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Cosmic evolution of AGN using self-consistent black hole energetics

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Abstract.

We consider a model that takes into account the mass and spin accreted by the hole and the angular momentum torque due to an electrodynamical jet. The spin evolution is calculated with and without accretion; if the accretion stops the jet power indicates an increase before a gradual decline if the initial spin, $j > \sqrt{3}/2$, as a result of the hole's increasing size. This naturally has implications for the evolution of the jet. Specific analytic forms have also been calculated for the case of Bondi accretion, thin disk and an MHD disk. The results indicate that the black hole achieves the maximum spin value when there is no jet. It is planned to compare this with fully relativistic MHD simulations.

Keywords :
black hole physics – accretion, accretion discs –galaxies: active – galaxies: evolution – galaxies: jets

1. Introduction

There are several models for a variety of astrophysical jet processes that rely on extracting the rotational energy of the black hole that is provided by the budget of the difference between the black hole mass and the irreducible mass, $m - m_i$ where $m_i = \sqrt{mr_+/2}$ which implies that about a fraction of 0.29 of the mass can be extracted. This has been motivated to suggest a law of black hole entropy and even the GRB phenomenon has been sought to be explained using this budget (van Putten 2009). There is another class of models that rely on the jet being powered by an MHD accretion disk based on the generic bead on a wire model. We consider the paradigm that the jets are

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powered totally by black hole spin, essentially by the Blandford-Znajek (1977; BZ) process. The jet powers in this case can be written as (McDonald and Thorne 1982)

$$\mathcal{L} = \frac{1}{32}\omega_F^2 B_\perp^2 R_H^2 j^2 c \tag{1}$$

where, $\omega_F \equiv \Omega_F(\Omega_H - \Omega_F)/\Omega_H^2$ depends on the angular velocity of the field, Ω_F, relative to that of the hole, Ω_H, $B_\perp$ is the component of the magnetic field perpendicular to the hole, $R_H = r(j)m \equiv \left(1 + (1 - j^2)^{1/2}\right) GM_\bullet/c^2$ is the radius of the event horizon of the BH, where $m \equiv GM_\bullet/c^2$, and $j = a/m$ is the dimensionless angular momentum of the BH. We investigate here the mass and spin evolution and its consequences taking into account the jet power, disk emission, mass and angular momentum accretion self-consistently.

2. Black hole mass and Spin evolution

Following the formulation in Shapiro (2005) we define $\epsilon_M \equiv L/\dot{M}_0 c^2$, where $\dot{M}_0$ is the rate of rest-mass accretion and L is the luminosity. Define ϵ_L, the efficiency of accretion luminosity, according to $\epsilon_L \equiv L/L_E$, where L_E is the Eddington luminosity, given by $L_E = \dfrac{4\pi M_\bullet \mu_e m_p c}{\sigma_T} \approx 1.3 \times 10^{46} \mu_e M_8$ erg s^{-1}. The mass increase will be then given by $\dot{M}_\bullet = (1 - \epsilon_M)\dot{M}_0$. Combining we obtain the black hole growth rate

$$\frac{dM_\bullet}{dt} = \frac{\epsilon_L(1 - \epsilon_M)}{\epsilon_M}\frac{M_\bullet}{\tau_a}, \tag{2}$$

where the characteristic accretion timescale, given by $\tau_a \equiv \dfrac{M_\bullet c^2}{L_E} \approx 0.45\mu_e^{-1}$ Gyr and is independent of $M_\bullet$. The mass accretion efficiency ϵ_M is typically a function of the black hole spin parameter $j = J/M^2$ and the spin evolution is given by

$$\frac{\mathrm{d}j}{\mathrm{d}t} = \frac{\epsilon_L}{\epsilon_M}\frac{j}{\tau} \quad + \mathrm{BZ\ \ TORQUE.} \tag{3}$$

In general, eqns (2, 3) must be integrated simultaneously to determine the mass and spin evolution of the black hole.

This lets us compute a spin-down time, $\tau_{j,BZ}$ from angular momentum conservation assuming that there is no accretion (see Mangalam et al. 2009), $\tau_{j,BZ} = \dfrac{\mathcal{J}_0}{\mathcal{G}_0}\displaystyle\int_{j_f}^{j_i}\frac{\mathrm{d}j}{r^3(j)j} = 7.0 \times 10^8$ yrs $\dfrac{\left[(\kappa(j_i, j_f)/0.1)\right]}{B_4^2 M_9}$

where, the angular momentum of the hole is $\mathcal{J} \equiv \mathcal{J}_0 j = cM_\bullet m$, the BZ torque

$\mathcal{G}_0 \simeq \frac{m^3}{8} B_\perp$, j_i and j_f are the initial and final spins respectively, $\kappa(j_i, j_f)$ is the value of the integral, $B_4 = B/10^4$ Gauss and $M_9 = M_\bullet/10^9 M_\odot$ (Mangalam et al. 2009). The $\mathcal{L}(j)$ goes through a maximum at $j = \sqrt{3}/2$. The evolution of the power is shown in Fig 1.

2.1 Bondi Case

This is the case where the net spin content in the accreting material is zero but the mass increases the horizon radius which reduces the spin according to

$$\frac{\mathrm{d}\mathcal{J}}{\mathrm{d}t} = \mathcal{J}_0 \dot{j} + 2\frac{\mathcal{J}_0}{M_\bullet} \dot{M}_\bullet j$$

which should be matched to the BZ torque $\mathcal{G}_0$. This results in the following equation for the spin parameter

$$-\left[\frac{2\epsilon_L(1-\epsilon_M)}{\epsilon_M \tau_a} + \frac{\mathcal{G}_0}{\mathcal{J}_0} r(j)^3\right] j = \frac{\mathrm{d}j}{\mathrm{d}t}.$$

We write $\mathcal{G}_0/\mathcal{J}_0 = \mu/\tau_j$, where $\mu = M_\bullet/M_s$ where M_s is the seed mass. So we find the differential equations for the spin:

$$\frac{\mathrm{d}j}{\mathrm{d}t} = -\left[\frac{2\epsilon_L(1-\epsilon_M)}{\epsilon_M \tau_a} + \frac{\mu}{\tau_j} r(j)^3\right] j \tag{4}$$

which is coupled to eqn (2). The spin down time scale is reduced further when the mass of the hole increases by Bondi accretion (with negligible net angular momentum) as it spins down and is estimated to be $\tau_{spin} \approx \dfrac{(\tau_a/2)\tau_j}{(\tau_j + \tau_a/2)}$, where the accretion time scale is $\tau_a \equiv \dfrac{M_\bullet c^2}{L_E}$ =0.45 Gyr, where L_E is the Eddington luminosity. As a result, $\tau_{spin} \approx 0.2$ Gyr for the typical case $j_i = 0.5, M_9 = 1, B_4 = 1$. Note that the timescales derived above are inversely proportional to the BH mass.

2.2 Thin disk Case

In a standard thin disk corotating with the black hole, the energy and angular momentum per unit rest mass accreted by a black hole are the energy and angular momentum of a unit mass at the ISCO, immediately prior to its rapid plunge and capture by the hole. The mass accretion efficiency and spin evolution parameters corresponding to the thin disk model are then given by $\epsilon_M = 1 - \tilde{E}_{\rm ISCO}$ and

$$\frac{\mathrm{d}j}{\mathrm{d}t} = \left(\tilde{l}_{\rm ISCO} - 2\frac{a}{M}\tilde{E}_{\rm ISCO}\right)\frac{\epsilon_L}{\epsilon_M(j)\tau_a}.$$

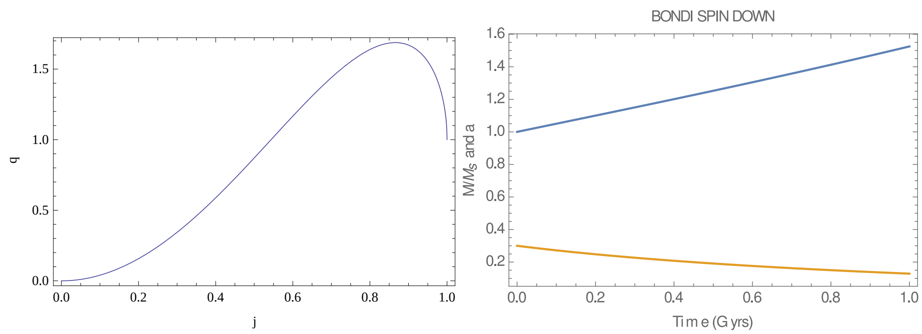

Figure 1. Left: For the case of a zero accretion spin down, the power of the BZ jet is shown as a function of the BH spin parameter j, normalized to the value at $j = 1.0$. The power goes through a maximum at $j = \sqrt{3}/2$ before dropping; this arises from the competition between the horizon radius and the spin of the BH. Right: An illustration of Bondi spin down for seed mass of $M_8 = 0.01$ for initial $j = 0.3$

where the standard expressions for $\tilde{E}_{\rm ISCO}, l_{\rm ISCO}$ and $r_{\rm ms}$ are functions of j. This leads to the following differential equation

$$\frac{\mathrm{d}j}{\mathrm{d}t} = \frac{\tilde{l}_{\rm ISCO}\epsilon_L}{\epsilon_M(j)\tau_a} - \left[\frac{2\epsilon_L(1-\epsilon_M)}{\epsilon_M\tau_a} + \frac{\mu}{\tau_j}r(j)^3\right]j \tag{5}$$

which is coupled with eqn (2) and the solution is illustrated in Fig 2.

2.3 MHD disk Case

The MHD disk accretion model of Gammie et al. (2004) is based on a fully relativistic, axisymmetric simulation of a nonradiative, magnetized plasma onto a Kerr-Schild black hole within the MHD approximation. The results of the numerical simulations suggest that can be represented reasonably well by the least squares linear fit (see McKinney and Gammie 2004, Table 2)

$$\tilde{l}_{\rm ISCO} - 2j\tilde{E}_{\rm ISCO} = 3.14 - 3.30j.$$

The numerical simulations demonstrate that the above parameters describing steady-state, MHD accretion-disk behavior are not particularly sensitive to the initial conditions in the disk (e.g. the initial B–field). The key results are also quite comparable to those found by De Villiers et al. (2005), who used a different numerical method and took the adiabatic index of the gas to be $\Gamma = 5/3$ instead of $\Gamma = 4/3$. We therefore model a relativistic MHD accretion disk in our evolution equations and is illustrated in Fig 2.

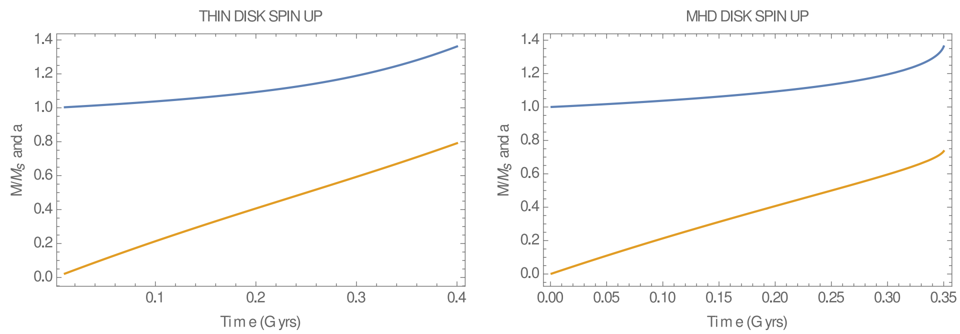

Figure 2. An illustration of thin disk (left) and MHD disk (right) spin up for seed mass of $M_8 = 0.01$ and initial $j = 0$.

3. Conclusions

The model parameters are $M_\bullet, L, L_j, j, \dot{M}_\bullet, z$. The spin-down time scale for the case of no accretion is about $\tau_{spin} = 0.5/(B_4^2 M_9)$ Gyr. The evolution of the jet power indicates an increase before a gradual decline if the initial spin, $j > \sqrt{3}/2$, as a result of the hole's increasing size. This naturally has implications for the evolution of the jet. When the Bondi accretion is on, $\tau_{spin} \approx \dfrac{(\tau_a/2)\tau_j}{(\tau_j + \tau_a/2)}$, where the accretion time scale is $\tau_a \equiv \dfrac{M_\bullet c^2}{L_E}$ =0.45 Gyr, resulting in a spin down time scale of 0.2 Gyr. When there is thin disk with MHD accretion then the *spin up* time scale is typically 0.35 Gyr. An important issue is the maximum spin j that can be achieved in disk accretion process. Preliminary results (Mangalam 2015, in preparation) indicate that the black hole achieves about 98% of the maximum value (close to $j_{max} = 0.998$, Thorne 1974 that includes radiation effects on the hole not included here) when there is no jet and 93% of j_{max} when there is a jet. This is model dependent and in reasonable agreement with various simulations; eg. Benson and Babul (2009). It is planned to expand this work to hybrid models in greater detail, and to thus explore other discs in ADAF mode. The results have natural implications to the black hole demographics with parameters: $M_\bullet$, redshift z, jet luminosity $L_{jet}(j)$, and disk luminosity $L(M_\bullet)$, and one can model the cosmological evolution heuristically.

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