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Soft X-ray Variability over the Present Minimum of Solar Activity as Observed by SphinX[1]

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Abstract—Solar Photometer in X-rays (SphinX) is an instrument designed to observe the Sun in X-rays in the energy range 0.85–15.00 keV. SphinX is incorporated within the Russian TESIS X and EUV telescope complex aboard the *CORONAS-Photon* satellite which was launched on January 30, 2009 at 13:30 UT from the Plesetsk Cosmodrome, northern Russia. Since February, 2009 SphinX has been measuring solar X-ray radiation nearly continuously. The principle of SphinX operation and the content of the instrument data archives is studied. Issues related to dissemination of SphinX calibration, data, repository mirrors locations, types of data and metadata are discussed. Variability of soft X-ray solar flux is studied using data collected by SphinX over entire mission duration.

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INTRODUCTION

SphinX (**S**olar **Ph**otometer **in X**-rays) is a fast and sensitive spectro-photometer for observations of Solar soft X-ray radiation in the nominal energy range 0.85–15.00 keV with an energy resolution of ~0.4 keV and a time resolution down to fraction of a second. SphinX is located inside the TESIS telescope aboard *CORONAS-Photon* satellite. SphinX started to work in orbit on February 20, 2009 about three weeks after the satellite launch from the Plesetsk Cosmodrome in northern Russia. Since that time the instrument observed the Sun nearly continuously and collected data with a telemetry rate of ~150 Mb/day in excess of compressed data during its operation. These data allow for analysis of quiet Sun X-ray flux, observations of emerging active regions, small flare energetics and statistical properties of the coronal activity.

In what follows we focus on analysis of variability of solar X-ray flux from SphinX measurements in a period of lower solar activity within the time interval from February 20, 2009 to November 28, 2009. We also discuss SphinX pre-flight calibration experiments, data types, method of access to SphinX data and give basic information about the instrument detectors and operation principle. Full description of SphinX instrument can be found in Gburek et al. (2010).

INSTRUMENT DETECTORS AND OPERATION PRINCIPLE

For measurements of soar X-ray flux SphinX uses four pure, 500 micron thick, silicon crystals placed inside XR-100CR detectors. The detectors were manufactured by US Amptek company. Each detector has 12.5 microns thick beryllium entrance window. Three of the detectors (called D1, D2 and D3) form a main SphinX measurement block and are exposed directly to solar X-rays. The detector D1 operates with its nominal effective area. Over the detectors D2 and D3 there are apertures placed in order to limit their sensitivity. The detector D1 with the highest effective area is designed to measure low intensity solar photon fluxes. Pileup and saturation in detector D1 take place even for moderate solar flux. The aperture of the second detector D2 is chosen so that it gives good signal/noise ratio (S/N) measurements during moderate solar fluxes for which pileup in D1 starts to appear. The third detector D3 with the smallest aperture can measure substantial signal for strong solar flux when pileup in detector D2 appears (detector D1 completely saturates at such flux values). The aperture of D3 detector is so small that it does not saturate even at the highest known solar activity level. Thus, using this three detector block, it is possible to observe solar fluxes from the weakest X-ray activity level to the strongest ever observed flares. There are overlaps in intensity ranges measured by detectors. For instance even for very low solar X-ray flux (which is well observed by D1 detector) some signal above the noise level is also present in D2 detector. Such a signal after integration over a longer time interval can provide measurements with good S/N ratio too.

The fourth detector D4 is in SphinX fluorescence measurement channel which is designed to measure X-ray fluorescence excited by solar radiation in narrow energy bands. The SphinX fluorescence channel needs a stronger solar flux to give signal above the noise

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[1] The article was translated by the authors.

level and due to low solar activity was not turned on during the selected time interval for analysis here. From the same reason there are no good measurements from detector D3. It registered only noises in the discussed period. Thus the data from D1 and D2 detectors only are analyzed here. Detailed description of SphinX detectors and instrument operation is given in Gburek et al. (2010).

SphinX CALIBRATION

Two calibration experiments were performed before SphinX launch in order to determine detectors efficiency and response and actual energy ranges of all measurement channels. Linearity with flux and exposure, pileup effects and dependence of detector resolution on energy of X-ray flux were investigated during these experiments too.

The first SphinX calibration experiment took place in October 2007 at X-ray Astronomy Calibration and Testing (XACT) Facility (http://www.astropa.unipa.it/XACT/) in Palermo.

During test at XACT SphinX was placed in a vacuum chamber connected to X-ray source through 35 m long tube. Several anodes made of different elements were used in the source to produce X-rays to which SphinX was exposed. The flux intensity was controlled by multichannel analyzer with solid state detector and gas flow proportional counter.

The experiment provided several tens of spectra consisting mainly of K_α and K_β lines of anode elements superimposed on a broad continuum radiation. Analysis of data collected at XACT allowed for determining the instrument resolution, energetic calibration of SphinX measurement channels and estimation of the overall channel efficiencies.

The final absolute calibration of the detectors has been performed in February and March 2008 using BESSY II (www.bessy.de) synchrotron in Berlin. First, for each detector, several measurements at selected energies were performed using BESSY II beamlines with monochromator. The measurements in monochromatized radiation were used to determine the energy resolution function of the channels and energy/bin scale for each of detectors.

Next SphinX measurement channels were calibrated using BESSY II as a primary standard source in undispersed radiation. During this test SphinX was exposed to synchrotron spectrum in a broad energy band. Exact shape of this incident spectrum can be always calculated from parameters of electrons bundle which circulate in the synchrotron storage ring and overall system geometry. Measurements in undispersed radiation were used to determine actual shape of efficiency curves for the detectors. The absolute calibration accuracy against the synchrotron beam has been found from calibration data analysis to be better than 5%. Results obtained from both calibrations at XACT and at BESSY II also agree within a few percents. The instrument characteristics from calibration experiments are used to interpretation and reduction of SphinX flight data.

SphinX DATA DESCRIPTION DISSEMINATION AND ACCESS

SphinX may operate in time stamping and spectral mode. In time stamping mode it sends to telemetry arrays with arrival time and energy of each X-ray photon registered in a particular detector. In spectral mode SphinX sums photons incident on a detector in a selected number of energy bins and give to telemetry a histogram of registered photons together with registration duration—the exposure time. Both modes can be run simultaneously.

SphinX can measure solar spectra with variable channel number ranging from 1, when the spectrum should be rather called a light curve to 1024 which is the highest number of channels possible to obtain for this instrument. Number of registered spectra channels can be changed depending on a particular observation program.

During calibration at BESSY II synchrotron and XACT facility a large number of 1024 channel spectra were recorded. Analysis of these calibration data showed that an optimum maximum number of channels for flight instrument operation is 256. Thus for discussed here measurements from detectors D1 and D2 a substantial amount of time stamping sequences and 256-channel spectra is present in the SphinX data archive.

Besides 256-channel spectra and time stamping measurements a four-channel ancillary spectrum is sent to each telemetry frame. These four-channel spectra give so-called SphinX basic mode observations. In the basic mode spectrum the first channel contains mainly electronics noises. The two next broadband energy channels contains useful detector signal when the incoming X-ray flux is strong enough to give counts above the noise level. The last fourth channel usually contains noises too but it also registers counts created by energetic particles in the detector crystals, particularly when the satellite passes through South Atlantic Anomaly (SAA) or polar ovals.

Together with SphinX data information about time of each measurement and block of technical data come in each telemetry frame. During on-ground processing all the SphinX data received from telemetry are decompressed and transformed to IDL native format. This is an intermediate format but it already allows performing data reduction and using the data for scientific research purposes. Typically a singe IDL SphinX data file covers a couple of SphinX observation hours. Next information from calibration experiments and ancillary data about spacecraft attitude and orbit is added to each measurement. Finally the data are converted to level-1 Flexible Image Transport System

(FITS) format in well documented and standardized OGIP/93-003[2].

All data files in IDL and FITS format can be directly downloaded from SphinX dedicated data servers. Two SphinX data servers have been established in 2009.

One is located in Space Research Centre in Wroclaw, Poland[3] and the second in Astronomical Institute of the Academy of Sciences of the Czech Republic in Ondrejov[4].

Two new servers in P.N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow and in Osservatorio Astronomico di Palermo Giuseppe S. Vaiana in Palermo, Italy will be fully operational in 2010.

All the SphinX dedicated data servers contain full SphinX data and ancillary data archive. The servers are mirrored on daily basis to make sure that their content is identical.

The access to SphinX data files on the servers is provided via web site catalogue which contains daily pages where advanced visualization of data and links for downloading IDL and FITS files for each particular day of observation is given. These data are publicly available and can be downloaded using any web browser.

Alternative, global range access to SphinX data is being organized via Virtual Solar Observatories (VSOs). Integration of SphinX FITS files and ancillary data (in ASCII text files) within operational VSO in US and a new one under development in Europe within SOTERIA project, (www.SOTERIA-space.eu) is expected after ultimate reduction off all raw SphinX data to level-1 data.

VARIABILITY OF SOLAR ACTIVITY OVER THE PRESENT MINIMUM

One of the interesting SphinX data products are lightcurves formed from the two middle channels of observations in basic mode for detectors D1 and D2. Such lightcurves are relatively low affected by noises and counts caused by energetic particles (at least when the spacecraft is outside SAA or polar ovals). These lightcurves can be used for determining physical plasma parameters such as temperature or emission measure of solar plasma. Due to high instrument sensitivity (100 times better than GOES) SphinX light curves can be used for determining temperature and emission measure for a very small events or even quiet sun.

The overall variability of the Sun, particularly in longer time intervals, can be monitored and analyzed using light curves from detector D2. This detector never got saturated during the mission and it registered useful signal even for lowest activity measured during the SphinX mission.

One of the standard SphinX data products is a plot of five minute count averages from D2 detector. This plot is shown in Fig. 1. Such a plot is regularly updated as the mission progresses.

It is seen in Fig. 1 that stronger and more variable solar flux shows up when the active regions are present on disk. On the other hand there is some minimum basal level about 5–6 counts per second in D2 detector below which the solar activity never drops down.

Evolution of active regions, their activity level, and statistical properties can be studied from these data as well.

Revision of basic mode observations from the D1 and D2 SphinX detectors taken during very low solar activity time intervals shows that there are still many events produced in solar corona with time profiles of light curves similar to flares. Such events are shown in Fig. 2 where start of flare activity in emerging active region 11024 on 03 July 2009, as observed at SphinX D1 channel, is presented. This flare activity starts at ~19:00 UT but according to GOES 1–8 Å lightcurve the activity began from ~22:00 UT when A6.0 GOES class flare precedes a series of consecutive ~B1–B5 class flares. Before 22:00 UT GOES signal was completely flat on the sensitivity threshold level of 3.7×10^{-9} W/m^2. Thick arrows in Fig. 2 indicate three flare events (at 19:18 UT, 19:39 UT, and 20:28 UT) which maxima are below this threshold level and so these events are not observed by GOES. For these small events two new classes S (from small, flux range 10^{-9}–10^{-8} W/m^2) and Q (from quiet, flux range 10^{-10}–10^{-9} W/m^2) were introduced by Sphinx team to keep consistence with GOES event classification.

A catalog of all events seen in SphinX data is created in Space Research Center, Polish Academy of Sciences in Wroclaw. At the moment the catalog contains about 800 events identified in the deep prolonged solar minimum between cycle 23 and 24. About 400 of them are below GOES spacecrafts sensitivity threshold. The catalog contains also the flares and events recorded by RHESSI and GOES instruments for comparison. To each catalogue record an additional information is added in the form of flags in order to identify events that were only partly observed, mark events for which measurements can be affected by spurious counts caused by energetic particles or give information about active regions present on solar disk if there were any.

In general, the data collected by SphinX in basic mode allows for studying the weak soft X-ray solar flux and small event properties. Similar data set was obtained from RF-15I-2 photometer (see Farnik et al. 1995). RF-15I-2 instrument launched on 03 August, 1995 aboard Interball-Tail mission (Galeev et al.

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[2] http://heasarc.gsfc.nasa.gov/docs/heasarc/ofwg/docs/rates/ogip_93_003/ogip_93_003.html) version.

[3] http://156.17.94.1/sphinx_catalogue/SphinX_cat_main

[4] http://147.231.104.188/catalog/SphinX_cat_main.html

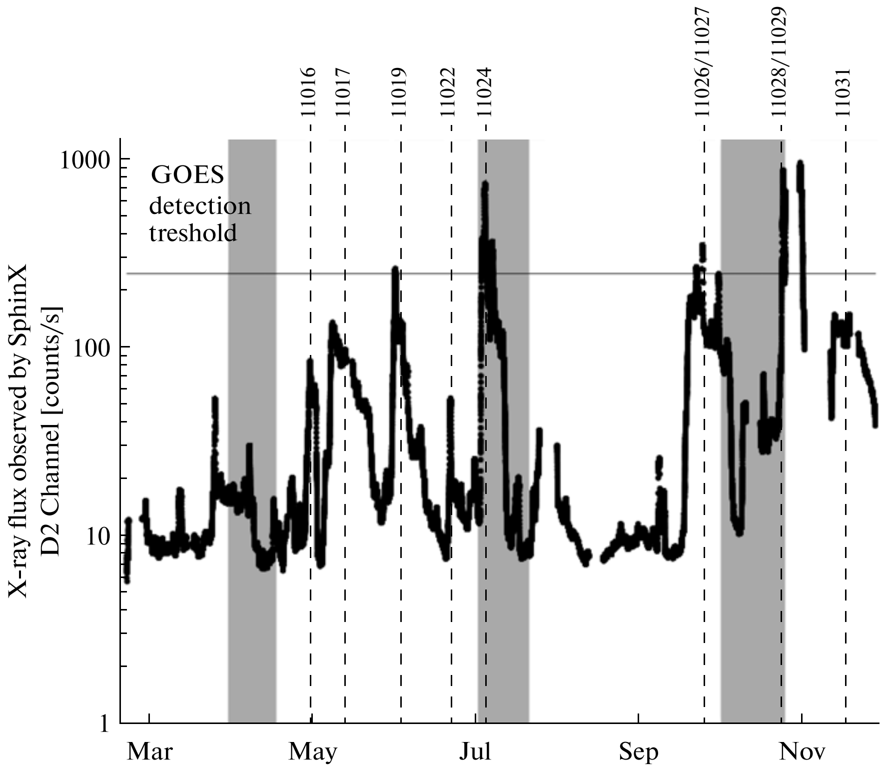

Fig. 1. The mission-long plot of SphinX lightcurve from D2 detector (five minute count averages). NOAA active region numbers are indicated above the plot.

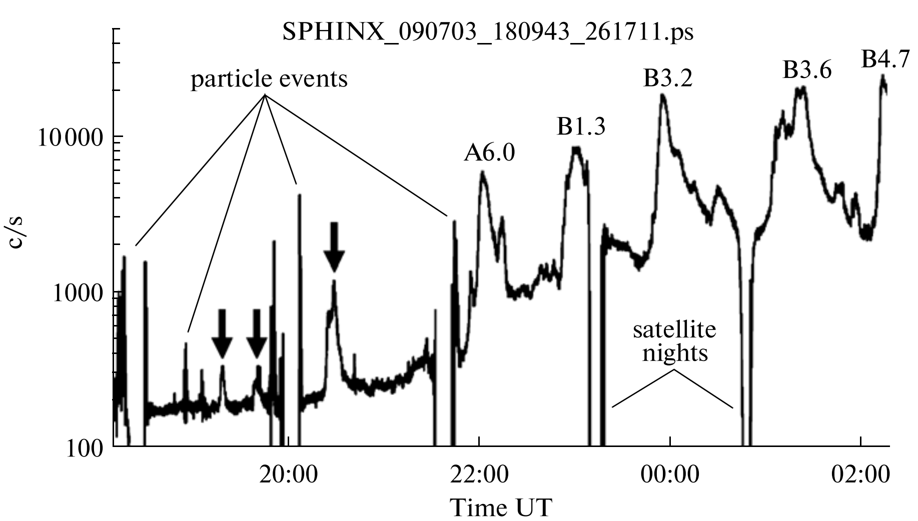

Fig. 2. Start of flare activity seen by SphinX in D1 channel on July 03, 2009. Before 22:00 UT GOES signal was completely flat on the sensitivity threshold level of 3.7×10^{-9} W/m^2. Thick arrows indicate three flare events which are below this threshold level and are not observed by GOES.

1996) also operated near the deep solar activity minimum between the 22nd and 23rd solar ativity cycle. In particular, RF-15I-2 also registered a couple of hundred of very small events below GOES sensitivity threshold. These events (with intensities in 10^{-9}–10^{-8} W/m^2 range) are discussed for instance in Mirzoeva, 2006 and Pisarenko and Mirzoevoy, 2008 and called class-0 events there.

It was found in Mirzoevoy, 2006 that there is a good correlation between intensities of weak flares (GOES

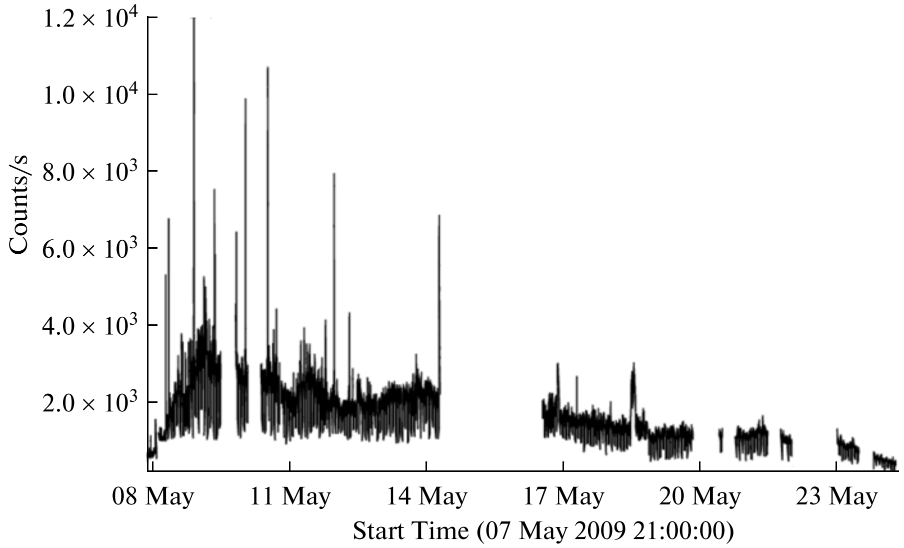

Fig. 3. Evolution of active region as seen by SphinX D1 detector.

class A, B and class—0) events with the level of the thermal background of solar corona.

Preliminary review of a sample of 533 SphinX events (194 events of class Q, 185 of class S, 191 of class A and 13 B class events) confirms that their intensities are also closely correlated to the thermal coronal X-ray flux background.

Analysis of X-ray event production rate with their intensity strength performed by Mirzoevoy, 2006 showed that class-0 events do not follow general trends observed for larger flares. For flares of a given class (A GOES class or higher), stronger events usually occur in smaller amounts than weaker ones in a given time interval. This is no longer the case for class-0 events which occur most frequently for intensities about 6 × 10^{-9} W/m^2 and their production rate decreases towards the class-0 definition edges (10^{-9}–10^{-8} W/m^2). Similar distribution of the event production rate has been found for SphinX events of class S (185 events taken for analysis) – it also is a single peaked function with the maximum near S5.0 (5 × 10^{-9} W/m^2). For the higher class (A and B class) events observed by SphinX are less frequent if their intensity gets stronger – what is a typical property. For SphinX event observations at Q flux level the flare intensity value is at present calculated with substantial uncertainty. Analysis of dependence of the event production rate on intensity for SphinX class Q events will be possible after reduction of data to level-1 format when a sub-class intensity level for Q events will be more precisely known.

Analysis of SphinX obtained spectra and lightcurve profiles for the mentioned above 533 small X-ray event sample shows that they typically occur within 1–5 keV energy range and usually do not come as well distinguishable single events with short impulsive phase followed by more gradual decay to the background level. Majority of SphinX events of class Q, S, A and B appears to have multipeaked timeline as they would consist of a series of smaller class events (see for instance class S event at 20:28 and the following events of classes A and B in Fig. 2). Studies of such brightenings and flare lightcurves or possibly decomposition of observed events into a chain of smaller events would give better insight in energy release processes in flaring plasma during the low solar activity level. Similar observations on small events were performed earlier by Pisarenko and Mirzoeva, 2008 based on the above mentioned RF-15I-2 photometer data. Both RF-15I-2 and SphinX datasets strongly support theoretical models in which flares form a vertical mosaic structure in which stronger events come as superposition of smaller ones.

Observations from SphinX and RF-15I-2 covers the deep solar activity minima and cycle rise phase in soft X-rays. For analysis of the solar X-ray flux and spectra in the increased intensity range an additional data sets are necessary. One of the solar missions that provided such data is CORONAS-F spacecraft which was launched near the vicinity of the maximum of the cycle 23 (on 31 July, 2001). This multi-instrument spacecraft started to observe the Sun in X-rays when background of solar X-ray flux was already above B GOES level. Scientific payload and review of results obtained from CORONAS-F mission can be found in Oraevsky et al. 2003. Observations from CORONAS-F are qualitatively and quantitatively different than these obtained by SphinX and RF-15I-2. These measurements form however complementary data sets allowing for comparison or studying differences of solar X-ray properties during high and low solar activity level respectively.

Tracing in time the emergence development and disappearance of active regions from solar disk is another research that can be performed using SphinX light curves from detector D1 and D2. An example of useful data for such analysis is shown in Fig. 3 where evolution of active region 11017 is shown during its entire lifespan. The flux in D1 detector rises here quiet rapidly during the region emergence phase. Intense flaring is observed during this phase and latter on when the region is well developed on disk. Then a decay phase comes where there is only weak flaring activity and flux gradually disappears.

SphinX lightcurves from detector D1 and D2 can also be used to study physical condition of the solar plasma before Coronal Mass Ejections (CMEs) which are released from the Sun even during very low activity periods. During low activity there may be no clear signs that the Sun may release a CME as plasma filaments, dimming, sigmoids which are often associated to CMEs releases during higher activity. During low activity CME may be released without any warning like that and, if Earth directed, can be geoeffective causing magnetic storms in Earth magnetosphere which are completely unpredictable. Five such a "stealth" CMEs were released for instance in August 2009 where even no single active region was present on disk. Studies of SphinX lightcurves from detectors D1 and D2, their time profiles and determination of plasma physical parameters before CME releases from quiet Sun can shed more light on general circumstances in which CMEs are ejected during low solar activity and help to workout methods for forecasting them. This is an important issue in the context of space weather.

CONCLUSIONS

Data from SphinX measurements in a period of low solar activity within the time interval from February 20, 2009 to November 28, 2009 has been reviewed and described.

Issues related to calibration of SphinX data, their dissemination and access to them has been discussed.

SphinX data from detector D1 and D2 can be useful for analysis of quiet Sun plasma physical parameters such as temperature and emission measure, evolution of active region and statistical analysis. Five minute count averages plotted versus time for the entire mission shows overall soft X-ray variability of solar flux. It is seen in these data that stronger and more variable solar flux is usually associated to presence of active regions on disk and that there is some minimum level of activity in corona. Data from both detectors D1 and D2 are useful for studies of active region emergence, development and decay phase. The analysis of SphinX lightcurves taken in basic mode, in time intervals before CME releases, may by useful in determining general plasma conditions in which CMEs are formed. Thus there are possible applications of SphinX data in space weather related issues—CMEs forecasting, even for low activity conditions.

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