**NuSTAR DISCOVERY OF A CYCLOTRON LINE IN KS 1947+300**

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1. INTRODUCTION

KS 1947+300 was independently discovered with *Mir*; *Kvant*/TTM by Borozdin et al. (1990) and with *CGRO*/BATSE by Finger et al. (1994). The major outburst was followed by a series of weaker outbursts, the strongest of which occurred in 2004 April and reached $\sim$45 mCrab in the 1.5–12 keV energy band. This series of outbursts was serendipitously monitored by the *Integral* Gamma-Ray Astrophysics Laboratory (INTEGRAL) during its Galactic plane scans. Tsygankov & Lutovinov (2005) described the INTEGRAL/ISGRI and JEM-X spectra using a power law with a high-energy cutoff and found indications for a spectral softening with increased flux. Accreting neutron stars sometimes show cyclotron resonant scattering features (CRSFs) in their X-ray spectra. These absorption-like lines are the only way to directly measure the magnetic field strength close to the neutron star surface. They are produced by photons that scatter off electrons quantized onto Landau-levels in the strong magnetic field ($B \approx 10^{12} G$). The new observation implies that KS 1947+300 has a magnetic field strength of $B \approx 1.1 \times 10^{12}(1 + z)$ G, which is at the lower end of known cyclotron line sources.

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**Online-only material:** color figures

In 2004 RXTE performed an extensive campaign to monitor a large outburst that reached a peak flux of 120 mCrab in the 1.5–12 keV band. Galloway et al. (2004) found that the energy spectrum could be described with a simple Comptonization model (compTT; Titarchuk 1994; Hua & Titarchuk 1995), a model often applied to highly magnetized neutron stars. They found no source-intrinsic absorption, but a broad excess around 10 keV which they described with a hot blackbody component with $kT_{bb} \approx 3–4$ keV.

Using *BeppoSAX* data taken during the decay of the same major outburst, Naik et al. (2006) found a similar spectral shape but a much cooler blackbody component, $kT_{bb} \approx 0.6$ keV. They additionally found evidence for an FeKα line at $\sim$6.6 keV.
RXTE, BeppoSAX, and INTEGRAL, a CRSF was not detected in previous outbursts of KS 1947+300 (Naik et al. 2006; Galloway et al. 2004; Tsygankov & Lutovinov 2005).

KS 1947+300 has been in quiescence from 2004–2013. In 2013 October MAXI (Matsuoka et al. 2009) detected increased flux levels (Kawagoe et al. 2013). The beginning of an outburst was immediately confirmed by Swift/XRT (Kennea et al. 2013) and monitored by Swift/Burst Alert Telescope (BAT). We triggered Swift/XRT ~1 ks snapshot observations every three days to monitor the outburst in soft X-rays (Figure 1). It reached a peak flux of ~130 mCrab in the 3–10 keV energy band, very comparable to the maximum of the bright 2000 outburst (Naik et al. 2006). Additionally, we triggered three observations with the Nuclear Spectroscopy Telescope Array (NuSTAR; Harrison et al. 2013). An overview of the observations and their exposure times can be found in Table 1.

2. OBSERVATIONS AND DATA REDUCTION

2.1. NuSTAR

NuSTAR consists of two independent grazing incidence telescopes focusing X-rays between 3–79 keV onto two focal plane modules, FPMA and FPMB. We used the standard NUSTARDAS software v1.2.0 as distributed with HEASOFT 6.14 to extract spectra and light curves. NuSTAR spectra were used between 3–60 keV. Above 60 keV the calibration at the time of writing shows increased systematic uncertainties, and we therefore do not use those data. A detailed analysis of the high-energy calibration will be presented in a forthcoming publication. The source data were extracted from a 130′′ radius circular region centered at $\alpha_{2000} = 19^h49^m36^s$ and $\delta_{2000} = +30^\circ12'22''$. Background spectra were extracted from a circular region with 105′′ radius as far away from the source as possible. This formally introduces systematic uncertainties in the background estimation, but since KS 1947+300 is at least a factor of 40 brighter than the background at all energies, the influence on the source flux is negligible. Light curves were extracted with a resolution of 1 s, the resolution corresponding to dead-time measurements in the standard operating mode.

2.2. Swift/XRT

Data from the Swift/XRT (Burrows et al. 2005) were extracted following the standard guidelines, using XSELECT to extract spectra and light curves and xrtmkarf to create the response files. All data were obtained in window timing mode. The source data were extracted from a circular region with a radius of 20 sky pixels ($\approx 47''$). Background spectra were extracted from the wings of the point-spread function using an annular region between 90 and 110 pixels radius (212′′ and 259′′, respectively). With the X-Ray Telescope (XRT), KS 1947+300 is a factor of 50 brighter than the background at all energies, rendering small uncertainties in the background negligible. We used the XRT spectra in the energy range between 0.8–10 keV. At lower energies the windowed timing mode shows larger calibration uncertainties and we therefore decided not to use those energies.15

2.3. Reduction Methods

All timing information for both satellites was transferred to the solar barycenter, using the FTOOL barycorr and the DE-200 solar system ephemeris (Standish et al. 1992), and corrected for the binary motion using the ephemeris by Galloway et al. (2004). Timing and spectral analysis was performed using the Interactive Spectral Interpretation System (ISIS v1.6.2; Houck & Denicolà 2000). All uncertainties are given at the 90% level ($\Delta x^2 = 2.7$ for one parameter of interest), unless otherwise noted.

3. PHASE-AVERAGED SPECTROSCOPY

For spectral modeling, we use FPMA and FPMB spectra as well as the corresponding XRT data for each epoch, as detailed in Table 1. The X-ray continuum is very well described with a simple power law with an exponential cutoff (model cutoffpl in XSPEC) plus a blackbody. The blackbody is responsible for about 50% of the flux at 2 keV and follows the overall flux evolution of the data. It likely originates from the hot-spot of the neutron star surface. The compTT model used by Naik et al. (2006) and Galloway et al. (2004) results in a clearly worse fit.

Naik et al. (2006) and Galloway et al. (2004) measured an absorption column toward the source which was lower than the maximal Galactic value along that line of sight ($\sim 9 \times 10^{21} \text{ cm}^{-2}$; Kalberla et al. 2005). We therefore allow the absorption to vary in our model, but require it to be the same in all three
observations. We describe it using an updated version of the tbabs (Wilms et al. 2000) model, with the corresponding abundances and cross-sections by Verner et al. (1996). Our best-fit value of $8.45 \pm 0.20 \times 10^{21}$ cm$^{-2}$ is consistent with the $21$ cm value along the line of sight and also with the $N_H$ obtained from the reddening of the source ($A_V = 3.38$; Negueruela et al. 2003) when using the calibration of Predehl & Schmitt (1995) as updated by Nowak et al. (2012).

Adding a Gaussian FeK$\alpha$ line at around $6.5$ keV to the continuum model we obtain a good description of the spectra, as updated by Nowak et al. (2012).

The remaining free parameters in the model are the photon index of the power law, the 3–10 keV flux, and the relative luminosity for a distance of $10$ kpc in $10^3$ erg s$^{-1}$.

$^4$ In $10^{22}$ cm$^{-2}$.
$^5$ Parameter tied across observations.
$^6$ Unabsorbed flux in $10^{-9}$ erg s$^{-1}$ cm$^{-2}$.
$^7$ Luminosity for a distance of $10$ kpc.
$^8$ In $10^{36}$ erg s$^{-1}$ for a distance of $10$ kpc.
$^9$ In $10^{-3}$ ph s$^{-1}$ cm$^{-2}$.
$^10$ In keV.

### 3.1. Time-resolved Spectral Analysis

To study the evolution of the spectrum over the outburst we use all available Swift/XRT data between MJD 56581–56639, and describe them with the same cut of fp1 plus bbbody model as the time-averaged spectra. We fix the cutoff energy at $23.2$ keV, the average value in the X-ray spectra it becomes clear, however, that an almost linear correlation between the blackbody temperature and the unabsorbed 3–10 keV flux is present,

$$kT_{bb} = m \times F_{3–10 \text{keV}},$$

where $kT_{bb}$ is measured in keV and $F_{3–10 \text{keV}}$ in keV s$^{-1}$ cm$^{-2}$. In the simultaneous fits we find $m = 0.576 \pm 0.010$ s cm$^2$. We use this correlation to tie the blackbody temperature to the X-ray flux in the time-resolved XRT spectra and consequently replace the degeneracy with an empirically motivated correlation.

The remaining free parameters in the model are the photon index of the power law, the 3–10 keV flux, and the relative normalization of the blackbody component. The latter does not show significant changes with time. The model describes all 19 XRT spectra relatively well, with an average $\chi^2_{red} = 1.05$ for 429 dof.

As shown in Figure 1(b), the photon index is highly variable and seems to soften with increased X-ray flux. This correlation is marginally significant at a bit above the 1σ level, with Spearman’s rank correlation coefficient $\rho = 0.31$. It also becomes clear that all three NuSTAR observations were performed during phases with relatively hard spectra.
Figure 3. Results of the phase-resolved spectroscopy. The left panel shows for observation 2 the (a) pulse profile between 3–79 keV, (b) hardness ratio \((H - S)/(H + S)\) between the energy bands \(S = 4.5–6\) keV and \(H = 10–15\) keV. The dotted lines indicate the seven, wider phase bins used to measure the CRSF energy. The photon index \(\Gamma\) and the folding energy are shown in panels (c) and (d), respectively. The right panel shows the parameters of the CRSF: (a) line energy for the second observation, (b)–(d) line strength for the first, second, and third observation, respectively. The red data points show the results of the phase bin covering the phases with the most significant CRSF in observation 2; see the text for details. The pulse is repeated once for clarity.

(A color version of this figure is available in the online journal.)

Lutovinov (2005) found a similar correlation between the photon index and the X-ray luminosity in the harder RXTE energy band (3–100 keV).

4. PHASE-RESOLVED SPECTROSCOPY

To investigate changes with viewing angle onto the neutron star we split each NuSTAR data set into 20 phase bins. For this analysis we did not use the Swift/XRT data, as their short exposure does not allow us to split them up further. We define the phase bins to stretch over intervals of similar flux and hardness ratio; see Figure 3. The pulse profile changes drastically with energy, developing from one broad pulse to a double-peaked profile, with a narrow primary and broader secondary peak above \(\sim 25\) keV (see also Naik et al. 2006).

To define the phase bins individually for each observation, we first measure the local pulse period by folding the cleaned NuSTAR event list on trial periods around the expected period of 18.8 s, following the description given by Leahy & Scott (1998). The uncertainties are estimated by phase-connecting pulse profiles from the beginning and end of each observation. We do not allow for a change in the pulse period during one observation, but the error introduced is below the precision needed for the analysis presented here. The measured periods show a continuous spin-up over the duration of the outburst (see Table 1), in agreement with the Swift/XRT snapshots and the Fermi/Gamma-ray Burst Monitor pulsar monitoring17 (Finger et al. 2009).

To describe the phase-resolved spectra we use the same model as for the phase-averaged spectrum, but fix the line energies and widths of the CRSF and the FeK\(\alpha\) line as well as the temperature of the blackbody due to the reduced statistical quality of the spectra. This model results in a very good description of the data in all phase bins, with an average \(\chi^2_{\text{red}} = 1.02\) for 345 dof.

Figure 3 shows the continuum parameters only for the second observation, since it provides the best statistics, but the other two observations show very similar behavior. Both the photon index \(\Gamma\) and the folding energy \(E_{\text{fold}}\) show a very strong dependence on phase, confirming the results by Naik et al. (2006) at a much higher resolution in phase space (Figure 3 left, panels (c) and (d)). Between phase 0.1–0.2 we observe a strong increase in \(\Gamma\) and \(E_{\text{fold}}\), coincident with the small dip between the narrow first peak and the broad main peak.

The strength of the CRSF shows a very interesting behavior with pulse phase, as shown for all observations in Figure 3, right panel. As expected from the phase-averaged spectra, the line is clearly strongest in observation 2, being detectable over a wide phase range between phases 0.6–1.3. During the main peak of the pulse profile the line strength drops to 0. In observation 1 the line is also significantly detected in absorption between phases 0.9–1.1. Around phase 0.3 there are low significance indications that the line is instead visible in emission. In observation 3 the line strength is scattering around 0, only one phase bin around phase 1.0 shows an absorption line clearly above the 95% limit.

In the phase-resolved spectra we allow the iron line normalization and the blackbody normalization to vary to obtain a statistically acceptable fit (not shown in Figure 3). We carefully checked that any variation in these parameters does not influence the strength of the CRSF. While the iron line shows the largest equivalent width during the minimum of the pulse profile, i.e., at the same phases where the CRSF is most prominent, it does not influence the spectral shape at the CRSF energy. The blackbody did not vary significantly over the pulse phase.

To investigate the energy dependence of the CRSF with pulse phase, we extracted spectra from observation 2 using seven wider phase bins to increase the signal-to-noise ratio. For these spectra we also allow the iron line energy and width, as well

as the blackbody temperature to vary. We keep the width of the CRSF fixed to the best phase-averaged value, as it otherwise became unconstrained during the fits. As can be seen in Figure 3, right panel (a), we do not detect a significant variation of the line energy with pulse phase. Between phases 0.4–0.6 we again detected no significant line, resulting in an unconstrained energy.

Besides changes with pulse phase, changes of the line energy with luminosity are quite common (see, e.g., Caballero et al. 2007; Tsygankov et al. 2010; Fürst et al. 2014, among others). To search for such a luminosity dependence between observations, we extract spectra for each observation of those phases, in which the line was significantly detected in observation 2. This approach allows us to obtain the most significant line and therefore most precise energy measurement, as indicated by the blue data points in Figure 3. We describe the spectra with the same model as for the seven wide phase bins described above. We do not detect a significant change of the line energy, with the measured values being 12.5 ± 0.7 keV, 12.3 ± 0.5 keV, and 12.2 ± 0.9 keV for observation 1, 2, and 3, respectively.

5. SUMMARY AND DISCUSSION

We have presented a spectral analysis of three NuSTAR observations of the Be-X-ray binary KS 1947+300 with simultaneous Swift/XRT data, taken during its large 2013/2014 outburst. The broad spectral coverage provided by the combination of these two instruments allowed us to discover a CRSF absorption feature around 12.5 keV. The feature was significantly detected in the phase-averaged spectrum of the brightest observation, and during the broad pulse minimum in phase-resolved spectroscopy in all observations. During the pulse maximum the feature is not seen significantly, either in absorption or emission.

The line energy and width is similar to the lines detected in 4U 0115+63 and Swift J1626.6–5156 (White et al. 1983; DeCesar et al. 2013). We deduce a surface magnetic field of \( \sim 1.1 \times 10^{25}(1+z) \) G, assuming that the line is the fundamental line. Here \( z \) is the gravitational redshift, defined by

\[
(1+z)^{-1} = \sqrt{1 - \frac{2GM}{Rc^2 z}}.
\]

(3)

For typical neutron star parameters, \( z \approx 0.3 \) if the line-forming region is close to the surface. This magnetic field strength puts KS 1947+300 at the lower end of known cyclotron lines sources (cf. Caballero et al. 2007).

During the broad minimum phase of the pulse profile, we detect the CRSF in all three observations. The luminosity near 10^{38} erg s^{-1} puts KS 1947+300 clearly in the super-critical accretion regime, where the radiation pressure is strong enough to decelerate the in-falling matter before the neutron star surface via a radiation-dominated shock (Becker et al. 2012). In this regime, a negative correlation between the CRSF energy and luminosity is expected (Becker et al. 2012), as observed, for example, in V 0332+53 (Tsygankov et al. 2010). If the correlation were of a similar strength as observed in V 0332+53 we would not have detected it due to the very small range of luminosities sampled.

The time-resolved Swift/XRT spectra show a strongly variable photon index \( \Gamma \) over the outburst, with changes of 10% or more within three days and softening with increasing X-ray flux. This softening agrees with the expected behavior in the super-critical accretion regime, as shown by Klochkov et al. (2011) for various other sources. However, because we restricted the model to describe basically all changes in spectral hardness in the photon index, it is probable that the true physical changes are more complex than a variable photon index, e.g., the blackbody temperature might vary independently of the X-ray flux. Nonetheless, intrinsic source variability must be present.

We clearly detect a FeKα line in all data sets, with an energy significantly above the line energy for neutral iron (see Table 2) and broadened in excess of the energy resolution of NuSTAR. While Doppler-broadening could be responsible for part of the observed width, the increased energy indicates that the fluorescence region is slightly ionized and the observed broadening originates from a blend of FeKα at different low ionization states. The data do not allow us to disentangle different lines from one single broad line.

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Facilities: NuSTAR, Swift

REFERENCES

Kawagoe, A., Mihara, T., Negoro, H., et al. 2013, A Tel, 5438
Swank, J., & Morgan, E. 2000, IAUC, 7531, 4

