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QUASI PERIODIC OSCILLATIONS AND THE POSSIBILITY OF AN OBSERVATIONAL DISTINCTION BETWEEN NEUTRON AND QUARK STARS*

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The X-rays emitted by accreting black holes and neutron stars are modulated quasi-periodically at very high frequencies. These kHz Quasi Periodic Oscillations (QPOs) often occur in pairs of frequencies that in black hole sources are in a 3:2 ratio. The frequencies likely represent two resonant oscillations of the accretion disk. We have evidence that the neutron star data point to the same ratio, and arguments suggesting that the 3:2 frequency ratio may be a signature of strong gravity. The modulation itself of the X-ray light curve may be caused by another effect of general relativity: light-bending close to the black hole. In some neutron star sources, the difference of the two kHz frequencies is very nearly equal to one-half of the stellar spin frequency, which is a clear signature of a non-linear resonance excited by the rotating neutron star.

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1. Accreting compact objects

Most of the objects observed by astronomers, from galaxies to our planetary system, have grown by accreting matter at some time in the past. In many instances, excess angular momentum of the accreting matter leads to the formation of flattened disk-like structures. As matter flows through them towards their center, gravitational binding energy is released in profuse quantity and is dissipated through the same frictional process that transports angular momentum outwards. These luminous accretion disks are observed in young stellar systems, at the centers of galaxies, and in numerous binary

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stars that orbit one another sufficiently close for tidal forces to cause transfer of matter from one star to the other.

When the accreting object is very compact — *i.e.*, it is a neutron star (perhaps even a quark star) or a black hole — the energy released is about ten percent, or more, of the rest mass of the accreting matter. For this reason, accretion disks around black holes and neutron stars are among the most luminous objects known: a modest solar-mass neutron star accreting matter from a white dwarf can be 100,000 times more luminous than the Sun, and most of this luminosity is coming out in X-rays. The accretion disk of a 10^9 solar-mass black hole at the center of a distant galaxy can outshine all the stars in that Galaxy, and very often we only see the light from this "active galactic nucleus" (AGN) and not from the underlying galaxy.

Although clearly important to the world around us, accretion disks are poorly understood. Their essential mechanism, the dissipative process, is of uncertain origin, although magnetic fields and turbulence are thought to be involved. Remarkably, many global properties of the disks do not depend on the details of the dissipation. For example, if the disk is geometrically thin — the ratio of its thickness to the radius being small, $h/r \ll 1$ — the gradients of pressure can be neglected and the disk is "rotation supported," *i.e.*, the fluid circles the central gravitating object in nearly circular orbits at velocities given by Kepler's law. More generally, once the mass accretion rate is known, as well as the opacity of the fluid in the disk, some other basic properties follow, such as the luminosity of the disk.

2. Characteristic frequencies and the space-time metric

Accretion processes are seldom steady, and variability on "all" time-scales is observed in the light curves of powerful X-ray sources. What is perhaps surprising is the appearance of *characteristic* frequencies in the modulated X-ray flux. Sometimes they take the form of characteristic "breaks" in the Fourier power spectrum of the light curves, in other cases quasi-coherent changes in the luminosity are observed. These are the QPOs ("quasi-periodic oscillations").

Already in 1973 G. Bath pointed out that in an accretion disk variability is expected at Keplerian frequencies, different at each radial position in the disk

$$\omega(r) = \left(\frac{GM}{r^3}\right)^{1/2} . \tag{1}$$

Here M is the mass of the central object, and G is Newton's constant. A characteristic frequency must then correspond to a characteristic radius, r_0. In Newtonian physics, Keplerian frequency is scale-free, and a characteristic radius must be imposed externally on the problem. For example, it could be the radius of the central star. Furthermore, in Newtonian physics, the orbital frequency is degenerate with the epicyclic frequencies (*i.e.*, those of radially or vertically perturbed orbits), and even non-circular bound orbits are closed. But the real, Einsteinian world, with a constant speed of light c, is more interesting. The same Keplerian formula (Eq. (1)) describes the frequency (as seen by a distant observer) of orbital motion in a circular geodesics in the Schwarzschild's metric, in which several characteristic radii are given by the *mass* of the central object: the Schwarzschild radius $r_{\rm S} = 2GM/c^2$, the radius of the innermost stable circular orbit, $r_{\rm ms} = 3r_{\rm S}$, the radius at which the radial epicyclic frequency is highest $r_1 = 4r_{\rm S}$. Each of these corresponds to a characteristic frequency, *e.g.* for a spherically symmetric neutron star (or quark star, or a black hole) twice as massive as the Sun, the highest possible orbital frequency (of a test particle, or of fluid in a geometrically thin disk) is $\omega(r_{\rm S}) = 1.1\,{\rm kHz}$.

The main points that are relevant to the QPO story are these. First, if the observed frequencies correspond to the characteristic frequencies of Einstein's gravity, then they should scale inversely with the mass of the object (this has indeed been observed). Second, the epicyclic frequencies are in general different from the orbital frequency (recall the precession of the perihelion of Mercury's orbit, and the Lense–Thirring precession of inclined orbits), so that more than one characteristic frequency is allowed. Third, for rotating objects, frame-dragging corrections increase the characteristic frequencies, which now depend not only on the mass and spin of the central object, but also on the distribution of matter in it. Thus, in principle, the characteristic frequencies observed in accretion disks allow one to determine whether the object is a black hole, a neutron star, or a quark star.

3. Twin kHz QPOs

Let us focus on the highest-frequency QPOs. In neutron stars they are in the kilohertz range, and typically they come in pairs. That is, for a given accreting neutron star, two quasi-coherent modulations of the flux are present, their frequencies are even higher than that of the fastest rotation rate measured in radio pulsars, which is "only" about 600 Hz. Interestingly, these kHz QPO frequencies are not fixed, but drift over time unpredictably. However, there is a reproducible one-to-one relationship between the two frequencies: as it turns out, on a frequency–frequency plot the data points are arranged on more or less a straight line, with a slightly different slope for each source.

4. Non-linear resonance

The QPO puzzle may be summarized as follows: what is the origin of two characteristic frequencies in an accretion disk, which are not constant, but are well correlated in their variability?

The signal is not coherent, so it cannot be a direct signature of the stellar spin. The frequency drift (and other more technical reasons) suggest strongly that the source of variability is in the accretion disk. The accretion disk, being a fluid body close to hydrostatic equilibrium, will have its own eigen-modes of oscillation. The question may then be rephrased: why there are only two modes of oscillation selected, why do their observed frequencies vary so much, and why do they vary in a correlated fashion? A compelling answer is that these are properties typical of a non-linear resonance (Kluźniak and Abramowicz 2001, Abramowicz and Kluźniak 2001). These properties are characteristic of a non-linear system in which two modes of oscillation are coupled. For example, the system may oscillate in a range of frequencies, even though the two eigenfrequencies are fixed. Detailed studies (see the bibliography) show that the non-linear resonance hypothesis is quite successful in explaining many of the observed QPO properties. To a large extent, these properties are independent of the underlying physical system, the only requirement being that the system be non-linear and have two coupled modes of oscillation.

5. Strong gravity

Some QPO properties may, in fact, reflect the specific properties of the physical system. For example, the ratio 3:2 of the twin QPO frequencies is observed in black holes and may be preferred in neutron stars. The simplest explanation is that we are witnessing a parametric resonance between two "epicyclic" modes of oscillation (Kluźniak and Abramowicz 2002). For a toroidal accretion "disk" a collective vertical motion of fluid is possible that will occur at the vertical epicyclic frequency, ω_z, and another radial breathing mode that will occur at the radial epicyclic frequency, $\omega_{\rm r}$. If the latter excites a parametric resonance of the former (much as a child excites a swing), it is known from the theory of Mathieu's equation that the resonance condition is satisfied when the frequencies are in a half-integer relation: $\omega_z = (n/2)\omega_{\rm r}$, with the fastest growing mode (strongest resonance) occurring for the lowest possible value of the integer n. But in Einstein's gravity the radial epicyclic frequency is always lower than the vertical $\omega_{\rm r} < \omega_z$, thus the parametric resonance condition can first be satisfied for $n = 3$, and the corresponding ratio of frequencies is 3:2.

6. Modulation mechanism

I have argued that we have identified the origin of kHz QPOs with parametric resonance between two modes of oscillation for an accretion disk, the two simplest modes being axi-symmetric. How can axisymmetric vertical motion (parallel to the disk axis) lead to observable modulation of the X-ray flux? We know the answer for black holes. It turns out that light bending close to the black hole is so sensitive to the position of the torus, that its motion can lead to appreciable modulation of the light observed at infinity (Bursa *et al.*, 2004).

7. More work

The topics touched upon here continue to be actively investigated, with the most recent work focusing on the interaction between the spin rate of the neutron star and the excited modes of disk oscillations. Observations of one source, in particular, seem to point to a non-linear interaction: the QPO frequency difference is accurately equal to one-half of the neutron star spin rate (for an interpretation see Kluźniak *et al.*, 2004).

The above text is a summary of work reported in the following original papers, where detailed pointers to the literature may also be found.

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