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Spiral Shock Oscillations and the QPOs at 2:3 ratio

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Several black hole candidates are reported to have shown existence of quasi-periodic oscillations (QPOs) at 2:3 ratio. We discuss a possible mechanism for this which is sufficiently generic and does not crucially depend on the general relativistic effects. We believe that just as axisymmetric shock oscillations cause normal low frequency QPOs, non-axisymmetric shocks or spiral shocks will cause the 2:3 ratio when two or three armed spirals are produced in a quasi-thin flow.

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1. Introduction

Several black hole candidates, such as GRS 1915+105, GROJ 1655-40, H 1743-322 and XTE 1550-564 exhibit a curious property in that its high frequency quasi-periodic oscillations (QPOs) often have 2:3 ratio. This is not a very common phenomenon. First of all, this behaviour seems to occur only for high frequencies, i.e., when the oscillating physical region is located closer to the black hole. Second, the objects which exhibit them have the disks inclined at an angle of about $\sim 35-70$ degrees or more. Third and perhaps more important, QPOs of this ratio are seen when the spectral state is becoming softer. Moreover, the fundamental is not seen at all. All these point to the fact that we are dealing with an oscillating region in the form of a non-axisymmetric spiral shock, having occasionally two arms and occasionally three arms. In this paper, we shall argue why this might be the cause of the QPOs appearing in 2:3 ratio.

2. Justification for Spiral Structure Formation

It is long known that in strictly two dimensional flows the turbulent energy is concentrated in larger scales and in strictly three dimensions the energy cascades into smaller and smaller scales (e.g., Frisch, 1996). An accretion disk is however neither two dimensional nor three dimensional. As a result, one could expect that the turbulent energy would neither go to the largest scale (single armed spiral), nor to the smallest scale (total chaos). But it could rather go to the intermediate scale (two or three arms). It has been observed by numerical simulations that the tidal processes do not induce one armed spiral shocks. Recent simulations with 3D flow also shows that the one arm is produced only due to ram pressure induced by the eccentric orbits (Hayasaki & Okazaki, 2005). Single armed spirals were seen to grow rapidly in a two dimensional, constant angular momentum simulation (Blaes & Hawley, 1988) but as the angular momentum distribution is changed towards Keplerian distribution, the growth rate is reduced. Single armed spiral waves may exist only in nearly Keplerian disks provided only a single central source of perturber is present (Lee & Goodman, 2005). In theoretical studies of self-similar spiral shocks it was found that when the adiabatic index γ is closer to 1.67 the density waves are fragmentary and no large scale structures can form (Chakrabarti, 1990). As γ starts going down to 1.5 or less, the radiation starts dominating and the standing shocks may form since the flow starts having more than one saddle type sonic points. Steady state spirals may also form. However when γ goes down even further to 1.2 or so, and the gas becomes cool. In this case, the spirals may fragment into two or three pieces but not to one. All these results suggest that the formation of more than one arm is more probable when we have a realistic disk and at a given time how many arms would form will depend on the nature of the viscous processes which dictate the angular momentum distribution inside the disk.

In this paper, we are suggesting that the 2:3 ratio that is observed in QPO frequencies in several objects is directly related to the behaviour of turbulence in a '2.5-dimensional' flow, such as the accretion disk. As the accretion rate increases and the axisymmetric shock is pushed inside due to ram pressure, it breaks partially and causes spiral structures to form (which may be sustained due to tidal effect of the companion). Thus these high frequency QPOs at 2:3 ratio occur when the spectrum is becoming softer.

3. Results of Our Numerical Simulation

We present results of numerical simulations in presence of a binary companion in an adiabatic accretion disk. Figures 1(a-c) show the density (Z-axis) distribution as a function of X and Y coordinates. The simulation was carried out with $\gamma = 1.2$ and $q = M_x/M_c = 1$, where, M_x and M_c are the masses of the compact object and the companion respectively. The three figures are drawn at $T = 2.296$, 3.422 and 3.746 respectively (Chakrabarti, 1996). Here, time is measured in units of the orbital time of the companion. Thus the number of arms are changing from (a) two to (b) three to (c) two respectively in about an orbital period. The post-shock region (which may be called Non-Axisymmetric CENtrifugal pressure supported BOundary Layer, or NACENBOL) will continue to be hot and will continue to Comptonize soft photons as the axisymmetric CENBOLs (see Chakrabarti & Mandal, this volume) do. In order that the effect of non-axisymmetry is reflected in the observed lightcurve, the inclination angle must be large, otherwise modulation due to non-axisymmetry will be absent or weak. The strongest emitting region from these shocks are very close to the inner region of the disk (Fig. 2) and when compared with the procedure by which CENBOL oscillates (Chakrabarti, Acharyya & Molteni, 2004) we expect that the NACENBOLs would also oscillate around the mean location at time scales comparable to the dynamical time (time to traverse from one shock to the other) at the inner region. Thus, the ratio of the QPOs would be the ratio of the dynamical time in the flow with two and three shocks.

4. Concluding Remarks

In this paper, we have presented a plausible model of why occasionally QPOs at high frequencies are observed at $\nu_2/\nu_3 = 2/3$. They can be present even when the axisymmetric shock is present. However, we expect that either of ν_2 or ν_3 would be present at a time though while the shock breaks from one to the other both could be seen, one becoming dimmer and the other becoming stronger. This model also explains why objects with disks having high inclination angle are more favorable to have QPOs with such a special frequency ratio. However, intrinsic variation of the shape of the NACENBOL causes differential variation of the intercepted soft photons. Thus, emitted hard photon numbers should continue to be modulated even at a smaller inclination angle also. But when viewed nearly end on, the modulation would be insignificant in comparison to the background photon.

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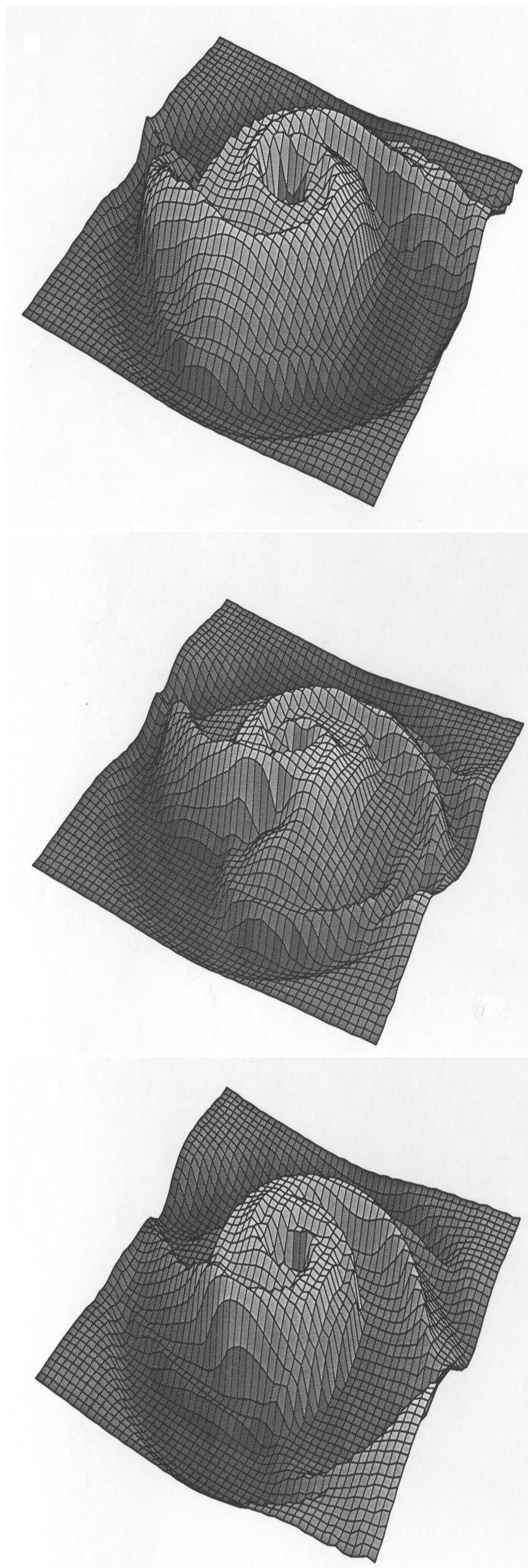

Figure 1: Variation of the shape of the spiral density wave in an accretion flow in presence of a binary companion. Two armed spiral in (a) is changed to three armed spiral in (b) before going back to a two-armed spiral again. The curves are drawn at $T = 2.296, 3.422$ and 3.746 respectively, where time is in units of the orbital period. The adiabatic index $\gamma = 1.2$ was used and the companion of equal mass has been used in the simulation.

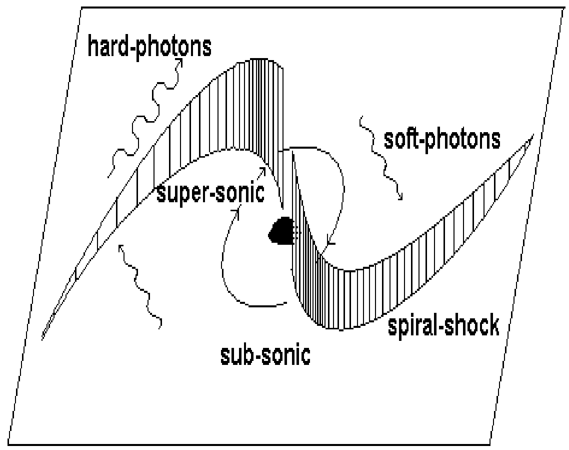

Figure 2: Nature of two non-axisymmetric CENBOLs which are puffed up to intercept soft photons from the pre-shock flow and re-radiate them in hard X-rays. Oscillations of these regions cause higher frequency QPOs. When the pattern changes to a three-armed spiral, QPO frequency increases further by another fifty percent, causing the appearance of QPOs at 2:3 ratio.

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