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Motion of the hot spot and spin torque in accreting millisecond pulsars

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Abstract.
The primary concern of this contribution is that accreting millisecond pulsars (AMXPs) show a much larger amount of information than is commonly believed. The three questions to be addressed are:
1. Is the apparent spin torque observed in AMXPs real ?
2. Why do we see correlations and anti-correlations between fractional amplitudes and timing residuals in some AMXPs ?
3. Why the timing residuals, the lightcurve and the 1Hz QPO in SAX J1808.4−3658 are related ?

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1. MOTIVATION

There has been a large debate in the accreting millisecond pulsar community, on how to interpret the apparent measurement of spin torques in accreting millisecond pulsars (AMXPs). The need of interpreting what the apparent spin torque really is needs hardly be explained in this meeting, and this is also the reason why I call it 'apparent' spin torque. An improved understanding of the nature of the apparent spin torque can have enormous implications to the knowledge of neutron star physics. For example the existence (or the lack) of a spin torque has consequences in the gravitational wave physics[1] [2], on the problem of the break up spin frequency of neutron stars[3] and on the strength of their magnetic fields. At the time of writing this contribution, we know ten AMXPs, seven of which show persistent pulsations, and other three are the so called intermittent AMXPs (see for example the contribution of Altamirano & Casella and Galloway for an observational overview at this meeting, and [4][5] [6][7][8]). The primary target of this contribution are the seven persistent AMXPs. In particular I will discuss the apparent spin torque measurement in XTE J1751-305 and XTE J1807-294 and show how a different and correct treatment of the statistical errors can completely change the interpretation of the observational results. Related to the problem of the apparent spin torque measurement is the interpretation of the relation between the fractional amplitude of the pulsations and the residuals of the pulse time of arrivals (TOAs). The residuals here refer to the coherent timing analysis of the AMXPs. In a few words: one measures the TOAs of the pulsations and then fits a model (usually a keplerian circular orbit plus a constant spin frequency or a spin torque) to the TOAs. What is left after the fit are the residuals, and they represent the relative location, with respect to an arbitrary reference position, of the hot spot on the neutron star surface, i.e., the relative pulse phases. I will call this relation “the FAR relation” throughout this contribution (FAR=Fractional Amplitude vs. Residuals). I will show that this relation exists in two sources, XTE J1807-294 and XTE J1751-305, and that it is probably a more general phenomenon among AMXPs. But why the existence of the FAR relation is connected with the interpretation of the apparent spin torque ? The reason is quite simple: we measure the apparent spin torque from the TOAs, and therefore whatever its origin is, it must be related in some way with the fractional amplitudes of the pulsations. Finally, I will discuss some intriguing relations between the lightcurve, the periodic timing and the aperiodic timing of the AMXP SAX J1808.4−3658. This AMXP shows some strange shifts of the pulse phases in the timing residuals that cannot be explained even with a torque model. Intriguingly, when the pulse phases start to shift the slope of the lightcurve changes. And when the phases stop to shift, the unexplained phenomenon of the 1 Hz QPO appears. The implications of the relation between such different phenomena are profound: if the unmodeled phase shifts are related with the lightcurve and the aperiodic variability, then a deep link between the accretion disk (responsible for the lightcurve and perhaps the QPO) and the surface of the neutron star (pulsations) exists. Is it possible that all these phenomena (apparent spin torque, FAR relation, lightcurve-periodic-aperiodic variability link) have a common unified explanation ? The search for an answer to this question is the motivation of this work.

2. THE PROBLEM OF THE APPARENT SPIN TORQUE

The measure of a spin torque has been claimed in six out of seven known AMXPs. The seventh AMXP has not a measured spin torque probably because it has been observed only during the tail of its outburst. Therefore the measure of the spin torque can appear a well established and thorough result of AMXP physics. My main concern however is that the measure of the spin torque, at least in some AMXPs, is the result of the combination of underestimated statistical errors plus a possible misleading use of standard timing techniques. The reason why the statistical errors are usually underestimated when using standard fitting techniques is a simple consequence of the so called *timing noise*. The term *timing noise* traces back to the early ’70s in the field of radio pulsar timing. In radio pulsar timing one calculates the pulse TOAs and then fits a polynomial expansion truncated at the second or third order. The first order (linear) term of the polynomial is the spin frequency, the second order (quadratic term) is the spin down due to dipole radiation, and, sometimes, the third order term is related with the breaking index of the pulsar. After removing these terms from the TOAs, one should expect a gaussian distribution of the residuals with zero mean. The gaussian distribution of the post-fit residuals should contain indeed only the measurement error component due to the counting statistics. However in many young pulsars, the post-fit timing residuals had a very large amount of quasi-sinusoidal structures that were indicating some unmodeled component of unknown origin. All this unmodeled component is what was called *timing noise*. The term ’noise’ can be a bit misleading since it has nothing to do with the *white noise* expected from the measurement error component. It is called ’noise’ only because we do not have any satisfactory model to interpret its presence in the post-fit residuals.

Now with the AMXPs the story repeats. One fits a polynomial expansion truncated at the first or second order (after removing the orbital component), and interprets the linear term as the spin frequency, and the quadratic term as the spin torque. However the post-fit residuals have not a gaussian distribution, and lots of structures are particularly evident in some of them. XTE J1807−294 is the AMXP that contains the largest amount of timing noise, regardless if we consider a constant spin or a spin torque model. On the other side, some AMXPs show very little timing noise after removing a quadratic component from the TOAs. However still some unmodeled structures are visible in the residuals and cannot be overlooked, especially when calculating the significance of an apparent spin torque measurement. Indeed all the standard χ^2 minimization techniques used for the polynomial fit and the statistical errors are based on least square numerical techniques, and as such they use the hypothesis that the source of noise in white, or in other words, that the distribution of the post-fit residuals is gaussian with zero-mean. However if there is also *timing noise*, the statistical errors obtained from the least square fit are meaningless. A better way for estimating realistic statistical errors is by means of Monte Carlo (MC) simulations, to take into account the presence of correlated noise. The concept behind the MC simulations is very simple: we measure some spin frequency and a spin frequency derivative (our candidate spin torque) plus some residual timing noise that can be decomposed in a Fourier series and analyzed with standard Fourier techniques. The power spectrum we obtain is the 'fingerprint' of the (unknown) physical process behind the TOAs. Now we generate thousands of almost identical power spectra and transform them back into timing residuals. Since the power spectra contain no information on the phases of the Fourier frequencies, we randomize the phases when transforming back the power spectrum into fake timing residuals. We then measure the spin frequency and its derivative in all the ensemble of fake residuals and create a distribution of spin frequencies and derivatives. The standard deviations of these two distributions are our statistical errors on the spin frequency and on the spin frequency derivative. In other words we assume that all the variability we see in the timing residuals is due to timing noise (including the variability due to the quadratic polynomial term). Then we try to answer to the following question: given our assumptions, what is the probability of measuring a spin frequency derivative identical to the one we observe if we suppose that *all* the variability we see is due to timing noise ? Of course this method has its limitations and its assumptions, but nonetheless it takes into account the effect of correlated (red) noise in the fit of the parameters. To show the effect of MC simulations on the significance of the quadratic component I will focus on two AMXPs: XTE J1807−294 (J1807 now on) and XTE J1751−305 (J1751 now on). The periodic and aperiodic variability of the two AMXPs were studied in detail by [9],[10],[11],[12] and [13] (for J1807) and [14](for J1751). The first one is the best example of a noisy AMXP, while the latter is a low noise AMXP. In J1807 the pulse profiles have a significant 1st overtone beside the fundamental frequency, so we analyzed the two harmonics separately. We found a significant spin derivative for the fundamental harmonic, even when taking into account the colored nature of the noise in the timing residuals, but the significance of the spin torque for the 1st overtone disappears. However, as already discussed in [13] and [11], the position error has to be taken into account for this source, since the best available position comes from *Chandra* observations whose 68% confidence level error circle is $0''.4$. The systematic error introduced in this way on the frequency and frequency derivative is respectively $3\times10^{-8}\,\mathrm{Hz}$ and $\approx 0.7\times10^{-14}\,\mathrm{Hz/s}$ (calculated with eq. A1 and A2 from [15]), that summed in quadrature with the statistical errors give a significance of $\approx 2.7\sigma$ and $\approx 1.5\sigma$ when considering also the astrometric errors for the two harmonics respectively. According to [14], J1751 has a spin up measurement of $\dot{\nu} = 3.7(1.0)\times10^{-13}\,\mathrm{Hz/s}$, where the error has to be considered at the 90% confidence level. If we repeat the timing analysis for this source and we apply the MC method just described, we obtain $\dot{\nu} = 4.7(1.2)\times10^{-13}\,\mathrm{Hz/s}$, where the error now is our 1σ uncertainty. We see that when considering the MC simulations, the significance of the apparent spin torque has decreased, but it is still above the 3σ acceptance level. It is interesting to note that without the MC simulations our statistical error on the fitted parameter is $0.5\times10^{-13}\,\mathrm{Hz/s}$, which is 2.4 times smaller than our final 1σ uncertainty. This shows how overlooking the timing noise during the parameter fitting leads to unrealistic, underestimated, parameter errors. The existence of timing noise in J1751 is reflected in the bad reduced χ^2 of the fit when using a spin torque model. Indeed our reduced χ^2 is close to 1.3, for 518 degrees of freedom. This means that we are leaving a small, but significant, amount of unmodeled structures in the residuals. If we try for example to fit a spin frequency second derivative $\ddot{\nu}$, then, according to an F-test, we get a significant measure of $\ddot{\nu}$. The significance of $\ddot{\nu}$ means that it absorbs some residual variability still present in the timing residuals.

3. THE FAR RELATION

In the previous section we have shown that the quadratic term of the fit (apparent spin torque) is significant in J1751, while it is not in J1807 when considering the timing noise in the determination of the statistical errors of the fit. Now we focus on the follow up of the discussion: if the measured quadratic component is significant even when considering the timing noise, what does it physically represent ? A natural answer to this is the spin torque expected from the transfer of angular momentum from the disk to the accreting neutron star. However the observed correlations between pulse fractional amplitudes and timing residuals throws a spanner in the works. Let's first focus on J1751 and let's apply the solution found by [14] but without the spin torque (constant spin frequency model). Of course this choice of a constant frequency model is somehow arbitrary, because we are not re-fitting the spin frequency and therefore we are not minimizing the rms of the residuals. However with this choice we are making the assumption that all the phase movements that we see in the residuals are due to something unrelated with the spin frequency. The phase wanderings in the phase residuals have a similar shape as the fractional amplitude of the pulsations. Equally interesting, the shapes of the residuals and the fractional amplitudes are similar to the lightcurve. In other words, the residuals, the fractional amplitude and the X-ray flux show a linear correlation. It is impressive to see that this correlation rises from the simple assumption that the phase wandering of the pulsations does not reflect a spin frequency variation. Moreover, while the shape of the residuals depends on the choice of the spin frequency, the shape of the fractional amplitudes and the X-ray flux is 'intrinsic' to the process of emission, and cannot change according to the chosen timing solution. In particular the pulse fractional amplitude shape (i.e., the shape of the F.A. curve vs. time) does not change if we fold the pulsations with or without a spin torque. The fact that the phase residuals have the same shape of the lightcurve and of the fractional amplitude is impressive but still, can be a simple coincidence or a consequence of the arbitrary choices made in the data analysis. Therefore let's look at J1807, to see if we observe the same behavior. If we use a constant frequency model we observe a linear anti-correlation in the FAR diagram of the fundamental, while nothing is seen for the 1st overtone. So, differently from J1751, in J1807 the phase residuals of the fundamental are anti-correlated with the fractional amplitudes. Here both the lightcurve, the fractional amplitudes and the residuals have lots of structures so the existence of the linear anti-correlation can hardy be justified with a simple coincidence. Also the lightcurve seems to be anti-correlated with the phases, but again, with the assumption that the structures in the residuals do not represent any variation of the spin frequency and the rms of the residuals is not minimized during the fit. Interestingly the anti-correlation becomes tighter when removing a quadratic component. A similar *anti-correlation* is observed in another source: XTE J1814-338. This is also an AMXP with a large amount of structures in the residuals (timing noise) and a strong 1st overtone in the pulse profiles. On the other side a similar *correlation*, as the one observed for J1751, exists in IGR J00291+5934 if we use a constant spin frequency model: the phase residuals, the fractional amplitude and the lightcurve follow a linear relation. This is a source with a small amount of timing noise, no significant 1st overtones in the pulse profiles, and a smooth lightcurve, quite similar to J1751.

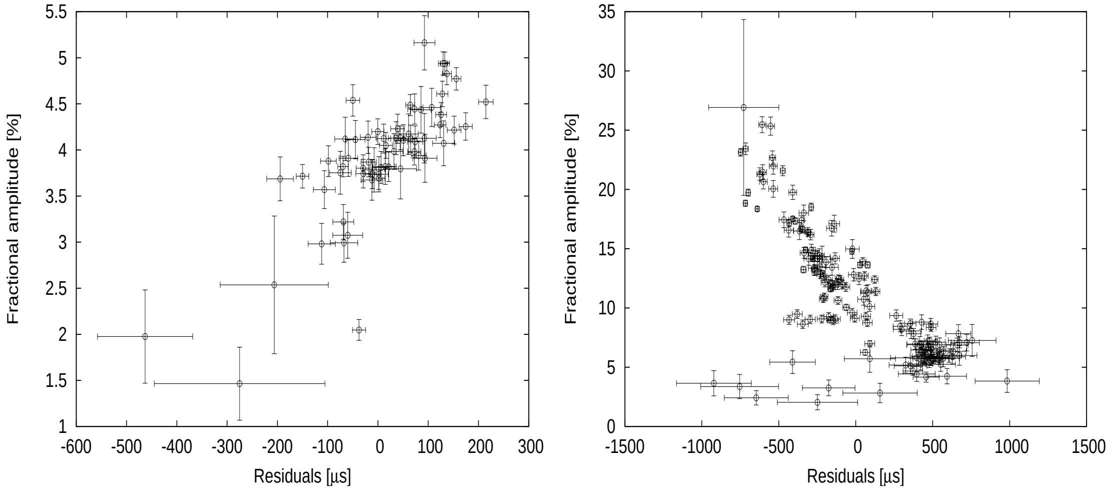

FIGURE 1. Fractional amplitude vs. Timing Residuals of two AMXPs: J1807 (right panel) and J1751 (left panel). In the left panel there is a linear correlation between the fractional amplitudes and the residuals, while in the right panel we see an anti-correlation. The residuals of J1751 and J1807 were calculated assuming a constant frequency model. In the case of J1807 the anti-correlation becomes tighter if we remove also a quadratic term from the fit.

4. THE 1HZ QPO AND THE TIMING NOISE IN SAX J1808.4−3658

The reason why the FAR and the flux-residual relations can be an essential ingredient in the AMXP physics is the tight link they imply between the position of the emitting region (phase), the strength of the pulsed signal received (fractional amplitude) and the accretion disk physics (lightcurve). An outstanding example of this interrelation is seen in the AMXP SAX J1808.4−3658 (J1808 from now on). This source has shown five outbursts since the 1996, four of which were observed with the *RXTE* satellite. During the 2000, 2002 and 2005 outbursts, J1808 has shown the puzzling phenomenon of the 1Hz QPO. This is a QPO with a fractional rms close to (or even larger than) 100% that appears when the lightcurve reaches its minimum and starts to bump in the so called re-flaring state. The origin of this QPO is unknown, its fractional rms shows an energy dependence, and it is observed always in the same position of the lightcurve (re-flaring) in all three outbursts. In the 1998 it was not observed, probably because the re-flaring state of the lightcurve was not observed with any X-ray telescope. This QPO cannot originate from the surface, as it is hard to explain its high rms, and also why we do observe only one mode of oscillation. It cannot be a QPO originating from the disk alone, for example in a dip or shadowing of the disk, since its energy dependence contradicts the expected flat energy dependence. Probably its origin comes from a disk-magnetospheric interaction associated with some kind of instability [16][17][18][19][20]. If we have a look at the pulse phases in the timing residuals, obtained using a constant spin frequency model, then we see a phase shift of approximately 0.2 cycles that was originally observed by [21]. This jump is not observed for the 1st overtone. When the phases start to shift, the lightcurve changes slope and decays faster before reaching the minimum

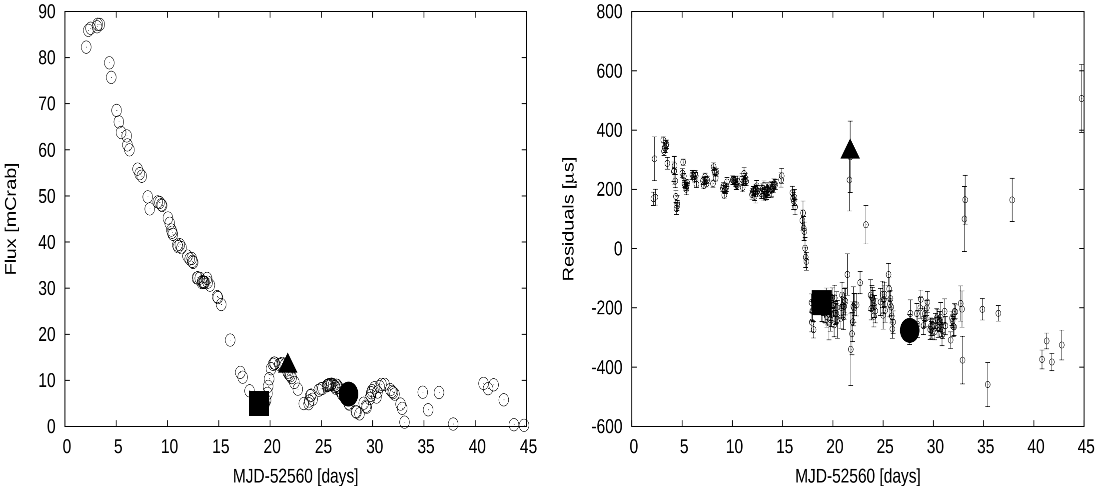

FIGURE 2. Left panel: lightcurve of the 2002 outburst of J1808. Right panel: timing residuals (relative to a constant spin frequency model) of the 2002 outburst of J1808. The solid square around MJD 52578 is the point where the pulse phases stop to drift and the 1Hz QPO appears. The solid triangle at MJD 52582 is the point where the 1Hz QPO disappears for the first time and the pulse phases jump by ≈ 0.3 cycles. The solid circle at MJD 52587 is the point where the 1Hz QPO rms fractional amplitude reaches its maximum. The behavior of the lightcurve, the QPO and the pulse phases is nearly identical in the 2005 outburst.

flux. At the minimum flux the phases stop shifting and in coincidence the 1 Hz QPO appears. A similar phase jump is also seen in the 2005 phase residuals, that still show the same behavior. And the same happens also for the decay point in the lightcurve and the appearance of the 1Hz QPO. One peculiarity is that this QPO is not observed persistently during the re-flaring state. It sometimes disappears, and when this happens the pulsations jumps by ≈ 0.3 cycles, in both the outbursts. This is once more an indication that what is seen in the lightcurve and in the aperiodic variability of the disk (QPO) has an effect on the pulse phases.

5. CONCLUSIONS

We conclude that, when calculating a timing solution, all these effect must be taken into account, otherwise we can confuse an effect of the magnetospheric-disk interaction with a surface effect due to, for example, a spin torque. Of course the final question is how do we take these effects into account when doing a coherent timing analysis. An answer here cannot be satisfactory, since all the described phenomena have not a clear theoretical explanation, yet. Certainly they all show that the quadratic component usually identified with a spin torque has not a higher dignity among the other terms of the polynomial expansion used in standard coherent timing techniques. Indeed it appears somehow arbitrary to treat the lowest order variation (quadratic component) as a distinct entity with respect to all the other phase shifts observed. This is particularly evident after proving that the phases of J1808 are influenced by the accretion disk-magnetospheric interaction. Another aspect to be considered in AMXP physics is the possibility that the phase variations we observe all come from the motion of the hot spot. There are several simulations and models [22][20][23],[24] that predict a moving hot spot around a quasi-equilibrium position on the neutron star surface. These movements can lead to an increase of the fractional amplitude directly anti-correlated with the time of arrival of the pulsations. However why the noisy AMXPs like J1807 and J1814 show an anti-correlation while J1751 an J00291 do not, is not easily explainable. Has the presence of a strong 1st overtone some influence on the properties of the AMXPs ? Another important point is that, beside the theoretical model required to explain the observations, one has to face a more serious problem that is how to extract the correct informations from the data and very little can be said until a satisfactory technique is developed.

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