Blue, green, and red bumps in AGN

A. Lawrence
1 Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ

ABSTRACT

I show that the summed spectral energy distribution (SED) \( L(\nu) \) of any extended blackbody radiator will scale in a predictable way if all parts of the body change in temperature by the same factor \( X \), such that \( L'(\nu) = X^3 L(\nu/X) \). This should for example apply to accretion disks around black holes, where \( X \) is relative accretion rate, or external heating rate, but will not apply to changes in black hole mass. I summarise evidence that AGN optical-UV SEDs become progressively redder with decreasing luminosity, and show that the trend in colour versus luminosity shown by Mushotzky and Wandel (1989) is matched extremely well by taking a template high-luminosity SED and scaling it in the manner described above. This agreement is striking because it involves no adjustable parameters. The agreement breaks down at low luminosities because of stellar contamination and reddening. I then consider the colour changes of an individual AGN (NGC 5548) during luminosity changes, which according to the popular X-ray reprocessing model, should follow the scaling law well. However the observed changes are clearly not consistent with the simple scaling prediction. Instead, these colour changes are quite well explained by the mixing of a constant red component and variable blue component. Overall, there is then strong support for the ideas (i) that AGN optical-UV SEDs arise from accretion discs, (ii) that accretion rate plays a significant role in the very large range of luminosity seen in AGN, and (ii) that the inner regions of AGN vary independently of the outer accretion disc.

Key words: galaxies:active – galaxies:quasars:general – accretion – accretion discs.

1 INTRODUCTION

The spectral energy distribution (SED) of a typical quasar is dominated by a broad optical-UV hump normally identified with the emission expected from an accretion disc surrounding a massive black hole, and often referred to as “Big Blue Bump”. The effective power law index (i.e. \( \alpha = -d \log S_\nu / d \log \nu \)) is \( \alpha \sim 0 \) in the optical region, steepening to \( \alpha \sim 1 \) in the UV (see for example the compilation of Elvis et al. (1994)). The composite spectrum of high redshift quasars compiled by Zheng et al. (1997) shows that the spectral index steepens further to \( \alpha \sim 2 \) in the far UV, and this seems consistent with extrapolation to the soft X-ray excess visible in most quasars.

Not all Active Galactic Nuclei (AGN) are the same however. Figure 1 compares the SEDs of three AGN. The first is the luminous quasar 3C273, which shows the characteristic UV Bump as described above. The curve shown is actually a model fit to optical, UV, and soft X-ray data by Kriss et al. (1999), which excludes the line emission and “small blue bump” composed of Balmer continuum and quasi-continuum of FeII lines. (The model curve is that in Fig. 8 of Kriss et al. and was kindly provided by G. Kriss). The second AGN is the Seyfert galaxy NGC 5548. This object is both variable and includes substantial starlight emission in the low state. The data points shown in Figure 1 represent the optical-UV mean of Rokaki and Magnan (1992) together with the near-IR data of Ward et al. (1987), after correcting for starlight emission following the data of Romanishin et al. (1995). The curve shown is a log-quadratic hand-fitted to the data points for illustrative purposes. Note that the U-band and 2670Å points certainly contain substantial “small blue bump” emission. I have not quantitatively modelled this; the curve shown is only a qualitative indication of the likely underlying continuum. The result is that the NGC 5548 Bump seems similar to that of 3C273 but shifted to lower frequency - more of a “Big Green Bump” than a “Big Blue Bump”. Finally, the third curve shown is the SED of the dwarf Seyfert nucleus in M81. The data has been adapted from the tables and figures of Ho, Filippenko and Sargent (1996), who applied a de-reddening using the ratios of observed narrow emission lines. The optical emission is from...
an unresolved point source in HST imaging, and so seems to be truly nuclear, with negligible starlight. This SED, with a UV slope of $\alpha \sim 2$, is quite different from that of luminous quasars, and indeed Ho, Filippenko and Sargent stress that dwarf Seyferts may not be completely analogous to luminous quasars. However, the optical slope seen in M81 is strikingly similar to that seen in the far-UV for luminous quasars, leading one to speculate that it too has a Bump, but shifted to much lower frequency - a “Big Red Bump”? That the continuum shape of AGN varies slowly and systematically with luminosity has been argued several times by previous authors. Figure 2 shows data collated by Mushotsky and Wandel (1989), demonstrating that optical slope varies with optical luminosity, ranging from $\alpha_{\text{opt}} \sim 0$ at the highest luminosities, through $\alpha_{\text{opt}} \sim 1$ in the Seyfert galaxy range, to $\alpha_{\text{opt}} \sim 2$ for very low luminosity AGN. (Starlight contamination and reddening is undoubtedly important in this figure; I consider this in more detail in Section 3.) A similar effect was shown in the RIXOS sample by Puchnarewicz et al (1996) and an analogous effect for UV slope was shown by Zheng and Malkan (1993).

There are also arguments against the whole AGN SED shifting bodily with luminosity. From an observational point of view, the fact that broad emission line ratios change little with luminosity means that the FUV/soft-X-ray spectrum cannot change much. From a theoretical point of view, the fact that broad emission line ratios change little with optical luminosity, but this is least likely to apply shortward of the SED peak, as I explain in Section 3. Nonetheless the evidence concerning the systematic trend of optical colour with luminosity is very clear, and scaling of accretion disc properties seems the best possibility to explore. (Other possible explanations of the colour-luminosity trend are considered in Section 5.)

The hypothesis I explore then in this paper is that this luminosity dependence of AGN is due to a quasi-universal SED which shifts to increasing frequency with increasing luminosity, and which results from the expected behaviour of accretion discs. Such shifting is qualitatively what one expects of a blackbody emitter changing temperature, but of course accretion discs are not single temperature objects, and their expected SEDs are still somewhat controversial, so this needs a little thought. In section 2 I derive a scaling law for the behaviour of multi-temperature blackbodies, and discuss how this applies to accretion discs. In section 3 I compare the predicted behaviour with that seen in the AGN data. In section 4 I ask whether the same behaviour applies to individual AGN during variability. Finally in section 5 I discuss the general implications for AGN models.

2 COLOUR-LUMINOSITY SCALING FOR BLACK-BODY EMITTERS

2.1 Black body scaling with temperature

As a blackbody changes temperature, it shifts in frequency and also scales in brightness. This shifting can be expressed as a simple scaling law that is very useful when we come to consider objects that emit the sum of many blackbodies. Consider the blackbody function

$$R(\nu, T) = \frac{2\pi h\nu^3}{c^2 (e^{h\nu/kT} - 1)}$$

Suppose initially the temperature is $T_0$ and then changes by a factor $X$ so that $T = XT_0$. Then

$$R(\nu, T) = \frac{2\pi h\nu^3}{c^2} \left[ \exp\left( \frac{h \nu}{kX T_0} \right) - 1 \right]$$

Let $\nu/X = \nu_0$; then

$$R(\nu, T) = \frac{2\pi h}{c^2} \nu_0^3 X^3 \left[ \exp\left( \frac{h \nu_0}{kT_0} \right) - 1 \right]$$

i.e. $R(\nu, T) = X^3 R(\nu_0, T_0)$ or

$$R_T(\nu) = X^3 R_{T_0}(\nu) = \frac{\nu}{X}$$

Thus blackbody SEDs show a kind of homologous scaling with temperature. The equation above can be interpreted as follows. If you know (numerically) the blackbody function at some temperature $T_0$, then the equation gives a recipe for creating the function at any other temperature $T$ step by step at each frequency.

2.2 Multi-temperature black bodies

We can show that under certain simple conditions, an object emitting as the sum of blackbodies follows the same homologous scaling law as derived above for single blackbodies. Consider two distinct regions. The first has area $A_1$ and is at temperature $T_1$. At frequency $\nu$ it will have an SED given by $L'_1(\nu) = A_1 R_{T_1}(\nu)$. Now suppose that its temperature changes by a factor $X_1$ to become $T'_1 = X_1 T_1$. Following equation (1) the new SED will be given by $L'_1(\nu) = A_1 X_1^3 R_{T_1}(\nu/X_1)$.

Likewise area $A_2$ at temperature $T_2$ has SED $L_2(\nu) = A_2 R_{T_2}(\nu)$, but when its temperature changes by factor $X_2$ then its SED becomes $L'_2(\nu) = A_2 X_2^3 R_{T_2}(\nu/X_2)$. Now we consider the summed emission. Before the temperature change this is

$$L(\nu) = A_1 R_{T_1}(\nu) + A_2 R_{T_2}(\nu)$$

$$L(\nu) = A_1 X_1^3 R_{T_1}(\nu/X_1) + A_2 X_2^3 R_{T_2}(\nu/X_2)$$

This shows that under certain conditions, the summed SED also scales homologously, with the same scaling law as the individual contributions.
and after the temperature change it is

\[ L'(\nu) = A_1 X_1^3 R T_1 \left( \frac{\nu}{X_1} \right) + A_2 X_2^3 R T_2 \left( \frac{\nu}{X_2} \right) \]

Now if \( X_1 = X_2 = X \) then

\[ L'(\nu) = X^3 \left( A_1 R T_1 \left( \frac{\nu}{X} \right) + A_2 R T_2 \left( \frac{\nu}{X} \right) \right) \]

and so

\[ L'(\nu) = X^3 L(\nu/X) \] (2)

By repeated addition one can see that our scaling law applies to any sum of blackbodies, with many sub-areas at various temperatures, as long as each sub-area changes temperature by the same factor \( X \). The beauty of this is that one does not need an analytic expression for \( L(\nu) \), or even an understanding of its origin - only a reasonably fine grained measurement of it. Given this “template” SED, one can numerically construct any other SED given a uniform temperature change by a factor \( X \). But is this restricted scenario of uniform temperature change relevant to the accretion disc problem?

### 2.3 Expected behaviour of accretion discs

Sophisticated accretion disc models have been developed and applied to AGN for some years (e.g. Sun and Malkan 1986). My aim here however is to draw out the basic points to see whether or not homologous scaling will apply.

To a good approximation, an accretion disc is the sum of many blackbodies. The temperature at radius \( R \) will be of the order of that given by the local release of binding energy

\[ T_{BE}(R) = \left( \frac{G M_H \dot{m}}{8\pi R^3 \sigma} \right)^{1/4} \]

where \( M_H \) is the central black hole mass, \( \dot{m} \) is the accretion rate and \( \sigma \) is the Stefan-Boltzmann constant. The correct \( T(R) \) formula depends on the physical model - for example assuming Newtonian dynamics and zero stress at an inner boundary \( R_* \) gives

\[ T^4 = T_{BE} \left( 1 - \left( \frac{R_*}{R} \right)^{1/2} \right) \]

(Frank, King and Raine 2002 p.90, Krolik 1999, p.148). However, the scaling with \( M_H \) and \( \dot{m} \) is just the same. If for example \( \dot{m} \) changes by a factor \( Y \), the temperature changes by the same factor \( X = Y^{1/4} \) at all radii, and we should expect to witness homologous scaling of accretion disc SEDs under changes of accretion rate.

At first, it seems that the same effect should apply to changes in black hole mass, but not when one considers the boundary condition, which is that the inner radius of the disc will change with \( M_H \). When changing from a small black hole to a large one, it is not the case that all annuli change temperature by the same factor, as the innermost radii cease radiating at all. The maximum temperature will be lower, and hence the peak frequency lower, and in this sense the SED from a large black hole looks “cooler” than the radiation from a small black hole. It is still the case that at each radius, the temperature gets larger with increasing black hole mass. One might therefore hope that if one was looking at wavelengths where the radiation is not dominated by

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**Figure 2.** Correlation between narrow band optical luminosity, measured at 4200Å, and spectral index between 4200Å and 7500Å. The data points are taken from Mushotzky and Wandel (1989). The two curves are the tracks predicted by taking SEDs of 3C273 and H1946+786 respectively, and shifting them homologously as expected for a multi-temperature black body, as explained in the text. Also shown is a reddening vector assuming standard Galactic reddening, and the high and low states of NGC 5548, both before and after starlight subtraction (see text).
emission from the inner radii, then the homologous scaling would still work. However a little numerical experimentation shows that this is not the case. Figure 3 shows some toy models of accretion disc emission using the simple $T_R C$ formula. This confirms that the homologous scaling works quite accurately for changes in accretion rate, but that changes in black hole mass produce an effect very different from homologous scaling. The manner in which mass changes alter the SED will depend on the actual $T(R)$ formula, and so is model dependent, but the accretion rate scaling should be generally applicable. Some similar experimentation with full relativistic modelling of accretion disks (Malkan 1991) shows a similar result - a homologous scaling with accretion rate, but not with black hole mass.

The above analysis applies to gravitationally heated discs, but a very similar argument applies to passive discs with an external heating source. For example, a flat passive disc which is heated by a point source of luminosity $L_*$ at a height $H$ above the disc will have a temperature profile given by

$$T(R) = \left(\frac{H}{8\pi\sigma} \frac{L_*}{R}\right)^{1/4}$$

For changes in heating rate $L_*$, the temperature will change by the same ratio at all radii, and so one expects homologous scaling.

So what are the limits on the applicability of homologous scaling to accretion discs in AGN? The first issue is the degree to which the radiation from an accretion disc will be blackbody like. Through most of the SED, this will be a good approximation - as with stars, disk atmosphere effects will be a second order affair. However at high frequencies, over the peak of the SED, this may not be the case, with Compton scattering and other effects producing an extended tail. The second issue is that most simple models assume some kind of heating and radiation on the spot. This is most likely to break down in the inner radii. Overall the expectation that accretion discs should show homologous scaling is quite good, and most likely to apply at wavelengths longward of the Big Blue Bump peak, i.e. in the optical and near ultraviolet, and not in the far ultraviolet or soft X-ray. The most likely parameters causing scaling effects will be accretion rate or heating rate. Varying black hole mass will not produce homologous scaling.

3 COMPARISON WITH DATA

3.1 The colour-luminosity relation

From our scaling law, we construct a recipe for calculating the spectral index between two fixed wavelengths as a function of the monochromatic luminosity at one of those wavelengths. The starting point needed is a numerical estimate of the SED of one particular actual quasar, $L_0(\nu)$. Then, using equation (2), other objects will have SED $L(\nu) = X^4 L_0(\nu/X)$ where $X$ is some unknown factor which controls temperature at each radius. Consider two fixed frequencies $\nu_1$ and $\nu_2$. The observed flux ratio as a function of $X$ will be

$$R_X = \frac{L(\nu_1)}{L(\nu_2)} = \frac{L_0(\nu_1/X)}{L_0(\nu_2/X)}$$

(3)

So starting with the observed $L_0(\nu)$ and varying $X$ one generates a sequence of points $(R_X, L_X(\nu_1))$ which can be plotted on the colour-luminosity plane.

I chose two observed template SEDs for high luminosity quasars. The reason for choosing two is that there is some dispersion in the observed SEDs of AGN at any given luminosity, and one wants to bracket the observed range. The first template SED is that of 3C273, using the model fit of Kriss et al (1999) as shown in Figure 1. This does not mean we are testing the specific model assumptions of Kriss et al - the curve is simply a convenient smooth curve that approximates well to the observed data. The second template SED is that of H1946+786 given in Kuhn et al (1995). As this quasar is at high redshift, there is some uncertainty about the high frequency correction to be applied. Kuhn et al show a range of such corrections. We choose the curve which gives a high frequency SED similar to the average found by Zheng et al (1997). (This makes little difference in the optical wavelength range). The curve was digitised from the plot in the Kuhn et al paper.

As we start at high luminosity, constructing a locus to lower luminosity involves values $X < 1$. Fig.2 shows the loci starting from the two templates at $X = 1$ through to values of $X = 0.01$. The two loci each re-produce the general trend of colour with luminosity, and even the curvature in the relation. Between the two templates, the range of SEDs is well covered. Although the agreement is not perfect, it is quite remarkable in one important respect : given a particular starting template, the locus has no free parameters whatsoever. It is a strict and simple prediction on the assumption that the SED is made of many blackbodies, and that we are well away from boundary conditions.

The fit seems least good at very low luminosities, but this may be expected for a number of reasons. First, the Bump is shifted so far to low frequencies that even at optical wavelengths we are looking over the peak at radiation probably produced in the inner regions. Second, the colours may be affected by reddening. Indeed, reddening could of
course broaden the locus at all luminosities. Fig. 2 shows a standard reddening vector to indicate this effect. Finally, even though Mushotzky and Wandel (1989) used small slit observations, there is very likely to be residual starlight affecting these data. For the Seyfert galaxy NGC 5548, the stellar contribution has been well studied (Romanishin et al. 1995). Figure 2 displays NGC 5548 data with and without the starlight correction, showing that the effect is about the right size to produce the divergence of the bulk of the data points from the locus prediction.

In summary, at luminosities of $L_{\text{opt}} = 10^{29}$ erg s$^{-1}$ Hz$^{-1}$ and less, a variety of effects makes it hard to come to a clear conclusion, but above this luminosity there is quite a strong case that the gross trend of colour with luminosity is caused by some kind of homologous scaling effect, caused for example by accretion rate varying by several orders of magnitude. The range of colours at a fixed luminosity could correspond to differing black hole masses, inclination effects, or to a relatively modest range of reddening.

### 3.2 Absolute SED comparisons

We can illustrate how the homologous scaling links high luminosity and low luminosity AGN by directly comparing the SEDs of 3C273 and M81. The optical-UV spectrum of M81 is well known for being very different from high luminosity AGN, showing $\alpha = 2$ as opposed to $\alpha = 0$ – 1. At longer wavelengths, it is not clear when small aperture nuclear measurements really are measuring quasar-like emission as opposed to normal stellar and stellar-related emission. Fig. 4 shows the effect of scaling the SED of 3C273 with $X = 0.03$. This produces a remarkably good fit to the mid-IR and optical data on M81, with the near-IR data looking like a stellar excess over this emission. (Note however that both near-IR and mid-IR points are essentially upper limits to the true nuclear emission.) The simplest bet for the mystery factor $X$ is of course accretion rate. The implication would be that the nucleus of M81 is essentially the same as 3C273 but with accretion rate lower by a factor $(1/0.03)^4$, in other words by roughly a factor of a million.

The fact that this exercise gives roughly the right answer must be important. However the impressively good fit should be taken with a pinch of salt, for several reasons. (i) The figure shows the soft X-ray emission from 3C273 matching on to the optical-UV emission for M81, but the soft X-ray emission is unlikely to be made up of multiple black-bodies, and so shouldn’t in itself show the homologous scaling. However, as it hangs off the peak of the SED, if the optical-UV emission scales, the soft-X-ray emission will fall roughly into place. (This does however suggest that the soft X-ray is somehow physically connected to the blackbody disc emission.) (ii) Figure 4 also shows the SED of NGC 5548 and an attempt to match a scaled version of 3C273 with $X = 0.21$. This is less impressive than the fit with M81 but still plausible. The comparison is complicated by the well known variability of NGC 5548. Figure 4 shows low, mean and high states from the extensive NGC 5548 AGN Watch literature. (All of these SEDs have been corrected for starlight.) The component which scales is presumably the non-varying part. (iii) The black holes in 3C273 and M81 may have different masses. Paltani and Turler (2003) estimate a mass of $10^8 M_\odot$ for 3C273, and Devereux et al (2003) give $7 \times 10^7 M_\odot$ for M81. Of course this difference of one order of magnitude is dwarfed by the possible six orders of magnitude in accretion rate. (iv) Finally, scaling the SED of H1946+786 doesn’t fit nearly so well. For simplicity, I don’t show this.

Overall, these tests support the idea that homologous scaling plays an important part in AGN SEDs, but also show clearly that it will not explain all the facts.

### 4 COMPARISON WITH AGN VARIABILITY DATA

There is a second well known colour-luminosity effect in AGN. Individual objects vary in luminosity by a factor of several, and become bluer as they become brighter. The best studied example is the Seyfert galaxy NGC 5548 (Clavel et al 1991; Peterson et al 1991; Krolik et al 1991). A well known puzzle in this variability behaviour is that variations occur more or less simultaneously at different wavelengths, whereas viscous effects should produce delays on the order of hundreds to thousands of years, and even instabilities should travel at sound speed, producing delays of the order of years. This led to the suggestion that AGN optical-UV emission actually arises from a passive disc heated by the central X-ray source or the inner disc (Krolik et al 1991) in which case variations are transmitted at light speed. For a fixed disc geometry such driving variations in the central source heating should then produce colour-luminosity changes that fit the predicted locus from homologous scaling.

Fig 2 shows the variability range for NGC 5548. Here I have taken the optical high and low states from Paper II of the AGN Watch series on NGC 5548 (Peterson et al 1991), at JD2447645 and JD2447574 respectively. The optical spectral index $\alpha_{\text{opt}}$ was calculated using the ratio of fluxes at 4300Å and 5800Å, and $L_{\text{opt}}$ calculated using the flux at 4300Å. The data in Peterson et al are reduced to a standard AGN Watch aperture. Starlight in the standard aperture was estimated by Romanishin et al (1995) at a wavelength of 5100Å. I extrapolated to other wavelengths using the standard bulge starlight colours of Ward et al (1987). It is clear that in the optical range, the starlight contribution through typical apertures in NGC 5548 is quite substantial, which in itself
can lead to the object being bluer when brighter. However, even for the starlight corrected data, the change in colour with brightness is very steep, and is clearly inconsistent with our predicted multi-temperature black-body track. In the UV, where the effect of starlight is negligible, the change of colour with brightness is also steep. If then the emission from NGC 5548 originates from an extended multi-temperature blackbody, it is not the case that all the parts of that extended body vary together, as one would expect with the X-ray source reprocessing model. (A similar conclusion was drawn by Berkeley, Kazanas, and Ozić (2000) in their attempt to model the simultaneous X-ray and UV monitoring data for NGC 7469.)

The variability of NGC 5548 can in fact be quite well explained by a simple mixing model, with a fixed cool component and a varying blue component, as explained in the text.

5 DISCUSSION

The arguments presented here do not confront specific accretion disc models, but support the generic idea that AGN SEDs are dominated by an extended object radiating as the sum of blackbodies. The recent results of Rokaki et al (2003) on aspect dependence of superluminal sources support the generic idea of a flat emitter, and those of Kishimoto et al (2003,2004) show the polarised Balmer edge absorption expected from an atmosphere above such a flat object. These results taken together strongly support the simple idea of accretion discs. Beyond this I have argued that most of the trend seen in the $\alpha - L$ diagram is due to differences in accretion rate, not differences in black hole mass. We are left with the challenge of explaining the variability seen. Beyond these simple statements, there are still significant problems and further work needed.

Is the SED peak really moving? The argument made in this paper rests mainly on the general trend of colour versus luminosity for the population of AGN, rather than detailed analysis of SEDs. If homologous scaling applies to the whole SED, then the peak of the SED should be shifting in frequency through the easily observable optical region in the lower end of the Seyfert galaxy range. With reasonably complete SEDs for a range of objects this should be a testable hypothesis, and a good target for future work. However we can expect some complications that may muddy this simple test. Starlight, small blue bump, and reddening will all need to be accounted for; and it is only at wavelengths longward of the peak that we are reasonably confident that scaling will apply. The inner regions may not be simple blackbodies; heating on the spot may break down; and the central variable component may not scale.

Can the $\alpha - L$ trend be explained by other effects? Starlight contamination, variability, and reddening are all clearly important. Is it possible that one or more of these effects themselves vary slowly with luminosity, producing the effect we see? This is most obviously a worry for starlight contamination. I have argued in section 3.1 that this effect is only important in the lower half of Fig. 2, and so does not explain the trend at higher luminosity. What about reddening? It has been previously suggested by Puchnarewicz et al (1996) and Gaskell et al (2004) that variation of reddening with luminosity is precisely what causes the colour-luminosity trends we have been discussing here. This is indeed a tenable alternative hypothesis. The main argument against it is the "fine tuning" worry - one has to postulate a reddening screen, and have its thickness vary very slowly with luminosity in just the right manner, for an unknown reason, whereas the tracks we have predicted in Fig.2 follow from the chosen template SEDs with no adjustable parameters. An attractive possibility is that the trend shown by the lower envelope of the points corresponds to the homologous scaling effect, whereas the observed vertical spread of the points is due to a range of reddening at each luminosity. Rather than the minimum reddening varying with luminosity, what probably alters is the probability of large reddening. Finally another possible explanation of the colour-luminosity effect is that the optical-UV continuum may be made of two components - for example, an accretion disc and an underlying power law, with the relative strengths of these varying with luminosity - the so-called "fading bump"
idea. This has been discussed by a number of authors (e.g. Zheng and Malkan 1993; McDowell et al. 1989; Carleton et al. 1987; Ward et al. 1987). As with the reddening trend model however, there is no obvious natural reason to produce just the right fading of blue bump strength with luminosity.

Can we separate mass and accretion rate effects? AGN range in luminosity over six orders of magnitude. What causes this range? Simple considerations, and the toy modelling in Fig. 3, suggest that changes in accretion rate will produce homologous scaling, whereas changes in black hole mass will not. The agreement of the scaling prediction with the data of Figs. 2 and 4 therefore suggests that accretion rate is a significant and perhaps even dominant factor in determining luminosity. There is a large vertical spread in Fig. 2 which could be due to differences in black hole mass. However there are several other likely causes of the vertical spread - reddening, variability, and starlight. Possibly understanding these better would restrict the range of allowed black hole mass considerably. An obvious programme of work is to produce $a - L$ tracks for changes in black hole mass, to compare and contrast with the homologous scaling tracks. Unlike the accretion rate effect, the result would be dependent on the detailed physical model, and in particular the correct $T(R)$ formula. The point of this paper is to examine the most model independent factors possible, so I don’t attempt this here.

Other available evidence suggests that the range in AGN luminosity is due in roughly equal measure to black hole mass and accretion rate. The first type of evidence is from accretion disc model fitting to AGN SEDs. For example, Fig. 2 from Szuszkiewicz, Malkan, and Abramowicz (1996) compiles results from a variety of papers and shows a range of about $10^5$ in fitted values for both mass and accretion rate. The second kind of evidence concerns dynamical mass estimates. Several tens of AGN now have fairly reliable mass measurements from reverberation studies (Kaspi et al. 2000; Peterson et al. 2004). These studies find that Seyfert galaxies and quasars have masses in the range $10^{7-9} M_\odot$ whilst covering four decades in luminosity. Kaspi et al quantify the relationship between mass and luminosity. Using three related methods they find that $M \propto L^{\beta}$ where $\beta = 0.16, 0.40$, and 0.55. Scott et al (2004) find a large scatter in far-UV slopes in a recent FUSE study of 100 AGN, and attribute this to AGN having a large range in both mass and accretion rate. Amongst very low luminosity “dwarf Seyferts”, there are few reliable mass estimates. M81 has a mass of the same order as luminous AGN (Devereux et al. 2003), but NGC 4395 is thought to have a very small mass, of the order $10^8 M_\odot$ (Lira et al. 1999; Kraemer et al. 1999; Shih et al. 2003). However including this object also extends the luminosity range even further, so we would be talking about four orders of magnitude of mass compared to eight orders of magnitude in luminosity. NGC 4395 is also quite blue despite having a very low luminosity, going against the trend of Fig. 2, as one might expect with a very small mass.

Can accretion disc models explain the observed variability? The nature of the optical-UV variability remains the most worrying and puzzling feature of AGN. Its steep colour dependence and simultaneity at different wavelengths cannot be explained by standard accretion disc models (Krolik et al. 1991) The usual explanation accepted for a decade was heating of a passive disc by the central X-ray source, but this model can now be rejected, firstly by the lack of the expected UV - X-ray variability correlation (e.g. Nandra et al. 1998; Berkeley, Kazanas, and Ozik 2000), and now by the lack of the expected colour-luminosity scaling behaviour. In section 5, I demonstrated that the observed colour variations can be quite well modelled by mixing a constant red component and a variable blue component. Can this be explained in the context of accretion discs? It seems reasonable that in fact the inner annuli of an accretion disc may vary on a short timescale while the outer annuli remain much the same. Krolik et al. (1991) attempt to construct the power spectrum of variability in this way by allowing the frequency of oscillations from different rings to vary with the orbital timescale of each ring, so that optical variability for example mostly varies on a timescale of months, whereas UV variability is on a timescale of days, with the optical tail of emission from the hot inner rings producing a small amplitude of variability on such timescales. However, as Krolik et al explain in their section 4.5.4, even within a small range of inner radii, significant delays between different wavelengths are expected for fluctuations transmitting at sound speed or even at orbital speed. Their proposed solution is hard photons from the inner disc being reprocessed in the outer disc, producing co-ordinated fluctuations. However, we are then back to square one, as such fluctuations due to changes in heating rate should follow the locus discussed in this paper. One more alternative is to abandon the accretion disc paradigm somewhere in the middle regions, so that we can mix a static accretion disc with a central source of unknown nature that is variable and has a broad SED.

A final possibility that has sometimes been mentioned (e.g. Gaskell et al. 2004) is that the optical-UV variability is not intrinsic, but due to a changing reddening screen. This certainly gives roughly the right slope in the colour-luminosity plane, but a cloud crossing the nucleus would occult different parts of the disc at different times, giving wavelength dependent delays. A model of this type would therefore need to involve radial changes in extinction, perhaps as a result of changing amounts of dust condensing in an outflowing wind.

6 CONCLUSIONS

Multi-temperature black-bodies should show a characteristic scaling behaviour when all regions of the body change temperature by the same factor. For black hole accretion disc models, we expect such a scaling to apply for changes of accretion rate or external heating rate, but not for changes of black hole mass. The trend in optical colour for AGN over a very wide range in luminosity seems to be well fitted by such homologous scaling of the AGN SED. Several other effects significantly affect AGN colours - starlight contamination, reddening, and variability. Separating all these effects is extremely difficult. Nonetheless, the trends over a very wide range in luminosity seem clear. The scaling effect seen applies only on average, amongst the population of AGN. From one typical object to another, other effects - black hole mass, variability, starlight, and reddening, are much more likely to cause differences. Within a single object, changes of colour with luminosity are not consistent with the expected scaling
at all - during variability it is clearly not the case that all the parts of the object vary together, as one would expect in the X-ray reprocessing model. Instead, variability seems consistent with mixing a static component, which could be identified with the accretion disc, with a variable blue component, whose nature is unknown.

Overall a number of considerations strongly support the general idea of accretion discs in AGN. The glaring exception is the optical-UV variability, and especially its simultaneity at different wavelengths, which remains puzzling.

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