A Double Outburst from IGR J00291+5934: Implications for Accretion Disk Instability Theory

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A DOUBLE OUTBURST FROM IGR J00291+5934: IMPLICATIONS FOR ACCRETION DISK INSTABILITY THEORY

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ABSTRACT

The accretion-powered millisecond pulsar IGR J00291+5934 underwent two ~10 day long outbursts during 2008, separated by 30 days in quiescence. Such a short quiescent period between outbursts has never been seen before from a neutron star X-ray transient. X-ray pulsations at the 599 Hz spin frequency are detected throughout both outbursts. For the first time, we derive a pulse phase model that connects two outbursts, providing a long baseline for spin frequency measurement. Comparison with the frequency measured during the 2004 outburst of this source gives a spin-down during quiescence of $-(4 \pm 1) \times 10^{-15}$ Hz s$^{-1}$, approximately an order of magnitude larger than the long-term spin-down observed in the 401 Hz accretion-powered pulsar SAX J1808.4−3658. If this spin-down is due to magnetic dipole radiation, it requires a $2 \times 10^{18}$ G field strength, and its high spin-down luminosity may be detectable with the Fermi Large Area Telescope. Alternatively, this large spin-down could be produced by gravitational wave emission from a fractional mass quadrupole moment of $Q/I = 1 \times 10^{-9}$. The rapid succession of the outbursts also provides a unique test of models for accretion in low-mass X-ray binaries. Disk instability models generally predict that an outburst will leave the accretion disk too depleted to fuel a second outburst after such a brief quiescence. We suggest a modification in which the outburst is shut off by the onset of a propeller effect before the disk is depleted. This model can explain the short quiescence and the unusually slow rise of the light curve of the second 2008 outburst.

Key words: binaries: general – stars: individual (IGR J00291+5934) – stars: neutron – stars: rotation – X-rays: binaries – X-rays: stars

1. INTRODUCTION

The longevity of the Rossi X-ray Timing Explorer (RXTE) has provided the opportunity to observe multiple outbursts from accretion-powered millisecond pulsars (AMSPs) with recurrence times of ~10 years or less. Such observations can address a diverse array of science. The pulse timing of multiple outbursts can measure changes in the spin of the neutron star (NS), which places limits on its magnetic field and gravitational wave emission. Comparison of the light curves and spin frequency derivatives during outburst probes the interaction between the NS and the accretion disk, while the shape of the pulses constrains the nature of the X-ray emission and the magnetically channeled accretion flow. Finally, the observation of multiple outbursts provides tests of disk instability models and other theories put forward to explain the recurrence of these sources. In this paper, we report on the observation by RXTE of a second and third outburst of the 599 Hz accreting pulsar IGR J00291+5934. These outbursts were separated by only 30 days of quiescence, a more rapid recurrence than has ever been seen before from an NS low-mass X-ray binary (LMXB). The proximity of the two outbursts proves particularly useful for addressing many of the above questions.

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) first detected IGR J00291+5934 at the onset of an outburst on 2004 December 2 (Eckert et al. 2004). Follow-up observations with RXTE revealed pulsations at a frequency of 598.89 Hz (Markwardt et al. 2004b), modulated by a 147.4 minute orbit (Markwardt et al. 2004a). Analysis of the pulsations revealed them to be highly sinusoidal across a wide range of energies (Galloway et al. 2005; Falanga et al. 2005b). Pulses arrived progressively sooner with increasing energy over 2–8 keV, following the pattern of soft lags observed in other AMSPs (Galloway et al. 2005), but above 8 keV these soft lags diminished, a reversal not seen in other AMSPs that may have important implications for the origin of these lags (Falanga & Titarchuk 2007). Fractional amplitudes were between 5%–10% rms, generally decreasing with energy (Galloway et al. 2005). Pulse timing models for the 2004 outburst require a spin derivative of 8.5(1.1) × 10−13 Hz s−1 (Falanga et al. 2005b; Burderi et al. 2007), which has been ascribed to the NS being spun up by the accreting matter (Burderi et al. 2007). (Note that paranthetical uncertainties are at the 1σ level throughout this paper.) Aperiodic timing of IGR J00291+5934 reveals an unusual amount of timing noise at very low frequencies (0.01–0.1 Hz), producing a timing spectrum more akin to black holes than to other NS LMXBs (Linares et al. 2007).

A mission-long light curve from the RXTE All Sky Monitor showed marginal (5σ) detections of earlier outbursts during 1998 November and 2001 September (Remillard 2004). With each outburst, the duration of quiescence increased by 160–170 days. A quadratic fit to these outburst times predicted a 3.6 year quiescence between the 2004 outburst and the start of the 2008 outbursts (Galloway 2008). This estimate proved to be accurate to within 1% of the recurrence period, with the source returning to outburst on 2008 August 13 (Chakrabarty et al. 2008).

X-ray observations between the 2008 outbursts show that IGR J00291+5934 reached a flux level consistent with prior measurements during longer intervals of quiescence. On August 21 the Swift X-ray Telescope (XRT) gave a 3σ upper limit on the unabsorbed 2–10 keV flux of $4.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, and on August 25 an XMM observation detected the source at an unabsorbed 2–10 keV flux of $(1.4 \pm 0.3) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$.
nearly two years after the 2004 outburst showed an unabsorbed flux of $1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (Jonker et al. 2008). Because the accretion episodes during 2008 were separated by a quiescent period during which accretion was very low or halted entirely, we refer to them as two separate outbursts, 2008a and 2008b.

In this paper, we present a detailed analysis of the 2008 outbursts of IGR J00291+5934 and the implications for our understanding of recurrent X-ray transients. We describe the RXTE observations and data analysis in Section 2, and we present the results of this analysis in Section 3. In Section 4, we examine what the 2008 double outburst can tell us about the theories of accretion disk instability. In Section 5 we consider other evidence for changes in the accretion regime at low fluxes, and in Section 6 we derive limits on the NS magnetic field. In Section 7, we discuss the long-term spin evolution and the possible sources of torque on the NS. In the final section, we summarize our results and conclusions.

2. OBSERVATIONS AND ANALYSIS

IGR J00291+5934 was found to be in outburst during an RXTE monitoring observation on 2008 August 13 (Chakrabarty et al. 2008). RXTE observed the source daily during this outburst (observation IDs 93013-07-*). By August 22, the source had faded below the RXTE detection threshold ($\approx 1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$). Intensive RXTE observation ended on August 30, and the program of twice-weekly $\approx 1$ ks monitoring observations (observation IDs 93435-01-*) resumed. On September 18 an optical observation found the source to have unexpectedly re-brightened, and a Swift XRT observation on September 20 confirmed that IGR J00291+5934 was again in outburst (Lewis et al. 2008). Longer, more frequent RXTE observations resumed shortly thereafter. This second outburst persisted through October 3. During the first outburst, 20 RXTE observations were taken, totaling 75.3 ks of exposure; during the second, 12 observations were taken, totaling 37.9 ks. Figure 1 shows the RXTE light curve of these outbursts and the times of observations.

We analyzed the data from the RXTE Proportional Counter Array (PCA; Jahoda et al. 1996), which comprises five identical, co-aligned proportional counter units (PCUs) sensitive to 2.5–60 keV photons within $\approx 1^\circ$ of the pointing axis. Due to the increased frequency of high-voltage breakdowns in the PCUs (Jahoda et al. 2006), an average of only 1.7 PCUs were taking usable data during the observations. For comparison, an average of 2.8 PCUs were active during the 2004 outburst of IGR J00291+5934. The resulting mean effective area during the 2008 outbursts was 2100 cm$^2$.

We derived outburst light curves using only PCU 2, which was active throughout all the observations. We fit each observation with an absorbed blackbody plus power-law model using XSPEC and the latest PCA response matrix (version 11.7) to estimate the 2.5–25 keV flux and its uncertainty. Note that the absorbed fluxes are given throughout this paper (i.e., the flux as observed by RXTE). Instrumental background levels were estimated using the FTOOL pcabackest.$^5$

The large field of view of the PCA also admits photons from the nearby intermediate polar V709 Cas, located 17 arcmin away from IGR J00291+5934. For all observations, the RXTE science axis was pointed at IGR J00291+5934, resulting in the PCA collimator admitting 70% of the photons from V709 Cas (using the linear collimator model from Section 8.3 of Jahoda et al. 2006). We estimated its contribution using the monitoring observations of the IGR J00291+5934 field that preceded and followed the 2008 outbursts. The mean 2.5–25 keV flux was $0.68 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ after subtracting the instrumental background, implying an unattenuated flux from V709 Cas of $1.0 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. Earlier observations suggest that its 2.5–25 keV flux varies within $(0.9–1.3) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (de Martino et al. 2001; Falanga et al. 2005a; and references therein), consistent with our results. The uncertainty in our V709 Cas flux measurements sets a PCA detection threshold of $\approx 1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for IGR J00291+5934. The flux of V709 Cas is modulated by its 312.8 s rotational period (Haberl & Motch 1995) with a fractional amplitude of 20%–30% (de Martino et al. 2001). When dividing RXTE observations into shorter intervals, we chose integral multiples of the V709 Cas period to simplify the estimation of its contribution.

For our coherent timing analysis, we included 2–15 keV photons to maximize the signal to noise ratio. We shifted the photon arrival times to the solar system barycenter using the DE405 solar system ephemeris and the optical and near-infrared position given by Torres et al. (2008): R.A. = $00^h29^m03^s05 \pm 0^s01$, decl. = $+59^\circ34'18''93 \pm 0''05$ (J2000.0). This position is consistent with the Chandra X-ray position (Paizis et al. 2005) and the optical point of Fox & Kulkarni (2004), which was used to derive the pulse timing ephemerides in Galloway et al. (2005). After barycentering the photon arrival times, we applied the RXTE fine clock correction and filtered out data during Earth occultations and intervals of unstable pointing. We searched the data for thermonuclear (type I) X-ray bursts; none were present.

To measure the times of arrival (TOAs) and fractional amplitudes of the persistent pulsations, we folded 626 s intervals of data (twice the V709 Cas period) using the Galloway et al. (2005) timing model. The timing models were applied and fitted using the TEMPO pulse timing program, version 11.005,$^7$ and

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$^5$ This R.A. differs by $-0.032 (3.2\sigma)$ relative to the radio position of Rupen et al. (2004), which was used to derive the pulse timing ephemerides of Falanga et al. (2005b) and Burderi et al. (2007). If these ephemerides had used the optical position, their frequencies would shift by $\Delta v = 4 \times 10^{-4}$ Hz and $\Delta v = 1.0 \times 10^{-4}$ Hz s$^{-1}$. This offset in $v$ is far too small to account for the spin-ups reported by these authors.

$^7$ At http://www.atnf.csiro.au/research/pulsar/tempo
assumed a circular orbit and a fixed spin frequency. From the resulting folded pulse profiles, we measured the phases and amplitudes of the fundamental harmonic of the pulsation. Higher harmonics had insufficient power to be useful for pulse phase timing. Estimation of phase and fractional amplitude uncertainties follows the procedures described in Hartman et al. (2008).

We also analyzed the aperiodic variability during the IGR J00291+5934 outbursts to characterize its broadband noise properties and search for quasi-periodic oscillations (QPOs). We followed the procedures and conventions of Linares et al. (2007), who measured the timing spectrum of the 2004 outburst, so that our results would be directly comparable. We selected 2.5–30 keV photons, as per the earlier study, and modified their properties and search for quasi-periodic oscillations (QPOs).

IGR J00291+5934 outbursts to characterize its broadband noise spectra using the rms normalization of van der Klis (1995). We averaged the power spectra to create a single spectrum for each observation, after subtracting the contribution from instrumental background and the nearby intermediate polar V709 Cas. The dotted gray line indicates the critical flux $f_{x,c}$, which marks the quickening of the decay during the 2004 and 2008a outbursts and the maximum during the 2008b outburst. The dotted gray line shows the best-fit models for each outburst. Phases and fractional amplitudes are shown for the 2.5–15 keV band. 95% upper limits on the fractional amplitudes are indicated for observations without detectable pulsations; these upper limits for the first and last observations of the 2008b outburst were very weak ($\approx0.05$% rms).

3. RESULTS

3.1. Outburst Light Curves and Fluences

The light curve of the first 2008 outburst showed a fast rise and slow decay. The rise of the outburst occurred in less than 3.5 days, the length of time separating the observations during the PCA monitoring campaign. A monitoring observation on MJD 54688.4 gave a 2.5–25 keV flux from the field of $(0.72 \pm 0.06) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, consistent with the flux of V709 Cas. By the next monitoring observation, on MJD 54691.9, the total 2.5–25 keV flux had risen to the outburst maximum of $(6.4 \pm 0.8) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, implying a peak flux from IGR J00291+5934 of $5.7 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. The daily averages from the Swift Burst Alert Telescope (BAT) suggest that this rise occurred in a single day, although their large uncertainties ($\approx3 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$) limit the significance of this measurement. After $\approx3$ days near its maximum, the first outburst decayed with an e-folding time of $(1.8 \pm 0.3)$ days, returning to quiescence in $\approx5$ days. The 2.5–25 keV fluence of the first outburst, after subtracting a $0.68 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ mean contribution from V709 Cas, was $(3.0 \pm 0.1) \times 10^{-8}$ erg cm$^{-2}$. Most of the uncertainty in this figure reflects the uncertainty in the V709 Cas flux.

Following the first outburst, IGR J00291+5934 returned to quiescence for 30 days. The mean 2.5–25 keV flux from the PCA field centered on IGR J00291+5934 was $0.70 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ during this period, with an rms scatter of $0.08 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. This flux and scatter are consistent with the monitoring observations before and after the 2008 outbursts and with the expected V709 Cas contribution.

Unlike the first outburst, the second had an approximately symmetric light curve. In $\approx7$ days it rose from quiescence to a peak 2.5–25 keV source flux of $(4.3 \pm 0.2) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, remained at this peak flux for 2–3 days, then dimmed back to quiescent levels over the subsequent $\approx7$ days. Observations during the decay were too sparse to determine whether the decay was exponential. Despite its qualitatively different light curve, the second outburst had approximately the same fluence as the first: $(3.1 \pm 0.1) \times 10^{-8}$ erg cm$^{-2}$.

A critical flux of $f_{x,c} = 4.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (2.5–25 keV) played an important role in the three outbursts observed from IGR J00291+5934. The top panels of Figure 2 show their light curves, with $f_{x,c}$ marked by the dotted horizon-

Figure 2. Light curves, phases, and fractional amplitudes of the observed outbursts of IGR J00291+5934. The light curves show the 2.5–25 keV flux, with one point per observation, after subtracting the contribution from instrumental background and the nearby intermediate polar V709 Cas. The dotted gray line indicates the critical flux $f_{x,c}$, which marks the quickening of the decay during the 2004 and 2008a outbursts and the maximum during the 2008b outburst. The phases and fractional amplitudes of the observed outbursts of IGR J00291+5934. The light curves show the 2.5–25 keV flux, with one point per observation, after subtracting the contribution from instrumental background and the nearby intermediate polar V709 Cas. The dotted gray line indicates the critical flux $f_{x,c}$, which marks the quickening of the decay during the 2004 and 2008a outbursts and the maximum during the 2008b outburst. The phases and fractional amplitudes of the observed outbursts of IGR J00291+5934. The light curves show the 2.5–25 keV flux, with one point per observation, after subtracting the contribution from instrumental background and the nearby intermediate polar V709 Cas. The dotted gray line indicates the critical flux $f_{x,c}$, which marks the quickening of the decay during the 2004 and 2008a outbursts and the maximum during the 2008b outburst. The phases and fractional amplitudes of the observed outbursts of IGR J00291+5934. The light curves show the 2.5–25 keV flux, with one point per observation, after subtracting the contribution from instrumental background and the nearby intermediate polar V709 Cas. The dotted gray line indicates the critical flux $f_{x,c}$, which marks the quickening of the decay during the 2004 and 2008a outbursts and the maximum during the 2008b outburst.
The 2004 outburst was the brightest, longest, and most frequently observed by RXTE. While its flux was above $f_{x,c}$, it decayed linearly at a rate of $(-0.89 \pm 0.01) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ day$^{-1}$. Upon reaching $f_{x,c}$, the decay quickened and became exponential, with an $e$-folding time of $(1.9 \pm 0.2)$ days (in reasonable agreement with the 2.2 day timescale reported by Falanga et al. 2005b in their analysis of the INTEGRAL light curve of this outburst). The critical flux played a similar role in the 2008a outburst: the slow decay seen during the first three days of the outburst quickened considerably after crossing below $f_{x,c}$. Finally, the symmetric light curve of the 2008b outburst slowly rose to a maximum flux of $\approx f_{x,c}$, then reversed and slowly decayed. The implications of this critical flux will be considered in Section 4.

The linear decay that we report during the first seven days of the 2004 outburst is contrary to theoretical expectations, and it therefore merits close examination. The accretion disk model of Powell et al. (2007), which we discuss in detail in Section 4.2, predicts an exponential decay for this part of the outburst, and Falanga et al. (2005b) reported an exponential fit to these data. To parameterize the shape of this decay, we use the following model:

$$f_x = \left( f_{x,0}^{-\xi} + f_{x,c}^{-\xi} \right)^{-\frac{1}{\xi}}.\tag{1}$$

We fit the initial flux $f_{x,0}$ at time $t = 0$, the decay timescale $\tau$, and the shape parameter $\xi$. This choice of model will be motivated by our investigation of irradiated accretion disks in Section 4.2, but for now note that it encompasses linear ($\xi = -1$), exponential (the limit $\xi \to 0$), and $1/\tau$ decays ($\xi = 1$).

The brightest portion of the 2004 light curve is consistent with linear decay: $\xi = -1.05 \pm 0.13$ with $\chi^2 = 38.2$ for 16 degrees of freedom. In comparison, forcing an exponential model (i.e., holding $\xi$ fixed at very nearly zero) gives $\chi^2 = 121.4$ for 17 degrees of freedom. Figure 3 compares these two fits. Some irradiated accretion disk models have $\xi = 1/4$, which fares even worse: $\chi^2 = 177.0$ for 17 degrees of freedom. The timescale for the linear fit is $\tau = 4.9 \pm 0.1$ days, which is the length of time needed for the flux to fall by the amount $f_{x,c}$. This $\tau$ is similar to the 6.6 day $e$-folding timescale reported by Falanga et al. (2005b) for an exponential fit. Note that we can exclude an exponential decay even without the outlying first observation (on MJD 53342), since the $\chi^2$ for an exponential fit remains roughly three times the linear $\chi^2$ without this point.

### 3.2. Spectral Evolution during the Outbursts

The unusual light curves of the 2008 outbursts of IGR J00291+5934 naturally raise the question of whether its spectrum undergoes significant change during the outbursts. In particular, does the spectrum show any transition accompanying the change in the decay rate at $f_{x,c}$?

Other sources with “knees” in their light curves do not have associated abrupt spectral changes. RXTE observations of AMSPs are generally well fit by an absorbed $\sim 1$ keV blackbody plus power law. In the case of SAX J1808.4—3658, the power-law index gradually softened from 1.5 to 1.9 over the course of the outbursts (Gierliński et al. 2002; Ibragimov & Poutanen 2009), but no significant change in this trend coincided with that source’s transition from slow to rapid decay (Hartman et al. 2009b). For SWIFT J1756.9—2508, the photon index softened from 1.8 to 2.0 (Linares et al. 2008). XTE J0929—314 and XTE J1751—305 had roughly constant spectral parameters, with no change across the knees of their light curves (Juett et al. 2003; Gierliński & Poutanen 2005). Analysis of the 2004 outburst of IGR J00291+5934 by Paizis et al. (2005) reported an unchanging spectrum: their fits used a $\sim 1$ keV blackbody component and a constant photon index of 1.6. They also found hints of a 6.4 keV iron line.

To measure the spectrum of IGR J00291+5934, we first fit the contribution from the nearby intermediate polar V709 Cas. For the 2004 outburst we used the RXTE observations of the IGR J00291+5934 field following its quiescence, and for 2008 we used the observations during the 30 day quiescence between outbursts. In both cases, we fit V709 Cas with an absorbed thermal bremsstrahlung spectrum plus a narrow iron line fixed at 6.4 keV. The resulting plasma temperatures of $26 \pm 5$ keV in 2004 and $31 \pm 4$ keV in 2008 agree with earlier findings (de Martino et al. 2001; Falanga et al. 2005a). When performing subsequent fits of IGR J00291+5934, we held the parameters of the V709 Cas contribution fixed for each epoch, effectively subtracting its contribution from the total flux. To reduce the uncertainty introduced by potential errors in our V709 Cas fits, we only measured the spectral parameters of IGR J00291+5934 using observations in which it was brighter than V709 Cas.

We fit the IGR J00291+5934 flux using an absorbed blackbody plus power law, with the addition of a 6.4 keV iron line when needed. The absorption column was held fixed at $N_H = 4.6 \times 10^{21}$ cm$^{-2}$ based on the optical work of Torres et al. (2008). Figure 4 shows the key results. The blackbody temperature was consistent with a constant 0.9 keV. In agreement with the analysis of Paizis et al. (2005), we found that this blackbody component fades more rapidly than the power-law component during 2004, becoming insignificant around the time when the total flux falls below $f_{x,c}$; however, this is not the case for the 2008 outbursts, for which the ratio of the blackbody and power-law contributions remains roughly constant throughout. We found that the power-law component softened during the 2004 and 2008a outbursts. Data for the 2008b outburst are limited but are consistent with a constant power-law index. This softening during 2004 is contrary to the results reported in Paizis et al. (2005). This discrepancy was likely due to an insufficient compensation for the harder spectrum of V709 Cas: if its contribution is not subtracted, the overall power-law index is indeed roughly constant. These 2008 spectra are generally compatible with the two contemporaneous Swift XRT detections, which yielded power-law indices of $\approx 1.6$ and did not require blackbody components (Lewis et al. 2010).
The proximity of the 2008 outbursts enables phase connection between two AMSP outbursts for the first time. With frequency accuracies of $\sim 30$ nHz for the two outbursts, the phase uncertainty when connecting across the 30 day interim of quiescence is $\sim 0.05$ cycles—small enough to ensure that we do not miss or include an extra rotation of the NS. This long baseline greatly improves the accuracy of our pulse timing model and the best constant-frequency fit is given in Table 1. This frequency is consistent with the frequencies measured for the individual outbursts. The addition of a frequency derivative does not significantly improve the fit.

This phase connection between outbursts does require the assumption that torques during the 30 day quiescence are small. A quiescent spin derivative of $|\dot{\nu}| \gtrsim 3 \times 10^{-13}$ Hz s$^{-1}$ would introduce an unknown number of phase wraps. We will address whether such torques are physical in the discussion. It is worth noting that the phases of the two 2008 outbursts line up quite well. If we extrapolate the phase solution of the 2008a constant-frequency model forward and apply it to the 2008b outburst without any additional fitting, the residuals during 2008b have a mean offset of only $+0.02$ cycles relative to our solution. If phase wraps occurred between 2008a and 2008b, then this excellent alignment would be purely coincidental.

Finally, we consider the possibility that the marginal spin-ups during the 2008 outbursts are real. For concision, we compare their effects relative to the best-fit constant frequency during 2008, $v_0 = 598.892130804$ Hz. The values of $\dot{\nu}$ listed in Table 1 would result in a frequency of $v = v_0 + 0.23(13)$ $\mu$Hz at the end of 2008a (at MJD 54697.0) and $v = v_0 - 0.24(11)$ $\mu$Hz at the beginning of 2008b (at MJD 54730.0). The NS would have to undergo a mean spin-down of $\dot{v} = -1.7(6) \times 10^{-13}$ Hz s$^{-1}$ during the intervening 33 days of quiescence to account for this decrease of frequency. If a spin-up is present during these outbursts, then a spin-down of a similar magnitude necessarily follows them.

### 3.4. Long-term Spin and Orbital Evolution

Despite the highly accurate (2 nHz uncertainty) timing solution attained by phase connecting the 2008 outbursts, it is still not feasible to phase connect the 2004 and 2008a outbursts. During the 3.6 years of quiescence separating these outbursts, magnetic dipole torques from the NS’s unknown field strength (say, $10^{7.5} - 10^{8.5}$ G) will produce $\sim 1$–$50$ phase wraps relative to a model with a constant frequency. This prevents the construction of a coherent timing model for all the data.

Comparing the frequencies of the outbursts is more useful. From the ephemeres of Falanga et al. (2005b), the frequency at the end of the 2004 outburst will be $v = v_0 + 0.32(4) \mu$Hz; the model of Burderi et al. (2007) and our own analysis give similar figures. As discussed in the previous section, the determination of $\dot{v}$ for the 2008a outburst is more ambiguous. If we accept the marginally significant spin-up, then the frequency at the beginning of the 2008a outburst is $v = v_0 - 0.21(19) \mu$Hz; if not, then we can phase connect the 2008 outbursts to give the constant frequency model of Falanga et al. (2005b).

### Table 1

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Note. For models with a non-zero $\dot{\nu}$, $\nu$ is specified in the middle of the outburst.
frequency of $v_0$ with an uncertainty of 0.002 $\mu$Hz. These scenarios produce respective frequency drops of 0.53(20) $\mu$Hz and 0.32(4) $\mu$Hz during the 3.6 years of quiescence. Averaged over the entire quiescent period, these drops represent a mean spin-down of $-(3-5) \times 10^{-15}$ Hz s$^{-1}$.

Connecting the orbital phases of the 2004 and 2008 outbursts provides a great increase in the accuracy of the orbital period. Table 2 summarizes the orbital ephemeris derived by combining the data from all three outbursts. Detecting an orbital period derivative is possible in principle with three orbital phase measurements, but the proximity of the 2008 outbursts prevents anything more than a weak upper limit on the orbital period derivative. The effect of any physically plausible derivative on the orbital phase during the 30 days separating the outbursts would be too small to measure.

3.5. Pulse Profiles

The pulses from IGR J00291+5934 were entirely consistent with a sinusoid across the 2–60 keV energy band of the PCA. A relatively low amount of timing noise allowed us to integrate the pulse profile over both 2008 outbursts. Folding all the 2.5–15 keV photons gave a profile that was well fit by a pure sinusoid with no harmonics ($\chi^2 = 259.8, 253$ degrees of freedom). The fractional amplitude in this band was 10% rms and remained roughly constant throughout both outbursts. The 95% upper limits on the fractional amplitude for the second and third harmonics were both 0.36% rms or $\lesssim 4\%$ of the fundamental’s amplitude. These results are consistent with the non-detection of harmonics during the 2004 outburst (Galloway et al. 2005; Falanga et al. 2005b).

To measure the energy dependence of the pulsations, we divided the PCA response into 15 energy bands and folded all the 2008 outburst data for each. Figure 5 shows the measured pulse arrival times and fractional amplitudes. Data from the 2004 outburst are also shown for comparison. Pulsations were detected with 99% confidence at 2–35 keV (2–48 keV during the 2008 outburst). Error bars show the statistical uncertainties. For the fractional amplitudes, an additional uncertainty in the overall vertical offset is introduced by the approximated flux from V709 Cas.

From 2 to 8 keV, the pulse arrival times follow the usual pattern of soft lags that is seen in most other AMSPs. As Falanga & Titarchuk (2007) noted for the 2004 outburst, above 8 keV the trend reverses and harder bands increasingly lag. Agreement between the 2004 and 2008 phases is generally good. There was no significant change in the magnitude of the lags over the course of the outbursts, in contrast to the flux dependence of the lags observed in SAX J1808.4–3658 (Hartman et al. 2009b).

The fractional amplitude decreases significantly until 8 keV, above which the energy dependence is weaker but with some evidence of further decrease. The error bars for both the phases and amplitudes only account for statistical uncertainty. The fractional amplitude errors do not include the uncertainty in the flux from V709 Cas, which is assumed to be the same for both outbursts. Nevertheless, the offset between the 2004 and 2008 amplitudes is significant. The V709 Cas flux would have to be 30% higher during 2004 to account for this fractional amplitude difference, but a comparison of its flux from monitoring observations after the 2004 and 2008 outbursts returned to quiescence show that this was not the case.

No pulsations were detected during the quiescent period between the 2008 outbursts. Folding all data in MJD 54700–54730 yields a 95% upper limit on the pulse fractional amplitude of 0.4% rms, accounting for instrumental background only. This limit further supports the assumption that the non-background photons during this period are from V709 Cas, and IGR J00291+5934 is indeed in quiescence.

3.6. Aperiodic Timing

A broadband power spectrum of IGR J00291+5934 reveals a number of notable features. Figure 6 shows the spectra, and Table 3 lists some of their properties. For comparison, the top plot of Figure 6 shows the power spectrum of the first 6 days of the 2004 outburst, a selection labeled “subset A1” in the analysis of Linares et al. (2007). High levels of aperiodic timing noise distinguish the spectra of this source from those of other NS LMXBs. The noise level is flat down to very low frequencies (∼0.01 Hz), resulting in integrated fractional variabilities over 0.01–100 Hz of 40%–60% rms. Additionally, two harmonically related QPOs are present at around 0.02 Hz and 0.04 Hz (Linares et al. 2007).

The broadband shape and integrated variability of the 2008 power spectra are similar. The spectra are roughly flat down to a break at ∼0.01 Hz, and the integrated fractional variability is ∼50% rms. No QPOs were detected during the 2008a outburst, but its higher overall noise level would be sufficient to bury the QPOs observed during 2004 if they were present at the same fractional amplitude and coherency (∼5% rms; $Q \approx 5$), so their non-detection is not constraining. During the 2008b outburst, a single QPO was definitively seen near the low-frequency break.
only the brightest part of that outburst, as defined by Linares et al. (2007). Lorentzians with non-zero coherences. Subset A1 of the 2004 outburst includes the overall variability and the flux and the positive correlation Linares et al. (2007), particularly the anticorrelation between (13 "hump" present during 2008b. This QPO has an amplitude of the QPO frequencies seen in the earlier outburst. An additional QPO at 0.45 Hz is needed to model the steeper power spectrum particularly the knee at the critical flux $f_{x,c}$. These two outbursts were preceded by a long (~3 year) period of quiescence, and they followed a fast rise/slow decay profile. Both showed a knee in the decay at a critical 2.5–25 keV flux of $f_{x,c} = 4.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. During the 2004 outburst, the decay prior to the knee was nearly linear, with a timescale of $f_{x,c}/f_{x} = 4.9$ days; during the 2008a outburst, a lower peak flux and sparser sampling prevented characterization of the nature of the pre-knee decay. Both outbursts showed exponential decays after the knee with e-folding times of ~1.9 days. Stop the 2008a outburst before the disk becomes too depleted to fuel the 2008b outburst. Unless the mass transfer rate from the companion can vary by orders of magnitude on a ~1 month timescale, the mass needed for 2008b could not have accumulated during the 30 day quiescence that preceded it. The 2.5–25 keV fluence of the 2004 outburst was $5.2 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$, and the summed fluence of the 2008 outbursts was similar, at $6.1 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$. Taking these fluences and a 3 year recurrence time as typical, we estimate that at least 95% of the matter accreted during 2008b must have been present in the disk at the end of 2008a. Account for the symmetric light curve of 2008b, and why its peak flux is $f_{x,c}$. In contrast to outbursts following a long period of quiescence, the 2008b outburst rose slowly over ~7 days until reaching a maximum flux of $f_{x,c}$. After 2–3 days at this maximum flux, the outburst then slowly decayed back to quiescent levels over another ~7 days. It is unclear which harmonic it represents if it is a member of a harmonically related QPO pair: at 0.026 Hz, it falls between the QPO frequencies seen in the earlier outburst. An additional QPO at 0.45 Hz is needed to model the steeper power spectrum “hump” present during 2008. This QPO has an amplitude of (13 ± 2)%, a coherency of $Q = 1.5 \pm 0.5$, and is present in all 2008b observations with sufficient integration time to detect it. The 2008 data support some of the overall trends identified by Linares et al. (2007), particularly the anticorrelation between the overall variability and the flux and the positive correlation between the break frequency and the flux.

4. MODELING THE OUTBURST LIGHT CURVES

The most unusual feature of the 2008 activity of IGR J00291+5934 is its light curve: the source undergoes two outbursts in rapid succession. We are unaware of any other NS LMXB for which this is the case.9 This double outburst provides a rigorous test of the accretion disk models put forward to explain the transient nature of many LMXBs. A successful theory must accomplish the following:

- Explain the light curves of the 2004 and 2008a outbursts, particularly the knee at the critical flux $f_{x,c}$. These two outbursts were preceded by a long (~3 year) period of quiescence, and they followed a fast rise/slow decay profile. Both showed a knee in the decay at a critical 2.5–25 keV flux of $f_{x,c} = 4.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. During the 2004 outburst, the decay prior to the knee was nearly linear, with a timescale of $f_{x,c}/f_{x} = 4.9$ days; during the 2008a outburst, a lower peak flux and sparser sampling prevented characterization of the nature of the pre-knee decay. Both outbursts showed exponential decays after the knee with e-folding times of ~1.9 days.
- Stop the 2008a outburst before the disk becomes too depleted to fuel the 2008b outburst. Unless the mass transfer rate from the companion can vary by orders of magnitude on a ~1 month timescale, the mass needed for 2008b could not have accumulated during the 30 day quiescence that preceded it. The 2.5–25 keV fluence of the 2004 outburst was $5.2 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$, and the summed fluence of the 2008 outbursts was similar, at $6.1 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$. Taking these fluences and a 3 year recurrence time as typical, we estimate that at least 95% of the matter accreted during 2008b must have been present in the disk at the end of 2008a.
- Account for the symmetric light curve of 2008b, and why its peak flux is $f_{x,c}$. In contrast to outbursts following a long period of quiescence, the 2008b outburst rose slowly over ~7 days until reaching a maximum flux of $f_{x,c}$. After 2–3 days at this maximum flux, the outburst then slowly decayed back to quiescent levels over another ~7 days.

We consider this unique phenomenology in light of three models: the disk diffusion model of Wood et al. (2001), which was developed to explain a similar double outburst from the black hole transient XTE J1118 + 480; accretion from a partially ionized irradiated disk; and accretion at rates near the onset of 9 Some NS LMXBs do show much shorter (~3 days) and dimmer mini-outbursts or flares that recur frequently; XTE J1751–305 (Markwardt et al. 2007) and NGC 6440 X-2 (Heinke et al. 2010) are notable examples. At the other extreme, the intermittently pulsating AMSP HETE J1900.1–2455 has been in outburst since 2005, with the exception of 1–6 days in 2007 during which it was briefly quiescent (Degenaar et al. 2007). Unlike these systems, all the outbursts from IGR J00291+5934 resemble the typical ~10 day outbursts seen in most NS LMXB transients.
a quasi-propeller state, in which the centrifugal acceleration of infalling matter by the NS magnetosphere inhibits but does not halt accretion.

4.1. Disk Diffusion Model

The one other LMXB with a published report of a double outburst is the black hole transient XTE J1118+480. Its first outburst lasted 40 days and followed a fast rise/exponential decay profile. After 30 day quiescence, a second outburst lasted 150 days and had an irregular profile with multiple peaks (Wood et al. 2001).

Additionally, IGR J00291+5934 and XTE J1118+480 have similar aperiodic timing properties. Lináres et al. (2007) note that the strong very-low-frequency (<0.1 Hz) variability and high overall variability of IGR J00291+5934 much more closely resemble the timing spectra of black hole LMXRs than other NS LMXBs. In Section 3.6, we reported a 0.45 Hz QPO during the 2008b outburst of IGR J00291+5934; scaled for the difference in central object masses (1.4 $M_\odot$ versus 6–7 $M_\odot$), it matches the ~0.1 Hz QPO observed during the second outburst of XTE J1118+480 (Wood et al. 2000). The data for the 2008b outburst were not adequate to determine whether the QPO frequency increased over the course of the outburst, as was observed for XTE J1118+480.

Given the observational similarities between these sources, it is worth considering the disk diffusion model of Wood et al. (2001). Noting that the disk instability model was insufficient to explain the double outburst of XTE J1118+480, they proposed that the light curve followed from a varying mass loss rate from the companion, which would accrete onto the NS after diffusing through the accretion disk. The resulting light curve would be the convolution of the companion’s mass loss function and a fast-rise, exponential-decay diffusion function that acts on the viscous timescale of the disk. It is unlikely that this model can account for the outbursts of IGR J00291+5934, however. If the viscous timescale of the disk is similar to the decay timescales of the 2004 and 2008a outbursts, then their observed light curves would require a very rapid (<3 days) transfer from the companion to the outer accretion disk of most of the mass consumed in those outbursts. Furthermore, a disk diffusion model cannot explain the knee in the light curves. The 2008b outburst would require only slightly slower transfer of matter from the companion to the disk.

4.2. Accretion from an Irradiated Disk

We next consider the outbursts from the perspective of the disk instability model as applied to soft X-ray transients by King & Ritter (1998, hereafter KR98) and Powell et al. (2007, hereafter P07). In this approach, the accretion disk is divided into two regions: a hot inner disk in which ionization results in a fully ionized, non-ionized outer disk in which the inward drift is much lower.

The radial extent of the hot, ionized region can be calculated by considering the temperature of the disk due to irradiation from the NS. If an accretion disk with a scale height $H \propto R^n$ and albedo $\eta_x$ is irradiated by a small central source with a luminosity $L_v$, de Jong et al. (1996) calculate its temperature profile to be

$$T^4 = \frac{1 - \eta_x}{4\pi R^2} \frac{H}{R} (n - 1) L_v. \quad (2)$$

Following the argument of P07, the hot region will extend out to some temperature $T_h$ at which the gas in the disk becomes mostly ionized. If we denote the radius of this temperature as $R_h$, we can solve to find

$$R_h^{3-n} \propto L_v \propto \dot{M}_x. \quad (3)$$

where $\dot{M}_x$ is the accretion rate on the compact object. When the disk is illuminated by a point-like central source, as is the case here, $n \approx 9/7$ (KR98).

Above some critical accretion rate $\dot{M}_{x,c}$, the luminosity will be sufficient to ionize the entire disk. Thus we can write

$$\frac{R_h}{R_{\text{disk}}} = \left( \frac{\dot{M}_x}{\dot{M}_{x,c}} \right)^{1/(3-n)} \equiv \tilde{m}_x^\gamma. \quad (4)$$

To simplify, we define the dimensionless accretion rate $\tilde{m}_x = \dot{M}_x/\dot{M}_{x,c}$ and the disk opening-angle parameter $\gamma = 1/(3 - n)$. As $\dot{M}_x$ falls below $\dot{M}_{x,c}$, the transition from a fully to a partially ionized disk will generally cause the decay rate to increase, causing a knee in the light curve. This mechanism has been invoked to explain the knee seen in the outburst light curves of many transient LMXBs (e.g., P07).

4.2.1. Assumptions of the Viscosity Model

The models of KR98 and P07 make two assumptions about the disk viscosity. (1) The viscous timescale of the ionized region of the accretion disk is shorter than the decay timescale of the outburst:

$$\tau_{\text{visc}} \sim \frac{R^2}{\nu} \approx \left| \frac{d \ln M_x}{dt} \right|^{-1}. \quad (5)$$

Here, $\nu$ is some mean kinematic viscosity of the ionized region. (Throughout this discussion, we adopt the convention that $T$ represents the kinematic viscosity rather than the NS spin frequency, unless otherwise noted.) If this condition is met, the surface density of the hot disk will relax into the quasi-steady profile:

$$\Sigma_{\text{hot}}(R) \approx \frac{\dot{M}_x}{3 \pi \nu}. \quad (6)$$

(2) The viscous timescale of the cold region is far longer than the decay timescale, so its surface density profile can be treated as independent of $\dot{M}_x$.

For simplicity, the calculations of these papers also make the approximation $n = 1$ (or equivalently $\gamma = 1/2$) for an NS LMXB, and they use a constant mean kinematic viscosity for $\nu$. We adopt a more general approach by keeping $\gamma$ a free parameter and by allowing the disk viscosity to vary with the radius and accretion rate:

$$\nu(R, \dot{M}_x) = \nu_0 \left( \frac{R}{R_{\text{disk}}} \right)^{\beta} \tilde{m}_x^\gamma. \quad (7)$$

For the Shakura & Sunyaev (1973) disk solution, $\xi = 3/10$ and $\beta = -3/4$. For an irradiation-dominated disk, we assume $\nu \propto T$, and Equation (2) gives $\xi = 1/4$ and $\beta = (n - 3)/4 \approx -3/7$.

4.2.2. Light Curve Decay of a Fully Ionized Disk

Following the arguments of KR98, we can analytically solve for the light curve when the accretion disk is entirely ionized:

$$\dot{M}_x = \left( \dot{M}_{x,0} + \dot{M}_{x,c} \cdot \frac{1}{\tau_{\text{hot}}} \right)^{-1/\xi}. \quad (8)$$
The initial accretion rate is $M_{x,0}$ at time $t = 0$, and the timescale for decay is

$$
\tau_{\text{hot}} = \frac{2(1 - \xi)}{3(2 - \beta)} \frac{R_{\text{disk}}^2}{v_0}.
$$

(9)

Note that in the limit of a uniform and constant viscosity ($\beta = 0$), these equations reduce to the exponential decay given in KR98: $M_{x} = M_{x,0} \exp(-t \cdot 3\gamma / R_{\text{disk}}^2)$.

In this model, a knee in the decay of the outburst is generally attributed to a transition from a fully to partially ionized disk. However, it is not possible to reconcile this hypothesis with the linear decay observed when $f_x > f_{x,c}$ during the 2004 outburst of IGR J00291+5934. Fitting Equation (8) to the light curve, we find $\gamma = -1.05 \pm 0.13$, in strong disagreement with the expected value of $\gamma = 0.25$ for an irradiated disk. Therefore the accretion disk of IGR J00291+5934 is not fully ionized during the initial decay of the 2004 and 2008a outbursts, and the significance of $f_{x,c}$ must be otherwise explained.

### 4.2.3. Behavior of a Partially Ionized Disk

When the disk is only partially ionized, we consider the mass budget of the hot disk, following P07:

$$
M_{\text{hot}} = -M_x + \mu_{\text{cold}}(R_h) + 2\pi R_h \dot{R}_h \Sigma(R_h).
$$

(10)

The $M_{\text{hot}}$ term can be derived by integrating the hot-disk surface density out to $R_h$, then taking the time derivative. From assumption 1, this surface density follows Equation (6). The $\mu_{\text{cold}}(R_h)$ term gives the viscously driven inward flow of matter from the cold disk at $R_h$. From assumption 2, the radial flow in the cold disk is far smaller than in the hot disk, so we can neglect this term. The $\Sigma(R_h)$ term reflects the addition of cold-disk material due to the encroaching ionization radius during the outburst rise, and conversely the return of matter to the cold disk as $R_h$ recedes during the outburst decay.

Applying these relations to Equation (10) and casting it in terms of the dimensionless accretion rate $\dot{m}_x = M_x / \dot{M}_{x,c}$ gives a general model for the partially ionized disk:

$$
\dot{m}_x = \left[ 2\pi \gamma \dot{m}_x 2^{y-2} \frac{R_{\text{disk}}^2 \Sigma(R_h)}{M_{x,c}} - \frac{1 - \xi}{1 - \xi} \tau_{\text{hot}} \dot{m}_x^{-1 - \frac{1}{\tau_{\text{hot}}}} \right]^{-1}.
$$

(11)

To simplify, we define the constant $\zeta = \xi - \gamma(2 - \beta)$. The behavior is determined by the form of $\Sigma(R_h)$. For $R_h < 0$, the surface density of the hot disk is relevant: $\Sigma(R) = \Sigma_{\text{hot}}(R)$ from Equation (6). For $R_h > 0$, $\Sigma(R)$ is the surface density of the cold disk, which depends on the state of the disk prior to outburst. As the forms of $\Sigma_{\text{hot}}$ and $\Sigma_{\text{cold}}$ are generally different, we must handle the two cases separately.

During the decay of an outburst from a partially ionized disk, the fall of $M_x$ will cause $R_h$ to move inward. As it does, the surface density of matter that this cooling front encounters will follow the quasi-stable hot disk profile of Equation (6), and from assumption 2 this $\Sigma_{\text{hot}}(R_h)$ will become “frozen” into the cold disk profile as $R_h$ passes inward.

This “freezing in” of the hot disk surface density provides another test of the hypothesis that the light curve knee marks the transition from a fully to partially ionized disk. The resulting density profile left behind is

$$
\Sigma(R) = \frac{M_{x,c}}{3\pi v_0} \left( \frac{R}{R_{\text{disk}}} \right)^{-\beta + (1-\zeta)/\gamma}.
$$

(12)

For the $\gamma, \xi$, and $\beta$ of an irradiation-dominated disk,

$$
\Sigma(R) = 0.5 \times \frac{\tau_{\text{hot}} M_{x,c}}{R_{\text{disk}}^2} \left( \frac{R}{R_{\text{disk}}} \right)^{1.7}.
$$

(13)

If we assume full ionization at $f_{x,c}$, then we can measure $\tau_{\text{hot}} = 6.6$ days from the initial decay of the 2004 outburst (Falanga et al. 2005b) and use $f_x/f_{x,c} = M_x/M_{x,c}$ to convert between flux and the relative accretion rate. Integrating Equation (13) over the disk then gives a post-outburst mass sufficient to account for only 70% of the observed fluence during the 2008b outburst. No physical viscosity model will leave 95% of the 2008b fluence remaining in the disk after the 2008a outburst, as required. Again, it is difficult to reconcile the observed outbursts with the accretion disk of IGR J00291+5934 ever being fully ionized.

In contrast, this approach can successfully model the outburst light curve when $f_x > f_{x,c}$ if we assume a partially ionized disk. In this scenario Equation (11) can be solved analytically, giving a decay for a partially ionized disk with the same form as the fully ionized case but with $\zeta$ as its shape parameter:

$$
\dot{M}_x = \left( \frac{M_{x,0} - M_{x,c}}{M_{x,c}} \right) \left( \frac{t}{\tau_{\text{hot}}} \right)^{-1/\zeta}.
$$

(14)

Assuming a constant viscosity and a disk scale height that increases linearly with radius, we obtain $\zeta = -1$, giving the linear decay predicted by KR98 and P07. For an irradiation-dominated disk and a gas-pressure-dominated SS disk, the shape parameter is $\zeta = -1.17$ and $\zeta = -1.30$, respectively. The observed decay shape parameter of $-1.05 \pm 0.13$ when $f_x > f_{x,c}$ is compatible with the expected irradiated disk. However, another mechanism must be invoked to explain the knee at $f_{x,c}$.

### 4.3. Magnetospheric Inhibition of Accretion

The drop in the accretion rate when the flux falls below $f_{x,c}$ may also be caused by the onset of magnetospheric effects. This explanation has been invoked to explain similar drops in the light curves of other NS LMXBs (e.g., Aql X-1, Campana et al. 1998; SAX J1808.4-3658, Gilfanov et al. 1998). As the accretion rate declines, the magnetospheric radius moves outward: $R_m \propto M_x^{-2/7}$. When $R_m$ exceeds the co-rotation radius $R_{\text{co}}$, which the Keplerian orbital frequency equals the NS spin frequency, infalling matter must accelerate to co-rotate with the magnetic field. At this point the source is typically said to enter the “propeller” regime, as it was originally thought that centrifugal acceleration would eject matter from the system (Illarionov & Sunyaev 1975). In fact, this picture is not energetically self-consistent, and $R_m/R_{\text{co}} \gtrsim 1.2$ is required for mass ejection (Rappaport et al. 2004; Perna et al. 2006). Below this limit, matter will build up in the vicinity of $R_m$ until its material pressure pushes the magnetosphere inward, allowing matter to accrete onto the NS and relieving the pressure on $R_m$ (Spruit & Taam 1993). We refer to this intermediate state as the “quasi-propeller” accretion mode, because the centrifugal acceleration of infalling matter throttles but does not entirely stop accretion.

Modeling the throttling of the accretion rate induced by the onset of a quasi-propeller state is beyond the scope of this paper, but we consider some qualitative predictions. In particular, it can account for the different shapes of the outburst light curves during 2004 and 2008a, which both exhibit a fast rise and a
linear-then-exponential decay, and 2008b, which has a roughly linear rise, a plateau, then a roughly linear fall. The key to this difference is the distribution of matter in the accretion disk prior to the outbursts. Additionally, the rapid drop in flux caused by the onset of the quasi-propeller state allows enough mass to remain in the disk following the 2008a outburst to fuel the 2008b outburst.

First, consider the 2004 and 2008a outbursts. An accretion disk that has been quiescent for a sufficient length of time will relax into a constant-density state (KR98):

$$\Sigma(R) \propto H \propto R^n \approx R^{1.2}.$$  \hspace{1cm} (15)

Distributing an initial disk mass accordingly and integrating Equation (11), we get a light curve that rises faster than exponentially. This rise breaks our first assumption, that the hot disk can maintain a quasi-steady-state density profile, but it is qualitatively instructive: it predicts the fast rise observed for an outburst following a long quiescence. For these outbursts, the rising flux never became bright enough to fully ionize the accretion disk, causing the initial outburst decay to be approximately linear, as discussed in the previous section. Finally, when the flux reached \( f_{x,c} \), magnetospheric throttling becomes effective, causing the decay rate to greatly increase and ultimately quenching the outburst.

The accretion disk that was present at the beginning of outburst 2008b would not have had time to relax into a quiescent profile, so it depended on the profile left behind by 2008a. Consider the instantaneous state of the accretion disk when the 2008a outburst reached the knee at \( f_x = f_{x,c} \). In the cold region of the disk (i.e., outside the \( R_h \)) corresponding to the flux \( f_{x,c} \), the disk profile left behind by the cooling front will follow Equation (13):

$$\Sigma(R) \propto R^{-\beta+\left(1-\alpha\right)/\gamma} \approx R^{1.7} \quad \text{for} \quad R \geq R_h(f_{x,c}).$$  \hspace{1cm} (16)

In the ionized region, the quasi-steady surface density profile of Equation (6) will be present:

$$\Sigma(R) \approx \frac{M_x}{3\pi v} \propto R^{-\beta} \approx R^{0.4} \quad \text{for} \quad R \leq R_h(f_{x,c}).$$  \hspace{1cm} (17)

As the flux continued to fall, the onset of magnetospheric throttling caused the decay timescale to become faster than the viscous timescale. The result is a greater amount of mass remaining in the inner disk than predicted by Equation (13): 40% more matter would have been accreted if the light curve had continued to follow a linear decay rather than becoming exponential. The distribution of the remaining inner disk mass will fall between its state at the onset of magnetic throttling and the distribution left behind by freezing in the quasi-steady profile: \( 0.4 < d \log \Sigma/d \log R < 1.7 \) for \( R \leq R_h(f_{x,c}) \). Finally, during the 30 day quiescence the disk profile would begin to relax toward the constant-density \( R^{1.2} \) distribution, but it likely would not have enough time to reach it.

This disk profile has two repercussions. First, the faster shutoff of accretion should leave sufficient mass in the disk to fuel the 2008b outburst. Second, the distribution of this mass can result in the observed 2008b light curve. \( \Sigma(R) \) of the inner disk has a smaller gradient than it would after a long period of quiescence, so the amount of mass that \( R_h \) encounters as it expands outward increases more gradually. As a result, we do not get the sudden, super-exponential brightening seen for 2004 and 2008a. Once the flux reaches \( f_{x,c} \), however, the heating front will encounter a lower surface density, as the disk ionized by fluxes higher than \( f_{x,c} \) will have been more fully depleted by 2008a. This change in \( d \log \Sigma/d \log R \) will stop the advance of \( R_h \), initiating the outburst decay. The result is a slow rise, slow decay outburst that peaks at \( f_{x,c} \), as observed.

We have not attempted to explain what stops the rapid rise of the 2004 and 2008a outbursts. One possibility is self-shadowing by the accretion disk: a warped disk or a point at which the radial dependence of the disk height decreased would halt or slow the outward movement of the ionization front during the outburst rise. Regardless of the mechanism, the lower peak flux of the 2008a outburst caused it to more quickly reach the onset of rapid decay at \( f_{x,c} \), ultimately leading to a shorter outburst with an accreted mass of roughly half the mass consumed during the 2004 outburst. It is likely that the lower peak flux of 2008a was a necessary condition for enough matter to be left in the disk to fuel the 2008b outburst.

5. EVIDENCE FOR CHANGES IN THE ACCRETION STATE

The previous section showed how the transition of IGR J00291+5934 from steady accretion to a quasi-propeller state at the light curve knee could successfully account for the other features of the outburst light curves. This explanation has two requirements of the accretion rate corresponding to the knee: first, it must not fully ionize the accretion disk, and second, it must be compatible with the expected accretion rate at which the NS magnetosphere begins transferring angular momentum to the infalling material. In this section, we address these requirements. We also consider other evidence suggesting that IGR J00291+5934 enters a quasi-propeller state during its outbursts. Throughout, we compare with the 401 Hz AMSP SAX J1808.4—3658, which also shows light curve knees that are most likely associated with the onset of the quasi-propeller state (e.g., Hartman et al. 2009b; Patruno et al. 2009a).

5.1. The Accretion Rate at the Light Curve Knee

Distance estimates to IGR J00291+5934 cover 2–5 kpc (see Torres et al. 2008 for a recent review); we choose 4 kpc for our calculations, which is consistent with mass transfer arguments and the lack of observed thermonuclear bursts (Galloway et al. 2005). The bolometric correction factor for our 2.5–25 keV fluxes is \( c_{bol} = 2.54 \) (Galloway et al. 2005). With an assumption of a canonical NS mass and radius \( (M_x = 1.4 M_\odot, R_x = 10 \text{ km}) \), the accretion rate at the light curve knee is

$$\dot{M}_{x,c} = \frac{4\pi d^2 R_x}{GM_x} c_{bol} f_{x,c} = 1.8 \times 10^{-10} M_\odot \text{ yr}^{-1}. \hspace{1cm} (18)$$

The distance uncertainty introduces a factor of \( \sim 2 \) uncertainty in this figure.

The outburst light curves of SAX J1808.4—3658 also show a knee at which decay steepens. Assuming a distance of 3.5 kpc (Galloway & Cumming 2006) and identical NS parameters, the accretion rate at that source’s knee is also \( 1.8 \times 10^{-10} M_\odot \text{ yr}^{-1} \) (Hartman et al. 2009b). The perfect agreement of these numbers is a coincidence, of course, but it does strongly suggest that the light curve knees of the two sources arise from the same physical process. Considerable evidence points to this knee marking the beginning of the quasi-propeller state for SAX J1808.4—3658. A \( \sim 1 \) Hz QPO with a very high amplitude (sometimes >100% rms) is present after the knee of some outbursts. Patruno et al.
(2009a) argue that a natural explanation is provided by the Spruit & Taam (1993) instability, wherein matter that accumulates near the magnetospheric radius quasi-periodically drips onto the NS surface. Hartman et al. (2009b) show that the behavior of the soft lags of the pulsations also changes at this critical flux in a surface. Hartman et al. (2009b) show that the behavior of the magnetospheric radius quasi-periodically drips onto the NS. Mx profiles that flatten out at larger radii (e.g., Dubus et al. 1999), is plausible that it, too, is due to the Spruit–Taam instability. The energy dependence of the IGR J00291+5934 pulsations in IGR J00291+5934 at fluxes below $\dot{M}_{\text{accrete}}$, required to ionize the non-screened portion of the disk. The disk radius of IGR J00291+5934 must be smaller than $10^6$ km for the observed orbital parameters and realistic masses, allowing irradiation of some outer regions of Rappaport et al. (2004) produces a similar threshold between the onset of a quasi-propeller state) occurs when $R_m < R_m$ for a 1.4 $M_\odot$ NS (0.09–0.13 $M_\odot$ for a 2.0 $M_\odot$ NS). If the assumption of full ionization is dropped, then their calculated $a$ and $M_2$ ranges become lower limits and their i becomes an upper limit. A weaker upper limit on $M_2$ is provided by the requirement that the companion fits within its Roche lobe, giving $M_2 \lesssim 0.25 M_\odot$ (Galloway et al. 2005; Torres et al. 2008). The resulting range of allowed inclinations is $10^\circ$–$32^\circ$. A low inclination for this system is supported by the lack of harmonic content in the X-ray pulsations (e.g., Muno et al. 2002).

5.2. The Magnetospheric Radius at the Knee

As discussed at the beginning of Section 4.3, the mass accretion (or ejection) regime depends on the magnetospheric radius,

$$R_m = k_m (2G M_a)^{-1/7} M_\odot^{-2/7} \mu^{4/7}. \quad (20)$$

Here, $\mu$ is the magnetic dipole moment and $k_m$ is an order-unity constant that encapsulates the complex disk/magnetosphere interaction. Magneto-hydrodynamic simulations of Long et al. (2005) suggest a value of $k_m \approx 0.5$, which we adopt for our calculations. The accretion mode depends on the relation between $R_m$ and the Keplerian co-rotation radius $R_{co} = (GM_a/4\pi^2 v^2)^{1/3}$. Roughly speaking, for $R_m \lesssim R_{co}$, matter can accrete steadily onto the star; for $R_m \approx R_{co}$, centrifugal acceleration of infalling matter by the NS magnetosphere slows but does not entirely inhibit accretion, a regime we refer to as the quasi-propeller mode; and for $R_m \gtrsim R_{co}$, a true propeller effect as described by Illarionov & Sunyaev (1975) becomes energetically possible, ejecting matter from the system and thereby preventing accretion. For AMSPs, the transition zone around $R_m$ from a Keplerian to a co-rotating flow is wide, so changes in the mode of accretion are likely to be gradual.

Magneto-hydrodynamic simulation, analytic models, and observational evidence, all indicate that the transition from steady accretion to a quasi-propeller regime occurs around $R_m \approx 0.7 R_{co}$. The magneto-hydrodynamic simulations of Long et al. (2005) identified this ratio as the critical magnetospheric radius below which $\dot{\nu} > 0$ and above which $\dot{\nu} < 0$. The analytic model of Rappaport et al. (2004) produces a similar threshold between spin-up and spin-down. Finally, the well-constrained distance and magnetic field of SAX J1808.4–3658 allow us to calculate its $R_{co}$ from its observed flux using Equation (20). The knee in the decay of that source (along with other phenomena indicating the onset of a quasi-propeller state) occurs when $R_m = 0.6 R_{co}$ (Hartman et al. 2009b).

The magnetospheric radius implied at the knee of the IGR J00291+5934 outburst light curves is also consistent with this value. The long-term quiescent spin-down of this source

10 The 2002 outburst of SAX J1808.4–3658, which had a peak flux 50% brighter than the other outbursts, initially followed an approximately exponential decay until reaching a first knee while still at a relatively high flux. The decay then slowed, but whether its subsequent form was better fit with an exponential or linear model depends on the region fit. After a second knee at that source’s critical flux, it entered rapid decay (see Figure 3 of P07 and Figure 1 of Hartman et al. 2008). The peak flux of this outburst possibly does fully ionize the accretion disk, with the first knee marking the transition to partial ionization.

11 The ratio given in Rappaport et al. (2004) is $R_m \approx 1.87 R_{co}$, but this relation is based on a formal definition of $R_{co}$ that is a factor of 2.2 greater than ours. Adjusting for this difference gives $R_m \approx 0.85 R_{co}$. 

Finally, we must consider the detection of Hz emission during the 2004 and 2008 outbursts (Torres et al. 2008; Lewis et al. 2010) under the assumption of partial ionization. The Hz lines were double-peaked and showed no variation with orbital phase, clearly indicating their origin in the disk. Torres et al. (2008) reported a peak-to-peak separation of $\Delta v_{pp} = 650 \pm 40$ km s$^{-1}$ on 2004 December 5 (MJD 53344), near the peak of the 2004 outburst. Assuming that this $\Delta v_{pp}$ measured the line-of-sight velocity at the edge of a fully ionized accretion disk, they estimated an orbital separation of $a = (7.2–8.3) \times 10^5$ km, an inclination of $i = 22^\circ$–$32^\circ$, and a companion mass of $M_2 = 0.07–0.11 M_\odot$ for a 1.4 $M_\odot$ NS (0.09–0.13 $M_\odot$ for a 2.0 $M_\odot$ NS). If the assumption of full ionization is dropped, then their calculated $a$ and $M_2$ ranges become lower limits and their $i$ becomes an upper limit. A weaker upper limit on $M_2$ is provided by the requirement that the companion fits within its Roche lobe, giving $M_2 \lesssim 0.25 M_\odot$ (Galloway et al. 2005; Torres et al. 2008). The resulting range of allowed inclinations is $10^\circ$–$32^\circ$. A low inclination for this system is supported by the lack of harmonic content in the X-ray pulsations (e.g., Muno et al. 2002).
the range $1 < \frac{f_x}{f_{x,c}} < 10$ (Lewis et al. 2010). Horizontal dotted lines indicate the onset of magnetic throttling ($f_x/f_{x,c} \approx 1$ by assumption), the approximate flux below which the propeller effect should halt accretion entirely ($f_x/f_{x,c} \approx 0.12$), and the typical flux observed by Chandra during quiescence (see text for references). The solid gray line shows an exponential fit to the light curve during the magnetic throttling regime, and the dashed line extrapolates this fit to later times. Note that the XMM flux falls far below this trend line. There must be another break in the light curve around the time that the source falls below the PCA detection level.

suggests a magnetic dipole moment of $\mu = 1.1 \times 10^{26}$ G cm$^2$, which we derive in Section 7.2. From this field strength and the critical $M_x$ derived in Equation (18), Equation (20) gives us

$$\frac{R_{m, \text{knee}}}{R_{\text{co}}} = \frac{16 \text{ km}}{23.6 \text{ km}} = 0.7.$$  

(21)

This figure is in excellent agreement with theoretical expectations and our observations of SAX J1808.4−3658. It further reinforces the validity of our assumption that the light curve knee marks the transition into a quasi-propeller accretion state.

### 5.3. Halting of Accretion by the Propeller Effect?

The transition to a true propeller state, in which the centrifugal acceleration is capable of ejecting matter from the system, occurs at $R_m \approx 1.26 R_{\text{co}}$ if the transfer of angular momentum is perfectly efficient but inelastic (Rappaport et al. 2004); if the transfer is also perfectly elastic, this limit becomes $R_m \approx 1.13 R_{\text{co}}$ (Perna et al. 2006). From Equation (20), these radii respectively correspond to $f_x/f_{x,c} \approx 0.12$ and 0.19, giving 2.5–25 keV fluxes of $(5–8) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for IGR J00291+5934. Within or slightly below this range, we predict another knee in the light curve as the decay rate again increases and the outburst rapidly shuts off.

*Swift* XRT and *XMM* observations following the 2008a outburst require the presence of such a break. The trend line in Figure 7 shows the exponential decay fit to the PCA fluxes in the range $1 \geq f_x/f_{x,c} \geq 0.12$, for which the NS magnetosphere should slow but not entirely halt accretion. Its $e$-folding time is $1.8 \pm 0.3$ days, as reported in Section 3.1. After the outburst falls below $f_x/f_{x,c} \approx 0.2$, the decay accelerates. The two last *RXTE* observations in which IGR J00291+5934 is confidently detected to fall somewhat $(2\sigma – 3\sigma)$ below the extrapolated exponential decay curve. 1.4 days after the last *RXTE* detection, a $3\sigma$

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**Figure 7.** Comparison of the observed fluxes and predicted accretion regimes during the 2008a outburst. Fluxes are from the PCA (dots), *Swift* XRT (× marks), and *XMM* (square). *(Swift* and *XMM* measurements are taken from Lewis et al. 2010.) Horizontal dotted lines indicate the onset of magnetic throttling ($f_x/f_{x,c} \approx 1$ by assumption), the approximate flux below which the propeller effect should halt accretion entirely ($f_x/f_{x,c} \approx 0.12$), and the typical flux observed by Chandra during quiescence (see text for references). The solid gray line shows an exponential fit to the light curve during the magnetic throttling regime, and the dashed line extrapolates this fit to later times. Note that the XMM flux falls far below this trend line. There must be another break in the light curve around the time that the source falls below the PCA detection level.

**Figure 8.** Comparison of the AMSPs (stars), *Fermi* pulsars (black points), and radio pulsars without γ-ray emission (gray points). Pulsars in binary systems are circled. The top plot shows the standard $P$–$\dot{P}$ diagram. The two AMSPs with known quiescent spin-downs, SAX J1808.4−3658 and IGR J00291+5934, are located in the lower left corner, among the radio millisecond pulsars. Lines of constant magnetic field were calculated using the formula of Spitkovsky (2006). The bottom plot shows the spin-down luminosities, normalized by distance squared. These values are proportional to the spin-down flux that would be incident if all the sources radiated with perfect efficiency. *Fermi* pulsar parameters are from Abdo et al. (2010); radio pulsar parameters are from the Australia Telescope National Facility pulsar catalog (Manchester et al. 2005), online at http://www.atnf.csiro.au/research/pulsar/psrcat. Pulsars in globular clusters have been omitted.

*Swift* XRT upper limit falls well below it (Lewis et al. 2010). Finally, a deep *XMM* observation 11 days after the outburst peak and 5 days after the last *RXTE* detection revealed that IGR J00291+5934 had dropped to an unabsorbed $2–10$ keV flux$^{12}$ of $1.4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. This flux is lower than previously reported quiescent levels by a factor of $\sim 3$ (Jonker et al. 2005, 2008; Torres et al. 2008), although Jonker et al. (2005) notes that the quiescent X-ray flux can vary. IGR J00291+5934 could not have reached this quiescent flux so quickly without another steepening of the decay: fitting a constant decay rate between the last PCA detections and the XMM observation establishes a maximum $e$-folding time of 0.7 days. The actual decay rate was likely faster.

If the majority of optical emission during outburst is due to X-ray reprocessing, then we should expect a knee in the optical light curve if and when the mass accretion rate becomes low enough to be entirely halted by the propeller effect. Such a break was seen in the R band during the 2004 outburst when the X-ray flux was $f_x/f_{x,c} = 0.13 \pm 0.03$, in excellent agreement with our predictions (Torres et al. 2008). Gaps in the optical coverage of the 2008a and 2008b outbursts around the expected times of

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$^{12}$ Using the spectral models of Section 3.2, we calculate a factor of 1.7 to convert from the unabsorbed $2–10$ keV fluxes given by Lewis et al. (2010) to the absorbed $2.5–25$ keV fluxes quoted in this paper.
breaks prevented their detection or exclusion (Lewis et al. 2010; F. Lewis & D. M. Russell 2010, private communication).

5.4. Accretion Torques during Outburst

Changes in the accretion state should also change the X-ray timing properties of IGR J00291+5934. At accretion rates above the onset of the quasi-propeller state, the infalling matter should spin up the NS. When accretion enters the quasi-propeller state, which we suggest corresponds to the knee in the X-ray light curve, the transfer of angular momentum to the NS becomes inefficient or negative.

The 2004 outburst of IGR J00291+5934, which had a peak flux of roughly twice what was seen during 2008, showed a clear spin-up of $8.4(6) \times 10^{-13}$ Hz s$^{-1}$, which (Burderi et al. 2007) attributed to accretion torque. Under the assumption that the light curve knee approximately corresponds to the spin-up/spin-down equilibrium point, this result is expected.

In contrast, the $\nu$ measurements for the 2008 outbursts were poorly constrained: $10(10) \times 10^{-13}$ Hz s$^{-1}$ and $4.5(2.5) \times 10^{-13}$ Hz s$^{-1}$ respectively. At 1.0$\sigma$ and 1.8$\sigma$ significance, it is possible that these marginal spin-ups reflect timing noise rather than any change in the spin of the NS. If they are real, the frequency at the end of the 2008a outburst would be $0.5(2) \mu$Hz higher than the frequency at the beginning of the 2008b outburst, requiring a mean spin-down of $-1.7(6) \times 10^{-13}$ Hz s$^{-1}$ during the intervening 30 day quiescence. Spin-ups during the 2008 outbursts would also increase the implied long-term spin-down.

Yet the 2008b outburst, which never rose above $f_{x,c}$, was likely spent entirely in the quasi-propeller state or at the limit of its onset. We should therefore expect the NS to be spun down during this outburst. This is at odds with its 1.8$\sigma$ spin-up measurement. Given the low significance of this detection and the otherwise solid evidence that the knee at $f_{x,c}$ reflects a transition into a quasi-propeller state, it is likely that this $\nu$ is due to timing noise rather than a change in the NS spin. The case of the 2008a outburst is similar: because it spent little time ($\approx 2.5$ days) above $f_{x,c}$, a large spin-up is not expected.

6. MAGNETIC FIELD LIMITS FROM PULSATIONS

The presence of accretion-powered pulsations across a nearly two orders of magnitude in flux constrains the magnetic field strength of the NS. Psaltis & Chakrabarty (1999) used the similarly wide range of fluxes with detectable pulsations from SAX J1808.4−3658 to derive limits that were compatible with the magnetic field implied by the spin-down of that source (Hartman et al. 2009a). Here we apply their arguments to IGR J00291+5934.

The detection of pulsations when IGR J00291+5934 was at its peak flux indicates that the magnetic field must be strong enough to columnate the accretion flow above the NS surface even when the accretion rate is at its maximum. Setting the magnetospheric radius $R_m$ from Equation (20) equal to the NS radius $R$, and solving for the magnetic dipole moment $\mu$ gives a lower limit:

$$\mu > 1.6 \times 10^{35} \text{ G cm}^3 \left(\frac{k_m}{1.0}\right)^{-7/4} \times \left(\frac{M_\ast}{2.3 M_\odot}\right)^{-1/4} \left(\frac{R}{10 \text{ km}}\right)^{9/4} \left(\frac{d}{3 \text{ kpc}}\right) \times \left(\frac{c_{bol} \cdot f_{x,\max}}{2.54 \cdot 11.1 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}}\right)^{1/2} \text{.}$$  \hspace{1cm} (22)

For this conservative limit, we have taken extreme values of the magnetospheric constant $k_m$, the NS mass and radius, and the distance to the source.

Conversely, at the lowest fluxes with detectable pulsations, the magnetic field cannot be so strong that it causes the ejection of matter due to the propeller effect. This propeller regime turns on at around $R_m = 1.3 R_\odot$ (Rappaport et al. 2004). Solving for $\mu$, we get an upper limit:

$$\mu < 1.2 \times 10^{27} \text{ G cm}^3 \left(\frac{k_m}{0.2}\right)^{-7/4} \left(\frac{v}{599 \text{ Hz}}\right)^{-7/6} \times \left(\frac{M_\ast}{2.3 M_\odot}\right)^{1/3} \left(\frac{R}{15 \text{ km}}\right)^{1/2} \left(\frac{d}{5 \text{ kpc}}\right) \times \left(\frac{c_{bol} \cdot f_{x,\min}}{2.54 \cdot 0.66 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}}\right)^{1/2} \text{.}$$  \hspace{1cm} (23)

Again, we have adopted parameter values that give a conservative estimate of this limit.

7. IMPLICATIONS OF THE LONG-TERM SPIN-DOWN

The measured 2004 and 2008 frequencies give a mean long-term spin-down of $-4(\pm 1) \times 10^{-15}$ Hz s$^{-1}$. If this is at odds with both $\nu$ and $\dot{\nu}$ being higher for IGR J00291+5934, we could use this more conservative value. Adopting the higher figure would only strengthen our conclusions here.

The resulting spin-down luminosity is $\dot{E} = -2\pi^2 \mu \nu \dot{\nu} = 7 \times 10^{34} \text{ erg s}^{-1}$. This figure is eight times greater than the spin-down luminosity of SAX J1808.4−3658 (Hartman et al. 2009a), due to both $\nu$ and $\dot{\nu}$ being higher for IGR J00291+5934. We consider three possible mechanisms for this spin-down.

7.1. The Propeller Effect

In Section 4.3, we discussed the centrifugal expulsion of matter by the NS magnetosphere, commonly known as the propeller effect. This ejection of matter will produce a spin-down of the NS; however, it is unlikely that it is sufficient to explain the large frequency change observed between the 2004 and 2008 outbursts.

The propeller effect will eject matter from near the magnetospheric radius, producing a torque of

$$N_{prop} \approx M_{ej}(GM_\ast R_m)^{1/2}$$  \hspace{1cm} (24)

if matter is ejected at a rate of $M_{ej}$. Centrifugal ejection occurs if $R_m \gtrsim 1.3 R_\odot \approx 30$ km. $R_m$ varies weakly with $M_{ej}$, so it will not be much greater than this value. The $\Delta \nu$ is 0.32(4)$\mu$Hz frequency difference between the end of the 2004 outburst and the beginning of 2008a would then require a total mass ejection of $\approx 4 \times 10^{-11} M_\odot$ during the 3.7 year quiescence. The associated rate is an order of magnitude greater than the expected mass transfer rate of $3 \times 10^{-12} M_\odot$ yr$^{-1}$ from the low-mass companion assuming that transfer is driven by gravitational radiation from the binary orbit (Galloway et al. 2005).

7.2. Magnetic Dipole Spin-down

Magnetic dipole spin-down is a more likely cause. Pulsar magnetosphere simulations by Spitkovsky (2006) give a magnetic dipole torque of $N = -\mu^2 (2\pi \nu/c)^3 (1 + \sin^2 \alpha)$. Here $\alpha$
is the colatitude of the magnetic pole, which we assume to be small (≈15°) based on the highly sinusoidal pulse profile (e.g., Poutanen & Beloborodov 2006; Lamb et al. 2009). If this torque accounts for the entirety of the quiescent spin-down, it would require a magnetic dipole of (9.4 ± 0.8) × 10^{25} \text{ G cm}^3. For an NS radius of 10 km, the corresponding surface field is B = 2\mu R^{-3} = 1.9 × 10^{9} \text{ G} at the magnetic poles. This field strength is consistent with the limits derived in the previous section from magnetospheric arguments. It also agrees with the B < 3 × 10^{8} \text{ G} limit of Torres et al. (2008) based on the quiescent luminosity. Finally, the long-term spin-down of IGR J00291+5934 places it among the radio millisecond pulsars on the P–P diagram, shown in Figure 8, suggesting a common spin-down mechanism.

The high spin-down luminosity of IGR J00291+5934 makes it a good candidate for pulsation searches during quiescence. The discovery of spin-powered pulsations from a quiescent AMSP would provide a final and elusive missing link between the AMSPs and radio millisecond pulsars. γ-ray pulsation searches may be even more promising. The first millisecond γ-ray pulsars detected by the Fermi Large Area Telescope (LAT) convert their spin-down luminosities into γ-ray emission at high efficiencies (6%–100%) and emit pulsations into wide opening angles (Abdo et al. 2009). If Fermi does not detect pulsations from IGR J00291+5934, it would require a lower dipole spin-down to γ-ray emission efficiency from this source or a different spin-down mechanism entirely.

### 7.3. Gravitational Radiation Torque

Angular momentum loss through gravitational wave emission has been suggested as a way to explain the absence of very rapidly spinning (≥ 730 Hz) millisecond pulsars (Bildsten 1998; Chakrabarty et al. 2003; Chakrabarty 2005). The highly nonlinear $\nu^5$ dependence of the gravitational wave torque on spin rate $\nu$ means that this torque would dominate at the very highest spin rates but be negligible for slower spins, with a rather sharp transition. While there is no evidence that this mechanism is important at spins as slow as 400 Hz (Hartman et al. 2008), IGR J00291+5934 is a strong candidate since it is the most rapidly spinning AMSP. However, as in the case of SAX J1808.4–3658 (Hartman et al. 2008), we have already found that magnetic dipole torques due to the known magnetic field strength of the pulsar likely account for most of the spin-down in quiescence, suggesting that gravitational wave torques are unimportant even at 599 Hz.

For IGR J00291+5934, the quiescent spin-down places an upper limit on the NS’s mass quadrupole moment of \textsuperscript{13}

\[
Q < 1.2 \times 10^{36} \left( \frac{I}{10^{45} \text{ g cm}^2} \right)^{1/2} \left( \frac{\nu}{599 \text{ Hz}} \right)^{-5/2} \times \left( \frac{-\nu}{2.8 \times 10^{-15} \text{ Hz s}^{-1}} \right)^{1/2} \text{ g cm}^2
\]

\text{(25)}

or an ellipticity of $Q/I \lesssim 10^{-9}$ for moment of inertia $I$. The rapid spin of IGR J00291+5934 makes this limit approximately an order of magnitude more stringent than the similarly derived limit for SAX J1808.4–3658 (Hartman et al. 2008). It is appreciably lower than the upper limits on NS ellipticity from direct gravitational wave detectors: targeted LIGO searches of radio millisecond pulsars give a strongest upper limit of $Q/I < 7 \times 10^{-8}$ for the nearby pulsar PSR J2124–3358 (Abbott et al. 2010).

The spin-down of IGR J00291+5934 begins to test predictions of the expected quadrupole moments of accreting NSs. Accretion could result in a mass quadrupole through a variety of mechanisms. Electron capture due to higher temperature base of the accretion columns (Bildsten 1998; Ushomirsky et al. 2000), hydrodynamic turbulence due to accretion-induced differential rotation (Melatos & Peralta 2010), and the accumulation of “mountains” of accreted material (e.g., Haskell et al. 2006) all could produce ellipticities of up to $Q/I \sim 10^{-3}$, magnetic confinement of the accreted material could allow an even higher limit (Melatos & Payne 2005; Payne & Melatos 2006). The absence of such a high ellipticity in IGR J00291+5934 does not rule out any of these mechanisms, as their predictions depend on unknown NS parameters (e.g., the maximum strain upheld by the NS crust, or the ohmic diffusion timescale governing the settling of accreted material). Nevertheless, we may be entering the regime in which it is possible to begin constraining some of these parameters.

This upper limit for IGR J00291+5934 still does not exclude the possibility that gravitational wave torques affect the fastest pulsar spins, since the torque near the limiting ≥730 Hz spin frequency would be 2.7 times greater than in IGR J00291+5934 for the same $Q$. It is also feasible that gravitational wave emission is present only for a short time in these sources, acting only during and shortly after an outburst. Our limits in this paper and in Hartman et al. (2008) are valid only for the magnitude of a persistent quadrupole and do not exclude a larger quadrupole that dissipates substantially faster than the ~3 year outburst recurrence period.

### 8. CONCLUSIONS

We have presented a comprehensive analysis of the outbursts of IGR J00291+5934 and a self-consistent explanation for the observed behavior. In contrast with previous analyses of irradiated accretion disks in NS LMXBs, we posit that the irradiation never fully ionizes the disk of this source during the outbursts observed with RXTE in 2004 and 2008. Instead, we suggest that the NS magnetic field and its interaction with the accretion disk plays a central role in shaping the light curves of these outbursts.

The long-term spin-down of IGR J00291+5934 is most likely due to the magnetic dipole torque of a $2 \times 10^{8}$ G field at the NS surface. A magnetic field of this strength will impede the infall of matter when the accretion rate falls below $2 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$, in excellent agreement with the critical flux at which knees are observed in the 2004 and 2008a light curves. If these knees are due to disk-magnetosphere interaction, then it is unlikely that the disk was ever fully ionized: irradiation is not sufficient to ionize the entire disk at the lowest accretion rates observed with RXTE, and a second knee would likely be detectable if the transition from fully to partially ionized had occurred. Furthermore, the near-linear decay observed during the first week of the 2004 outburst is inconsistent with the exponential decay expected for a fully ionized disk but matches well with theoretical predictions when partial ionization is assumed.

Substantial evidence points to the onset of a “quasi-propeller” state at accretion rates below the light curve knee. By shutting off accretion more quickly than if the outburst was driven solely by irradiation, enough matter is left in the disk after the 2008a

\textsuperscript{13} The coefficient of Equation (25) differs from the value derived using Equation (17) of Hartman et al. (2008). The coefficient in that paper is incorrect: it should read $1.4 \times 10^{36} \text{ g cm}^2$, not $4.4 \times 10^{36} \text{ g cm}^2$. 

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outburst to fuel the 2008b outburst 30 days later. Additionally, the mass distribution left behind in the disk differs from the distribution expected after a long period of quiescence, priming the disk for the slow rise and maximum at $f_{1,c}$ seen in the 2008b outburst. In the quasi-propeller regime below the knee, accretion torques should be small or negative, and the non-detection of spin derivatives during the 2008 outbursts stands in contrast with the significant spin-up seen during the brighter 2004 outburst. Accretion instabilities associated with the magnetic throttling may explain the ~0.5 Hz QPO observed during the 2008b outburst. Finally, if the light curve knee is associated with the onset of the quasi-propeller effect, then there should be another knee near the RXTE PCA detection threshold beyond which the propeller effect can entirely eject infalling matter from the system, entirely halting accretion; indeed, Swift XRT observations and a deep XMM observation show that another light curve break must be present, causing the source to return to quiescent levels within days of falling below the RXTE detection threshold. Clearly there remains much work to be done, however, our invocation of magnetospheric effects has been largely qualitative or based on simplistic models, and more substantial analysis and modeling is necessary to gain a fuller understanding.

We thank Jean Swank and the RXTE team for scheduling these observations. We thank Diego Altamirano, Craig Heinke, Miriam Krauss, Fraser Lewis, Paul Ray, Michael Rupen, Dave Russell, and Kent Wood for helpful conversations and an anonymous referee for useful comments. J.M.H. thanks the NRAO for its hospitality and the use of its facilities during the writing of this paper. Two other papers analyzing the X-ray timing of these outbursts were posted on arXiv.org almost concurrently with this one: Patruno (2010) and Papitto et al. (2010). These authors derived compatible results for the spin frequencies during the outbursts and the long-term spin-down between 2004 and 2008, although Patruno (2010) claimed a higher significance for the bursts were posted on arXiv.org almost concurrently with this one: Patruno (2010) and Papitto et al. (2010). These authors derived compatible results for the spin frequencies during the 2008b outburst. In the quasi-propeller regime below the knee, accretion torques should be small or negative, and the non-detection of spin derivatives during the 2008 outbursts stands in contrast with the significant spin-up seen during the brighter 2004 outburst. Accretion instabilities associated with the magnetic throttling may explain the ~0.5 Hz QPO observed during the 2008b outburst. Finally, if the light curve knee is associated with the onset of the quasi-propeller effect, then there should be another knee near the RXTE PCA detection threshold beyond which the propeller effect can entirely eject infalling matter from the system, entirely halting accretion; indeed, Swift XRT observations and a deep XMM observation show that another light curve break must be present, causing the source to return to quiescent levels within days of falling below the RXTE detection threshold. Clearly there remains much work to be done, however, our invocation of magnetospheric effects has been largely qualitative or based on simplistic models, and more substantial analysis and modeling is necessary to gain a fuller understanding.

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