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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 *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 *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

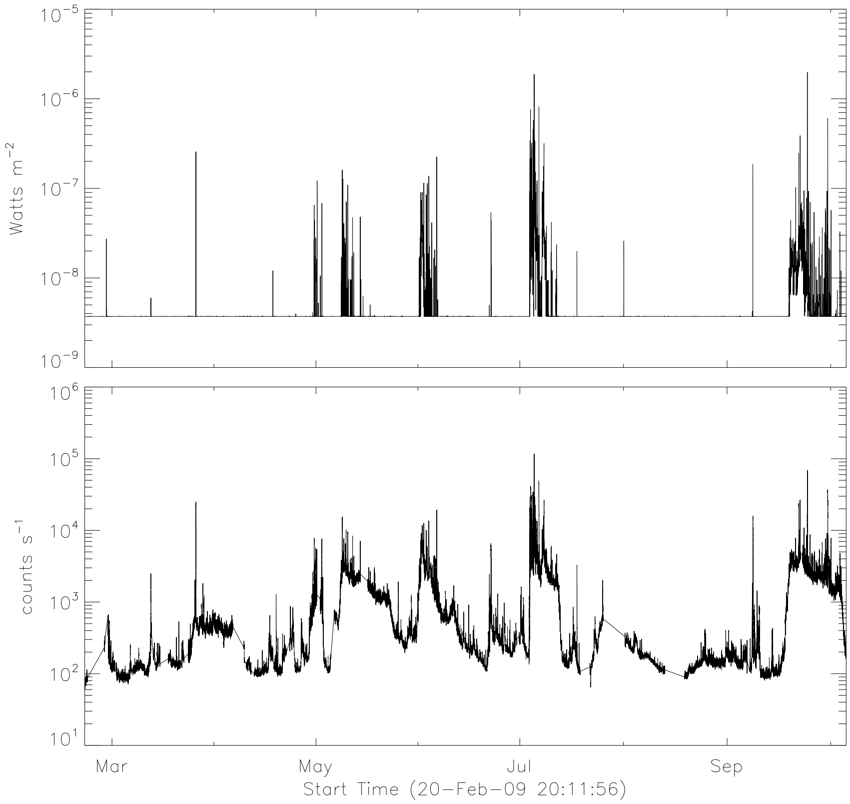

Figure 1: X-ray light curves for the time period February 1st – December 1st 2009. Top panel: *GOES* 1-8 Å light curve. Bottom panel: *SphinX* light curve.

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

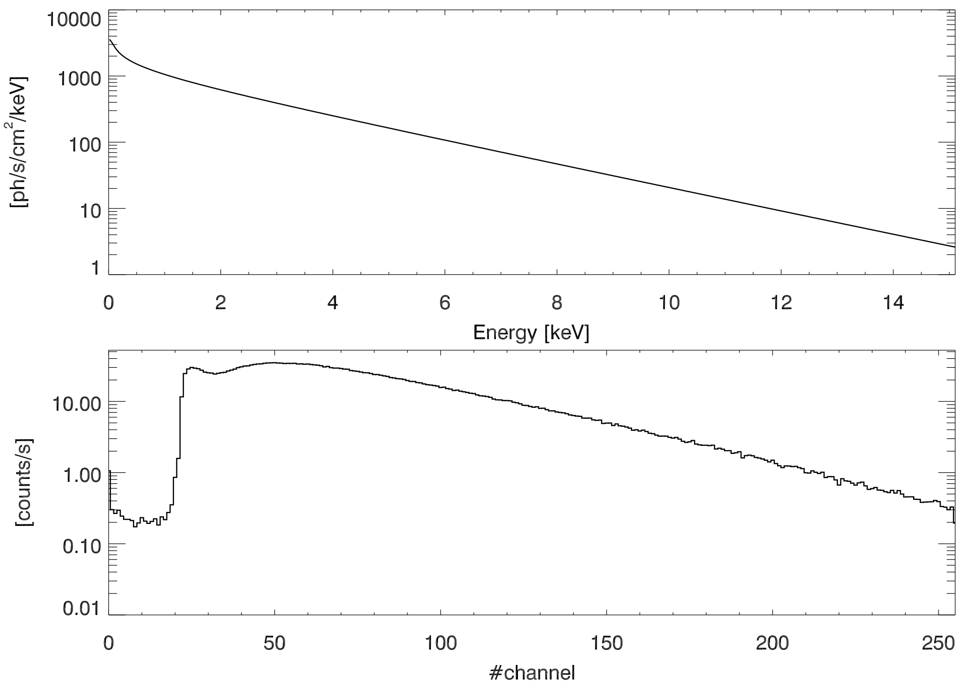

Figure 2: Calculated spectrum of BESSY II synchrotron undispersed radiation (upper panel). The synchrotron spectrum from the upper panel as seen in SphinX spectrometer channels is shown at the bottom (channel numbers correspond to energies on the x-axis in the top plot).

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 *SphinX* is obvious. During the analysed period *GOES* recorded few active regions with a small number of flares. At the same time *SphinX*, 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 *SphinX* has observed activity which was practically missed in *GOES* data.

For data selection the *SphinX* 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 *SphinX* and *RHESSI*.

We compared photon spectra obtained from count rates with a use of detector response matrices (DRM). SphinX 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 SphinX 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 SphinX 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 *SphinX* 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 *SphinX* spectra

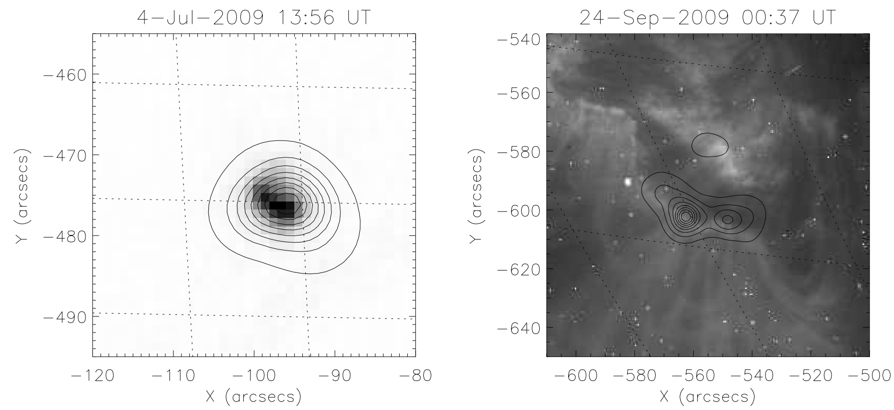

Figure 3: Left panel: XRT image (gray scale) with overplotted *RHESSI* contours (10 - 15 keV) for the SOL2009-07-04T1355 flare. Right panel: *TRACE* 195Å image (gray scale) with overplotted *RHESSI* contours (3-6 keV) for the SOL2009-09-24T00:20 flare.

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

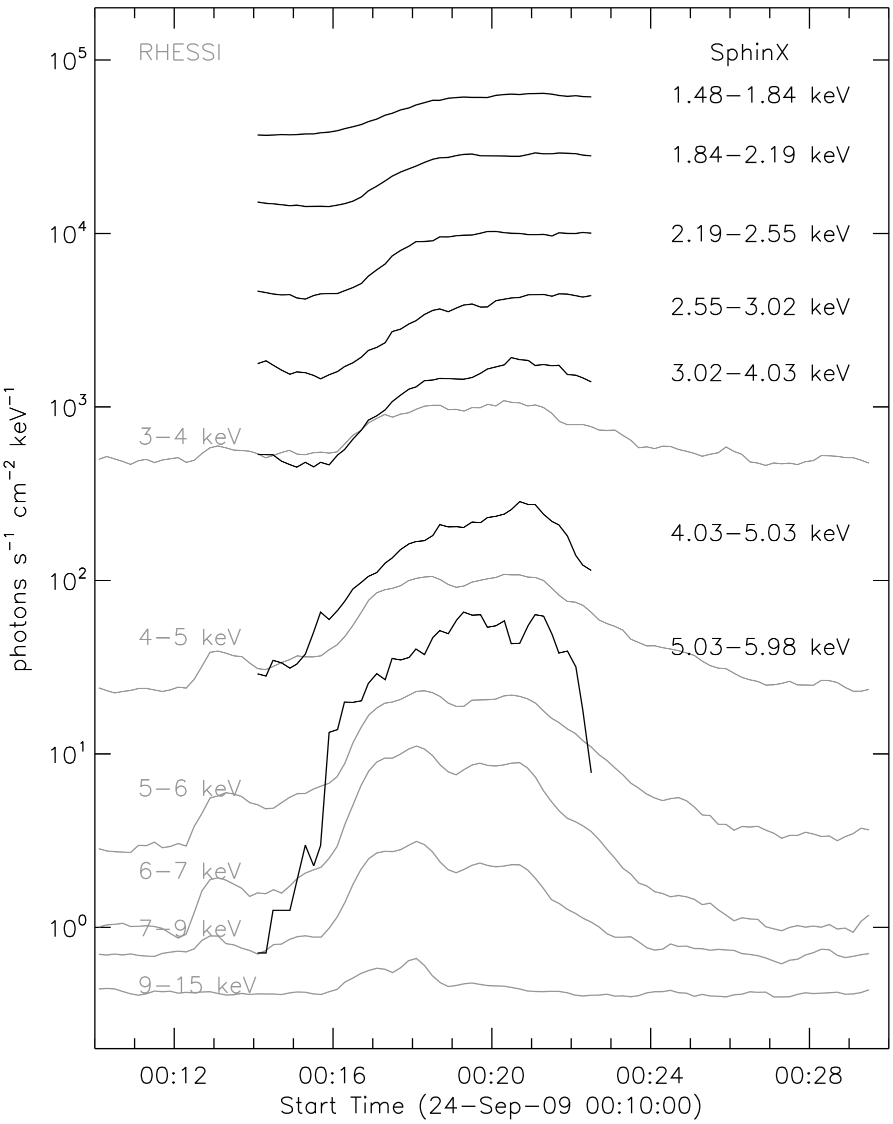

Figure 4: *SphinX* (black) and *RHESSI* (gray) light curves for the SOL2009-09-24T00:20 flare. Time resolution is 12 s.

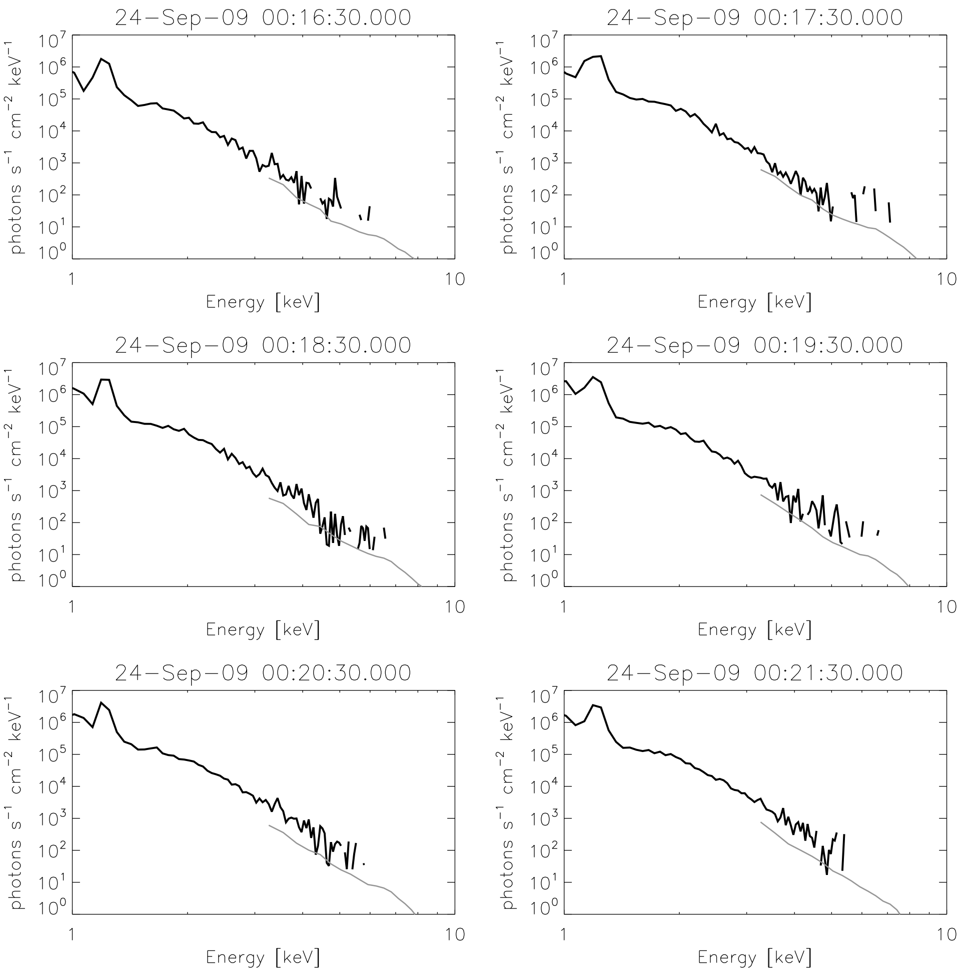

Figure 5: *SphinX* (dark line) and *RHESSI* (gray line) spectra of the SOL2009-09-24T00:20 flare obtained for 1-minute time intervals.

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.

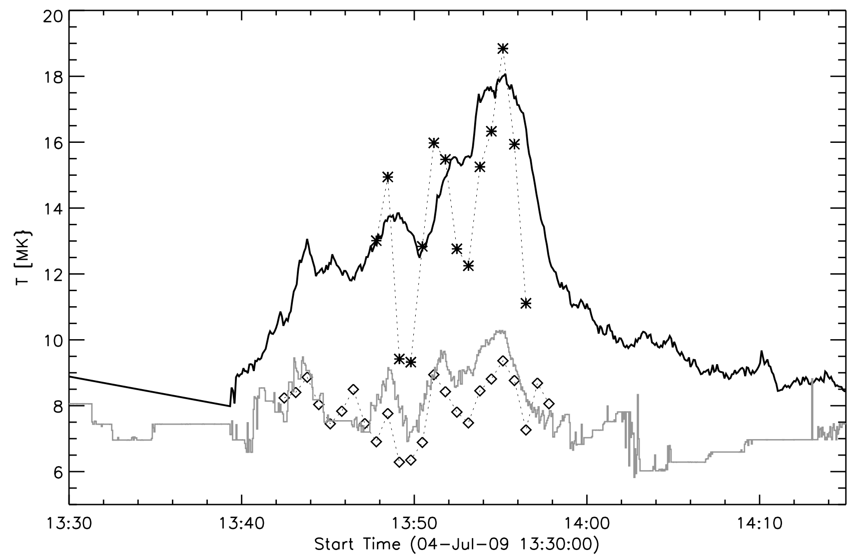

Figure 6: Temperatures obtained by different instruments for the SOL2009-07-04T13:55 flare. Thick black line - *SphinX* flaring component. Dotted line with symbols - *RHESSI* hot (asterisks) and cold (diamonds) components. Gray line - *GOES* temperature.

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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References

Aschwanden, M.J.: 2005, *Physics of the Solar Corona. An Introduction with Problems and Solutions (2nd edition)*, Praxis Publishing Ltd., Chichester, UK; Springer, New York, Berlin, 283.

Beuermann, K., Burwitz, V., and Rauch, T.: 2008, *Astron. Astrophys.* **481**, 769.

Engell, A.J., Siarkowski, M., Gryciuk, M. *et al.*: 2011, *Astrophys. J.* **726**, 12.

Friedman, H., Lichtman, S. W., and Byram, E. T.: 1951, *Phys. Rev.* **83**, 1025.

Gburek, S., Sylwester, J., Kowalinski, M., Bakala, J., Kordylewski, Z. *et al.*: 2011, *Astronomicheskii Vestnik* **45**, No. 3, 195.

Landolt, A. U.: 2007, *Astron. J.* **133**, 2502.

Lin, R.P., Dennis, B.R., Hurford, G.J., Smith, D.M., Zehnder, A., *et al.*: 2002, *Solar Phys.* **210**, 3.