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PHYSICAL CHARACTERISTICS OF AR 11024 PLASMA BASED ON SPHINX AND XRT DATA

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Abstract. We have studied the evolution of basic physical properties of plasma within the coronal part of the isolated, new cycle region (AR 11024) during its crossing over the solar disc in July 2009. Our analysis is based on the high temporal and spectral resolution measurements performed by the Polish X-ray spectrometer SphinX onboard the *CORONAS–Photon* satellite. *Hinode* XRT images provide information on spatial extension of the emission within this active region. It is found that the average temperature of the plasma within the analysed region is the highest (∼6 MK) when the region is young and gradually declines to ∼2 MK when the emission measure is the highest. An average density during this first part of the evolution is estimated to be ∼2 x 10^9 cm^{-3}.

Key words: solar physics - quiet corona - X-rays

1. Introduction

We have investigated the physical conditions of the active region (AR) 11024 plasma during its crossing over the solar disc. The analysis covers the period from July 3 till July 14, 2009. A more thorough analysis is performed from July 3 through July 8 only. The AR selected for the analysis has been unique as it was the only region present on the visible solar disc at that time. At `www.cbk.pan.wroc.pl/bs/Hvar2010` one can find the images of the Sun made in different spectral bands illustrating this fact (Figure: *Active Region 11024 location.pdf*). Moreover the analysed period occurred during the deep and prolonged solar minimum. The data used for the analysis consist of X-ray spectra collected with the SphinX (Solar PHotometer IN X-rays) aboard the *CORONAS-Photon* satellite (Sylwester *et al.*, 2008) and of X-ray images obtained with X-ray Telescope (XRT) onboard the *Hinode* spacecraft (Golub *et al.*, 2007). SphinX was developed and constructed using a Polish concept, design and manufacture. During its time of operation the photometer measured the global X-ray fluence of the Sun in the spectral range 0.8 − 15 keV using three Peltier cooled silicon PIN detectors made by Amptek. The observed spec-

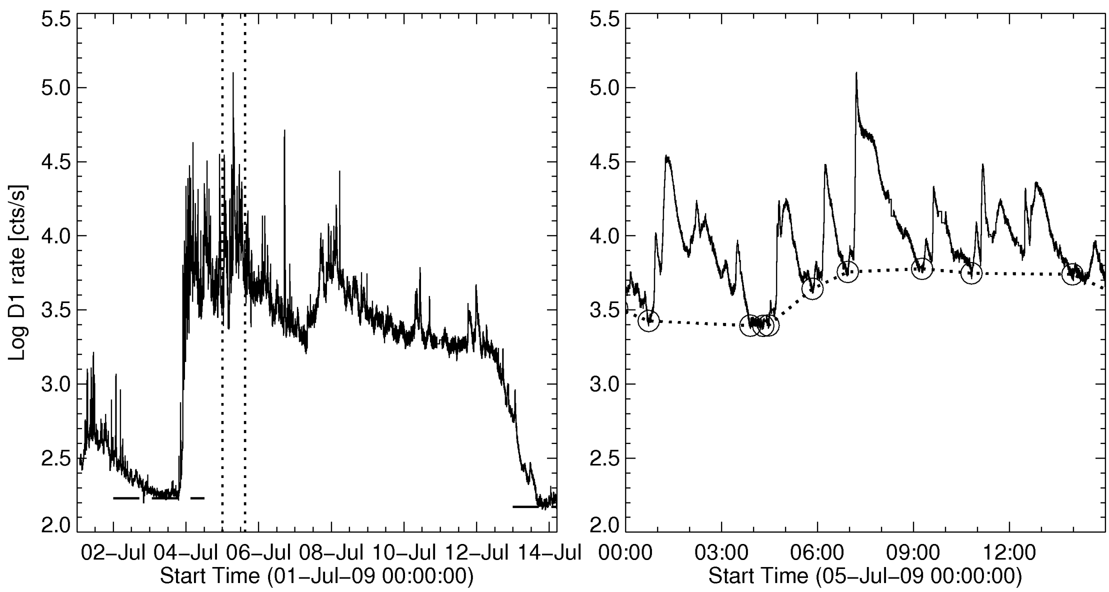

Figure 1: Left: The global flux of the active region as seen from the detector D1 of SphinX during the period from July 1 to July 14, 2009. Right: The enlargement of a part of the global flux in the D1 detector corresponding to the time interval between the dotted lines in left panel. The time range presented in the right panel covers 15 hours.

tral range was resolved electronically into 256 energy bins and the unprecedented time resolution was as short as 1 millisecond (the photon arrival time was measured to within few microseconds). Apertures of different sizes were placed in front of each detector (the size was progressively decreasing by a factor of about 50). The sensitivity threshold of the D1 SphinX channel has been measured to be about 100 times better than the corresponding *GOES* 1–8 Å. The energy resolution of SphinX has also been measured to be twice as good as for RHESSI in its lower energy channels (`www.hesperia.gsfc.nasa.gov/hessi/instrumentation.htm`). In the present analysis we used the signal of the D1 detector (with the largest aperture of 21.5 mm^2) as the photon signal was the highest in this channel. In the left panel of Figure 1 we present the **global** solar soft X-ray flux variability as measured by the D1 SphinX detector from July 1 to July 14, 2009.

The period presented is longer than the more detailed analysis because it

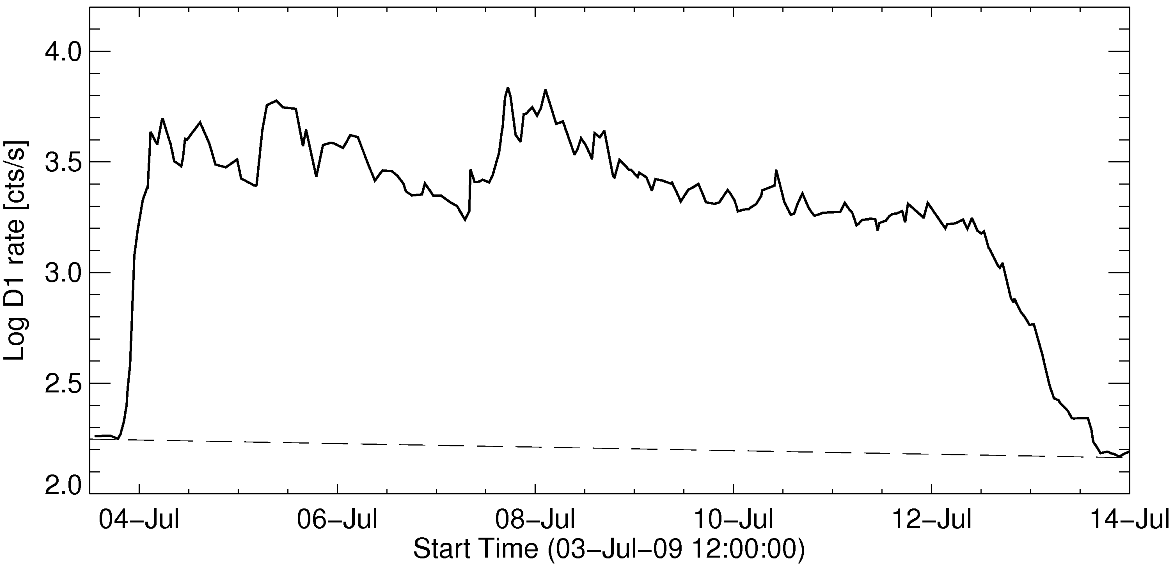

Figure 2: The active region AR 11024 and quiet Sun X-ray flux (solid) observed with the D1 SphinX detector. The contributions of microflares and soft X-ray brightenings have been removed. The dashed line indicates the interpolated behaviour of the "quiet Sun" corona. The time range presented corresponds to the period of the AR crossing over the visible solar disc.

shows the overall variability of X-ray flux related with the presence of AR 11024. The global solar flux presented is composed of the contribution from the "quiet Sun", AR and the occurrence of microflares. The level of quiet Sun X-ray radiation is slightly different before and after the AR 11024 was visible on the disc. These levels are shown as two dashed lines at both ends of the variability curve. The spikes seen atop the curve represent the fast variations due to flares. During the investigated period about 180 flaring events/brightenings were observed with SphinX. The contribution of these flares has been subtracted from the global X-ray flux for purposes of the present study. The analysis of flares which occurred within this AR during the investigated period is described in the paper by Engell *et al.*, (2011). The expanded part of the time interval between the two dotted vertical lines in the left panel of Figure 1 (15 hours) is shown in the right panel of Figure 1. The envelope flux of the non-flaring component of the solar corona and the AR 11024 emission is represented by the dotted line. This component is displayed in Figure 2 for the whole analysed period (from July 3, 2009 at 14:00 UT to July 14, 2009 at 00:00 UT). In Figure 2 we also present the interpolated level of quiet Sun contribution to the observed X-ray flux. As we

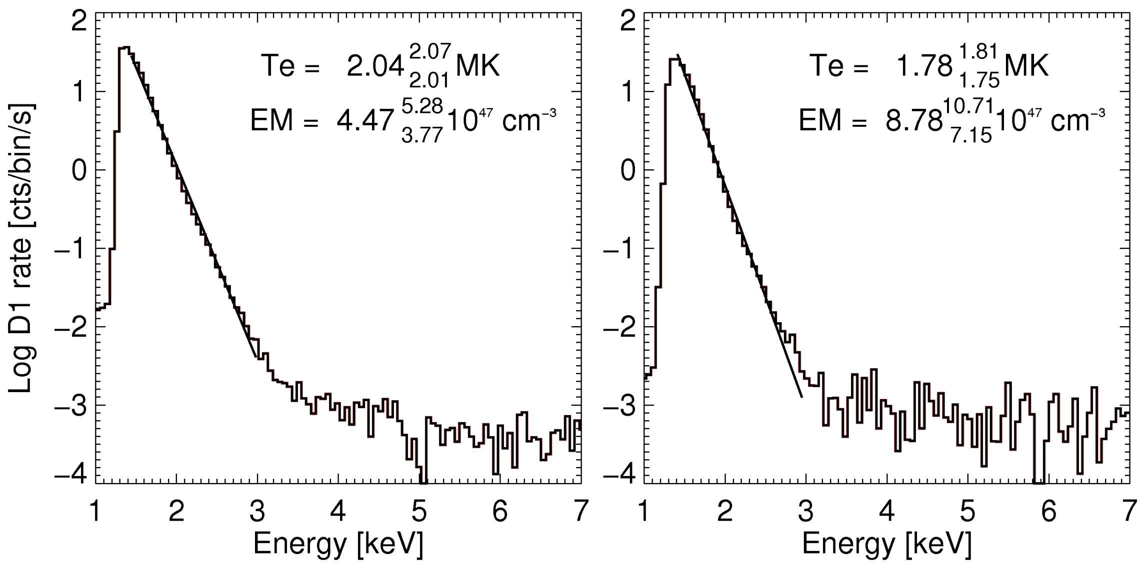

Figure 3: Results of the fitting of observed quiet Sun spectra with the theoretical ones for times before the AR appearance on the solar disc (left panel) and after the AR turned out behind the limb (right panel). See the text for details.

are interested in the active region plasma characteristics, the contribution of the quiet Sun emission to the observed flux has been removed.

The complementary data used in the present analysis consist of X-ray images obtained with the X-Ray Telescope (XRT) on *Hinode*. The Ti-poly and Be-thin filter sequences have been mostly used during the considered time interval with a pixel resolution of 1.03" with a time cadence of one image every 90 seconds on average. Here, we used the Be-thin images for estimation of the AR emitting volume.

2. Data Analysis

2.1. SphinX measurements

The SphinX data have been used to determine the physical parameters of the plasma composing the investigated AR. The signal from the detector D1 has been used as this detector has the largest aperture, providing substantial count rates during the considered period of low solar activity. Although the spectral range covered by SphinX is up to 15 keV, the photons above 4.5 keV were rarely observed during the analysed period (after the flare contribution has been removed). The sequence of spectra can be seen in colour: *AR 11024 spectra.pdf* at `www.cbk.pan.wroc.pl/bs/Hvar2010`. The simplest way to analyse SphinX spectra is to use the isothermal ap-

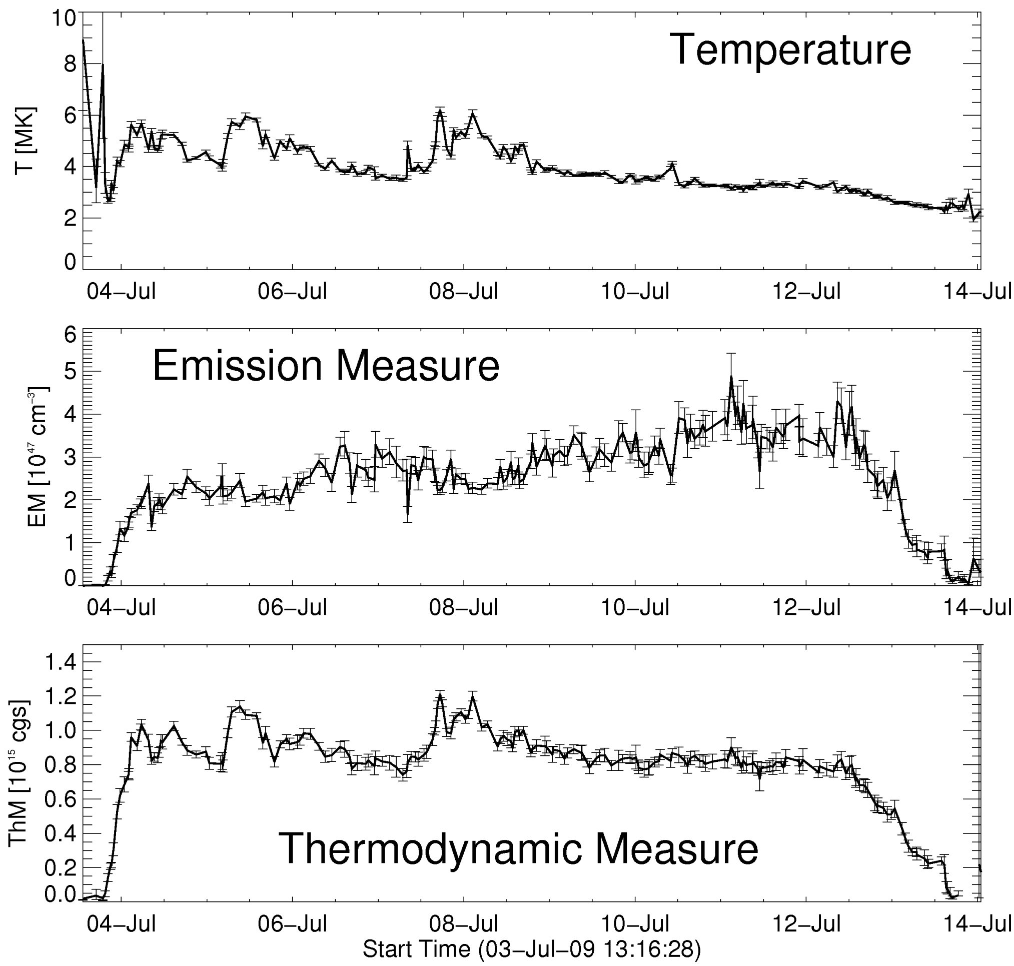

Figure 4: The time variability of the AR 11024 plasma parameters as obtained based on fitting observed spectra with theoretical ones. The top panel: temperature T; the middle panel: emission measure EM, the bottom panel: thermodynamic measure ThM.

proximation and determine the temperature T and emission measure EM based on the observed shape of each spectrum (count rate in D1 vs energy bin) constructed for consecutive 5 seconds data gather interval (DGI). The theory predicts a monotonic dependence of the slope of the spectrum on the temperature. The appropriate calculations have been performed based on the CHIANTI v5.2 spectral code and the laboratory calibrated energy dependence of the detector's effective area. The slope has been calculated in the energy range between 1.2 and 3 keV. The fitting of the observed spectrum inclination with the theoretical one in this statistically important range has been performed and the temperature is determined from the fitted value of the slope. The corresponding emission measure can be calculated based on the total number of photons above 1.2 keV. The method adopted is somewhat time consuming, but it works with retaining full spectral information. The examples of fitting the spectra of the quiet Sun (pre and post AR epoch) are presented in Figure 3. The spectra have been collected before the appearance of the AR (on July 3, 2009 during the period between 01:02:27 UT and 09:49:47 UT; left panel) and after the AR rotated off the limb (on July 14, 2009 from 08:38:14 UT to 13:32:25 UT; right panel).

The histograms represent the observed spectra while the corresponding solid lines (in the range $1.2 - 3$ keV) come from optimized least squares fitting. It is seen from the figure that for the case presented, the fitting is very good which results in small errors of the plasma parameters being determined. (See the numbers on the plots.) The quiet Sun temperature before the AR shows up in soft X-rays is a little higher (2.04 MK) in comparison with the value obtained after the AR rotated off the limb (1.78 MK). This difference in T corresponds to the higher level of X-ray flux for the pre-AR emergence era. The corresponding amount of EM is nearly twice as small at this time as compared with the post-AR period.

The described procedure of fitting the theoretical spectra to the observed ones has been adopted to all of the spectra available during the analysed period from July 3, 2009 12:00 UT to July 14, 2009 24:00 UT (a total of 226 AR spectra). The corresponding spectrum of the "quiet Sun" for the given time (see the dashed line at the bottom of Figure 2) has been subtracted in order to obtain the spectrum of the AR plasma alone. The time variations of such determined temperature for the plasma of AR 11024 together with corresponding error bars as obtained from the uncertainties of the fit are presented in the upper panel of Figure 4. It is seen that the AR non-flaring plasma temperature varies in a wide range between 2 MK and 6 MK. It is also seen that three periods of enhanced temperature are present on top of a rather systematic temperature decreasing trend. These three periods are probably related to the emergence of new magnetic flux regions as observed on the *SOHO* MDI magnetograms (discussed by Engell *et al.*, 2011). Based on the total number of photons observed above 1.2 keV and the temperature value determined for a given time, a respective value of corresponding emission measure has been calculated. The results together with error bars are shown in the middle panel of Figure 4. The general rising trend for the EM evolution is noticed. The EM is continuously increasing over the period when the AR is fully seen on the disc. With the values of T and EM determined we may estimate the total thermal energy contained in the soft

X-ray emitting AR plasma. It has been shown by Sylwester *et al.* (2010) that the thermal energy content can be expressed as:

$$E_{th} = 3kT\,N_e\,V = 3kT\,\sqrt{EM/V} \qquad [\text{ergs}], \tag{1}$$

where V and N_e are the emitting volume and electron density respectively. In case that the determinations of the emitting volume V are not available, we can use the "thermodynamic measure" ThM, defined as

$$ThM = 3kT\,\sqrt{EM} \qquad [\text{g cm}^{1/2}\,\text{s}^{-2}]. \tag{2}$$

The use of the ThM is convenient as its variation can directly be estimated from the observations and its behaviour reflects the changes of thermal energy, provided the emitting volume does not change substantially. The variability of the values of thermodynamic measure during the analysed period is shown in the bottom panel of Figure 4. The characteristic enhancements seen on the T behaviour and related to the emerging magnetic flux are evident also in the thermodynamic measure plot. It is also seen that the errors in ThM determination are much reduced in comparison with both T and EM.

2.2. *Hinode* XRT images

Inserting the definition of ThM from Equation 2 into Equation 1 one can obtain:

$$E_{th} = ThM\,\sqrt{V} \qquad [\text{ergs}], \tag{3}$$

which relates the total thermal energy content of the AR plasma E_{th}, with known from SphinX spectra thermodynamic measure ThM and with a yet to be determined plasma emitting volume V. Provided that the volume of the AR is known, it is also possible to determine the density of plasma N_e from the definition of EM:

$$N_e = \sqrt{EM/V} \qquad [\text{cm}^{-3}] \tag{4}$$

In order to estimate the volume of the soft X-ray emitting AR plasma we have used the X-ray images obtained with XRT on *Hinode*. Available processed images have been made in full XRT resolution of about 1 arcsec pixel resolution. They have been taken each 90 sec with overall size of 400 x 400 pixels by using Be medium and Ti filters. For the period from

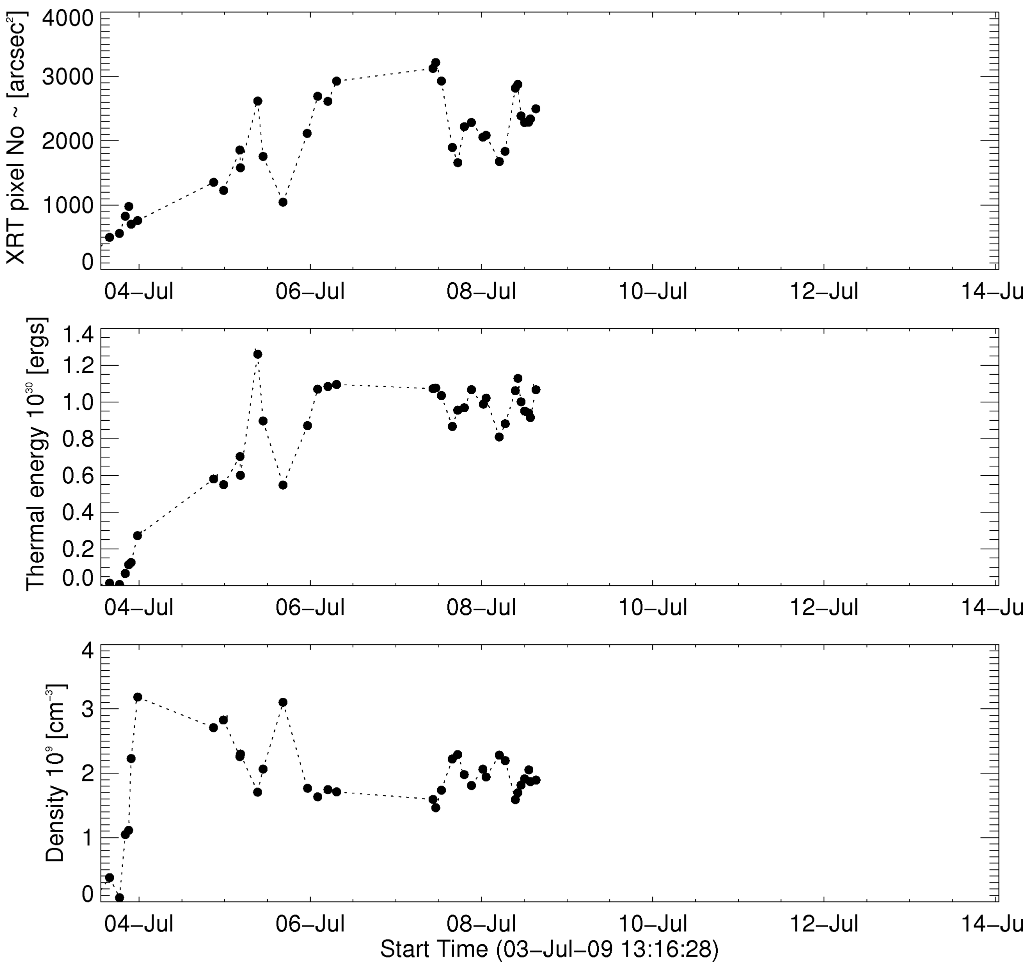

Figure 5: The time variability of the AR 11024 plasma characteristics as obtained using the XRT *Hinode* images. The top panel: XRT pixel number which characterizes the emitting volume; the middle panel: thermal energy content; the bottom panel: plasma density.

July 3, 2009 at 13:13 UT through July 8 at 15:20 UT we have identified 36 times where SphinX AR spectra and Be XRT images were taken within 2 minutes. These images are shown at www.cbk.pan.wroc.pl/bs/Hvar2010 as: *Be XRT Ar 11024 morph evol.pdf*. As was noticed in the paper by Engell *et al.*, (2011), during this period the region was positioned within 45 degrees of the disc centre, which allows us to avoid the significant projection effects. The morphology of AR 11024 is noticed to change dramatically up until July 4. Thereafter, the changes are more steady.

In order to determine the size of the AR on XRT images, the average background determined based on the intensity in the selected left edge stripe on each XRT image has been subtracted. (See example in Figure: *Be con-*

tour above 50.pdf at `www.cbk.pan.wroc.pl/bs/Hvar2010`). Pixels within the area contributing to the upper half of the flux in *Hinode* XRT Be image have been selected in order to determine the area of the AR contributing to the 1/2 of the flux as measured by SphinX. The resulting areas for the 36 times of XRT observations (common to within 2 min. with SphinX spectral measurements) are presented at the top panel of Figure 5. Only the first part of XRT data (to July 8, 2009 at 18:00 UT) has been analysed in the framework of this contribution. However, the horizontal scale is the same as in Figure 4 in order to allow for direct comparison of time behaviour of individual parameters. An "equivalent" volume of the emitting region has been estimated by finding the radius of the circle with the same area as measured, assuming a spherical symmetry of the source. It is apparent that due to the significant flux emergence in the birth of the AR the most prominent changes of the AR morphology and volume occurred when the region was "young". Later variations of the AR volume are slow on time scales of hours.

Based on the estimated values of the AR volume, the thermal energy content and the average density of the plasma can be derived using Equations 3 and 4. The resulting time variations of these parameters are shown in the middle and bottom panels of Figure 5 respectively. It is seen that beginning July 6 through July 8 at 18:00 UT these parameters are changing slowly. The average AR plasma thermal energy content during this period is about 1 x 10^{30} $ergs$ while the average electron density is about 2 x 10^9 cm^{-3}.

3. Concluding Remarks

We have analysed the X-ray observations of the AR 11024 which consisted of the spectra observed with the X-ray spectrometer SphinX on the *CORONAS-Photon* in the energy range above 1 keV and X-ray images obtained with XRT on the *Hinode*. The study concerns the period of very low solar activity during July 2009. The analysed AR 11024 region was the only one present on the solar disc during the considered period. The average temperature for quiet Sun emission preceding/following the Ar 11024 appearance is about 1.9 MK as determined from SphinX data. Concerning the present study, the following conclusions can be drawn:

1. Exceptional database is available for AR 11024 containing $\sim$ 120 000 spectra (including flares) from SphinX and about 2500 images as ob-

tained using Be and Ti filters from XRT.

2. The X-ray activity of the analysed AR follows (∼2 days delay) the appearance of this particular active region as seen in EUV. (Compare the left panel of Figure 1 and *Active Region 11024 location.pdf* at `www.cbk.pan.wroc.pl/bs/hvar2010`.)
3. The temperature of AR 11024 plasma is the highest when the region is young which is most probably connected with a rapid rise and increasing complexity of the magnetic flux. The thermodynamic measure is a very good and observationally robust characteristic reflecting changes of the thermal energy.
4. The sequence of *Hinode* images in full XRT resolution shows the evolution of morphology. It gives insight into variations of the AR volume containing heated plasma. Common interpretation of SphinX spectra and XRT images allow for determination of AR plasma density and thermal energy content.

We plan to extend the analysis of the AR 11024 emitting volume behaviour for later phases of its evolution, after July 8th and to perform similar analysis for the other active regions (AR 11019) as well as for multiple individual flaring events.

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