THE ACCRETING MILLISECOND X-RAY PULSAR IGR J00291+5934: EVIDENCE FOR A LONG TIMESCALE SPIN EVOLUTION

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ABSTRACT
Accreting millisecond X-ray pulsars like IGR J00291+5934 are important because they can be used to test theories of pulsar formation and evolution. They give also the possibility of constraining gravitational wave emission theories and the equation of state of ultra-dense matter. Particularly crucial to our understanding is the measurement of the long-term spin evolution of the accreting neutron star. An open question is whether these accreting pulsars are spinning up during an outburst and spinning down during quiescence as predicted by the recycling scenario. Until now it has been very difficult to measure torques, due to the presence of fluctuations in the pulse phases that compromise their measurements with standard coherent timing techniques. By applying a new method, I am now able to measure a spin-up during an outburst and a spin-down during quiescence. I ascribe the spin-up ($\dot{\nu}_{\text{sp}} = 5.1(3) \times 10^{-13}$ Hz s$^{-1}$) to accretion torques and the spin-down ($\dot{\nu}_{\text{sd}} = 3.0(8) \times 10^{-15}$ Hz s$^{-1}$) to magneto-dipole torques, as those observed in radio pulsars. Both values fit in the recycling scenario and I infer the existence of a magnetic field for the pulsar of $B \approx 2 \times 10^8$ G. No evidence for an enhanced spin-down due to gravitational wave emission is found. The accretion torques are smaller than previously reported, and there is strong evidence for an ordered process that is present in all outbursts that might be connected with a motion of the hot spot on the neutron star surface.

Key words: stars: neutron – X-rays: stars

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1. INTRODUCTION
The recycling scenario (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982) provides an evolutionary link between the young slowly rotating pulsars and the old fast millisecond pulsars. The evolutionary phase during which the pulsar is spun up occurs when a neutron star in a binary accretes gas stripped from the donor companion. The gas is channeled onto the magnetic poles producing X-ray pulses modulated at the rotational frequency of the neutron star. When the accreting pulsar starts to spin in the millisecond range it is called an accreting millisecond X-ray pulsar (AMXP).

To establish the presence of a spin-up process the measurement of torques is crucial. According to accretion theory, the excess angular momentum brought by the accreting gas is responsible for the acceleration of the neutron star rotation. However, if the angular momentum of the gas is not sufficiently high, the neutron star can be spun down during accretion (propeller regime; see the seminal works of Illarionov & Sunyaev 1975, Ghosh & Lamb 1979 and Ustyugova et al. 2006 for a recent study). The magnitude of the spin-up/down is correlated with the amount of accreted matter, and hence with the X-ray flux. In the past, several attempts have been made to measure a spin-up/down in several AMXPs, and a wealth of measurements are now available for at least 11 out of the 13 known AMXPs (see Wijnands 2004, Poutanen 2006, and di Salvo et al. 2008). To accomplish this, the X-ray pulse phases are measured and a timing model is fitted to represent the orbital motion, the spin frequency, and its first time derivative. In this model, one makes the assumption that the rotational parameters of the neutron star (spin frequency and its derivatives) are coincident with the observed pulse frequency and time derivatives (see, for example, Galloway et al. 2005 and Burderi et al. 2007).

However, large deviations from this model are usually seen in the timing residuals. These deviations, referred to as X-ray timing noise, represent some unmodeled component in the pulse phases that does not yet have a conclusive explanation. Recently, it has been shown that timing noise in at least six AMXPs is strongly correlated with the X-ray flux (Patruno et al. 2009). The major conclusion was that it is the pulse phase rather than its second time derivative (i.e., the pulse frequency derivative) to be correlated with the X-ray flux, in contrast to what predicted by accretion theory. A similar problem for accretion theory was seen in XTE J1807–204 (Patruno et al. 2010b), in which the pulse frequency derivative has no correlation with the X-ray flux, whereas the pulse phases are strongly correlated at all timescales with the X-ray flux. This is particularly convincing given the presence of large fluctuations in the X-ray flux at different timescales.

The first claim for a detection of an accretion torque in an AMXP was made by Falanga et al. (2005) for the AMXP IGR J00291+5934 (henceforth referred to as IGR J00291) during the first outburst extensively observed by Rossi X-Ray Timing Explorer/Proportional Counter Array (RXTE/PCA) and International Gamma-Ray Astrophysics Laboratory in 2004. Differently from many other AMXPs, the timing residuals of IGR J00291 look quite smooth, and the presence of timing noise is not as dramatic as in other AMXPs (Patruno et al. 2009). Therefore, at a first sight, it looks quite obvious to look for the presence of a spin-up which manifests as a parabolic trend in the pulse phases and can be measured according to standard coherent timing techniques. However, also the 2004 X-ray flux of IGR J00291 shows a smooth decay in time, and no sudden flux variations are observed. Therefore, if a correlation between the X-ray flux and the pulse phases is present, it is difficult to disentangle it from a parabolic variation due to a true spin-up, which is expected to be uncorrelated with the X-ray flux variations.

Patruno et al. (2009) studied the 2004 outburst of IGR J00291 and claimed that already during this outburst there
was a possible correlation between flux and pulse phases as seen in other AMXPs. Indeed, these authors questioned the presence of a torque as strong as that detected by Falanga et al. (2005), although they did not quantify the magnitude of the expected torque in IGR J00291.

In 2008, the AMXP IGR J00291 went in outburst again (Chakrabarty et al. 2008). This outburst was quite anomalous with respect to the previous one observed in 2004, since it showed first a faint outburst with a peak flux of about half the value of the 2004, and then went into a very low flux level for more than 30 days. During this low-level activity phase, the source was not detected by RXTE and was marginally detected by XMM-Newton (Lewis et al. 2010). After this period, a new high-level activity episode was recorded: the flux slowly rose for about 6 days, before decaying again and entering into quiescence on a timescale of approximately one week from the outburst peak. The 2008 outburst has shown therefore strong flux variations that might be correlated with the pulse phases.

The behavior of the 2008 outburst is also very attractive for the purpose of testing accretion theory and pulsars evolution. Thanks to the long baseline of the observations, it is possible to follow the evolution of the spin parameters in IGR J00291 on a timescale of four years. Only for two other AMXPs it has been possible to accomplish this: SAX J1808.4−3658 (Hartman et al. 2008, 2009; Patruno et al. 2009) and SWIFT J1756−2508 (Patruno et al. 2010a). The spin of these sources is consistent with very weak or no accretion torques during the outbursts, and with a spin-down during quiescence that can be interpreted as a magneto-dipole torque like that operating in radio millisecond pulsars.

The plan of the paper is as follows. In Section 2, I give a detailed summary of the observations used and explain the methodology applied to analyze the pulse phases and the X-ray flux.

In Section 3, I perform a detailed standard coherent analysis of the pulse phases of IGR J00291. The assumption made in this section is that accretion theory provides a good description of the behavior of pulse phases and consequently of the neutron star spin parameters, even if timing noise is present. This analysis is made to verify whether the minimal assumptions made in accretion theory are sufficient to provide a satisfactory explanation of the pulse phase behavior. I discuss inconsistencies in the results obtained with this methodology.

In Section 4, I study the correlations between X-ray flux and pulse phase variations. I propose an extended version of the method first appeared in Patruno et al. (2009) to measure the spin frequency and accretion torques under the assumption that X-ray flux variations have an effect on pulse phases. I call this method correlation coherent analysis, as opposed to the standard coherent analysis (see Sections 2.2 and 2.3). With this method I am able to remove the effects of the X-ray flux variations from the pulse phases and measure “cleaned” spin parameters.

In Section 5, I discuss the implication of the measurement of the spin period of IGR J00291. I first discuss the behavior of the pulsar spin during quiescence (Section 5.1) and then consider the detection of a spin-up during the 2004 outburst (Section 5.2). A discussion on the origin of X-ray flux and pulse phase correlations is provided in Section 5.3, where I suggest a possible connection of the pulse phase variations with a hot spot moving on the neutron star surface.

The spin-up timescale of IGR J00291 and the consequences on the lack of detected submillisecond pulsars and the spin distribution of accreting pulsars are discussed in Section 6.

Finally, the implications of the observed spin evolution are summarized in the framework of the recycling scenario (Section 7).

2. PULSATIONS AND X-RAY LIGHT CURVE: DATA REDUCTION

I use all RXTE PCA public data for the 2004 and 2008 outbursts of IGR J00291 (Table 1). I refer to Jahoda et al. (2006) for PCA characteristics and RXTE PCA absolute timing. I used all available Event 125 μs and Good-Xenon data,1 rebinned to 1/8192 s and in the 5−37 absolute channels that maximize the signal-to-noise ratio (S/N). The absolute channels correspond to ≈2.5−16 keV. The time of arrivals is correct to the solar system barycenter (TDB timescale) by using the best available astrometric position reported in Rupen et al. (2004). An optical position has also been reported by Torres et al. (2008) which differs by 0′.25 from the determination of Rupen et al. (2004). If the optical position is used, then a shift in pulse frequency and frequency derivative of 4×10−8 Hz and 10−14 Hz s−1 are expected (see, for example, Equations (A1) and (A2) in Hartman et al. 2008). These shifts are small enough to not affect the results reported in the paper.

The light curve is folded in data chunks of different length, between ∼1000 and ∼3000 s, keeping only those with S/N>3σ−3.3σ, giving <1 false pulse detection per source. The presence of V709 Cas in the field of view of IGR J00291 has no effect on the determination of the pulse phases. Indeed, using the harmonic decomposition (Boynton & Deeter1985), only the pulse phases at the very frequency of IGR J00291 are measured. The pulse amplitudes are instead strongly affected by the presence of V709 Cas, whereas the contamination cancels out when calculating the ratio between the amplitudes and the 1σ error. I detect only a significant number of pulsations at the fundamental frequency (ν) and then fitted the phases with a Keplerian orbit plus a linear and possibly a parabolic term representing v and v′ (see Sections 2.2 and 2.3 for more details).

I constructed the X-ray light curve using the counts in PCA absolute channels 5−37 (≈2.5−16 keV). The background contribution (calculated with the FTOOL pcabackest) is subtracted from the total counts.

2.1. X-ray Light Curves for the 2004 and 2008 Outbursts

The X-ray light curves for the 2004 and 2008 outbursts are shown in Figure 1. The first outburst has an approximately linear decay, with pulsations detected for 14 days, and a peak luminosity of 75 count s−1 PCU−1 in the 2.5−16 keV energy band, corresponding to an unabsorbed flux of 9.5×10−10 erg s−1 cm−2 (Markwardt et al. 2004) for a hydrogen absorption column of NH ∼ 7×1021 cm−2 and photon index

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1 Care has to be taken when combining Events 125 μs and Good-Xenon data, since a rigid shift of 2−12 s is present in the 2004 data due to a bug in an early version of the FTOOL xenon2fits (C. B. Markwardt 2010, private communication).
Before the 2004 outburst, other two outbursts were detected in the RXTE/ASM, with recurrence times of 2.80 yr and 3.23 yr (Remillard 2004; Galloway et al. 2008). The average recurrence time seems therefore to slightly increase on the long timescale. By using all these information, I can calculate the long-term average mass accretion rate in IGR J00291 for two outburst/quiescence cycles:

\[
\langle \dot{M} \rangle_{2004} = 7 \times 10^{-10} \times \frac{13.6 \text{ days}}{365 \text{ days}} \times \frac{1}{3.20 \text{ yr}} \simeq 8 \times 10^{-12} \, M_{\odot} \, \text{yr}^{-1}
\]

\[
\langle \dot{M} \rangle_{2008} = 5 \times 10^{-10} \times \frac{12.4 \text{ days}}{365 \text{ days}} + 6 \times 10^{-10} \times \frac{4.8 \text{ days}}{365 \text{ days}} \times \frac{1}{3.20 \text{ yr}} \simeq 7 \times 10^{-12} \, M_{\odot} \, \text{yr}^{-1}.
\]

Both values are in excellent agreement and point toward an accretion rate similar to that calculated for the AMXP SAX J1808.4–3658, which has showed six outburst/quiescence cycles with an \( \langle \dot{M} \rangle \simeq 10^{-11} \, M_{\odot} \, \text{yr}^{-1} \) (Bildsten & Chakrabarty 2001).

2.2. Old Method: Standard Coherent Analysis

Standard coherent methods (e.g., Taylor 1992) are based on folding procedures and to \( \chi^2 \) minimization techniques with a model describing the time evolution of the pulse phase \( \phi(t) \) at the barycentric reference frame. The pulse phases are then fitted with a Keplerian orbit and a spin frequency and its first time derivative (see, for example, Patruno et al. (2010b), and references therein for a discussion of the method). I performed this fit by using the standard coherent timing software TEMPO2 (Hobbs et al. 2006).

The spin frequency derivative is then associated with the accretion torque \( N \) via the simple expression given by accretion theory:

\[
N = 2\pi \dot{I} \dot{\psi}_a.
\]

If the orbital and astrometric components are correctly removed from the pulse phases, one expects to see in the timing residuals a set of independent values which are normally distributed around the zero average with an amplitude that can be predicted by propagating the Poisson uncertainties due to counting statistics.
coherent analysis instead of standard coherent analysis, the number of parameters used in the fit (and therefore the degrees of freedom) is exactly the same for the two methods, so there is no risk to over-fit the data when using the former method.

In Sections 3 and 4, I discuss the results and the implications of the two methods. If one applies standard coherent analysis, then the physical consequences seem contradictory and require extraordinary explanations. If one considers correlation coherent analysis, then the results match with a high degree of accuracy of the predictions of accretion theory.

### 3. STANDARD COHERENT ANALYSIS AND ACCRETION THEORY

The spin parameters for the three outbursts are shown in Table 2. The orbital parameters are instead shown in Tables 3–5.

According to this method of analysis the spin frequency between the first and the second 2008 outburst decreases by $\sim 0.7 \mu \text{Hz}$. This means that during the first 2008 outburst, or in between the two 2008 outbursts, a spin-down must have occurred. However, a spin-down during the outburst is not a realistic hypothesis because we detect positive spin frequency derivatives, firmly excluding any spin down. According to this method of analysis, the required spin-down must have occurred in between the two 2008 outbursts and it needs to be of the order of $-3 \times 10^{-13} \text{Hz s}^{-1}$. This value appears to be too large to be explained with a propeller scenario. Indeed, at MJD 54,703, during the 30 days of low-level activity, an XMM-Newton observation was performed, with upper limits on the $0.5–10 \text{keV}$ X-ray flux of $\sim 10^{-14} \text{erg s}^{-1} \text{cm}^{-2}$ (Lewis et al. 2010), which are almost five orders of magnitude lower than the peak luminosity of the first 2008 weak outburst. This means that the accretion level must have been extremely low, around $10^{-14} M_\odot \text{yr}^{-1}$ or less, and this is not compatible with the required mass that need to be ejected from the system (which is of the order of a few $10^{-10} M_\odot \text{yr}^{-1}$) to explain the $\sim 0.7 \mu \text{Hz}$ spin frequency shift. Of course, one can argue that at the onset of the propeller a large amount of mass is still present, but the X-ray luminosity is suppressed by the lack of accretion on the neutron star surface. However, also the production of X-rays in the inner accretion disk must be suppressed, since the X-ray luminosity observed is comparable with the quiescent luminosity (Campana et al. 2008; Torres et al. 2008).

Also, a magnetic dipole induced spin-down can be considered a quite unlikely possibility, since the spin-down between the two 2008 weak outbursts requires a magnetic field of at least $2 \times 10^9 \text{G}$, and there is no reason why such large spin-down is not observed between the 2004 and the first 2008 outbursts.

### 2.3. New Method: Correlation Coherent Analysis

In this second method, one also takes into account possible additional effects other than the rotational motion of the neutron star on the observed pulse phases. A first attempt to apply this method in AMXPs was made by Patruno et al. (2009). In that paper, the authors considered the possible influence of the X-ray flux on the pulse phase, suggesting that the mass accretion rate $M$ induced hot spot motion dominates the observed pulse phase variations.

The method I present here follows the same route and searches for higher/lower reference pulse frequencies than the one selected in standard coherent analysis by using the correlation between pulse phases and X-ray flux. I make a non-trivial assumption on the nature of the correlation: there is a linear relation between the pulse phases and the X-ray flux. The selected pulse frequency is then the one that minimizes the $\chi^2$ of the linear fit between phase and flux, instead of the pulse frequency derivative that minimizes the pulse phase residuals in the fit with TEMPO2. The reason why I choose a linear relation among all the possible choices is because this is the simplest law, and it is by no means necessarily a universal law that can be applied in all circumstances. One has to take this assumption as the “minimal hypothesis,” so that it is possible to verify whether under the simplest circumstances it is possible to already obtain results which are statistically better than standard coherent analysis.

Differently from Patruno et al. (2009), that used a constant spin frequency model, I select the best pulse frequency and pulse frequency derivative instead of varying simply the pulse frequency (see also Patruno et al. 2010b). I scanned 3000 pulse frequency derivatives in the range $(-10^{-12} \text{Hz s}^{-1})$ to $+10^{-12} \text{Hz s}^{-1}$ and 1000 pulse frequencies for each outburst. Only for the 2004 outburst it is possible to detect a significant spin derivative, while in 2008 only non-constraining upper limits were calculated. Since no significant pulse frequency derivative is detected in 2008, I re-fit the same data with a constant spin frequency model.

By applying this technique I obtain results for all the outbursts which show clear improvement in the $\chi^2$ of the fit when using the correlation coherent analysis rather than standard coherent analysis. It is relevant to note that when using the correlation coherent analysis instead of standard coherent analysis, the number of parameters used in the fit (and therefore the degrees of freedom) is exactly the same for the two methods, so there is no risk to over-fit the data when using the former method.
Indeed, the spin frequency at the end of the 2004 outburst is $598.89213111(5) \, \text{Hz}$ and with a spin-down of $-3 \times 10^{-13} \, \text{Hz s}^{-1}$ constantly operating in the $\sim 1336$ days of quiescence, the spin frequency expected at the beginning of the first 2008 outburst should have been $\sim 598.8920965 \, \text{Hz}$. This is $34 \, \mu\text{Hz}$ off the measured spin frequency at the beginning of the first 2008 outburst and $\textit{hundreds}$ of sigma away.

A final possibility of explaining these mismatching spin frequencies is via glitches occurring during quiescence, since no signature of glitches is seen in the timing analysis of the outbursts. Glitches in AMXPs have never been observed and those detected in millisecond (radio) pulsars are a rare phenomenon. In these latter systems, the magnitude on the spin frequency variation during a glitch is orders of magnitude smaller than in normal young pulsars (Cognard & Backer 2004). There is only one detection of a glitch in slowly rotating accreting pulsars for the source KS 1947+300 (Galloway et al. 2004). However, in this accreting pulsar the glitch resulted in an acceleration of the spin rotation, while we need here a deceleration. Therefore, although a glitch cannot be completely ruled out, it appears an unlikely explanation for the measured mismatching frequencies.

I ascribe this behavior of the spin frequencies to the presence of timing noise as already suggested in Patruno et al. (2009). A further consequence of this is that phase connection between the two 2008 outbursts is not a correct procedure of analysis. Indeed, although certainly possible, the phase connection with the standard coherent technique ignores the presence of timing noise and assumes that the pulse phases are well behaved. Therefore, the spin frequency that one finds by phase connecting the two 2008 outbursts in this way is just an average value of the spin frequencies plus torques and contamination of timing noise and as such it is a meaningless quantity. However, this average value does not necessarily deviate from the true value by a large amount. This depends on the weighted effect of several factors, such as the outburst length, the strength of timing noise, and the magnitude of torques during and in between outbursts that might also partially compensate each other and mislead the judgment on the validity of the results.

Another problem is related to the magnitude of the spin frequency derivative detected in 2004. If one does not take into account the effect of timing noise, then also this quantity, and hence the inferred accretion torques, will appear higher than they really are. I give here an example of this effect on the measured spin frequency derivatives of IGR J00291. The 2004 outburst of IGR J00291 started on December 3 and stopped on December 21. Galloway et al. (2005) analyzed the data between December 3 and 6 and did not detect any spin frequency derivative, with large upper limits due to the short baseline of the observation. Falanga et al. (2005) and Burderi et al. (2007) analyzed the pulsations from December 7 to 21 and they both detect a consistent spin frequency derivative between $8 \times 10^{-13} \, \text{Hz s}^{-1}$ and $12 \times 10^{-13} \, \text{Hz s}^{-1}$. However, if one splits the data differently, for example, one analyzes the data between December 3 and 10 and between 10 and the end of the outburst, one finds $\dot{\nu}_\text{in} = 3.6(5) \times 10^{-13} \, \text{Hz s}^{-1}$ and $\dot{\nu}_\text{in} = 2.4(5) \times 10^{-13} \, \text{Hz s}^{-1}$. So if one believes accretion theory, the torque has increased when the flux was lower, completely contradicting the expectation that a smaller amount of mass should bring less angular momentum and produce a smaller and not a higher spin frequency derivative. There might be possible explanations for this, i.e., considering modifications to the accretion theory, but taking into account the presence of timing noise might be a more straight-forward explanation. Indeed, something similar was observed in XTE J1807−294 (Patruno et al. 2010b) where the short-term spin frequency derivatives were behaving in a way not predicted by accretion theory. The conclusion was that the observed spin frequency derivatives were affected by red timing noise, so they were not true spin frequency derivatives. The same conclusion applies here. In the following section, I propose a method that takes into account the effect of timing noise and calculates unbiased spin frequencies and time derivatives.

4. CORRELATION COHERENT ANALYSIS AND ACCRETION THEORY

A possibility of explaining the pulse frequency discrepancy of the previous section is via the presence of timing noise in the pulse phases. To take this into account, I have applied the correlation coherent analysis (see Section 2.3) to the 2004 and 2008 outburst data.

I used the orbital solution as found in Section 3, since the orbit is only marginally affected by the pulse phase noise, which operates on completely different timescales than the orbital modulation. Indeed, the orbital period of IGR J00291 is $\sim 2.4$ hr, while the flux changes on timescales of days. The very weak dependence of the orbital parameters on timing noise was already noticed by Hartman et al. (2008) and Patruno et al. (2010b), and it is not relevant for compact binaries in which the timing noise operates on timescales longer than the orbital period. I refer to the aforementioned papers for a detailed discussion of the problem and further references.

I fit a linear relation between the pulse phases $\phi$ and the X-ray flux $f_X$: $\phi = A + B \cdot f_X$. The coefficients $A$ and $B$ are reported in Table 6, along with the spin frequency and its first derivative found minimizing the $\chi^2$ of the linear fit. All coefficients are consistent within the statistical uncertainties. All the statistical errors are calculated for a $\Delta \chi^2 = 1$. The correlations for the three outbursts are shown in Figure 2, where it is evident that all three outbursts behave in a consistent way. Of particular
relevance is the fact that the second 2008 outburst also follows a similar correlation as the 2004 and the first 2008 outburst, even though the shape of this X-ray light curve is very different from the other two. The pulse phases suggest a drift of approximately 0.2 cycles in 2004 and 0.1 cycles in the two 2008 outbursts.

There is still some unmodeled component in the fits, which is particularly evident in 2004, where the pulse phases slightly deviate toward the end of the outburst and affect the goodness of fit. However, the $\chi^2$ of the fits obtained with this method is statistically much better than those obtained with standard coherent analysis (see the last column of Tables 2 and 6). The uncertainties found with this method are larger than those found with standard coherent analysis because here I also take into account the effect of timing noise in the fit. The statistical uncertainties found in this way can be considered a good approximation of the true uncertainties, different from those obtained with standard coherent timing techniques.

In a recent work, Ibragimov & Poutanen (2009) demonstrated that pulse phase variations have an energy dependence on the AMXP SAX J1808.4−3658. Something similar might also happen in IGR J00291, so it is useful to test whether the linear correlation and the best spin frequency and frequency derivative have an energy dependence. I split the data into two energy bands, a soft band (2–7 keV) and a hard band (8–16 keV) and repeated the entire procedure outlined above for the full band (2–16 keV). The best spin parameters as well as the coefficients $A$ and $B$ are consistent with being the same for the soft, hard, and full bands. However, since the photon statistics is degraded when splitting the data in sub-bands, the statistical errors in the soft and hard bands are much larger than in the full band, so that a possible energy dependence cannot be firmly excluded.

The long-term spin frequency evolution is reported in Figure 3. During the 2004 outburst there is a detection of a spin-up, while in the two weak 2008 outbursts it is only possible to set confidence intervals for the non-detections which are consistent within the statistical uncertainties. The long-term spin frequency evolution requires a constant spin-down during quiescence. A detailed discussion follows in the following section.

### 5. LONG-TERM SPIN EVOLUTION

#### 5.1. Pulsar Spin-down in Quiescence

The spin-down evolution of the neutron star in IGR J00291 is reported in Figure 3. The pulsar spin frequency requires a spin-down between the end of the 2004 outburst and the beginning of the first 2008 outburst. Since it is not possible to find a significant torque in the first and second 2008 outbursts, the reported spin frequencies refer to a constant spin frequency model. The value of the spin-down is $v_{\text{sd}} \simeq -(3 \pm 0.8) \times 10^{-15} \text{ Hz s}^{-1}$.

It is not possible to verify whether a spin-down is also required between the two weak outbursts, since the uncertainty on the spin frequencies of the first 2008 outburst is too large ($\sim 10^{-7} \text{ Hz}$).

### Table 6

| Outburst | $A$   | $\sigma_A$ | $B$   | $\sigma_B$ | Spin Frequency | Spin Frequency Derivative ($10^{-15} \text{ Hz s}^{-1}$) | Epoch | $\chi^2$/dof |
|----------|------|------------|------|------------|----------------|---------------------------------|-------|-------------|
| 2004     | −0.08| 0.01       | 0.0024| 0.0003     | 598.89213030(3) | 5.1(3)                          | 53342.27 | 184.23/88   |
| 1st 2008 | −0.10| 0.04       | 0.0034| 0.0013     | 598.89213061(11)| [0; 18] (95% c.l.)          | 54692.00 | 46/26       |
| 2nd 2008 | −0.08| 0.01       | 0.0032| 0.0004     | 598.89213070(2) | [1; 11] (95% c.l.)          | 54730.50 | 19.4/11     |

#### Figure 3

Long-term spin frequency evolution of the pulsar in IGR J00291. The spin frequencies are plotted with an offset $v_0 = 598.8921300 \text{ Hz}$. The symbols and colors are the same as those in Figures 1 and 2. The red circle and blue square are the average spin frequencies as measured in the first and second 2008 outbursts. The cyan triangle is the spin frequency at the beginning of the 2004 outburst and the open cyan triangle is the spin frequency at the end of the 2004 outburst, after a spin-up has taken place. The spin frequency during the first 2008 weak outburst has decreased with respect to 2004 and requires a spin-down in quiescence of $-3 \times 10^{-15} \text{ Hz s}^{-1}$.

(A color version of this figure is available in the online journal.)

While other effects might also contribute to the spin-down, the rotating neutron star magnetic field is always present and causes a continuous emission of low frequency radiation. By using the force-free magnetohydrodynamic (MHD) approximation of Spitkovsky (2006), the determination of $v_{\text{sd}}$ provides an upper limit on the dipole moment:

$$
\mu < 10^{26} (1 + \sin^2 \alpha)^{-1/2} \left( \frac{I}{10^{45} \text{ g cm}^2} \right)^{1/2} \left( \frac{v}{600 \text{ Hz}} \right)^{-3/2} \times \left( \frac{-v_{\text{sd}}}{3 \times 10^{-15} \text{ Hz s}^{-1}} \right)^{1/2} \text{ G cm}^3.
$$

For the extreme values of $\alpha = 90^\circ, 0^\circ$, and considering all sources of uncertainty (co-latitude, period, and period derivative), the maximum dipole magnetic field at the poles is

$$
B_{\text{sd}} = [1.5; 2.0] \pm 0.3 \times 10^8 \text{ G}.
$$

If the pulsar in IGR J00291 switched on as a radio pulsar during quiescence, then its position on the $P–P'$ would fall exactly in the expected region occupied by radio millisecond pulsars (see Figure 4).

#### 5.1.1. The Pulsar Magnetic Field

Besides IGR J00291, there are only two other AMXPs in which it was possible to constrain the magnetic field from the long-term spin frequency behavior: SAX J1808.4−3658 (Hartman et al. 2008 and Hartman et al. 2009) and SWIFT
Figure 4. $P$–$\dot{P}$ diagram for radio pulsars. The cross represents the position of the pulsar in IGR J00291 with period and period derivative as determined in Section 5.1, under the assumption that the observed spin-down is caused by magneto-dipole torques. I plot also the position of SAX J1808.4–3658 (red star; Patruno et al. 2009) and SWIFT J1756.9–2508 (blue circle; Patruno et al. 2010a). The latter has no detected spin-down during quiescence, and therefore the position is determined by using an upper limit on the spin-down. (A color version of this figure is available in the online journal.)

J1756.9–2508 (Patruno et al. 2010a). For SAX J1808 a spin-down of $-5.5 \times 10^{-16}$ Hz s$^{-1}$ was found. For SWIFT J1756, only upper limits on the spin-down were given.

The strength of the spin-down in quiescence and hence of the magnetic field of SAX J1808 was also revised by Patruno et al. (2009), who applied a similar technique to that reported in this paper and found a spin-down of $-2 \times 10^{-15}$ Hz s$^{-1}$ and a magnetic field of $\nu_2=2.8 \times 10^8$ G, slightly higher than the $1.4 \times 10^8$ G reported in Hartman et al. (2009).

The magnetic fields $B$ of the three pulsars are therefore as follows:

1. IGR J00291+5934: [1.5; 2.0] $\pm 0.3 \times 10^8$ G;
2. SAX J1808.4–3658: [2.0; 2.8] $\pm 0.2 \times 10^8$ G;
3. SWIFT J1756.9–2508: [0.4; 9] $\times 10^8$ G (95% c.l.).

The ranges [1.5; 2.0] and [2.0; 2.8] reflect the indetermination of the co-latitude of the magnetic pole, while the errors on each determination are calculated by propagating the errors on the spin parameters in Equation (4). The $B$ field of IGR J00291, SAX J1808, and SWIFT J1756 is perfectly compatible with the minimal hypothesis that only magneto-dipole torques are at work. Under this assumption, the derived magnetic fields are exact values and not upper limits. There is no clear evidence for an alternative/additional mechanism to explain the observed spin-down other than magneto-dipole torques.

5.2. Pulsar Spin-up During Outbursts

According to accretion theory, a pulsar accreting from a disk will experience a positive torque (spin-up) when the magnetospheric radius $r_m$ is smaller than the corotation radius $r_{co}$. The latter is defined as the position at which the gas in the accretion disk has the same angular velocity of the neutron star:

$$r_{co} \simeq 17 \, \text{km} \times \left( \frac{P_{\text{spin}}}{1 \, \text{ms}} \right)^{2/3} \left( \frac{M}{1.4 \, M_\odot} \right)^{1/3}. \quad (5)$$

For a pulsar spinning at $\sim 600$ Hz like IGR J00291, the corotation radius is at $\sim 24$ km, which is within approximately one stellar radii from the neutron star surface.

The magnetospheric radius is related to the neutron star magnetic dipole moment $\mu$, to the neutron star mass $M$, and to the mass accretion rate $\dot{M}$ via the equation

$$r_m \simeq 35 \, \text{km} \xi \left( \frac{\mu}{10^{29} \, \text{Gc m}^2} \right)^{4/7} \left( \frac{10^{-10} \, M_\odot \, \text{yr}^{-1}}{\dot{M}} \right)^{2/7} \left( \frac{1.4 \, M_\odot}{M} \right)^{1/7}. \quad (6)$$

The accretion disk model-dependent factor $\xi$ lies in the range $\sim 0.1–1$ (see, e.g., Psaltis & Chakrabarty 1999; Ghosh & Lamb 1979 and Bildsten et al. 1997). By assuming $M = 1.4 \, M_\odot$, and using the 2004 average mass accretion rate as calculated in Section 2.1, I obtain $r_m = 2–20$ km, for $0.1 < \xi < 1$. Values of $r_m$ smaller than $8–10$ km are non-physical because of the presence of the hard surface of the neutron star. Nonetheless, given the large uncertainties in the determination of $M$ (distance, accretion efficiency, and bolometric flux) it is over-simplistic to favor values of $\xi$ closer to 1 and the calculations have to be interpreted just as order of magnitude estimates of the quantities involved.

The condition $r_m = r_{co}$ to enter the propeller regime\(^2\) is met when $M \simeq 10^{-10} \, M_\odot \, \text{yr}^{-1}$, which corresponds to an RXTE count rate of $\sim 5 \text{ count s}^{-1} \, \text{PCU}^{-1}$, in excellent agreement with the minimum count rate at which significant pulsations are detected: $\sim 8 \text{ count s}^{-1} \, \text{PCU}^{-1}$. Although this value depends on several additional sources of uncertainty, it shows that the magnetospheric radius really lies within $r_{co}$ during the whole period in which pulsations are observed from 2004 to 2008.

The maximum observed X-ray flux, and hence the maximum mass accretion rate as determined in Section 2.1, is $M = 2 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}$. The magnetospheric radius at this flux is $r_m \simeq 1.5–15$ km, for $0.1 < \xi < 1$.

To check the consistency of our results I can compare the maximum expected dipole magnetic filed calculated with accretion theory with the magneto-dipole torque inferred independently from the spin-down (Sections 5.1 and 5.1.1). Under the minimal assumption that $r_m = r_{co}$:

$$\mu_{\text{max}} = 2.0 \times 10^{23} \, \text{G cm}^{-3} \left( \frac{r_{co}}{\xi} \right)^{7/4} \times \left( \frac{M}{10^{-10} \, M_\odot \, \text{yr}^{-1}} \right)^{1/2} \left( \frac{1.4 \, M_\odot}{M} \right)^{1/4}. \quad (7)$$

The value of $\mu_{\text{max}}$ and hence of the magnetic dipole field depends on the choice of $\xi$ and on the average outburst mass accretion rate. By choosing the least constraining values for $\xi = 0.1$ and $\langle M \rangle = 6 \times 10^{-10} \, M_\odot \, \text{yr}^{-1}$, I obtain a maximum dipole magnetic field at the magnetic poles of $B_{\text{max}} \simeq 1.5 \times 10^{10}$ G. For $\xi = 1$ the maximum $B$ field becomes $B_{\text{max}} \simeq 2.5 \times 10^{8}$ G. These values
\(^2\) More recent works (such as Rappaport et al. 2004 and Spruit & Taam 1993) show that the onset of the propeller is more complicated than simply $r_m = r_{co}$. However, this does not substantially affect the argument used in this paper.
are within the expected range for accreting millisecond pulsars and they match the spin-down dipole magnetic field $B_{\text{sd}}$ as well as the upper limits of $B_{\text{max}} < 3 \times 10^8 \text{G}$ proposed by Torres et al. (2008).

To further check the self-consistency of the accretion theory, it is useful to obtain a minimum magnetic field. I use the same argument as used in Psaltis & Chakrabarty (1999) and Miller et al. (1998): pulsations are seen at the outburst peak; therefore, the magnetic field must be strong enough to channel the accretion flow and enforce corotation of the accreted gas when the accretion rate is maximum. By using the least-constraining mass accretion rate $M = 2 \times 10^{-9} M_\odot \text{yr}^{-1}$ (see Section 2.1) and using Equation (11) in Psaltis & Chakrabarty (1999), I obtain a minimum magnetic field at the poles $B_{\text{min}} = 6 \times 10^7 \text{G}$. In this calculation, I have assumed the conservative quantities $R = 10 \text{km}$, $M = 1.4 M_\odot$ and $\xi = 1$ (here $\xi$ is what is called $\gamma_B$ in Psaltis & Chakrabarty 1999).

Both maximum and minimum magnetic fields as inferred from accretion theory are therefore consistent with the spin-down magnetic dipole field obtained in Section 5.1.

### 5.3. Motion of the Hot Spot

In Section 4, I showed that in both 2004 and in the two weak outbursts of 2008 the coefficients of the linear correlation are consistent, which suggests some ordered process acting during each outburst that provides an identical response of the phase to a fixed perturbation of the X-ray flux.

Lamb et al. (2009) suggested a moving hot spot on the neutron star surface as the origin of timing noise in AMXPs. Moving hot spots were also observed in MHD simulations of Romanova et al. (2003) and Romanova et al. (2004), although the number of simulated neutron star rotations is still too small to reach a firm conclusion.

Applying the correlation coherent technique, I find that the pulse phases drift by approximately 0.2 cycles when the X-ray flux varies by a factor $\sim 10$ from the maximum to the minimum in 2004 and by 0.1 cycles in the two 2008 outbursts (see Figure 2). Such variations might be induced by a motion of the hot spot. A movement along the latitude of the neutron star will produce only minimal changes in phase, so a drift in longitude is also required.

Under the assumption that the accretion rate tracks the X-ray luminosity, the magnetospheric radius $r_m$ will move away from the neutron star surface and approach the corotation radius $r_{co}$ as the source luminosity drops from the peak of the outburst down to quiescence. During this process, the hot spot can move about the magnetic pole depending on the co-latitude of the magnetic axis, as was observed in MHD simulations by Romanova et al. (2003).

In a recent work, Bachetti et al. (2010) performed detailed MHD simulations of accreting neutron stars and found that the hot spot does indeed move about the magnetic pole, with small co-latitudes favoring a more pronounced motion. Although these authors could simulate only a few rotational cycles of the neutron star, due to computational power limitations, their results clearly show that the accretion flow in the pulsar magnetosphere is a highly dynamical process and questions the traditional picture of a static hot spot.

A detailed discussion on the modeling of the hot spot movement is beyond the scope of this paper. A model taking into account variations of the X-ray flux and the hot spot motion will be presented in a forthcoming paper.

### 6. SPIN EQUILIBRIUM AND SPIN-UP TIMESCALE

A self-consistent measurement of the spin frequency and its long-term evolution has been given, and by knowing the approximate duty cycle for the outbursts/quiescence cycle of IGR J00291, it is possible to determine a timescale for the spin-up of the pulsar.

I call $\Delta^{-1}$ the inverse of the duty cycle for the outbursts/quiescence episodes, whose value is approximately 1% (2004 outburst length $\sim 13$ days, 2004–2008 quiescence length $\sim 1350$ days) which is a necessary term because the accretion torques act only during the outbursts, while they are not effective during quiescence. In this first approximate calculation, I do not include the effect of the spin-down due to magnetic dipole torques in order to obtain the shortest timescale possible. I use $v_s \approx 600 \text{Hz}$ and $v_{su} \approx 5 \times 10^{-13} \text{Hz s}^{-1}$, with a duty cycle $\Delta \approx 0.01$. Therefore, the spin-up timescale is

$$t_{\text{spin-up}} = \frac{v_s}{v_{su}} \Delta^{-1} \approx 4 \text{Gyr},$$

which means that the pulsar will not change its spin frequency significantly for a long timescale, or in other words that it is close to the spin equilibrium (see, for example, Campana et al. 1998).

Furthermore, there is a further spin-down on this timescale deriving from the spin-down observed in quiescence. The timescale for the spin-down ($v_{sd} \approx -3 \times 10^{-13} \text{Hz s}^{-1}$) is

$$t_{\text{spin-down}} = \frac{v_s}{|v_{sd}|} (1 - \Delta)^{-1} \approx 8 \text{Gyr},$$

which is of the same order of magnitude as the spin-up timescale. By combining these two timescales, under the hypothesis that they are both representative of the long-term behavior of the pulsar, the long-term timescale for the spin evolution is

$$t_{\text{spin}} = \left( \frac{v_s}{v_{sd} \times (1 - \Delta) + v_{su} \times \Delta} \right) \approx 7 \text{Gyr}.$$  

This timescale strengthens the suggestion that the pulsar in IGR J00291 is indeed close to spin equilibrium.

### 6.1. The Lack of Submillisecond Pulsars

A very important problem in neutron star physics is how to justify the absence of pulsars with the spin period in the submillisecond range. Although only a rather limited number of sources were known at the time, Chakrabarty et al. (2003) and Chakrabarty (2005) studied the spin distribution of AMXPs and nuclear-powered pulsars and discovered that this was consistent with a flat distribution truncated at approximately 730 Hz with a 95% confidence level. Although strong observational biases exist for the detection of a radio pulsar above this frequency, X-ray observations taken with observatories like RXTE/PCA should not be affected by a significant loss of sensitivity at least up to 2 kHz (see Chakrabarty 2008 and references therein). Hence, it remains unexplained why the maximum spin frequency known for accreting neutron stars is 619 Hz (Hartman et al. 2003). Hessels et al. (2006) discovered the fastest known radio millisecond pulsar, which spins at 716 Hz, surprisingly close to the cutoff spin limit of 730 Hz. If I repeat the calculation of the spin distribution cutoff as done by Chakrabarty et al. (2003), with a sample size which has doubled in the meantime (from 11 to 23 known accreting neutron star spins; see Table 7)
I still find a cutoff of 730 Hz, but with a higher confidence level of 99%. IGR J00291 is the third fastest known accreting neutron star and is among the fastest neutron stars known. It is therefore at the upper end of the spin distribution of accreting neutron stars, which is plotted in Figure 5 (see Watts et al. 2008; Markwardt et al. 2007 and Galloway et al. 2010 for references). If the spin evolution of this source is representative of the behavior of AMXPs, then it explains the existence of a cutoff of 730 Hz in the spin distribution of accreting pulsars.

Several mechanisms have been proposed to explain the lack of submillisecond pulsars, but what appears certainly true is that these spin frequencies are not limited by the break-up frequency of neutron stars, which sets in when the centrifugal force exceeds the gravitational pull. The break-up frequency depends on the equation of state of ultra-dense matter, and its determination is therefore of fundamental importance to understand the spin evolution of more accreting neutron stars, but it seems to suggest a simpler (and in this sense more likely) explanation for the existence of a 730 Hz cutoff.

If the timescale for the spin-up in IGR J00291 is of the order of 7 Gyr (see Section 5.2), then a plausible explanation for the 730 Hz cutoff is that accreting neutron stars reach the spin equilibrium earlier than it is required to reach submillisecond periods. In this sense, the reason why there are no observed submillisecond pulsars might be a simple consequence of binary and magnetic field evolution (see also Lamb & Yu 2005 and Lamb & Boutloukos 2008).

It is possible to compare this behavior with the only other AMXPs with a measured spin-down in quiescence: SAX J1808.4–3658 (Hartman et al. 2008; Hartman et al. 2009; Patruno et al. 2009). The overall long-term spin frequency in SAX J1808.4–3658 is decreasing over an observed baseline of ~10 yr, suggesting that no significant accretion torque operates during the outbursts. Therefore, this pulsar will also not significantly move in the spin distribution diagram on a timescale comparable with the Hubble time. Unless the neutron star was born with a spin already in the millisecond range, strong accretion torques must have spun up the pulsar in the past. Its current magnetic field and average mass accretion rate might be instead too small to allow a significant spin-up during the outbursts. Therefore, the spin evolution of these two AMXPs is compatible with a scenario in which AMXPs evolve close to the spin equilibrium on a timescale shorter than it is required to spin-up to the submillisecond range.

Before drawing a firm conclusion it is important to investigate the spin evolution of more accreting neutron stars, but it seems justified here to propose that, given the observed spin evolution of IGR J00291 and SAX J1808, submillisecond pulsars might be, at best, extremely rare.

### 7. SUMMARY IN THE FRAMEWORK OF THE RECYCLING SCENARIO

A first achievement for the recycling theory arrived with the discovery of the first accreting millisecond X-ray pulsar in 1998 (Wijnands & van der Klis 1998). Another fundamental step has

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**Table 7**

| Source Name | Spin Frequency (Hz) |
|-------------|---------------------|
| Swift J1756−2508 | 182 |
| XTE J0929−314 | 185 |
| XTE J1807−294 | 190 |
| NGC 6440 X-2 | 205 |
| IGR J17511−3057 | 245 |
| IGR J17191−2821 | 294 |
| MXB 1730−335a | 306 |
| XTE J1814−338 | 314 |
| 4U 1728−34 | 363 |
| HETE J1900.1−2455 | 377 |
| SAX J1808.4−3658 | 401 |
| 4U 0614+09 | 415 |
| XTE J1751−305 | 435 |
| SAX J1748.9−2021 | 442 |
| SWIFT J1749.4−2807 | 518 |
| KS 1731−260 | 526 |
| Aql X−1 | 550 |
| EXO 0748−676 | 552 |
| MXB 1659−298 | 556 |
| 4U 1636−536 | 581 |
| IGR J00291−5934 | 599 |
| SAX J1750.8−2900 | 601 |
| 4U 1608−52 | 620 |

**Figure 5.** Spin frequency distribution. The red bars represent 10 nuclear powered pulsars whose spin frequency is measured via burst oscillations during thermonuclear bursts. The 13 accretion powered pulsars are identified by blue bars, and no accreting pulsar with spin below 100 Hz is counted in the sample, according to the definition of millisecond pulsar. Note that the red and the blue histograms are not overlapped, but they are added. If a pulsar is both accretion powered and nuclear powered, I have counted it as an accretion powered. The total number of neutron stars in the sample (accretion plus nuclear powered) is 23.

(A color version of this figure is available in the online journal.)

Note. a The spin frequencies of these sources need to be confirmed (see Watts et al. 2008).
been the recent detection of a millisecond radio pulsar in a position coincident with a previously known quiescent neutron star X-ray binary (Archibald et al. 2009; Homer et al. 2006). This was a further evidence that accreting millisecond pulsars might indeed turn on as millisecond radio pulsars.

However, there was still a missing test that needed to be performed before the recycling scenario could be accepted as the correct theory of accreting neutron stars: the accreting pulsar is spun up, so it must be possible to observe accretion torques in the process of accelerating the neutron star rotation and spin-down during quiescence due to magneto-dipole torques. Many claims have been made for a detection of an accretion torque in accreting millisecond pulsars, but none of these has been broadly accepted until now because of the presence of timing noise that affects the determination of spin and accretion torques when using a standard coherent timing analysis.

The results presented here show that accretion torques are present in IGR J00291, and the spin evolution over four years is entirely consistent with the prediction of the recycling scenario. The gas is channeled along the weak magnetic field lines very close to the neutron star surface, at a distance of less than 24 km from the neutron star center. Furthermore, a slow spin-down is detected when the accretion halts (or is strongly reduced), which I ascribe to magnetic dipole spin-down as observed in radio pulsars. This allows the measurement of the magnetic field of the neutron star, which I determine to be $B \lesssim (2 \pm 0.3) \times 10^8$ G. This value is consistent with that inferred from the accretion torques during the 2004 outburst. Given the large uncertainties in the analysis discussed in Section 5, it is still premature to state that the results reported in this paper finally confirm the recycling scenario. However, it has been shown here that there is no need for new physics to explain the results reported. For example, there is no evidence for a spin-down mechanism other than magneto-dipole torques.

There is instead strong evidence for an ordered process that is always present in all observed outbursts that might be ascribed to a motion of the hot spot on the neutron star surface. Finally, I find evidence for IGR J00291 being very close to the spin equilibrium, with the pulsar spin evolving on timescales of $\sim 7$ Gyr. These findings open new possibilities on the interpretation of a lack of detected sub-millisecond pulsars: intrinsic evolutionary processes that modify the mass transfer rate and the magnetic field might bring the pulsar close to the spin equilibrium at a much earlier stage than it is required to reach sub-millisecond periods.

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