Faint-end quasar luminosity functions from cosmological hydrodynamic simulations

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ABSTRACT
We investigate the predictions for the faint-end quasar luminosity function (QLF) and its evolution using fully cosmological hydrodynamic simulations which self-consistently follow star formation, black hole growth and associated feedback processes. We find remarkably good agreement between the predicted and observed faint end of the optical and X-ray QLFs (the bright end is not accessible in our simulated volumes) at \( z < 2 \). At higher redshifts, our simulations tend to overestimate the QLF at the faintest luminosities. We show that although the low- (high-)luminosity ranges of the faint-end QLF are dominated by low- (high)-mass black holes, a wide range of black hole masses still contributes to any given luminosity range. This is consistent with the complex light curves of black holes resulting from the detailed hydrodynamics followed in the simulations. Consistent with the results on the QLFs, we find a good agreement for the evolution of the comoving number density (in optical, soft and hard X-ray bands) of active galactic nuclei for luminosities \( \geq 10^{43} \) erg s\(^{-1}\). However, the luminosity density evolution from the simulation appears to imply a peak at higher redshift than constrained from hard X-ray data (but not in optical). Our predicted excess at the faintest fluxes at \( z \geq 2 \) does not lead to an overestimate to the total X-ray background and its contribution is at most a factor of 2 larger than the unresolved fraction of the 2–8 keV background. Even though this could be explained by some yet undetected, perhaps heavily obscured faint quasar population, we show that our predictions for the faint sources at high redshifts (which are dominated by the low-mass black holes) in the simulations are likely affected by resolution effects.

Key words: black hole physics – methods: numerical – galaxies: active – galaxies: evolution – galaxies: nuclei – quasars: general.

1 INTRODUCTION
In recent years, quasars have been used as instrumental tools for probing properties of their host galaxies as well as large-scale structure through cosmic time. The existence of black holes (BHs) at the centre of most galaxies (Kormendy & Richstone 1995) combined with the correlation between supermassive BHs and their parent galaxies (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Graham & Driver 2007) significantly strengthens the link between the BH and the formation and evolution of galaxies. Although the origins of these correlations are not completely understood, recent observational and computational studies point to the fundamental role of some form of quasar feedback for establishing them (e.g. Burkert & Silk 2001; Granato et al. 2004; Sazonov, Ostriker & Sunyaev 2004; Churazov et al. 2005; Di Matteo, Springel & Hernquist 2005; Springel, Di Matteo & Hernquist 2005a; Kawata & Gibson 2005; Bower et al. 2006; Begelman, Volonteri & Rees 2006; Croton et al. 2006; Ciotti & Ostriker 2007; Hopkins et al. 2007a; Malbon et al. 2007; Sijacki et al. 2007; Treu et al. 2007; Okamoto, Nemmen & Bower 2008).

One fundamental aspect of the study of quasars is the form and evolution of the quasar luminosity function (QLF). Recent surveys, including the Sloan Digital Sky Survey (York et al. 2000) and the 2dF QSO Redshift Survey (Lewis et al. 2002), are now providing large samples over sufficient redshift ranges that the QLF shape and evolution can be investigated in detail. Also, numerous studies of the QLF have been made, covering the X-ray (Page et al. 1997; Miyaji, Hasinger & Schmidt 2001; La Franca et al. 2002; Fiore et al. 2003; Ueda et al. 2003; Cowie et al. 2003; Barger et al. 2003b, 2005; La Franca et al. 2005; Silverman et al. 2008; Ebrero et al. 2009; Yencho et al. 2009), optical (Wolf et al. 2003; Croom et al. 2004; Richards et al. 2004; Sazonov, Ostriker & Sunyaev 2004; Churazov et al. 2005; Di Matteo, Springel & Hernquist 2005; Springel, Di Matteo & Hernquist 2005a; Kawata & Gibson 2005; Bower et al. 2006; Begelman, Volonteri & Rees 2006; Croton et al. 2006; Ciotti & Ostriker 2007; Hopkins et al. 2007a; Malbon et al. 2007; Sijacki et al. 2007; Treu et al. 2007; Okamoto, Nemmen & Bower 2008).

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Theoretical investigation of the QLF has been done using semi-
analytical models (e.g. Kauffmann & Haehnelt 2000; Volonteri,
Haardt & Madau 2003; Wyithe & Loeb 2003; Granato et al. 2004;
Malbon et al. 2007; Marulli et al. 2008; Bonoli et al. 2009). Since
these models do not self-consistently follow BH growth, the active
galactic nuclei (AGN) light curves and luminosity have to be cal-
culated via a specified prescription. The predominant method for
modelling the quasars in this context is to treat quasars as radiating
at a fixed fraction of their Eddington luminosity for a characteristic
time-scale after a galaxy merger before shutting off completely due
to feedback effects. The determination of the characteristic time-
scale varies between methods. For example, Haiman, Quataert &
Bower (2004) assume quasar radiation at the Eddington luminosity
for a fixed time-scale of $2 \times 10^7$ years for the radio-loud lifetime of
the quasars. Volonteri et al. (2003) assume the quasar will maintain
Eddington accretion until it has accreted a total mass proportional to
the fifth power of the circular speed of the merged system. Wyithe
& Loeb (2003) adopt a model where the quasars radiate at a fixed
fraction of the Eddington luminosity for the dynamical time of the
galactic disc, at which point the gas has been given more energy
than its binding energy. These methods have produced promising
results, but are all based on variants of the simple on–off model.

Hopkins et al. (2005a,b,c, 2006a,b) took a different approach to
modelling the QLF by analysing the light curves of quasars in hydro-
dynamical galaxy merger simulations which included BH growth,
accretion and feedback (see Di Matteo, Springel & Hernquist 2005;
Springel, Di Matteo & Hernquist 2005b), and used the results to
express the quasar lifetime as a differential time a quasar spends
radiating in a logarithmic luminosity bin (Hopkins et al. 2005a,b,c).
The quasar lifetimes were fit to a Schechter function dependent on
both peak and current luminosity. In this way, quasars were mod-
elled using detailed predictions from hydrodynamic simulations for
their light curves and were shown to radiate at a range of luminosi-
ties both at and below their peak, rather than being restricted to
radiating at a primarily constant peak luminosity.

Hopkins et al.’s approach found that using the predicted form
for quasar lifetime the faint end of the QLF could be explained by
quasars radiating well below their peak luminosities, rather than
by quasars with low peak luminosities. In this case, to match the
observational form of the QLF, the quasar creation rate must peak
at the critical break luminosity of the QLF, with a very rapid drop-
off for luminosities below the break (Hopkins et al. 2005b). This
work provided a fundamentally different explanation for the physi-
cal source of the faint-end slope and the break luminosity while still
reproducing the form and evolution of the observed QLF (Hopkins
et al. 2006b). However, the conclusions were based upon data ex-
ttracted from individual galaxy merger simulations and have yet to
be investigated with cosmological hydrodynamical simulations.

In this paper, we analyse fully cosmological hydrodynamic sim-
ulations which directly include modelling of BH growth, accretion
and associated feedback processes (as well as the dynamics of dark
matter, dissipation, star formation and stellar feedback) and make
predictions for the QLF and its evolution. The simulations are cur-
rently among the largest, highest resolution hydrodynamical sim-
ulations which include gas hydrodynamics, and have been shown
already to reproduce many aspects of the BH evolution, such as the
mass function and accretion rate distribution, and in particular the
assembly and evolution of the BH galaxy correlations (Di Matteo
et al. 2008). In this paper, we compare the BH luminosity functions
and their evolution from the simulations with appropriate observa-
tions in various energy bands. This is both an important test for
assessing the value of the simulations and for providing a physical
context within which to interpret the observations and quasar
evolution in general.

In Section 2, we describe the numerical modelling for the BHs
accretion and luminosity (Section 2.1) and the simulation param-
ters used (Section 2.2). In Section 3, we present the results for the
BH luminosity function, comoving number density evolution and
luminosity density evolution, and compare with observational data.
In Section 4, we discuss the implications of our simulation on the
hard X-ray background (XRB), and in Section 5 we summarize and
discuss our results.

2 METHOD

2.1 Numerical simulation

In this study, we analyse the set of simulations published in Di
Matteo et al. (2008). Here, we present a brief summary of the
simulation code and the method used. We refer the reader to Di
Matteo et al. (2008) for all details.

The code we use is the massively parallel cosmological TREEM-
PH code GADGET2 (Springel 2005), with the addition of a multiphase
modelling of the ISM, which allows treatment of star formation
(Springel & Hernquist 2003), and BH accretion and associated
feedback processes (Di Matteo et al. 2005; Springel et al. 2005b).

Black holes are simulated with collisionless particles that are
created in newly emerging and resolved groups/galaxies. A friends-
of-groups friend finder is called at regular intervals on the fly (the
time intervals are equally spaced in log $a$, with $\Delta \log a = \log 1.25$),
and employed to find groups of particles. Each group that does not
already contain a BH is provided with one by turning its densest
desert into a sink particle with a seed BH of fixed mass, $M = 10^7 h^{-1} M_\odot$. The BH particle then grows in mass via accretion
of surrounding gas according to $M_{\text{BH}} = \frac{4\pi c^2 M_{\text{BH}}}{(c^2 + \gamma v^2)^2} t$ (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944; Bondi 1952), and by merging with
other BHs.

For the simulations used here, it is assumed that accretion is
limited to a maximum of three times the Eddington rate. Note that
very few sources accrete at this critical value (as seen in Fig. 1).

The accretion rate of each BH is used to compute the bolometric
luminosity, $L = \eta M_{\text{BH}} c^2$ (Shakura & Sunyaev 1973). Here, $\eta$ is the
radiative efficiency, and it is fixed at 0.1 throughout the simulation
and this analysis. Some coupling between the liberated luminosity
and the surrounding gas is expected: in the simulation 5 per cent of
the luminosity is (isotropically) deposited as thermal energy in the
local BH kernel, acting as a form of feedback energy (Di Matteo
et al. 2005).

Note that to derive luminosities in specific wavebands (consistent
with the observational constraints) we need to apply a bolometric
correction to our quasar luminosities. We apply the bolometric
correction from Hopkins, Richards & Hernquist (2007b) (consistent
with Marconi et al. 2004):

$$
\frac{L}{L_{\text{band}}} = c_1 \left( \frac{L}{10^{12} L_\odot} \right)^{k_1} + c_2 \left( \frac{L}{10^{12} L_\odot} \right)^{k_2},
$$

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Figure 1. Relation between mass and bolometric luminosity for BHs in the D6 simulation for redshifts 1, 3 and 5. The lines show $L_{\text{Edd}}$ (solid pink) and 0.01 $L_{\text{Edd}}$ (dashed green).

Table 1. Numerical parameters.

| Run  | Box size $(h^{-1} \text{Mpc})$ | $N_p$ | $m_{\text{DM}}$ $(h^{-1} M_\odot)$ | $m_{\text{gas}}$ $(h^{-1} M_\odot)$ | $\epsilon$ $(h^{-1} \text{kpc})$ |
|------|-------------------------------|-------|----------------------------------|----------------------------------|-------------------------------|
| D4   | 33.75                         | 2 $\times$ 216$^3$ | $2.75 \times 10^8$ | $4.24 \times 10^7$ | 6.25                          |
| D6   | 33.75                         | 2 $\times$ 486$^3$ | $2.75 \times 10^7$ | $4.24 \times 10^7$ | 2.73                          |
| E6   | 50                            | 2 $\times$ 486$^3$ | $7.85 \times 10^7$ | $1.21 \times 10^7$ | 4.12                          |

$N_p$: total number of particles.  
$m_{\text{DM}}$: mass of dark matter particles.  
$m_{\text{gas}}$: initial mass of gas particles.  
$\epsilon$: comoving gravitational softening length.

where $c_1 = (6.25, 17.87, 10.83)$, $c_2 = (9.00, 10.03, 6.08)$, $k_1 = (-0.37, 0.28, 0.28)$, $k_2 = (-0.012, -0.020, -0.020)$ for B band, 0.5–2 keV soft X-ray band and 2–10 keV hard X-ray band, respectively.

2.2 Simulation parameters

Three simulation runs are analysed in this paper to allow testing for resolution effects. The main parameters are listed in Table 1. The three runs were of moderate volume, with box sizes of side length 33.75 $h^{-1}$ Mpc (D6 and D4 simulations) and 50 $h^{-1}$ Mpc (E6). For the D6 and E6 runs, $N_p = 2 \times 486^3$ particles were used, and the D4 used $2 \times 216^3$. The moderate box sizes prevent the simulations from being run below $z \sim 1$ ($z \sim 0.5$ for D4 run) to keep the fundamental mode linear, but provide a large enough scale to produce sufficiently luminous sources, albeit rare. The limitation on the box sizes is necessary to allow for appropriate resolution to carry out the subgrid physics in a converged regime (for further details on the simulation methods, parameters and convergence studies see Di Matteo et al. 2008 and also the discussion at the end of this paper).

3 RESULTS

3.1 Mass–luminosity relation

In order to illustrate the range of properties of the BH population in the simulations, in Fig. 1 we show the relation between BH mass and luminosity for the whole sample of objects in the D6 simulation (at $z = 1, 3$ and 5). Note the D4 and E6 mass–luminosity relations are not plotted, but both produced similar results. There is some correlation, albeit weak, between luminosity and mass of BHs, however in most regimes a significant scatter is seen, implying a fair range of luminosities for a fixed BH mass. This is the direct result of our simulations and in particular the complex light curves associated with the accretion history (and the evolution of the gas supply) which is followed in detail for all the BHs in our simulations. As an example, in Fig. 2 we show the BH mass assembly history for three specific BHs in the D6 simulations and their associated light curves (in terms of bolometric luminosity). The high level of variability in the light curves is induced by the detailed hydrodynamics, interplay between gas inflows, associated accretion and feedback processes self-consistently modelled in the simulations (see also Di Matteo et al. 2008 for more examples of accretion and merger histories of BHs in the simulations). This implies that in turn we expect the same BHs, at different stages of activity, to contribute to different regions of the luminosity function.

3.2 Luminosity functions

To illustrate the effect of different BH populations to the QLF in detail, in Fig. 3 we plot the relative contribution from the different BH mass ranges to the luminosity function at $z = 1$ and 3. At $z = 1$, the BHs with mass below $10^7 M_\odot$ provide the dominant contribution to the luminosity function for luminosities below
fit functions is redshift dependent, and ranges from \(9.97 L_{\odot} \) at \(z = 1 \) to \(11.53 L_{\odot} \) at \(z = 6 \).

Comparing observed and predicted LFs, it is apparent that the simulations can only reproduce the ‘faint end’ of the LF: this is expected as the number density of AGN in the ‘bright end’ is simply too low to be accessible in our simulated volumes. Thus, our predictions are limited to a relatively small range of luminosities which can be compared directly to observational data, and the largest overlap is in the X-ray band, rather than in the B band due to the significantly fainter AGN populations in the former. Related to this is the lack of predictions for the knee of the QLF, which occurs at a higher luminosity than the simulations produce.

Within the range of comparison, our predictions agree well with the data. Our simulations are fully consistent with the constraints from the B band (albeit with very limited region of overlap). In the hard X-ray band, at \(L \sim 10^{10} L_{\odot} (L \sim 10^{43.5} \text{ erg s}^{-1}) \), close to the maximum luminosities probed with our simulations, there is also a very good agreement. For \(z \leq 1 \), the overall shape and slope of the faint end is also reproduced remarkably well. At \(2 \leq z \leq 4 \), however, the slope predicted from the simulation is typically steeper than in the observed LFs. At \(z > 4 \), if compared to the fits of the observations, the slopes are again consistent. The same result is found in the comparison with the bolometric luminosity functions (where indeed the hard X-ray data significantly dominates Hopkins’ fits in the low-luminosity end) and where the discrepancy in the slope is the greatest at \(z \sim 2 \).

It is promising that the simulations agree well with the data at \(z \leq 1 \) where the observations in the ‘faint end’ are most complete and the bolometric corrections (which are derived from the local samples and have no redshift dependence) are most appropriately applied. The larger number of AGN at the faintest luminosities (hence the steeper slopes) at higher redshifts may have two possible implications. One is that there is still a population of the faint, possibly heavily obscured AGN above \(z = 2 \) that have not yet been detected. Alternatively, our simulations are actually overproducing the faint AGN population due to lack of appropriate resolution or appropriate feedback physics (either due to stellar processes or AGN) in the faint, low-mass BH population. The latter possibility is also hinted at from our results in Fig. 3 and the fact that the D6 predictions (highest resolution simulation) typically predict the flattest slopes (albeit barely as the convergence between the predictions for the three simulations is good). We will investigate this further in the course of the paper.

### 3.2.1 Model-dependent effects on the predictions for QLF

Even though our simulations predict directly an accretion rate for each of the BHs (from the hydrodynamics), at any given time there are two major model-dependent assumptions that we have made in order to the translate the accretion rate into a luminosity in a particular waveband: one is the assumption of a fixed radiative efficiency of 10 per cent and the second is the use of an empirically derived bolometric correction. Here, we wish to investigate the main effects on the QLF predictions of varying these two assumptions.

The bolometric luminosities are compared to the best-fitting function computed by Hopkins et al. (2007b) who compiled all available data from observational studies across several bands, including the optical, mid-IR, hard and soft X-ray bands, and fitted them to a double-power-law function (see Hopkins et al. 2007b for the function and the table of redshift-dependent parameters). The best-fitting function is plotted consistent with the range of observed bolometric luminosities. This is why the minimum luminosity shown in these

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1. Note that both Silverman et al. (2008) and Yencho et al. (2009) considered 2–8 keV rather than 2–10 keV, so their functions were adjusted using a photon index of \(\Gamma = 1.8\) to maintain a consistent definition of the hard X-ray band. In addition, neither Silverman et al. (2008) nor Yencho et al. (2009) consider absorption, whereas Ueda et al. (2003), La Franca et al. (2005) and Ebrero et al. (2009) all use absorption corrected data.
changes in accretion physics at low accretion rate remain somewhat uncertain) that sources accreting at a sufficiently low Eddington fraction (typically at \( \approx 0.01 \) Eddington) are expected to transition to a radiatively inefficient state with associated changes in the spectral energy distribution that are dramatically different. These radiatively inefficient accretion models (e.g. Narayan 2005; Quataert & Narayan 1999; Yuan & Narayan 2004, and references therein) (and also observations of both AGN and X-ray transients) indicate that such transitions occur around accretion rates of 1 per cent the Eddington value. The simplest way to investigate the overall effect this may have on our QLF predictions is to eliminate all sources accreting below \( 0.01 L_{\text{Edd}} \) (blue line). As shown in Fig. 1, most sources are above this cut-off luminosity at \( z > 1 \), so we expect a minimal effect on the QLF above this redshift. Eliminating low-luminosity sources for \( z \leq 1 \) leads to a flattening of the QLF slope (Fig. 5), as most sources are actually below this threshold at this point (as indeed generally expected that such modes of accretion will be well below the quasar peak). In short, low radiative efficiency accretion is expected to lead to some flattening of the QLF at \( z \leq 1 \). This effect therefore would not help flattening the QLF function at

Figure 4. The BH luminosity function for all three simulations (blue – D6 simulation; red – D4 simulation; green – E6 simulation) using sources with \( M_{\text{BH}} > 10^6 M_\odot \). The first column is the bolometric QLF computed directly from the simulation. The solid black line is the double-power-law QLF function given in Hopkins et al. (2007b). The second and third columns show the luminosity function after applying a bolometric correction (equation 1) to produce the B band and hard X-ray band. Open circles for optical bands are data points from the following studies: bright purple – Richards et al. (2005); blue – Richards et al. (2006); dark green – Wolf et al. (2003); red – Hunt et al. (2004); yellow – Cristiani et al. (2004); orange – Kennefick, Djorgovski & de Carvalho (1995); dark purple – Schmidt, Schneider & Gunn (1995); bright green – Fan et al. (2001a,b, 2003, 2004); black – Siana et al. (2008). Closed circles for hard X-ray bands are data points from the following studies: pink – Ueda et al. (2003); blue – Silverman et al. (2005); green – Barger et al. (2005); Barger et al. (2003a,b); orange – Nandra, Laird & Steidel (2005). Dotted lines in the hard X-ray column are best-fitting LDDE functions from the following studies: pink – Ueda et al. (2003); orange – La Franca et al. (2005); purple – Silverman et al. (2008); black – Ebrero et al. (2009); red – Yencho et al. (2009). Dotted lines in the B-band column are best-fitting LDDE functions from the following studies: pink – Boyle et al. (2000); orange – Croom et al. (2004); green – Richards et al. (2005). The dashed line in the hard X-ray at \( z = 2 \) is the D6 QLF if only \( M_{\text{BH}} > 10^7.5 M_\odot \) are included.
higher redshift and therefore better reconcile our predictions with observations.\footnote{Additionally, because our simulations use a single feedback model for all BHs, they do not model separate ‘quasar’ and ‘radio’ modes. In addition to having an effect on the radiative efficiency used to determine the BH luminosity, the inclusion of a radio mode will have a quenching effect during the simulation, due to the radio mode suppressing inflow of cooling gas (Croton et al. 2006). As the majority of our sources at $z > 1$ are accreting above 0.01 times the Eddington accretion rate, it is only at low redshifts (at or below $z \approx 1$, which is the limit of our simulations) that we would expect the radio mode to have a significant effect on BH growth. Additionally, Sijacki et al. (2007) found that, although the effect of the radio mode does become large at $z < 1$, the bulk of BH growth is always during the quasar mode (with the quasar mode accretion contributing 95 per cent of the integrated BH mass density), and that modelling a separate radio mode has negligible effect on $M_{\text{BH}} - M_*$ and $M_{\text{BH}} - \sigma_*$ relations.}

Our predictions for the various wavebands are of course dependent on the form of the bolometric correction used (the one adopted here is shown in equation 1). Even though there is a luminosity dependence in our bolometric correction, it is less well constrained at low luminosities (also for the reasons discussed above), where the majority of our sources lie. To explore the effects that the luminosity dependence has on our results in Fig. 5 (green line), we show the QLFs for a luminosity-independent bolometric correction, using the value of the correction factor evaluated at $L = 10^{12} L_\odot$, where the correction factor is best constrained. Doing this has a small effect on the $B$-band QLF, where in any case (see equation 1) the correction has a small dependence on luminosity. In the hard X-ray band, however, a luminosity-independent correction produces significantly lower magnitude for the QLF, which more closely matches the observational data. This illustrates that the exact form of the bolometric correction, particularly the form of its luminosity dependence, may have a strong effect on our final results.

## 3.3 Comoving number density evolution

The quasar comoving number density evolution is plotted in Fig. 6. This is derived by integrating the luminosity functions plotted in Fig. 4 (we average over all three simulations). Again, we plot the predictions for the bolometric, $B$ band, hard X-ray band and in this case soft X-ray band also. For the latter two bands, we also show the observational constraints from Ueda et al. (2003) (hard X-ray) and Hasinger et al. (2005) (soft X-ray).
in this band (this adjustment is somewhat model dependent, but provides a first approximation for comparison). We have also plotted the predictions from the best-fitting functions of Richards et al. (2005) (B band) and Ueda et al. (2003) (hard X-ray). The B-band function is terminated at \( z = 3 \) since the fits were based only on sources below this redshift. In some cases, a linear extrapolation (to higher luminosities) was applied to the simulation to allow the range of integration to match the observational data (given in specific luminosity bins).

In virtually every band, the quasar number density from the simulations peaks at \( z \sim 2.5 \) and as expected their number density is dominated by the lower luminosity populations. When comparing to the X-ray data (both hard and soft bands), we again find there is a good agreement with the observed evolution in the intermediate/high-luminosity ranges. Consistent with the results from the luminosity functions, the evolution in the lowest luminosity range implies larger number densities in the soft X-ray band above \( z \geq 2 \). The hard X-ray data from Ueda et al. (2003) for the lowest luminosity range are limited to \( z < 0.5 \), preventing direct comparison; however, the best-fitting function’s extrapolation shows that we may have a similar overestimate for the hard X-ray band.

3.4 Luminosity density evolution

In Fig. 7, we show the total luminosity density evolution from the simulated quasars with the appropriate observational constraints. A linear extrapolation of the QLF was made for the highest luminosity bins such that consistent luminosity ranges could be used across all simulations and redshifts. To cover the full range of observational constraints, we have used the best-fitting luminosity-dependent density evolution (LDDE) functions from the following studies to bound the shaded regions: in optical – Richards et al. (2005) and Boyle et al. (2000); in hard X-ray – Ueda et al. (2003), La Franca et al. (2005) and Ebrero et al. (2009). For these reasons, Fig. 7 is less of a direct comparison between simulations (where we extrapolate somewhat) and observations (where we used model dependent fits to data as constraints).

While the predicted peak in the total luminosity density is at \( z \sim 2.5 \) across the various bands, there are some fairly marked differences in the objects that dominate the contribution to the total luminosity evolution. The bolometric luminosity density (top panel) is dominated by the highest luminosity bins, with the brightest objects peaking at \( z \sim 4 \) while the lower luminosity bins peak at \( z \sim 2 \). In the optical band (second panel), the luminosity density is dominated by the brightest objects, comparable to the observational constraints.

The most significant difference is in the X-ray band, where the low-luminosity population produces most of the contribution to the luminosity density. Additionally, the peak in observed luminosity density is close to \( z \sim 1 \) rather than \( z \sim 2.5 \) as implied by the simulations. The overall reversal of trends in the relative contributions in various bands is of course caused by the form of the bolometric correction used in equation (1).

Finally, Fig. 8 shows the contribution to the bolometric luminosity density evolution as a function of BH mass. The lower plot in Fig. 8 is identical to the upper plot except the single most luminous BH from the D6 simulation at redshift 3 has been neglected (to explicitly show effects due to small statistics). We find that it is typically the mid-range BHs masses (\( 10^6 < M_{\text{BH}} < 10^8 \, M_{\odot} \)) which provide the largest contribution to the luminosity density. As one might expect, at higher redshifts, the low-mass BHs provide a more significant contribution, which was expected due to the lack of high-mass BHs (see also Fig. 1).

4 DISCUSSION

One of our primary results from the luminosity function and the global number density and luminosity density evolution is that our simulations are in good agreement with the observational constraints but imply a larger number of low-luminosity X-ray sources (at \( z > 2 \)) than observed. In order to assess the viability of our results, we need to check whether this population may violate the current constraints on the total XRB. The XRB intensity is calculated according to (Peacock 1999)

\[
I_\nu = \frac{c}{4 \pi H_0} \int_{z_1}^{z_2} \epsilon_\nu \epsilon_\nu (1 + z) \nu_b, z \frac{dz}{(1+z) \sqrt{(1+z) L(z)}},
\]

where the emissivity, \( \epsilon_\nu \), is the hard X-ray emissivity shown in Fig. 7, \( z \) is the redshift, \([z_1, z_2]\) is the range of redshifts being considered, \( \nu_b \) is the frequency at redshift zero, \( H_0 \) is the Hubble
parameter at redshift zero and $\Omega_0$ is the total density parameter at redshift zero. A photon index of $\Gamma = 1.8$ was assumed when computing $\epsilon_c([1 + z] \nu_h)$ to account for the form of the power spectrum of the BHs. Since we only have simulation information at discrete redshifts, we interpolate $\epsilon_c$ linearly between data points to compute the integral.

We find that the total contribution to the 2–10 keV XRB from our simulated BHs is $I_{2-10\,\text{keV},\text{D}6} = 1.28 \times 10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \text{deg}^{-2}$ for the D6 simulation (recall the simulations are restricted to $z \geq 1$). This is well within the observed 2–10 keV hard XRB intensity, $I_{2-10\,\text{keV},\text{obs}} = 2.02 \pm 0.11 \times 10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \text{deg}^{-2}$ (Moretti et al. 2003). If we apply a linear extrapolation to the simulation to include an approximate contribution from $z < 1$, we predict a total XRB intensity of $I_{2-10\,\text{keV}} = 1.8 \times 10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \text{deg}^{-2}$, still below the observed value.

When we do a similar calculation using the E6 and D4 simulations (which have lower resolution), we produce XRB intensities of $I_{2-10\,\text{keV},\text{E6}} = 1.94 \times 10^{-11}$ and $2.87 \times 10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \text{deg}^{-2}$ for the E6 and D4 simulations at $z > 1$, respectively. With the D4 simulation, we are starting to violate the observed XRB even without including $z < 1$. This result is quite fundamental for our analysis as it indicates that the simulation resolution plays an important role in estimating the effect from the faintest sources (those that were found to be in excess of the observed LF) and that their contribution decreases with higher resolution (note in Fig. 4 the steepest slopes of LF are always predicted from the D4 simulation).

Our simulations also predict that the QLFs extend to fainter fluxes than currently observed. We therefore compare our predictions for the unresolved fraction of the 2–8 keV XRB from the D6 simulation to test whether current observational constraints are still consistent with our predictions (i.e. if we could still be missing a faint population of, for example, heavily obscured AGN). We found that our prediction for the XRB contribution from luminosities limited to the range of overlap between observation and simulation provides an excess intensity of $1.85 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} \text{deg}^{-2}$ in the 2–8 keV band (assuming photon index of 1.8). This is below the 2–8 keV unresolved background of $I_{2-8\,\text{keV},\text{unres}} = 3.4 \pm 1.7 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} \text{deg}^{-2}$ (Hickox & Markevitch 2006). If we take into account the total contribution from the whole population in the simulations (well below the faintest sources currently observed but still assuming the same X-ray spectrum), we are in excess of the unresolved background by almost a factor of 2. To further illustrate and elucidate this issue, in Fig. 9 we plot the differential contribution to the 2–10 keV background from the simulations and the observations in several redshift bins [the filled curves are the regions bounded by the predictions from Ueda et al. (2003), La Franca et al. (2005) and Ebrero et al. (2009)]. This shows again that the excess in our predictions is caused by the contribution from low-luminosity sources ($L < 10^{43} \text{erg s}^{-1}$) and originates mostly at $z \geq 2$. This supports the idea that the faintest sources at high redshift are problematic in our predictions. Figs 3 and 7 do indeed show that above $z = 2$ this population is dominated by the lowest mass BHs (as opposed to lower redshifts where a more significant fraction of high-mass BHs has ‘turned off’) and those that are likely to suffer more strongly from lack of resolution. For illustration, in Fig. 4, at $z = 2$, in the hard X-ray band we show how the predictions look when only $M_{\text{BH}} > 10^{7.5} M_\odot$ are plotted. The excess in our prediction is eliminated and the lowest luminosity end of the LF is now in good agreement with all the observations.

Note also that we have used a redshift-independent correction to convert the simulations’ bolometric luminosity to the hard X-ray band to compare with observations. Direct determinations of
the bolometric correction as a function of redshift are not yet available and this may further bias our results at \( z \geq 2 \).

5 CONCLUSIONS

Here, we study the luminosity function and its evolution for populations of quasars extracted from full cosmological hydrodynamical simulations which include direct modelling for the growth of BHs. Noting that our simulations (due to limitations on the volumes probed) can only be used to study the faint end of the QLF, we summarize our main results as follows.

(i) Consistent with the complex light curves and various phases of activity that BHs undergo through their cosmic history, we have shown that there is a significant spread in luminosities for a given BH mass and in turn different BH masses contribute to the same regions of the QLF.

(ii) At low redshift (\( z < 2 \)), the low-luminosity ranges (below \( 10^9 \, L_\odot \)) of the QLF are dominated by BHs below \( 10^7 \, M_\odot \), while the luminosities above \( 10^9 \, L_\odot \) contain comparable contributions from both low and high masses. At high redshift, the majority of BHs are below \( 10^7 \, M_\odot \), and thus the entire QLF is dominated by low BH mass sources.

(iii) We have shown that our predictions for the faint end of the QLF agree remarkably well with observations at \( z \leq 1 \), but produce steeper slopes than implied by current constraints for the hard X-ray band at redshifts \( z = 2 \) and 3.

(iv) Taking into account a possible transition to low-radiative-efficiency accretion modes for low accretion rate sources tends to flatten the QLF at low redshifts but this does not affect significantly any of our results.

(v) The exact form of the bolometric correction has a significant effect on our predictions. In particular, when comparing to a fixed correction, the empirically determined (equation 1) luminosity dependence leads to a larger QLF magnitude in the X-ray band. Note also that in addition no constraints are currently available on the redshift dependence of the correction.

(vi) The evolution of the comoving number density is in agreement with current constraints for the luminosity ranges above \( 10^{43} \, \text{erg s}^{-1} \). Agreement for luminosities below \( 10^{43} \, \text{erg s}^{-1} \) is significantly worse, but the more limited observational data at these ranges combined with the dominance of BHs with \( M_{BH} < 10^7 \, M_\odot \), which are less well resolved in our simulation, make these results less meaningful.

(vii) The luminosity density evolution predicts a peak luminosity density at \( z = 2.5 \), with comparable contributions from different luminosity bins.

(viii) Based on the slope of the faint-end QLF, the luminosity density evolution and a moderate excess in the unresolved XRB, it appears that our simulations are overproducing low-luminosity sources, particularly at intermediate redshifts. We have shown however that the higher resolution simulations produce fewer low-luminosity BHs, which makes it likely that this overproduction is dominated by resolution effects. Additionally, our results are most accurate at low redshift, when the high-mass (and thus least likely to be affected by resolution limits) sources are most important, further suggesting that our overproduction of low-luminosity sources is dominated by resolution effects.

Overall our results support the interpretation of the faint-end luminosity function put forward by Hopkins et al. In an upcoming work, we will compare detailed characteristics of BH light curves in our simulations and compare their instantaneous luminosities to their peak luminosities, so as to determine more precisely if the faint-end slope is dominated by quasars radiating below their peak, or by quasars with faint peak luminosities, as previous models assumed. It may be possible (although currently infeasible due to technological constraints) to run larger volume simulations at similar or higher resolution to increase the statistics at the bright end of the luminosity function and further investigate the rapid drop off in comoving number density at \( z < 1 \) found in the observational data.

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