

SEARCHING FOR THE PHYSICAL DRIVERS OF EIGENVECTOR 1: FROM QUASARS TO NANOQUASARS

R. ZAMANOV AND P. MARZIANI

Osservatorio Astronomico di Padova, Istituto Nazionale di Astrofisica, Vicolo dell'Osservatorio 5,

I-35122 Padua, Italy; zamanov@pd.astro.it, marziani@pd.astro.it

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ABSTRACT

We point out an analogy between two accreting white dwarfs (CH Cyg and MWC 560) with jets and powerful quasars. In spite of the enormous difference in the mass of the central object (a factor $\sim 10^7$), the emission lines are strikingly similar to those of I Zw 1 (the prototype “narrow-line Seyfert 1” nucleus whose spectrum is widely used as an Fe II template for almost all quasars). The spectral similarities give us the unique possibility to consider the optical Eigenvector 1 diagram using objects less massive by a factor of millions. Our results reinforce the interpretation of the “Eigenvector 1 correlations” found for low-redshift quasars as driven mainly by the source luminosity-to-central compact object mass ratio. The accreting white dwarfs CH Cyg and MWC 560, their jets and emission lines, may well represent the low-energy, nonrelativistic end of the accretion phenomena, which encompass the most powerful quasars and microquasars. The remarkable similarities suggest that they may be legitimately considered “nanoquasars.”

Subject headings: binaries: symbiotic — quasars: emission lines — quasars: general — stars: individual (CH Cygni, MWC 560)

On-line material: color figures

1. INTRODUCTION

The accretion processes have a lot of similarities in spite of the differences in the type and the mass of the accreting object. In the last years a few microquasar sources have been discovered. They are galactic X-ray binaries in which a black hole (BH) or neutron star is accreting from the companion star, producing jets and even superluminal motion (Mirabel & Rodríguez 1999). The accreting stellar mass compact objects give us a tool to investigate phenomena in active galactic nuclei (AGNs) at much lower energy and much shorter timescale.

The aim of this Letter is to show the striking similarities between the emission lines of two accreting white dwarfs and the emission lines coming from the broad-line region of the AGNs, in spite of the mass difference (a typical BH in an AGN has a mass of $\sim 10^6$ – $10^9 M_\odot$, and the white dwarf in the interacting binaries has a mass of $\sim 1 M_\odot$). A comparison between such different objects can give us a better understanding of the accretion/ejection phenomenology as well as of the so-called “Eigenvector 1 correlations” that seem to be fundamental for AGN interpretation. We think it is appropriate to call the two accreting white dwarfs of this Letter “nanoquasars” because they seem to represent the very low energy analog of quasars and microquasars.

2. EMISSION-LINE SIMILARITIES

CH Cyg and MWC 560 are interacting binary stars in which a white dwarf accretes matter from the wind of a red giant. Their spectra and the spectrum of I Zw 1 are plotted in Figure 1. I Zw 1 is a “narrow-line” Seyfert 1 nucleus, well known because of its strong Fe II emission and relatively narrow lines (FWHM $\sim 1000 \text{ km s}^{-1}$); it is widely used as a template for subtraction of the Fe II complex in the $H\gamma$ – $H\beta$ region of quasar spectra. In Figure 1 we show the spectral region at 4200–4900 Å (*top panel*) and the UV region (*middle panel*). The optical spectrum of I Zw 1 was obtained with the 1.52 m ESO telescope at La Silla, and the UV was retrieved from the *Hubble Space Telescope* archive. The optical spectrum of MWC 560 is the

average of the Fiber-fed Extended Range Optical Spectrograph public archive spectra observed in the period 1998 November–December at ESO (Kaufer, Stahl, & Tubbesing 1999; Schmid et al. 2001). Both optical and UV spectra of CH Cyg were obtained in 1984, when the star underwent jet activity. The optical spectrum of CH Cyg is from the plate archive of the Bulgarian National Astronomical Observatory “Rozhen” (observed on 1984 July 10). The UV spectrum has been retrieved from the *International Ultraviolet Explorer* database (observed on 1985 January 23).

A clear similarity between the emission lines can be seen in Figure 1. Practically almost every emission line visible in the spectrum of I Zw 1 has corresponding features in the spectra of CH Cyg and MWC 560. An obvious similarity is also visible between the UV spectrum of CH Cyg and that of I Zw 1. We note in passing that similar emission lines are also visible in the spectrum of XX Oph (Kolev & Tomov 1993), where the accreting object is probably a main-sequence star (Evans, Albinson, & Barrett 1993). Despite the general similarity, some differences are visible as well. In MWC 560 these are the absorption components in the Balmer lines. These absorptions are due to the jet coinciding with the line of sight (Tomov et al. 1990). They also dominate the UV spectrum of MWC 560 (not shown here), making it quite different from the ones of CH Cyg and I Zw 1. In the optical spectrum of CH Cyg numerous absorptions due to the photosphere around the white dwarf are visible.

In the bottom panel of Figure 1 the optical emission line spectra of MWC 560 and CH Cyg are shown after having been continuum-subtracted, scaled, and broadened. This standard procedure is widely used for the emission-line measurements of AGNs, using I Zw 1 itself as a template. After this processing, good identity is achieved with the spectrum of I Zw 1. Our best fit corresponds to a width of $\text{FWHM}(\text{Fe II}_{\text{opt}}) = 970 \pm 90 \text{ km s}^{-1}$.

The hydrogen emission lines, as well as the Fe II emissions of AGNs, are emitted from the so-called broad-line region (BLR). This region is thought to be within $\lesssim 1 \text{ pc}$ of the central

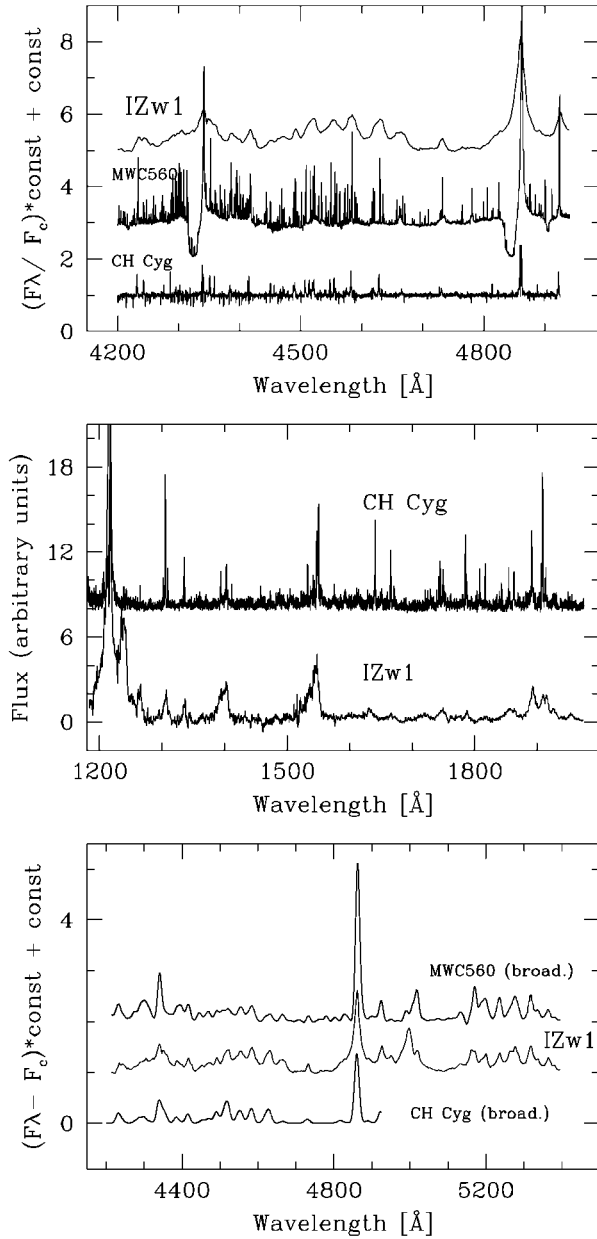


FIG. 1.—Comparison between the spectra of the interacting binaries CH Cyg and MWC 560 and the low-redshift quasar I Zw 1. *Top*, optical spectra; *middle*, UV region; *bottom*, optical spectra of MWC 560 and CH Cyg after broadening and scaling. A clear similarity between the emission lines is visible in all panels. [See the electronic edition of the *Journal* for a color version of this figure.]

BH. Its structure is poorly understood as yet. The clear similarity between the emission lines means that in objects like MWC 560 and CH Cyg we are observing a scaled-down version of the quasar BLR.

It is worth noting that the interacting binaries, in which a white dwarf accretes material from the wind of a red giant (usually classified as symbiotic stars), are strongly variable objects. For CH Cyg and MWC 560 we show that their spectra are similar to low-redshift quasars in moments when jet activity has been detected (see § 4).

3. THE EIGENVECTOR 1 DIAGRAM

During the last decade, several investigations of AGN emission lines emphasized the importance of a set of correlations

conventionally called “Eigenvector 1” (hereafter E1) and related to the principal component analysis of the properties of Palomar-Green quasars (Boroson & Green 1992). In the most important diagram associated with E1 (Sulentic, Marziani, & Dultzin-Hacyan 2000), the x -axis is the ratio between the equivalent width of the Fe II complex in the range of 4434–4684 Å and the equivalent width of the H β broad component ($H\beta_{BC}$), namely, $R_{Fe II} = W(Fe II) / W(H\beta_{BC})$. The y -axis is the FWHM of $H\beta_{BC}$. We measured for CH Cyg: $W(Fe II) = 4.5$ Å, $W(H\beta) = 5$ Å, and $FWHM(H\beta) = 200$ km s $^{-1}$; and we measured for MWC 560: $W(Fe II) = 34$ Å, $W(H\beta) = 31$ Å, and $FWHM(H\beta) = 110$ km s $^{-1}$.

The diagram is shown in Figure 2. The left panel includes the AGN sample (marked with crosses and plus signs) of Sulentic et al. (2002). The positions of MWC 560 and CH Cyg are marked with triangles. As could be expected, they are located outside of the AGN population, but close to the narrow-line Seyfert 1 galaxies (marked with plus signs), which are supposed to have systematically lower BH masses. The diagram in Figure 2 is believed to play a role for AGNs that is similar to that of the Hertzsprung-Russell diagram in regard to stars (Sulentic et al. 2000; Sulentic, Calvani, & Marziani 2001). The physical drivers can be the source luminosity-to-central compact object mass ratio (L/M) convolved with orientation (Marziani et al. 2001) or $L/L_{Edd} (\propto L/M)$ and BH mass (Boroson 2002). Here we want to use the nanoquasars to better understand this correlation space. The nanoquasars give us the unique possibility to consider the effect of L/M along with that of varying the mass by 7–8 orders of magnitude.

The reverberation mapping studies of the AGN (Kaspi et al. 2000) give the following dependence of $FWHM(H\beta_{BC})$ on mass and L/M :

$$FWHM(H\beta) = 4350 \left(\frac{L}{M} \right)_{su}^{-0.35} \left(\frac{M}{M_{\odot}} \right)^{0.15} \text{ km s}^{-1}, \quad (1)$$

where $(L/M)_{su}$ is the luminosity-to-mass ratio in solar units, with the solar value $(L/M)_{\odot} = 1.92$ ergs s $^{-1}$ g $^{-1}$. The distance of the BLR from the central continuum source is found to depend on the bolometric luminosity L :

$$r = 9.36 \times 10^8 \left(\frac{L}{L_{\odot}} \right)^{0.7} \text{ cm}. \quad (2)$$

The ionization parameter can be defined as follows:

$$U = \frac{Q(H)}{4\pi cr^2 n_e}, \quad (3)$$

where $Q(H) = fL/h\nu$ is the number of the hydrogen-ionizing photons, r is the distance of the BLR from the central continuum source, f is the fraction of ionizing photons, ν is the average frequency of the ionizing photons, and n_e is the electron density. The appearance of the same lines in quasars and in symbiotic stars means that the density in the line-emitting region should be similar. A relation connecting n_e and the L/M ratio is

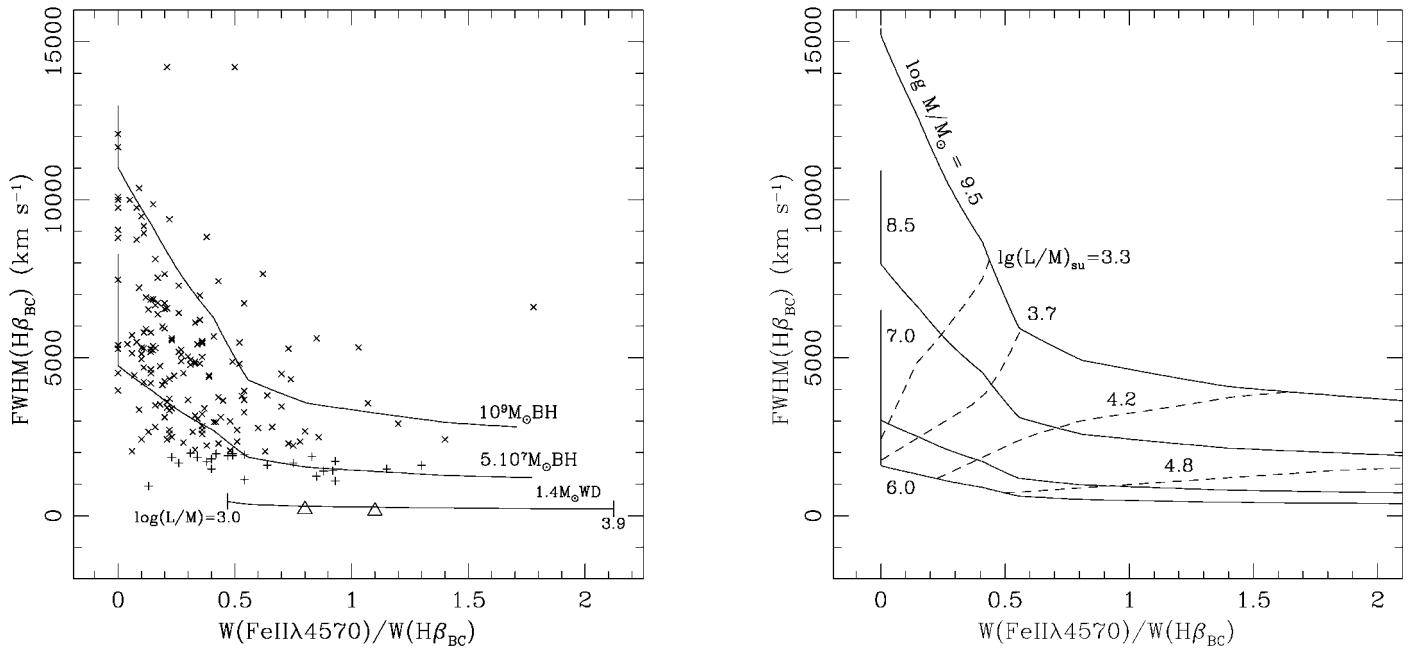


FIG. 2.—Fe II–H β E1 diagram. The abscissa is the rest-frame equivalent width ratio between Fe II $\lambda 4570$ and H β_{BC} ; the ordinate is FWHM(H β_{BC}) in units of kilometers per second. *Left*: AGNs from the sample of Sulentic et al. (2002; crosses and plus signs; the plus signs refer to narrow-line Seyfert 1 galaxies), MWC 560 (located at $R_{Fe II} = 1.1$) and CH Cyg ($R_{Fe II} = 0.8$, triangles). The lines are plotted for (from top to bottom) $M_{BH} = 10^9 M_{\odot}$, $M_{BH} = 5 \times 10^7 M_{\odot}$, and a white dwarf mass $M_{WD} = 1.4 M_{\odot}$. The line for the $1.4 M_{\odot}$ white dwarf is calculated in the limits $\log(L/M)_{su} = 3.0$ –3.9. *Right*: Theoretical grid for quasars in the optical E1 diagram. The solid lines are plotted for fixed BH mass $\log(M/M_{\odot}) = 9.5, 8.5, 7.0$, and 6.0 . The dashed lines are for fixed L/M ratio $\log(L/M)_{su} = 3.3, 3.7, 4.2$, and 4.8 . [See the electronic edition of the Journal for a color version of this figure.]

(Marziani et al. 2001)

$$n_e = 5.248 \times 10^7 \left(\frac{L}{M} \right)_{su}^{2/3} \text{ cm}^{-3}. \quad (4)$$

Combining the above equations we obtain

$$U = 3.3 \times 10^6 f \left(\frac{10^{16} \text{ Hz}}{\nu} \right) \left(\frac{L}{M} \right)_{su}^{-1.07} M_{su}^{-0.4}. \quad (5)$$

A typical AGN continuum (Laor et al. 1997) yields $\nu \approx 1.22 \times 10^{16}$ Hz and $f \approx 0.39$. We can then calculate $R_{Fe II}$ following Marziani et al. (2001). In the right panel of Figure 2 are the theoretical lines covering the range of masses expected for AGNs, $\log(M/M_{\odot}) \approx 6$ –9.5.

In symbiotic and symbiotic-like stars the ionizing photons are coming from an accreting white dwarf, the effective temperature of which could be in the range from 6000 up to $\approx 200,000$ K (Mürset & Nussbaumer 1994). In CH Cyg and MWC 560 the UV continuum shape indicates a region of extremely large column density (a “cocoon”) that obscures the inner disk and the hot white dwarf surface (Michalitsianos et al. 1993). The UV continuum fitting of CH Cyg during the active phase indicates temperatures of $T_{eff} = 8500$ –15,000 K, and the temperature is the lowest at the maximum of brightness (Mikolajewska, Selvelli, & Hack 1988). Because the jet ejection is at the maximum, we will adopt $T_{eff} = 8500$ K corresponding to $f = 1 \times 10^{-5}$ and $\nu = 3.48 \times 10^{15}$ Hz. For MWC 560 there are also no signs of temperatures hotter than 15,000 K (Shore, Aufdenberg, & Michalitsianos 1994), and even the column density of the absorbing material is higher than in CH Cyg (Michalitsianos et al. 1993).

The resulting FWHM(H β) versus $R_{Fe II}$ is plotted in Figure 2. In the left panel the lines are for masses $M_{BH} = 5 \times 10^8 M_{\odot}$, $M_{BH} = 10^7 M_{\odot}$, and a white dwarf mass $M_{WD} = 1.4 M_{\odot}$. We

adopted f and ν following the above considerations. The L/M ratio was running within the limits of $\log(L/M)_{su} = 2.5$ –4.4 for $M_{BH} = 1 \times 10^9 M_{\odot}$, $\log(L/M)_{su} = 2.5$ –4.9 for $M_{BH} = 10^7 M_{\odot}$, and $\log(L/M)_{su} = 3.0$ –3.9 for $M_{WD} = 1.4 M_{\odot}$.

The total luminosity of the white dwarf of CH Cyg during the time of jet ejection in 1984 was $L \lesssim 1600 L_{\odot}$ (Mikolajewska et al. 1988) and that of MWC 560 was $L \approx 1000 L_{\odot}$ (Schmid et al. 2001). Assuming a typical white dwarf mass in symbiotic stars of $M_{WD} = 1.0$ – $1.4 M_{\odot}$ (or a total mass of the binary system of about 3–5 M_{\odot}), we obtain $(L/M)_{su} \approx 10^3$, in agreement with parameters used to plot the lowest line in the left panel of Figure 2.

If we use a higher effective temperature for the ionizing continuum (i.e., $T_{eff} = 15,000$ K corresponding to $f = 6.61 \times 10^{-3}$ and $\nu = 3.66 \times 10^{15}$ Hz), to have reasonable results from equation (5) we need to go to a stronger dependence, e.g., $U \propto (L/M)^{-(1+x)} M^{-1}$ with x up to $x \approx 0.67$ (more details are given in Marziani et al. 2001). This points out that the number of ionizing photons and the shape of the UV and X-ray continuum are important in the E1 correlations. It is worth noting that the soft X-ray photon index is the third axis in the E1 diagrams of Sulentic et al. (2000, 2001). The line widths, FWHM(H β) = 100 km s $^{-1}$ for MWC 560 and FWHM ≈ 200 km s $^{-1}$ for CH Cyg, are a little bit smaller than expected from equation (1), which predicts values around 300–400 km s $^{-1}$. It is also possible that the luminosities of CH Cyg and MWC 560 were lower (i.e., 100–500 L_{\odot}) at the time the spectra were obtained, if the distances used in the calculations are too large. We regard the agreement acceptable, considering the huge difference in masses and the limited range of luminosities and masses from which the relationships of Kaspi et al. (2000) and Marziani et al. (2001) were derived. The white dwarfs have a lower efficiency of accretion ($\eta \approx 10^{-4}$) than expected for typical AGNs ($\eta \approx 10^{-1}$ to 10^{-2}). The

equations used give good results without considering the effect of efficiency. This is in agreement with the interpretation of the E1 as mainly driven by the L/M ratio. Efficiency, along with several other parameters, may have some (minor) influence.

Following the above equations and Figure 2, a change in mass by a factor of $\sim 10^7$ times changes $\text{FWHM}(\text{H}\beta)$ by a factor of 10–50. A change in mass by a factor of 50 (from 10^7 to $5 \times 10^8 M_\odot$, in the range expected for BH masses of low-redshift quasars) leads to an $\text{FWHM}(\text{H}\beta)$ change by a factor 2–3. In a sample of quasars with a limited BH mass spread, mass change may lead to a second-order effect that may be even smaller than the effect of orientation (Marziani et al. 2001).

4. JETS

Jets are detected in systems quite different from the ones harboring black holes (for a review see Livio 2001): young stellar objects, planetary nebulae, and supersoft X-ray sources. The jets of MWC 560 and CH Cyg, as well as other nonrelativistic jets, are visible in atomic spectral lines. Among the relativistic jets, only in SS 433 are atomic lines visible (Fender 2001). In the accreting white dwarfs we call nanoquasars, the jet velocities observed are $\approx 1000 \text{ km s}^{-1}$ in CH Cyg (Taylor, Seaquist, & Mattei 1986) and $1000\text{--}6000 \text{ km s}^{-1}$ in MWC 560 (Tomov et al. 1992). These velocities are much slower than the jet velocities in microquasars: $0.26c$ in SS 433 (Margon 1984), $0.5c$ in Cyg X-3 (Martí, Paredes, & Peracaula 2001), and $0.9c$ in GRS 1915+105 (Mirabel & Rodríguez 1999). However, they are consistent with an overall picture in which the jet velocity is of the order of the escape velocity (Livio 2001). A rough estimation is $v_{\text{esc}}(\text{WD}) \approx 0.02c$.

The compact object luminosities of MWC 560 and CH Cyg are considerably less than the Eddington limit $L \leq 0.05L_{\text{Edd}}$. At such accretion luminosity the most probable jet energy source is the extraction of rotational energy from the compact object. In the case of nanoquasars the extraction is probably going on via the propeller action of a magnetic white dwarf (Mikolajewski, Mikolajewska, & Tomov 1996). The most probable source of jet formation in quasars is the extraction of energy and angular momentum via the Blandford & Znajek (1977) mechanism. In this sense the jets in the nanoquasars probably represent a low-energy (nonrelativistic) analog of the jets of quasars and microquasars, having a similar energy

source—the extraction of rotational energy from the central compact object.

5. CONCLUSIONS

We showed a clear similarity between the emission-line spectra of the accreting white dwarfs CH Cyg and MWC 560 and those of low-redshift quasars. Their jets may have a similar energy source—the rotational energy of the central object. The discussed similarities have been used in this Letter to aid the interpretation of the E1 diagrams for AGNs. Their position in the diagram confirms the interpretation that the physical driver of Boroson & Green's E1 is primarily the L/M ratio and that the mass of the accreting object also plays a role. We could call the accreting white dwarfs with jets and with AGN-like spectra nanoquasars, by analogy with the quasar and microquasar denomination (also, *nanos* in ancient Greek means dwarf).

In the future, the spectral similarity discussed here could be used to better understand the conditions and the structure of the BLRs of quasars and to identify numerous emission lines in the spectrum of I Zw 1 (and by extension, of the wide majority of AGNs that show an Fe II spectra almost identical to that of I Zw 1). The FWHM of emission lines in AGNs is ≥ 1000 , which means that most Fe II lines are blended together. In accreting white dwarfs the FWHM is a factor of 10 less, making it possible to identify weak lines. The diversity of symbiotic binary properties could be used to test and to “calibrate” AGN correlations, using objects with well-known mass. It will be very useful to detect a stellar mass BH (i.e., a galactic microquasar) with similar emission lines. Discovery of an interacting binary in which a BH accretes from the wind of a red giant will be extremely interesting, although very difficult to find from an evolutionary point of view.

Ultimately, the nanoquasars could be an important link in our understanding of all accreting sources. They could help us to create a unified picture of all accreting objects from cataclysmic variables and stellar mass BHs up to the most powerful quasars.

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