The black hole spin in GRS 1915+105, revisited

Brianna S. Mills,1 Shane W. Davis,1 and Matthew J. Middleton2

1Department of Astronomy, University of Virginia, 530 McCormick Road Charlottesville, VA 22904, USA
2Department of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, UK

Abstract

We estimate the black hole spin parameter in GRS 1915+105 using the continuum-fitting method with revised mass and inclination constraints based on the very long baseline interferometric parallax measurement of the distance to this source. We fit Rossi X-ray Timing Explorer observations selected to be accretion disk-dominated spectral states as described in McClintock et al. (2006) and Middleton et al. (2006), which previously gave discrepant spin estimates with this method. We find that, using the new system parameters, the spin in both datasets increased, providing a best-fit spin of $a^* = 0.86$ for the Middleton et al. data and a poor fit for the McClintock et al. dataset, which becomes pegged at the BHSPEC model limit of $a^* = 0.99$. We explore the impact of the uncertainties in the system parameters, showing that the best-fit spin ranges from $a^* = 0.4$ to 0.99 for the Middleton et al. dataset and allows reasonable fits to the McClintock et al. dataset with near maximal spin for system distances greater than $\sim 10$ kpc. We discuss the uncertainties and implications of these estimates.

1. INTRODUCTION

A soft, apparently thermal emission component is frequently observed in the spectra of black hole candidate X-ray binaries (hereafter BHXRBs) along with a second, harder X-ray component. The soft component is widely believed to be emission from an optically-thick, geometrically thin accretion disk (Shakura & Sunyaev 1973), while the hard component is thought to be Comptonized emission from hot electrons near the disk (the corona). Most BHXRBs display variability between spectral states where the relative strengths of these components vary, with the high/soft state referring to cases where the disk component dominates (Remillard & McClintock 2006; Done et al. 2007).

When BHXRBs enter strongly disk-dominated high/soft states, one might expect the emission to be well-represented by a bare accretion disk model, which accounts for the relativistic effects on photon emission and the possible change in flow properties at or near the black hole’s innermost stable circular orbit (ISCO). This has motivated a number of relativistic accretion disk spectral models (Hanawa 1989; Gierliński et al. 1999; Li et al. 2005; Davis & Hubeny 2006), which have had success in fitting the spectrum and its variation with accretion rate in the high/soft state of many BHXRBs (Gierliński & Done 2004; Davis et al. 2005; Shafee et al. 2006; McClintock et al. 2011). Placing constraints on the black hole angular momentum, or spin, is a key motivation of many such studies (for a review, see Middleton 2016). The spectrum of the disk is sensitive to the spin through location of the ISCO as well as the relativistic effects on the photon propagation through the black hole spacetime. This technique of spin measurement is generally referred to as the continuum-fitting method (Zhang et al. 1997; McClintock et al. 2011), which distinguishes it from other spectral-fitting spin measurements such as those that fit the reflected emission features, including the prominent Fe Kα line (Fabian et al. 1989).

The continuum-fitting method has previously been applied to the BHXRB GRS 1915+105, yielding inconsistent estimates for the black hole spin (McClintock et al. 2006; Middleton et al. 2006). Although these studies used similar spectral models and fitting methods, Middleton et al. (2006) (hereafter MID06) found a more moderate spin parameter ($a^* \sim 0.7$) while McClintock et al. (2006) (hereafter MCC06) favored high spin ($a^* \gtrsim 0.98$), where we define the dimensionless spin parameter $a_*= Jc/(GM^2)$ and $J$ is the angular momentum of the black hole. This discrepancy in spin can be primarily attributed to differences in the selection of spectra used in their analyses. These differences arise from the difficulties in unambiguously identifying a disk-dominated state in this source, which is famous for its complex variability, with a diversity not generally seen...

bri@virginia.edu
in other low mass X-ray binaries (Belloni et al. 2000) except for the black hole source IGR J17091-3624 (Altamirano et al. 2011).

Both studies focused on analysis of spectral observations using data taken by the PCA detector on board the Rossi X-Ray Timing Explorer (hereafter RXTE). MCC06 identified a selection of apparently disk-dominated spectra in the 3-25 keV range based on a number of screening criteria, including RMS variability and hardness ratio, ultimately arriving at 20 candidates. MID06 argued against identifying the MCC06 sample as disk-dominated, instead arguing these observations are more like very high/steep power law states (Remillard & McClintock 2006; Done et al. 2007), in which a low temperature Comptonization component is present (Zdziarski et al. 2005, MID06). Instead, MID06 generated large libraries of spectra determined to be disk-dominated. We briefly summarize the key differences in the two data selections, but refer the reader to the respective papers for further details.

MID06 generated a large library of spectra in the 3-20 keV range. They then selected out intervals of 16 seconds in which the disk contribution was more than 5% of the total bolometric luminosity. The 16 second exposures were set by the shortest timing resolution of RXTE and were chosen to avoid the variability seen in the longer exposures. However, MID06 note that the variability of GRS 1915+105 can be seen on timescales shorter than 16 seconds and thus require that the 16 second intervals have a rms variability less than 5%. Ultimately, 34 disk-dominated spectra across 6 RXTE observations in 16 second intervals were identified. These observations are within the β and κ variability classes of Belloni et al. (2000), in which the transition between spectral states is slow. Three of the 34 spectra were chosen by MID06 for their continuum-fitting analysis, which we also adopt in this paper: RXTE observation IDs 20402-01-45-03, 10408-01-10-00, and 10408-01-38-00, hereafter referred to as MID06a, MID06b, and MID06c, respectively. The following start and stop times for each observation’s 16 second interval used in our data reduction are: MID06a (116417059 - 116417075), MID06b (75756947 - 75756963), and MID06c (87295987 - 87296003) (see MID06 their Figure 2). These start and stop times are in RXTE mission elapsed time (seconds). In their analysis, MID06 did not include the conventional 1% systematic error that is often added while performing spectral fitting to account for residuals that can be as large as 1% in the power law fits to the Crab Nebula. Since these observations are very short, the systematics are not expected to domi-

2. DATA SELECTION AND REDUCTION

The spectral states of GRS 1915+105 are known to vary quite rapidly on timescales of seconds to days, making it difficult to obtain disk-dominated spectra for continuum-fitting analyses (Greiner et al. 1996). MID06 and MCC06 sifted through archival RXTE data and generated large libraries of spectra determined to be disk-dominated. We briefly summarize the key differences in the two data selections, but refer the reader to the respective papers for further details.
We conducted a continuum-fitting analysis, where observations as "key low-luminosity" spectra were critical to their identification. MCC06 identified five of the 20 observations used for the MCC06 analysis remained thousands of seconds long. MCC06 generated a large library of observations for the MID06 analysis, the spectra were extracted using FTOOLS (Davis, 2005) and were not expanded to 256 channels. All spectra were corrected for dead-time. A 1% systematic error was added to all spectra using grppha. During the data reduction, a Good Time Interval (GTI) is usually specified to screen out undesirable data from events such as earth occultations, passage through the South Atlantic Anomaly, the target being at the edge of the field of view, etc. For the MID06 observations, we did not use any GTI criteria as these were only 16 second exposures. For the MCC06 observations, the GTI criterion specified was only data from observation. MCC06 identified five of the 20 observations as "key low-luminosity" spectra critical to their continuum-fitting analysis, where $L/L_{\text{Edd}} < 0.3$, and $L_{\text{Edd}}$ is the Eddington luminosity. We note that this inferred luminosity and mass depends on the distance to GRS 1915+105, which given the closer VLBI distance and smaller mass should push the inferred $L/L_{\text{Edd}}$ up. This implies that the MCC06 Eddington ratio criterion was more strict than was required. Contrary to the MCC06 observations, MID06 did not impose an Eddington ratio cut-off for their spectra. From the five, key, low-luminosity MCC06 observations, we chose three for our re-analysis: RXTE ObsIDs 10408-01-20-00, 10408-01-20-01, and 30703-01-13-00, hereafter referred to as MCC06a, MCC06b, and MCC06c, respectively. Note that the spectral energy range of interest for these spectra is 3-25 keV, which is slightly larger than the 3-20 keV range used for the MID06 spectra since the MCC06 observations are much longer and afford more signal-to-noise in the highest energy bins.

We emphasize that neither of the above selection criteria rely on any assumptions about the GRS 1915+105 system parameters. Therefore, we do believe it is necessary to repeat the selection analysis in response to the new VLBI distance constraints. The only exception is that MCC06 chose to focus on a low-luminosity subset of their selected data (with $L/L_{\text{Edd}} < 0.3$) for their discussion and we retain that focus here.

We used data reduction software tools from HEASOFT version 6.26.1. Following the same reduction steps in both MID06 and MCC06, Standard-2 PCA spectra were extracted using FTOOLS saextrct and corrected for background using runpcabackest, where all individual xenon gas layers were included. PCU gain variations were not corrected for and xenon layer spectra were not expanded to 256 channels. All spectra were corrected for dead-time. A 1% systematic error was added to all spectra using grppha. During the data reduction, a Good Time Interval (GTI) is usually specified to screen out undesirable data from events such as earth occultations, passage through the South Atlantic Anomaly, the target being at the edge of the field of view, etc. For the MID06 observations, we did not use any GTI criteria as these were only 16 second exposures. For the MCC06 observations, the GTI criterion specified was only data intervals in which all five PCUs were active during the observation.

3. SPECTRAL FITTING

The primary focus of the continuum-fitting method is to apply relativistic accretion disk models such as kerrbb (Li et al. 2005) and bhspec (Davis et al. 2005; Davis & Hubeny 2006) to disk-dominated X-ray spectra and fit for the spin of the black hole. These models can fit for all parameters but degeneracies in how the model parameters affect the spectrum mean that prior knowledge of the distance to the source, $D$, the mass of the black hole, $M$, and the inclination of the accretion disk, $i$, are required for robust constraints. The most recent constraints on these values for the GRS 1915+105 system come from R14: $D = 8.6$ kpc, $M = 12.4 M_{\odot}$, and $i = 60^\circ$, hereafter referred to as the R14 preferred values. We utilize XSPEC (Arnaud 1996) for all of our spectral fitting, and the models used in this paper are collected in Table 1 with their corresponding XSPEC notations.

| Model Name     | XSPEC Notation                      |
|----------------|-------------------------------------|
| diskbb+nthcomp | varabs'*smedge(diskbb+nthcomp+gaussian) |
| diskbb+powerlaw | phabs'*smedge(diskbb+powerlaw+gaussian) |
| mid:bhspec+simp | varabs'*simp(bhspec) |
| mid:bhspec+nthcomp | varabs'*smedge(bhspec+nthcomp+gaussian) |
| mcc:bhspec+simp | phabs'*edge'smedge'simpl(bhspec+gaussian) |
| mcc:bhspec+comptt | phabs'*edge'smedge(bhspec+comptt+gaussian) |
| mcc:kerrbb+simp | phabs'*edge'smedge'simpl(kerrbb+gaussian) |

Table 1. List of models used in this paper and their full corresponding XSPEC notation. The prefix “mid” refers to models used to fit the selected MID06 observations following the same parameter and abundance prescriptions in MID06, and the prefix “mcc” is similarly used for the selected MCC06 observations for their parameter and abundance prescriptions (see Section 3.1).
3.1. Non-relativistic accretion disk model

We first confirmed that our data are consistent with those reported in MCC06 and MID06 by comparing our fits with the non-relativistic accretion disk model, diskbb (Mitsuda et al. 1984), with corresponding fits in the two papers. Following the same fit procedure as MID06, we fit MID06a, MID06b, and MID06c together with the model diskbb+nthcomp (see Table 1). This model includes the variable abundance photoelectric absorption model varabs, the diskbb model, the thermal Comptonization model nthcomp (Zdziarski et al. 1996; Życki et al. 1999), the smeared edge component smedge (Ebisawa 1991), and Gaussian line component gaussian. MID06 used abundances from Anders & Ebihara (1982), fixing all column densities in varabs to $4.7 \times 10^{22}$ cm$^{-2}$, except for Si and Fe which were fixed to $16.4 \times 10^{22}$ cm$^{-2}$ and $10.9 \times 10^{22}$ cm$^{-2}$, respectively (Lee et al. 2002). The smeared edge energy was fixed to lie between 6.9 – 9.0 keV, following MCC06 (as MID06 did not specify any restriction for this parameter), and width fixed at 7.0 keV Shafee et al. (2006). The gaussian line energy was fixed to lie between 6 – 7 keV, and the width was fixed at 0.5 keV. We obtained a fit with $\chi^2$ per degree of freedom = 109.66/113 for all three observations tied together, with diskbb seed photon temperatures of $1.38^{+0.06}_{-0.06}$ keV, $1.68^{+0.06}_{-0.11}$ keV, and $1.93^{+0.14}_{-0.17}$ keV for MID06a, MID06b, and MID06c, respectively, which are within 10% of the values reported for the same model fit in MID06.

We also fit the MID06 observations with simpl (Steiner et al. 2009) in place of nthcomp. The simpl model relies on an approximate treatment of inverse Compton scattering, but it assumes the observed soft model component (in this case diskbb) provides the seed photon distribution that is Comptonized to give the hard X-ray emission. With simpl, the additional smedge and gaussian components that are necessary for fitting with nthcomp no longer significantly improve the diskbb+simpl fits. Our best fit $\chi^2_v = 173.86/113$, is notably worse with simpl than nthcomp.

Following the fit procedure in MCC06, the observations MCC06a, MCC06b, and MCC06c were all fit separately using the model diskbb+powerlaw. While MID06 used varabs for the absorption component, MCC06 used the photoelectric absorption model phabs with relative abundances from Anders & Grevesse (1989) and a lower fixed column density of $4.0 \times 10^{22}$ cm$^{-2}$ (see Section 4.2 for a discussion on the impact that chosen absorption models and column densities have on our analysis). The smeared edge energy was again fixed to lie between 6.9 – 9.0 keV and the width fixed at 7.0 keV. The Gaussian energy was fixed to lie between 6.3 – 7.5 keV and the normalization was allowed to go to negative values to allow for absorption, following MCC06. The diskbb temperatures and best-fit $\chi^2$ per degree of freedom we obtained for each observation are $2.05^{+0.03}_{-0.03}$ keV with $\chi^2_v = 48.84/44$ for MCC06a, $2.06^{+0.03}_{-0.03}$ keV with $\chi^2_v = 45.76/44$ for MCC06b, and $2.11^{+0.02}_{-0.02}$ keV with $\chi^2_v = 58.08/44$ for MCC06c. Note that the 44 degrees of freedom reflect that each observation was fit independently of the others, in order to compare with the results from MCC06. We find that the results are consistent with the fits reported in MCC06.

3.2. Relativistic accretion disk models

We fit both the MCC06 and MID06 datasets using the relativistic accretion disk model bhspec (Davis & Hubeny 2006) for $\alpha = 0.01$. In their analysis, MID06 used the model mid:bhspec+nthcomp with the same varabs prescription and parameter ranges discussed previously in Section 3.1. Instead, we chose to fit MID06a, MID06b, and MID06c simultaneously with the model mid:bhspec+simpl. This model differs from the model MID06 used in that we chose to use simpl (Steiner et al. 2009) to fit the hard X-ray emission rather than nthcomp. We performed fits with bhspec and nthcomp, but only report the simpl results here since we believe that tying the seed photon distribution to the soft model component is more self-consistent with a physically motivated accretion disk model. Furthermore, when used with bhspec, we do not consistently find best-fit results that are disk-dominated since nthcomp can account for a fraction of the softer emission when the temperature of the Comptonizing gas $T_c$ is only slightly larger than seed photon temperature. simpl only has two free parameters (photon power-law index and photon scattered fraction) and we also drop the additional smedge and gaussian components, which do not significantly improve the fit when simpl is used. We constrained the simpl photon index to $\Gamma > 2$. If $\Gamma < 2$ is allowed, fits with high simpl scattering fractions are favored for observation MID06c, resulting in almost all of the Comptonized emission being present outside the limit of our data $E > 20$ keV. Hence, instead of fitting a power law in the hardest observed X-ray channels, simpl simply depresses the bhspec model flux fitting the softer photons, effectively renormalizing it. Fixing the values for the mass, distance, and inclination in bhspec to the values MID06 assumed ($M = 14 M_\odot$, $D = 12.5$ kpc, and $i = 66^\circ$), we find that MID06c became pegged at the luminosity limit of bhspec ($L/L_{\text{Edd}} = 1.77$), causing the spin to unrealistically drop to 0. Fixing the mass, distance, and inclination to the new R14 preferred values, we obtained a
reasonable fit with $\chi^2 = 136.3/125$ and a moderately high spin of $a_* = 0.863^{+0.014}_{-0.015}$. The best-fit parameters are reported in Table 3.2, and the three spectra fit simultaneously with the model mid:bhspec+simp1 assuming the R14 preferred values are shown in Figure 3.2.

When we fit only observation MID06a, the closest in luminosity to the MCC06 observations, the best-fit preferred a high simp1 scattering fraction and a significantly lower spin. We found that when separately fitting MID06a, MID06b, and MID06c assuming the R14 preferred values and the model mid:bhspec+simp1, the two lower luminosity datasets (MID06a and MID06b) preferred higher scattering fractions with lower spins, whereas the higher luminosity dataset (MID06c) preferred a lower scattering fraction with a slightly higher spin compared to the best-fit values when all three datasets were tied together. This preference for high scattering fraction in the lower luminosity observations is partially attributable to simp1 depressing the flux of the bhspec model at soft X-ray energies, an effect that is absent when additive models like nthcomp or comptt are fit for the harder X-ray component.

In their analysis, MCC06 used a variation of bhspec and kerrbb which they call kerrbb2 to fit the soft X-ray continuum. This hybrid model includes the returning radiation and limb darkening capabilities from kerrbb while constraining the color correction factor, or spectral hardening factor, $f_{\text{col}}$ using look-up tables generated from bhspec. They also used the Comptonization model comptt (Titarchuk 1994) to fit the hard X-ray spectral component. To stay consistent in our re-analysis of the two papers, we chose to use simp1 for the MCC06 data as we did for the MID06 data. We first fit MCC06a, MCC06b, and MCC06c tied together using only phabs, bhspec, and simp1, fixing the mass, distance, and inclination to the values previously assumed by MCC06 ($M = 14 M_\odot$, $D = 11$ kpc, and $i = 66^\circ$). We were unable to obtain a reasonable fit, with $\chi^2 = 4090.6/150$. We then added the smedge and gaussian components, along with an addition absorption edge component, edge, which MCC06 used to improve their fit results. Here we adopt the same edge prescription, fixing the energy to lie between 8.0—13.0 keV. We also kept the same abundance and parameter constraints as outlined in Section 3.1, and label this model mcc:bhspec+simp1. Adding these components significantly improved the fit results with $\chi^2 = 139.4/132$ and provided a similar spin ($a_* \sim 0.977$) when compared to the spin reported by MCC06 ($a_* \gtrsim 0.98$). Keeping these model components in our fit, we then fixed the mass, distance, and inclination to the R14 preferred values, but were unable to get a good fit with $\chi^2 = 835.5/132$ and the $a_*$ became pegged at the maximum spin allowed by bhspec ($a_* = 0.99$). Note that the 132 degrees of freedom reflects all three observations fit simultaneously with the spin parameter tied across all observations.

In contrast to bhspec, the relativistic accretion disk model kerrbb allows the color correction factor $f_{\text{col}}$ to vary as a free parameter. However, fitting for $a_*$ while allowing $f_{\text{col}}$ to be free did not give reliable spin estimates, as the two parameters share a strong degeneracy (Salvesen & Miller 2020). We discuss fitting kerrbb to the selected MCC06 observations fixing $f_{\text{col}}$ at different values in the next section.

3.3. Color correction factor

We fit MCC06a, MCC06b, and MCC06c tied together and fit with the model mcc:kerrbb+simp1. The same parameter restrictions for the edge, smedge, and gaussian components discussed in Section 3.2 were again used in this model. For the kerrbb parameters, we assumed zero torque at the inner boundary, limb-darkening, and self-irradiation. The mass, distance, and inclination were fixed at the R14 preferred values.
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| Model Component | Parameter | MID06a         | MID06b         | MID06c         |
|-----------------|-----------|----------------|----------------|----------------|
| simpl           | $\Gamma$  | $3.59_{-0.33}^{+0.34}$ | $4.15_{-0.44}^{+0.47}$ | $5.00^1$       |
|                 | $f_{\text{sc}}$ | $0.22_{-0.07}^{+0.05}$ | $0.33_{-0.10}^{+0.12}$ | $0.24_{-0.01}^{+0.06}$ |
| bhspec          | $L/L_{\text{Edd}}$ | $0.30_{-0.01}^{+0.01}$ | $0.47_{-0.01}^{+0.01}$ | $0.87_{-0.01}^{+0.01}$ |
|                 | $a_*$     | $0.863_{-0.015}^{+0.014}$ | (tied) | (tied) |
|                 | $\chi^2$  | $136.3/125$ | |

$^a$Parameter was completely unconstrained.

Table 2. Best-fit values for the three MID06 observations, MID06a, MID06b, and MID06c tied together and fit with the model mid:bhspec+simpl (see Table 1). From top to bottom, the parameter values are the simpl model photon index, fraction of scattered photons, the bhspec luminosity, dimensionless spin parameter, and the reported $\chi^2$ per degree of freedom for the entire fit. The mass, distance, and inclination were fixed at the R14 preferred values (12.4 $M_\odot$, 8.6 kpc, and 60°).

We then fixed $f_{\text{col}}$ at different values ranging between 1.4 – 3.1 and show each resulting best-fit $a_*$ and $\chi^2_d$ (126 degrees of freedom) plotted as black dots in Figure 2. Over-plotted in the figure are two estimates of $f_{\text{col}}$ obtained by fitting kerrbb to bhspec: one for fixed $L/L_{\text{Edd}} = 0.1$ (shown as blue diamonds), and one for fixed $L/L_{\text{Edd}} = 1$ (shown as red X’s). We obtain the $f_{\text{col}}$ estimates by running the XSPEC fakeit command to generate artificial datasets with a phabs*bhspec model, the response from the MCC06b observation, and assuming an exposure of $10^4$ seconds. We then fit these datasets with phabs*kerrbb, fixing $a_*$, $M$, $D$, $i$, $n_\text{H}$ and the accretion rate to match the values assumed in the faked spectrum, but allowing $f_{\text{col}}$ to be a free parameter.

A reasonable fit can be obtained for color correction factors $f_{\text{col}} \gtrsim 1.7$ if $a_* = 0.999$. Lower spins only provide acceptable fits with higher values of $f_{\text{col}}$, but sufficiently high values of $f_{\text{col}}$ only occur for $L/L_{\text{Edd}}$ greater than inferred for the MCC06 data. A representative best-fit to the three spectra by arbitrarily fixing $f_{\text{col}} = 2.0$ is shown in Figure 3 where the best-fit spin is $a_* = 0.995_{-0.003}^{+0.002}$ and $\chi^2_d = 77.6/126$.

3.4. Exploring System Uncertainties

The uncertainty on the best-fit spin depends directly on the uncertainties in the distance, mass, and inclination. We explored this uncertainty in parameter space by fixing the mass, distance, and inclination at a range of different values above and below the R14 preferred values. A distance was randomly sampled from a Gaussian distribution centered on 8.6 kpc, with a 2.0 kpc width chosen to approximately match their uncertainty. From R14, the dependence of the inclination on a given distance is constrained from VLBI proper motion constraints, assuming ballistic trajectories for the plasma emitting in the jet. This gives

$$\tan i = \left(\frac{2D}{c}\right) \frac{\mu_a \mu_r}{\mu_a - \mu_r}, \quad (1)$$

Figure 2. Plot showing the range of color correction factor values $f_{\text{col}}$ for the three chosen MCC06 observations MCC06a, MCC06b, MCC06c tied together and fit with the mcc:kerrbb+simpl model, shown as black dots. The corresponding best-fit dimensionless spin parameter $a_*$ is shown in the top panel, and $\chi^2_d$ (126 degrees of freedom) is shown in the bottom panel. These fits were calculated assuming a mass, distance, and inclination fixed at the R14 preferred values ($M = 12.4 \ M_\odot$, $D = 8.6 \text{ kpc}$, and $i = 60^\circ$). Estimates for $f_{\text{col}}$, found by fitting kerrbb to bhspec are overplotted for a fixed $L/L_{\text{Edd}} = 0.1$ (blue diamonds) and a fixed $L/L_{\text{Edd}} = 1$ (red X’s). The horizontal line in the bottom panel shows $\chi^2_d = 1$ for reference.
Figure 3. The top panel shows the three MCC06 RXTE observations MCC06a, MCC06b, MCC06c tied together and fit with the model `mcc:kerrbb+simpl`. The mass, distance, and inclination were fixed at the R14 preferred values for GRS 1915+105 ($M = 12.4 \ M_\odot$, $D = 8.6 \text{ kpc}$, and $i = 60^\circ$). The `kerrbb` color correction factor, or spectral hardening factor, was arbitrarily fixed at $f_{\text{col}} = 2.0$. The dashed lines show the contribution of the disk emission for each spectral fit by setting the `simpl` scattering fraction to zero. The bottom panel shows the fit residuals for each spectrum.

where $i$ is the inclination of the accretion disk with respect to the line of sight ($i = 0$ is a face-on disk), $D$ is the distance to the black hole, $\mu_a$ is the apparent speed of the approaching radio jet, and $\mu_r$ is the apparent speed of the receding radio jet. The values for $\mu_a$ and $\mu_r$ were also sampled from Gaussian distributions centered on their reported values of $23.6 \pm 0.5 \text{ milliarcseconds/yr}$ and $10.0 \pm 0.5 \text{ milliarcseconds/yr}$, respectively (R14). The mass of the black hole is then determined by using the inclination from equation (1) in the following expression:

$$M = \frac{\mathcal{M}}{\sin^3 i},$$

where $M$ is the black hole mass, and $\mathcal{M}$ is a constant adopted from the values for the mass function and binary mass ratio in Steeghs et al. (2013). For each fit, the randomly selected distance and subsequent inclination and mass were held fixed while the three MID06 observations were simultaneously fit with the model `mid:bhspec+simpl`. The results from each fit are plotted in Figure 3.4 which shows the spread in parameter space for mass, distance, and inclination, as well as a histogram of all best-fit $a_\ast$ obtained. The blue dots are fits which are within 99% confidence, $\chi^2_0 \leq 164.7/125$, and the red dots are fits with $\chi^2_0 > 164.7/125$ which highlight regions where fits either became pegged at the maximum spin or the maximum luminosity limit of `bhspec`. The pile-up of fits at high spin have pegged at the maximum spin limit of `bhspec` ($a_\ast = 0.99$), and fits below $a_\ast \sim 0.5$ signify observation MID06c has pegged at the luminosity limit of `bhspec` ($L/L_{\text{Edd}} = 1.77$). The R14 preferred values are marked as black X’s at our best-fit spin, $a_\ast = 0.86$, for the MID06 observations. The previously assumed values for the mass, distance, and inclination from MID06 are marked as green X’s at the best-fit spin reported in MID06, $a_\ast \sim 0.72$. The bottom x-axis is the logarithm of $(1 - a_\ast)$ to better show the portion of moderate to maximal spins, while the top x-axis is just $a_\ast$. Calculating a 1-sigma confidence interval on either side of our best-fit spin for only the acceptable fits (in blue) gives a spread of $a_\ast \sim 0.60 - 0.97$.

The same random sampling continuum-fitting analysis was done for the three MCC06 observations, the results of which are shown in Figure 3.4. This plot shows the range of distances, masses, and inclinations which produce fits to this dataset within 99% confidence ($\chi^2_0 < 172.66/132$) using the model `mcc:bhspec+simpl` and the same parameter prescription in Section 3.2. Each dot is one realization for a fixed mass, distance, and inclination. When compared to the MID06 results from Figure 3.4, the MCC06 results show poorer fits for distances below $\sim 10$ kpc, with most of the best-fit spins pegging at the maximum spin limit of `bhspec` ($a_\ast \sim 0.99$). There are also a number of poor fits that prefer more moderate spins ($a_\ast \gtrsim 0.90$), but the `simpl` scattering fractions become high in these cases and are no longer consistent with disk-dominated results. Note that the range of the x-axes differ from Figure 3.4 in that the MCC06 fits do not reach spins below $a_\ast \sim 0.9$.

4. DISCUSSION

4.1. Implications for the GRS 1915+105 system

The relative merits of the MCC06 and MID06 data selection were debated in those papers and are summarized in Section 1. We will not discuss this at further length here but we note that one of the objections to the MID06 datasets is that their larger Eddington ratios imply thicker accretion disks, potentially invalidating the assumptions of the thin disk model underlying the `bhspec` model. With the revised system parameters, the implied Eddington ratios are now slightly lower, with the lowest Eddington observation being in a range where the disk model remains relatively thin. More generally, the relatively high Eddington ratio of GRS 1915+105...
Figure 4. Range of parameter space for the mass, distance, inclination, and resulting best-fit spin, $a_*$, for fits to the three MID06 observations, MID06a, MID06b, MID06c tied together and fit with the model $\text{mid:bhspec+simpl}$ (see Section 3.2). These fits account for the parameter dependence of inclination and mass on the distance to GRS 1915+105 via equations (1) and (2) (R14). Each distance was randomly sampled from a Gaussian distribution centered on the R14 preferred value $D = 8.6$ kpc. The blue dots indicate fits with $\chi^2 / \nu \leq 164.7 / 125$ which are within 99% confidence. The red dots in each panel indicate fits with $\chi^2 / \nu > 164.7 / 125$ which are outside the 99% confidence. The pile-up of red dots at high spins is due to fits which have pegged at the maximum spin limit of $\text{bhspec}$ ($a_* = 0.99$). The red fits at lower spins $a_* \lesssim 0.5$ indicate fits in which observation MID06c has pegged at the luminosity limit of $\text{bhspec}$ ($L / L_{\text{Edd}} = 1.77$, where $L_{\text{Edd}}$ is the Eddington luminosity). The R14 preferred values ($D = 8.6$ kpc, $M = 12.4 M_\odot$, $i = 60^\circ$) are marked with a black “X” at the best-fit spin for these assumed values, $a_* = 0.863^{+0.014}_{-0.015}$. The best-fit parameter values are listed in Table 3.2 for the R14 preferred values. The distance, mass, and inclination previously assumed by MID06 (12.5 kpc, 14 $M_\odot$, 66°, respectively) are marked with a green “X” for comparison. The bottom right panel shows a histogram of all the resulting best-fit spins obtained for the MID06 observations. Note that the histogram is stacked rather than superimposed, and the area under the histogram integrates to 1.
Figure 5. The same analysis in Figure 3.4 is performed for the three MCC06 observations MCC06a, MCC06b, MCC06c. Note that when comparing this figure to Figure 3.4, the spin axis here is truncated at $a_* = 0.900$ as there were no best-fit, moderate spin values below this for the MCC06 fits. These observations were similarly fit together with spins tied in the model $\text{mcc:bhspec+simpl}$. Each dot represents one realization for a fixed mass, distance, and inclination. All blue fits shown here are within 99% confidence ($\chi^2 < 172.7/132$). All red fits have a $\chi^2 > 172.7/132$ where the $\text{simpl}$ scattering fractions have become high and are no longer consistent with disk-dominated results. A pile-up of spins is shown at $a_* = 0.99$ where fits have pegged at the maximum spin limit of $\text{bhspec}$, similar to Figure 3.4. The lower right panel shows a stacked histogram of all best-fit spins where the sum over all bins equates to 1.
is sometimes hypothesized to account for its relatively unique variability, but our best-fit constraints imply the source is generally sub-Eddington or at most slightly super-Eddington.

Although more moderate spins are allowed by the MID06 datasets, relatively high spin is implied for the R14 best-fit system parameters. Black holes in X-ray binaries are expected to be born with low to moderate spins \( \langle a_\ast \rangle \lesssim 0.7 \), although this is subject to uncertainties in the core-collapse process (Gammie et al. 2004). It is also not clear that they can be significantly spun up by accretion under standard assumptions about mass transfer (King & Kolb 1999). The high spins inferred here would then imply that either black holes are born with higher natal spin than expected or experience phases of high mass transfer to spin them up.

It is perhaps notable that the best-fit values from MID06 are in the ballpark where general relativistic magnetohydrodynamic simulations suggest magnetic torques would balance the spin–up due to accretion (Gammie et al. 2004). This limit \( \langle a_\ast \rangle \lesssim 0.94 \) is more stringent than the commonly cited limit of \( a_\ast = 0.998 \) from Thorne (1974), which only accounts for the angular momentum carried by the radiated photons. The MID06 results are thus consistent with GRS 1915+105 being spun up by accretion and reaching an equilibrium with magnetohydrodynamic torques provided by field lines connected to the black hole, while MCC06 results exceed this nominal limit. Note, however, that the presence of such torques may have an effect on the accretion disk emission (Gammie 1999; Agol & Krolik 2000; Kulkarni et al. 2011; Schnittman et al. 2016) and are not accounted for in the present analysis.

Our results for the MID06 data are inconsistent with those of R14, who report best-fit \( a_\ast \approx 0.98 \). Accounting for systematic uncertainties, they report \( a_\ast > 0.92 \), which is consistent with spin estimates in Figure 3.4. Our results for the MCC06 data are in better agreement in that both analyses favor near maximal spin but differ in that R14 managed to find suitable fits for the revised distance of 8.6 kpc. This may owe in part to R14 reanalyzing a large sample of RXTE observations, selecting all observations that obey a criterion \( L/L_{\text{Edd}} \leq 0.3 \), \( \chi^2 \leq 2 \), and \( f_{\text{sc}} < 0.25 \). It is possible that the MCC06 selected datasets may have been selected out in the process using the revised system parameters. Sreehari et al. (2020) also find a near maximal best-fit spin for kerrbb fits to AstroSat observations of GRS 1915+105. These results are notable in that, like MID06, they are for observations that would nominally place the emission above the Eddington limit. Their analysis differs in allowing the mass to be a free parameter, although their best-fit mass is consistent with the R14 constraints.

In addition to the continuum-fitting method, the spin of GRS 1915+105 has also been estimated by fitting the relativistically broadened reflection spectrum due to irradiation of the accretion disk by a corona (Blum et al. 2009; Miller et al. 2013) or via modeling of quasi-periodic oscillations (QPOs; Török et al. 2011; Srámková et al. 2015). Although a range of results have been reported with both methods, the reflection fitting efforts are both consistent with high spins \( a_\ast \approx 0.98 \) while the QPO model favors somewhat lower spins \( a_\ast \approx 0.7 - 0.9 \). Based on previous results, this puts the reflection fitting results in good agreement with MCC06 and the QPO estimates in better agreement with MID06. For our results, the MCC06 fits are still broadly in agreement with near maximal spin as long as GRS 1915+105 lies at the far end of the distance distribution allowed by VLBI parallax. The MID06 data now provide a larger best-fit spin in better agreement with reflection fitting. More moderate spins are still favored albeit with large uncertainty.

4.2. Impact and Uncertainties in Interstellar Absorption

Typically when fitting the continuum of a BHXB, a model for the photoelectric absorption along the line of sight (e.g. \texttt{phabs}, \texttt{varabs}) is needed. Using the model \texttt{varabs} and abundances from Anders & Ebihara (1982), MID06 assumed a column value of \( n_H = 4.7 \times 10^{22} \text{ cm}^{-2} \) for all elements except Si and Fe which were fixed at \( 16.4 \times 10^{22} \text{ cm}^{-2} \) and \( 10.9 \times 10^{22} \text{ cm}^{-2} \), respectively. These values were reported by Lee et al. (2002) for Chandra X-ray observations of GRS 1915+105 assuming ISM abundances. Relativistic disk reflection studies constraining the spin in GRS 1915+105 report best-fit values which also favor a high absorption column using the \texttt{phabs} model \( (n_H = 4.15 - 5.64 \times 10^{22} \text{ cm}^{-2}, \text{ Blum et al. 2009; n_H = 6.1} \times 10^{22} \text{ cm}^{-2}, \text{ Miller et al. 2013). Lee et al. (2002)} \) also reported a S- and Mg-derived hydrogen column assuming solar abundances, giving a more moderate column value of \( n_H \sim 3.1 \times 10^{22} \text{ cm}^{-2} \). This is in better agreement with other modest column estimates from ASCA X-ray observations \( (n_H = 3.8 \times 10^{22} \text{ cm}^{-2}, \text{ Ebisawa et al. 1994} \) along with millimeter and radio observations \( (n_H = 3.6 \times 10^{22} \text{ cm}^{-2}, \text{ Chapuis & Corbel 2004). Following these modest estimates, MCC06 adopted a value of n_H = 4.0 \times 10^{22} \text{ cm}^{-2} (assuming abundances from Anders & Grevesse 1989)\). Not only did MCC06 and MID06 assume different values for the column, they also chose different...
XSPEC absorption models. MCC06 selected phabs for their analysis, while MID06 chose varabs. We found that when using the same $n_\text{H}$ value and all other variables kept the same, varabs tended toward a lower $a_\ast$ than phabs did. Fits to the MCC06 data with either phabs or varabs tended to fit better with low $n_\text{H}$ values, while fits to the MID06 data tended to fit better with higher $n_\text{H}$ values. An overall trend between both varabs and phabs is that the value for $a_\ast$ decreased as the $n_\text{H}$ column increased for both datasets. To maintain consistency in our re-analysis we kept the same XSPEC absorption models and values for $n_\text{H}$ chosen by each group, but note the sensitivity and dependence of the spin on the assumed $n_\text{H}$ column value as a source of uncertainty in the $a_\ast$ estimate in this work.

Aside from the line-of-sight hydrogen column estimates, kinematic studies near GRS 1915+105 have also located a molecular cloud at a distance of 9.4 ± 0.2 kpc (Chaty et al. 1996; Chapuis & Corbel 2004). The new VLBI constraints may have implications for the history and conception of the GRS 1915+105 system given the distance of 8.6 kpc, which could place it with the observed interstellar structure (R14).

4.3. Uncertainties in Models and System Parameters

The R14 VLBI parallax measurements provide much stronger constraints on the system parameters than were previously available, but our analysis shows that remaining uncertainties still allow for a rather large range of spins. If we treat the models as robust to systematic uncertainties, then our fitting constraints nominally imply strict limits on the system parameters. Figure 3.4 implies that for relatively low distances and inclinations, the implied spin from the MID06 data would be higher than $a_\ast = 0.99$, challenging the theoretical understanding on black hole spin limits. The constraints are even stronger for the MCC06 data, which would limit the distances to $D \gtrsim 10$ kpc, near the outer limits of what is allowed by the R14 constraints. In fact, this result is consistent with predictions made in Figure 18 of MCC06, which predicted GRS 1915+105 lie within an error triangle whose minimum distance was just under ~ 10 kpc.

The model for system parameters implied by equations (1) and (2) is also subject to systematic uncertainties. First, equation (1) assumes the observed superluminal motion can be interpreted as emission from plasma following ballistic trajectories and that these trajectories lie along the spin axis of the black hole. Furthermore, it is conceivable that the plane of the binary is not perpendicular to the black hole spin axis (Fragile et al. 2001; Maccarone 2002), although there are theoretical arguments that such misalignments should typically be modest (Fragos & McClintock 2015). If such misalignment is present, it seems likely that the inner accretion disk would align with the spin axis due to the action of Lense-Thirring precession (Bardeen & Petterson 1975). In this case, our use of the jet to fix the disk inclination would still be reasonable as long as the jet is aligned with the spin axis, although GRMHD simulations of misaligned disks indicate this may not be guaranteed (Liska et al. 2018) and observations of V404 Cygni show the jet angle to precess (Miller-Jones et al. 2019) perhaps due to Lense-Thirring precession associated with the high mass accretion rates inflating the disk (Middleton et al. 2018, 2019). The inclination implied by observations of the jet would then not correspond to the binary inclination in equation (2), and the inferred black hole mass would be incorrect.

An independent constraint on the inclination comes from the reflection spectral modeling, where the relativistic line profiles are sensitive to the viewing inclination. The best-fit inclinations from Blum et al. (2009) are $i = 55^\circ$ or $i = 69^\circ$ depending on the reflection model used. Miller et al. (2013) found inclinations ranging from 65$^\circ$ to 74$^\circ$ depending on the model. Blum et al. (2009) constrained the inclination to lie between 55$^\circ$ and 75$^\circ$, while Miller et al. (2013) constrained it to be between 65$^\circ$ and 80$^\circ$, both based on interpretations of constraints from the superluminal jet model (Fender et al. 1999). The allowed inclination ranges are generally higher than those used in our analysis because these papers predate the R14 measurements. The higher inclinations ($i \gtrsim 70^\circ$) would pose a challenge to the superluminal motion interpretation for the new parallax distance, but if we assume they imply that the inclination should be towards the high end of the allowed range, they would push the MID06 results to low spins that would be at odds with the best-fit spins from these reflection models. The MCC06 results could remain consistent with near maximal spin, but again this requires GRS 1915+105 to be located at the more distant end of the range allowed by VLBI parallax measurements.

We emphasize that these constraints are subject to unquantified systematic uncertainties in the underlying accretion disk model. This could arise from inaccuracies in the underlying thin disk model (Shakura & Sunyaev 1973; Novikov & Thorne 1973) or because of errors in the TLUSTY atmosphere models (Davis & Hubeny 2006). The former is perhaps most worrisome for the highest Eddington ratio observations from MID06, where the thin disk assumption would begin to break down. It is also possible that some aspect of the model is inaccurate, such as the stress prescription.
for fits to
with a finite disk thickness led to a modestly higher spin down. Zhou et al. (2020) found that considering a model accretion rates where the thin disk assumption breaks also assume a razor thin disk even though they can be at spin, but not necessarily maximal spin. These models might still be indicative of high maximal best-fit spins might still be a higher spins when using standard models (Kulkarni et al. 2011; Schnittman et al. 2016). In that case, the near maximal best-fit spins might still be indicative of high spin, but not necessarily maximal spin. These models also assume a razor thin disk even though they can be at accretion rates where the thin disk assumption breaks down. Zhou et al. (2020) found that considering a model with a finite disk thickness led to a modestly higher spin for fits to RXTE observations of GRS 1915+105, but their thin disk fits were already near maximal.

The spectra derived from atmosphere modelling with TLUSTY are another potential source of error. Errors in the atmosphere models and spectra could arise from inaccurate assumptions about the vertical distribution of dissipation, contributions from magnetic pressure support, inhomogeneities in the turbulent disk, and lack of irradiation of the surface (Davis et al. 2005; Blaes et al. 2006; Davis et al. 2009; Tao & Blaes 2013; Narayan et al. 2016). Figure 2 provides a sense of the degree to which spectral hardening errors would impact our spin results. Further discussion of the spectral hardening implied by TLUSTY calculations can be found in Davis & El-Abd (2019) while Salvesen & Miller (2021) provide a thorough review of uncertainties and quantitative estimates of their impact on spin measurements.

We note that the selection criteria is also a clear source of uncertainty, since two different methods provide nominally disk-dominated spectra that yield different results. This concern for GRS 1915+105 contrasts with other sources (mainly soft X-ray transient low mass X-ray binaries) that tend to approximately follow a luminosity proportional to temperature to the fourth power relation (Gierliński & Done 2004; Dunn et al. 2011). Since color corrections tend to vary relatively weakly (Davis & El-Abd 2019), this means different observations of the same source likely yield consistent inner disk radii and consistent spins. GRS 1915+105 tends to be highly variable and less consistent, which is partly why Dunn et al. (2011) exclude it from their analysis. Nor is it clear that its variability properties are consistent with other sources in its nominally disk-dominated states, possibly indicating contamination from a warm Comptonizing component (Zdziarski et al. 2005; Ueda et al. 2010). The quality of fit for our spectral modelling is sensitive to the chosen hard X-ray model. Fits with the nthcomp model can provide a lower $\chi^2$ than with the simpl model, and did not provide consistently disk-dominated fits when paired with bhspec. Although the simpl model provides a poorer fit, it provides relatively disk-dominated results, consistent with Comptonization models where the seed photons are provided by the accretion disk and scattered in a hot corona. Further work is needed to robustly characterize the disk-dominated states of GRS 1915+105 and ascertain how this may affect the best-fit spin constraints.

5. SUMMARY AND CONCLUSIONS

We re-examine the continuum-fitting based spin estimates for GRS 1915+105 in light of new constraints on the mass, distance, and inclination from VLBI parallaxes (R14). We find that the discrepancies between data selected by MID06 and MCC06 persist, implying that the selection criteria of one (or both) is inconsistent with the assumptions of the thin disk model. MCC06 showed a trend towards lower spin as the luminosity of the observations increased, indicating the discrepancy may be driven primarily by different Eddington ratio ranges of the two datasets. The revised system parameters lower the mass, but lead to relatively smaller implied luminosities, leading to lower overall Eddington ratios for fits to both datasets. This somewhat mitigates concerns that the Eddington ratios in the MID06 models were too high, but the highest Eddington ratio is still close to unity ($L/L_{\text{Edd}} = 0.87$), where the scale height of the disk is unlikely to remain small compared to the radius, as assumed in the model.

The new system parameters drive both datasets to higher spins. Since MCC06 were already fitting for near maximal spin, this presents a challenge. For the bhspec model (or kerrbb model with color corrections set to match bhspec), we cannot obtain a good fit for the preferred (R14) system parameters. Good fits to these data can only be found if the color correction is allowed to vary to values significantly higher ($f \gtrsim 2.2$) than implied by bhspec or the distance to GRS 1915+105 is near or greater than 10 kpc, consistent with the prediction of MCC06 (their Figure 18). The spin would remain near maximal ($a_* \simeq 0.99$) for a distance of 10 kpc, consistent with constraints from modeling of the reflection spectrum.

For the MID06 data, the best-fit spin is moderately high ($a_* \simeq 0.86$) for the best-fit R14 system parameters. We find, however, that a fairly broad range of spins are allowed when the uncertainty in the parallax distance and jet model inclination are accounted for, as indicated by Figure 3.4. In principle, this allows the spin to match constraints from either the near maxi-
mal spins from reflection modeling or the more moderate spins from QPO models. Near maximal spin, however, would result for fairly low inclinations in our model, which would be inconsistent with the best-fit inclinations from reflection modelling. The low end of the allowed spin distribution is sensitive to the maximum Eddington ratio permitted by \texttt{bhspec} \((L/L_{\text{Edd}} = 1.77)\). Therefore, the lower limit on \(a^*\) is tied to the Eddington ratio beyond which one says the thin disk model is no longer valid.

Although the VLBI parallax measurements are an impressive achievement, our results indicate that even stronger constraints are necessary to provide a tight constraint on the spin with the continuum-fitting method, and to help resolve the discrepancies driven by data selection. We note that such constraints also have implications for the reflection spectrum modeling through the dependence of relativistic Doppler shift and beaming on the observer inclination. This analysis would also benefit from better constraints on the interstellar absorption toward GRS 1915+105. The datasets modeled here prefer different models for the absorption and are particularly sensitive to the hydrogen column assumed. The range of columns used in the literature vary by more than a factor of two, which is enough to modify the best-fit spin, with larger assumed columns generally providing lower spins.

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