Mon. Not. R. astr. Soc. (1982) **200**, 115–122

Masses of quasars

Andrzej Sołtan *N. Copernicus Astronomical Centre, Bartycka 18, 00-716 Warsaw, Poland*

Received 1981 October 18; in original form 1981 August 19

Summary. Quasar masses are investigated assuming that accretion on to massive black holes is the ultimate source of energy produced by quasars. Lower limit for the total energy emitted and the mass accumulated in black holes in 1 Gpc^3 is calculated using various data on quasar counts and bolometric luminosities. The energy produced is at least $8.5 \times 10^{66}\,\mathrm{erg\,Gpc^{-3}}$. This result is independent of the cosmological model. Assuming that quasars reside in nuclei of giant galaxies it is shown that minimum masses of dead quasars are of the order of $10^8 M_\odot$, close to the observational threshold for ground-based telescopes.

1 Introduction

Some aspects of the quasar phenomenon seem to be at least qualitatively resolved. It is now widely accepted that quasars belong to a class of active galactic nuclei together with Seyfert galaxies and BL Lac objects. A consensus is not reached, however, on the most 'interesting' point, namely, what is the central 'engine'. Several interpretations are given in the literature (Rees 1978, and references therein). At present, 'the most promising' is the massive black-hole model. In this model energy is supplied by matter accreting on to the black hole. While details of the processes involved are quite uncertain, it is clear that infalling matter is accumulated in the black hole during a lifetime of the quasar. In this paper I analyse implications of this trivial fact for estimates of the present masses of quasars. In particular, the question whether virtually each galaxy undergoes for a short time an active phase as a quasar, or whether quasars are more permanent but rare objects occurring only in some galaxies, is addressed here. Some observations elucidating this problem are indicated. Basic assumptions and calculations are given in Section 2. In Section 3 prospects for observational detection of the evaluated masses are presented.

The central mass is practically a free parameter in the quasar models. Constraints derived from observations have not been very restrictive yet. There were in effect two methods of quasar mass determination. In one approach a gravitational lens effect was tested. This was applied to a close pair of quasars 1548 + 115a, b (Paczyński 1974; Gott & Gunn 1974). Lack of an appreciable imaging of the more distant pair member by the nearer one provided an upper limit of $4\text{–}7 \times 10^{12} M_\odot$ for 1548 + 115a. In the other method (Burbidge & Perry 1976) central mass is evaluated by the analysis of its interaction with emission line clouds. Burbidge & Perry found that the quasar masses are between 5×10^7 and $2 \times 10^9 M_\odot$. It is, however, difficult to judge whether these limits are firm since the method is based on some speculative assumptions. The approach given in this paper provides less restrictive limits but is more straightforward and only well-motivated assumptions are made.

2 Method of calculation

Total mass accumulated in the black hole due to the accretion is given by

$$m = c^{-2} \kappa^{-1} LT, \tag{1}$$

where L is the luminosity, T is the lifetime of the quasar and κ is the efficiency of energy conversion. Only L is known for an individual object. Using quasar counts one can calculate the total energy emitted by all quasars in a unit volume and find limits for the total mass of the black holes. The quasar lifetime is immaterial for that problem. Let $E(L, t)$ denote the energy produced in $1\,\mathrm{Gpc}^3$ by sources with the luminosity L in cosmic epoch t. Thus

$$E(L, t)\, dL\, dt = L\phi(L, z)\, dL,\, dt, \tag{2}$$

where $\phi(L, z)$ is the luminosity function i.e. the number of objects having the luminosity L in $1\,\mathrm{Gpc}^3$. Comoving coordinates are used and $1\,\mathrm{Gpc}^3$ corresponds to the volume measured in the present epoch. Quasar evolution is allowed by dependence of the luminosity function on redshift z. The luminosity function is related to the number of quasars in one steradian at redshift z with observed flux S by equations

$$n(S, z)\, dS\, dz = \phi(L, z)\, dL \frac{dV}{dz}\, dz, \qquad L = 4\pi D^2 S, \tag{3}$$

where D is the photometric distance. Using equation (3), relation (2) becomes

$$E(L, t)\, dL\, dt = 4\pi S\, n(S, z)\, dS\, D^2 \left(\frac{dV}{dz}\right)^{-1} dt. \tag{4}$$

It is straightforward to show that for Friedmann model

$$D^2 \left(\frac{dV}{dz}\right)^{-1} dt = \frac{1}{c}(1 + z)\, dz. \tag{5}$$

Thus the total energy emitted by the whole population of quasars in $1\,\mathrm{Gpc}^3$ is

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

where integrals are over entire range of quasar redshifts and fluxes. The energy E in equation (6) is expressed only by observable quantities and is independent of the Hubble constant and the deceleration parameter.

One can obtain equation (6) in the more elegant way by noting that observed intensity of the radiation due to all the sources in one steradian with redshift z is given by

$$b(z) = \int dS\, S\, n(S, z). \tag{7}$$

For a static isotropic universe energy density u is related to the radiation intensity by

$$u = \frac{4\pi}{c} b = \frac{4\pi}{c} \int dz\, b(z), \tag{8}$$

(here z is a measure of distance). From a homogeneity of the Universe it implies that the energy density u is equal to the emitted energy E. In the expanding Universe, E is greater than u by a factor of $(1+z)$. This $(1+z)$ correction combined with equations (7) and (8) leads again to equation (6).

It is more convenient to use blue magnitude B rather than bolometric flux S in equation (6). I have assumed that flux S is proportional to the flux in B band

$$S = K_{\mathrm{BC}}\,(f_{\mathrm{B}}\,\nu_{\mathrm{B}}), \tag{9}$$

where $\nu_{\mathrm{B}} = 6.80 \times 10^{14}$ Hz is the effective frequency of filter B, f_{B} is the flux at frequency ν_{B}, and K_{BC} is the 'bolometric correction' for quasars. K_{BC} will be estimated below. Substitution of equation (9) and (10) into equation (6) gives

$$E = \frac{4\pi}{c} K_{\mathrm{BC}} \int dB (f_{\mathrm{B}}\,\nu_{\mathrm{B}})\, n(B)\, (1 + \langle z\,|B\rangle). \tag{10}$$

Factor $(1 + \langle z\,|B\rangle)$ is a result of integration over redshifts and $\langle z\,|B\rangle$ denotes the average quasar redshift at magnitude B. Following calibration is used in this paper

$$\log f_{\mathrm{B}} = -22.39 - 0.4B, \tag{11}$$

where f_{B} is in W m^{-2} Hz^{-1}.

Two remarks concerning equation (10) are implied by the observational data. First, uncertainty in $n(B)$ relation at faint end of counts is much higher than errors introduced by uncertainties of $\langle z\,|B\rangle$. Second, there are no data on quasar counts below ~ 22.5 mag. Thus only lower limit of E can be determined.

2.1 $n(B, z)$ RELATION FOR QUASARS

Quasar counts have been investigated by several authors in the last few years. In this section some results are briefly discussed in the context of the present consideration. At bright end ($B < 18$) cumulative quasar counts are adequately represented by the formula: $\log N(<B) = 2.16\,(B - 18.33)/2.5$ (Braccesi *et al.* 1980), where N is per square degree. It is well established that at fainter magnitudes counts become flatter (e.g. Vaucher & Weedman 1980). For $18 < B < 19$ I have used quasar samples selected from ultraviolet excess objects (Braccesi, Formiggini & Gandolfi 1970) and from emission line objects (Osmer 1980). Selection using the ultraviolet excess is effective for redshifts $z \lesssim 2.1$ (Braccesi *et al.* 1980) and using the emission lines for $z > 1.8$. Combining both samples and taking into account contamination by stars of the Braccesi sample (Setti & Woltjer 1973), I find $N(18 < B < 19) = 2.9$ sq. deg^{-1}. This estimate is consistent with quasar surface density derived by Steppe, Véron and Véron (1979).

For $19 < B < 20$ '$13^{\mathrm{h}} + 36°$ very faint' sample (Formiggini *et al.* 1980; Bònoli *et al.* 1980) was used together with the data quoted above. Results of 12 quasars sq. deg.$^{-1}$ is in agreement with recent estimate by Vaucher & Weedman (1980). Below $B = 20$ only very rough estimate of the quasar surface density is available. Consistent with the remark at the end of the last section, I took from the literature the lowest estimate of 50 QSOs sq. deg.$^{-1}$ above $B = 22.5$ (Bahcall & Soneira 1980). This is by a factor of 4 lower than the probably more

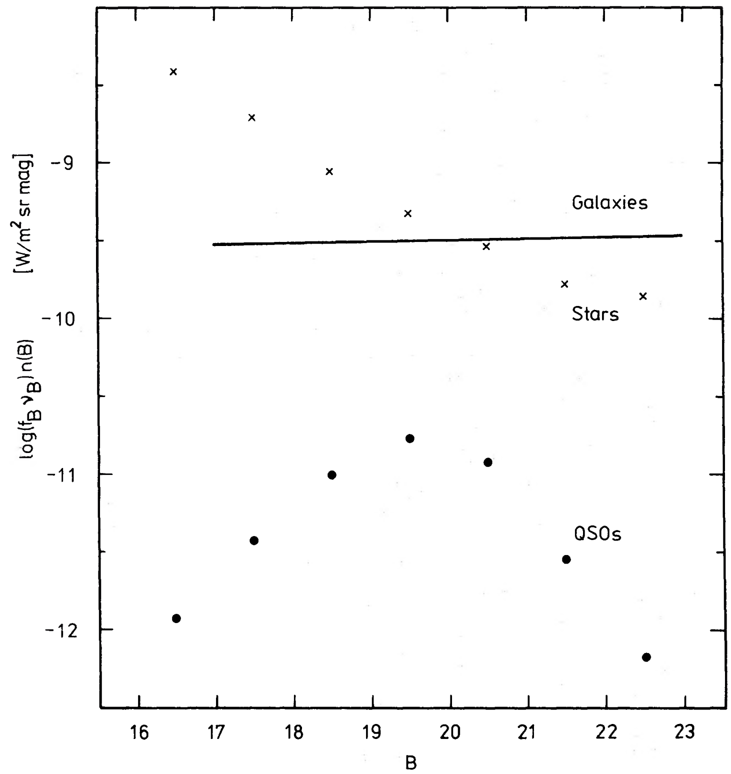

Figure 1. Adopted intensity of quasar radiation in the B band $(f_B \nu_B) \times n(B)$ versus apparent magnitude B. The intensity of radiation from stars and galaxies (Tyson & Jarvis 1981) is shown for comparison.

realistic estimate by Gilmore (1981). In calculations I have assumed that counts between $B = 20$ and 22.5 follow a power law with the slope and normalization implied by the data given above. Adopted quasar counts multiplied by $(f_B \nu_B) \sim 10^{-0.4B}$ are presented in Fig. 1. Counts of stars and galaxies from Tyson & Jarvis (1981) are plotted for comparison. A steep decline of the quasar counts below $B = 20$ is of course a result of the very low quasar surface density taken from Bahcall & Soneira. If data by Gilmore are accepted, function $10^{-0.4B}\, n(B)$ would have a flat maximum around 20 mag with the slow decline towards the fainter objects. It means that a substantial fraction of energy is emitted by quasars above the observational threshold of 22.5 mag.

To estimate the average quasar redshift between 17 and 19 mag, I have used the published redshifts from Braccesi's and Osmer's samples. Properly weighted values are $\langle z \rangle_{17-18} = 0.9$, $\langle z \rangle_{18-19} = 1.5$. At the fainter magnitudes the average redshift of 1.5 was adopted. This was derived from the radio-selected quasars in a quasar catalogue compiled by Hewitt & Burbidge (1980). Redshift distributions of optically and radio-selected quasars are similar at 18 mag and it was postulated by Schmidt (1970) that these distribution are identical.

2.2 QUASAR BOLOMETRIC LUMINOSITY

Available data on the electromagnetic spectrum of quasars are discussed elsewhere (Sołtan 1980). In this section results on quasar bolometric luminosities are summarized, including some recent results. Spectrophotometry in infrared and optical region (Neugebauer *et al.* 1979) and in ultraviolet up to the Lyman limit (Osmer 1979) was obtained for a substantial number of quasars. Continuous spectra between $\sim 10\,\mu$m and $\sim 0.1\,\mu$m are on the average satisfactorily approximated by a power law $(f_\nu \sim \nu^{-\alpha})$ with a spectral index equal to 1.

This can be expressed in the form

$$S(10\text{–}0.1\,\mu\text{m}) = 4.6\,(f_B\,\nu_B), \tag{12}$$

where $S(10\text{–}0.1\,\mu\text{m})$ is the flux within indicated limits. In the far infrared, data are too scarce to be included in this consideration, while at the radio frequencies energy emitted by quasars is on the average negligibly small. The high energy part of the quasar spectrum requires some discussion. Extensive data on the quasar luminosities in soft X-rays were collected during the last two years (Tananbaum *et al.* 1979; Zamorani *et al.* 1981). At higher energies, devices nowadays are not sufficiently sensitive to detect quasars. The only quasar detected both in hard X- and γ-ray region is 3C 273 (Bradt *et al.* 1979; Bignami *et al.* 1979 and references therein). Giacconi *et al.* (1979) have shown that a significant fraction of an extragalactic background is produced by the discrete X-ray sources, mostly quasars. Thus, the average quasar spectrum is not very different from the background spectrum. Zamorani *et al.* (1981) calculated 'spectral index' between 2500 Å and 2 keV for the large number of quasars. The average of 1.45 for the whole quasar population was obtained. Using this value and the background spectrum compiled by Schwartz (1979) it is straightforward to show that

$$S(1\text{–}1000\,\text{keV}) = 1.4\,(f_B\,\nu_B). \tag{13}$$

This is based on the assumption that the quasar contribution to the X-ray background does not vary drastically from soft X-rays up to 1000 keV.

Equations (12) and (13) give the lower limit (far infrared and γ-ray region are excluded) for the 'bolometric correction' $K_{BC} = 6.0$. All the numerical values necessary to calculate E are now collected and can be substituted into equation (10). This is done in the next section.

3 Results and prospects for observational tests

According to the data derived in the preceding section

$$E = 2.9 \times 10^{-10}\,\text{erg m}^{-3} = 8.5 \times 10^{66}\,\text{erg Gpc}^{-3}. \tag{14}$$

As was stressed in Section 2 this result is independent of H_0 and q_0. The mass accumulated in quasars is

$$M = \kappa^{-1}\,9.4 \times 10^{42}\,\text{kg Gpc}^{-3} = \kappa^{-1}\,4.7 \times 10^{12} M_\odot\,\text{Gpc}^{-3}. \tag{15}$$

For any reasonable energy conversion κ, it has a negligible contribution to the total mass density and to the critical density $\rho_c = 3H^2/8\pi G$:

$$M/\rho_c = \kappa^{-1}\,7 \times 10^{-8}\,(H/50\,\text{km s}^{-1}\,\text{Mpc}^{-1})^{-2}. \tag{16}$$

However, M is distributed discretely and chances for its detection are substantially increased. Numbers given in equation (14)–(16) are actually the lower limits for E and M because very low value of the quasar counts was used here. With the more realistic $n(B)$ relation for $B > 20$, E and M are increased by a factor of ~ 2.

It is well known that quasars as a class rapidly evolve (Schmidt 1968). Space density of the luminous quasars is now about 150 times smaller than at $z = 1$. It implies that substantial number of dead quasars exists locally (Schmidt 1978). The mass M in equation (15) is distributed mostly among these objects. Several quasars at deep photographs have diffuse images (Wyckoff *et al.* 1980, references therein). In some cases a physical association between quasar and the underlying galaxy is undoubtedly established. Due to the obvious selection only giant galaxies are observed around quasars. It cannot be ruled out that quasars are associated also with 'normal' galaxies. To explore this conjecture, let us assume that quasars are transient phenomena which can occur randomly in galaxies brighter than limiting magnitude M_B. The space density of galaxies is of course given by the luminosity function. I have used the cumulative luminosity distribution $\psi(M_B)$ based on the analytical expression for the luminosity function by Schechter (1976). A Hubble constant $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ was assumed. Ratio $\epsilon = E/\psi(M_B)$ is the average energy per galaxy emitted by quasars. In Fig. 2 the full line shows ϵ as a function of M_B. To find the black hole mass per galaxy one should multiply the value read from the figure by κ^{-1}. For instance, if all the galaxies brighter than M31 ($M_B = -20.3$) contain dead quasars the black hole mass $m \approx \kappa^{-1} 2 \times 10^6 M_\odot$. To facilitate comparison with the observational data on massive objects in galactic nuclei, the broken line in Fig. 2 shows $m \sim M_B$ relationship assuming $\kappa = 0.1$ and the quasar counts by Gilmore (1981). Obviously, it is likely that quasars were not distributed uniformly among galaxies. If only some of galaxies brighter than M_B have flared up as a quasar in the past, the masses of dead quasars are higher than indicated by the curve in Fig. 2.

These predictions can be confronted with the observations of the galactic nuclei. The mass distribution in elliptical galaxies and in bulges of spiral galaxies is usually consistent with the King model (King 1966). Deviation from the King distribution at the Galactic Centre can be attributed to the existence of a massive object in the nucleus. On this ground a point mass of the order of $10^9 M_\odot$ in M 87 and NGC 6521 was postulated (Sargent *et al.* 1978; Young *et al.* 1978, 1979). Those estimates are marked by filled circles in Fig. 2. Evidence for a black hole in M 87 was questioned by Duncan & Wheeler (1980) and Dressler (1980). It was pointed out that assumptions inherited in the King model (e.g. isotropy of the velocity dispersion in the nucleus) are not fulfilled in M 87. If the present data do not necessarily invoke the black hole in M 87, results quoted above may be considered as the upper limits for masses of such objects. Two other galaxies (NGC 4874 and 4889) analysed by Young

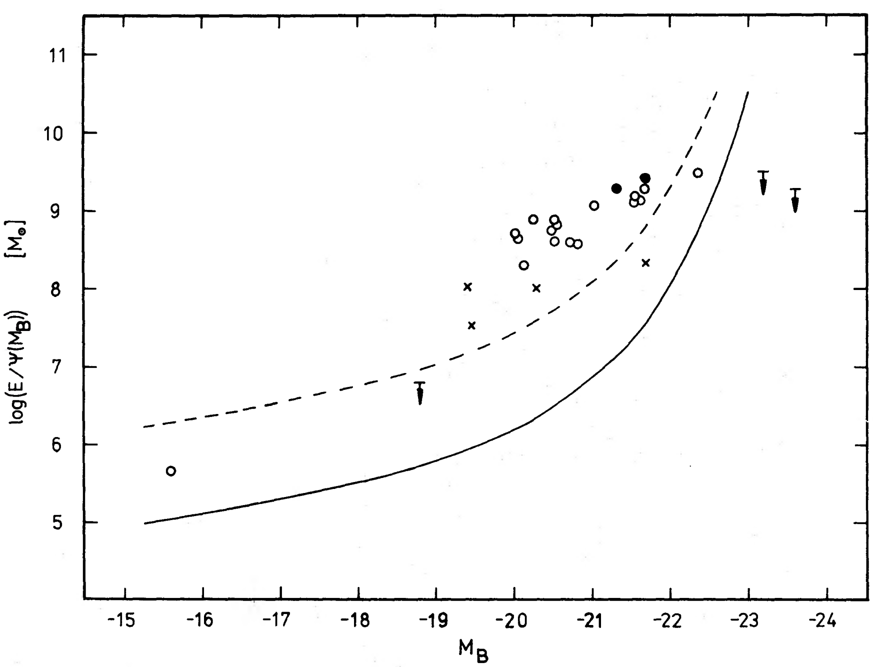

Figure 2. Solid curve: energy emitted by quasars in 1 Gpc^3 divided by the number of galaxies brighter than absolute magnitude M_B. Broken curve: 'the best estimate' of quasar masses assuming that quasars occupy all galaxies brighter than M_B. Filled circles and upper limits are the estimates of masses for central point objects in nearby galaxies. Open circles and crosses are the core masses of some elliptical and spiral galaxies. See text for details.

et al. (1979) fit the King distribution very well. The upper limits for possible central point masses in these galaxies in terms of the core mass were derived by the authors. Using standard relation for the King model, I have expressed given upper limits in solar masses and plotted them in Fig. 2. The detection of the massive objects in the galactic nuclei is limited by 'seeing'. With ground-based telescopes, a point mass of the order of a few tenths of the core mass – the characteristic mass in the King model – can be detected. In Fig. 2, core masses of several elliptical galaxies (open circles) and of nuclei of spiral galaxies (crosses) are shown. The data were collected from the available observations. The upper limit of $6 \times 10^6 M_\odot$ for the compact object in the nucleus of the Galaxy (Lacy, Baas & Townes 1979; Oort 1977) is also shown. Proximity of the observational upper limits to the masses derived from the quasar counts provides prospects for the detection of the black holes in the galactic nuclei with the Space Telescope. High resolution of the Space Telescope will allow observation of masses of a factor of 10 or more below the present limits. It is likely that the mass distribution of quasar remnants will be determined. These data combined with the improved quasar counts would provide constraints on the energy conversion κ and discriminate between specific models of the quasar evolution. Nevertheless, new light can be shed on this subject also, using present-day observations. Galaxies associated with quasars for which the luminosity estimates are available have absolute magnitudes around -20 to -22. At -21 mag the point mass below $\sim 10^9 M_\odot$, i.e. just above the broken line in Fig. 2, can be detected. Observations, say, of a dozen of -21 mag galaxies may provide important information on the number of dead quasars. Suppose that such observations give negative results. It would mean that either quasars on the average occupy nuclei of more numerous fainter galaxies or that only small fractions of the luminous galaxies have undergone an active phase as a quasar and contain the massive black hole. In the latter case the accumulated mass would be extremely high, much above the mass range found by Burbidge & Perry (1976).

4 Summary

Quasar counts are used as an indicator of the total mass accumulated in quasars in 1 Gpc^3. If there are ~ 200 QSOs sq. deg.$^{-1}$ brighter than 22.5 mag (Gilmore 1981), the mass contained in the dead quasars in 1 Gpc^3 is $8 \times 10^{13} M_\odot$ assuming 10 per cent efficiency of conversion of mass into radiation. Within a framework of the standard quasar model, this mass is distributed in some number of black holes in the galactic nuclei. If the quasar masses are of the order of 10^8–$10^9 M_\odot$, then the number of dead quasars in 1 Gpc^3 is 10^5–10^6. Such high space density of the dead quasars makes good prospects for the observational detection of the quasar remnants in the nearby galaxies. It is reasonable to search for the quasar remnants in the giant galaxies with high central density, where conditions for building up the massive black hole are more favourable than in galaxies without a distinct central condensation. Thus, postulated black holes in M87 and NGC 6521 are fully consistent with the conjecture that quasars are powered by massive black holes. Moreover, lack of massive point objects in the nuclei of a few dozens of galaxies with $M_B = -20$ to -21 would be striking.

Acknowledgment

I wish to thank Professor B. Paczyński for suggesting the idea of this work.

References

Bahcall, J. N. & Soneira, R. M., 1980. *Astrophys. J.*, **238**, L17.
Bignami, G. F., Fichtel, C. E., Hartman, R. C. & Thomson, D. J., 1979. *Astrophys. J.*, **232**, 649.

Bònoli, F., Braccesi, A., Marano, B., Merighi, R. and Zitelli, V., 1980. *Astr. Astrophys.*, **90**, L10.
Braccesi, A., Formiggini, L. & Gandolfi, E., 1970. *Astr. Astrophys.*, **5**, 264.
Braccesi, A., Zitelli, V., Bònoli, F. & Formiggini, L., 1980. *Astr. Astrophys.*, **85**, 80.
Bradt, H. V., Doxsey, R. E., Johnson, M. D., Schwartz, D. A., Burkhead, M. S., Dent, W. A., Liller, W. & Smith, A. G., 1979. *Astrophys. J.*, **230**, L5.
Burbidge, G. & Perry, J., 1976. *Astrophys. J.*, **205**, L55.
Dressler, A., 1980. *Astrophys. J.*, **240**, L11.
Duncan, M. J. & Wheeler, J. C., 1980. *Astrophys. J.*, **237**, L27.
Formiggini, L., Zitelli, V., Bònoli, F. & Braccesi, A., 1980. *Astr. Astrophys. Suppl. Ser.*, **39**, 129.
Giacconi, R. *et al.*, 1979. *Astrophys. J.*, **234**, L1.
Gilmore, G., 1981. *Mon. Not. R. astr. Soc.*, **195**, 183.
Gott, J. R. & Gunn, J. E., 1974. *Astrophys. J.*, **190**, L105.
Hewitt, A. & Burbidge, G., 1980. *Astrophys. J.*, **227**, L17.
King, I. R., 1966. *Astr. J.*, **71**, 64.
Lacy, J. H., Baas, F. & Townes, C. H., 1979. *Astrophys. J.*, **227**, L17.
Neugebauer, G., Oke, J. B., Becklin, E. E. & Matthews, K., 1979. *Astrophys. J.*, **230**, 79.
Oort, J. H., 1977. *A. Rev. Astr. Astrophys.*, **15**, 295.
Osmer, P. S., 1979. *Astrophys. J.*, **227**, 18.
Osmer, P. S., 1980. *Astrophys. J., Suppl. Ser.*, **42**, 523.
Paczyński, B., 1974. *Nature*, **249**, 329.
Rees, M. J., 1978. *Phys. Scripta*, **17**, 193.
Sargent, W. L. W., Young, P. J., Boksenberg, A., Schortridge, K., Lynds, C. R. & Hartwick, F. D. A., 1978. *Astrophys. J.*, **221**, 731.
Schechter, P., 1976. *Astrophys. J.*, **203**, 297.
Schmidt, M., 1968. *Astrophys. J.*, **151**, 393.
Schmidt, M., 1970. *Astrophys. J.*, **162**, 371.
Schmidt, M., 1978. *Phys. Scripta*, **17**, 135.
Schwartz, D. A., 1979. *CFA preprint No. 1039.*
Setti, G. & Woltjer, L., 1973. *Ann. NY Acad. Sci.*, **224**, 8.
Sołtan, A., 1980. *Acta Astr.*, **30**, 365.
Steppe, H., Véron, P. & Véron, M. P., 1979. *ESO preprint No. 40.*
Tananbaum, H. *et al.*, 1979. *Astrophys. J.*, **234**, L9.
Tyson, J. & Jarvis, J. F., 1981. *Astr. J.*, **86**, 476.
Vaucher, B. G. & Weedman, D. W., 1980. *Astrophys. J.*, **240**, 10.
Wyckoff, S., Wehinger, P. A., Gehren, T., Morton, D. C., Boksenberg, A. & Albrecht, R., 1980. *Astrophys. J.*, **242**, L59.
Young, P. J., Sargent, W. L. W., Kristian, J. & Westphal, J. A., 1979. *Astrophys. J.*, **234**, 76.
Young, P. J., Westphal, J. A., Kristian, J., Wilson, C. P. & Landauer, F. P., 1978. *Astrophys. J.*, **221**, 721.
Zamorani, G. *et al.*, 1981. *Astrophys. J.*, **245**, 357.