A Possible Mechanism for Hot Corona Formation and Angular Momentum Transfer in Accretion Disks around Black Holes

THCA
Tsinghua Center for Astrophysics
Tsinghua University
100084 Beijing, China
Tangsm99@mails.tsinghua.edu.cn

Su Min TANG, S.Nan ZHANG (also UAH and MSFC, Huntsville, Alabama)

Introduction:

Hot coronae have been found to exist in black hole and low-mass neutron star X-ray binaries. However the origin of the hot coronae has not been understood completely. In this poster we investigate a possible mechanism for hot corona formation and also for angular momentum transfer.

We use Shakura-Sunyaev disk model to consider the following scenario:

General Relativity effects → high orbital ellipticity and orbital precession near a black hole → violent collisions in the accretion disk →

- Electrons escape from the disk to form a hot corona
- Angular momentum transfer outwards via collisions

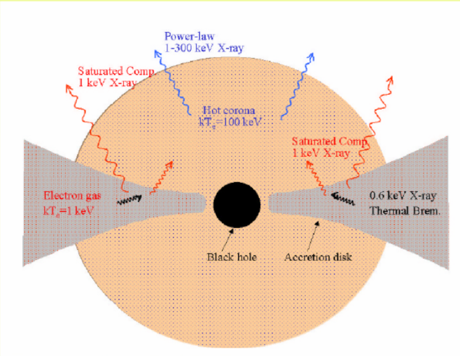


Figure 1. Three-layered atmospheric structure in accretion disks. (S. N. Zhang et. al. 2000)

Part I: The deviation from Keplerian motion in a disk around a black hole

In the whole poster, r_s denotes the Schwarzschild radius. We Consider a stellar mass black hole with 7 solar masses and a supermassive black hole with $2*10^9$ solar masses.

General Relativity vs Newton's Theory

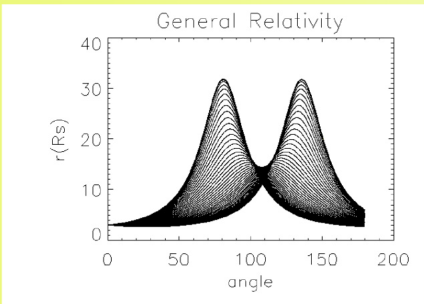


Figure 2. The orbital motion of electrons due to the disturbance of the Maxwellian velocity distribution with a temperature of $4×10^7$K for 7 solar masses black hole. Different curves present different initial velocities. Due to high orbital ellipticity and orbital precession, there will

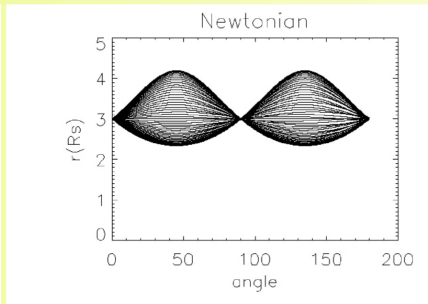


Figure 3. Electrons $3r_s$ away from a 7 solar mass black hole in Newton's theory. Apparently, the ellipticity is far lower than in Fig 1 which is calculated in General Relativity. Furthermore, these electrons have no orbital precession in Newton's theory. So there won't exist considerable collisions among the particles in the disk.

Since the difference between this two theories is so great, this effect is a manifestation of the General Relativity.

Part II: Properties of the Hot Corona Formed

Properties of the Hot Corona formed through collisions of electrons and protons

Angular distribution of the flying out particles at $10r_S$:

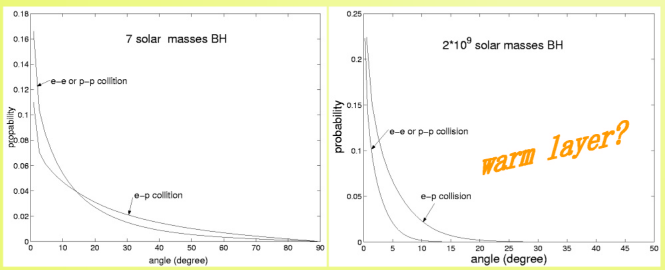


Figure 4. Angular distribution of the flying out particles at $10r_s$.
We define 90 degree as the direction parallel to the axis of the disk. We take unit Eddington accretion rate and α = 1 if not specified.

Summary

. We study some properties of black hole accretion disks, and then consider a possible mechanism for hot corona formation and angular momentum transfer.

. In the inner region of black hole accretion disks, particles' orbits are very unstable because of high orbital ellipticity and precession; General Relativity plays an important role in this process.

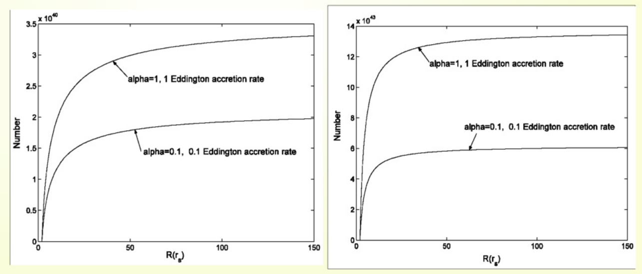
. So there will be violent collisions occurring in the disk and then some particles escape from the disk to form a hot corona. Angular momentum also transfer outwards via collisions.

. We use the Shakura-Sunyaev disk model to estimate this effect. We calculate the properties of the corona and do some Monte-Carlo simulations to estimate the rate of angular momentum transfer.

. Also we find this effect will generate instability in the innermost region of accretion disks.

Properties of the Hot Corona:

Total particle escaping rate versus distance

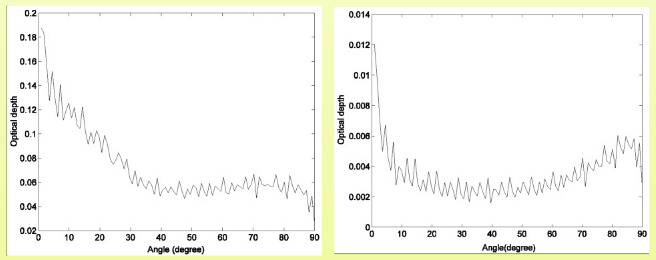


7 solar mass BH　　　$2*10^9$ solar mass BH

Figure 5. Total particle escaping rate versus distance for a 7 solar mass black hole and a $2*10^9$ solar mass black hole, with different accretion rate and α.

Properties of the Hot Corona:

Optical Depth versus Viewing Angle



7 solar mass BH　　　$2*10^9$ solar mass BH

Figure 6. Optical depth of hot corona versus viewing angle.

Brief Summary of the Hot Corona Formed

- Size：about $50r_S$。
- Temperature：10^8 ~ 10^9K for electrons & 10^{11} ~ 10^{12}K for protons
- Time scale：as Keplerian period

Part III: Angular Momentum Transfer:

- Angular momentum transfers when collisions occur. But normally the transfer is not effective, because the particles move without preferred directions.
- Close to the horizon, particles with lower angular momentum rapidly fall into black hole, while the others go outside——angular momentum transfers from inner region to out region.

- Equation of motion of a particle in Schwarzschild field:

$$\frac{d^2u}{d\theta^2}=-u+\left(\frac{GM}{Lc}\right)^2+3u^2 \qquad u=\frac{GM}{rc^2}$$ L is angular momentum of unit mass

- Equation of motion of a particle if the gravitational field is ignored:

$$\frac{d^2u}{d\theta^2}=-\frac{GM}{v_t^2c^2}\frac{d^2r}{dt^2}+u\frac{v_r^2}{v_t^2}+\frac{GMv_r}{c^2v_t^3}\frac{dv_t}{dt}=-u+u\frac{v_r^2}{v_t^2}+\frac{GMv_r}{c^2v_t^3}\frac{dv_t}{dt}$$

- Equation of motion of a particle if the gravitational field is ignored and collisions are allowed:

The random force: $\vec{F}=\frac{\text{impulse}}{\text{time}}=\frac{\Delta\vec{P}_e}{\tau_e}+\frac{\Delta\vec{P}_p}{\tau_p}$ Where τ_e is the timescale of collisions between the particle and electrons while τ_p of protons

The acceleration: $\vec{a}=\frac{\vec{F}}{m}=\frac{\Delta\vec{P}_e}{m\tau_e}+\frac{\Delta\vec{P}_p}{m\tau_p}=\frac{\vec{v}_e}{\tau_e}+\frac{\vec{v}_p}{\tau_p}$ Where v_e is the velocity changed in collisions with electrons while v_p of protons; both are random

In polar coordinate: $\vec{a}=(\ddot{r}-r\dot{\theta}^2)\hat{r}+(2\dot{r}\dot{\theta}+r\ddot{\theta})\hat{\theta}$

In radial direction: $a_r=\frac{v_{er}}{\tau_e}+\frac{v_{pr}}{\tau_p}=\frac{d^2r}{dt^2}-r\left(\frac{d\theta}{dt}\right)^2$ Where v_{er} is the radial part of v_e while v_{pr} the radial part of v_p

so $\frac{d^2r}{dt^2}=\frac{v_{er}}{\tau_e}+\frac{v_{pr}}{\tau_p}+r\left(\frac{d\theta}{dt}\right)^2=\frac{v_{er}}{\tau_e}+\frac{v_{pr}}{\tau_p}+\frac{v_t^2}{r}$ *Where v_r is the radial velocity and v_t is the tangent velocity.*

Substituted by $u=\frac{GM}{rc^2}, rd\theta=v_tdt$

we get:

$$\frac{d^2u}{d\theta^2}=\frac{d}{d\theta}\left(\frac{du}{d\theta}\right)=-\frac{rGM}{v_tc^2}\frac{d}{dt}\left(\frac{1}{rv_t}\frac{dr}{dt}\right)$$
$$=-\frac{GM}{v_t^2c^2}\frac{d^2r}{dt^2}+\frac{GM}{rc^2}\frac{v_r^2}{v_t^2}+\frac{GMv_r}{c^2v_t^3}\frac{dv_t}{dt}$$
$$=-\frac{GM}{v_t^2c^2}\left(\frac{v_{er}}{\tau_e}+\frac{v_{pr}}{\tau_p}\right)-u+u\frac{v_r^2}{v_t^2}+\frac{GMv_r}{c^2v_t^3}\frac{dv_t}{dt}$$

- Combine the equations above, we find the equation of motion of a particle in Schwarzschild field with collisions:

$$\frac{d^2u}{d\theta^2}=-u+\left(\frac{GM}{Lc}\right)^2+3u^2-\frac{GM}{v_t^2c^2}\left(\frac{v_{er}}{\tau_e}+\frac{v_{pr}}{\tau_p}\right)$$

The last term comes from collisions.

- Do Monte-Carlo simulations to calculate motions of particles in different initial radius, estimate the rate of angular momentum transfer.
- Now we only calculate the efficiency of the angular momentum transfer for a 7 solar mass black hole at z=4H (z is height from the center of disk plane and H is the scale height); we find the angular momentum transfer is very efficient in the inner disk region.

Angular Momentum Transfer:

Mass transfer rate due to collisions at different radius

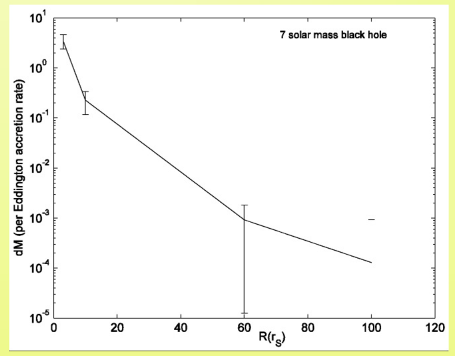


Figure 7. Mass transfer rate due to collisions at different radius for a 7 solar mass black hole. The accretion rate in the SS disk the is unit Eddington accretion rate.

. Mass transfer rate due to collisions increases rapidly matter approaches the black hole.

. The mass transfer rate in the inner most region is greater than the accretion rate supplied in the disk, so the disk is unstable.

. When z becomes smaller, i.e., closer to the center of the disk plane, the angular momentum transfer efficiency due to collisions will be even higher.

So this effect will produce instability in the innermost region and a stable and optically thick disk will not exist very close to the horizon of a black hole. Effectively matter will fall into the hole sporadically and the disk is truncated at a distance beyond the last stable orbit: the truncation radius is larger for lower accretion rate.

References

Juhan Frank, Andrew King, Derek Raine, *Accretion Power in Astrophysics*, 2002; S. N. Zhang, Wei Cui, et. al., 2000, Science, Vol 287, Feb. 18; I. HUBENY, 1990, ApJ, 351, 632; E. Meyer-Hofmeister, F. Meyer, 2003, A&A, 402,1013