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Citation: [AIP Conf. Proc.](#) **1427**, 48 (2012); doi: 10.1063/1.3696149

View online: <http://dx.doi.org/10.1063/1.3696149>

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Suzaku Observations of 4U 1957+11: The Most Rapidly Spinning Black Hole in the Galaxy?

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Abstract. We present three *Suzaku* observations of the black hole candidate 4U 1957+11— a source that exhibits some of the simplest and cleanest examples of soft, disk-dominated spectra. 4U 1957+11 also presents among the highest peak temperatures found from disk-dominated spectra. Such temperatures may be associated with rapid black hole spin. The 4U 1957+11 spectra also require a very low normalization, which can be explained by a combination of small inner disk radius and a large distance (> 10 kpc) which places 4U 1957+11 well into the Galactic halo. We perform joint fits to the *Suzaku* spectra with relativistic disk models. Assuming a low mass black hole and the nearest distance ($3 M_{\odot}$, 10 kpc), the dimensionless spin parameter $a^* \equiv Jc/GM^2 \gtrsim 0.9$. Higher masses and farther distances yield $a^* \approx 1$. Low spin cannot be recovered unless 4U 1957+11 is a low mass black hole that is at the unusually large distance of $\gtrsim 40$ kpc.

Keywords: accretion, accretion disks – black hole physics – X-rays:binaries

PACS: 04.70.Bw; 97.10.Gz; 97.60.Lf; 97.80.Jp

INTRODUCTION

4U 1957+11 is one of the few black hole candidates (BHC) that historically has been persistently active. It is a Low Mass X-ray Binary [1, 2, 3, 4], and it always has been observed in a spectrally soft state [5]. Its soft spectrum is well-modeled as a simple disk [6, 7, 5, 8], i.e., a multi-temperature blackbody [9] characterized by a peak temperature and a normalization related to the disk inner radius, inclination, and object distance.

Optical observations suggest that we may be viewing the disk in 4U 1957+11 at a high inclination of $\sim 75^\circ$. Modulation over a 9.33 hr orbital period has ranged from $\pm 10\%$ and sinusoidal [1] to $\pm 30\%$ and complex [2]. The latter has been interpreted as a high inclination warped disk being partly occulted by the secondary. Other authors, however, have attributed the optical modulation to illumination of the secondary and modeled the system inclination with values as low as 20° and not greater than 70° [4].

Thus the mass, distance, and inclination of 4U 1957+11 currently are unknown. Based upon a comparison of the optical flux to the estimated optical luminosities of other BHC, it has been argued that 4U 1957+11 must lie at a distance > 20 kpc [3]. Based upon high resolution X-ray spectroscopic observations of Ne IX 13.45 Å absorption associated with the warm/hot phase of the interstellar medium, 4U 1957+11 resides *above* the galactic plane and at a minimum distance of > 5 kpc [10, 5].

TABLE 1. Log of 4U 1957+11 Observations

Date (yyyy-mm-dd)	Date (MJD)	ObsID	Exposure (ksec)
2010-05-04	55320.82	405057010	35.80
2010-05-17	55333.80	405057020	37.20
2010-11-01	55502.19	405057030	15.50

The persistent, soft spectra of 4U 1957+11 are perhaps the simplest and cleanest examples of “disk spectra”. *XMM-Newton* and *Chandra* observations show that there is very little absorption ($N_{\text{H}} = 1\text{--}2 \times 10^{21} \text{ cm}^{-2}$), while *RXTE* observations show that a hard tail contributes usually $< 20\%$ of the flux. Thus the soft spectrum of 4U 1957+11 becomes the ideal testbed for modern disk atmosphere models that incorporate spin and other General Relativistic effects into their calculations [e.g., 11, 12, 13, 14].

We have shown [5] that disk fits to the *XMM-Newton*, *Chandra*, and *RXTE* spectra of 4U 1957+11 are characterized by a very low normalization — indicating some combination of large distance and low compact object mass — and very high inner disk temperature (1.3–1.8 keV). High disk temperature and low normalization have been associated with high black hole spin. We tested this possibility using the relativistic disk model, `kerrbb` Li et al. [11], which has model parameters that include compact object mass and distance, disk inclination, accretion rate, spectral hardening factor (ratio of color temperature to effective temperature), and dimensionless spin of the black hole, $a^* \equiv Jc/GM^2$. For a wide variety of masses and distances, fits to *XMM-Newton* and *Chandra* spectra preferred maximal spin, $a^* \approx 1$. We have further explored these results with three recent *Suzaku* observations, as we have described in a recent work [15].

OBSERVATIONS AND DATA ANALYSIS

A log of the *Suzaku* observations are presented in Table 1. The *Suzaku* data were reduced with tools from the HEASOFT v6.9 package and the calibration files current as of 2010 September. We corrected the attitude of the individual observations, and excluded $\approx 1/3$ of the counts in the center of the image to minimize pileup of the spectra [15]. Although spectra for each observation and each XIS chip were kept separate, *all* spectra were jointly grouped on a common grid such that the XIS 0 spectra for the faintest and shortest integration time observation had a minimum combined signal-to-noise ratio of 5 in each energy bin and that the minimum number of channels per energy bin was at least the half width half maximum of the spectral resolution.

In Fig. 1 we present the flux corrected spectra, i.e., the counts spectra divided by the integrated response. This figure also shows the ratio of the spectra to one another. These ratios are exactly what one would expect for a thermal disk spectrum varying solely due to temperature/accretion rate changes — flat but shifted over the Rayleigh-Jeans portion of the spectrum, and upward sloping on the Wien tail. As such, we perform a series of joint spectral fits to all three *Suzaku* spectra using the `kerrbb` relativistic disk model wherein we tie all the parameters together save the disk accretion rate. We assume a

FIGURE 1. Left: The combined XIS 0, 1, and 3 spectra from each of the three *Suzaku* observations of 4U 1957+11, flux corrected with the detector responses. (ObsID 405057010 is the top spectrum, obsID 405057020 is the middle spectrum, and obsID 405057030 is the bottom spectrum.) Lighter colored data points represent energy bands that were ignored in the spectral fits. Right: Ratios of the flux corrected spectra shown on the left. The top ratio is observation 1/observation 3, the middle line is observation 1/observation 2, and the bottom line is observation 2/observation 3.

disk inclination of $i = 75^\circ$, the theoretically preferred color-correction value of $f_c = 1.7$ [12, 13] for the disk spectrum, and choose two sets of parameters: $3M_\odot$ and 10 kpc, and $16M_\odot$ and 22 kpc. The resulting fits are good, with the $3M_\odot$, 10 kpc model yielding $a^* = 0.897 \pm 0.001$ and $\chi^2_\nu/\nu = 2063/1014$, and the $16M_\odot$, 22 kpc model yielding $a^* = 0.999$ and $\chi^2_\nu/\nu = 1830/1014$. The latter fit is shown in Fig. 2.

We have chosen the two sets of masses and distances above because we have shown that, for a reasonable set of assumptions, that there is a scaling relation for mass, $M \propto f_c^4$, and distance, $D \propto f_c^2$, as a function of color correction factor, f_c [15]. Allowing the color-correction factor f_c to be a free-parameter, the best fit value is $f_c \approx 1.1$ for the $3M_\odot$, 10 kpc assumptions. This suggested $16M_\odot$, 22 kpc as the mass and distance that would yield $f_c \approx 1.7$. In Fig. 3, we show the best fit spin for these two mass/distance assumptions as a function of color-correction factor. We see from these fits that unless the color-correction factor is *very* large, the fitted spin of the hole is large. The two sets of solutions with the lowest χ^2 either have $f_c \lesssim 2$ and $a^* \approx 1$, or $f_c \gtrsim 3$. Even then, low spin solutions are only found for the lower mass assumption.

CONCLUSIONS

There are four salient features of these *Suzaku* observations of 4U 1957+11. The peak disk temperatures are high, the disk normalizations (or equivalently, emitting areas or inner disk radii) are small, all observations can be fit with the same inner disk radius, and the spectra are remarkably simple. The best fits assuming a small mass and distance ($3M_\odot$, 10 kpc) require a black hole spin $a^* \gtrsim 0.9$. The required spin increases if we instead assume $16M_\odot$ and 22 kpc. Altering the assumed disk inclination does not change this situation. Higher disk inclinations are ruled out by the lack of system eclipses. Lower disk inclinations allow for more observed gravitational redshifting, and less relativistic beaming, and thus require high spin with even larger color correction factors [15].

FIGURE 2. Left: Joint fit of a *kerrbb* model to the three spectra, assuming a black hole mass and distance of $16M_{\odot}$ and 22 kpc. The spectra share a common black hole mass and spin, disk inclination, and a fixed color correction factor of $f_c = 1.7$, but have independent disk accretion rates. (Lightly shaded data were not included in the fit.) The residuals panels show the ratio residuals for each individual observation. Right: Fitted black hole spin vs. spectral hardening factor for the observations on the left. The bottom panel shows the reduced χ^2 value of the fits. The blue (thicker) lines represent models with the mass and distance fixed to $16M_{\odot}$ and 22 kpc, respectively, and orange lines represent models with the mass and distance fixed to $3M_{\odot}$ and 10 kpc, respectively.

ACKNOWLEDGMENTS

Michael Nowak was supported by NASA Grants NNX10AR94G and SV3-73016. Jörn Wilms was partly supported by the European Commission under contract ITN 215212 “Black Hole Universe” and by the Bundesministerium für Wirtschaft und Technologie through Deutsches Zentrum für Luft- und Raumfahrt grants 50OR0701 and 50OR1005.

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