Broadband Observations of the Transient X-ray Pulsar
SAX J2103.5+4545

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Abstract. We investigated the optical, X-ray, and gamma-ray variability of the pulsar SAX J2103.5+4545. Our timing and spectral analyses of the X-ray and gamma-ray emissions from the source using RXTE and INTEGRAL data show that the shape of its spectrum in the energy range 3 – 100 keV is virtually independent of its intensity and the orbital phase. Based on XMM-Newton data, we accurately (5\arcsec) localized the object and determined the optical counterpart in the binary. We placed upper limits on the variability of the latter in the R band and the $H_\alpha$ line on time scales of the orbital and pulse periods, respectively. © 2004 MAIK ”Nauka/Interperiodica”.

Key words: X-ray pulsars, neutron stars, Be stars.

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INTRODUCTION

The X-ray transient SAX J2103.5+4545 was discovered by the BeppoSAX observatory during its outburst in 1997 (Hulleman et al. 1998). Almost immediately, coherent pulsations with a period of \( \sim 358 \) s were detected in the source, which allowed it to be classified as a transient X-ray pulsar. RXTE observations of the source during the next outburst in 1999 revealed another type of periodicity attributable to the orbital motion of the compact object. Based on these observations, Baykal et al. (2000) found the pulsar to be a member of a binary and to have an elliptical orbit with an eccentricity of \( e \approx 0.4 \) and an orbital period of \( \sim 12.68 \) d. Subsequently, Baykal et al. (2002) estimated the distance to the source, \( \sim 3.2 \) kpc, and its X-ray luminosity, \( L_x \sim 6 \times 10^{34} - 10^{36} \) erg s\(^{-1}\).

An analysis of the light curves for the object showed that the intensity of the pulsar is highly variable within one orbital cycle and peaks near the periastron (Baykal et al. 2000). Such a behavior of the light curves is typical of binaries with relatively high eccentricities and high-mass companions – early-type (O – B) stars. Hulleman et al. (1998) suggested that the star HD 200709 could be the optical counterpart. However, the position of this star outside the BeppoSAX error region and its spectral type (B8 V) made this candidacy highly questionable. Using the localizations of SAX J2103.5+4545 by the BeppoSAX observatory and by the IBIS and JEM-X telescopes of the INTEGRAL observatory as well as the observations of this region at the Skinakas observatory (Crete), Reig et al. (2004) pointed to another candidate; their error region for the sources \( \sim 30'' \).

In this paper, we make an attempt to investigate the variability of the source on time scales from several hundred seconds (the spin period of the neutron star) to several days (the orbital period of the binary) over a wide energy range, from optical (RTT-150) to hard X-rays (RXTE and INTEGRAL). In addition, using XMM-Newton data, we were able to increase the localization accuracy for the X-ray pulsar to 5''.

OBSERVATIONS

RTT-150

Optical observations of SAX J2103.5+4545 were performed in the fall of 2003 with the Russian-Turkish 1.5-m telescope (RTT-150, TUBITAK National Observatory, Turkey, Mount Bakyrly, 2547 m, 2\(^h\)01\(^m\)20\(^s\) E, 36\(^\circ\)49'30'' N). The observations were carried out with a back-illuminated Andor Technologies 2\(\times\)2 CCD array placed at the Cassegrain focus of the telescope (1:7.7). A median zero-exposure frame and dark current were subtracted from all images, and the images were divided by a flat field. We reduced the images using the IRAF (Image Reduction and Analysis Facility) standard software package\(^1\) and our own software.

\(^1\)http://tucana.tuc.noao.edu/
To improve the celestial coordinates of the source, we used data from the XMM-Newton observatory. Its main instruments are three grazing-incidence X-ray telescopes with (MOS1, MOS2, PN) CCD arrays placed at the foci. The typical angular size of a point source on the detectors is of the order of several arcseconds, which allows the coordinates of the source to be determined with a high accuracy. Here, we used data from the EPIC MOS instruments operating in the energy range 0.15 – 12 keV.

The International gamma-ray observatory INTEGRAL (Winkler et al. 2003) was placed into a high-apogee orbit by the Russian Proton Launcher from the Baikonur Cosmodrome on October 17, 2002 (Eismont et al. 2003). The payload of the satellite includes the SPI gamma-ray spectrometer, the IBIS gamma-ray telescope, the JEM-X X-ray monitor, and the OMC optical monitor (for more details, see Winkler et al. (2003) and references therein). We used data from the IBIS telescope, its upper ISGRI detector (Lebrun et al. 2003), and data from the JEM-X X-ray monitor (Lund et al. 2003). Both instruments operate on the principle of a coded aperture. The field of view is $29^\circ \times 29^\circ$ (total) and $9^\circ \times 9^\circ$ (the full-coding region) for IBIS and $4^\circ$ in diameter (the full-coding region) for JEM-X.

We used the publicly accessible INTEGRAL calibration observations of the Cyg X-1 region performed in December 2002. Preliminary results of the analysis of the INTEGRAL observations for the pulsar SAX J2103.5+4545 were presented by Lutovinov et al. (2003).

The standard OSA-3.0 software package provided by the INTEGRAL Science Data Center (ISDC)$^2$ was used for the timing analysis of ISGRI data and the analysis of JEM-X data. A method described by Revnivtsev et al. (2004) was used to reconstruct the images and to construct the spectrum of the source from ISGRI data. An analysis of the observational data for the Crab Nebula indicates that the technique used allows the spectrum of the source to be accurately reconstructed; the systematic uncertainty is 10% for the absolute normalization of the flux obtained and 5% in each energy channel when reconstructing the spectrum of the source. The latter was added as a systematic uncertainty in the spectral analysis of the source in the XSPEC package.

For our comparative analysis of the INTEGRAL results, we used the simultaneous observations of the pulsar SAX J2103.5+4545 that were performed by the RXTE observatory (Bradt et al. 1993) in December 2002 (Obs. ID. 70082-02-43 – 70082-02-52) and that are publicly accessible.

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$^2$http://isdc.unige.ch
The main instruments of the RXTE observatory are the PCA and HEXTE spectrometers that jointly cover the energy range 3 – 250 keV. The PCA spectrometer is a system of five xenon proportional counters. The PCA field of view is bounded by a circular collimator with a radius of 1° at half maximum, the operating energy range is 3 – 20 keV, the effective area at energies of 6 – 7 keV is \( \sim 6400 \text{ cm}^2 \), and the energy resolution at these energies is \( \sim 18\% \). The HEXTE spectrometer is a system of two independent packages of four phoswich NaI(Tl)/CsI(Na) detectors rocking with a period of 16 s for the observations of off-source areas at a distance of 1.5° from the source. At each specific time, the source can be observed only by one of the two detector packages; thus, the effective area of the HEXTE detectors is \( \sim 700 \text{ cm}^2 \). The operating energy range of the spectrometer is 15 – 250 keV.

The standard FTOOLS/LHEASOFT 5.3 software package was used to reduce the RXTE data. In our spectral analysis of the PCA data in the energy range 3 – 20 keV, we introduced a systematic uncertainty of 1%.

LOCALIZATION AND DETERMINATION OF THE OPTICAL COUNTERPART

Using INTEGRAL observations, we obtained an image of the sky region with the source in the energy range 18 – 60 keV (Fig. 1). The position of the source can be determined from these data with an accuracy of 1′. This accuracy is too low to unambiguously determine the optical counterpart to the source. Reig et al. (2004) made an attempt to improve the localization accuracy using the overlapping BeppoSAX and INTEGRAL error regions.

Here, we used archival XMM-Newton (Obs.Id 0149550401) data to improve the position of SAX J2103.5+4545. During these observations, the telescope operated in fast-variability mode, in which information is read from the CCD array only along one of the axes. Compared to the standard modes, this mode allows the time resolution to be increased significantly, but at the same time, it has a shortcoming: there is no direct spatial information. To determine the celestial coordinates of the source, we used data from two detectors, MOS1 and MOS2, in which information is read along the mutually perpendicular directions. We used the following algorithm:

1. We determined the detector coordinate of the centroid of the one-dimensional photon distribution for each of the detectors (RAWX1\(_{\text{src}}\), RAWX2\(_{\text{src}}\)).

2. We generated a set of celestial coordinates in the region where the source was presumably located. Subsequently, this set was transformed into two sets of detector coordinates (one for MOS1 and the other for MOS2) using the standard esky2det code from the Science Analysis System (SAS) of the XMM observatory.

3. From the set of celestial coordinates, we chose those for which the detector coordinates (RAWX1, RAWX2) corresponded to those of the source (RAWX1\(_{\text{src}}\), RAWX2\(_{\text{src}}\)).
As a result, we obtained the following coordinates of the source: \( \alpha = 21^h03^m36^s, \delta = 45^d45^m07^s \). The localization accuracy is determined by the response function of the telescope, the astrometric referencing accuracy, and the peculiarities of our coordinate determination procedure. We obtained \( \sigma_{\text{RADEC}} = 5'' \) as an estimate of the total error.

The RTT-150 map of the sky region around the pulsar SAX J2103.5+4545 is shown in Fig. 2. The circles indicate the error regions determined from BeppoSAX and XMM-Newton data. It clearly follows from this figure that the optical counterpart to SAX J2103.5+4545 is determined with a high degree of confidence from the results of our analysis. It is the star shown in Fig. 2. This result agrees with that obtained by Reig et al. (2004). The RTT-150 measurements yield the magnitudes \( R = 13.60 \) and \( V = 14.20 \) for this star. The derived color is consistent with the emission from an O-B star at an interstellar reddening of \( A_V = 3.12 \).

### TIMING ANALYSIS

#### Variability on Time Scales of the Orbital Period

Lutovinov et al. (2003) showed that the intensity of the source in the hard energy ranges 15 – 40 and 40 – 100 keV is highly variable and depends on the orbital phase. Figure 3a presents the light curve of the pulsar constructed from ISGRI data in the energy range 18 – 60 keV. Each point was obtained by averaging over five individual pointings and has an exposure time of \( \sim 15 \) ks. To depict the dependence of the source’s intensity more conveniently, orbital phases are plotted along the horizontal axis together with time (the parameters of the binary were taken from Baykal et al. (2000)). The flux from the binary is at a maximum (\( \sim 40 – 50 \) mCrab) near orbital phases of 0.55 – 0.7 and decreases to \( \sim 10 – 20 \) mCrab at phases of 0.1 – 0.2. As was noted by Lutovinov et al. (2003), the observed hard X-ray light curve follows almost closely the light curve in the standard X-ray energy range (Baykal et al. 2000).

The variability of the source was also studied at optical wavelengths on time scales of the order of the orbital period, \( \sim 12.6 \) days. For this purpose, the source’s field was imaged in the R band (the band was chosen arbitrarily) in the second half of October and November 2003 on each night, where possible. The derived light curve is shown in Fig. 3b. We found no variability of the source related to its orbital motion in the binary; the upper limit on its amplitude is 1%.

#### Variability on Time Scales of the Pulsation Period

The periods of X-ray pulsars are known to be variable and subject to both long-term changes and small-scale fluctuations (see, e.g., Nagase 1989; Lutovinov et al. 1994; Bildsten et al. 1997). While monitoring SAX J2103.5+4545 during its 1999 outburst, Baykal et al.
(2002) found a significant spin-up of the neutron star, with the observed spin-up rate being proportional to the flux from the source. Figure 4 shows the changes in the pulsar’s period with time throughout the history of its observations by different observatories.

An epoch-folding technique was used to determine the pulsar’s period during the INTEGRAL observations. The source’s light curve in the energy range 20 – 100 keV with a time step of 40 s was constructed from ISGRI data using standard software and corrected for the orbital motion of the neutron star in the binary using known orbital parameters (Baykal et al. 2000). The pulsation period calculated in this way was 355.10±0.04 s. Figure 5 shows the $\chi^2$ periodogram for the source’s light curve obtained by searching for flux pulsations from it. The error in the period was determined by the Monte Carlo method from an analysis of the simulated light curves.

Figure 6a shows the phase light curve for the pulsar SAX J2103.5+4545 constructed from INTEGRAL data in the energy range 20 – 100 keV. It has a single-peaked shape extended over the entire phase cycle of the pulsar’s period. The intensity rapidly rises and smoothly decays. Baykal et al. (2000) and Inam et al. (2004) provided the source’s pulse profiles for different soft X-ray energy ranges. Our hard X-ray pulse profile slightly differs from the previous soft X-ray profiles, whose peaks occupy only half of the cycle, and the rise in intensity is smoother than its decay. Based on the INTEGRAL data reduction results, we failed to estimate the pulse fraction in the hard energy range, because the standard software used to construct the light curves of sources does not properly estimate the contribution from the background radiation on the detector. Therefore, to estimate this contribution, we used the HEXTE/RXTE data obtained over the same time interval as the INTEGRAL data. According to these data, the pulse fraction is $\sim 20\pm5\%$. In the soft energy range 0.9 – 11 keV, the pulse fraction is 50.9 $\pm$ 0.3% (Inam et al. 2004).

The variability of the source on time scales of its X-ray pulsations was also studied at optical wavelengths, in an $H_\alpha$ filter. The observations of such variability in other high-mass binaries with pulsars were reported previously (e.g., in the object X Persei; Mazeh et al. 1982). The $H_\alpha$ observations of the source were performed on November 18, 2003 (52961 MJD), with the RTT-150 telescope. The observations were carried out for 1.1 h with a time resolution of $\sim 15$ s.

Since the source has exhibited a nonuniform spin-up of the neutron star throughout the history of its observations, to calculate the expected period at the epoch of our optical observations, we have obtained a conservative estimate of the mean spin-up rate as follows. For all of the possible pairs of points in Fig. 4, we calculated the spin-up rate between them and then determined its mean value, $\dot{P}/P \sim 3.2 \times 10^{-3}$ yr$^{-1}$. In this procedure, we excluded the period measured by the INTEGRAL observatory in the series of observations in May – June 2003 (Sidoli et al. 2003). This decision was justified in part by the large uncertainty in the measure period at this epoch and by the fact that, if the presumed spin-up rate of the pulsar was estimated from our measurements and from the measurements by Inam et al. (2004) and Sidoli et al. (2004), then the value obtained would be several times higher than the maximum spin-up rate observed by Baykal et al. (2002) during the 1999 outburst. It is
important to note that the 3 – 20 keV flux from the source in December 2003 – April 2004 was comparable to its flux in 1999 – 2000. The ultimate answer to the question concerning the behavior of the spin-up rate of the neutron star in the binary SAX J2103.5+4545 may be given after analyzing the large set of RXTE observations of this object in 2003 that is not yet publicly accessible.

The presumed pulsation period at the epoch of our optical observations estimated by the method described above is 354.02 s. The $H\alpha$ light curve of the optical counterpart folded with this period is shown in Fig. 6b. We found no variability of the source in then $H\alpha$ band; the upper limit is 1%. The zero phase of the X-ray pulse profile and the presumed zero phase at the epoch of our optical observations calculated using the procedure described above were brought into coincidence.

**SPECTRAL ANALYSIS**

As we noted above, the intensity of the source varies greatly with the orbital motion of the neutron star in the binary. Therefore, we performed a spectral analysis of the pulsar emission for various orbital phases of the binary with the goal of finding the possible dependence of the source’s spectrum on its intensity and its position in the orbit. Such an analysis was performed by Baykal et al. (2002) using RXTE data for the standard X-ray energy range 3 – 20 keV. In contrast, we investigated the behavior of the source over a wide energy range up to 100 keV using INTEGRAL and RXTE data.

We used JEM-X and ISGRI data to construct the spectrum of the source from its INTEGRAL observations in the energy ranges 6 – 20 and 20 – 100 keV, respectively. To test the validity of the normalization of the JEM-X spectra, we analyzed a series of spectra for the Crab Nebula. Where possible, we took observations when this object was within the same areas of the JEM-X field of view as our source. We found that the shape of the spectrum for the Crab Nebula is reconstructed satisfactorily, while the normalization proves to be underestimated by a factor of $\sim 1.6$. This factor was used for the correction of the normalization of the JEM-X spectrum for the source. Our analysis of the source’s spectrum at various orbital phases revealed no appreciable deviations of its shape over a wide energy range either. This allowed us to subsequently study the source’s average spectrum shown in Fig. 7. For comparison, this figure also shows the pulsar’s spectrum constructed from the RXTE observations performed over the same period as the INTEGRAL observations. We used PCA and HEXTE detector data for the energy ranges 4 – 20 and 20 – 70 keV, respectively. It should be noted that the total time of RXTE observations of the source is shorter than the time of its INTEGRAL observations.

The spectrum of the X-ray pulsar SAX J2103.5+4545 is typical of this class of objects and can be described by a simple power law with an exponential high-energy cutoff. This model has long and widely been used to fit the spectra of X-ray pulsars (White et al. 1983). Based on XMM-Newton data, Inam et al. (2004) measured the neutral hydrogen column density $N_H$. Depending on the model used to describe the pulsar’s spectrum, this parameter
varies over the range \( N_H = (0.6 - 0.9) \times 10^{22} \) atoms cm\(^{-2} \), in agreement with our optical measurements (see above). Since there are no INTEGRAL data at energies below 6 keV in our case and since the RXTE sensitivity is lower (than the XMM-Newton sensitivity) at soft energies, we fixed \( N_H \) at \( 0.9 \times 10^{22} \) atoms cm\(^{-2} \) in the subsequent analysis.

The table gives the best-fit parameters for the model fit to the source’s spectrum described above for the INTEGRAL and RXTE data. The derived parameters for the two data sets are in good agreement between themselves and with the values from Baykal et al. (2002) and Inam et al. (2004), except for the e-folding energy that proved to be slightly lower. This may be because we greatly extended the energy range under study. Note also that the RXTE spectrum of the source exhibits a neutral iron line at an energy of 6.4 keV (see the table).

**CONCLUSIONS**

The transient X-ray pulsar SAX J2103.5+4545 is a member of a high-mass Be binary with a moderate eccentricity and the shortest orbital period known to date among all such binaries. Identifying the optical counterpart of the binary plays one of the most important roles in understanding the nature of binaries with compact objects and the processes that take place in them.

We have been able to localize the pulsar with an accuracy of 5″ and to firmly establish its nature: an emission-line O-B star. We performed optical observations of this object with the RTT-150 telescope with the goal of finding its possible variability. We found no variability of the optical counterpart on time scales of the orbital period and the spin period of the pulsar; the upper limit on its amplitude is about 1% in both cases.

The X-ray pulsar has exhibited a spin-up almost throughout the history of its observations, with the spin-up rate depending on the luminosity of the source (Baykal et al. 2002). During the INTEGRAL observations, the pulsation period was 355.10±0.04 s. The pulse fraction decreases with increasing energy and is 20% in the energy range 20 – 100 keV.

Our analysis of the INTEGRAL and RXTE observational data for the pulsar shows that the source is detected at a statistically significant level up to energies of \( \sim 100 \) keV. As in the standard X-ray energy range, the intensity of the source in the hard energy range also depends on the orbital phase of the binary and peaks near the periastron. At the same time, the shape of the source’s spectrum remains virtually unchanged over a wide energy range (3 – 100 keV) and can be described by the standard (for X-ray pulsars) model: a simple power law with a high-energy cutoff and low-energy absorption.

We detected no features in the 3 – 100 keV spectrum of the source that could be interpreted as cyclotron lines. Thus, we can impose lower and upper limits on the magnetic field strength of the source: \( B \lesssim 8.6 \times 10^{12} \) G and \( B \gtrsim 2.6 \times 10^{11} \) G, respectively. We know X-ray pulsars with a weak magnetic field \( (B \sim 10^{11} \) G), for example, SMC X-1 (see, e.g., Lutovinov et al. (2004) and references therein) and GRO J1744-28 (Rappaport and Joss 1997). The detection
of type II X-ray bursts from them provides evidence that the magnetic field in these sources is weak. No such bursts are observed from the pulsar SAX J2103.5+4545. Baykal et al. (2002) estimated the magnetic field from the relationship between the rate of change in the pulsar’s period and its parameters (Ghosh and Lamb 1979): $B \sim 12 \times 10^{12}$ G. Thus, most of the arguments suggest that the neutron star in the binary under consideration has a strong magnetic field.

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Translated by V. Astakhov
### Table: Best-fit parameters for the spectrum of the pulsar SAX J2103.5+4545

| Parameters                          | Values                  |
|------------------------------------|-------------------------|
| **Derived from INTEGRAL data**     |                         |
| $N_H,10^{22}\text{cm}^{-2}$        | 0.9 (fixed)             |
| Photon index $\Gamma$              | 1.04±0.15               |
| Cutoff energy $E_{\text{cut},\text{keV}}$ | 8.5±2.4                |
| e-folding energy $E_{\text{fold},\text{keV}}$ | 21.37±2.75          |
| $\chi^2$(degree of freedom)        | 1.21                    |
| **Derived from RXTE data**         |                         |
| $N_H,10^{22}$                      | 0.9 (fixed)             |
| Photon index $\Gamma$              | 0.979±0.066             |
| Cutoff energy $E_{\text{cut},\text{keV}}$ | 6.97±1.26              |
| e-folding energy $E_{\text{fold},\text{keV}}$ | 22.98±1.73           |
| Fe line center, keV                | 6.34±0.32               |
| Fe line width, keV                 | 0.81±0.21               |
| Fe line intensity, photons cm$^{-2}$ s$^{-1}$ | (1.2±0.4)×10$^{-3}$   |
| $\chi^2$(degree of freedom)        | 0.99                    |
Fig. 1: The region of ISGRI observations of SAX J2103.5+4545 in the energy range 18 – 60 keV.
Fig. 2: The region of ground-based RTT-150 R-band observations of SAX J2103.5+4545. The arrow indicates the optical counterpart to the pulsar, and its error region determined here from XMM-Newton data is highlighted.
Fig. 3: Light curve of the pulsar SAX J2103.5+4545 on time scales of the orbital period: constructed from ISGRI data in the energy range 18 – 60 keV (upper panel) and from ground-based RTT-150 R-band observations in October – November 2003 (lower panel). For convenience, optical phases are plotted along the horizontal axis. The errors correspond to one standard deviation. The dashed line indicates the mean R magnitude of the star.
Fig. 4: Changes in the pulsation period of SAX J2103.5+4545 throughout the history of its observations by different observatories. The dashed line marks the epoch of optical observations.
Fig. 5: $\chi^2$ periodogram obtained by searching for flux pulsations from SAX J2103.5+4545 by the epoch-folding technique. The solid line indicates the Gaussian best fit.
Fig. 6: Pulse profiles for the pulsar SAX J2103.5+4545 in the energy range 20 – 100 keV as constructed from IBIS/ISGRI data (the background was not subtracted) (a) and in an $H_\alpha$ filter as constructed from the RTT-150 observations on November 18, 2003 (b).
Fig. 7: Energy spectrum of the pulsar SAX J2103.5+4545 as constructed from INTEGRAL and RXTE data. The normalization of the RXTE spectrum was multiplied by 0.2. The lines indicate the model fits to the spectra with the best-fit parameters (see the table).