Variation of efficiency of accretion with spin around rotating black hole

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Introduction

As per the current understanding, the source for energy in astrophysical system like X-Ray Binaries, Active Galactic Nuclei (AGNs)etc are accretion powered rather than the nuclear powered. The studies also indicates that accretion powered system are more efficient than the nuclear powered system. In many such system , the energy generation process is explained on the basis of accretion of gas onto astrophysical black holes (BHs) as the underlying mechanism for powering these sources. Further, due to very high gravity around BHs, all the the study of accreting BH systems involves solving general relativistic (GR) hydrodynamic/magnetohydrodynamic (MHD) equations in a strong gravitational field regime. Solving MHD equation in GR is very complex due to nonlinear character of the underlying equations in GR regime. So, the analytical/quasi numerical treatment of the problem is virtually discarded. Apart from that even numerical simulation is complicated by several issues such as different characteristic time scales for propagating modes of general relativity and relativistic hydrodynamics.

Several early works on these type of system were based on either through pure Newtonian gravity or through introduction of some GR effects in ad hoc manner. Following the the seminal work of Paczyński and Witta [1], now most of the Astrophysicist prefer to treat accretion and its related processes around BHs using hydrodynamical/MHD equations in the Newtonian framework by using or developing suitable Pseudo-Newtonian Potentials (PNPs) are per requirement. Most of these PNPs are essentially some modification of Newtonian gravitational potential developed with the objective to reproduce (certain) features of relativistic gravitation. This is done just to avoid GR gas dynamical equations as they are inconceivable in practice in describing a complex physical system such as accreting plasma.

Variation of efficiency of accretion with spin

To obtained the variation of radiative flux or radiative efficiency around a rotating black hole, we need a Pseudo-Newtonian Potential(PNP) that mimic the Space Time around a rotating black hole. In GR, we have Kerr Space-time to describe Space Time around a rotating black hole , here for our study, we have selected the Kerr Pseudo-Newtonian Potential developed by Ghosh et. al. [3] as given below to study the variation of efficiency of accretion using the method described in the paper Tejeda et. al [2] under section 3.6

$$V_{\rm GK} = -\frac{GM}{r}(1-\omega\dot{\phi}) - \frac{\left(\mathcal{G}_1\dot{r}^2 + \mathcal{G}_2 r^2\dot{\phi}^2\right)}{2\left(1+\omega\dot{\phi}\right)} + \frac{\dot{r}^2 + r^2\dot{\phi}^2}{2} \qquad (1)$$

where $\omega = 2ar_s/c(r-2r_s), \Delta = r^2 + a^2 - 2r_s r$ $\mathcal{G}_1 = \frac{r^3}{(r-2r_s)\Delta}, \mathcal{G}_2 = \frac{\Delta}{(r-2r_s)^2}$

Here, for sake of simplicity, we considered that the accretion flow system is simple as considered in the standard accretion disk model of Shakura and Sunyaev, i.e, the accretion disk is assumed to be geometrically thin and optically thick and is Keplerian in nature and is

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rotating around a Kerr black hole. Further, the mass of accretion disk is negligible compare to the mass of the spinning black hole. The accretion is considered as stationary and axially symmetric which imply no physical observables depend on time and azimuthal angle. The whole disk is in hydrostatic equilibrium. The gas flows from the disk through the cusp into the black hole. The accretion flow is in free fall which means the pressure and viscosity are not dynamically important. The flux of radiation emitted from the surface of the stated thin accretion disk is given by equation (2)

$$F_{\rm rad} = \frac{\mathcal{Q}^{+}}{2} = \frac{-\dot{M}}{4\pi r}\left(-\frac{d\Omega^K}{dr}\right)\left(\lambda^K - \lambda^K_{\rm in}\right) \quad (2)$$

and the total luminosity is given by equation(3)

$$L_{\rm rad} = 2\int_{r_{\rm in}}^{\infty} \left(-F_{\rm rad}\right) 2\pi r\, dr\,, \qquad (3)$$

$\dot{M}$ is the usual mass accretion rate. Ω^K and λ^K are Keplerian angular velocity and Keplerian angular momentum, respectively. $r_{\rm in}$ is the radius of the inner edge of the disk, which in this case would be the radius of the marginally stable orbit $r_{\rm ms}$. Variation of the radiative flux $|F_{\rm rad}|$ generated from a geometrically thin and optically thick Keplerian accretion disk with radial distance r for various 'a' describing co-rotating and counter-rotating scenario corresponding to Keplerian accretion flow around Kerr geometry can be studied using equation (1) to equation (3)and taking $\dot{M} = 1$, $G = M = C = 1$.

Results and discussions

The radial profile of the flux and radiative efficiency is higher for co-rotating accretion disk around Kerr black hole than the Schwarzschild black hole of equal mass and the flux as well as efficiency increases (decreases) with a for co-rotating (counter-rotating) disk. The radiative efficiency also reflects such a feature as shown in the Table I. For co-rotating disk, the inner edge can come much closer to the black hole compare to Schwarzschild case and hence has the higher radiative efficiency and flux. We restricted a up to 0.7 in our accretion analysis , due to the limitation of the proposed Pseudo-Newtonian potential by Ghosh et. al. But, there is no such limitation in case of counter-rotating accretion disk.

TABLE I: *Efficiency of the accretion*

$co - rotating$		$counter - rotating$	
a	η	a	η
$a = 0.1$	~ 0.059	$a = -0.1$	~ 0.053
$a = 0.2$	~ 0.063	$a = -0.2$	~ 0.050
$a = 0.3$	~ 0.068	$a = -0.3$	~ 0.048
$a = 0.4$	~ 0.075	$a = -0.4$	~ 0.046
$a = 0.5$	~ 0.083	$a = -0.5$	~ 0.044
$a = 0.6$	~ 0.095	$a = 0.6$	~ 0.042
$a = 0.7$	~ 0.113	$a = -0.7$	~ 0.041

Conclusions

The analytical form of the Kerr-Newtonian potential which has been evaluated by Ghosh et. al. from the conserved Hamiltonian restricts its applicability to $r \sim 2r_s$. This would not cause any major difficulties for astrophysical scenarios as accretion studies are mainly focused on regions with $r > 2r_s$.

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