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A Population of "Ultraluminous" AGNs: Super-Eddington Accretion at High z

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Abstract

There is a whole population of luminous active galactic nuclei (AGNs) in which supermassive black holes accrete close to the Eddington rate or at super-Eddington rates. Some of AGNs in this population are classified as narrow-line Seyfert 1 galaxies (NLS1s). It has been suggested that they might be normal Seyfert galaxies at an early stage of evolution. If confirmed, NLS1s could be an ideal class of objects to study the accretion history and growth of supermassive black holes. Slim accretion disk models provide a powerful tool for such studies. For high accretion rates they give a natural explanation for the strong soft X-ray emission observed in these objects. Moreover, due to intrinsic disk instabilities predicted in the framework of these models, the average mass fuelling rate might be much lower than implied by their current luminosities.

1.1 Super-Eddington Accretion

The most luminous long-lived objects in the universe (active galactic nuclei) are believed to be powered by the accretion of gas onto supermassive black holes. Given the extremely large luminosities of the high redshift quasars (Fan et al. 2000), they are likely accreting at Eddington, or even super-Eddington rates. Comparing different groups of AGNs, it appears as a systematic trend that higher redshift and more luminous objects tend to have larger black hole masses and luminosities closer to the Eddington limit (Wandel 1999). The NLS1s, nearby AGNs seem to be accreting also close to this limit. Similar to the high redshift quasars, they show steep hard X-ray spectra (Brandt, Mathur, & Elvis 1997). Mathur(2000) has argued that NLS1 galaxies might be low redshift, low luminosity analogues of the high redshift quasars.

Fitting spectra (the absolute luminosity and shape of the energy distribution) of AGNs with the standard, optically thick and geometrically thin accretion disk models often led to luminosities close to or higher than the Eddington limit (for fairly complete summary see Szuszkiewicz, Malkan, & Abramowicz 1996). Using the slim models, Szuszkiewicz et al. (1996) have found that, unlike the disks with a low accretion rate, the spectra of the high accretion rate disks extend into the soft X-ray band. A comparison with observations shows that such disks could produce the soft X-ray excesses claimed in some AGNs and confirms that the underlying and common feature of the NLS1 galaxies is a high rate of accretion taking place in these objects (Szuszkiewicz et al. 1996; Wang et al. 1999; Mineshige et al. 2000; see also Ohsuga & Mineshige in these Proceedings). More recently, Boroson

(2002) reinforced this claim, noting that NLS1s consistently exhibit the lowest estimated central black hole masses for similar luminosities and highest inferred relative accretion rates among the various AGN types. Collin et al. (2002), using a sample of 34 active galactic nuclei which mass has been determined by reverberation studies, have shown that if the optical luminosity is emitted by a steady accretion disk, it implies that about half of the objects of the sample are accreting close to the Eddington rate or at super-Eddington rates.

There is no known reason for which the accretion rates in AGNs should not be larger than the Eddington limit. It was shown, some time ago, that more general slim accretion disk models are self-consistent even for moderately super-Eddington luminosities (Abramowicz et al. 1988) and even earlier that thick accretion disks can reach luminosities as high as $100L_E$ (Abramowicz, Calvani, & Nobili 1980).

Moreover, there are known X-ray binaries, which shine with super-Eddington luminosities (Grimm, Gilfanov, & Sunyaev 2002). They are all accreting objects. The similarities in the NLS1 galaxies spectra to the high-state spectra from the galactic black hole candidates (Pounds, Done, & Osborne 1995), indicate that a very similar physical mechanism is responsible for the observed spectra in these objects. So they might as well have super-Eddington luminosities.

The fact that the Eddington ratio can be larger than unity has important evolutionary implications. One of them is connected with the accretion efficiency in different luminosity ranges.

1.2 Efficiency of Accretion in Slim Disk Models

The total luminosity L of the accreting disk, is related to $\dot{M}$ through the relation:

$$L = \eta \dot{M} c^2, \tag{1.1}$$

where η is the efficiency at which the gravitational energy is converted into radiation. It has been rigorously shown that the efficiency of a stationary disk accreting onto a black hole equals the binding energy of fluid elements at the inner edge of a disk r_{in}. For the pseudo-Newtonian potential, which mimics the case of a Schwarzschild black hole (Paczyński & Wiita 1980), assuming that the matter falls from infinity, we have:

$$\eta = \frac{1}{4}\frac{r-2}{(r-1)^2}\,, \qquad r = \frac{r_{in}}{r_G}, \tag{1.2}$$

where $r_G = 2GM/c^2$ is the Schwarzschild radius, c is the speed of light and G is the gravitational constant.

The $L-\dot{M}$ relation for slim accretion disks obtained by constructing a sequence of self-consistent models for a wide range of $\dot{m} = \dot{M}/\dot{M}_C$ and fixed mass $m = M/M_\odot = 10^8$ is shown in Figure 1.1. The critical accretion rate is given in the form

$$\dot{M}_C = \frac{L_E}{\eta c^2}, \quad \text{where} \quad L_E = \frac{4\pi c G M}{\kappa} = \frac{2.5\cdot 10^{38}}{1+X}\frac{M}{M_\odot}\ \mathrm{erg/s}, \tag{1.3}$$

X is the hydrogen content by mass and the opacity κ is due to electron scattering only. Figure 1.1 shows that for $\dot{m} \geq 1$ the luminosity rises only logarithmically with the accretion rate. This was first found by Jaroszyński, Abramowicz, & Paczyński (1980), and Paczyński (1980) in the context of thick accretion disks. Abramowicz et al. (1988) showed that slim accretion disks around stellar mass black holes exhibit the same logarithmic behaviour.

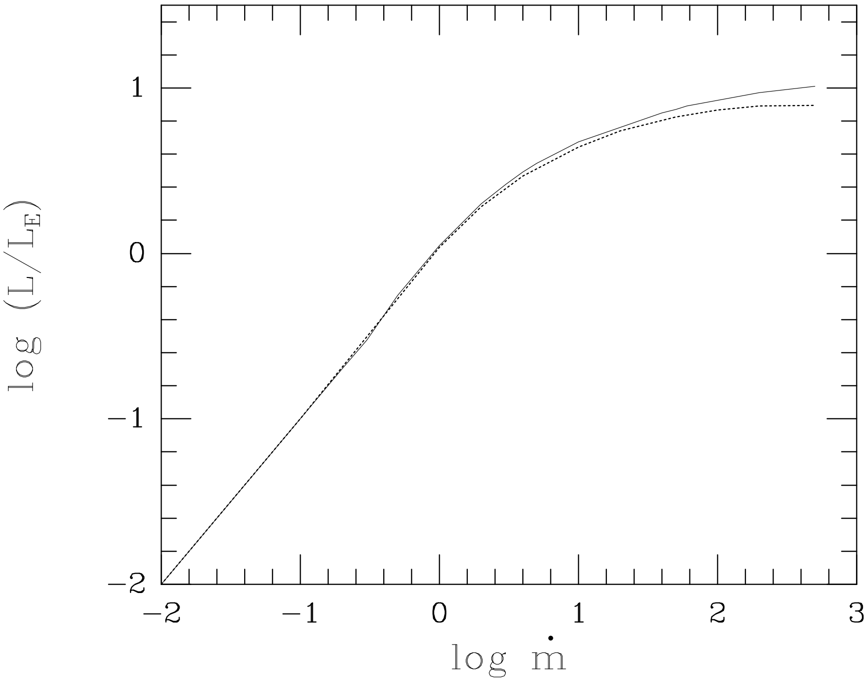

Fig. 1.1. The total luminosity - accretion rate relation for slim disk models with the two different forms of viscosity: $\tau_{r\varphi} = -\alpha P$ (solid line) and $\tau_{r\varphi} = -\alpha (P P_g)^{1/2}$ (dotted line). In both cases $\alpha = 0.001$. Taken from Szuszkiewicz et al. (1996).

The luminosity—accretion rate relation has important implications for the interpretation of the observed properties of AGNs. Depending on their location in the $\dot{M}$ - M plane, accretion disks have quite different physical properties.

1.3 Recurrent Accretion

Salucci et al. (1999) state that the increasing evidence of the presence of inactive black holes in a large number of galaxies endowed with significant spheroids favours the scenario according to which the nuclear activity is a relatively short phase, which takes place in a large fraction of galaxies. The continuity paradigm is excluded by their findings and the recurrent activity is confined to low mass objects (like NLS1s).

The idea of intermittent activity in AGNs was already suggested by Shields & Wheeler (1978). They noticed that the fuelling problem could be solved if active nuclei store mass during quiescence and this mass then feeds the hole for a shorter period of intense activity. The thermal–viscous hydrogen ionization instability found to operate in AGN accretion disks (Lin & Shields, 1986) is capable of triggering such behaviour. Clarke & Shields (1989), Mineshige & Shields (1990), Cannizzo & Reiff (1992), Cannizzo (1992) studied the full range of black hole masses and accretion rates in order to determine the observational consequence of the instability for the AGN population. Siemiginowska & Elvis (1997) attempted to reproduce the observed luminosity function, assuming that this mechanism operates in all AGNs. Burderi, King, & Szuszkiewicz (1998) have investigated whether the

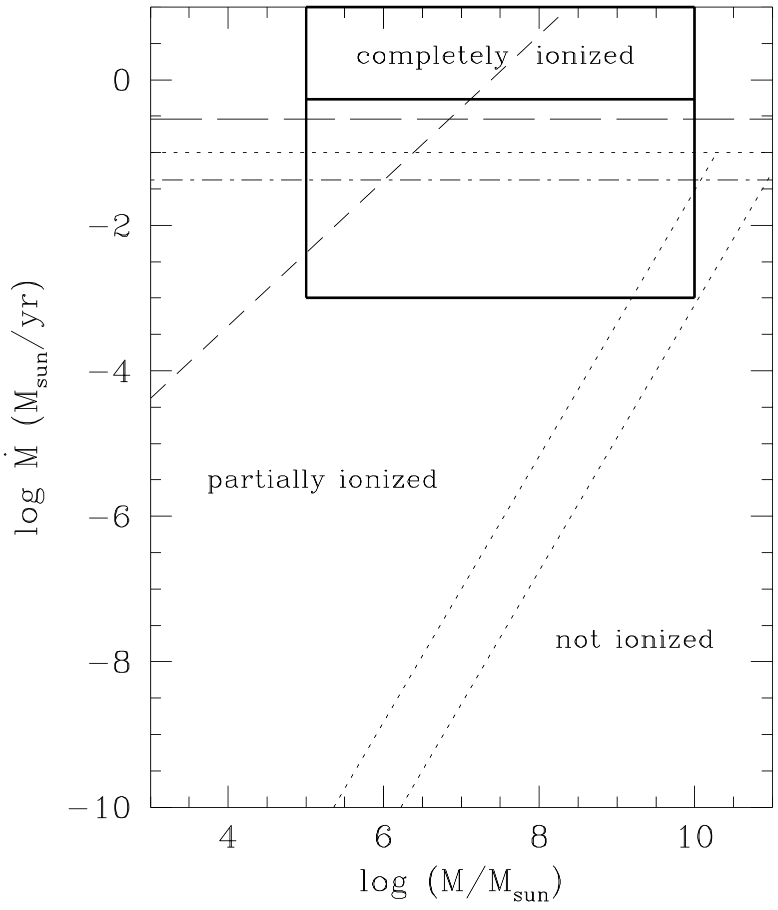

Fig. 1.2. $\dot{M} - M$ plane for AGN disks, divided into three distinct regions according to the degree of hydrogen ionization: neutral, partially ionized and completely ionized. We take $\alpha = 0.1$. The box with thick solid lines defines the domain discussed in Burderi et al. (1998), while the horizontal line inside it shows the accretion rate above which disks are completely ionized (stable). Previous studies of the $\dot{M} - M$ plane are shown by different lines: Clarke & Shields (1989) – dot–dashed, Mineshige & Shields (1990) – dotted, Cannizzo (1992) – long–dashed. The short–dashed line represents the Eddington limit.

thermal–viscous ionization instability operates in AGNs in the presence of irradiation. They have studied stationary, optically thick and geometrically thin disks in the range of accretion rates and central black hole masses for which these models are self–consistent. They have found that most AGN disks, if not all, are unstable, even if they are irradiated by a central point source. The suppression of central accretion in the quiescent state means that we can identify only the outburst states of unstable systems as AGNs. Two important consequences follow: quiescent AGNs must appear as quite normal galaxies, and the average mass fuelling rate in many might be much lower than implied by their current luminosities. This in turn limits the masses that their central black holes are expected to reach. Since most quasars have observed central accretion rates above the stability limits, some or all of them could have steady disks. This group would then form a separate class with much higher fuelling rates $\dot{M} \sim 0.1 - 1\ M_{\odot}\ \mathrm{yr}^{-1}$. It is clear from Figure 1.2 that the instability present in the zone of partial ionization is relevant mainly for low mass objects. The expected characteristic time scale for this instability is $10^4 - 10^7$ years. The whole picture is more complicated as many of the objects with high steady fuelling rates would be subject to the radiation–pressure (Lightman–Eardley) instability and needs further investigation.

1.4 Conclusions

It is important to stress that there is no physical reason for which luminosity should not exceed the Eddington limit. Slim accretion disk models offer one of the most promising scenarios for generating super-Eddington luminosities. Detailed evolutionary calculations using slim disk approach, including intrinsic disk instabilities taking place in different regimes of accretion, are in progress. I am currently extending my previous investigations concerned with accreting black holes in X-ray binaries (see Szuszkiewicz & Miller 2001) for a case of NLS1s. Of course, there are also other mechanisms for getting high luminosity emission (see e.g. Begelman 2002, King 2002). An increasing number of Seyfert 1 galaxies with strong soft X-ray emission presents a particularly powerful diagnostic of AGNs and will be helpful in distinguishing between different models.

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References

Abramowicz, M. A., Calvani, M., & Nobili, L. 1980, ApJ, 242, 772
Abramowicz, M. A., Czerny, B., Lasota, J-P., & Szuszkiewicz, E. 1988, ApJ, 332, 646
Begelman, M. C. 2002, ApJ, 568, 97
Boroson, T. A. 2002, ApJ, 565, 78
Brandt, W. N., Mathur, S., & Elvis, M. 1997, MNRAS, 285, L25
Burderi, L., King, A. R., & Szuszkiewicz, E. 1998, ApJ, 509, 85
Cannizzo, J. K. 1993, ApJ, 419, 318
Cannizzo, J. K., & Reiff, C. M. 1992, ApJ, 385, 87
Clarke, C. J., & Shields, G. A. 1989, ApJ, 338, 32
Collin, S., Boisson, C., Mouchet, M., Dumont, A.-M., Coupé, S., Porquet, D., & Rokaki, E. 2002, A&A, 388, 771
Fan, X., et al. 2000, AJ, 120, 1167
Grimm, H.-J., Gilfanov, M., & Sunyaev, R. 2002, A&A, 391, 923
Jaroszyński, M., Abramowicz, M. A., & Paczyński, B. 1980, Acta Astron., 30, 1
King, A. R. 2002, MNRAS, 335, 13
Lin, D. N. C., & Shields, G. A. 1986, ApJ, 305, 28
Mathur, S. 2000, MNRAS, 314, L17
Mineshige, S., Kawaguchi, T., Takeuchi, M., & Hayashida, K. 2000, PASJ, 52, 499
Mineshige, S., & Shields, G. A. 1990, ApJ, 351, 47
Paczyński, B. 1980, Acta Astron., 30, 347
Paczyński, B., & Wiita, P. J. 1980, A&A, 88, 23
Pounds, K. A., Done, C., & Osborne, J. P. 1995, MNRAS, 277, L5
Salucci P., Szuszkiewicz, E., Monaco, P., & Danese, L. 1999, MNRAS, 307, 637

Shields, G. A., & Wheeler, J. C. 1978, ApJ, 222, 667
Siemiginowska, A., & Elvis, M. 1997, ApJ, 482, L9
Szuszkiewicz, E., Malkan, M. A., & Abramowicz, M. A. 1996, ApJ, 458, 474
Szuszkiewicz, E., & Miller, J. C. 2001, MNRAS, 328, 36
Wandel, A. 1999, ApJ, 519, 39
Wang, J.-M., Szuszkiewicz, E., Lu, F.-J., & Zhou, Y.-Y. 1999, ApJ, 522, 839