Estimating the Spin of the Black Hole Candidate MAXI J1659-152 with the X-Ray Continuum-fitting Method

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Abstract

As a transient X-ray binary, MAXI J1659-152 contains a black hole candidate as its compact star. MAXI J1659-152 was discovered on 2010 September 25 during its only known outburst. Previously published studies of this outburst indicate that MAXI J1659-152 may have an extreme retrograde spin, which, if confirmed, would provide an important clue as to the origin of black hole spin. In this paper, utilizing updated dynamical binary system parameters (i.e., the black hole mass, the orbital inclination, and the source distance) provided by Torres et al., we analyze 65 spectra of MAXI J1659-152 from RXTE/PCA, in order to assess the spin parameter. With a final selection of nine spectra matching our $f_{ic} \leq 25\%$, soft state criteria, we apply a relativistic thin disk spectroscopic model $kerrbb2$ over 3.0–45.0 keV. We find that inclination angle correlates inversely with spin, and, considering the possible values for inclination angle, we constrain spin to be $-1 < a_\text{h} \lesssim 0.44$ at a 90% confidence interval via X-ray continuum fitting. We can only rule out an extreme prograde (positive) spin. We confirm that an extreme retrograde solution is possible and is not ruled out by considering accretion torques given the young age of the system.

Unified Astronomy Thesaurus concepts: Black hole physics (159); X-ray astronomy (1810); X-ray transient sources (1852)

1. Introduction

Spin is one of the most important basic physical quantities that characterizes a black hole. Knowledge of this parameter is essential for understanding the physics governing black holes and their phenomena such as jets (Narayan & McClintock 2012). Spin is described by a dimensionless parameter $a_\text{h} = cJ/GM^2$, which lies in a range from $-1$ to $1$ (where $c$ is the speed of light, $J$ is the angular momentum of the black hole, $G$ is the gravitational constant, and $M$ is the black hole mass).

The spin of a black hole X-ray binary (BHXRB) is generally measured in one of two spectroscopic methods. The first technique, X-ray “reflection fitting” was pioneered by Fabian et al. (1989). Subsequently, the X-ray “continuum-fitting” method was proposed by Zhang et al. (1997). In recent years, nonspectroscopic techniques for measuring spin have also been proposed and explored, for instance, the high-frequency quasi-periodic oscillations method (Wagoner et al. 2001; Motta et al. 2014), the X-ray polarization method (Dovčiak et al. 2008), and methods for other black holes not in X-ray binaries such as the black hole horizon method (Dokuchaev & Narazova 2019), and numerous gravitational waveform measurements of black hole mergers (see the Gravitational Wave Open Science Center).

Of these methods, only X-ray continuum fitting (hereafter CF) and X-ray reflection fitting (also known as the Fe Ko method) are widely used for BHXRBs. To date, less than 100 BHXRBs have been found (see BlackCAT for details), and the spin of more than two dozen BHXRBs (including persistent and transient sources) in and around the Galaxy have been measured by at least one method, for example, GRS 1915+105 (McClintock et al. 2006), M33 X-7 (Liu et al. 2008), LMC X-1 (Gou et al. 2009), A 0620-00 (Gou et al. 2010), XTE J1550-564 (Steiner et al. 2011), Cyg X-1 (Gou et al. 2014), GS 1124-683 (Chen et al. 2016), XTE J1752-223 (García et al. 2018), 4U 1543-47 (Dong et al. 2020), and so on.

The CF method is based on the classic relativistic thin disk model (Novikov & Thorne 1973). Through fitting the thermal continuum emission of the accretion disk, the inner disk radius is constrained. By adopting the usual assumption that the inner radius of the accretion disk extends to the innermost stable circular orbit (ISCO), we can ascertain the spin based on the unique mapping between the ISCO and spin as revealed in Bardeen et al. (1972). The CF method relies on the accurate measurement of the system parameters (such as black hole mass ($M$), the inclination of the accretion disk ($i$, which is assumed to be equal to the orbital inclination), and the source distance ($D$)). The Fe Ko fitting method also measures the inner disk radius by modeling the relativistic reflection spectrum and is only weakly dependent upon inclination, which may also be fitted alongside spin. The CF method is generally only applicable to stellar-mass black holes, while Fe Ko fitting is widely used for both stellar-mass black holes and

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5 https://www.gw-openscience.org/catalog/GWTC-1-confident/html/

6 http://www.astro.puc.cl/BlackCAT/
supermassive black holes. Aside from the mutual reliance on the association between inner disk radius and the ISCO, both methods are independent and can be used to cross-check one another. In this paper, we apply the CF method to estimate the spin of MAXI J1659-152.

As the capability of a spin measurement by the CF method relies upon ensuring that the inner radius of the accretion disk extends to the ISCO, we implement a screening to identify data for which that requirement is most sound: namely, high/soft (HS) state spectra whose emission is dominated by the accretion disk (e.g., McClintock et al. 2006). This also avoids potential contamination by a strong Compton component. We additionally require that the disk is geometrically thin by requiring that the dimensionless luminosity $l = L(\alpha_0, M)/L_{\text{Edd}} < 0.3$ (where $H$ is the thickness of the disk, $R$ is the local disk radius, and $l$ is the bolometric Eddington-scaled luminosity; e.g., Gou et al. 2011). To ensure the data are sufficiently dominated by the thermal disk emission, we apply a bound on the relative strength of the nonthermal emission (Steiner et al. 2009) that has been applied in similar analyses of other black hole systems (e.g., Steiner et al. 2011; Chen et al. 2016; Zhao et al. 2020). Briefly the proportion of thermal photons that scatter in the corona (the “scattering fraction”) $f_{\text{sc}} \lesssim 25\%$, where $f_{\text{sc}}$ is a parameter of the Comptonization model simpl in XSPEC.

Generally, BHXBs can be divided into high-mass x-ray binaries (HMXBs) and low-mass x-ray binaries (LMXBs) according to the mass of the black hole’s companion star. Typically, HMXBs are fueled by the capture of strong winds from the companion star (Shakura et al. 2015). However, LMXBs are usually fueled via Roche-lobe overflow in a stream through the first Lagrangian point (L1; Savonije 1978). In theory, natal kicks may lead to a random initial distribution of prograde/retrograde black hole X-ray binaries. However, the strong majority of black holes observed have a positive spin. For these black holes with a positive spin, Nielsen (2016) shows that black holes in HMXBs usually have a higher spin, while LMXB black hole spins range from very low to very high. Notably, the binary black holes (BBHs) detected by LIGO/Virgo by O3a appear to exhibit spin magnitudes of close to zero (see Abbott et al. 2021 for details on BBHs). At present, there is scant information on retrograde-spin systems. There are four black hole systems for which a retrograde spin has been suggested as likely: IGR J17091-3624 (Rao & Vadawale 2012), Swift J1910.2-0546 (Reis et al. 2013), GS 1124-683 (Morningstar et al. 2014), and XMMU J004243.6+412519 (Middleton et al. 2014). Of these, a revised estimate of GS 1124-683 has offered instead a moderate prograde spin (Chen et al. 2016).

MAXI J1659-152 (hereafter MAXI J1659) is a Galactic black hole candidate X-ray binary (de Ugarte Postigo et al. 2010). As a transient source, MAXI J1659 has been dormant during the monitoring of the Gas Slit Camera on board the Monitor of All-sky X-ray Image (MAXI/GSC) over the past 11 yr. On 2010 September 25, it was first detected entering a seven-month outburst (Homan et al. 2013). The discovery was reported by the Burst Alert Telescope of the Neil Gehrels Swift Observatory (Swift/BAT; Mangano et al. 2010) and MAXI/GSC (Negoro et al. 2010) in the gamma-ray and X-ray bands, individually. Later, optical (de Ugarte Postigo et al. 2010), radio (Plotkin et al. 2013), and near-infrared (Kaur et al. 2012) data were also obtained. Its fast timing behavior flagged it as a likely stellar-mass black hole candidate (Yamaoka et al. 2012). Kuulkers et al. (2013) report that the orbital period of the binary system is just 2.42 hr and that the binary system consists of an M5 dwarf companion with a mass of $0.15-0.25 M_\odot$ and a radius of $0.2-0.25 R_\odot$, establishing MAXI J1659 as a low-mass X-ray binary. Since its outburst, the black hole has attracted much attention, and there has been extensive discussion about its mass (Kennea et al. 2011; Shaposhnikov et al. 2011; Yamaoka et al. 2012; Rao Jassal & Vadawale 2015; Molla et al. 2016), inclination (Kennea et al. 2011; Yamaoka et al. 2012), and distance (Kennea et al. 2011; Kaur et al. 2012; Kong 2012; Jonker et al. 2012; Kuulkers et al. 2013). By contrast, due to the faintness of the quiescent optical counterpart and the short orbital period of MAXI J1659, it is difficult to measure its dynamic parameters (Torres et al. 2021). Recently, Rout et al. (2020) claim that the black hole’s spin is retrograde and that it may be maximal. Using the Hα emission, Torres et al. (2021) find a radial velocity semiamplitude of the donor of $K_{2} = 750 \pm 80$ km s$^{-1}$. Furthermore, Torres et al. (2021) obtain $q = M_{2}/M_{1} = 0.02-0.07$ based on the interdependence between the ratio of line double-peak separation and FWHM with $q$. Since the system lacks eclipses, based on modeling the light curve, Torres et al. (2021) further consider a case where the disk’s outer rim occults the central X-ray source from the donor, and compares the Hα line profile with that of multiple black hole systems. Taken together, the inclination is restricted in the range 70° $\lesssim i \lesssim 80°$. In addition, the detection of X-ray absorption dips during the early outburst indicates a high inclination (e.g., Kuulkers et al. 2013). The mass of MAXI J1659 is constrained between $5.7 \pm 1.8 M_\odot$ ($i = 70°$) and $4.9 \pm 1.6 M_\odot$ ($i = 80°$) at the confidence level of 68.3% (for details, see Torres et al. 2021). In recent years, measuring properties of the Hα emission line profile emitted by the quiescent accretion disk to estimate $K_{2}$ and $q$ has become more mature and reliable (Casares 2015, Casares 2016, 2018; Casares & Torres 2018), which also inspires us to revisit the spin of MAXI J1659.

Our work is based upon the CF method and utilizes the latest measurement results of Torres et al. (2021), adopting two limiting solutions: $M = 5.7 \pm 1.8 M_\odot$ ($i = 70°$, $D = 6 \pm 2$ kpc, and $M = 4.9 \pm 1.6 M_\odot$ ($i = 80°$, $D = 6 \pm 2$ kpc. For the above two sets of system parameters $(M, i, D)$, we fit nine selected spectra of RXTE/PCA of MAXI J1659 throughout its 2010 outburst in the soft state with a relativistic thin disk model kerrbb2 (McClintock et al. 2006) to constrain its spin.

The paper is organized as follows. In Section 2, we introduce the data selection and reduction, including both RXTE/PCA and XMM-Newton/EPIC-pn data. In Section 3, we describe the spectral analysis and results in detail. A discussion is presented in Section 4. We offer our conclusions in Section 5.

2. Data Selection and Reduction

During MAXI J1659’s 2010 outburst, the Rossi X-ray Timing Explorer (RXTE) carried out a total of 65 continuous observations, which were stored in three program IDs (95358, 95108, and 95118, respectively). We employ the Proportional Counter Array data of RXTE (RXTE/PCA; Jahoda et al. 1996). In addition, we also consider data from the European Photon Imaging Camera on X-ray Multi-Mirror Newton (XMM-Newton/EPIC-pn; Strüder et al. 2001). All data are
grouped to achieve a signal-to-noise ratio (S/N) of 25 per energy bin. Spectra are fitted using XSPEC v12.11.1 (Arnaud 1996) using $\chi^2$ statistics. We also check nine spectra separately using the “Ignore bad” command in XSPEC, and no bad channels need to be ignored.

2.1. RXTE Observations

The PCA spectra are extracted according to the standard procedures described in the RXTE Cook Book, based on the New PCA Tools with HEAsoft v6.28. The whole procedure uses the PCA calibration files $^{10}$ v20200515. We select the data from the top layer of the best-calibrated detector PCU2 in Standard 2 mode. A dead time correction is taken into account. The latest bright-source background model is used to generate background spectra. After generating standard data products, we also apply calibration correction pccorr, $^{11}$ which can reduce the systematic error that accounts for the uncertainties in the instrumental responses (García et al. 2014). We adopt a 0.1% systematic error. In this work, we choose the energy band of 3.0–45.0 keV. Following on these stringent screening requirements on $l$ and $f_{\text{acc}} \lesssim 25\%$, we select nine spectra (SP1–SP9). To account for the significant flux normalization differences between X-ray missions, we follow the previous work (Steiner et al. 2010) in attempting to standardize the calibration using the Crab as a reference. We opt for observations of Crab that are close to the target dates for SP1–SP9, and adopt $N = 9.7$ photons s$^{-1}$ keV$^{-1}$ (Toor & Seward 1974) as the standard values. For spectra SP1–SP8, we determine that the normalization correction coefficient $C_{\text{TS}}$ is 1.128 and the slope difference $\Delta T_{\text{TS}}$ is 0.021. For SP9, $C_{\text{TS}}$ and $\Delta T_{\text{TS}}$ are 1.123 and 0.018, respectively. This standardization is implemented in XSPEC via cracorr. We list the detailed information about SP1–SP9 in Table 1. It is worth noting that MAXI J1659 is a bright source, whose peak flux reaches about 300 mCrab (Kalamkar et al. 2011). Jahoda et al. (2006) put forward that the threshold of pile-up significance of RXTE/PCA is 10,000 cts s$^{-1}$ PCU$^{-1}$. In other words, below this threshold, the photon pile-up is not significant. SP1–SP9 are all far below this threshold.

2.2. XMM-Newton Observations

With RXTE/PCA coverage beginning at 3 keV, the hydrogen column density ($N_{\text{H}}$) cannot be well constrained. So we turn to XMM-Newton data, which cover the low-energy band in which $N_{\text{H}}$ is most prominent. We employ EPIC-pn timing-mode data during an observation (ObsID 0656780601) that spanned ~23 ks during the X-ray outburst. Data reduction is carried out using the Science Analysis System (SAS) $^{12}$ v18.0 with the latest calibration files. We follow the standard procedures and remove the influence caused by pile-up. In addition, we include a 0.5% systematic error as suggested by the XMM-Newton team. $^{13}$ Crab calibration is also made for XMM-Newton data. Implementing TBabs (diskbb +powerlaw), eventually, we get an $N_{\text{H}} = 3.22 \times 10^{22}$ cm$^{-2}$ via fitting the spectrum over the energy range of 0.7–12.0 keV with a reduced chi-square $\chi^2_r = 1.179$ (2451.8/2080.0). In subsequent work, all $N_{\text{H}}$ are fixed to this value.

3. Spectral Analysis and Results

3.1. The Nonrelativistic Model

As shown in Figure 1, MAXI/GSC has been monitoring MAXI J1659 for up to eleven years. The horizontal axis represents MJD and the vertical axis represents the flux at 2.0–20.0 keV detected by MAXI/GSC. As can be seen from Figure 1, MAXI J1659 has exhibited just one major outburst and has shown no other signs of activity. As displayed in Figure 2, the hardness–intensity diagram shows a classical “q”-like shape, which is a typical for an outbursting black hole LMXB.

First, we present the nonrelativistic case, which consists of multiple blackbody disk components diskbb (Mitsuda et al. 1984; Makishima et al. 1986). The composite nonrelativistic model cracorr"TBabs"(diskbb +powerlaw) is used to fit the data for the nine screened RXTE/PCA spectra. The model cracorr and model simpl have been mentioned earlier (see Section 2 and Section 1, respectively). The photoionization cross sections of the interstellar medium in model TBabs are based on Vernier et al. (1996), the abundances are based on Wilms et al. (2000), and we set $N_{\text{H}}$ to 3.22 $\times 10^{22}$ cm$^{-2}$ (see Section 2). The best-fitting results of SP1–SP9 are listed in Table 2. As can be seen, these nine spectra are well fitted and

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Table 1

Properties of SP1–SP9

| Spec. | ObsID   | MJD    | Start Time | End Time | Exposure (s) | Count Rates (cts s$^{-1}$) |
|-------|---------|--------|------------|----------|--------------|-----------------------------|
| SP1   | 95118-01-03-00 | 55,486 | 2010-10-17 19:01:04 | 2010-10-17 19:42:40 | 2345 | 248.8 |
| SP2   | 95118-01-05-00 | 55,488 | 2010-10-19 00:27:44 | 2010-10-19 01:17:52 | 2696 | 249.9 |
| SP3   | 95118-01-05-01 | 55,488 | 2010-10-19 20:52:32 | 2010-10-19 21:34:56 | 2249 | 222.3 |
| SP4   | 95118-01-06-00 | 55,489 | 2010-10-20 06:20:48 | 2010-10-20 07:23:44 | 2938 | 221.0 |
| SP5   | 95118-01-07-01 | 55,490 | 2010-10-21 02:45:04 | 2010-10-21 03:33:04 | 2764 | 247.9 |
| SP6   | 95118-01-13-00 | 55,496 | 2010-10-27 12:26:24 | 2010-10-27 13:07:44 | 2139 | 158.1 |
| SP7   | 95118-01-14-00 | 55,497 | 2010-10-28 12:03:12 | 2010-10-28 12:16:48 | 749 | 140.3 |
| SP8   | 95118-01-15-00 | 55,498 | 2010-10-29 11:40:48 | 2010-10-29 12:00:48 | 1126 | 140.3 |
| SP9   | 95118-01-15-01 | 55,499 | 2010-10-30 07:57:36 | 2010-10-30 08:21:36 | 1378 | 137.0 |

Note. In columns 2–7, we show: the observation ID (ObsID), Modified Julian Date (MJD), the start time, the end time, the exposure time in units of s, and the net count rates of SP1–SP9 for the PCU2 top layer measured at 3.0–45.0 keV in units of cts s$^{-1}$.

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$^9$ https://heasarc.gsfc.nasa.gov/xanadu/xspec/
$^8$ https://heasarc.gsfc.nasa.gov/docs/xtc/recipes2/Overview.html
$^7$ https://heasarc.gsfc.nasa.gov/docs/software/heasoft/download.html
$^10$ https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_supported_missions.html
$^{11}$ http://www.srl.caltech.edu/personnel/javier/crabcorr/index.html
$^{12}$ https://www.cosmos.esa.int/web/xmm-newton/download-and-install-sas
$^{13}$ https://heasarc.gsfc.nasa.gov/docs/xmm/sl/epic/image/sas_cl.html
the reduced chi-square $\chi^2$ of SP1–SP9 are basically in the vicinity of 1. Figure 3 shows the fitting of SP1 and SP4 as representatives. We can discover that the model fitted well without any significant residual.

3.2. The Relativistic Model

We next move to the fully relativistic accretion disk model kerrbb2 (McClintock et al. 2006). Model kerrbb2 merges two different disk models, bhspec and kerrbb. Specifically, bhspec is used to determine the value of the spectral hardening factor $f \equiv T_{\text{col}}/T_{\text{eff}}$ (also known as the color correction factor; Davis et al. 2005), while kerrbb employs ray-tracing computations to model the disk (Li et al. 2005). We first use bhspec\(^\text{14}\) to compute spectral hardening look-up tables according to two representative values of the viscosity parameter ($\alpha = 0.1$ and $\alpha = 0.01$). It is worth noting that the calculations with the model BHSPEC are made for spins ranging from $-1$ to $1$. During kerrbb2 fitting, the $f$-table is read in and used to automatically set the $f$ value; otherwise the

\(^{14}\) http://people.virginia.edu/~swd8g/xspec.html
The mass is restricted to 5.7 \(\pm\) 1.8.\(^{\alpha}\) reduced chi-square \(\chi^2\) and the degrees of freedom (d.o.f.).

For both bracketing sets of system parameters: \(M = 5.7 \pm 1.8 M_\odot\) (1\(\sigma\)), \(i = 70^\circ\), \(D = 6 \pm 2\) kpc (hereafter Group 1) and \(M = 4.9 \pm 1.6 M_\odot\) (1\(\sigma\)), \(i = 80^\circ\), \(D = 6 \pm 2\) kpc (hereafter Group 2), we show our results in Table 3. Group 1 (70\(^\circ\)) would have MAXI J1659 with a moderate positive spin, whereas Group 2 (80\(^\circ\)) finds an extreme retrograde spin to be most likely.

Although, in this paper, we focus upon results for \(\alpha = 0.1\) as our default, for the alternative case of \(\alpha = 0.01\) we have performed the same calculations. Those results are in Table 4. The errors that appear in Tables 3 and 4 are only due to the statistical uncertainties estimated by XSPEC for 90% confidence. Next, we will discuss the error from uncertainties of the input parameters \(M\), \(i\), and \(D\) in detail.

### 3.3 Error Analysis

The dominant source of uncertainty in CF is the uncertainty of the input parameters: \(M\), \(i\), and \(D\). In order to determine those uncertainties, Monte Carlo (MC) methods are often used (see, e.g., Liu et al. 2008; Gou et al. 2009). We follow these works, but differ in that, unlike those, here there are two distinct sets of input system parameters (Group 1 and Group 2). We first consider these groups separately.
Table 3
The Best-fitting Parameters for SPI–SP9 with \texttt{crabcor'TBabs*(simple'kerrbb2)} (\(\alpha = 0.1\))

| Group 1 | Group 2 |
|---------|---------|
| Spec.   | ObsID   | \(\Gamma\) | \(f_{\text{sc}}\) | \(a_\sigma\) | \(M\) | \(\chi^2\) | \(\chi^2(\text{d.o.f.)}\) | \(L/L_{\text{Edd}}\) |
|---------|---------|-------------|-----------------|-----------|------|---------------|--------------------------|-----------------|
| SP1     | 95118-01-03-00 | 2.39 ± 0.02 | 0.189 ± 0.003 | 0.163 ± 0.03 | 1.36 ± 0.05 | 1.141 | 77.62 (68) | 0.109 |
| SP2     | 95118-01-05-00 | 2.40 ± 0.02 | 0.227 ± 0.003 | 0.146 ± 0.03 | 1.33 ± 0.04 | 1.422 | 96.71 (68) | 0.104 |
| SP3     | 95118-01-05-01 | 2.31 ± 0.02 | 0.191 ± 0.003 | 0.217 ± 0.02 | 1.18 ± 0.03 | 1.085 | 73.76 (68) | 0.097 |
| SP4     | 95118-01-06-00 | 2.35 ± 0.02 | 0.166 ± 0.003 | 0.205 ± 0.02 | 1.24 ± 0.03 | 0.961 | 65.34 (68) | 0.102 |
| SP5     | 95118-01-07-01 | 2.37 ± 0.02 | 0.245 ± 0.003 | 0.234 ± 0.03 | 1.15 ± 0.04 | 1.171 | 79.63 (68) | 0.096 |
| SP6     | 95118-01-13-00 | 2.31 ± 0.02 | 0.237 ± 0.003 | 0.263 ± 0.04 | 0.84 ± 0.05 | 0.834 | 56.71 (68) | 0.074 |
| SP7     | 95118-01-14-00 | 2.25 ± 0.05 | 0.152 ± 0.004 | 0.277 ± 0.06 | 0.86 ± 0.07 | 0.852 | 57.94 (68) | 0.086 |
| SP8     | 95118-01-15-00 | 2.34 ± 0.03 | 0.203 ± 0.005 | 0.143 ± 0.07 | 0.96 ± 0.08 | 1.133 | 77.02 (68) | 0.076 |

Note. In columns 3–10, we show: the observation ID (ObsID), the dimensionless photon index of the power law (\(\Gamma\)), the scattered fraction (\(f_{\text{sc}}\)), the dimensionless spin parameter (\(a_\sigma\)), the effective mass accretion rate of the disk in units of \(10^{18} \text{g s}^{-1} \text{M}\)), the reduced chi-square (\(\chi^2\)), the total chi-square (\(\chi^2\)), and the degrees of freedom (d.o.f.), and the bolometric Eddington-scaled luminosities (\(L/L_{\text{Edd}}\)); where \(L_{\text{Edd}} = 1.3 \times 10^{38} (\text{M}_\odot \text{M}_\odot)^{-1} \text{erg s}^{-1}\); see Shapiro & Teukolsky (1983). The two sets of system parameters: \(M = 4.9 \text{M}_\odot\), \(i = 80^\circ\), \(D = 6\text{ kpc}\) (Group 1) and \(M = 4.9 \text{M}_\odot\), \(i = 80^\circ\), \(D = 6\text{ kpc}\) (Group 2) are shown separately. Within each group, a horizontal line distinguishes between simultaneous fitting and independent fitting; above the horizontal line are the results of independent fitting of nine spectra, and below the horizontal line are the results of simultaneous fitting of nine spectra.

For each individual spectrum in SPI–SP9, assuming that randomly generated data points are independent of each other and obey a Gaussian distribution, we have generated 3000 data points of \(M\) and \(D\) respectively. Inclination \(i = 70^\circ\) (\(i = 80^\circ\)), and these 3000 data points constitute 3000 data sets as input parameters. We next compute the look-up tables of \(f\) for these 3000 data sets. Lastly, we use the composite model \texttt{crabcor'TBabs*(simple'kerrbb2)}; (see Section 2) to fit 3000 data sets to obtain the histogram of spin, so as to determine the errors. The MC determined error analysis of each spectrum is shown in Figure 4. The histograms of \(a_\sigma\) for SPI–SP9 are shown in Figure 5. As shown in Figure 5, Group 1 with a higher mass and a lower inclination yields a spin \(a_\sigma = 0.21^{+0.14}_{-0.20} (1\sigma)\); Group 2 gives \(a_\sigma = -0.79^{+0.31}_{-0.20} (1\sigma)\).

We now combine Groups 1 and 2 in order to establish a net constraint on spin. We are interested in assessing the lower and upper bounds on spin that are mostly constrained by Groups 2 and 1, respectively. We mark the appropriate 1\(\sigma\) limit for each spectrum in Figure 4, and for the composite result in Figure 5. In total, we find that the spin of MAXI J1659 is poorly constrained, with an allowable range \(-1 < a_\sigma < 0.35\) in the 1\(\sigma\) interval. The 90\% upper limit on spin is 0.44 from Group 1.

4. Discussion

4.1. Effect of the Hydrogen Column Density

In order to assess whether the hydrogen column density significantly affects the spin results, we explore varying the value of \(N_H\) from 0.322 to 0.2, 0.4, and 0.5 in units of...
Note. In columns 3–10, we show: the observation ID (ObsID), the dimensionless photon index of the power law ($\Gamma$), the scattered fraction ($f_{sc}$), the dimensionless spin parameter ($a_*$), the mass accretion rate through the disk in units of $10^{18} \text{ g s}^{-1}$ (M), the reduced chi-square ($\chi^2_\nu$), the total chi-square ($\chi^2$) and the degrees of freedom (d.o.f.), and the luminosity (l). The two sets of system parameters: M = $5.7 \times 10^6$, $i = 70^\circ$, $D = 6.2 \text{ kpc}$ (Group 1) and M = $4.9 \times 10^6$, $i = 80^\circ$. $D = 6 \pm 2 \text{ kpc}$ (Group 2) are shown separately. Within each group, a horizontal lines distinguishes between simultaneous fitting and independent fitting; above the horizontal line are results of independent fitting of nine spectra, and below the single horizontal line are the results of simultaneous fitting of nine spectra.

$10^{22} \text{ cm}^{-2}$. These alternates are chosen as round numbers covering the range of values given by Kennea et al. (2011). The fitting is systematically affected for all of the spectra in the same way. We illustrate this difference by showing such results for SP1 in Table 5. When $N_H$ increases from $2 \times 10^{21} \text{ cm}^{-2}$ to $5 \times 10^{21} \text{ cm}^{-2}$, for Group 1, $a_*$ varies from 0.210 to 0.134, with $\Delta a_*$ equaling 0.076. And for Group 2, $a_*$ changes from $-0.834$ to $-0.957$, and $\Delta a_*$ is 0.123. As expected, a slight increase of $N_H$ causes the inferred spin to decrease. Compared to the dynamical sources of uncertainty in hand, changing the value of $N_H$ has a very minor effect on the final spin results.

### 4.2. Effect of Simultaneous Fitting of Nine Spectra on Spin Results

In addition to fitting each spectrum individually with the relativistic model, we also consider the case that all of the spectra are fitted simultaneously and look into its effect. We link the spin parameters among all nine spectra, and let the other fit parameters free. For the convenience of comparison, we also list the results of simultaneous fits in Table 3 and 4 to other Group 1 and 2. As a showcase, the simultaneous fit to all of the spectra is also shown in Figure 6(a). As we can see, the spin ranges over $-1 < a_* < 0.33$ (1$\sigma$) as obtained from the MC result (Figure 6(b)), and it is clear that the results are fully consistent with ones obtained from individual spectral fits (Figure 5), which is expected. Therefore, the effect of joint fits is negligible and our work uses the fit results from the individual spectra as our primary results.

### 4.3. Differences from Previous Measurements

Rout et al. (2020) construct a wider range of system parameter ($M, i, D$) grids based on an older set of measurement
results. They found a simultaneous data set with XMM/EPIC-pn and RXTE/PCA overlapping on 2010 September 28. Fitting the two data sets together, they simultaneously adopt the X-ray reflection fitting and continuum-fitting method. On this basis, they use meaningful values of the mass accretion rate $\dot{M}$ to constrain the spin of MAXI J1659. Their results of the X-ray reflection fitting are shown in Figure 4.

Figure 4. (a) The results of MC error analysis of $a_*$ for SP1–SP9 for Group 1. (b) The analogous results for Group 2. For both (a) and (b), black dotted lines represent the center value of $a_*$, and red dotted lines represent the ±68.3% (±1σ) lower and upper limits between Groups 1 and 2, respectively.
continuum fitting show that the lower limit of the spin is pegged at $-0.998$, while the upper limit is 0.4. However, it should be noted that the spectra in Rout et al. (2020) do not meet the $f_{\text{sc}} \leq 25\%$ criterion. Different from Rout et al. (2020), we first screen the spectra with $f_{\text{sc}} \leq 25\%$ for the X-ray continuum fitting and make the crabcor correction. In addition, we use the relativistic model kerrbb2 that allows the spectral hardening factor $f$ to change, which will be closer to the actual situation. And we do not ignore the influence of self-irradiation in kerrbb2. Based on the use of different spectra, different models, and updated dynamical parameters, we find a spin ranging over $-1 < a_\ast \leq 0.35$ (1$\sigma$). As reported by Rout et al. (2020), we also rule out an extreme prograde spin.

4.4. The Possible Relation between the Scattering Fraction in the Spectrum and the Spin

To verify that a stronger hard tail does not introduce bias, we also check for a possible correlation between the scattering fraction in the spectrum and the spin. We take SP1 as an example, and find for any individual spectrum, the contour map between black hole spin and $f_{\text{sc}}$ shows a strong degenerate relation (see subgraph (a) of Figure 7). However, we find that as an ensemble that encompasses a range of $f_{\text{sc}}$ values, the spin does not exhibit a correlation (see subgraph (b) of Figure 7). Accordingly, we conclude that $f_{\text{sc}}$ does not affect our spin results.

4.5. Further Discussion on the Possibility of an Extreme Negative Spin

King & Kolb (1999) considered the effect of prograde accretion in changing the black hole mass and its spin (see their Figure 3). We also consider the influence of retrograde accretion in changing the black hole mass and spin in the Appendix. As stated above, Kuulkers et al. (2013) found that the companion of MAXI J1659 had an initial mass of about $1.5 M_{\odot}$, and evolved to its current mass in about 4.6–5.7 billion years. Let us make a simple estimate. We assume that MAXI

\[ N_\text{H} \times 10^{22} \text{ cm}^{-2} \]

| $N_{\text{H}}$ | $\Gamma$ | $f_{\text{sc}}$ | $a_\ast$ | $M$ | $\chi^2_\nu$ | $\chi^2_{\text{d.o.f.}}$ | $L/L_{\text{Edd}}$ |
|----------------|----------|----------------|----------|-----|--------|----------------|----------------|
| 0.200          | 2.38 ± 0.02 | 0.189 ± 0.003 | 0.210 ± 0.02 | 1.29 ± 0.03 | 1.118 | 76.03 (68) | 0.106 |
| 0.322          | 2.39 ± 0.02 | 0.189 ± 0.003 | 0.163 ± 0.03 | 1.36 ± 0.05 | 1.141 | 77.62 (68) | 0.109 |
| 0.400          | 2.39 ± 0.02 | 0.189 ± 0.003 | 0.152 ± 0.03 | 1.39 ± 0.05 | 1.159 | 78.81 (68) | 0.110 |
| 0.500          | 2.39 ± 0.02 | 0.188 ± 0.003 | 0.134 ± 0.03 | 1.42 ± 0.04 | 1.185 | 80.56 (68) | 0.111 |
| 0.200          | 2.39 ± 0.02 | 0.192 ± 0.003 | -0.834 ± 0.06 | 4.42 ± 0.16 | 1.143 | 77.71 (68) | 0.258 |
| 0.322          | 2.39 ± 0.02 | 0.191 ± 0.003 | -0.872 ± 0.05 | 4.55 ± 0.14 | 1.175 | 79.92 (68) | 0.263 |
| 0.400          | 2.40 ± 0.02 | 0.192 ± 0.003 | -0.929 ± 0.06 | 4.71 ± 0.17 | 1.197 | 81.41 (68) | 0.267 |
| 0.500          | 2.40 ± 0.02 | 0.191 ± 0.003 | -0.957 ± 0.05 | 4.82 ± 0.16 | 1.209 | 82.23 (68) | 0.271 |

Note. In columns 1–8: the hydrogen column density in units of $10^{22}$ cm$^{-2}$ ($N_{\text{H}}$), the dimensionless photon index of the power law ($\Gamma$), the scattered fraction ($f_{\text{sc}}$), the dimensionless spin parameter ($a_\ast$), the effective mass accretion rate of the disk in units of $10^{18}$ g s$^{-1}$ ($M$), the reduced chi-square ($\chi^2_\nu$), the total chi-square ($\chi^2$) and the degrees of freedom (d.o.f.), and the bolometric Eddington-scaled luminosity ($L/(a_\ast M_{\odot})/L_{\text{Edd}}$). The two sets of system parameters: $M = 5.7 M_{\odot}$, $i = 70\degree$, $D = 6 \pm 2$ kpc (Group 1) and $M = 4.9 M_{\odot}$, $i = 80\degree$, $D = 6 \pm 2$ kpc (Group 2) are shown separately, with the first four rows belonging to Group 1 and the second four rows belonging to Group 2.
J1659 is a retrograde black hole with an extreme spin, approaching $a_* = -1$. And we suppose the initial mass of the black hole is $4 M_\odot$. The outburst-averaged dimensionless mass accretion rate ($\dot{m} = \dot{M}/M_{\text{Edd}}$) of the standard thin disk model is usually in the range $0.01 - 0.3$ (Narayan & Yi 1995; Ohsuga et al. 2002); nonetheless, if we take into account that only one 7 month outburst has been observed from the source in the last 25 yr, the time-averaged accretion rate $\dot{m} = 2 \times 10^{-4}$ would be more realistic. When $\dot{m} = 2 \times 10^{-4}$, the Eddington accretion rate ($M_{\text{Edd}}$) of a black hole of $4 M_\odot$ is about $10^{-8} M_\odot$ yr$^{-1}$. According to Equation (A1), in 4.6–5.7 billion years, the accreted mass onto MAXI J1659 should fall within the range $0.0092 - 0.0114 M_\odot$ as $\dot{m} = 2 \times 10^{-4}$. In other words, $\Delta M/M_i$ (defined in the Appendix) should fall within the range of $0.0023 - 0.00285$. This obviously is insufficient to rule out the possibility that MAXI J1659 has an extreme negative spin (see Figure 8, the two red dashed lines represent 0.0023 and 0.00285, respectively).

5. Conclusion

In this paper, we present an X-ray continuum-fitting spectral analysis of the black hole candidate MAXI J1659. We select nine spectra of RXTE/PCA satisfying luminosity and state/coronal-brightness restrictions. Based on the two sets of plausible system parameters: $M = 5.7 \pm 1.8 M_\odot$, $i = 70^\circ$, $D = 6 \pm 2$ kpc and $M = 4.9 \pm 1.6 M_\odot$, $i = 80^\circ$, $D = 6 \pm 2$ kpc reported by Torres et al. (2021), we constrain the spin to $-1 < a_* \lesssim 0.44$ at a 90% confidence interval via the X-ray continuum-fitting method; as suggested in Rout et al. (2020), there is a possibility of an extreme negative spin. Then, we exclude the influence of changing $N_H$ on the spin. The possible effect of scattering fractions on spin results is also considered. We demonstrate that an extreme negative spin cannot be ruled out on the basis of theoretically expected...
accretion spin-up alone when considering the companion lifetime and a theoretical maximally retrograde black hole as a possible formation state.

Besides, it is important to note that, taking the linked spectra for Group 1 with $\alpha = 0.1$ as an example, when we fix spin to its positive maximum value ($a_*=0.998$) and thaw inclination angle, we can obtain $i = 26^\circ.02 \pm 0^\circ.17$, which is well below $i = 70^\circ.0$ in Group 1. This indicates that the inclination angle has a great impact on the spin. Therefore, accurate system parameters are very important for the CF method. It should be noted that, for MAXI J1659, more accurate spin results can be obtained when more precise measurements of system parameters are available in the future.

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**Figure 7.** (a) For SP1 under the default Group 1 settings, the contour map of $f_{sc}$ and $a_*$. The three contour lines represent 68.3%, 90%, and 99.7%, respectively. (b) The relation between $a_*$ and $f_{sc}$ for SP1 to SP9 in different groups.
when the amount by which the spin changes is the same, the retrograde black hole accretion time is much shorter than the prograde black hole accretion time. In other words, when the amount by which the spin changes is the same, the retrograde black hole accretion time is much shorter than the prograde black hole accretion time.

Combining Equations (A1) and (A2), the relation between \( a_\phi \) and \( \Delta M \) can be easily obtained, which is shown in Figure 8. When a maximum retrograde black hole is accreting the mass of its donor, it causes \( a_\phi \) to change from \(-1\) to \(0\). The mass that needs to be accreted is \( \Delta M \approx 0.22 M_i \), where \( M_i \) represents the initial mass at \( a_\phi = -1 \). It can also be expressed as \( \Delta M \approx 0.18 M_f \), where \( M_f \) typifies the final mass at \( a_\phi = 0 \).

**Appendix**

**Retrograde Accretion**

Retrograde accretion means that the black hole rotates in the opposite direction to its accretion disk (\( a_\phi < 0 \)). In order to keep consistency with King & Kolb (1999), \( \Delta M \) is used (where \( \Delta M \) is the rest mass added to the black hole from the initial state). And we assume the initial state of the black hole is \( M = M_i \), \( a_\phi = -1 \). Under the assumption of King & Kolb (1999), for a retrograde black hole, through derivation, \( \Delta M \) can be expressed as

\[
\Delta M = \left( \frac{27 M_i^2}{2} \right)^{1/2} \left[ \sin^{-1}\left( \frac{2 M_i}{27 M_i^2} \right) \right]^{1/2} - \sin^{-1}\left( \frac{2}{27} \right)^{1/2}
\]

(A1)

\[
a_\phi = \frac{M_i}{M} \left[ 4 - \frac{27 M_i^2}{M^2} - 2 \right]^{1/2}
\]

(A2)

When \( a_\phi = 0 \), \( M/M_i = (3/2)^{1/2} \). The spin will increase as the accretion mass increases, as indicated by Equation (A2). And the speed of the spin’s increase is much faster than that of a prograde black hole. In other words, when the amount by which the spin changes is the same, the retrograde black hole accretion time is much shorter than the prograde black hole accretion time.

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