Quasi Periodic Oscillations at Kepler and Beat Frequencies as Wave Packets

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February 4, 1997

In the beat frequency model for horizontal branch (HB) QPO, the accretion from the neutron star surface is modulated at the frequency difference between the rotation frequency of the neutron star magnetosphere and the Keplerian rotation rate of the inner boundary of the accretion disk (Alpar and Shaham 1985). The structure in the inner disk that is necessary to realize the modulation at the beat frequency was modelled as "clumps" in previous work (Lamb et al. 1985). The clumps can also be viewed as wave packets (Yılmaz, 1992). A wave picture was first proposed for the normal branch (NB) QPO by Alpar et al (1992). This talk presents in summary the results of Alpar and Yılmaz (1996) who obtain Kepler and beat frequency QPOs from simple wave dispersion relations in a rotating medium.

Alpar et al (1992) modelled the NB QPOs as optical thickness oscillations due to sound modes in a thick accretion disk. The normal-branch spectral state is interpreted as a special state of the disk when the accretion rate approaches the Eddington value, with a thick subsonic "hump" region. The longest wavelength sound modes are responsible for the dominant optical thickness modulations that are imparted on the X-rays comptonized while going through the accretion disk. As the frequency of the global modes in a (Keplerean) rotating medium coincides with the rotation frequency, the QPO frequency is the Kepler rotation frequency and the QPO frequency band corresponds to a wavepacket of these modes. The dispersion relation is $w^2 = \kappa^2 + c_s^2 k^2$ for axisymmetric sound modes propagating at right angles to the rotation axis. One can relate the QPO frequency and bandwidth $\Delta\nu$ to a typical wavelength $\lambda_{QPO} \approx (c_s/\nu_{QPO})(\Delta\nu/\nu_{QPO})^{-1/2}$. Taking c_s from kT inferred from spectral fits for the NB QPO (Miller and Lamb 1992), ν_{QPO} and $\Delta\nu$ from the observed power spectra on the NB leads to wavelengths (4.5-8.9)$\times 10^6$ cm and wave packet sizes (0.5-1.0)$\times 10^6$ cm. These are commensurate with reasonable thick disk dimensions.

For the HB beat frequency QPOs, the inner boundary region of the disk is modelled as a rotating medium where the magnetic field of the neutron star is taken to be a uniform magnetic field rotating at the beat frequency with respect to the disk at the beat frequency $\nu_B = \nu_K - \nu_S$ where ν_K is the Kepler frequency of the disk and ν_S is the stellar rotation frequency. The penetration of the stellar magnetic field in relative motion at the beat frequency with respect to the conducting disk occurs in a thin boundary region and is made possible by the contribution of reconnection and turbulence mechanisms. We make the simplifying (and artificial) assumption that those mechanisms determining the balance in the boundary region do not contribute to linear perturbations, at least not in the long wavelength limit. An alternative approach would be to treat the disk as a rotating medium, without including magnetic fields, and to put in a band of frequencies around the observed QPO frequency, and with the observed bandwidth, as oscillations at the boundary driving excitations in the disk, and extract the related wavelengths and wavepacket sizes. This approach would miss magnetic restoring forces and the Alfven velocity, which can be much larger than the velocity of sound in the boundary region. In the long wavelength limit, the model dispersion relation gives branches with $w^2 \to 0$ as $k^2 \to 0$, or $w^2 \to w_B^2$ as $k^2 \to 0$, or $w^2 \to \Omega_K^2$ as $k^2 \to 0$.

One of the two branches of the dispersion relation which have frequencies around the beat frequency in the long wavelength limit has a frequency minimum at a finite wavelength. The associated long wavelength scale is $\lambda = V_A/\nu_{QPO}$. Noting that V_A decreases at least as r^{-3} in the inner disk, we find that the inner boundary region where $\lambda < r$ extends to $\bar{r}$ ~(2.1-2.7)$\times r_{in}$, where r_{in} is the inner radius of the disk. The wavepacket sizes $\triangle x$ are (1.9-2.5) $\times r_{in}$. For the other branch with frequency ν_B in the long wavelength limit, $\bar{r} = (2.5 - 3.2) \times r_{in}$ and $\triangle x = (1.9 - 2.5) \times r_{in}$ again.

The wavepacket models require the existence of a medium that supports wave propagation. The radial drift velocity must be subsonic (or sub-Alfvenic). For the NB QPOs a subsonic region $V_r < c_s$ was postulated to occur in a radiation dominated thick accretion disk (Alpar et al 1992), while for the HB QPOs, we note that $c_s < V_A$ and $V_r < V_K \sim V_A$ in the inner disk.

The interpretation for the kHz QPOs has been that the higher frequency QPO reflect Kepler frequencies while the lower band is due to the beat frequency (Strohmayer et al 1996, van der Klis et al 1996a). The kilohertz QPOs pose two problems for wave models. First, their amplitudes are high compared to the HB QPO amplitudes. If both kinds of QPOs are due to excitation of wavepackets by boundary conditions it is difficult to understand the different amplitudes. Second, the HB QPOs and the kHz QPOs are observed simultaneously from the Z source GX 5-1 (van der Klis et al 1996b), so two distinct boundary layers supporting waves are implied to be simultaneously present.

Miller, Lamb and Psaltis (1996) proposed that the kHz QPOs originate in a supersonic boundary region: The Kepler frequency of clumps arriving at the sonic surface is imprinted on the supersonic accretion flow, and the beat frequency is produced by interaction of the radiation pattern originating from the star with the clumps arriving at the sonic surface. If the magnetospheric field perturbations at the sonic surface partially penetrate the subsonic or sub-Alfvenic region beyond, wavepackets at Kepler and beat frequencies would be excited there. The stellar rotation frequency is indicated by the difference between the two kHz QPO frequencies to be $\nu_s \approx 300 Hz$. Taking the inner boundary for the wave region at the sonic surface r_{so} and $\bar{r} \sim 2 - 3r_{so}$ gives local beat frequencies for the wave propagation region $\nu_B(\bar{r}) \sim 50$ Hz in agreement with the range of HB QPOs. This beat frequency would modulate the total mass arriving at the sonic surface and therefore the accretion luminosity would be modulated at the HB beat frequency, as long as there is a boundary between the wave region and the sonic surface or the magnetosphere. The simultaneous presence of the kHz oscillations would depend on the presence of a sonic surface and of clumpiness (wavepackets) at the sonic surface. In conclusion we venture the notion that the presence of supersonic and subsonic regions simultaneously may explain both the simultaneous presence of two different beat frequencies and the qualitative difference between the kHz and HB QPOs regarding coherence and pulsed amplitude.

I thank Guy Miller for a helpful comment, and acknowledge support from the Academy of Sciences of Turkey, from The Scientific and Technical Research Council of Turkey (TÜBITAK) High Energy Astrophysics Research Unit TBAG Ü -18, from NSF under Grant PHYS-9417296, and from COSPAR for participation at this meeting.

References

Alpar, M.A. and Shaham, J., 1985, Nat., **316**, 239

Alpar, M.A., Hasinger, G., Shaham, J., and Yancopoulos, S., 1992, A & A , **257**, 627

Alpar, M.A., and Yılmaz, A., 1996, submitted to New Astronomy.

Lamb, F.K., 1991, Proc. of NATO ASI "Neutron Stars: Theory and Observation", eds. J. Ventura, and D. Pines, Kluwer

Lamb, F.K., Shibazaki, N., Alpar, M.A., Shaham, J., 1985, Nat., **317**, 681

Miller, G.S. and Lamb, F.K, 1992, ApJ **388**, 541

Miller, M.C., Lamb, F.K, and Psaltis,D., 1996, submitted to ApJ

Strohmayer, T., Zhang, W., Swank, J.H., Smale, A., Titarchuk, L., & Day, C., 1996, ApJ Lett **469**, L9.

van der Klis, M., Swank,J., Zhang,W., Jahoda, K., Morgan,E., Lewin, W., Vaughan, B., & van Paradijs, J. 1996a, ApJ Lett., **469**, L1.

van der Klis, M., Wijnands, R., Kuulkers, E., Lamb,F.K., Psaltis, D., Dieters, S., van Paradijs, J., Lewin, W., & Vaughan, B., 1996b, IAU Cir.6511.

Yılmaz, A., 1992, MS Thesis, Dept. of Phys., METU, Ankara