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Deriving the quasar Luminosity Function from the time-dependent phenomena on the accretion disks and the CDM models.

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Abstract. We have developed a consistent analytical model to describe the observed evolution of the quasar luminosity function. Our model combines Black Hole mass distributions based on the Press - Schechter formalism and quasar light curves derived from a physics-based emission model that takes into account the time-dependent phenomena occurring in the accretion disks. Our model gives an estimation of the exponent, n, of the power spectrum, $P(k)$, which is found to be $-1.8 \leq n \leq -1.6$. We were able to reject a generally assumed hypothesis of a constant ratio between Dark Matter Halo and the Black Hole mass, since the observed data could not be fitted under this assumption. We found that the relation between the Dark Matter Halos and Black Hole masses is better described by $M_{BH} = 10^{-0.332 \times log(M_{DMH})} \times M_{DMH}$. This model provides a reasonable fit to the observed quasar luminosity function at redshifts higher than ~ 2.0. We suggest that the disagreement at lower redshift is due to mergers, which have not been considered here, and whose rate at redshifts lower than 2 has been estimated.

1. Model and Assumptions

We assume that each quasar hosts a super-massive black hole (BH) surrounded by an accretion disk, which is the main emission component and driver of the quasar activity. The quasar light curve is calculated under the assumption that quasar emission is due to a non-stationary accretion disk. Our time-dependent accretion disk model [9] takes into account thermal-viscous instabilities due to Hydrogen ionization, which can develop in the disk [10], [11]. These instabilities can cause luminosity outbursts of a factor of 10^4, in timescales of the order of hundreds to some hundred million years. As a consequence, a single source can emit within a wide luminosity range depending on the current state of the disk, even if the accretion rate is constant and the fuel supply is continuous.

Figure 1 shows the light curves for 4 different BH masses. From top to bottom and left to right the BH masses are $10^6 M_\odot$, $10^7 M_\odot$, $10^8 M_\odot$ and $10^9 M_\odot$. Accretion rate at the outer edge of the disk is equal to $0.04\dot{M}_{Edd}$ Eddington limit (critical) accretion rate.

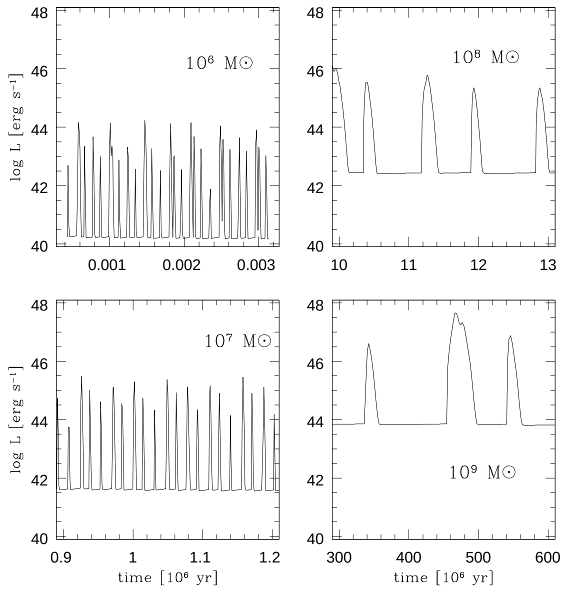

Fig. 1. Quasar light curves (disk luminosity vs time in 10^6 yr) due to thermal-viscous instabilities in the accretion disk around a central BH. From top to bottom and left to right the BH masses are $10^6 M_\odot$, $10^7 M_\odot$, $10^8 M_\odot$ and $10^9 M_\odot$.

Both the number of outbursts and their duration depend quadratically on the BH mass. Integration of the light curves over time shows that each source spends the greater part of its lifetime (around 70%) in a "quiescent" state and 30% in an active state ($L \geq 0.001 L_{Edd}$) with $\sim 10\%$ in a very active state ($L \geq 0.1 L_{Edd}$), almost independently of the BH mass.

To derive the black hole mass function, we use the Press - Schechter (1974) formalism. The mass function of the dark matter halos (DMHs) can be written as:

$$n(M,z)dM = -\left(\frac{2}{\pi}\right)^{1/2} \frac{\bar{\rho}}{M}\frac{\delta_c}{\sigma^2}\frac{d\sigma}{dM} exp\left(-\frac{\delta_c^2}{2\sigma^2}\right) dM$$

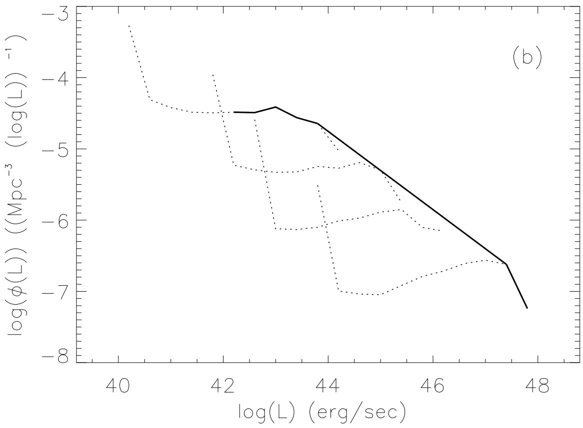

Fig. 2. Contribution of the different BH mass sources to the LF at $z = 2$, for BH masses ranging from $10^6 M_\odot$ (upper curve) to $10^9 M_\odot$ (lower curve). $\alpha 0 - 3.2$ for all BH masses. The slope defined by the very active sources gives roughly the slope of the LF. In the case of an upper (here $10^9 M_\odot$) or lower (here $10^6 M_\odot$) BH mass limit, the LF will follow the shape of the corresponding light curves, creating two breaks.

This formula gives the number of DMHs of mass M formed up to a redshift z.

We assume that in each newly collapsed DMH a BH is "instantly" formed, i.e. that all galaxies harbor a BH. For the masses of the DMHs and the BHs we adopt the relation $M_{BH} = 10^\alpha M_{DMH}$ and examine the possibilities of varying α between –4.5 and –3.2 (compatible with Wandel 1999 and Magorrian et al., 1998, respectively). We also examine the possibility of an α that is a linear function of the DMH mass, $\beta \times log(M_{DMH})$.

The quasar luminosity function (LF) will be the result of the convolution of their mass function with the light curve, L(t), of an individual source of each mass.

Figure 2b shows the contribution of sources with BH masses from $10^6 M_\odot$ to $10^9 M_\odot$, to the overall LF, for a Press - Schechter derived BH mass function at a redshift of 2. The sources with black hole masses within the abovementioned range have luminosities within the observed limits ($10^{41} erg/sec \leq L \leq 10^{48} erg/sec$). In each case, a low state activity for a high mass source, is a high state activity for a lower mass source, and vice versa. The slope defined by the high activity sources gives roughly the shape and slope of the luminosity function. In the case of an upper or lower mass limit, the luminosity function will follow the shape of the corresponding light curves, creating two breaks: one towards the lower and one towards the higher luminosities.

2. Constraints on the power spectrum

Observations show that the quasar space density increases as $\Phi(z) = \Phi_0(1 + z)^3$ from the current epoch up to a turnover redshift, z_t, of 2.5-4, where it stops or possibly drops. Our models naturally produce a z_t by integrating over the whole redshift range the predicted LF, for sources with absolute magnitudes brighter than $M_B = -26$ (figure 3a). We find that the z_t predicted by our models is a parabolic function of n, as shown in figure 3b, for 3 different values of the parameter α. The observed z_t is at least as high as 2.5 [4] and may be as high as ~ 4 [6], but quasar space density declines rapidly for $z > 4$, as suggested by both optical and radio observations, and theoretical models [2]. This puts a strong constraint on n, which can only take the values between –1.6 and –1.8.

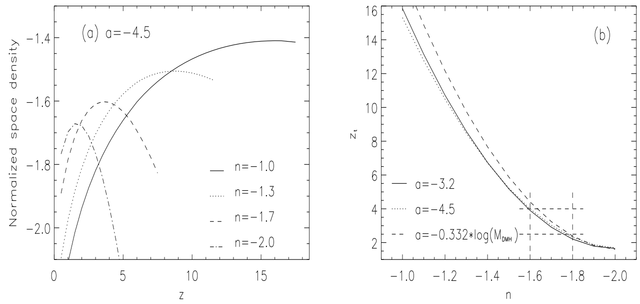

Fig. 3. (a) Predicted normalized quasar space density for n=–1.0 (solid line), n=–1.3 (dotted line), n=–1.7 (dashed line) and n=–2.0 (dash-dotted line) for α=–4.5. (b) Variation of z_t with the power spectrum exponent, n, for α=–3.2 (solid line), α=–4.5 (dotted line) and $\alpha = -0.332 \times log(M_{DMH})$. The relation is parabolic and almost independent of α. The dashed lines mark the accepted values for z_t, deduced from observations and the constraints they impose on the values of n.

3. BH and DMH mass relation

Most theoretical models have assumed for simplicity that the black hole mass is a constant fraction of the dark matter halo mass, independent of the masses involved. Observationally the results of Magorrian et al (1998) suggest that this is roughly obeyed. Therefore we first examine this possibility and compare our predictions with observations, both for low and for high redshifts. A constant α always produces a LF which is much smoother than the observed. For a high value of α (–3.2) the luminosity function is over-estimated at high luminosities, while for a low value ($\alpha = -4.5$) the numbers of faint quasars are under-predicted. The same tendencies are seen at all redshifts. This suggests that α cannot be constant, but may be a function of the masses involved.

Next we assumed that α depends on the DMH's mass with the relation $\alpha = \beta \times log(M_{DMH})$. In order to obtain the best value of a parameter β we fit this function to the observed luminosity function from Warren et al. (1994) at redshifts 2.6 and 3.25. We found that $\beta = -0.332^{+0.04}_{-0.016}$ gives the best fit.

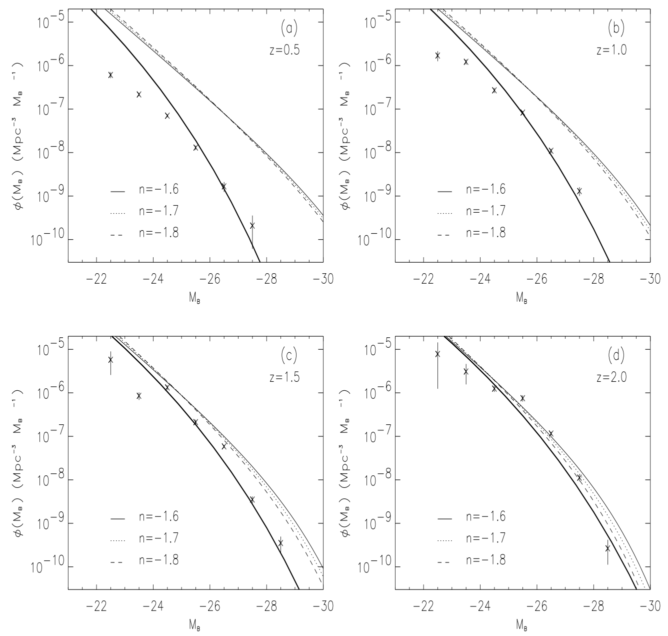

Fig. 4. The predicted quasars luminosity function for –1.8 $< n <$ –1.6 at z = 0.5 (a), z = 1.0 (b), z = 1.5 (c) and z = 2.0 (d). The symbols represent the observed luminosity function (Wisotzki - private communication). The thick solid line represents the single power law LF of Pei (1995).

4. Predicted Luminosity Function

Our model predicts a single power law LF, result that seems to be observationally confirmed by recent surveys [13] and that is also in agreement with previous theoretical work (Giallongo & Vagnetti, 1992; Pei, 1995).

Figures 4a to 4d show the a comparison of the predicted LF at $z = 0.5$ (a), $z = 1$ (b), $z = 1.5$ (c) and $z = 2$ (d), the data given by Boyle et al (1988) (symbols) and the single power law of the form $L^{1/4}$ given by Pei (1995) (thick solid line).

5. The Merger rate

Galaxy mergers, if taken into account, could significantly modify the assumed mass function. If this is the primary cause of the low z disagreement of our model with observation then the difference of the observed to predicted evolution rates, $\gamma_o - \gamma_p$, provides a crude estimate of the merger rate, γ_m, for redshifts between 0.5 and 2 i.e. $\gamma_m = 3$. Hence the merger rate can be expressed as a function of the redshift: $\sim (1+z)^3$.

The disagreement between the observed and the predicted luminosity function at $z \leq 2$ may also be due to the role of obscured (type II) AGN. The estimates of their number density are not yet accurate.

The model presented here can be extended and used for the study of the UV-background and the re-ionization history of the Universe (Siemiginowska et al., 2000, in preparation). Issues such as whether quasars are entirely responsible for the re-ionization of the Universe, the redshift at which it occurred, whether it is homogeneous or inhomogeneous or its effects on the primordial power spectrum, can be examined.

References

Boyle, B.J., Shanks, T. & Peterson, B.A., 1988, MNRAS, 235, 935

Cavaliere, A. & Vittorini, V., 1998, *The Young Universe: Galaxy Formation and Evolution at Intermediate and High Redshift.* Edited by S. D'Odorico, A. Fontana, and E. Giallongo. ASP Conference Series; Vol. 146; 1998, p.26

Giallongo, E. & Vagnetti, F., 1992, ApJ, 396, 411

Hook, I. M., Shaver, P. A. & McMahon, R. G., 1998, *The Young Universe: Galaxy Formation and Evolution at Intermediate and High Redshift.* Edited by S. D'Odorico, A. Fontana, and E. Giallongo. ASP Conference Series; Vol. 146; 1998, p.17

Magorrian, J., Tremaine, S., Richstone, D., Bender, R., Bower, G., Dressler, A., Faber, S. M., Gebhardt, K., Green, R., Grillmair, C., Kormendy, J., Lauer, T., 1998, AJ, 115, 2285

Miyaji, T., Hasinger, G. & Schmidt, M., 2000, A&A, 353

Pei, Y.C., 1995, ApJ, 438, 623

Press, W. H & Schechter, P., 1974, ApJ, 193, 437

Siemiginowska, A., Czerny, B. & Kostyunin, V., 1996, ApJ, 458, 491

Smak, J.I., 1982, Acta Astron, 32, 199

Tuchman, Y, Mineshige, S. & Wheeler, J.C. 1990, ApJ 359, 164

Wandel, A., 1999, ApJ, 519, L39-L42

Wisotzki, L., 2000, A&A, 353, 853