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To cite this article: Wolfgang J Duschl and Peter A Strittmatter 2012 *J. Phys.: Conf. Ser.* **372** 012002

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The Cosmogony of Super-Massive Black Holes¹

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Abstract. We summarize our recent results on the evolution of super-massive black holes in the cores of galaxies. Our models are based on the viscous, Eddington-limited evolution of self-gravitating accretion disks. We find that, within this framework, one can explain the growth time scales and the luminosities of individual objects as well as the variation of these quantities for AGN with different black hole masses.

1. Introduction

There is overwhelming evidence that (almost) all galactic centers contain super-massive black holes (SMBHs) with the vast majority of them in the mass range of $10^{6...10} M_{\odot}$ [2,3]. Accretion into these black holes is held responsible for the energy output of (active) galactic nuclei [4,5]. Surveys in the optical and X-ray wavelength regimes find that the lower the BH mass, the later in the evolution of the Universe the co-moving space density peaks [6-13]. This indicates that the evolution of black holes with a smaller (final) mass takes longer than that of more massive ones.

In this contribution, we summarize our results on the evolution of self-gravitating accretion disks in galactic centers and the resulting luminosity and mass evolution of AGN and their SMBHs.

2. The Scenario

The scenario behind our models is that a galaxy-galaxy interaction or merger has driven by tidal forces a considerable amount of gas and dust towards the galactic center. As the tidal forces are not capable of removing all the angular momentum of the gas, a massive disk will form. Viscous forces will then lead to accretion which ultimately will transport the gas into the center of the galaxy and feed a black hole there. Observations, for instance, of ultra-luminous infrared galaxies indicate that the most massive of these disks may have initial masses of $M_{d,i} = 10^{10} M_{\odot}$ and, in some cases, even more [14]. Their typical sizes are of order of a few 10^2 pc. These disks are the configurations from where our model calculations start. For numerical reasons a seed black hole with an initial mass $M_{BH,i} \ll M_{d,i}$ is added. Our models are (i) rotationally symmetric; (ii) symmetric with respect to their rotational plane; (iii) geometrically thin; and (iv) in vertical hydrostatic equilibrium. Their main differences to standard accretion disk models are that (i) we allow for self-gravity of the disk to be of relevance; (ii)

¹ This contribution is partly based on [1].

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in order to be able to deal with self-gravitating disks, we use the β -parameterization for the viscosity [15]; (iii) we take the Eddington limit into account [16]; and (iv) we allow the size of the disk to evolve as required by the conservation laws (for further physical and numerical details, see [1]).

3. The Reference Model

We define a reference model with an initial disk mass $M_{d,i} = 10^{10}M_{\odot}$, an outer radius of 10^2 pc, an initially constant radial distribution of the surface density Σ , a viscosity parameter $\beta = 10^{-3}$, and an initial central mass $M_{BH,i} = 10^4M_{\odot} \ll M_{d,i}$.

Figure 1 shows the evolution of the mass flow rate \dot{M} and the luminosity L as a function of time, with \dot{M}_d the rate at which the disk delivers mass, \dot{M}_{Edd} the mass flow rate corresponding to the respective Eddington limit, and \dot{M}_{BH} the growth rate of the black hole, given by

$$\dot{M}_{BH} = \min(\dot{M}_d, \dot{M}_{Edd}).$$

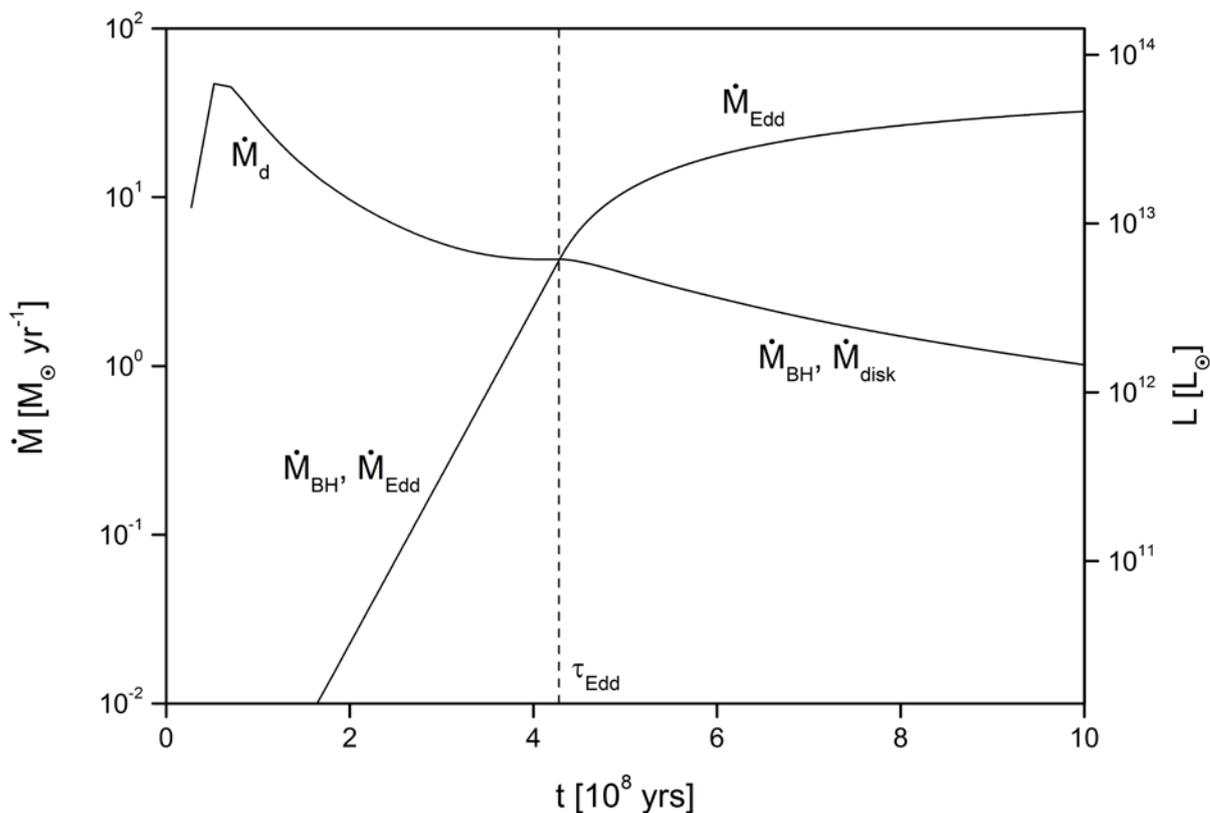


Figure 1: The evolution of the mass flow rates and the luminosity of the Reference Model (adapted from [1]).

We find that initially the evolution is dominated by the Eddington limit. Only a (initially small) fraction of the mass delivered by the disk actually contributes to the growth of the black hole. We assume that whatever falls victim to the Eddington limit is lost from the system, for instance as a jet or outflow. In the present context, however, we do not follow the further fate of this material. After a time τ_{Edd} the mass of the black hole has grown and the mass flow rate from the disk fallen enough for the latter to become smaller than the Eddington limit. From now on the black hole can accrete all the material coming from the disk. During this free accretion phase, the Eddington ratio $\dot{M}_{BH}/\dot{M}_{Edd}$ continues to become ever smaller. We expect that at a later time radiation-inefficient accretion will

take over and lead to considerably smaller luminosities [17]. In the present context, we have, however, followed the evolution of the disks and black holes for not long enough for that transition to be reached.

4. Variations of the Model Parameters

Starting from the reference model, we have varied its parameters with an emphasis on the initial disk mass $M_{d,i}$ and the initial disk size. We find that in general, unless the Eddington limit is not reached at all, the evolution of the mass flow rates follows the same pattern: An initially Eddington-limited phase during which the black hole mass grows exponentially is followed by free accretion which still can contribute considerably to the black hole mass, albeit no longer exponentially. Among other results ([1]), we find that the evolution time scale depends strongly on the initial mass and the size of the disk. The smaller and the more massive the initial disk is, the faster it evolves. This translates into the most massive black holes forming the quickest, and is in remarkable agreement with the observational findings of the above-mentioned surveys. Due to the Eddington limit, there is, however, a lower limit to the disk size which is still beneficial to a faster evolution: too small disks are so strongly Eddington-limited that most of their mass is lost rather than accreted into the black hole. Our models also allow for black hole masses $> 10^9 M_{\odot}$ in the very young Universe (redshifts $z > 6$), in agreement with the observations of the most distance quasars known to date [18-21].

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