High-redshift galaxies, their active nuclei and central black holes

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ABSTRACT

We demonstrate that the luminosity function of the recently detected population of actively star-forming galaxies at redshift three and the B-band QSO luminosity function at the same redshift can both be matched with the mass function of dark matter haloes predicted by standard variants of hierarchical cosmogonies for lifetimes of optically bright QSOs anywhere in the range $10^6$ to $10^8$ yr. There is a strong correlation between the lifetime and the required degree of non-linearity in the relation between black hole and halo mass. We suggest that the mass of supermassive black holes may be limited by the back-reaction of the emitted energy on the accretion flow in a self-gravitating disc. This would imply a relation of black hole to halo mass of the form $M_{bh} \propto v_{halo}^5 \propto M_{halo}^{5/3}$ and a typical duration of the optically bright QSO phase of a few times $10^7$ yr. The high integrated mass density of black holes inferred from recent black hole mass estimates in nearby galaxies may indicate that the overall efficiency of supermassive black holes for producing blue light is smaller than previously assumed. We discuss three possible accretion modes with low optical emission efficiency: (i) accretion at far above the Eddington rate, (ii) accretion obscured by dust, and (iii) accretion below the critical rate leading to an advection dominated accretion flow lasting for a Hubble time. We further argue that accretion with low optical efficiency might be closely related to the origin of the hard X-ray background and that the ionizing background might be progressively dominated by stars rather than QSOs at higher redshift.

Key words: galaxies:formation,nuclei — quasars:general — black hole physics

1 INTRODUCTION

For three decades optically bright QSOs were our only beacons in the high redshift universe. Soon after the discovery of QSOs it became clear that their comoving space density increases dramatically up to redshift two to three. Larger systematic surveys confirmed early suggestions that this evolution is reversed at even higher redshift and established an epoch of optically bright QSO activity with a peak around redshift $z=2.5$ (Schmidt, Schneider & Gunn 1994; Warren, Hewett & Osmer 1994; Shaver et al. 1996; McMahon, Irwin & Hazard 1997). QSO activity is widely believed to be the result of accretion onto super-massive black holes at the centre of galaxies (e.g. Rees 1984 and references therein) and a number of authors have linked the change in QSO activity to a corresponding change in fuel supply at the centre of the host galaxies (Cavaliere & Szalay 1986; Wandel 1991; Small & Blandford 1992; Yi 1996). Haehnelt & Rees (1993; HR93 henceforth; see also Efstathiou & Rees 1988) recognized that the epoch of QSO activity coincides with the time when the first deep potential wells form in plausible variants of hierarchical cosmogonies.

The past few years have seen dramatic improvements in detecting ordinary galaxies and starbursts out to $z \gtrsim 3$, transforming our knowledge of galaxy and star formation in the high redshift universe. There are also far more extensive data on the demography of supermassive black holes in nearby galaxies, and on low level activity of AGN both in the optical and the X-ray bands. We discuss here some implications for the formation and evolution of active galactic nuclei, attempting to tie these lines of evidence together in a consistent model.

The paper is organized as follows. In section 2 we discuss the general framework used to relate the luminosity function of QSOs and star-forming galaxies to the mass function of dark matter (DM) haloes. Section 3 focuses on constraints on the accretion history of supermassive black holes. Section 4 summarizes observational implications and Section 5 briefly discusses the respective role of stars and QSOs for the re-ionization history of the inter-galactic medium. Section 6 contains our conclusions.
and without a cosmological constant and standard CDM model, ΛCDM and OCDM are open models with the low redshift universe on galaxy and cluster scales. SCDM is a Jenkins et al. (1997) to comply with observational constraints in the low redshift universe on galaxy and cluster scales. In Fig. 1 we plot the mass function of DM haloes at z\(=3\), the mass functions of these objects can be obtained assuming a linear relation between star formation rate and halo mass, i.e. a constant mass-to-light ratio. In Figure 2a we plot such a fit for the SCDM model. A weakly non-linear relation is also consistent with the data and would indeed be required to match the shallow slope of the luminosity function at the high luminosity end reported recently by Bershady et al. (1997). The fits obtained for the other CDM variants are of the same quality. Note, however, that the observed \(H_\alpha\) widths of these galaxies, \(\sigma \sim 80\,\text{km s}^{-1}\) (Pettini et al. 1997), might be in conflict with the virial velocities of 300 km s\(^{-1}\) quoted above.

2.1 The space density of dark matter haloes

It is widely believed that the matter distribution in the universe is dominated by dark matter and that the gravitational growth of density fluctuations created in the early universe is responsible for the formation of the observed structures. The strongest constraints on the fluctuation amplitude of the DM density field on small scales comes from the observed space density of rich galaxy clusters which probe only slightly larger scales than we are interested in here (White, Frenk & Efstathiou 1993). We therefore take the four variants of cold dark matter (CDM) models chosen by Jenkins et al. (1997) to comply with observational constraints in the low redshift universe on galaxy and cluster scales as a representative sample of viable models (for parameters see Table 1).

The Press-Schechter formalism gives simple but still reasonably accurate estimates of the space density of DM haloes. In Fig. 1 we plot the mass function of DM haloes at \(z=3\) for the four models. As expected the mass function is essentially a power-law at small masses and falls off exponentially at the high mass end. While at \(z=0\), the mass functions for the different models are, by design, very similar, at \(z=3\) the characteristic turnover mass in the mass function differs considerably between the models. In the next two sections we will explore the link between star-forming galaxies and QSOs at high redshift, assuming that both populations trace the mass function of DM haloes.

2.2 Matching the luminosity function of high-redshift galaxies

Steidel and collaborators (Steidel & Hamilton 1992; Steidel, Pettini & Hamilton 1995; Steidel et al. 1996; Giavalisco, Steidel & Macchetto 1996) detected a population of actively star-forming galaxies at redshift 2.5 to 3.5 with a space density of about \(10^{-2}\,\text{h}^3\,\text{Mpc}^{-3}\) — similar to that of present-day galaxies — and star formation rates of order \(1-100\,M_\odot\text{yr}^{-1}\). The optical observations carried out correspond to the rest-frame UV and probe the star formation rate rather than the integrated stellar light. Little is known about the masses of these objects and the relation of their mass to the rate of detected star formation. As Figure 1 demonstrates, the space density of these star-forming galaxies corresponds to those of haloes with masses of \(10^{12-13}\,M_\odot\) and virial velocities of \(300\,\text{km s}^{-1}\) 70 km s\(^{-1}\) (see also Baugh et al. 1997). Further evidence for masses of this order comes from the strong clustering of these galaxies (Steidel et al. 1997, Bagla 1997, Jing & Suto 1997, Frenk et al. 1997, Peacock 1997). A reasonable fit to the luminosity function of these objects can be obtained assuming a linear relation between star formation rate and halo mass, i.e. a constant mass-to-light ratio. In Figure 2a we plot such a fit for the SCDM model. A weakly non-linear relation is also consistent with the data and would indeed be required to match the shallow slope of the luminosity function at the high luminosity end reported recently by Bershady et al. (1997). The fits obtained for the other CDM variants are of the same quality. Note, however, that the observed \(H_\alpha\) widths of these galaxies, \(\sigma \sim 80\,\text{km s}^{-1}\) (Pettini et al. 1997), might be in conflict with the virial velocities of 300 km s\(^{-1}\) quoted above.

2.3 Matching the luminosity function of optically selected QSOs at high redshift

The space density of optically selected QSOs at \(z=3\) with \(M_B < -23\) is smaller than that of the detected star-forming galaxies by a factor of a few hundred. It is therefore less obvious how to match the mass function of DM haloes with the B-band luminosity function of QSOs. As demonstrated by HR93 the well-synchronized evolution of optically selected QSOs can be linked to the hierarchical growth of DM haloes on a similar timescale if the duration \(t_Q\) of the optically bright phase is considerably shorter than the Hubble time. The comoving space density of DM haloes hosting QSOs then exceeds that of observed QSOs by a factor \(1/t_Q\,\Omega^{1/2}H_0(1+z)^{5/2}\) where we have assumed that one new generation of haloes forms per unit redshift. For small \(t_Q\) this comes more and more in line with the predicted space density of DM haloes and that of star-forming galaxies at high redshift. However, hardly is anything known about the masses of the host objects of optically selected QSOs and this still leaves considerable freedom in the exact choice of \(t_Q\). Following the approach of HR93 we estimate the forma-

### Table 1. The model parameter of the CDM variants explored:

| MODEL    | \(\sigma_8\) | \(h\) | \(\Omega_0\) | \(\Omega_\Lambda\) | \(\Gamma\) |
|----------|---------------|-------|--------------|-------------------|---------|
| SCDM     | 0.67          | 0.5   | 1.0          | 0.0               | 0.5     |
| OCDM     | 0.85          | 0.7   | 0.3          | 0.0               | 0.21    |
| ACDM     | 0.91          | 0.7   | 0.3          | 0.7               | 0.21    |
| \(\tau\)CDM | 0.51         | 0.5   | 1.0          | 0.0               | 0.21    |
tion rate of active black holes by taking the positive term of the time derivative of the halo mass function and a simple parameterization for the black hole formation efficiency. It is further assumed that active black holes radiate with a light curve of the form, \( L_B(t) = f_B f_{\text{Edd}} L_{\text{Edd}} \exp(-t/t_Q) \), where \( f_{\text{Edd}} = 1 \) is the ratio of bolometric to Eddington luminosity and \( f_B = 0.1 \) is the fraction of the bolometric luminosity radiated in the B-band. The black hole mass is assumed to be determined by the virial velocity of the DM halo, \( M_{\text{bh}} \propto v_{\text{halo}} \) (model A) and the black hole mass indicated on the plot scales with \( (M_{\text{bh}}/M_\odot)^{1/3} \).

We obtain reasonable fits for a wide range of lifetimes and for all the CDM variants if we allow ourselves some freedom in the relation between halo mass and black hole mass. There are, however, systematic trends: with increasing lifetime, and these fall on successively steeper portions of the halo mass function. In Figure 2b and 2c we plot two specific choices of parameters which we denote as model A and B hereafter. For Fig. 2b a QSO lifetime close to the Salpeter timescale \( t_{\text{Salp}} = \epsilon c/4\pi G M_\odot = 4.5 \times 10^8 \) yr and a scaling of black hole mass with halo virial velocity as \( M_{\text{bh}} \propto v_{\text{halo}}^3 \propto M_{\text{halo}}^{3/2} (1+z)^{5/2} \) was assumed (\( \epsilon \) is the total efficiency for transforming accreted rest mass energy into radiation). A physical motivation for this particular dependence is discussed in section 3. Fig. 2c shows the case of a linear relation between the halo and black hole mass advocated by Haiman and Loeb (1997, HL97) which requires a QSO lifetime of less than \( 10^6 \) yr much shorter than the Salpeter time for usually assumed values of \( \epsilon \). Figure 2 is for the SCDM model while Figure 3 is for the other CDM variants (model A only). In principle \( t_Q \) could also depend on mass or other parameters and the degree of agreement which can be obtained with our simple assumptions seems gratifying.

### 2.4 The demography of black holes in nearby galaxies

The last few years have seen tremendous progress in establishing the existence of supermassive black holes in our own Galaxy and nearby galaxies. There are now a number of excellent cases (including that of our own Galaxy) where observations strongly imply the presence of a relativistic potential well (Watson & Wallin 1994; Miyoshi et al. 1995; Genzel et al. 1997). Furthermore, the number of mass estimates has increased to a level where it becomes possible to make statistical arguments. Magorrian et al. (1997; Mag97 henceforth) published a sample of about thirty estimates for the masses of the putative black holes in the bulges of nearby galaxies. Mag97 confirm previous claims of a strong correlation between bulge and black hole mass (Kormendy & Richstone 1995, but see Ford et al. 1997). A linear relation of the form, \( M_{\text{bh}} = 0.006 M_{\text{bulge}} \), was obtained by Mag97 as a best fit. However, considering the large scatter a mildly non-linear relation would probably also be consistent with the data. We would further like to note here that a linear relation between black hole to bulge mass does not necessarily imply a linear relation between black hole and halo mass and as we will argue later a non-linear relation might be more plausible. Fugukita, Hogan & Peebles (1997) estimate the total mass density in stellar bulges as \( 0.001 M_\odot \leq \rho_{\text{bulges}} \leq 0.003 M_\odot \) and together with the above ratio of black hole to bulge mass we get,

\[
\rho_{\text{bh}}(\text{nearby galaxies}) = 3.3 \times 10^6 \left( \frac{M_{\text{bh}}/M_{\text{bulge}}}{0.006} \right)^{1/3} \left( \frac{\Omega_{\text{bulge}}}{0.002 \Omega_\text{h}} \right) M_\odot \text{ Mpc}^{-3}.
\]

Considering the complicated selection biases of the Mag97 sample, the small sample size and possible systematic errors in the black hole mass estimates this number is still rather uncertain. Van der Marel (1997) e.g. emphasizes the sensitivity of black hole mass estimates to the possible anisotropy...
of the stellar velocity distribution and argues that the Mag97 mass estimates might be systematically too high.

Nevertheless, as pointed out by Phinney (1997; see also Faber et al. 1996) $\rho_{bh}$ (nearby galaxies) exceeds the mass density in black holes needed to explain the blue light of QSOs purely by accretion onto super-massive black holes, $\rho_{acc}(QSO) = 1.4 \times 10^5 \left( \frac{f_B \epsilon}{0.01} \right)^{-1} M_\odot \text{Mpc}^{-3}$, (2)

by a factor of about ten unless the value of $f_B \epsilon$ is smaller than usually assumed (Soltan 1982, Chokshi & Turner 1992). While a few years ago it seemed difficult to discover the total mass in black holes necessary to explain the blue light emitted by QSOs at high redshift, black hole detections in nearby galaxies now suggest that accretion onto supermassive black holes may actually be rather inefficient in producing blue light.

3 THE FORMATION AND ACCRETION HISTORY OF SUPERMASSIVE BLACK HOLES

3.1 When and how did supermassive black holes gain most of their mass?

There are three options to explain the apparently large value of $\rho_{bh}$ (nearby galaxies)/$\rho_{acc}(QSO)$: (i) $\rho_{bh}$ (nearby galaxies) is strongly overestimated, or (ii) $f_B \epsilon$ during the optically bright phase is smaller than previously assumed, or (iii) supermassive black holes do not gain most of their mass during the optically bright phase. A plausible solution with $f_B \epsilon$ significantly smaller than 0.01 is discussed in the next section. Here we will explore the last possibility somewhat further. The typical mass of a black hole at the end of the optically bright phase of duration $t_Q$ exceeds that accreted during this phase by a factor $M_{bh}/M_{acc} = f_{Edd} t_{Salp}/t_Q$. This factor should be larger than 1 and smaller than $\rho_{bh}$ (nearby galaxies)/$\rho_{acc}(QSO)$ and therefore,

$$1 \leq f_{Edd}^{-1} \epsilon^{-1} \left( \frac{t_Q}{4.5 \times 10^8 \text{ yr}} \right)^{-1}$$

$$\leq 25 h \left( \frac{f_B \epsilon}{0.01} \right) \left( \frac{\rho_{bh}(\text{nearby galaxies})}{3.3 h \times 10^8 \text{ Mpc}^{-3}} \right).$$

The question when supermassive black holes gained most of their mass is therefore closely related to $t_Q$ and $f_{Edd}$. For bright quasars, $f_{Edd}$ must be $\geq 0.1$; otherwise excessively massive individual black holes would be required. Furthermore, $f_{Edd}$ will always be smaller than unity even if the ratio of the accretion rate to that necessary to sustain the Eddington luminosity, $\dot{m}$, greatly exceeds unity. This is because a “trapping surface” develops at a radius proportional to $\dot{m}$, within which the radiation advects rather than escapes. In consequence, the emission efficiency declines inversely with $\dot{m}$ for $\dot{m} \geq 1$ (Begelman 1978).

For $0.1 \leq f_{Edd} \leq 1$ the possible range for $t_Q$ is,

$$2h^{-1} \times 10^6 \left( \frac{f_B \epsilon}{0.1} \right)^{-1} \left( \frac{\rho_{bh}(\text{nearby galaxies})}{3.3 h \times 10^8 \text{ Mpc}^{-3}} \right) \text{ yr}$$

$$\leq t_Q \leq 4.5 \times 10^7 \left( \frac{\epsilon}{0.1} \right) \text{ yr.}$$

If $t_Q$ is very short (as in model B) and $f_B \epsilon$ is not significantly smaller than 0.01 it seems inevitable that supermassive black holes have acquired most of their mass before the optically bright phase. We would like to point out here that a value of $\rho_{bh}$ as large or larger than we infer from Mag97 is actually needed for small $t_Q$ ($\leq 10^6 \text{ yr}$).

For the remainder of this section we assume that $t_Q$ is of the order of the Salpeter time (as in model A). The ratio of accreted mass to total mass at the end of the optically bright phase is then equal to $J_{Edd}^{-1}$. If $f_{Edd} \sim 1$ during the optically bright phase (and if $f_B \epsilon$ is not significantly smaller than 0.01) then the corresponding gain in mass by a factor $\rho_{bh}(\text{nearby galaxies})/\rho_{acc}(QSO)$ indicated by Mag97 has to occur after the optically bright phase. As the accretion should not be optically bright the most plausible options are advection dominated accretion flows (ADAFs) and dust-obscured accretion (Narayan & Yi 1995, Fabian et al. 1997 and earlier references cited therein). ADAFs require low accretion rate with $\dot{m} < \dot{m}_{crit}$ where $\dot{m}_{crit} = 0.3 \alpha_{ADAF}^2$ and $\alpha$ is the Shakura-Sunyaev viscosity parameter. There is therefore a maximum growth factor for the black hole mass density due to ADAFs $\sim 3 \alpha_{ADAF}^2 / \alpha_{ADAF} / t_{Salp} (\epsilon = 1)$ and $\alpha_{ADAF} \geq 0.3 [\epsilon \rho_{bh}(\text{nearby galaxies})/\rho_{acc}(QSO)]^{0.5}$ would be required even if the accretion lasts all the way from $z=3$ to $z=0$.

If, however, $f_{Edd} \sim 0.1$ (and $t_Q \sim t_{Salp}$) then the gain in mass by a factor $\rho_{bh}(\text{nearby galaxies})/\rho_{acc}(QSO)$ has to occur before the optically bright phase as in the case of small
where $m$ is the fraction of the accretion luminosity which is deposited as kinetic energy into the accretion flow (cf. Silk & Rees 1998). The accretion rate will then drop dramatically. The back-reaction timescale will be related to the dynamical timescale of the outer parts of the disk and/or the core of the DM halo and should set the duration of the optically bright phase. It is interesting to note here that the accretion rate will change from super-Eddington to sub-Eddington without much gain in mass if the back-reaction timescale is shorter than the Salpeter time. The overall emission efficiency is then determined by the value of $\dot{m}$ when the back-reaction sets in and is reduced by a factor $1/\dot{m}$ compared to accretion at below the Eddington rate. This results in a low overall value of $f_{\Delta} \epsilon$ which is -- as we discussed in the previous section -- one option to explain a large value of $\rho_{\text{bd}}$ (nearby galaxies)/$\rho_{\text{acc}}$ (QSO). Subsequently the accretion rate will fall below the critical rate permitting an ADAF, and the black hole will spend most of its time accreting with low efficiency. As discussed above it will depend on the value of $\alpha_{\text{ADAF}}$ whether black holes can gain most of their mass during this late phase of accretion.

As is apparent from equation (6) the black hole mass is very sensitive to the value of $m_{\Delta}/j_{\Delta} \lambda$. Numerical simulations have demonstrated that the distribution of $\lambda$ depends very little on any halo properties (Barnes & Efstatthiou 1987; Lemson & Kauffmann 1997). Numerical simulations, however, also show that angular momentum is very efficiently transferred from the gas to the DM halo unless considerable energy and/or momentum input prevents the infalling gas from clumping (Navarro & Steinmetz 1997). A moderate change in the ability of the gas to transfer angular momentum to the DM halo and in the amount of gas settling into a self-gravitating disc with redshift would result in a strong redshift dependence of the black hole formation efficiency. Such a strong redshift dependence was proposed by HR93 to explain the rapid decline of the typical QSO luminosity at $z < 3$. As discussed by Cavaliere & Vittorini (1997) the decrease of the ability of the gas to cool once the hierarchical build-up of DM haloes has progressed from galaxy to group and cluster scales and the reduced merger rates of galaxies compared to that of DM haloes contribute to this rapid decline. The redshift evolution of the black hole formation efficiency and the expected scatter in $\lambda$ can easily explain the large scatter in the observed black hole to bulge mass relation. Furthermore, it seems likely that the bulge-to-disc ratio of a galaxy is also related to the value of $m_{\Delta}/j_{\Delta} \lambda$. This fits in well with the fact that the black hole mass seems to correlate better with the bulge mass than the total mass of the galaxy and naturally explains the correlation of black hole formation efficiency with the Hubble type of the galaxy. Obviously the evolution described in this section need not to occur strictly in that time sequence. In hierarchical cosmogonies, where DM haloes undergo continuous merging the process will be re-started several times. At which step of the above scheme the evolution starts depends on whether the accretion rate in the core of a newly-formed DM halo on a given level of the hierarchy is super-Eddington, sub-Eddington or sub-critical with respect to the supermassive black hole already present. A question which we have not addressed here but that certainly deserves more attention is the merging history of supermassive black holes. Here we would only like to remark that in models with a strictly linear relation of black hole to halo mass constant with time (as in model B) the growth of black holes will actually be
dominated by the merging of black holes, while a non-linear relation (as in model A) leaves room for a substantial gain in mass by accretion of gas at each step of the hierarchy.

3.3 Possible accretion histories with low optical efficiency

Figure 4 sketches two possible accretion histories with a low overall efficiency for producing blue light. The solid curves describe an accretion history where most of the mass is accreted during the ADAF phase while the dashed curves are for an accretion history where the black hole gains most of its mass during a short-lived early phase with \( \dot{m} > 1 \). The panels show (from top to bottom) mass accretion rate in terms of the Eddington accretion rate, the mass relative to the final mass and the optical and hard X-ray luminosity. The accretion rate is constant at the beginning with \( \dot{m} > 1 \). The mass is therefore linearly rising and \( \dot{m} \) decreases. The spectral energy distribution for accretion with \( \dot{m} > 1 \) is rather uncertain (as indicated by the three parallel lines for \( \dot{m} > 1 \) in the two bottom panels) and should depend on the absorbing column and the dust content of the outer parts of the self-gravitating disc and/or the host galaxy. The sharp drop of \( \dot{m} \) marks the onset of the back-reaction on the accretion flow and either the start or the peak of the optical bright phase (with a rather inefficient production of hard X-rays). Once the accretion rate has fallen below the critical rate for an ADAF (indicated by the dashed lines in the top panel) the spectral energy distribution will change to one peaked in the hard X-ray waveband.

4 OBSERVATIONAL IMPLICATIONS

4.1 Masses, luminosities and clustering properties of QSO hosts at redshift three

In Figure 5 we plot some properties of the host objects predicted by our fiducial models for the different CDM variants. As expected in model A, where \( t_Q \) is longer, the halo masses are considerably larger than in model B especially at low luminosities. This is also reflected in the expected luminosity of the host galaxy. While in model A QSO hosts \( (M_B < -23) \) would sample only the bright end of the luminosity function of star-forming galaxies \( (M_{AB} < -21) \), in model B the faintest QSOs would reside in objects well beyond the current spectroscopic limit at these redshifts (Fig. 3a). Large \( t_Q \) seem therefore to stand a better chance to be consistent with the large host galaxy luminosities of bright QSOs reported by Aretzaga, Terlevich & Boyle (1997). Figure 3c illustrates the “rareness” of host haloes/galaxies in terms of the peak height in a Gaussian distribution. In model A QSO hosts correspond to significantly rarer peaks. The clustering strength of haloes depends mainly on the rareness of the peaks (Kaiser 1984, Mo& White 1996, Bagla 1997) and the two models should therefore differ strongly in the predicted clustering length of QSOs. With the upcoming larger surveys such as the 2dF and the SDSS it should be possible strongly to constrain the clustering length, and thus also \( t_Q \). The strong clustering recently confirmed by La Franca & Cristiani (1997) seems already to dis-favour small \( t_Q \).
4.2 Faint X-ray sources and the hard X-ray background

As pointed out by many authors, the X-ray emission of optically selected QSOs is too soft to explain the hard X-ray background. Di Matteo & Fabian (1996) and Yi & Boughn (1997) argued that the emission from ADAFs has a spectral shape similar to the hard X-ray background. Fabian (1997) argued that the emission from ADAFs has a spectral shape similar to the hard X-ray background. Di Matteo & Fabian (1996) and Yi & Boughn (1997) suggested that this might also be true for dust-obscured accretion. It is therefore tempting to link the rather large value of $\rho_{ph}$ (nearby galaxies) to $\rho_{acc}$ (QSO) inferred from Mag97 to the origin of the hard X-ray background and the recently detected large space density of faint X-ray sources (Almaini et al. 1996; Hasinger et al. 1997, Schmidt et. al 1997, McHardy et al. 1997, Hasinger 1998).

The presence of extremely low-level optical AGN activity in a large fraction of galaxies reported by Ho, Fillipenko & Sargent (1997) would also fit in nicely with such a picture. The present-day black hole mass density is sufficient to produce the hard X-ray background if $f_{hardX-ray} \epsilon \sim 0.002 (\rho_{acc}/\text{hard X-ray})/10^3 M_\odot \text{ Mpc}^{-3})$. The efficiency of ADAFs is $\epsilon_{ADAF} = 0.1 (\alpha/0.3)^2 m/\dot{m}_{crit}$ and decreases rapidly for small $\alpha$ and small $m/\dot{m}_{crit}$. If the hard-Xray background was produced by ADAFs onto supermassive black holes in ordinary galaxies this requires a value of $\rho_{ph}$ (nearby galaxies) as high as we infer from Mag97, a large value of $\alpha$ and a value of $m/\dot{m}_{crit}$ below but still close to $\dot{m}_{crit}$ lasting for a Hubble time for the majority of all supermassive black holes.

One should note here that at present it is not easy to discriminate observationally between dust-obscured accretion and an ADAF as little work has been done on the detailed spectral shape of an ADAF embedded in an AGN environment. Furthermore, at faint flux levels and high redshifts a possible star-burst contribution to the total spectral energy distribution will become more and more important in the optical and probably also the soft X-ray.

4.3 Faint point sources in the optical and infrared at very high redshift

In section 3.2 we speculated that there might exist a minimum black hole mass. Such a minimum mass will have a strong bearing on the number of point sources at faint magnitudes. Fig. 6 shows the predicted number of sources per unit redshift per arcm$^2$ above a certain flux limit. We have assumed that the sources emit a fraction $f_X=0.3$ of the Eddington luminosity in the corresponding band. No correction for dust absorption or intervening Ly$\alpha$ absorption has been made. Since the universe becomes optically thick to Ly$\alpha$ absorption at $z \geq 4$ these faint sources could only be detected longward of the redshifted Ly$\alpha$ wavelength (i.e K band or redder). For model A a minimum black hole mass of $10^{6} M_\odot$ and for both models a minimum halo virial velocity $v_{halo} \geq 30 \text{ km s}^{-1}$ was assumed. At magnitudes $M_X \geq 28$ model A predicts a progressively smaller number of faint sources than model B mainly due to the assumed minimum black hole mass. As pointed out by HL97 the Next Generation Space Telescope (NGST) should be an excellent tool to probe the black hole mass spectrum at high redshifts and small masses. The rather small number of very faint point sources in the HDF might already be in conflict with a linear relation of black hole to bulge mass which extends below $10^{6} M_\odot$ and to high redshift (Madau, private communication; see also Almaini & Fabian 1997).

5 THE ROLE OF STARS AND QSOS FOR THE RE-IONIZATION HISTORY OF THE UNIVERSE

The contribution from newly-formed stars relative to that from super-massive black holes to the re-ionization history of the universe is still rather uncertain. At $z=3$ the flux of ionizing photons attributed to observed QSOs is probably just sufficient to explain the observed UV background at the hydrogen Lyman limit if the ionizing flux is as low as in-
Figure 6. Model predictions for the number of faint point sources per unit redshift per arcmin$^2$ for the four different flux limits as indicated on the plot. The black holes are assumed to emit a fraction $f_X=0.3$ of the Eddington luminosity in the corresponding band (no extinction). Model A ($t_Q$ long) assumes a minimum black hole mass of $10^6 M_\odot$ and for both models a minimum halo virial velocity $v_{\text{halo}} \geq 30 \text{km s}^{-1}$ was assumed. Note that the solid curves for $M_X=30$ and $M_X=32$ coincide.

Dedicated by recent studies of the flux decrement distribution in QSO spectra which make use of hydrodynamical simulations (Rauch et al. 1997; Bi & Davidsen 1997). Rauch et al., however, find that the ionizing background necessary to fit the mean flux decrement decreases more slowly towards higher redshift than the expected contribution of observed QSOs. This indicates that at $z > 3$ the ionizing background might be dominated by stars. Direct estimates of the stellar contribution to the ionizing background are still difficult as we do not know how much ionizing flux is actually escaping star-forming galaxies at high redshift. Just longward of the hydrogen Lyman limit the photon flux due to star-forming galaxies exceeds that due to quasars by a factor of about thirty. The spectra of star-forming galaxies certainly have a strong intrinsic Lyman break but it is still unclear whether the ionizing flux from galaxies exceeds that due to QSOs even at $z \approx 3$. A more precise assessment of this question will have to await detailed spectra of star-forming galaxies which extend beyond the hydrogen Lyman limit. Theoretical predictions for the relative contribution of stars and QSOs to the UV background are also hampered by our lack of knowledge of the photon escape fraction in both star-forming galaxies and QSOs, its possible dependence on halo/galaxy properties and its evolution with redshift. In Figure 7, we have plotted predictions for the photon generation rate just longward of the hydrogen Lyman limit evolving our two fiducial models backwards in time and assuming a minimum black hole mass of $10^6 M_\odot$ (units are photons per baryon per unit redshift). In model A the black hole formation efficiency strongly decreases with halo virial velocity. In
such a model the ionizing background should eventually be dominated by stars at high redshift. In model B, the fraction of “blue” photons coming from by QSOs is only weakly redshift dependent. This is primarily due to the linear scaling of the black hole and halo mass. As argued by HL97, in such a model the ionizing background could be dominated by QSOs at all redshifts.

Model predictions for the re-ionization redshift are even more uncertain and as discussed by many authors they differ strongly between different CDM variants and depend strongly on the assumed escape fraction. While mixed-dark matter models are just capable of re-ionizing hydrogen at or before redshift five, in open models hydrogen re-ionization by stellar radiation might occur well before redshift ten. Further clues to the question of how and when the universe was re-ionized might be obtained from the thermal history of the inter-galactic medium and the closely related issue of the re-ionization history of helium. The spectrum of radiation emitted from star forming regions is generally believed to be too soft to fully ionize helium. If hydrogen were re-ionized by stars, then helium would have to be re-ionized by the harder output from QSOs which might have occurred considerably later. Recently, there has been some evidence for a change in the spectral shape of the ionizing background at redshift three and only partial re-ionization of helium at the same redshift has been reported (Songaila & Cowie 1996, Reimers et al. 1997, but see Miralda-Escudé 1997 for a discussion and also Boksenberg 1997). However, Haehnelt & Steinmetz (1997) use an investigation of the observed Doppler parameter distribution of QSO absorption lines to argue that helium was probably fully re-ionized by UV radiation with a QSO-like spectrum before $z=4$.

6 DISCUSSION AND CONCLUSIONS

The optical QSO luminosity function at $z \sim 3$ can be plausibly matched with the luminosity function of star forming galaxies at the same redshift and the mass function of DM haloes predicted by a range of variants of CDM cosmogonies believed to comply with observational constraints in the low-redshift universe. This is possible for lifetimes of optically bright QSOs anywhere in the range $10^6$ to $10^9$ yr. There is a correlation between the lifetime and the required degree of non-linearity in the relation between black hole and halo mass. The non-linearity has to increase for increasing lifetime. Predicted host halo masses, host galaxy luminosities, and the clustering strength all increase with increasing lifetime and further observations of these offer our best hope of constraining the duration of the optically bright phase of QSOs.

The present-day black hole mass density implied by the integrated luminosities of optically bright QSO may be significantly smaller than that inferred from recent black hole estimates in nearby galaxies for generally assumed efficiencies for producing blue light. We have discussed three possibilities for how and when this mass could be accreted in an optically inconspicuous way: (i) in the early stages of accretion at rates far above the Eddington rate, (ii) by accretion where optical emission is obscured by dust, or (iii) in the late stages of accretion at a rate below the critical rate for an advection dominated accretion flow with an Shakura-Sunyaev parameter of $q_{\text{ADAF}} \gtrsim 0.3$. For the latter two possibilities the space density of faint X-ray sources should exceed that of optically selected QSOs considerably and might reach that of present-day $L_e$ galaxies at the faintest flux levels. The expected shape of the luminosity function of faint X-ray sources and its evolution with redshift should, however, differ and improved determinations of this luminosity function together with broader spectral coverage of the sources should soon determine to what extend one or more of these possibilities are realized.

We have speculated that the formation and accretion history of supermassive black holes is determined by accretion at the centre of a gravitationally unstable self-gravitating disc in the core of a newly-formed dark matter halo and could proceed in the following steps:

(i) accumulation of enough material to form a supermassive star,
(ii) growth to the limit for post-Newtonian instability and collapse to a supermassive black hole of $10^6 M_\odot$ on a timescale less than $10^6$ yr,
(iii) steady accretion at well above the Eddington rate for about $10^5$ yr with linearly increasing mass,
(iv) reduction of the accretion rate due to back reaction on the accretion flow once the luminosity exceeds $v_{\text{esc}}/G$ by a sufficient factor, and
(v) late accretion for a Hubble time at a (slowly decreasing) reduced level.

This accretion history can explain the rather short optically bright phase, can account for a low overall efficiency for producing blue light and leaves room for the production of the hard X-ray background. It gives a physical explanation for the mass of the black hole formed and the predicted scaling with virial velocity/mass of the halo that is required to match the optical QSO luminosity function with the mass function of DM haloes for a duration of the optical bright phase of 10^7 yr. The rapid redshift evolution of the black hole formation efficiency can be attributed to a modest evolution in the fraction of the gas settling into a self-gravitating configuration at the centre of a DM halo and the ability of the gas to transfer angular momentum to the halo. It might further have the interesting implication of a minimum black hole mass of about 10^6 M⊙. The predicted decreasing black hole formation efficiency towards smaller halo masses and the presence of a minimum black hole mass may suggest that the ionizing background is progressively dominated by stars at high redshift.

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