as exceptional for the observations of the Sun in hard X-rays, but it remains within the limits of possible energies according to the theoretical estimations.
Acknowledgements

We are grateful to the RHESSI and INTEGRAL teams for the available data used in this work. We also thank Dr. A.B. Struminsky for a number of useful criticisms and A. Lysenko for the help with the Konus/Wind data. This work is supported by the Russian Science Foundation under grant 17-72-20134.

References

References

Acton, C.H., 1996. Ancillary data services of NASA’s Navigation and Ancillary Information Facility. Planetary and Space Science 44, 65–70. doi:10.1016/0032-0633(95)00107-7

Aptekar, R.L., Frederiks, D.D., Golenetskii, S.V., Ilinskii, V.N., Mazets, E.P., Panov, V.N., Sokolova, Z.J., Terekhov, M.M., Sheshin, L.O., Cline, T.L., Stilwell, D.E., 1995. Konus-W Gamma-Ray Burst Experiment for the GGS Wind Spacecraft. Space Sci. Rev. 71, 265–272. doi:10.1007/BF00751332

Aulanier, G., Démoulin, P., Schrijver, C.J., Janvier, M., Pariat, E., Schmieder, B., 2013. The standard flare model in three dimensions. II. Upper limit on solar flare energy. Astron. Astrophys. 549, A66. doi:10.1051/0004-6361/201220406 [arXiv:1212.2086]

Bieber, J.W., Clem, J., Evenson, P., Pyle, R., Ruffolo, D., Sáiz, A., 2005. Relativistic solar neutrons and protons on 28 October 2003. Geophys. Res. Lett. 32, L03S02. doi:10.1029/2004GL021492

Boynton, W.V., Feldman, W.C., Mitrofanov, I.G., Evans, L.G., Reedy, R.C., Squyres, S.W., Starr, R., Trombka, J.I., D’Uston, C., Arnold, J.R., Englert, P.A.J., Metzger, A.E., Wänke, H., Brückner, J., Drake, D.M., Shinohara, C., Fellows, C., Hamara, D.K., Harshman, K., Perry, K., Turner, C., Ward, M., Barthe, H., Fuller, K.R., Storms, S.A., Thornton, G.W., Longmire, J.L., Litvak, M.L., Ton’chev, A.K., 2004. The Mars Odyssey Gamma-Ray Spectrometer Instrument Suite. Space Sci. Rev. 110, 37–83. doi:10.1023/B:SPAC.0000021007.76126.15

Brandenburg, A., Giampapa, M.S., 2018. Enhanced stellar activity for slow antisolar differential rotation? ArXiv e-prints [arXiv:1802.08689]
Brodrick, D., Tingay, S., Wieringa, M., 2005. X-ray magnitude of the 4 November 2003 solar flare inferred from the ionospheric attenuation of the galactic radio background. Journal of Geophysical Research (Space Physics) 110, A09S36. doi:10.1029/2004JA010960

Brown, J.C., 1971. The Deduction of Energy Spectra of Non-Thermal Electrons in Flares from the Observed Dynamic Spectra of Hard X-Ray Bursts. Solar Phys. 18, 489–502. doi:10.1007/BF00149070

Emslie, A.G., Dennis, B.R., Shih, A.Y., Chamberlin, P.C., Mewaldt, R.A., Moore, C.S., Share, G.H., Vourlidas, A., Welsch, B.T., 2012. Global Energetics of Thirty-eight Large Solar Eruptive Events. Astrophys. J. 759, 71. doi:10.1088/0004-637X/759/1/71 arXiv:1209.2654

Gopalswamy, N., Barbieri, L., Cliver, E.W., Lu, G., Plunkett, S.P., Soug, R.M., 2005. Introduction to violent Sun-Earth connection events of October-November 2003. Journal of Geophysical Research (Space Physics) 110, A09S00. doi:10.1029/2005JA011268

Grechnev, V.V., Chertok, I.M., Slemzin, V.A., Kuzin, S.V., Ignat’ev, A.P., Pertsov, A.A., Zhitnik, I.A., Delaboudinière, J.P., Auchère, F., 2005. CORONAS-F/SPRIT EUV observations of October-November 2003 solar eruptive events in combination with SOHO/EIT data. Journal of Geophysical Research (Space Physics) 110, A09S07. doi:10.1029/2004JA010931

Gros, M., Tatischeff, V., Kiener, J., Cordier, B., Chapuis, C., Weidenspointner, G., Vedrenne, G., von Kienlin, A., Diehl, R., Bykov, A., NMéndez, M., 2004. INTEGRAL/SPI Observation of the 2003 Oct 28 Solar Flare, in: Schoenfelder, V., Lichti, G., Winkler, C. (Eds.), 5th INTEGRAL Workshop on the INTEGRAL Universe, p. 669.

Kane, S.R., Fenimore, E.E., Klebesadel, R.W., Laros, J.G., 1988. Directivity of 100 keV-1 MeV photon sources in solar flares. Astrophys. J. 326, 1017–1031. doi:10.1086/166159

Kane, S.R., Hurley, K., McTiernan, J.M., Sommer, M., Boer, M., Niel, M., 1995. Energy Release and Dissipation during Giant Solar Flares. Astrophys. J. Lett. 446, L47. doi:10.1086/187927

Kane, S.R., McTiernan, J.M., Hurley, K., 2005. Multispacecraft observations of the hard X-ray emission from the giant solar flare on 2003 November 4. Astron. Astrophys. 433, 1133–1138. doi:10.1051/0004-6361:20041875
Katsova, M.M., Kitchatinov, L.L., Livshits, M.A., Moss, D.L., Sokoloff, D.D., Usoskin, I.G., 2018. Can superflares occur on the sun? a view from dynamo theory. Astronomy Reports 62, 72–80. URL: https://doi.org/10.1134/S106377291801002X

doi:10.1134/S106377291801002X

Kiener, J., Gros, M., Tatischeff, V., Weidenspointner, G., 2006. Properties of the energetic particle distributions during the October 28, 2003 solar flare from INTEGRAL/SPI observations. Astron. Astrophys. 445, 725–733. doi:10.1051/0004-6361:20053665. arXiv:astro-ph/0511091

Kiplinger, A.L., Garcia, H.A., 2004. Soft X-ray Parameters of the Great Flares of Active Region 486, in: American Astronomical Society Meeting Abstracts #204, p. 739.

Klassen, A., Krucker, S., Kunow, H., Müller-Mellin, R., Wimmer-Schweingruber, R., Mann, G., Posner, A., 2005. Solar energetic electrons related to the 28 October 2003 flare. Journal of Geophysical Research (Space Physics) 110, A09S04. doi:10.1029/2004JA010910

Kontar, E.P., Jeffrey, N.L.S., Ensmie, A.G., Bian, N.H., 2015. Collisional Relaxation of Electrons in a Warm Plasma and Accelerated Non-thermal Electron Spectra in Solar Flares. Astrophys. J. 809, 35. doi:10.1088/0004-637X/809/1/35. arXiv:1505.03733

Kopp, G., Lawrence, G., Rottman, G., 2005. The Total Irradiance Monitor (TIM): Science Results. Solar Phys. 230, 129–139. doi:10.1007/s11207-005-7433-9

Krucker, S., Kontar, E.P., Christie, S., Lin, R.P., 2007. Solar Flare Electron Spectra at the Sun and near the Earth. Astrophys. J. Lett. 663, L109–L112. doi:10.1086/519373

Kudryavtsev, I.V., Charikov, Y.E., 2012. Hard X rays of relativistic electrons accelerated in solar flares. Geomagnetism and Aeronomy 52, 875–882. doi:10.1134/S0016793212070080

Kurt, V.G., Yushkov, B.Y., Kudela, K., Galkin, V.I., 2010. High-energy gamma radiation of solar flares as an indicator of acceleration of energetic protons. Cosmic Research 48, 70–79. doi:10.1134/S0010952510010053

Kuznetsov, S.N., Kurt, V.G., Yushkov, B.Y., Myagkova, I.N., Kudela, K., Belov, A.V., Caroubalos, C., Hilaris, A., Mavromichalaki, H., Moussas, X., Preka-Papadema, P., 2005. Type II Radio Emission and Solar Particle
Lin, R.P., 1985. Energetic solar electrons in the interplanetary medium. *Solar Phys.* 100, 537–561. doi:10.1007/BF00158444

Lin, R.P., Dennis, B.R., Hurford, G.J., Smith, D.M., Zehnder, A., Harvey, P.R., Curtis, D.W., Pankow, D., Turin, P., Bester, M., Csillaghy, A., Lewis, M., Madden, N., van Beek, H.F., Appleby, M., Raudorf, T., McTiernan, J., Ramaty, R., Schmahl, E., Schwartz, R., Krucker, S., Abiad, R., Quinn, T., Berg, P., Hashii, M., Sterling, R., Jackson, R., Pratt, R., Campbell, R.D., Malone, D., Landis, D., Barrington-Leigh, C.P., Slassi-Sennou, S., Cork, C., Clark, D., Amato, D., Orwig, L., Boyle, R., Banks, I.S., Shirey, K., Tobbert, A.K., Zarro, D., Snow, F., Thomsen, K., Henneck, R., McHedlishvili, A., Ming, P., Fivian, M., Jordan, J., Wanner, R., Crubb, J., Preble, J., Matranga, M., Benz, A., Hudson, H., Canfield, R.C., Holman, G.D., Cranell, C., Kosugi, T., Emslie, A.G., Vilmer, N., Brown, J.C., Johns-Krull, C., Aschwanden, M., Metcalf, T., Conway, A., 2002. The Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI). *Solar Phys.* 210, 3–32. doi:10.1023/A:1022428818870.

Lin, R.P., Hudson, H.S., 1976. Non-thermal processes in large solar flares. *Solar Phys.* 50, 153–178. doi:10.1007/BF00206199

Livshits, M.A., Zimovets, I.V., Golovin, D.V., Nizamov, B.A., Vybornov, V.I., Mitrofanov, I.G., Kozyrev, A.S., Litvak, M.L., Sanin, A.B., Tretyakov, V.I., 2017. Catalog of hard X-ray solar flares detected with Mars Odyssey/HEND from the Mars orbit in 2001-2016. Astronomy Reports 61, 791–804. doi:10.1134/S1063772917090037, arXiv:1706.01116.

Maehara, H., Shibayama, T., Notsu, S., Notsu, Y., Nagao, T., Kusaba, S., Honda, S., Nagami, D., Shibata, K., 2012. Superflares on solar-type stars. *Nature* 485, 478–481. doi:10.1038/nature11063.

Mewaldt, R.A., Cohen, C.M.S., Labrador, A.W., Leske, R.A., Mason, G.M., Desai, M.I., Looper, M.D., Mazur, J.E., Selesnick, R.S., Haggerty, D.K., 2005. Proton, helium, and electron spectra during the large solar particle events of October-November 2003. Journal of Geophysical Research (Space Physics) 110, A09S18. doi:10.1029/2005JA011038.

Miroshnichenko, L.I., Klein, K.L., Trottet, G., Lantos, P., Vashenyuk, E.V., Balabin, Y.V., 2005. Electron acceleration and relativistic nucleon production in the 2003 October 28 solar event. Advances in Space Research 35, 1864–1870. doi:10.1016/j.asr.2005.02.041.
Panasyuk, M.I., Solar Extreme Events in 2003 Collaboration SEE-2003, Kuznetsov, S.N., Lazutin, L.L., Avdyushin, S.I., Alexeev, I.I., Ammosov, P.P., Antonova, A.E., Baishev, D.G., Belenkaya, E.S., Beletsky, A.B., Belov, A.V., Benghin, V.V., Bobrovnikov, S.Y., Bondarenko, V.A., Boyarchuk, K.A., Veselovsky, I.S., Vyushkova, T.Y., Gavrileva, G.A., Gaidash, S.P., Ginzburg, E.A., Denisov, Y.I., Dmitriev, A.V., Zherbtsov, G.A., Zelenyi, L.M., Ivanov-Kholodny, G.S., Kalgaevev, V.V., Kanonidi, K.D., Kleimenova, N.G., Kozyreva, O.V., Kolomiitsev, O.P., Krasheninnikov, I.A., Krivolutsky, A.A., Kropotkin, A.P., Kuminov, A.A., Leshchenko, L.N., Mar’in, B.V., Mitrikas, V.G., Mikhailov, A.V., Mullayarov, V.A., Muravieva, E.A., Myagkova, I.N., Petrov, V.M., Petrikovich, A.A., Podorolsky, A.N., Pudovkin, M.I., Samsonov, S.N., Sakharov, Y.A., Svidsky, P.M., Sokolov, V.D., Soloviev, S.I., Solosnovets, E.N., Starkov, G.V., Starostin, I.I., Tverskaya, L.V., Teltsov, M.V., Troshichev, O.A., Tsetlin, V.V., Yushkov, B.Y., 2004. Magnetic Storms in October 2003. Cosmic Research 42, 489–535. doi[10.1023/B:COSM.0000046230.62353.61].

Shibayama, T., Maehara, H., Notsu, S., Notsu, Y., Nagao, T., Honda, S., Ishii, T.T., Nogami, D., Shibata, K., 2013. Superflares on Solar-type Stars Observed with Kepler. I. Statistical Properties of Superflares. Astrophys. J. Suppl. 209, 5. doi[10.1088/0067-0049/209/1/5 arXiv:1308.1480].

Simnett, G.M., 2005. Near-relativistic electron emission following the 28 October 2003 X17 flare. Journal of Geophysical Research (Space Physics) 110, A09S01. doi[10.1029/2004JA010789].

Struminsky, A.B., 2013. Giant events in the 23rd solar cycle: Common and specific features. Geomagnetism and Aeronomy 53, 843–851. doi[10.1134/S0016793213070190].

Su, Y.N., Golub, L., van Ballegooijen, A.A., Gros, M., 2006. Analysis of Magnetic Shear in An X17 Solar Flare on October 28, 2003. Solar Phys. 236, 325–349. doi[10.1007/s11120-006-0039-z].

Syrovatskii, S.I., Shmeleva, O.P., 1972. Heating of Plasma by High-Energy Electrons, and Nonthermal X-Ray Emission in Solar Flares. Soviet Astron. 16, 273.

Veselovsky, I.S., Panasyuk, M.I., Avdyushin, S.I., Bazilevskaya, G.A., Belov, A.V., Bogachev, S.A., Bogod, V.M., Bogomolov, A.V., Bothmer, V., Boyarchuk, K.A., Vashenyuk, E.V., Vlasov, V.I., Gnezdilov, A.A., Gorgutsa,
R.V., Grechnev, V.V., Denisov, Y.I., Dmitriev, A.V., Dryer, M., Yermolaev, Y.I., Eroshenko, E.A., Zherebtsov, G.A., Zhitnik, I.A., Zhukov, A.N., Zastenker, G.N., Zelenyi, L.M., Zeldovich, M.A., Ivanov-Kholodnyi, G.S., Ignat’ev, A.P., Ishkov, V.N., Kolomiytsev, O.P., Krasheninnikov, I.A., Kudela, K., Kuzhevsky, B.M., Kuzin, S.V., Kuznetsov, V.D., Kuznetsov, S.N., Kurt, V.G., Lazutin, L.L., Leshchenko, L.N., Litvak, M.L., Logachev, Y.I., Lawrence, G., Markeev, A.K., Makhmutov, V.S., Mitrofanov, A.V., Mitrofanov, I.G., Morozov, O.V., Myagkova, I.N., Nusinov, A.A., Oparin, S.N., Panasenco, O.A., Pertsov, A.A., Petrukovich, A.A., Podorol’sky, A.N., Romashets, E.P., Svertilov, S.I., Svidsky, P.M., Svirzhevskaya, A.K., Svirzhevsky, N.S., Slemzin, V.A., Smith, Z., Sobel’man, I.I., Sobolev, D.E., Stozhkov, Y.I., Suvorova, A.V., Sukhodrev, N.K., Tindo, I.P., Tokhchukova, S.K., Fomichev, V.V., Chashey, I.V., Chertok, I.M., Shishov, V.I., Yushkov, B.Y., Yakovchouk, O.S., Yanke, V.G., 2004. Solar and Heliospheric Phenomena in October-November 2003: Causes and Effects. Cosmic Research 42, 435–488. doi[10.1023/B:CODM.0000046229.24716.02].
Figure 1: Background-subtracted count rates in different channels of HEND (20 s resolution), RHESSI (4 s resolution) and ACS/INTEGRAL (50 ms resolution, smoothed over 1 s, and divided by 20) during the flare on 28 October 2003. The difference in time on Mars and Earth (205.46 s) is taken into account. The time interval when RHESSI was in the SAA is shown at the top. The light gray region indicates the time interval over which the total number and energetics of non-thermal electrons are calculated. Four dark gray vertical stripes indicate the time intervals for which HXR spectra are shown in Fig. 4.

Figure 2: Relative positions of Earth, Mars and the flaring site on the Sun on 2003 October 28 (view from the heliographic north pole). The angle Earth–Sun–Flare is 8°, the angle Mars–Sun–Flare is 13°.
Figure 3: **Left.** Ratio of the RHESSI to HEND fluxes (blue circles with errors shown by red vertical stripes) for the HEND energy channels 3, 5, 7, 9 and its fitting (green curves). **Right.** Uncorrected HEND and RHESSI fluxes for the same HEND channels.
Figure 4: HEND and RHESSI (where available) spectra for four 20-second intervals shown with dark gray vertical shadings in Fig. 1 (the initial time of each interval is shown in the corner of each panel). The blue circles are corrected HEND fluxes in channels 3–11. The green circles represent the background level. The red line represents the power law fit to the HEND data. The cyan line shows the broken power law fit to the RHESSI spectral data.

Table 1: Total electron number and energy calculated using warm target model and cold target model with various cutoff energies adopted. In the columns marked "RHESSI" the results are given for the time interval when RHESSI was observing the flare. In columns marked "full time" the results are given for the whole time span of the flare.

| Model | with RHESSI | full time |
|-------|-------------|-----------|
|       | electrons   | energy, ergs | electrons | energy, ergs |
| warm target | $4.3 \times 10^{40}$ | $2.0 \times 10^{34}$ | $1.1 \times 10^{41}$ | $3.9 \times 10^{44}$ |
| 10 keV | $1.7 \times 10^{41}$ | $3.9 \times 10^{33}$ | $2.5 \times 10^{41}$ | $5.7 \times 10^{33}$ |
| 20 keV | $1.7 \times 10^{40}$ | $7.5 \times 10^{32}$ | $2.4 \times 10^{40}$ | $1.1 \times 10^{33}$ |
| 30 keV | $4.2 \times 10^{39}$ | $2.8 \times 10^{32}$ | $6.3 \times 10^{39}$ | $4.3 \times 10^{32}$ |
| 46 keV | $9.8 \times 10^{38}$ | $1.0 \times 10^{32}$ | $1.5 \times 10^{39}$ | $1.6 \times 10^{32}$ |
| RHESSI | $1.3 \times 10^{39}$ | $1.7 \times 10^{32}$ | — | — |
Figure 5: Examples of the RHESSI spectra fitting and residuals for the time intervals 11:07:34–11:07:54 and 11:11:34–11:11:54 UT (see bottom panels on Fig. 4). In the bottom right plot the effect of pile-up is evident around 30-50 keV. The green and yellow curves represent the fitting functions of thermal and non-thermal components respectively.

Table 2: Total number and energy of interplanetary energetic electrons with energies higher than $E_0$.

| $E_0$, keV | Impulsive | Gradual |
|------------|-----------|---------|
|            | electrons | energy, ergs | electrons | energy, ergs |
| 0.1        | $5.7 \times 10^{42}$ | $3.0 \times 10^{35}$ | $1.4 \times 10^{42}$ | $3.4 \times 10^{35}$ |
| 1          | $2.3 \times 10^{41}$ | $1.0 \times 10^{33}$ | $2.2 \times 10^{41}$ | $2.9 \times 10^{33}$ |
| 10         | $8.5 \times 10^{39}$ | $2.8 \times 10^{32}$ | $3.1 \times 10^{40}$ | $2.0 \times 10^{33}$ |
| 20         | $2.9 \times 10^{39}$ | $1.6 \times 10^{32}$ | $1.6 \times 10^{40}$ | $1.7 \times 10^{33}$ |
| 30         | $1.4 \times 10^{39}$ | $9.9 \times 10^{31}$ | $1.1 \times 10^{40}$ | $1.5 \times 10^{33}$ |
| 46         | $5.1 \times 10^{38}$ | $4.8 \times 10^{31}$ | $6.6 \times 10^{39}$ | $1.3 \times 10^{33}$ |
Figure 6: 

a. Raw count rate and the background level in the HEND channel 3 (87–107 keV). 
b. The corrected normalization factor of the HEND power law fits. 
c. The corrected power law index of the HEND fits and the power law indexes of RHESSI spectra. 
d. The temperature of the hot flare region plasma derived from GOES (blue) and RHESSI (red). The green segment is obtained via linear interpolation. Thick lines represent the data used in the analysis. The saturation of GOES is manifested as a spurious suppression. One also sees that the temperature derived from the RHESSI data is higher than that derived from the GOES data. 
e. The time variation of the total number of accelerated electrons for the models used in this work. 
f. Same for the total energy carried by the accelerated electrons.