Nonlinear Oscillation of the Magnetosphere around Neutron Stars

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SUMMARY; We investigate the unsteady motion of mass reservoir formed by the accretion onto the magnetosphere around rotating neutron stars. The unsteady motion of the reservoir induces secondary accretion to neutron star by R-T instability. The nonperiodic or quasiperiodic phenomena of X-ray bursters seems to be related to this property of mass reservoir on the magnetosphere. We classify the typical dynamical state of the reservoir into three types with the parameters which are accretion rate $\dot{M}_{acc}$ and angular velocity of neutron star Ω_s. They are nonsequential oscillation, sequential periodic (quasi-periodic) oscillation, and chaotic oscillation states.

1. Physical Model; We propose a symplified model for the non-linear-like phenomena in X-ray sources, considering the properties of Rayleigh-Taylor instability on the magnetopause which is formed by the accreting matter to the neutron star, and then obtain the motion of this magnetopause.

We assume that the stellar magnetic field is dipolar ($\propto \tilde{\omega}^{-3}$), and has axial symmetry everywhere. We use cylindrical coordinates ($\tilde{\omega}$, Φ, z) centered on the neutron star and aligned with the stellar rotation axis. This configuration is sketched in Figure 1. We obtain the nondimensionalized equations which construct a complete set for the dynamics of reservoir ring, as following,

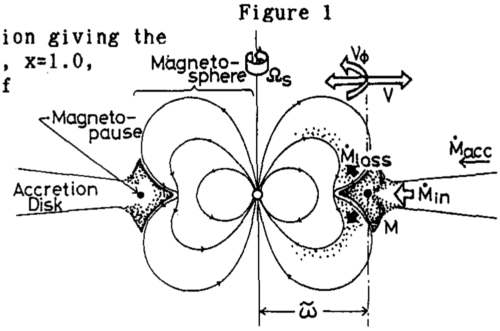
$$\Sigma\frac{dV}{dt} = Q(Bp^2-\alpha)x + 1/2\cdot(-x^{-2}+2H^2x^{-3}) - (Vx^{(d+1)}+\dot{\Sigma}_{acc})^2\cdot x^{-(d+1)} \leftarrow(1), \quad \frac{dx}{dt} = V \leftarrow(2),$$

$$\Sigma\frac{dH}{dt} = 2Qx^2\cdot Bp\cdot Bt + \dot{\Sigma}_{in}(x/2)^{1/2} \leftarrow(3), \quad \frac{dBt}{dt} = \frac{Bp}{L}(H/x - \Omega x) - \dot{\Sigma}_{loss}/\Sigma \cdot Bt \leftarrow(4),$$

$$\frac{d\Sigma}{dt} = \dot{\Sigma}_{in} - \dot{\Sigma}_{loss} \leftarrow(5), \quad \dot{\Sigma}_{in} = \theta(Vx^{(d+1)} + \dot{\Sigma}_{acc}) \leftarrow(6), \quad \dot{\Sigma}_{loss} = \Sigma\cdot(\theta(\frac{dV}{dt}/x))^{1/2} \leftarrow(7),$$

$Bp = x^{-3} \leftarrow(8)$, where t, x, V, H, Bp, Bt, Σ, $\dot{\Sigma}_{acc}$, Ω, and $\dot{\Sigma}_{loss}$ are the nondimensinal time, radius, radial velocity, specific angular momentum, mass, poloidal, toroidal magnetic field of the reservoir, accretion rate, angular velocity of central star, and mass loss rate from reservoir.

Figure 1



3. Results; We have started our calculation giving the initial condition fixed on Σ = 1.0, V=0.0, x=1.0, H = 0.1, Bt=0.0, and the various values of the control parameters $\dot{\Sigma}_{acc}$ and Ω. We get three types solutions, as shown below.

	Ω	Σacc	dynamics
case (a)	1.0	3.00	Periodic
case (b)	-1.0	2.50	Expansion
case (c)	-1.0	2.53	Chaotic
case (d)	-1.0	3.00	Periodic
case (e)	0.0	1.00	Periodic
case (f)	-1.0	2.80	Periodic

4. Physical Meanings; We will consider the physical meaning of the results shown in above section. Now, for experimental approach, we introduce a test circular ring which does not change its mass M and also Σ. This test ring is initially rotating with Keplerian velocity, and then, for the interaction with stellar magnetic field, the ring losses the angular momentum. When the ring falls into the magnetosphere, the rotating velocity of the ring may become the same velocity as that of the magnetosphere.

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These situations, which represent the difference between the direct and the retrograde rotation of the star against the disk, shows schematically in figure 3 (a) and (b).

Direct Rotation; A (Stable) ——↑—— Periodic Oscillation
Perturvation
B (Stable)↓
Retrograd Rotation; +Mass Change → Chaotic Oscillation
D (Stable)↑ (Shift of Stable Point)

For retrograde case, the shift of two stable equilibrium points may randumly mix the oscillation modes related two points by changing of the mass. Then, the chaotic oscillation of this system may be generated.

5. Discussion; We introduce typical time scale and burst energy of this system.

$$td = \tilde{\omega}_0 \left(\frac{2GM_s}{\tilde{\omega}_0} \right)^{-1/2} = 0.2 \left(\frac{\tilde{\omega}_0}{10^9 \text{ cm}} \right)^{3/2} \left(\frac{M_s}{1M_\odot} \right)^{-1/2} \text{(sec)},$$

$$E = 2.58\text{x}10^{38} \cdot \left(\frac{M_s}{1M_\odot} \right)^{1/2} \left(\frac{\tilde{\omega}_s}{10^6 \text{cm}} \right)^{3/2} \left(\frac{\dot{M}_{acc}}{10^{18} \text{g/s}} \right) \left(\frac{\tilde{\omega}_0}{10^9 \text{cm}} \right)^{3/2} \Delta\tau \quad \text{(erg)}.$$

where $\Delta\tau$ is nondimensionalized burst interval time.

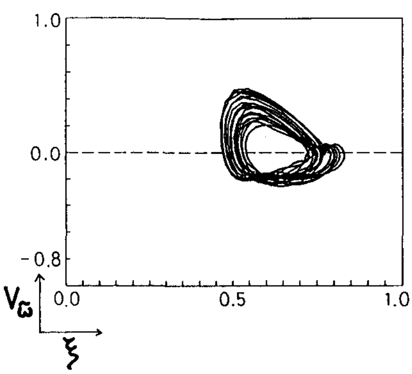
$$B = 2.98\text{x}10^{13} \cdot \left(\frac{M_s}{1M_\odot} \right)^{1/4} \left(\frac{\tilde{\omega}_s}{10^6 \text{cm}} \right)^{-3} \left(\frac{\dot{M}_{acc}}{10^{18} \text{g/s}} \right) \left(\frac{\tilde{\omega}_0}{10^9 \text{cm}} \right)^{7/2} \Delta\tau^{1/2} \quad \text{(gauss)} .$$

From X-ray observations (van der Klis et al. 1985), the typical frequency of quasi-periodic oscillations ω = 20 ~ 40 Hz. The typical period of oscillation cases is 2td for case (a) and 5td for case (b). If the typical radius of this magnetosphere is 1000 km, typical frequency of our model is a good agreement with the observational data. This value of $\tilde{\omega}$ requires surface magnetic field log(B(G))=10. On the other hand, for Rapid Burster, the time to following burst spreads from 10s to 1000 s. These time scale requires $\tilde{\omega} > r_\odot$cm, and log(B(G))>15 for explaining with our model. Furthermore, the retrograde stellar rotation against that of the disk is important for chaotic behavior of Rapid Burster for our model.

References

van der Klis et al., 1985, Nature, 317, 681.

Hanami, H. 1987, M.N.R.A.S., submitted.



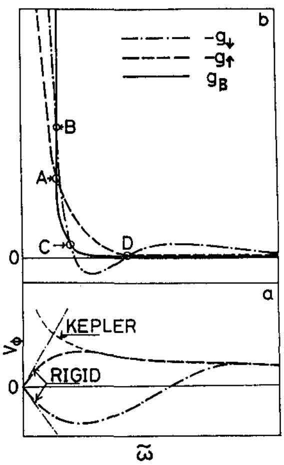


Figure 2 ;Orbits in phase space (velocity, radius) for cases (c).

Figure 3 (a);Schematic sketch of the rotation velocity as a function of the radius of test circulating ring along experimental orbit. (b);Each absolute value of the acceleration on test circular ring by magnetic pressure and effective gravity which includes the centrifugal force of rotation motion. The subscripts ↑ and ↓ of g represent the values for direct and retorograd rotation cases. Open circles A, B, C, and D represent dynamical equilibrium points.

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