COMMON SPHINX AND RHESSI OBSERVATIONS OF SOLAR FLARES

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Abstract. The Polish X-ray spectrofotometer SphinX has observed a great number of solar flares in the year 2009 - during the most quiet solar minimum almost over the last 100 years. Hundreds of flares have been recorded due to excellent sensitivity of SphinX’s detectors. The Si-PIN diodes are about 100 times more sensitive to X-rays than GOES X-ray Monitors. SphinX detectors were absolutely calibrated on Earth with a use of the BESSY synchrotron. In space observations were made in the range 1.2-15 keV with 480 eV energy resolution. SphinX data overlap with the low-energy end of the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) data. RHESSI detectors are quite old (7 years in 2009), but still sensitive enough to provide us with observations of extremely weak solar flares such as those which occurred in 2009. We have selected a group of flares simultaneously observed by RHESSI and SphinX and performed a spectroscopic analysis of the data. Moreover, we compared the physical parameters of these flares plasma. Preliminary results of the comparison show very good agreement between both instruments.

Key words: Sun: corona - flares - X-rays

1. Introduction

The first solar X-ray radiation measurements were made more than 60 years ago (Friedman \textit{et al.}, 1951). Since that time we have learned a lot about the nature of high energy radiation produced in solar flares, but many questions are still open (Aschwanden, 2005). Observations made with different instruments have to be cross-calibrated. In stellar observations we simply have photometric standards - typical stars which are used to calibrate telescopes and detectors (Landolt, 2007; Beuermann \textit{et al.}, 2008). There is no such possibility in solar physics - flares may have similar physical parameters and time evolution but each one is unique. For this reason we have to
Figure 1: X-ray light curves for the time period February 1st – December 1st 2009. Top panel: GOES 1-8 Å light curve. Bottom panel: SphinX light curve.

utilize simultaneous observations made by many instruments in any case. This helps us to understand different detectors, materials and optics used in solar flares observations.

In this paper we present the first attempt to cross-calibrate the SphinX and RHESSI observations. We compare light curves obtained in different energy bands, spectra and physical parameters of plasma determined from measurements.

2. Observational Data

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is a rotating Fourier imager with nine detectors made of pure germanium
crystals (Lin et al., 2002). The detectors record the energy and time of arrival for each detected X-ray photon. The energy resolution in the 3-20 keV band is of the order of 1 keV. The temporal resolution is limited to 2 s by the rotation of the whole instrument but may be increased with a use of some demodulation methods. The detectors are large (7.1 cm diameter × 8.5 cm height) and very sensitive for incoming X-ray photons. However, in 2009 the sensitivity of RHESSI detectors was significantly decreased due to radiation damage. It is possible to partly restore their sensitivity through annealing. The annealing of RHESSI detectors was performed twice: in 2007 and 2010.

SphinX was an X-ray spectrometer which operated in 2009 on the Russian CORONAS - Photon satellite. SphinX provided nearly continuous measurements of solar soft X-ray flux in the time interval extending from the end of February till the end of November 2009. The instrument energy range was 1.2 keV - 15.0 keV and resolution about 0.4 keV. SphinX had an excellent time resolution. It could distinguish and measure correctly energies of two X-ray photons coming as short as 6 µs one after another.

For X-ray measurements SphinX used three silicon PIN-diode detectors with different effective areas. The most sensitive detector measured the solar X-rays at its low level. The two other detector channels were designed for measuring medium and strong fluxes. The mission took place during a deep and prolonged minimum of solar activity when the X-ray flux was very weak. Thus data of quality good enough for scientific analysis are available only from the most sensitive detector. The other detector measurements contain mainly noises. They can be used however to determine background from energetic particle which is present in data from all the detectors. The less sensitive detectors would provide data with good signal to noise ratio later on when the solar activity increased but the satellite became inactive early December 2009. Data from SphinX are publicly available in the Internet catalogue\(^1\) in Flexible Image Transport Format (FITS) files. The SphinX User Guide, example of data processing and calibration information can be also accessed from SphinX catalogue website. These data are already reduced to level-1 format of scientific grade.

The SphinX data are organized as event lists. A couple which consists of a X-ray photon arrival time and its energy is understood as a single event of solar origin. In SphinX data there also are events of other origins. These

\(^1\)http://156.17.94.1/sphinx_l1_catalogue/SphinX_cat_main.html
were caused by electronic resets or glitches or by energetic particles which interacted with the sensitive detector volume. To each SphinX event a four byte long flag is associated. For solar events the flag is set to zero. The non-solar events have non-zero flag. Particular flag values and meanings are also described in SphinX catalogue website. Flags can be used to reject the spurious events before performing solar X-ray flux analysis and preparing data in a form spectra or light curves.

The SphinX light curve obtained for the whole observational period (February-November 2009) is presented in Figure 1 (bottom panel). In the top panel we show GOES 1-8 Å flux for comparison. The greater sensitivity
of SpinX is obvious. During the analysed period GOES recorded few active regions with a small number of flares. At the same time SpinX, in a similar energy band, has detected hundreds of flares. Many events were of classes below GOES A0. That observation suggests that present classification of solar flares should be stretched and completed with new classes. Such classes, S for 'small' and Q for 'quiet', have been proposed recently (Gburek et al., 2011). There are also 'missed' active regions. For example, in late March and early April or late July and early August SpinX has observed activity which was practically missed in GOES data.

For data selection the SpinX catalogue has been compared with the RHESSI catalogue and periods of common observations have been carefully selected. We have found almost 40 flares which were entirely observed by both instruments. This gave us a few hours of common observations performed with SpinX and RHESSI.

We compared photon spectra obtained from count rates with a use of detector response matrices (DRM). SpinX DRM was calculated on the basis of data from calibration mission performed in Physikalisch-Technische Bundesanstalt laboratory at BESSY II synchrotron in Berlin.

During the calibration experiment a series of measurements in monochromatized radiation (with the use of a four crystal monochromator) were taken for each of SpinX detectors. From these measurements the energy resolutions were determined.

Next the detectors were exposed to undispersed synchrotron radiation which spectrum can be calculated with a very high accuracy. An example of such a spectrum and how was it measured by SpinX is shown in Figure 2. Exposures obtained in undispersed radiation together with resolutions and effective areas allowed for determining detectors efficiencies and fold all these informations into DRM.

Our results were obtained in two ways. First, we compared light curves and spectra obtained with the use of SpinX and RHESSI DRMs only. RHESSI spectra are usually analysed with a use of full DRM that consist of diagonal and off-diagonal elements related to different effects influencing the response (attenuator state, decimation, pile-up etc.). In addition we selected time intervals when RHESSI was outside the radiation belts. Moreover, analysed flares were very weak hence we did not have to make the pile-up correction. For these reasons we decided to use only diagonal elements of RHESSI DRM. In that way we compare RHESSI and SpinX spectra.
which are converted from counts to photons in a similar way and are model independent.

The second part is an analysis of physical parameters of plasma which have been calculated with dedicated software. For SphinX we decided to subtract the background in the following way. For a long (several hours) time interval we estimated several points in the light curve which were used for background estimation. We assumed that the background is mainly composed of quiet Sun and active region emissions. After subtracting the background we obtained the pure-flaring component. The temperature (T) and emission measure (EM) have been calculated from the ratio of signals observed in two energy bands (1.16–1.51 keV and 1.51–15.0 keV similarly like in Engell et al. (2011)). For analysis of RHESSI data we used the standard OSPEX package available in Solar SoftWare (SSW) library.

3. Data Comparison

In this section we present some results of comparing the SphinX and RHESSI data. Light curves and spectra have been analysed for the SOL2009-09-24T00:20 flare. It was a B1.1 GOES class event that occurred close to
the eastern limb of solar disc (S38E47). The EUV TRACE images were obtained several minutes after the flare maximum. Figure 3 (right panel) shows the TRACE (195 Å) image obtained 17 minutes after the flare maximum. RHESSI (3-6 keV) contours are spatially related to a dark structure visible in the EUV image. There are no bright sources seen in EUV which are related to HXR sources. Such structures might be present closer to the maximum phase, but there are no observations made for that time.

The second of analysed flare is the SOL2009-07-04T13:55 event. It was a B5.3 GOES class solar flare observed close to the centre of the solar disc (S30E06). Observations made by HINODE/XRT and RHESSI show (Figure 3, left panel) a very compact source. Its diameter measured at the 50% of maximum brightness level is less than 10 arcsec. For this flare we compared the temperatures of plasma obtained by SphinX and RHESSI.

### 3.1. Light curves

In Figure 4 we present light curves obtained for the SOL2009-09-24T00:20 flare. We have chosen several energy intervals of different bin widths, namely from 0.36 to 1.0 keV for SphinX and from 1.0 to 6 keV for RHESSI. The data overlap in the energy band 3-6 keV. The shift between curves is observed. The SphinX data are above RHESSI about a factor of 2-6. The difference is rising with energy which we also observed in other events. We expect that this is a result of background related to noise in SphinX detectors. We examined this by taking a longer time for integrating spectra. The result shows less discrepancy in data for higher energies. The analysis of SphinX detectors background is still under investigation.

### 3.2. Spectra

In Figure 5 we present a sequence of spectra obtained for 1-minute time intervals around the maximum of the SOL2009-09-24T00:20 flare. Despite small systematic shift the spectra agree very well. Above 4 keV SphinX spectra are more noisy than for lower energies. The larger difference is observed for energies above 6 keV where Si-PIN detectors background may dominate. We are able to obtain better agreement above 6 keV by taking longer time intervals for accumulating SphinX spectra. Nevertheless, the observed agreement is well enough to perform a common spectral analysis based on
Figure 4: SphinX (black) and RHESSI (gray) light curves for the SOL2009-09-24T00:20 flare. Time resolution is 12 s.
data from both instruments. For example, it is now possible to control the low temperature component fit to RHESSI data by comparing the results with SphinX spectra. It is crucial for RHESSI data analysis since below 6 keV the RHESSI response function drops abruptly which may produce large errors during converting between counts and photons.
3.3. Physical parameters of plasma

Spectral fitting has been performed for the SOL2009-07-04T13:55 flare. In Figure 6 we present the evolution of temperatures as calculated with data from three instruments: SphinX, RHESSI and GOES. SphinX parameters were estimated from the filter ratio method. Since the background from the quiet Sun and active region have been subtracted we obtained pure emission from the flaring component. The temperature is changing from 8-10 MK during the early rising and decay phases to about 18 MK close to the flare maximum. We calculated background subtracted GOES temperatures and obtained values significantly lower - the maximum temperature is below 10 MK.

The RHESSI spectral fit has been performed with two thermal components and Gaussian representing Fe complex at 6.7 keV. We tried also thermal plus non-thermal model and fits were very similar. The double thermal
fit to RHESSI data shows very nice agreement with the two other instruments. Namely, the cold component is in excellent agreement with GOES temperatures - time evolution, maxima and minima are very similar. The hot component was observed by RHESSI starting from 13:47 UT. Despite worse, than SphinX, time resolution three maxima are clearly seen. They are observed very close in time to maxima registered by SphinX. RHESSI hot component have slightly higher maxima and deeper minima in comparison to SphinX. Nevertheless the agreement is very good.

4. Summary

Preliminary investigation of solar flares observed simultaneously by SphinX and RHESSI is very promising. Our analysis may be summarized as follows:

- The SphinX and RHESSI data should overlap in the range 3-15 keV. In practice SphinX measured solar signals up to 7-8 keV. This is mainly related to S/N ratio above 7 keV - observed flares were below C1.0 GOES class.

- For overlapping energies (roughly 3-8 keV) we observed some systematical shift between light curves. This shift was observed to be larger for higher energies. We interpret this shift as an effect caused mainly by the background related to noise in Si-PIN detectors.

- Spectra agree well. We calculated them with a use of diagonal elements of SphinX and RHESSI DRMs - they are model independent. Again, we observed that SphinX spectra are slightly above RHESSI spectra. On average SphinX gives fluxes larger by a factor of 2 but sometimes it may be larger by a factor of 6.

- The shift in total fluxes may produce some difference in obtained emission measures, but temperatures should be similar. We compared temperatures from SphinX flaring component, GOES and two thermal fits to RHESSI spectra. Obtained results are consistent. RHESSI cold component is in good agreement with GOES data and RHESSI hot component fits well with SphinX flaring component.

A similar analysis will be performed for a larger group of events. Comparing SphinX and RHESSI catalogues we found almost 40 flares observed
simultaneously by the instruments. Moreover there is plenty of short intervals for which observations overlap. The analysis of common observations of both instruments will help us to investigate background in Si-PIN detectors and will help to understand the low-energy RHESSI data during solar minimum.

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