SQUEEZED MAGNETOSPHERE AND EVOLUTION OF THE MAGNETIC FIELD IN LMXBs

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ABSTRACT

We show that recent observations of kHz QPOs in several LMXB can be interpreted as Keplerian frequencies from the inner rim of an accretion disc extending close to the neutron star surface. Variations of the QPO frequency with source luminosity suggest that the edge of the disc is in dynamical equilibrium as it is expected if a magnetosphere surrounds the neutron star. The QPO frequencies span a relatively small range for sources that covers almost three orders of magnitude in luminosity implying that, independently of the accretion rate, the magnetosphere has comparable size in all the systems and is squeezed against the neutron star surface by the pressure of the accretion flow. The existence of this marginally stable magnetosphere is suggestive of a mechanism of accretion-induced magnetic field decay that stops once the magnetospheric radius skims the neutron star surface. We also discuss the possibility that the neutron star radius is inflated by the rapid rotation of these objects.

1. Introduction

Recently, the capabilities of the RXTE instruments permitted the observation of kHz Quasi Periodic Oscillations (QPOs) from LMXBs containing neutron stars. In nearly all the kHz QPO sources two simultaneous kHz peaks (hereafter: twin peaks) are observed in the power spectra, only in Aql X-1 and 4U 1735-44 a single peak was observed. When the accretion rate $\dot{M}$ increases both peaks move to higher frequencies. The lower frequency peak has been observed between 325 and 900 Hz, the higher frequency peak has been observed at frequencies between 500 and 1228 Hz. One possibility to explain the presence of twin peaks is given by the so called beat frequency model (Strohmayer et al. 1996, Ford et al. 1997a), originally introduced by Alphar & Shaman (1985) and Lamb et al. (1985) to explain the 15-60 Hz Horizontal Branch Oscillations (HBOs) discovered in the Z sources (van der Klis 1989). According to this the higher peak correspond to the Keplerian frequency ν_k at the innermost radius of an accretion disk surrounding the neutron star, while the lower peak is the beat frequency between the spin frequency of the compact object ν_s and ν_k. Although attractive, this model have difficulties in explaining the not constancy of the difference between the higher peak and the lower peak observed in some sources. On the other hand, the interpretation of the higher peak as the Keplerian frequency at the inner rim of the accretion disc seems quite natural in consideration of the fact that this Keplerian frequency is the highest dynamical frequency of the system. In the following we just concentrate on the higher peak assuming this interpretation.

2. The Sample

We selected a sample of 4 atoll and 4 Z sources. For each source we plotted the higher peak frequency vs. the X-ray luminosity (figure 1). The atoll sources we used are: 4U 1731-26 (Wijnands & van der Klis, 1997), 4U 0614+91 (Ford et al. 1997b), 4U 1820-30 (Zhang et al. 1998), 4U 1728-34 (Strohmayer et al. 1996). For the Z sources in the “normal branch” (NB) the frequencies increases monotonically with $\dot{M}$ as inferred from source displacement along the Z track (Hasinger & van der Klis 1989). The Z sources we used are: SCO X-1 (van der Klis et al. 1996), GX 17+2 (Wijnands et al. 1997b), GX 340+0 (Jonker et al. 1998) and GX 5-1 (Wijnands et al. 1998). As it is possible to observe the sample spans three orders of magnitude in X-ray luminosity.

3. Evidence of a squeezed magnetosphere

Analysing the figure 1, we note that a linear relationship (in a log-log scale) exists between the higher peak frequency and $\dot{M}$ for each source, independently of the source luminosity. Moreover the slopes are similar. This behavior could be explained allowing for the presence of a magnetosphere and assuming that the higher peak frequency is the Keplerian one at the magnetospheric radius (R_M). In fact if $\dot{M}$ increases the magnetosphere is compressed by the increased pressure of the accretion flow, the magnetospheric radius decreases and the correspondent Keplerian frequency increases also. According to Campbell (1997) the relationship between the magnetospheric radius R_M and the mass accretion rate in a thin disk with a central density ρ and magnetic dipole aligned with the spin axis is:

$$R_M \propto \rho^{1/9} \mu^{2/3} \dot{M}^{-4/9}. \tag{1}$$

Substituting ρ with its expression for different disc structures we obtain:

$$R_M \propto \dot{M}^{-1/3} \mu^{4/7} \qquad \text{gas pressure dominated disk} \tag{2}$$

$$R_M \propto \dot{M}^{-4/5} \mu^{4/5} \qquad \text{radiation pressure dominated disk} \tag{3}$$

Therefore the expected slopes of the relationship $\nu - \dot{M}$ are between 1/2 (gas pressure dominated) and 6/5 (radiation pressure dominated). In figure 2 we plot the two expected slopes on each source data. It is evident that, for nearly all the sources, the observed slope is within the expected range. In most of the cases the slopes are closer to the value expected for radiation pressure dominated discs.

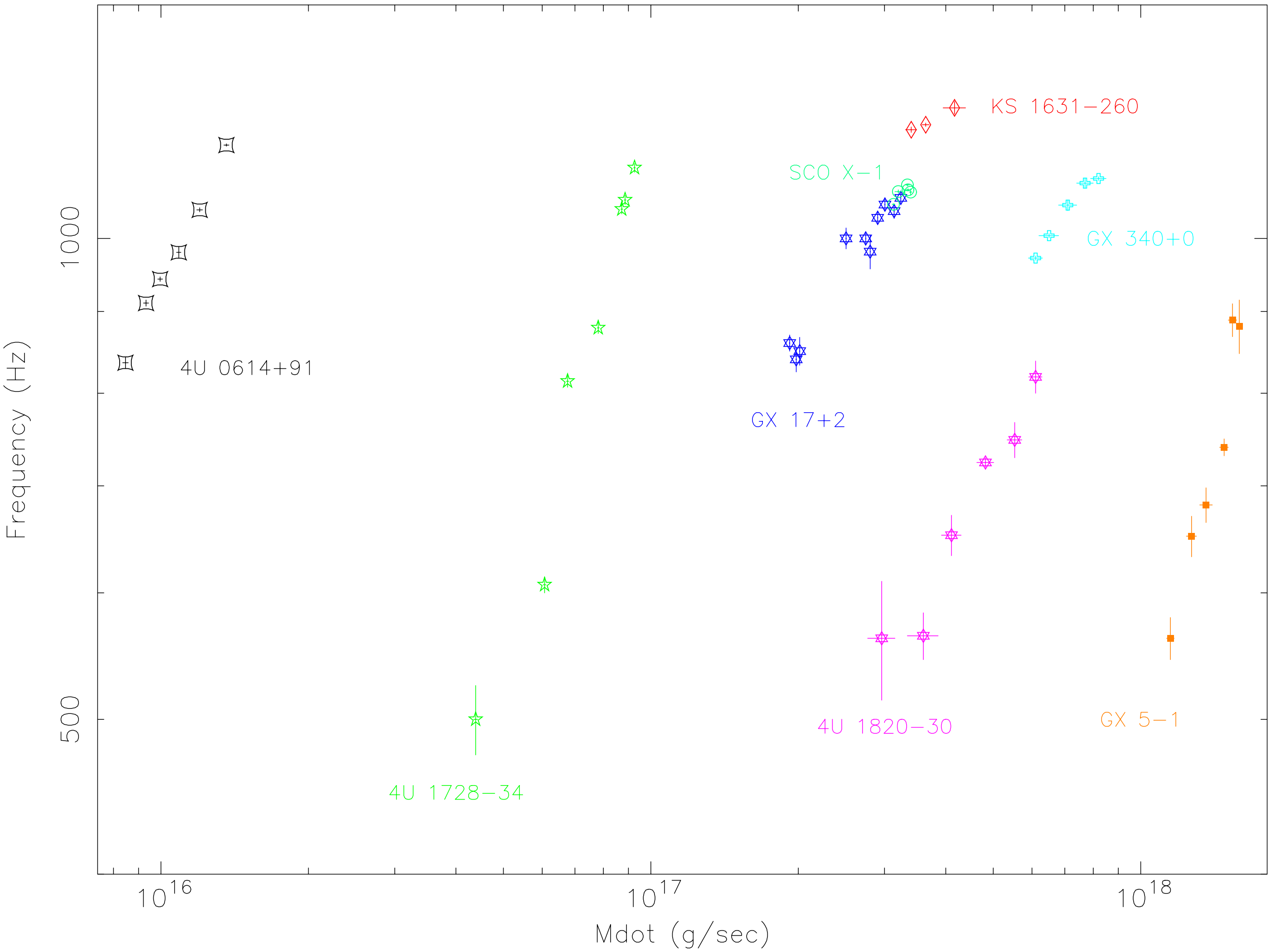
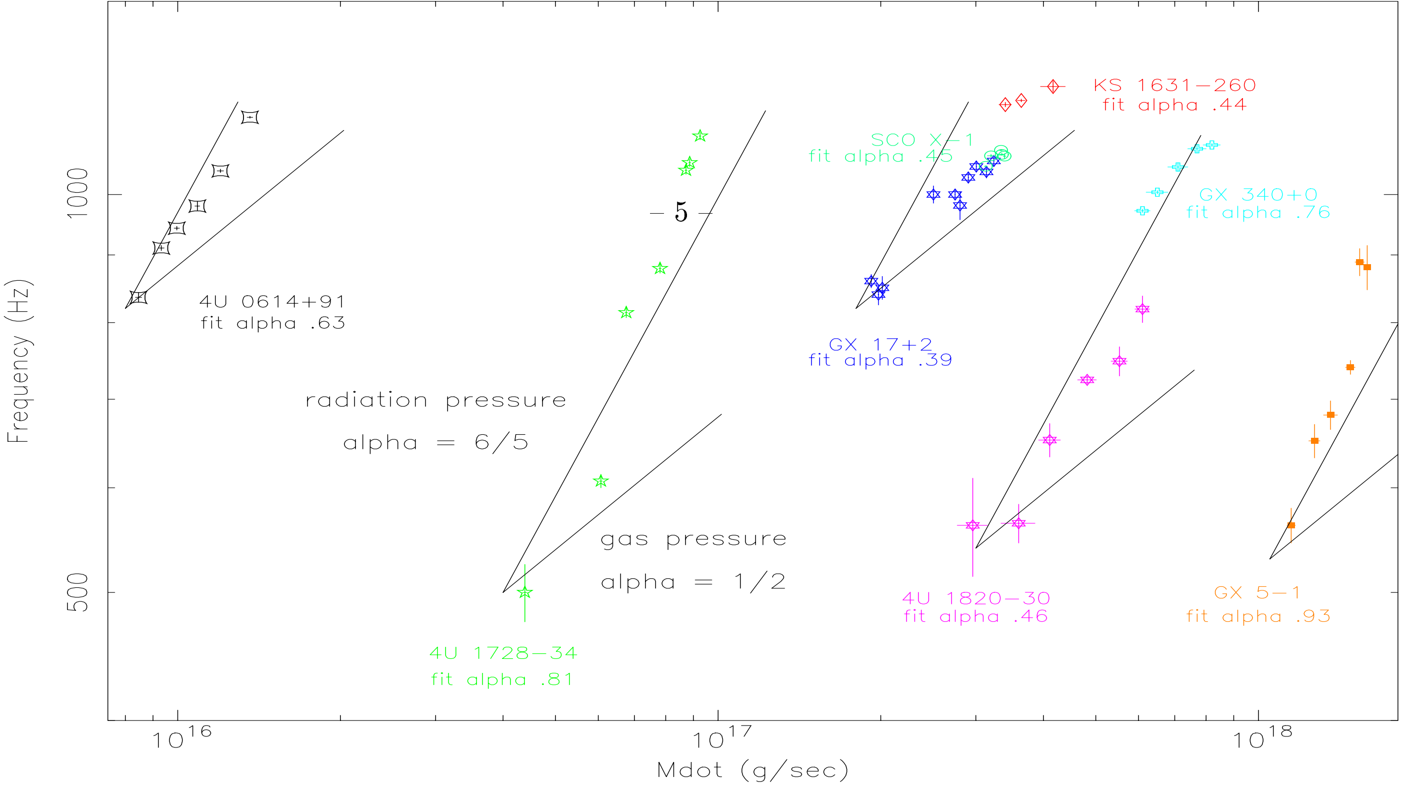


Fig. 1.— High Khz QPO vs. Mdot for the sources of our sample

From the figure is also evident that the maximum value of the higher peak frequency is almost the same for all the sources despite the luminosity spans three orders of magnitude. This suggests that at the maximum luminosity of each source the magnetospheric radius reaches the neutron star surface (or the Last Stable Orbit, LSO, see below) squeezing the magnetic field against the neutron star surface (we call this value of the magnetic field $B_{squeezed}$). The condition $R_M = R_{NS}$ and the equation (2) imply that $B \propto \dot{M}^{7/12}$ in a gas pressure dominated disk, while the same condition combined with the equation (3) imply that $B \propto \dot{M}$. In both cases the magnetic field seems to depend on the average luminosity of the source. This could mean that the magnetic field at the end of its evolution reaches an equilibrium value (that is $B_{squeezed}$) dependent on the mass accretion rate $\dot{M}$. This is possible if an accretion-induced magnetic field decay mechanism operates in these systems until the magnetospheric radius reaches the neutron star surface and then stops (Burderi, King, and Wynn, 1996; Burderi, 1997). X-ray pulsators show evidence that, inside the magnetosphere, strong magnetic fields funnel the accretion flow focusing it onto the magnetic caps. On the other hand, when the magnetospheric radius is close to the neutron star surface, the funneling becomes less effective and the matter starts to accrete onto the whole neutron star crust. If the ordered accretion onto the magnetic caps is responsible for the field decay, the decay naturally stops once $R_M \sim R_{NS}$. Moreover, because the funneling is no more effective, no coherent pulsations are expected, as observed in these sources.

4. Inferred radius of the neutron star

As stated above, the magnetospheric radius reaches the neutron star surface or the Last Stable Orbit (LSO) at the higher luminosity of each source. In figure 3 we plotted the lines at the Keplerian frequencies corresponding to several neutron star radii, masses, and last stable orbits. For reference we used radii and masses corresponding to a stiff Equation Of State (EOS) L and to a moderately soft EOS FPS. In the case of a rapidly rotating star (using 1.7 $M_\odot$ in the case of rapidly rotating star we included the $\sim$ 50% inflation of the radius induced by the rapid rotation (see Burderi et al. 1998). The data are in agreement with a LSO of a very massive neutron star, or with a less massive slow L or a fast FPS.



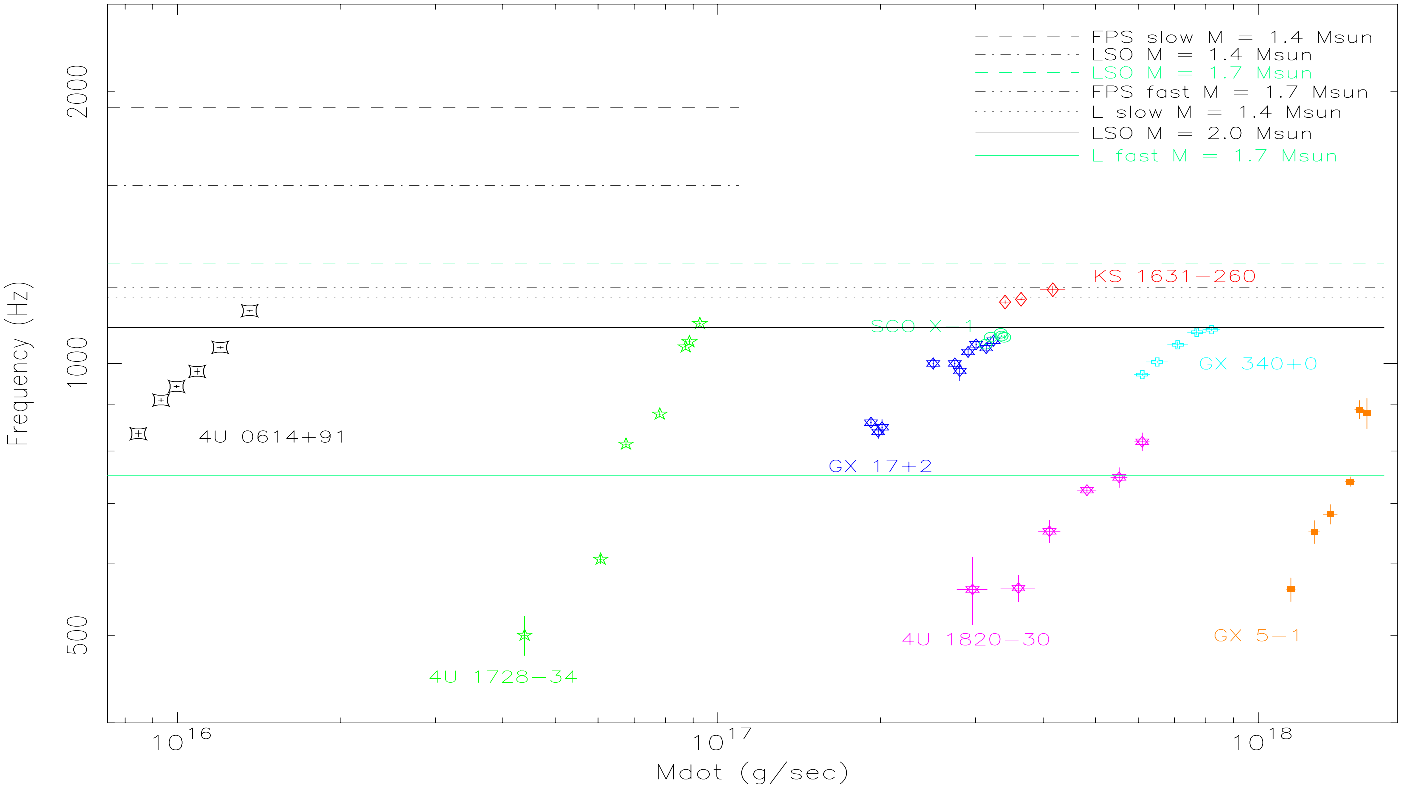


Fig. 2.— Comparison between the observed and theoretial slopes

Fig. 3.— Maximum frequencies calculated for several EOS

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