Black hole masses from power density spectra: determinations and consequences

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ABSTRACT

We analyze the scaling of the X-ray power density spectra with the mass of the black hole on the example of Cyg X-1 and Seyfert 1 galaxy NGC 5548. We show that the high frequency tail of the power density spectrum can be successfully used for determination of the black hole mass. We determine the masses of the black holes in 6 Broad Line Seyfert 1 galaxies, 5 Narrow Line Seyfert 1 galaxies and two QSOs using available power density spectra. The proposed scaling is clearly appropriate for other Seyfert galaxies and QSOs. In all but 1 normal Seyferts the resulting luminosity to the Eddington luminosity ratio is smaller than 0.15, with a source MCG -6-15-30 being an exception. The applicability of the same scaling to Narrow Line Seyfert 1 is less clear and there may be a systematic shift between the power spectra of NLS1 and S1 galaxies of the same mass, leading to underestimation of the black hole mass. However, both the method based on variability and the method based on spectral fitting show that those galaxies have relatively low masses and high luminosity to the Eddington luminosity ratio, supporting the view of those objects as analogs of galactic sources in their high/soft or very high state based on the overall spectral shape. Bulge masses of their host galaxies are similar to normal Seyfert galaxies so they do not follow the black hole mass - bulge mass relation for Seyfert galaxies, being evolutionary less advanced, as suggested by Mathur (2000). The bulge mass–black hole mass relation in our sample is consistent with being linear, with black hole to bulge ratio ~ 0.03 %, similar to Wandel (1999) and Laor (1998, 2001) for low mass objects but significantly shifted from the relation of Magorrian et al. (1998) and McLure & Dunlop (2000).

Key words: galaxies: active – accretion, accretion discs – black hole physics – binaries – X-rays: stars – galaxies: Seyfert, quasars – X-rays.

1 INTRODUCTION

Determination of the masses of black holes in active galactic nuclei (AGN) is a key element in studies of the nature of accretion process and evolution of an active nucleus.

Several methods were used so far for this purpose: estimation of the virial mass from the emission line data through reverberation techniques (see e.g Wandel 1999), estimation of the virial mass on the basis of the source luminosity and estimates of the ionization parameter in Broad Line Region (e.g. Wandel, Peterson & Malkan 1999), and model fits (usually of accretion discs) to the broad band spectra (e.g. Edelson & Malkan 1986, Sun & Malkan 1989, Merloni, Fabian & Ross 2000).

Suggestion that variability properties of the sources are affected by their mass and/or luminosity was made by Barr & Mushotzky (1986) and Wandel & Mushotzky (1986), and subsequently explored by many authors (e.g. McHardy 1989, Green, McHardy & Lehto 1993, Turner et al. 1999, Leighly 1999a).

A convenient and powerful method of determination of black hole mass from variability properties was recently used by Hayashida et al. (1998) and Hayashida (2000). The method uses the normalization of the X-ray power density spectra (hereafter PDS) in comparison with Cyg X-1 in the hard state. The method, however, lead to surprisingly small values of the black hole masses and, consequently, to luminosity to the Eddington luminosity ratios frequently larger than one.

In the present work we reconsider the method of Hayashida et al. (1998). We determine better scaling coefficient on the basis of the new available power spectra of Cyg X-1, the new power spectrum of NGC 5548, and the independent black hole mass measurement for this AGN.
2 METHOD

2.1 Determination of black hole mass in NGC 5548

Seyfert 1 galaxy NGC 5548 (z = 0.0174) is one of the most frequently studied AGN. The mass of the central black hole in this object is therefore determined relatively accurately. Peterson & Wandel (1999) give the value 6.8 \pm 1.5 \times 10^7 M_\odot from reverberation studies of the various lines emitted by the Broad Line Region. This technique may potentially suffer from systematic errors up to a factor of 3 (Krolik 2000) but recent comparison of statistical properties of reverberation and dynamical mass measurement indicated smaller errors (Gebhardt et al. 2000). Virial mass of the black hole in NGC 5548, determined on the basis of ionization method for a number of emission lines is equal to 5.9 \pm 2.5 \times 10^7 M_\odot (Peterson & Wandel 2000).

Those measurements confirmed earlier results based on the study of the BALR which indicated the mass about 10^8 M_\odot (Wanders et al. 1995), or somewhat smaller (Done & Krolik 1996). Rokaki et al. (1993) argued for the value between 5 \times 10^7 M_\odot and 6 \times 10^7 M_\odot and Kaspi et al. (2000) obtained values 9.4 \pm 12.3 \times 10^7 M_\odot.

Fits of a simple disc/corona model to the optical/UV continuum data from the AGN Watch (Clavel et al. 1991, Peterson et al. 1992) favored the value 10^8 M_\odot although the value 6 \times 10^7 M_\odot was also acceptable (Loska & Czerny 1997). Fits of the more advanced disc/corona model of Witt, Czerny & Zycki (1997) which was based also on the X-ray data indicated rather larger value 1.4 \times 10^8 M_\odot (Karaszkiewicz, Loska & Czerny 1997).

The value of the black hole mass 6.8 \pm 1.5 \times 10^7 M_\odot seems to be determined most accurately, since it resulted from the analysis of several emission lines coming from the Broad Line Region. It is also consistent with other determinations, taking into account quite large and unspecified errors in measurements based on other methods.

2.2 Power density spectrum of NGC 5548 and the comparison with galactic sources

Time variability of the X-ray and optical emission from the nucleus of NGC 5548 was studied by a number of authors (e.g. Papadakis & Lawrence 1993, Clavel et al. 1992, Czerny, Schwarzenberg-Czerny & Loska 1999, Chiang et al. 2000 and references therein). The power density spectrum is basically featureless, as in other AGN, and the variability is caused by some stochastic process (Lawrence et al. 1987, McHardy & Czerny 1987, Czerny & Lehto 1997). Since Comptonization is directly responsible for the formation of the hard X-ray spectra this variability must be related to variable seed photon flux and/or hot plasma properties but the exact physical mechanism is still unknown (for a review of X-ray spectra and variability of AGN, see e.g. Mushotzky, Done & Pounds 1993, Nandra et al. 1997, Leighly 1999a,b; but see also Abramart & Czerny 2000 and the references therein for an alternative view). The same mechanism is expected to operate in galactic black holes (GBH; for a review, see e.g. van der Klis 1995, Cui 1999, Poutanen 2000).

The basic similarity of AGN and GBH with respect to the spectra and variability was discussed by a number of authors (e.g. Zdziarski 1999). There are, however, also some systematic differences reflecting the direct dependence on the mass of the central body: (i) the temperature of the disc component is about two orders of magnitude higher in galactic sources than in AGN (ii) GBH in their soft/high state are generally less variable than AGN dominated by the disc component.

Recent study of NGC 5548 with RXTE satellite allowed to determine an exceptionally accurate PDS for this source in the X-ray band (Chiang et al. 2000).

We compare PDS of NGC 5548 with PDS of a number of galactic sources in various luminosity states (see Fig. 1). We plot these spectra in the form of \( \nu \times \text{power} \) for more convenient comparison. We rescale the PDS of NGC 5548 to the

![Figure 1. Power density spectrum times frequency for NGC 5548 from Chiang et al. (2000) (stars connected with continuous line) and for galactic black holes: Cyg X-1 in transition state from Cui et al. (1997) (open triangles connected with continuous line), Cyg X-1 in hard state from Lin et al. (2000) (solid triangles connected with long dash line), GRS 1758-258 from Lin et al. (open octagons connected with short dash-long-dash line), 1E 1740.7-2942 from Lin et al. (stars connected with dot-short-dash line), GX 339-4 from Lin et al. (solid squares connected with dot line). Power density spectrum of NGC 5548 was shifted by 6.83 in \( \log(\nu) \) which corresponds to rescaling this source to a black hole mass of 10\( M_\odot \).]
mass of the black hole $10M_\odot$, appropriate for Cyg X-1 (see Nowak et al. 1999 and the references therein) through simple horizontal shift by a factor of $6.8 \times 10^6$. We show separately the comparison of NGC 5548 with the high quality data of Cyg X-1 in its high/soft (Gilfanov et al. 2000) and low/hard (Revnivtsev, Gilfanov & Churazov 2000) states (see Fig. 2).

The exact comparison of the two distributions is however difficult since the quality of the PDS for NGC 5548 is much lower than that of Cyg X-1. The fit to the overall shape of the PDS found by Chiang et al. (2000) suggests that there is a systematic shift between the two distributions (see continuous line in Fig. 2) by about 0.4 in the logarithmic scale. The high frequency turn off is best reproduced by Cyg X-1 in soft or in the transition state, but the normalization which assures that the integral of the PDS gives the variance. All distributions, together with NGC 5548, are normalized different by a factor of 2 from the original normalization different by a factor of 2 from the original normalization which assures that the integral of the PDS gives the variance. All distributions, together with NGC 5548, are plotted in Fig. 3.

The exact position of the high frequency part of the spectrum is the basis of the mass measurement proposed by Hayashida et al. (1998). The dependence on the luminosity is constrained to low frequencies (Belloni & Hasinger 1990) so the high frequency part (above 10 Hz for galactic sources and correspondingly lower for AGN) is promising for mass determination.

According to Hayashida et al., the frequency $\nu_{0.001}$ where the power spectrum in $\nu \times$ Power representation is equal $10^{-3}$ scales with the mass, $\log(M_{BH}/M_\odot) = C - \log\nu_{0.001}$. Hayashida et al. (1998) adopted the value $C$ equal 2.66 at the basis of their Cyg X-1 spectrum. The new hard state data indicates the value of $\nu_{0.001}$ by more than a factor of 2 higher, $(C = 3.1)$.

The power spectrum of NGC 5548, if well represented by the fit, is slightly shifted towards higher frequencies and if the mass of Peterson & Wandel (1999) is adopted, $C = 3.5$.

The difference between the value of $C$ from Cyg X-1 and NGC 5548 is larger than the formal error given on the mass measurement of NGC 5548 (0.1; Peterson & Wandel 1999).

This difference may be partially caused by the poor quality of NGC 5548 data. Simulations indicate that the determination of the high frequency slope of the PDS may be biased by the power leak to high frequencies connected with the window function if the PDS slope is close to $-2$ (Green, McHardy & Lehto 1993; see also Czerny et al. 1999).

The shift may also reflect the uncertainty in our knowledge of the masses: neither the mass of Cyg X-1 nor of NGC 5548 is known very accurately, if systematic errors connected with reverberation method are taken into account (Krolik 2000). From this point of view, it would be more convenient to use the galactic source GRO J1655-40 because the mass determination for this source is by far the most accurate ($M = 7.2 \pm 0.22 M_\odot$, Orosz & Bailyn 1997; see the discussion of Ziolkowski 2001). Unfortunately, the currently available power spectrum for this source (Sunyaev & Revnivtsev 2000) is not as accurate as for Cyg X-1 so at the basis of this source the value of $C$ should be roughly between 2.9 and 3.3, supporting the result from Cyg X-1.

The systematic shift between NGC 5548 and Cyg X-1 comes predominantly from the EUVE results biasing the fit proposed by Chiang et al. (2000). The XTE results themselves (a histogram in Fig. 2) are roughly consistent with Cyg X-1.

Therefore, assuming the value $C = 3.1$ for both galactic objects and AGN seems reasonable.

### 3 DETERMINATION OF THE CENTRAL BLACK HOLE MASSES IN AGN

We use the available PDS for a number of Seyfert galaxies in order to determine their masses: PKS 2155-304, NGC 4051, NGC 4151 and NGC 5506 is taken from Hayashida et al. 1998, MCG -6-30-15 is from Nowak & Chiang (2000), and NGC 3516 from Edelson & Nandra (1999). PDS for NGC 7469 is from Nandra & Papadakis (2001), but with the normalization different by a factor of 2 from the original normalization which assures that the integral of the PDS gives the variance. All distributions, together with NGC 5548, are plotted in Fig. 3.

The PDS of various AGN are essentially similar to each other and to the PDS of NGC 5548. Horizontal shifts between them can be explained as the differences in their black hole masses. However, there are also some differences in total normalization. Some of the effect may be connected with the finite length of the data, not extending beyond the maximum of the PDS at the longest timescales. However, the effect may be also connected with their luminosity. Similar
dispersion is also seen among the galactic sources. It clearly limits the accuracy of the method.

We determine the black hole masses from their PDS using the method of scaling adopted by Hayashida et al. (1998). We adopt the PDS value of $10^{-3}(\text{rms})^2 \text{ Hz}^{-1}\text{Hz}$ as the characteristic value and we compare the frequencies $\nu_{0.001}$ where these value is reached in various sources (thick horizontal line in Fig. 3). Our formula is (see Sect. 2.2)

$$\log(M_{BH} / M_\odot) = 3.1 - \log\nu_{0.001}. \quad (1)$$

For those sources analyzed by Hayashida et al. (1998) and Hayashida (2000) for which no better PDS are currently available we simply adopt their results after scaling the masses by a factor 2.8 (shift by 0.44 in logarithm), which results from systematic difference between new and previous results for Cyg X-1 (see Sect. 2.2). Those sources are: PHL 1092, PG 1244, IRAS 13224, 3C 273, ESO 103-G35, PKS 2155-304, NGC 4051, NGC 4515 and NGC 5506 from Hayashida et al. (1998).

All masses of central black holes, are given in Table 1.

4 BULGE MASSES OF HOST GALAXIES

We determine the bulge masses of the considered AGN using the data available from the literature and following the approach of Laor (1998) and Wandel (1999).

No data are available on the host galaxy of PHL 1092 and PKS 2155-304, so we were unable to determine bulge masses of host galaxies in the case of these two objects.

For NGC 5548, NGC 4051, NGC 3516, NGC 4151, NGC 5506 we take the blue bulge magnitude $M_B$ from Whittle (1992), we calculate the visual magnitude as $M_V = M_B - 0.95$ (Worthey 1994), bulge luminosity as $\log(L_{\text{bulge}} / L_\odot) = 0.4(M_V + 4.83)$ and finally $\log(M_{\text{bulge}} / M_\odot) = 1.18\log(L_{\text{bulge}} / L_\odot) - 1.11$, after Magorrian et al. (1998). Our values of masses for 5548, NGC 4051, and NGC 4151 differ by a factor of $\sim 2$ from those of Wandel (1999) due to the $M_V = M_B - 0.95$ correction applied by us.

For 3C 273 we take the visual magnitude of the host galaxy $M_{\text{total}} = -22.58$ from Laor (1998), and the type of the galaxy E4 after Bahcall et al. (1997), then we calculate the bulge luminosity from the formula $M_{\text{bulge}} = M_{\text{total}} - 0.324T - 0.554T^2 + 0.00047T^3$, where $\tau = T + 5$ and $T$ is the Hubble type of the galaxy and we further proceed as described above.

In the case of remaining AGN, apart from IRAS 13224-3809, we took their apparent magnitudes and redshifts from NED, we corrected for the contamination of the total flux by the nuclear emission using the measured equivalent width of the $H_\beta$ line, $EW_{H_\beta}$, as $M_{\text{bulge}} = M_{\beta} - 2.5\log(1 + 1.10 + (1 + z)EW_{H_\beta}/100)$, after Whittle (1992), assuming the spectral slope equal -1 in all objects. $EW_{H_\beta}$ values were taken from Morris & Ward (1988) for MCG -6-30-15, and ESO 103-G35, and from Miller et al. (1992) for PG 1244+226, and from Giannuzzo & Stirpe (1996) for 1H 0707-495. We also included the correction for intrinsic absorption, 0.14, the same in all sources, after Whittle (1992). The host galaxy luminosity of IRAS 13224-3809 was estimated on the basis of V band magnitude of the active nucleus 15.2 from Young et al. (1999) and large aperture value of $EW_{H_\beta}$ equal to 23.6 given by Boller et al. (1993).

We see that S1 galaxies and 3C 273 follow the bulge mass–black hole mass relation determined by Laor (1998) and Wandel (1999) but they are clearly shifted from the Magorrian et al. (1998) relation for low mass objects. Formally, in our data the relation holds

$$M_{\text{bulge}} \propto M_{BH}^{0.98}, \quad (2)$$

if the black hole mass is determined from the variability (Sect. 3).

The relation recently found by McLure & Dunlop is close to the original relation of Magorrian et al. (1998) and it is clearly inconsistent with our results.

NLS1 galaxies are strongly shifted from the S1 distribution towards low black hole mass range for approximately the same range of bulge masses of host galaxies.

5 DETERMINATION OF THE $L/L_{\text{edd}}$ RATIO OF AGN

We determine the bolometric luminosity of AGN as a sum of two independent contributions from X-ray and opti-
Table 1. Properties of AGN. Black hole masses are determined from variability (Section 3), photoionization and reverberation method (Wandel, Peterson & Malkan 1999), accretion disk fits (Section 6.2), and the first value is used to calculate the first luminosity to the bulge. Units: $M$ is in $M_{\odot}$ and $L$ is in erg s$^{-1}$. 

| object       | type | $\log M_{\text{var}}^{\text{BH}}$ | $\log M_{\text{ph}}^{\text{BH}}$ | $\log M_{\text{rev}}^{\text{BH}}$ | $\log M_{\text{disk}}^{\text{BH}}$ | $\log L_{\text{bol}}$ | $L/L_{\text{Edd}}^{\text{var}}$ | $L/L_{\text{Edd}}^{\text{disk}}$ | $\log M_{\text{bulge}}$ |
|--------------|------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|-----------------|-------------------------------|-------------------------------|-------------------|
| NGC 5548     | S1.5 | 7.39                             |                                  |                                  | 7.31                             | 44.36           | 0.074                         | 0.089                         | 11.47             |
| NGC 7469     | S1.2 | 7.03                             | 6.87                             | 6.88                             | 7.41                             | 44.30           | 0.15                          | 0.062                         | 11.03             |
| MCG -6-30-15 | S1.2 | 5.94                             |                                  |                                  | 6.98                             | 43.85           | 0.646                         | 0.059                         | 10.23             |
| NGC 4151     | S1.5 | 7.57                             | 7.35                             | 7.08                             | 7.03                             | 43.70           | 0.010                         | 0.037                         | 11.05             |
| NGC 5506     | S1.9 | 6.86                             |                                  |                                  | 7.33                             | 43.93           | 0.018                         | 0.032                         | 10.78             |
| ESO 103-G35  | S1.2 | 7.14                             |                                  |                                  | 7.23                             | 43.88           | 0.083                         | 0.036                         | 10.78             |
| NGC 3516     | S1.5 | 7.25                             | 7.30                             |                                  | 7.44                             | 43.39           | 0.014                         | 0.007                         | 10.62             |
| NGC 4051     | NLS1 | 5.39                             | 5.37                             | 6.15                             | 6.50                             | 42.40           | 0.082                         | 0.006                         | 10.91             |
| IRAS 13224-3809 | NLS1 | 4.52                           |                                  |                                  | 8.01                             | 44.95           | 215                           | 0.069                         | 12.16             |
| 1H 0707-495  | NLS1 | 5.61                             |                                  |                                  | 6.77                             | 43.69           | 0.95                          | 0.066                         | 11.39             |
| PG 1244+026  | NLS1 | 5.85                             |                                  |                                  | 6.85                             | 44.60           | 7.73                          | 0.45                          | —                 |
| PHL 1092     | NLS1 | 6.09                             |                                  |                                  | 6.62                             | 44.13           | 1.51                          | 0.26                          | 11.42             |
| 3C 273       | QSO  | 8.12                             |                                  |                                  | 8.26                             | 45.70           | 32                            | 0.22                          | —                 |
| PKS 2155-304 | QSO  | 7.39                             |                                  |                                  | 8.12                             | 46.21           | 5.26                          | 0.98                          | —                 |

6 DISCUSSION

6.1 Comparison with black hole mass determination from Broad Line Region

The applicability of the method based on the Power Density Spectrum can be tested using those objects which black hole mass was determined independently.

Some of the sources in our study were extensively monitored (NGC 4151, NGC 4051, and NGC 7469) which allowed to use reverberation or photoionization method, or both, to determine the mass of the central black hole. The values obtained by Wandel, Peterson & Malkan (1999) are given in Table 1. NGC 3516 was also monitored and the black hole mass determined by reverberation method was given by Wanders & Horne (1994). We see that for three objects there is a good agreement between the black hole mass determined from X-ray variability with the values from both the ionization and reverberation method. Methods based on the Broad Line Region properties are themselves accurate within a factor of three, according to the discussion recently made by Krolik (2000), and the mass from PDS is contained in the expected range.

In case of NGC 4151 the black hole mass determined from variability is larger by a factor of 1.7 than the value from photoionization and by a factor of 3 than the value from reverberation. In that case the power density spectrum taken from Hayashida et al. (1998) may not be determined accurately. This object, having larger mass, requires longer monitoring than NGC 4051 and the Ginga results may not be adequate. The source was earlier observed by EXOSAT and the power spectrum was determined by Papadakis & McHardy (1995) but without the normalization. If we normalize their spectrum according to the provided mean intensity and the excess variance and use their PDS we obtain even larger black hole mass ($\log M_{BH} = 8.43$). However, true high frequency part of the PDS may be actually flatter.
than the slope -2 given in the paper due to the power leakage effect discussed by the authors. If we arbitrarily assume that the turning point is correct but the slope is -1.5 we obtain
\[ \log M_{BH} = 7.5. \]
This last value is closer to the values determined from the BLR properties, but this discussion mostly points out a need of high quality PDS of AGN.

6.2 Comparison with black hole mass determination from accretion disk fitting

For most of the sources from our sample such determinations are not available (and for other objects from Wandel et al. (1999) sample the power spectra were not determined). Therefore, in order to test better the method we determine the black hole masses for all sources based on the following assumptions: (1) outer part of the flow responsible for the UV emission is well modeled by the standard accretion disk (2) the X-ray emission is produced closer in, and the total efficiency of conversion of the accreting mass into observed radiation is 1/16, as appropriate for non-advecting flow onto a Schwarzschild black hole.

The first assumption results in adopting the relation between the black hole mass, accretion rate, intrinsic luminosity \( L_\nu \) at a frequency \( \nu \) after Tripp, Bechtold & Green (1994)
\[ \log M + \log \dot{M} = 1.5(\log L_\nu - 19.222) - 0.5\log \nu, \] (3)
where \( M \) is in solar masses, \( \dot{M} \) is solar masses per year, \( \nu \) in Hz, and \( L_\nu \) in erg s\(^{-1}\) Hz\(^{-1}\).

This relation, combined with the second assumption and calculated at 2500 Å, gives
\[ \log M = 1.5\log(\nu L_\nu^{2500}) - \log L_{bol} - 13.44. \] (4)
Since it relies on disk assumption we call it \( M_{BH}^{disk} \) in Table 1.

Such an approach does not take into account the departure of the locally emitted spectrum from the black body, and advection or outflow may lead to smaller energetic efficiency \( \eta \) than assumed. The resulting black hole mass depends on those factors as
\[ M \propto f^2 \eta \] (Janiuk et al. 2001), where \( f \) is the color temperature to the effective temperature ratio so the mass may be either underestimated or overestimated by a factor of a few.

The relation between the masses determined in two ways are shown in Fig. 5.

The black hole masses obtained in this way for S1 galaxies and QSOs are quite similar to values obtained from variability. Mean value of the logarithm of the black hole mass for a S1 galaxy is equal to 7.03 from variability and 7.27 from disk fitting, and for the two quasars these two numbers are equal 7.75 and 8.36, correspondingly. It might indicate a slight systematic non-linearity required in the formula connecting the mass with the frequency \( \nu_{0.001} \) (see Section 2.1) but the uncertainties are currently too large to address this issue.

Recent paper of Collin & Hure (2001) claimed a considerable problem with accretion disk luminosity but we did not found any evidence for such an effect (see Appendix A).

However, we note a large discrepancy between the methods in the case of NLS1, with mean masses equal 5.49 from
variability and 7.16 from disk fitting. The power spectra for four out of five objects comes from Hayashida (2000) and they are of low quality, as indicated by large errors given by the author, but better spectra are not available. Higher quality spectrum available for NGC 4051 gives the value of the mass located between the two values provided by the BLR studies which may indicate that the scaling with NGC 5548 which is S1 may be nevertheless appropriate for NLS1 objects. In this case a larger error may be actually connected with the way how we determined the bolometric luminosity which influenced both the luminosity to the Eddington luminosity ratio as the determination of the $M_{BH}^{\text{disk}}$. Our formula (given in Sect. 2) is appropriate for sources either strong in X-rays (as S1 galaxies) or sources with a Big Blue Bump having a maximum in $\nu F_{\nu}$ in UV band, like PG 1211+143 or quasar composite spectrum of Laor et al. (1997). However, for some NLS1 the Big Blue Bump may be located in very far UV or even soft X-rays. One example of such a source (RE J1034+396) was found by Puchnarewicz et al. (1995). In this extreme case the bolometric luminosity estimated from our formula is 6.4 $\times$ 10$^{43}$ erg s$^{-1}$, while direct integration of the broad band spectra would give about 2 $\times$ 10$^{45}$ erg s$^{-1}$, a factor of 30 higher, and the first value would give a black hole mass by a factor of 30 too high. Large error is therefore possible, particularly for sources which are weakly variable in the optical band like NGC 4051, which may also have a Big Blue Bump shifted considerably towards higher energies, although not as high as in RE J1034+396. Therefore, $M_{BH}^{\text{disk}}$ may be sometimes too high while on the other hand the values of $M_{BH}^{\text{disk}}$ for IRAS 13224-3809, 1H 0707-495 and PHL 1092 are clearly too low, leading to extreme super-Eddington luminosities.

Recent results for the X-ray variability of NLS1 galaxy Akn 564 does not solve the issue since only the rising and the flat part of the power spectrum on $\nu \times \text{Power}$ diagram were detected (Pounds et al. 2001) thus giving only a lower limit on the frequency $\nu_{0.01} \sim 10^{-4}$ Hz and subsequently an upper limit on the black hole mass $(10^7 M_{\odot})$ since the monitoring procedure did not allow to study higher frequencies.

Summarizing, the PDS method seems to lead to good black hole mass estimation for normal Seyfert galaxies and QSOs the high quality PDS is available. The conclusion is less firm for NLS1 but this is probably caused by low quality of the available PDS spectra for those objects.

6.3 Luminosity to the Eddington luminosity ratio

The luminosity to the Eddington luminosity ratio for S1 galaxies is $\sim 0.05$ up to 0.07, practically independently from the method used to determine the masses of their central black holes.

Only one source, MCG -6-30-15, has this ratio higher than 0.15. This object is rather exceptional with respect to the properties of its X-ray spectra: it has relatively broad iron Kα line, with a strong red wing (Tanaka et al. 1995, Nandra et al. 1997). MCG -6-30-15 has also very soft spectrum, with a hard X-ray photon index in ASCA data 1.95 and 2.04 in two data sets (Nandra et al. 1997). The $H_{\beta}$ line of MCG -6-15-30 is rather narrow, about 2000 km s$^{-1}$, and the $H_{\beta}$ line also seems quite narrow (Morris & Ward 1988), although the exact value may strongly depend on the de-composition of the line into narrow and broad component. Turner et al. (1999) quote the value of 1700 km s$^{-1}$ after Pineda et al. (1980). Classification of this source should be perhaps reconsidered.

NLS1 galaxies show systematically higher luminosity to the Eddington luminosity ratios (although the strength of this effect depends on the black hole mass measurement method). This is consistent with suggestion of Pounds, Done & Osborne (1995), confirmed by a number of later studies (e.g. Czerny, Witt & Zycki 1996, Wandel 1997, Brandt & Boller 1998, Kuraszkiewicz et al. 2000).

Black hole mass estimate based on the variability method leads for three sources to unrealistic, highly super-Eddington values of the accretion rate. Higher quality power spectra for these sources are clearly needed. Spectral fitting approach lead to much smaller ratios, with mean value 0.18, more than three times higher than for S1 galaxies. NLS1 galaxies have on average higher luminosity to the Eddington luminosity ratio although some NLS1 galaxies have those ratios (usually only slightly) smaller than some of S1 galaxies.

Only NGC 4051 among NLS1 has an exceptionally low luminosity to the Eddington luminosity ratio. The mass determined from the variability seems to be correct for this source, as it is intermediate between the other values quoted in the literature: $H_{\beta}$ study gave $(1.1 - 1.4) \times 10^7 M_{\odot}$, (Peterson et al. 2000), Kaspi et al. (2000) obtained $(1.3 - 1.4) \times 10^7 M_{\odot}$ and Wandel et al. (1999) values were $2.3 \times 10^7 M_{\odot}$ and $1.4 \times 10^6 M_{\odot}$, as given in Table 2. It may be that the source bolometric luminosity is by an order of magnitude underestimated if the broad band spectrum is dominated by the unobserved XUV range. On the other hand Peterson et al. (2000) argue that this source may have relatively narrow $H_{\beta}$ line due to high inclination ($\sim 50^\circ$, Christopoulou et al. 1997) instead of high $L/L_{Edd}$. Better determination of the PDS for this source may resolve this issue.

Two QSO included in our sample have rather high $L/L_{Edd}$ ratios. The black hole mass of 3C 273 based on variability and on our simple spectral fit is smaller than the value determined from detailed spectral fitting (e.g. Leach, McHardy & Papadakis 1995). The problem may be connected with too short monitoring, i.e. the lack of coverage of frequencies close to flattening point and subsequently, a problem with normalization of the PDS. On the other hand, in the Leach et al. (1995) fits the energy required to heat the Comptonizing corona is not included in the computation of the accretion rate, possibly giving too low accretion rate and too high mass. The analysis of longer timescale variability in these sources is clearly needed.

6.4 Spectral states of AGN

There are considerable similarities between the accretion process onto stellar black holes and supermassive black holes: similar range of X-ray spectral slopes (Zdziarski 1999), similar correlation between the normalization of the reflected component and X-ray spectral slope (Zdziarski, Lubinski & Smith 1999) and basically similar featureless PDS (Hayashida et al. 1998). The shape of X-ray PDS for both NLS1 galaxies and normal S1 galaxies look quite similar to the GBH in their hard state.

Detailed comparison of AGN and GBH shows, however, a systematic difference: (i) GBHs in their soft state show very little variability, with rms at a level of a few per
Figure 6. The comparison of the optical power density spectrum times frequency for NGC 5548 (Czerny et al. 1999; disconnected points) with the X-ray power density spectrum of NGC 5548 from Chiang et al. (2000) (histogram: continuous line - XTE; stars connected with continuous line - fit) and for galactic black holes: Cyg X-1 (hard) from Revnivtsev et al. (2000) (open squares connected with continuous line - fit) and XTE (hist: continuous line - XTE; stars connected with dot line). Power density spectra of NGC 5548 were shifted by 6.83 in log(ν) which corresponds to rescaling them to a black hole mass of 10M_{⊙}.

6.5 Black hole to galactic bulge mass ratio

The mass of the central black hole residing in local massive galaxies is well correlated with the mass of the bulge (Magorrian et al. 1998). It suggests a close relation between the host galaxy and the formation, or evolution, of its central black hole. Laor (1998) showed that nearby quasars studied by Hubble Space Telescope follow the same relation.

However, Wandel (1999) studied this relation for Seyfert galaxies and found that they form a similar relation as normal galaxies and quasars but systematically displaced towards small black hole masses. Similar study performed by Mathur et al. (2000) for Narrow Line Seyfert 1 galaxies showed even further displacement towards small black hole masses.

Our mass determination used in Fig. 4 was based on PDS analysis so it was different from method used by Mathur et al. (2000) and Wandel (1999), and mostly performed for other objects. Our results, however, confirm the trends found by those authors - Seyfert galaxies follow basically the relation determined by Wandel but NLS1 galaxies depart from it systematically. The strength of the effect, however, significantly depends on the adopted method of...
black hole mass measurement for NLS1 galaxies: NLS1 are shifted by ~ 1.5 orders of magnitude in Fig. 3 (black hole mass from variability) and it is marginally shifted by ~ 0.5 magnitude in Fig. 4 (black hole mass from spectral fits). We therefore may even neglect the difference between NLS1 galaxies and S1 galaxies and look for a universal relation between the bulge mass and black hole mass for our objects. Spectral black hole mass determination gives

\[ M_{\text{bulge}} \propto M_{\text{BH}}^{\text{disk} 0.82} \]  

(6)
closer to the non-linear relation found recently by Laor (2001). However, without NLS1 galaxies this relation remains linear for our objects even in the case of the black hole mass determination from spectral fits.

The quasar 3C 273 in our analysis follows the relation for Seyfert galaxies.

Recent study of normal galaxies seem to indicate that even for these objects the black hole mass and bulge mass relation is not universal, showing trends with the mass of the galaxy (Merritt & Ferrarese 2000).

6.6 Ionization instability in AGN

Ionization instability, first found to be responsible for the outbursts of cataclysmic variables (e.g. Meyer & Meyer-Hoffmeister 1984, Smak 1984) operates also in binary systems containing accreting neutron stars or black holes. It develops in outer, partially ionized part of the disc. Causing periodically temporary enhancement or suppression of the accretion it leads to transient behavior of many sources in timescales of years (e.g. King 1995). It was suggested that similar instability may operate in AGN (e.g. Clarke & Shields 1989, Siemiginowska, Czerny & Kostyunin 1996, Hatziminaoglou, Siemiginowska & Elvis 2000) although expected timescales are of thousands to millions of years. Such instability may modify the accretion rate in the central parts of the flow thus being responsible for temporary change of the object status from highly active (NLS1) to regular (Seyfert 1) and perhaps quiescence (LINERS) in similar timescales. On the other hand it is not clear that this instability operates in AGN since the self-gravity effects are extremely important in the outer partially ionized parts of discs around massive black holes, leading to significant modification of the disc structure in comparison with discs in low mass objects (e.g. Huré 1998). The fact that NLS1 galaxies and normal Seyfert 1 galaxies have different black hole mass to bulge mass ratio and therefore different evolutionary status argues against the temporary transition between NLS1, S1 and LINER stages and in favor of the self-gravity preventing the ionization instability to operate in AGN. Further studies, however, are needed to confirm this conclusion.

7 CONCLUSIONS

- high frequency part of the PDS is luminosity-independent and can be used to determine the mass of the central object
- Cyg X-1 may be used as a reference object for AGN although systematic differences between AGN and GBH in the appropriate normalization of the PDS up to an order of 0.4 in logarithm are not excluded
- NLS1 galaxies may possibly require another scaling than S1 galaxies
- the \( L/L_{\text{Edd}} \) ratio based on mass determination from PDS has large values for NLS1 galaxies and lower values for most BLS1 galaxies. The effect is still present, although significantly reduced, if complementary black hole mass measurement based on simple spectral fitting is adopted.
- NLS1 galaxies seems to have systematically lower black hole masses in comparison to bulge masses of the host galaxies which supports the conclusion of Mathur (2000) about their different evolutionary status. MCG -6-30-15 occupies its appropriate part of the diagram despite having relatively large \( L/L_{\text{Edd}} \).
- ionization instability operating in cataclysmic variables and X-ray novae probably cannot be responsible for variations of accretion rate corresponding to transitions between NLS1 and BLS1 state over the periods of thousands - millions of years. This instability may be suppressed in AGN by self-gravity effect.

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APPENDIX

In their recent paper Collin & Hure (2001) analyzed the objects from the sample of Kaspi et al. (2000) and they found serious deficiency of the putative accretion disk luminosity in the optical band. Therefore, we checked our approach outlined in Section 3.2 against this sample.

If we assumed the same prescription for the bolometric luminosity as Kaspi et al. (2000), i.e.

\[ L_{bol} = 9 \times L_\nu(5100\AA), \]

determine the accretion rate at the basis of the accretion efficiency \( \eta \)

\[ L_{bol} = \eta M c^2, \]

and adopt the value of the black hole mass from either of the two fits (mean or rms, Equation 9 and 10 of Kaspi et al. 2000), we can calculate the expected monochromatic accretion disk luminosity at 5100 Å, in order to compare it with the observed value.

Expressing \( M \) in solar masses and \( \dot{M} \) in solar masses per year we obtain from Tripp et al. (1994) (see Equation 3) in case of mean mass fit

\[ \log L_{\nu}^{disk}(5100) = 1.03 \log L_\nu^{obs}(5100) - 1.22 - \frac{2}{3} \log(16\eta), \]

and for rms fit

\[ \log L_{\nu}^{disk}(5100) = 0.94 \log L_\nu^{obs}(5100) + 2.56 - \frac{2}{3} \log(16\eta), \]

and for sources at the typical luminosities \( \nu L_\nu^{5100} \sim 10^{44} \text{ erg s}^{-1} \) there is no discrepancy between the disk luminosity and the actual luminosity, contrary to Collin & Hure (2001), if \( \eta = 1/16 \) and \( \cos i = 0.5 \) is assumed, as we did in our consideration. Collin & Hure (2001) adopted \( \eta = 0.1 \) and \( \cos i = 1 \) which partially although not fully explains their conclusion about too low disk luminosity. Applying the top view may actually be correct; however in that case such a factor should be probably included in the formula for the isotropic bolometric luminosity as calculated from the observed flux which will weaken the dependence to the power 1/3.

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