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THE MASS FUNCTION OF SEYFERT 1 NUCLEI

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ABSTRACT

The first mass function of Seyfert 1 nuclei is derived from optical spectra of the complete CfA sample of Seyfert galaxies by estimating the mass for each object from the dynamical relation $M \simeq v^2 r/2G$. An independent estimate is also derived using a complete infrared-selected sample. The two mass functions are indistinguishable, and the differential mass function is well described by $\phi(M) \propto M^{-2}$ for $M \gtrsim 5 \times 10^6 M_\odot$. The mean mass of Seyfert 1 nuclei is $\sim 2 \times 10^7 M_\odot$, and the integrated mass density is $\sim 6 \times 10^{11} M_\odot$ Gpc^{-3}. This is approximately two orders of magnitude less than the value inferred from the energetics associated with quasar counts. A careful analysis of the various parameters and assumptions involved suggests that this large difference is not due to systematic errors in our determinations. Therefore, the bulk of the mass related to the accretion processes connected with past quasar activity does not reside in Seyfert 1 nuclei. Instead, the remnants of past activity must be present in a much larger number of galaxies, and a one-to-one relation between distant and local active galactic nuclei seems then to be excluded.

Subject headings: galaxies: nuclei — galaxies: Seyfert — quasars

I. INTRODUCTION

The determination of the nuclear masses of Active Galactic Nuclei (AGN) is one of the best ways to obtain information about their past history and constrain the evolutionary pattern of the single objects. As shown by Cavaliere and Padovani (1988, 1989, hereafter CP88, CP89), it can be helpful in trying to answer long-standing questions such as those concerning the duration of their active phase and the number of galaxies which have ever harbored an active nucleus. In the framework of models where the primary energy source is accretion onto a black hole (see Rees 1984 and references therein), the accreted nuclear mass constitutes an archive of the history of each individual nucleus. This is important for models of continuous luminosity evolution, which posit that present-epoch Seyfert 1 galaxies are the only remnants of more luminous quasars. If this is the case, the integrated mass density of black holes in current Seyfert 1 galaxies must be at least as large as that required to produce the observed luminosity in quasars from earlier epochs. The goal of this paper is to test this prediction.

CP88 have shown in two different ways that observational estimates of the Eddington ratio (the ratio between the bolometric and the Eddington luminosity, $L_E = 1.26 \times 10^{38} M/M_\odot$ ergs s^{-1}) for local AGN, $L/L_E \sim 5 \times 10^{-2}$, are more than two orders of magnitude larger than the values predicted assuming that AGN are continuously active from $z \simeq 2.2$ to 0. This suggests that the duration of the active phase is much less than a Hubble time with a duty cycle (the ratio between the total activity time and the lifetime of the host galaxy) less than 10^{-2}. However, the first approach is in part model-dependent (as discussed by Cavaliere and Padovani 1990), while the second one, although more direct, still has to go through the luminosity function for obtaining information concerning the masses, assuming an average value of the mass-luminosity ratio.

In this paper, we will make the first direct determination of the mass function of Seyfert 1 nuclei using the complete CfA sample (Huchra and Burg 1990) and the infrared-selected sample of Spinoglio and Malkan (1989). This will allow a direct test of the continuous luminosity evolution model. We have used the dynamical method (e.g., Padovani and Rafanelli 1988) to estimate the masses of the objects in the samples, deriving the velocity of the emitting regions from the Hβ line width. The distance from the central nucleus was estimated from the observed number of ionizing photons using the definition of the ionization parameter, taking into account recent direct determinations of broad line region (BLR) radii. We will also estimate the total mass density accumulated in AGN by the method of Soltan (1982). Finally, we will compare our estimate of the mass density of Seyfert 1 nuclei to that accumulated in AGN to test directly the hypothesis of a one-to-one relation between local and distant AGN, which is suggested by the scaling of the AGN luminosity function at various redshifts (e.g., Boyle, Shanks, and Peterson 1988).

In § II we discuss the samples used, while in § III we describe the spectroscopic observations and the data reduction. In § IV, we discuss the mass estimates, and § V is devoted to the derivation of the mass function. In § VI, we summarize the method for estimating the total mass density of AGN, and § VII discusses the results and gives our conclusions. Throughout this paper, the values $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$ have been used, unless otherwise stated.

II. THE SAMPLES

The objects used in this study belong to the CfA sample of Seyfert galaxies (Edelson 1987; Edelson, Malkan, and Rieke 1987; Huchra and Burg 1990) a complete, magnitude-limited sample with $B(0) \leq 14.5$. The presence of strong emission lines was the sole selection criterion used to distinguish these objects from other galaxies in the survey. None of the surveys which observed the same part of the sky uncovered any AGN which met the selection criteria of the CfA sample but which were missed.

For comparison, we also used Spinoglio and Malkan's (1989) infrared-selected sample. This is a flux-limited complete sample of Seyfert galaxies with $F > 0.3$ Jy at 12 μm, a wavelength where the contribution of the host galaxy should be minimized. The luminosity functions of Seyfert 1 and Seyfert 2 galaxies derived from the two surveys are indistinguishable.

Our main purpose is to compare the mass density of Seyfert 1 nuclei with the total mass density accumulated in the AGN contributing to the quasar counts. These are usually complete down to $M_B \sim -23$ and include objects with $M_B \lesssim -21$. Since the luminosity function of Seyfert 1 galaxies at the present epoch is similar to that of quasars at high redshifts but shifted to lower luminosities by about two orders of magnitude (e.g., Boyle, Shanks, and Peterson 1988), the comparison should be made with Seyfert 1 galaxies having a nuclear magnitude $M_B \lesssim -18$ (or at most $M_B \lesssim -16$): objects of lower luminosity could not be dimmed bright quasars. Our sample meets this requirement: it includes objects with $M_B \sim -17$ (NGC 4051) and $M_B \sim -17.5$ (NGC 3227 and NGC 5273), as estimated using the small-aperture photometry collected by Huchra and Burg 1990). The true nuclear magnitude may be even larger (see, for example, the values given by Cheng *et al.* 1985). We then conservatively estimate that the mass function derived in this paper refers to Seyfert 1 nuclei having $M_B \lesssim -17$.

III. OBSERVATIONS AND DATA REDUCTION

Absolute optical spectra covering the range 3200–7100 Å of the 26 Seyfert 1 galaxies in the CfA sample were obtained by one of us (R. A. E.) in 1983–1984 with the SIT Vidicon spectrograph on the Palomar Observatory 1.5 m telescope (Kent 1979). The "3G" grating, blazed at 5000 Å, with 300 lines per inch, was used with a large 12″ slit to ensure photometric accuracy. The pixel size was 8 Å, and the instrumental resolution was 25 Å. Wavelength calibration was done with helium arc lines and is good to ~5 Å. Flux calibration was done relative to the AB_{79} system (Oke and Gunn 1983), using the standard stars BD +26°2606 and HD 84937 for the objects with right ascension between 6^h and 18^h and BD +17°4708 and HD 19445 for objects between 18^h and 6^h. As the SIT has a limited dynamic range (~500), the final spectrum of each object was determined by combining typically four to eight exposures, each of about 2–10 minutes, taken over a number of different nights. On the basis of spectra taken on different nights, the overall photometric accuracy is estimated to be about 10%.

The spectra were reduced to flux units (ergs $\mathrm{cm^{-2}\ s^{-1}\ Å^{-1}}$). The Image Reduction and Analysis Facility (IRAF) was used to measure the Hβ line widths and fluxes. To do this, the line-free continua were first fitted by a polynomial and then subtracted off. The contaminating [O III] lines were also fitted by Gaussians and removed. The full widths at zero intensity (FWZI) and the line widths at zero intensity of the blue ($\mathrm{HWZI_{blue}}$) and the red ($\mathrm{HWZI_{red}}$) wings of Hβ were measured. The maximum velocity in the BLR, $v_{\max}$, is measured as the larger of the two HWZIs. The data are presented in Table 1. In order to quantify the errors on the velocity and to test the relative stability of two different ways of measuring the line widths, the FWZI and the full width at half-maximum (FWHM), we remeasured the widths using another set of spectra of the same objects (Burg 1987) at higher resolution (5 Å) but with lower S/N on average. We also compared $v_{\max}$ for

TABLE 1

MEASURED Hβ LINE WIDTHS

Object	z	$FWZI$ km s^{-1}	$HWZI_{blue}$ km s^{-1}	$HWZI_{red}$ km s^{-1}
MKN 335	0.0259	12600	5600	7000
A0048+29	0.0359	8900	4600	4200
I ZW 1	0.0604	10300:	6700	3600:
MKN 590	0.0263	14300	8900	5300
MKN 1243	0.0353	12500	7700	4800
NGC 3227	0.0038	11500	6400	5100
NGC 3516	0.0085	13000	7500	5500
MKN 744	0.0091	11900:	8300:	3600
NGC 4051	0.0022	10800:	5000	5800
NGC 4151	0.0030	11000	6100	4900
NGC 4235[a]	0.0077	15000	...	...
MKN 766	0.0128	7200	4500	2700
MKN 205	0.0699	14200:	7100	7100
MKN 231	0.0410	16900	9300	7600
NGC 5033[a]	0.0030	8000	...	...
MKN 789	0.0311	4100:	2600:	1500:
NGC 5273	0.0036	16000:	10700:	5300:
MKN 279	0.0304	11800	7200	4600
NGC 5548	0.0166	11200	5700	5500
MKN 817	0.0314	13600	8000	5600
MKN 841	0.0364	11700:	5900	5800
NGC 5940	0.0339	13400	9300	4500
NGC 6104[b]	0.0280	11100:	5000:	6130:
2237+07	0.0250	10600	5000	5600
NGC 7469	0.0160	11300	5400	5800
MKN 530	0.0290	14900:	8300	6600

[a] Spectrum with very low S/N: FWZI refers to Hα (Filippenko and Sargent 1985).

[b] Line widths refer to Hα and are very uncertain.

1990ApJ...353..438P

TABLE 2

LINE WIDTH COMPARISON

Mean Value	$\bar{x} \pm \sigma$	N
$\langle$FWZI(Hβ)/FWZI(Hβ)$_{\rm HR}\rangle$	1.15 ± 0.34	21
$\langle$FWHM(Hβ)/FWHM(Hβ)$_{\rm HR}\rangle$	1.76 ± 1.04	16
$\langle v_{\rm max}$(Hβ)/$v_{\rm max}$(Hβ)$_{\rm HR}\rangle$	1.20 ± 0.35	21
$\langle$FWZI(Hβ)/FWZI(Hβ)$_{\rm publ}\rangle$	1.01 ± 0.23	10
$\langle$FWHM(Hβ)/FWHM(Hβ)$_{\rm publ}\rangle$	1.52 ± 0.56	11

NOTE.—Comparison between the widths used in this paper and those measured from spectra of higher resolution (HR) or found in literature (publ).

the two samples and checked our measurements for some of the objects in our sample with published values. The results of these comparisons, reported in Table 2, show that the FWZIs agree very well (to within ~20%), while the FWHMs vary greatly. We therefore conservatively estimate that the uncertainties on the FWZIs are ~25%: the data in Table 1 followed by colons have larger than average errors as derived from the low S/N and/or the comparison with the high-resolution spectra or with published data.

IV. THE MASS ESTIMATES

The mass has been derived using the dynamical (virial) method (see, e.g., Padovani and Rafanelli 1988) under the assumption of infall. The mass of the central nucleus can then be expressed as

$$M = v^2 r/2G \, , \tag{1}$$

where v is the infall velocity of the emitting matter at distance r (this is an upper limit to the mass if the motion is not gravitationally bound).

We estimate r by using the definition of the ionization parameter $U = Q(H)/(4\pi c n r^2)$ (e.g., Mushotzky and Ferland 1984), where $Q(H)$ is the number of ionizing photons $[\int L(\nu)/h\nu \, d\nu]$, and n is the particle density:

$$r_{\rm in} = \left[\frac{Q(H)}{4\pi c (Un)_{\rm in}}\right]^{1/2} . \tag{2}$$

Since we are using the maximum velocity in the BLR, the estimate of r must refer to $r_{\rm in}$, measured at the inner regions of the BLR. Thus, it is necessary to determine $Q(H)$ and $(Un)_{\rm in}$ to complete the mass estimates.

The number of ionizing photons has been derived following Padovani (1989). Ultraviolet and X-ray data have been used to estimate $Q(H)$ between 1 and 10^3 rydberg, assuming a power-law continuum between ultraviolet and X-ray energies and isotropic emission (see Padovani and Rafanelli 1988). Since $r_{\rm in} \propto [Q(H)/4\pi]^{1/2}$, the estimated radii would not change even if the emission were anisotropic. These values represent a conservative estimate in view of the possible presence of a "big bump" in the extreme ultraviolet, where the spectrum of AGN is not known. However, the number of ionizing photons depends mostly on the level of the ultraviolet continuum at energies ~1 rydberg, and therefore our estimates should be fairly reliable (see § VII).

Six objects had no ultraviolet or X-ray data: for those we estimated $Q(H)$ from their Hβ luminosity using the mean relationship between the two quantities obtained from the Seyfert 1 sample of Padovani (1989), $Q(H) \simeq 3.4 \times 10^{14} L({\rm H}\beta)^{0.95}$. The same data base was used for one object (NGC 6104) which had very low S/N in the Hβ region and no ultraviolet or X-ray data so that the mass was derived from the (very uncertain) HWZI(Hα) making use of the M–v relationship.

The value of the product of the ionization parameter and particle density in the inner parts of the BLR—$(Un)_{\rm in}$—is more difficult to determine. Early attempts to estimate the dimension of the BLR by cross-correlation of the temporal behavior of the emission lines (Gaskell and Sparke 1986) were found to be inaccurate, due to inadequate sampling, poor S/N, unfounded geometrical assumptions, and errors introduced by interpolation (Gaskell and Peterson 1987; Edelson and Krolik 1988; Maoz and Netzer 1989). Newer approaches have better sampling and S/N and employ more sophisticated analysis techniques, but they still require assumptions about the distribution of matter in the BLR. Netzer *et al.* (1990) have recently presented a detailed spectroscopic monitoring of the Seyfert galaxy NGC 5548 over a period of about 5 months on a time scale of the order of 3–4 days. Their measurement of the cross-correlation function between Hβ and the optical continuum suggests a BLR inner radius near 7 lt-days, assuming spherical symmetry. This corresponds to $(Un)_{\rm in} \sim 10^{10.2}$ cm^{-3}, using $Q(H) \simeq 2 \times 10^{54}$ s^{-1} (see Table 3). For NGC 4151, Edelson and Krolik (1988) used *IUE* data to set limits of 1.2–20 lt-days to the C IV–emitting region, corresponding to $(Un)_{\rm in}$ in the range $10^{8.4}$–$10^{10.9}$ cm^{-3}.

Photoionization models can also be used to estimate $(Un)_{\rm in}$, but they suffer from different problems. First, the results are very indirect, and thus suffer from the effects of uncertainties in many observed parameters. Second, they measure the mean value $[(Un)_m]$: since $Un \propto r^{-2}$, $(Un)_m$ will be smaller than the value at the inner edge, $(Un)_{\rm in}$. Collin-Souffrin and Lasota (1988) predict a "typical" value for the region emitting the Hβ line $(Un)_m \lesssim 10^{8.3}$–$10^{9.3}$ cm^{-3}, depending on the shape of the spectrum of the ionizing radiation.

Therefore, as a "best guess", we will adopt $(Un)_{\rm in} \approx 10^{9.3}$ cm^{-3} noting that, since $r_{\rm in} \propto (Un)_{\rm in}{}^{-1/2}$, the systematic variation in radius is only about a factor of 3. This value yields reasonably good agreement between masses estimated with the dynamical method and those derived by Sun and Malkan (1989) from accretion disk fits to the optical-ultraviolet spectra of Seyfert 1 galaxies. These values lead to the relation $r_{\rm in} \simeq 3.6 \times 10^{16} Q(H)_{54}{}^{1/2}$, and the mass can be expressed as

$$M \simeq 4.9 \times 10^7 Q(H)_{54}{}^{1/2} v_{6000}^2 \, M_\odot \, , \tag{3}$$

where $Q(H)_{54} = Q(H)/10^{54}$ s^{-1} and $v_{6000} = v/6000$ km s^{-1}. The estimated values for $Q(H)$, the inner radii of the BLR, and the masses are reported in Table 3. The random errors on the masses should be of the order of a factor of 2–3: the data referring to objects having a larger error (mostly the ones with no ultraviolet and X-ray data) are followed by colons.

V. THE MASS FUNCTION

Our derivation of the mass function is based on the $\sum 1/V_m$ method (Schmidt 1968), where V_m is the maximum accessible volume within which an object could be detected above the survey limit. The differential mass function is given by

$$\phi(M) = \frac{4\pi}{\Omega \Delta M} \sum_{i=1}^{n} \frac{1}{V_{mi}} \, , \tag{4}$$

where $\Omega = 2.66$ sr of sky surveyed, summed over all n objects in each bin of width ΔM. The results are shown in Figure 1 and the numerical values are given in Table 4, where the errors represent the 1 σ Poisson errors (Gehrels 1986).

TABLE 3

RESULTS

Object	$Q(H)$ s^{-1}	r_{in} cm	$M/M_\odot$	Ref. (UV/X-ray)
MKN 335	54.9	17.0	8.3	1,2/3,4
A0048+29	53.7	16.4	7.3:	...
I ZW 1	54.9	17.0	8.2	1,2/4,5
MKN 590	54.0	16.6	8.0	6/5
MKN 1243	53.8	16.5	7.8:	...
NGC 3227	52.3	15.7	6.9	/7
NGC 3516	53.4	16.3	7.6	2/8
MKN 744	52.9	16.0	7.4	6/
NGC 4051	51.9	15.5	6.6	2/9
NGC 4151	53.4	16.3	7.4	1,2/3,5
NGC 4235	52.2	15.7	7.1:	/10
MKN 766	52.7	15.9	6.8	/5
MKN 205	55.0	17.1	8.3	2/11
MKN 231	54.0	16.6	8.1	12/
NGC 5033	51.0	15.0	5.9:	/13
MKN 789	54.0	16.6	7.0:	...
NGC 5273	52.3	15.7	7.4:	...
MKN 279	54.5	16.8	8.1	1,2/3,7
NGC 5548	54.2	16.7	7.8	1,2/3,14
MKN 817	54.7	16.9	8.3	6/
MKN 841	55.3	17.2	8.3	15/11
NGC 5940	54.3	16.7	8.3	6/8
NGC 6104	...	...	7.7:	...
2237+07	53.9	16.5	7.6:	...
NGC 7469	54.2	16.6	7.8	1,2/14
MKN 530	54.0	16.6	8.0	16/17

NOTES.—All columns give the logarithm of the quantity. The mass of NGC 6104 has been derived from the relationship *M*–*v* and therefore is quite uncertain.

REFERENCES.—(1) Wu *et al.* 1983; (2) Véron-Cetty *et al.* 1983; (3) Rothschild *et al.* 1983; (4) Tananbaum *et al.* 1986; (5) Kriss *et al.* 1980; (6) Edelson *et al.* 1989; (7) Reichert *et al.* 1985; (8) Persic *et al.* 1989; (9) Lawrence and Elvis 1982; (10) Kriss 1982; (11) Wilkes and Elvis 1987; (12) O'Brien *et al.* 1988; (13) Halpern and Steiner 1983; (14) Petre *et al.* 1984; (15) Elvis *et al.* 1986; (16) Clavel and Joly 1984; (17) Kriss 1985.

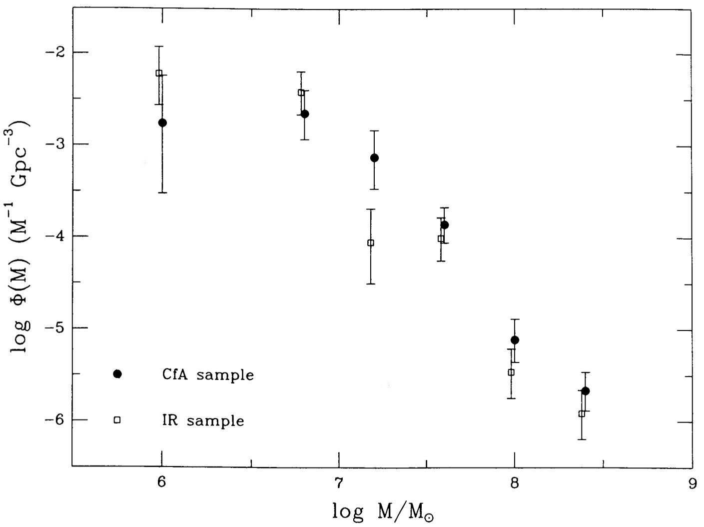

FIG. 1.—Differential mass function of Seyfert 1 nuclei. The filled points represent the determination based on the CfA sample, while the open squares are based on the 12 μm infrared selected sample. The 1 σ error bars are derived assuming Poisson statistics (Gehrels 1986). The objects in the infrared sample having $F_{12\,\mu m} < 0.50$ Jy were weighted by a factor of 1.8 following Spinoglio and Malkan (1989).

The mass function can be well approximated by a single power law for $M \gtrsim 5 \times 10^6\ M_\odot$. For a bin size $\Delta \log M = 0.4$, which was the most representative, a weighted least-squares fit yielded a mass function of the form $\phi(M) \simeq 1.3 \times 10^{-3}\ (M/10^7\ M_\odot)^{-2.0\pm0.2}$ ($\chi^2_{\rm d.o.f.} \sim 1$ for 3 d.o.f.). Different bin widths yield slopes in the range 1.83–2.04, with a typical uncertainty of 0.2, and a change in normalization of less than a factor of 2.

As a check of our results, which are based on the CfA sample of Seyfert 1 galaxies, we derived an independent estimate of the mass function from the 12 μm Seyfert 1 sample of Spinoglio and Malkan (1989). Eleven objects were in common with the CfA sample, while for nine more we used the mass estimates given by Padovani and Rafanelli (1988) and Padovani (1989), multiplied by 1.3 to normalize them to the value of $(Un)_{\rm in}$ used

TABLE 4

SEYFERT 1 DIFFERENTIAL MASS FUNCTION

log $M/M_\odot$	Number of Objects in Bin	$\phi(M)$ (M^{-1} Gpc^{-3})
6.0	1	$1.7^{+4.0}_{-1.4} \times 10^{-3}$
6.4	0	...
6.8	4	$2.3^{+1.8}_{-1.1} \times 10^{-3}$
7.2	3	$7.5^{+7.3}_{-4.1} \times 10^{-4}$
7.6	7	$1.4^{+0.8}_{-0.5} \times 10^{-4}$
8.0	5	$7.8^{+5.3}_{-3.4} \times 10^{-6}$
8.4	6	$2.2^{+1.3}_{-0.9} \times 10^{-6}$

in this paper. Finally, the masses of Mkn 1040, Mkn 1239, and IC 4329A were estimated from published values of line widths and X-ray fluxes. Therefore, we have data for 23 out of the 25 infrared selected Seyfert 1 galaxies. The remaining two objects are likely to have $M \approx 10^8$–10^9 $M_\odot$, as estimated from the masses of objects having similar luminosities, but were not included in the analysis. The mass function derived from the infrared-selected sample is in very good agreement with the one obtained from the CfA sample, as shown in Figure 1.

The differential mass function seems to exhibit a break below $M \sim 5 \times 10^6$ $M_\odot$. There is only one object (NGC 5033) in the CfA sample and three objects (NGC 1566, NGC 2992, NGC 5033) in the infrared sample with $M < 4 \times 10^6$ $M_\odot$, and they all have $M \sim 10^6$ $M_\odot$. The break is then probably due to the fact that our samples, although complete with respect to the blue magnitude and infrared flux, respectively, could be missing low-luminosity ($M_B \gtrsim -17$)—and low-mass—objects. This is confirmed by the linear regression between mass and absolute (small-aperture) magnitude which, for the CfA sample, gives for $M_B \sim -17$ a nuclear mass $M \simeq 10^{6.5 \pm 0.3}$ $M_\odot \sim 3 \times 10^6$ $M_\odot$: objects with a smaller mass have $M_B \gtrsim -17$.

The integrated mass density of Seyfert 1 nuclei can be derived in a nonparametric fashion by summing the contribution of each single object:

$$\rho(\geq M_j) = \frac{4\pi}{\Omega} \sum_{i=j}^{N} \frac{M_i}{V_{m_i}} . \tag{5}$$

The function $\rho(>M)$ is plotted in Figure 2, which shows that the mass density increases very slowly for $M \lesssim 2 \times 10^7$ $M_\odot$, where it has already reached 90% of its final value. The total nuclear mass density of Seyfert 1 galaxies having $M_B \lesssim -17$ is $\rho(M) \simeq 6.5^{+6.1}_{-2.7} \times 10^{11}$ $M_\odot$ Gpc^{-3}. The error estimates were derived by summing in quadrature the uncertainties on the single terms M_i/V_{m_i}, taking an uncertainty of a factor of 3 on the masses and of 0.3 on the observed $B(0)$ magnitudes (Huchra 1976). Using the infrared-selected sample, we obtain $\rho(M) \simeq 4.0^{+2.7}_{-1.0} \times 10^{11}$ $M_\odot$ Gpc^{-3}, in very good agreement with the previous estimate. We focus on the results obtained from the CfA sample, which has more reliable mass estimates since the line widths were measured in a homogeneous way for all the objects. The mean mass of Seyfert 1 nuclei is derived from the mass density and the number density ($N_T \simeq 3.2 \times 10^4$ Gpc^{-3}): $\langle M \rangle \equiv \rho(M)/N_T \simeq 2.0 \times 10^7$ $M_\odot$. The exclusion of the most uncertain mass determinations (see Table 3) is of little influence on our results: the mass function is slightly flatter, with a typical slope of ~ 1.8, while the mass density decreases by about 40%.

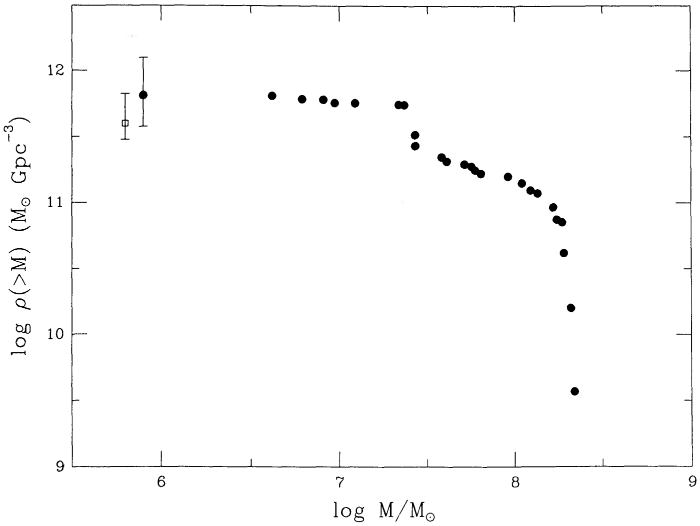

FIG. 2.—Mass density of Seyfert 1 nuclei. The filled points refer to the CfA sample. The error bar on the first point, which represents the total mass density of Seyfert 1 nuclei, has been derived summing in quadrature the uncertainties on the contributions of all the objects (see text). To avoid confusion, only the total mass density derived from the infrared selected sample is shown (*open square*).

Filippenko and Sargent (1989) have recently discovered a low-luminosity ($M_B \sim -10$) Seyfert 1 nucleus in the dwarf galaxy NGC 4395. This object is in the original CfA redshift survey sample of 2400 galaxies. It was not discovered because it is one of the approximately 100 galaxies in the parent sample that do not have measured optical spectra because of their extremely low surface brightness. Although the space density of this class of objects could be quite high (its $1/V_m$ value is $\sim 2 \times 10^5$ Gpc^{-3} at $M_{B(0)} \sim -17$), the expected mass of these nuclei is probably low, and its contribution to the total mass density should be negligible.[1] We stress, however, that even if the contribution of objects having $M_B \gtrsim -17$ were important, this would not affect our results (see § II).

VI. THE TOTAL AGN MASS DENSITY

The total mass density accumulated in AGN can be estimated from the observed quasar counts (Soltan 1982). The total energy produced per comoving volume by sources having luminosity between L and $L + dL$ at a cosmic epoch between t and $t + dt$ is $E(L, t)dL\,dt = LN(L, t)dLdt$. Using the relations between number counts and luminosity function, flux and luminosity, and comoving volume and redshift, it can be shown that

$$E = \iint E(L, t)dL\,dt = \frac{4\pi}{c} \int (1 + z)dz \int SN(S, z)dS . \tag{6}$$

Finally, assuming that the energy production is due to accretion on a compact object, the total mass density is

$$\rho_S = \frac{4\pi}{c^3} \frac{1 - \eta}{\eta} \kappa \int (1 + z)dz \int S_B N(S_B, z)dS_B , \tag{7}$$

where the subscript B indicates the blue flux, κ is the ratio between the bolometric and the blue flux, and η is the efficiency of mass-energy conversion. Note that ρ_S is independent of H_0 and q_0 and also of any anisotropy of the emitted radiation.

In terms of the blue magnitude, $\rho_S \propto \int N(B)10^{-0.4B}[1 + \langle z(B) \rangle]dB$, where $\langle z(B) \rangle$ denotes the average redshift of a quasar having magnitude B. Using the quasar counts for $z \lesssim 2.2$ and $B \lesssim 22.5$, as given by Koo, Kron, and Cudworth (1986), CP88 derived (including an average K-correction) $\rho_S \sim 2 \times 10^{14}(\kappa/30)(\eta/0.1)^{-1}$ $M_\odot$ Gpc^{-3}. The same result is obtained using more recent quasar counts, as given, for example, by Boyle, Shanks, and Peterson (1988). This value should be regarded as a lower limit, since it does not take into account accretion processes occurring at higher redshifts and

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[1] If the bolometric luminosity of NGC 4395 is $\sim 1.5 \times 10^{40}$ ergs s^{-1} [as estimated from $L(\mathrm{H}\beta)$ by Filippenko and Sargent 1989] and if it has an Eddington ratio similar to the one typical of Seyfert 1 nuclei ($L/L_\mathrm{E} \sim 5 \times 10^{-2}$: CP89), then its nuclear mass would be $\sim 2 \times 10^3$ $M_\odot$ and $M/V_m \sim 5 \times 10^8$ $M_\odot$ Gpc^{-3} $\sim 10^{-3}\rho(M)$.

the contribution of faint objects. Since more than 50% of ρ_S comes from the range $19 \lesssim B \lesssim 21$, an extension to fainter magnitudes is not likely to change its value much. Even if the counts go like $N(B) \propto 10^{0.32B}$ (Boyle, Shanks, and Peterson 1988) up to $B \simeq 25$, the increase is only ~20%. A more sizable increase is expected from the extension at $z \gtrsim 2.2$, but a quantitative estimate is difficult because studies of complete high-redshift samples are still in progress (e.g., Schmidt, Schneider, and Gunn 1988; Warren, Hewett, and Osmer 1988). Moreover, any incompleteness in the quasar counts, which is likely for $M_B \gtrsim -23$, will decrease the estimated value of ρ_S.

VII. DISCUSSION

The key point of this paper is that the nuclear mass density of Seyfert 1 galaxies having $M_B \lesssim -17$ is about two orders of magnitude smaller than the total mass density accumulated in AGN contributing to quasar counts. It is important to determine the significance of this result. Expressing it in the form of the ratio of the two quantities, $\delta = \rho(M)/\rho_S$ and in terms of the parameters on which they depend, we have

$$\delta \approx 3\ 10^{-3}(H_0/50)^2[(Un)_{\rm in}/10^{9.3}]^{-1/2}(\kappa/30)^{-1}(\eta/0.1)/(1-\eta)\,. \tag{8}$$

We now study the influence of the various parameters and assumptions on δ.

1. H_0 is believed to be in the range 50–100 km s^{-1} Mpc^{-1} so that the term containing it could give an increase of up to a factor of 4.

2. The value of $(Un)_{\rm in}$ for the Hβ–emitting region is probably in the range $10^{8.3}$–$10^{10.2}$ cm^{-3}, as discussed in § IV, and the error on δ a factor of ~3.

3. Various "bolometric corrections" (κ) have been derived by Padovani and Rafanelli (1988) and Padovani (1989) estimating the bolometric luminosity for a sample of AGN from data in the range 100 μm–100 keV. The one relative to the blue luminosity was not given in those papers, but it is $L_{\rm Bol}/L_{300-600\,{\rm nm}} \simeq 10^{1.5\pm0.4} \approx 30$ for low-redshift AGN. This is derived assuming a power-law behavior between ultraviolet and X-ray energies, as in the derivation of the number of ionizing photons. To study the effect of the presence of a "big bump" on our results, we have considered the case of PG 1211+143, the quasar with the highest ratio of $L_x/L_{\rm opt}$ in the Palomar Bright Quasar Survey. In particular, we have considered the accretion disk fit *B* to the optical, ultraviolet, and X-ray data of this object by Bechtold *et al.* (1987). As can be seen from their Figure 5, this fit gives an enormous "big bump": it is easy to show that the increase in ionizing luminosity as compared to the case of a power law is of about a factor of 15, which corresponds to an increase of a factor of 3 in bolometric luminosity (Padovani 1989). On the other hand, the number of ionizing photons increases only by a factor of 4. Since the mass goes like $Q(H)^{1/2}$, it then follows that even in this extreme case δ varies very little. In other words, the increase in ρ_S due to the increment in total luminosity cancels out the effects of the larger number of ionizing photons.

4. The efficiency of the mass-energy conversion is usually assumed to be ~0.1. The theoretical value for a Schwarzschild black hole is $\eta = 0.057$ while for a Kerr black hole $\eta \lesssim 0.3$ (Thorne 1974), so the variation of the efficiency term is in the range $\frac{1}{2}$–4. It has to be kept in mind that the efficiency here discussed is the average one between $z \simeq 2.2$ and 0. In the framework of luminosity evolution, most of the mass is accreted at high redshifts because the accretion rate was then larger. Since there is evidence that high-redshift quasars have super-Eddington luminosities (Padovani 1989), any accretion disk around the central object of primeval AGN is going to be thick and therefore not very efficient (cf. Abramowicz, Calvani, and Madau 1987). It follows that it is quite unlikely to have a substantial increase in the efficiency term.

5. Incompleteness could affect our results. However, we have shown (§ V) that the mass function derived from an independently selected sample is indistinguishable from the one obtained from the CfA sample, indicating that both estimates are free from strong biases. Moreover, the contribution of low-luminosity objects ($M_B \gtrsim -17$), which could have been missed, is not important even if it is not negligible, because those objects could not be dimmed quasars contributing to the quasar counts.

6. If the emitting matter is orbiting the central object instead of being in infall, the mass is a factor of 2 larger than estimated; on the other hand, if the motion is gravitationally unbound, the masses are smaller, and therefore δ decreases.

7. As previously discussed, ρ_S is only a *lower* limit to the total mass accumulated in AGN: therefore δ is actually an upper limit.

8. Our result relies on the hypothesis of accretion on a compact object as primary mode of energy production: if this is not the case, then ρ_S is meaningless. Nevertheless, one way to test the gravitational idea is through the study of the nuclear masses of AGN.

It follows that even taking $H_0 = 100$ km s^{-1} Mpc^{-1} and $\eta \simeq 0.3$, one gets $\delta \lesssim 6 \times 10^{-2}$, and therefore, in view of the above discussion, it is extremely unlikely that δ is as large as 1.

It could be argued that, since some Seyfert 2 galaxies show polarized flux spectra similar to those of Seyfert 1 nuclei (Miller 1989 and references therein), suggesting the existence of a thick torus around the central source, a fraction of the total mass density of AGN could actually reside in the nuclei of Seyfert 2 galaxies. There are very few nuclear mass estimates for Seyfert 2 galaxies. If we assume that their masses are comparable to those of Seyfert 1 nuclei (which is not inconsistent with the data for six Seyfert 2 galaxies in the sample of Wandel and Mushotzky 1986) and if we take into account that Seyfert 2 galaxies are about 3 times more numerous than Seyfert 1 galaxies (Huchra and Burg 1990), they could have a mass density a factor of 3 larger. Since there are no "narrow-line quasars," δ could increase by a factor of 3 only if *all* Seyfert 2 galaxies had obscured Seyfert 1 nuclei, while the available observations seem to favor the picture that Seyfert 1 and Seyfert 2 galaxies are *not* intrinsically identical objects viewed from different directions (Miller 1989). Moreover, broad-line quasars should evolve not only in Seyfert 1 but also in Seyfert 2 galaxies, against the evidence derived from the study of the luminosity functions.

In summary:

1. Using the CfA complete sample (Huchra and Burg 1990), we have derived the first mass function of Seyfert 1 nuclei ($M_B \lesssim -17$). It is well described by $\phi(M) \propto M^{-2}$ for $M \gtrsim 5 \times 10^6\,M_\odot$. This estimate is free of strong selection effects since it is in very good agreement with the mass function obtained using a completely independent sample, the infrared-selected sample of Spinoglio and Malkan (1989).

2. The mean mass of Seyfert 1 nuclei having $M_B \lesssim -17$ is $\sim 2 \times 10^7\,M_\odot$, and the nuclear mass density is $\sim 6 \times 10^{11}\,M_\odot$ Gpc^{-3}. Since the total mass density of AGN, estimated from

the energetics associated with quasar counts, is more than two orders of magnitude larger, Seyfert 1 galaxies cannot be the only "aged-quasars." Instead, remnants of past activity have to be present in a much larger number of galaxies (as derived using a different approach by CP89). We regard as extremely unlikely the possibility that this discrepancy could be due to systematic errors in our determination of the masses of Seyfert 1 nuclei and/or the total mass density of AGN.

This result has very important consequences for models of AGN evolution. In particular, in the framework of a gravitational origin of the emitted radiation, it rules out a long-lived activity phenomenon restricted to a few percent of normal galaxies, as predicted by models of continuous luminosity evolution. Different scenarios, such as recurrent, short bursts of activity or a single flash in the host galaxy lifetime, with a total duration of activity $\approx 10^8$ yr, are favored.

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