FRAME DRAGGING IN BLACK HOLE-PULSAR BINARIES

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The discovery of frame-dragging effects in binary pulsar timing experiments requires a compact companion with sufficiently large spin. A pulsar orbiting a fast rotating black hole could provide an appropriate test system. In this paper we address questions concerning the identification of a black hole companion in such a system, the measurability of the frame dragging caused by the rotation of the black hole, and the measurability of the quadrupole moment, which would prove the presence of a Kerr black hole.

1 Introduction

For radio pulsars in orbit with a compact companion, pulsar timing observations have proved to be a powerful tool for identifying the physical nature of the companion and studying gravitational physics present in the binary system. The discovery of the binary pulsar PSR B1913+16 by Hulse and Taylor and its continuous observation is an excellent example for this branch of high precision astrophysics (see Joe Taylor’s contribution in this volume). Unfortunately, perhaps the most intriguing system where such a tool could be used, a pulsar in orbit with a black hole (BH), has yet to be discovered. A pulsar orbiting a BH in a close orbit would certainly be a high precision laboratory for BH physics. There are three basic questions related to the discovery of a (tentative) BH-pulsar binary:

• How do we identify the BH companion?
• What BH physics can be studied?
• Can we prove the presence of a Kerr BH?

The answer to these three questions does not only depend on the BH properties, but also on the properties of the pulsar and its orbit around the BH. The observed pulsar can be a young pulsar which was formed during the second supernova explosion in the binary system. The BH was formed during the first explosion of the more massive star. For such a system we expect a highly eccentric binary orbit (≈ 0.9) and a long orbital period (10 . . . 1000 days). A millisecond pulsar orbiting a BH is more difficult to create, since we need a phase of mass-transfer to recycle the pulsar. The pulsar could be recycled by a low-mass companion and later be captured by a BH in a three body interaction. The high star densities in the core of globular clusters seem to be the most likely ‘breeding ground’ for such kind of systems. But also binary evolution might allow a situation where the pulsar is created before the BH. It was argued by Ergma and van den Heuvel that neutron-star/BH formation is connected with other stellar parameters besides just the mass of the progenitor star alone (at least for initial masses ≥ 20 M⊙). Therefore, the explosion of
the more massive star could form the pulsar, which then is recycled during the evolution of the second star, which is still massive enough to form a BH. A millisecond pulsar orbiting a BH is of particular interest, since the timing accuracy is typically more than two orders of magnitude better than for young pulsars, and, in general, millisecond pulsars are free of timing noise, at least on time scales of a few years.

2 Identification

So far the best arguments for the existence of stellar mass black holes (BHs) are based on dynamical mass estimates in X-ray binaries. The measurement of absorption-line velocities of the secondary star allows us to determine the mass function of the binary, which is a lower limit to the mass of the compact companion. If the mass of the companion exceeds the calculated maximum mass of a neutron star (∼3$M_\odot$) we call it a BH candidate (see the paper by Wijers16 for a list of BH candidates).

In pulsar timing experiments the mass function of the system is known with high precision as soon as the pulsar’s binary nature is identified. Even for modest timing precision and long orbital periods, the relativistic precession of periastron is measurable within a few years of regular timing observation (see Fig. 1). This would provide the total mass of the system and thus, assuming a pulsar mass of 1.4 $M_\odot$, the mass of the BH companion. However, the absence of any mass transfer, like in X-ray binaries, does not allow (at that moment) to distinguish between a compact object or a normal star being the companion of the observed binary pulsar.

Additional optical or infrared observations have the potential to rule out a massive star. A characteristic age of the pulsar which is much larger than the lifetime of a tentative main-sequence star companion would already strengthen the case for a black-hole companion. For orbital periods of less than one year the presence of a (rotating) massive main-sequence star companion should cause a precession of the binary orbit due to its rotation induced quadrupole moment, like in X-ray binaries, does not allow (at that moment) to distinguish between a compact object or a normal star being the companion of the observed binary pulsar.

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3 Frame dragging

Astrophysical BHs are expected to rotate. The spin of the BH gives rise to a so called gravitomagnetic field which causes the relativistic dragging of inertial frames in the vicinity of the BH. This gravitomagnetic field influences the motion of matter and the propagation of light in the vicinity of the rotating body. It was suggested that in pulsar-timing experiments a rotating BH companion may be identified by its influence on the propagation time of the radio signals. Based on numerical ray-tracing calculations it was argued by Laguna and Wolszczan that high precision pulsar-timing experiments could, indeed, test the gravitomagnetic field of a rotating BH companion, if the pulsar is a millisecond pulsar in a tight orbit around a 10–20 $M_\odot$ BH with an orbital inclination very close to 90 degrees. It was shown, however, by Wex and Kopeikin that in practice a direct measurement of this effect is not possible for stellar mass BH companions, due to the presence of an additional relativistic effect found by Doroshenko and Kopeikin.

A different approach in studying the importance of frame-dragging in pulsar-timing experiments was presented by Wex and Kopeikin. Eighty-one years ago Lense and Thirring pointed out that the gravitomagnetic field of a central rotating body will cause a precession of the orbit of a test particle (relativistic spin-orbit coupling). In the same way, the rotation of one or both components of a binary system will cause a precession of the binary orbit. It was shown that
the observation of such a precession can lead to the direct determination of the spin of the BH companion.\textsuperscript{13} In this section we give a brief summary of their basic ideas.

Since the spin of a 10 $M_{\odot}$ extreme Kerr BH is more than two orders of magnitude larger than the spin of a pulsar, the spin of the BH will completely dominate the orbital precession, leading to a simple picture of the spin-orbit dynamics of the binary (see Fig. 2). The precession of the angles $\phi$ and $\psi$, which is linear in time, translates into a non-linear-in-time evolution of the observable quantities $x$ and $\omega$, where $x$ is the projected semi-major axis of the pulsar orbit and $\omega$ is the longitude of periastron. In a second order approximation we can write

$$\Delta x_{\text{SO}}(t) = \dot{x}_{\text{SO}} (t-t_0) + \frac{1}{2} \ddot{x}_{\text{SO}} (t-t_0)^2,$$

$$\Delta \omega_{\text{SO}}(t) = \dot{\omega}_{\text{SO}} (t-t_0) + \frac{1}{2} \ddot{\omega}_{\text{SO}} (t-t_0)^2.$$

The observational parameters $\dot{x}_{\text{SO}}$, $\ddot{x}_{\text{SO}}$, $\dot{\omega}_{\text{SO}}$, and $\ddot{\omega}_{\text{SO}}$ are functions of the orbital parameters of the binary system and the spin (magnitude and orientation) of the BH.

The precession in $\omega$ caused by spin-orbit coupling is only a small fraction of the total $\dot{\omega}$ ($\sim 10^{-3}$) and there is no independent measurement of $\dot{\omega}_{\text{SO}}$, until the masses of pulsar and BH are determined with sufficient accuracy from the measurement of additional relativistic parameters. Therefore, the first parameter indicating relativistic spin-orbit coupling will be $\dot{x}$, i.e. a change in the inclination of the binary orbit with respect to the line of sight (see Fig. 3). Combined with the measurement of (total) $\dot{\omega}$, which allows to derive the total mass of the system and thus gives a good estimate of the BH mass, the measurement of $\dot{x}$ gives the quantity $S_\bullet \sin \theta \sin \Phi_0$ which is a lower limit to the BH spin $S_\bullet$. On the other hand, if the companion is a main-sequence star and the orbit is undergoing ‘classical’ spin-orbit precession, then this method has the potential to rule out a BH since general relativity predicts an upper limit for the spin of a (Kerr) BH. Stairs et al. (this proceedings) reported the discovery of a binary pulsar in a highly eccentric 8-month orbit, where the mass of the companion exceeds 11 solar masses. Numerical simulations show, that if the companion is a main-sequence star rotating at just 20% of its breakup velocity then even for moderate timing accuracy, the method presented here will help to rule out a BH companion after 5 to 10 years of regular timing observations, unless the
inclination of the companion spin with respect to the orbital plane is very small.

A millisecond pulsar BH system with orbital periods below one day will allow the measurement of higher order precessional contributions, i.e. $\ddot{\epsilon}_{SO}$ and $\ddot{\omega}_{SO}$ and the separation of $\dot{\omega}_{SO}$, from the total precession of periastron. We then know the magnitude and direction of the BH spin.

4 Is there more?

The ‘no-hair’ theorem of general relativity implies that the external gravitational field of an astrophysical (uncharged) BH is fully determined by the mass and the spin of the black hole. Therefore, if we are able to extract independently the quadrupole moment of the companion from our timing observations we could actually test whether the observed pulsar is orbiting a Kerr BH or another compact relativistic object, like a Q or boson star. The quadrupole moment of the BH companion will lead to an additional precession of the binary orbit (‘classical spin-orbit precession’). Unfortunately these secular changes in the orientation of the orbit caused by the quadrupole moment of a BH companion are typically three orders of magnitude smaller than the changes caused by the relativistic spin-orbit coupling and hence cannot be extracted from the overall precession. On the other hand, the anisotropic nature of the quadrupole component of the external gravitational field will lead to characteristic short-term periodic effects every time the pulsar gets close to the oblate companion.\[\] Numerical simulations show, however, that only for black hole companions that exceed $\sim 1000 \, M_\odot$ the quadrupole moment can give rise to an observable signature in the timing residuals (see Fig. 4). The discovery of such a system in our Galaxy seems, however, unlikely.

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Figure 3: Simulated fractional measurement precision for the (total) relativistic precession of periastron, $\dot{\omega}$ (lower points), and the secular change, $\dot{x}_{SO}$ (upper points), in the projected semi-major axis caused by frame-dragging as a function of observing time. Estimations were done for a pulsar in a 20 days highly eccentric ($e = 0.8$) orbit with a 10 solar mass extreme Kerr BH. It was assumed, that there is one timing observation every month with a timing accuracy of 0.1 ms (young pulsar). This represents a limiting case for the detection of frame-dragging in a BH pulsar binary. A tighter orbit or/and a millisecond pulsar would certainly allow the discovery of frame-dragging on much shorter time scales.

Figure 4: Typical signature in the timing residuals caused by the quadrupole moment of a $10^4 M_\odot$ extreme Kerr BH companion. We used an orbital period of 10 days and an eccentricity of 0.9. The inclination of the BH spin with respect to the orbital plane (the angle $\theta$) was assumed to be 70 degrees.
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