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THE EXTREME SPIN OF THE BLACK HOLE IN CYGNUS X-1

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ABSTRACT

The compact primary in the X-ray binary Cygnus X-1 was the first black hole to be established via dynamical observations. We have recently determined accurate values for its mass and distance, and for the orbital inclination angle of the binary. Building on these results, which are based on our favored (asynchronous) dynamical model, we have measured the radius of the inner edge of the black hole's accretion disk by fitting its thermal continuum spectrum to a fully relativistic model of a thin accretion disk. Assuming that the spin axis of the black hole is aligned with the orbital angular momentum vector, we have determined that Cygnus X-1 contains a near-extreme Kerr black hole with a spin parameter $a_* > 0.95$ (3σ). For a less probable (synchronous) dynamical model, we find $a_* > 0.92$ (3σ). In our analysis, we include the uncertainties in black hole mass, orbital inclination angle and distance, and we also include the uncertainty in the calibration of the absolute flux via the Crab. These four sources of uncertainty totally dominate the error budget. The uncertainties introduced by the thin-disk model we employ are particularly small in this case given the extreme spin of the black hole and the disk's low luminosity.

Subject headings: accretion, accretion disks – black hole physics – stars: individual (Cygnus X-1) – X-rays: binaries

1. INTRODUCTION

In our two companion papers (Reid et al. 2011; Orosz et al. 2011), we report accurate measurements of the distance, black hole mass and orbital inclination angle for the black-hole binary system Cygnus X-1. Herein, we use these results to determine the spin of the black hole primary by fitting the thermal component of its X-ray spectrum to our implementation of the Novikov-Thorne model[7] of a thin accretion disk (Li et al. 2005).

Cygnus X-1 was discovered at the dawn of X-ray astronomy (Bowyer et al. 1965) and is one of the brightest and most persistent celestial X-ray sources. Its compact primary was the first object to be established as a black hole via dynamical observations (Webster & Murdin 1972; Bolton 1972). For several decades, the source has been extensively observed at radio, optical, ultraviolet and X-ray wavelengths.

Cygnus X-1 is typically in a hard spectral state, but occasionally it switches to a soft state, which may persist for up to a year (see Figure 1). It is only in this soft state, when the disk spectrum is prominent, that one can measure the spin using the continuum-fitting method we employ. In this soft state, which corresponds to the steep power-law (SPL) state[8], a strong Compton component is always present. Although Cygnus X-1 has been observed on thousands of occasions, it has never been observed to reach the thermal dominant (TD) state, the state that is most favorable for the measurement of spin via the continuum-fitting method (Steiner et al. 2009a).

Following the pioneering work of Zhang et al. (1997), we measure black hole spin by estimating the inner radius of the accretion disk $R_{\rm in}$. In this approach to measuring spin, one identifies $R_{\rm in}$ with the radius of the innermost stable circular orbit $R_{\rm ISCO}$, which is predicted by general relativity. $R_{\rm ISCO}$ is a monotonic function of the dimensionless spin parameter a_*, decreasing from 6 GM/c^2 to 1 GM/c^2 as spin increases from $a_* = 0$ to $a_* = 1$ (Bardeen et al. 1972)[9]. This relationship between a_* and $R_{\rm ISCO}$ is the foundation for measuring spin by either the continuum-fitting method (Zhang et al. 1997) or by the Fe Kα method (Fabian et al. 1989; Reynolds & Nowak 2003).

The identification of $R_{\rm in}$ with $R_{\rm ISCO}$ is strongly supported by the abundant empirical evidence that the inner radius of the disk in the soft state of a black hole binary does not appear to change even as the temperature and luminosity change. LMC X-3 is a prime example; its inner-disk radius has been shown to be stable to several percent over a period of 26 years (Done et al. 2007; Steiner et al. 2010). Strong theoretical support for identifying $R_{\rm in}$ with $R_{\rm ISCO}$ is provided by magnetohydrodynamic simulations of thin accretion disks, which show the disk emission falling off rapidly inside the ISCO (Shafee et al. 2008; Reynolds & Fabian 2008; Penna et al. 2010; Kulkarni et al. 2011; Noble et al. 2010).

In our early work on measuring spin, we relied solely on TD-state data (e.g., Shafee et al. 2006; McClintock et al.

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[7] Note that we have corrected the original Novikov-Thorne equations (Novikov & Thorne 1973) for the problem identified by Riffert & Herold (1995). The term "Novikov-Thorne" here refers to a relativistic and geometrically-thin accretion disk in Kerr geometry with a no-torque boundary condition at the disk's inner edge.

[8] Throughout, we use the X-ray states defined by Remillard & McClintock (2006): hard; thermal dominant (TD); steep power-law (SPL); and intermediate states. In the alternative state classification scheme of Homan & Belloni (2005), the only states reached by Cygnus X-1 are the Low/Hard, Hard-Intermediate and Soft-Intermediate, which correspond respectively to our hard, intermediate (i.e., hard:SPL) and SPL states.

[9] $a_* \equiv cJ/GM^2$ with $|a_*| \leq 1$, where M and J are respectively the black hole mass and angular momentum.