The obscured growth of massive black holes

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ABSTRACT
The mass density of massive black holes observed locally is consistent with the hard X-ray Background provided that most of the radiation produced during their growth was absorbed by surrounding gas. A simple model is proposed here for the formation of galaxy bulges and central black holes in which young spheroidal galaxies have a significant distributed component of cold dusty clouds which accounts for the absorption. The central accreting black hole is assumed to emit both a quasar-like spectrum, which is absorbed by the surrounding gas, and a slow wind. The power in both is less than the Eddington limit for the black hole. The wind however exerts the most force on the gas and, as earlier suggested by Silk & Rees, when the black hole reaches a critical mass, it is powerful enough to eject the cold gas from the galaxy, so terminating the growth of both black hole and galaxy. In the present model this point occurs when the Thomson depth in the surrounding gas has dropped to about unity and results in the mass of the black hole being proportional to the mass of the spheroid, with the normalization agreeing with that found for local galaxies by Magorrian et al. for reasonable wind parameters. The model predicts a new population of hard X-ray and sub-mm sources at redshifts above one which are powered by black holes in their main growth phase.

Key words: galaxies:active – quasars:general – galaxies:Seyfert – infrared:galaxies – X-rays:general

1 INTRODUCTION
The local mass density of massive black holes residing in the nuclei of galaxies (Magorrian et al 1998; Richstone et al 1998) is in good agreement with that expected from the intensity of the X-ray background at 30 keV (Fabian & Iwasawa 1999; Salucci et al 1999). The X-ray background is assumed to be due to radiatively-efficient accretion onto black holes at redshifts $z \sim 1 - 2$, with accretion accounting for the bulk of their mass. An important requirement is the presence of large column densities of absorbing matter, $N_H \sim 10^{24} \text{ cm}^{-2}$, around many of the X-ray sources. Intrinsically they are assumed to radiate the broad-band spectrum of a typical quasar (Elvis et al 1994), with a large UV bump, and a power-law X-ray continuum of photon index, $\Gamma \approx 2$, up to a few 100 keV. Photoelectric absorption in this matter then hardens the observed spectrum considerably below 30 keV so that the cumulative spectrum from a population of sources with a range of column densities and redshifts resembles that of the observed X-ray Background (Setti & Woltjer 1989; Madau et al 1994; Celotti et al 1995; Matt & Fabian 1994; Comastri et al 1995; Wilman & Fabian 1999). Provided that the sources are not too Thomson-thick, it is only above about 30 keV that the unabsorbed radiation from growing black holes is observed.

Two major issues for the model are discussed here; a) the typical mass and luminosity of the obscured objects and b) the source of the obscuring matter. The first a) is an issue because few luminous obscured quasars $L(2 - 10 \text{ keV}) > 10^{44} \text{ erg s}^{-1}$ have yet been found by X-ray (or other waveband) surveys or studies (Boyle et al 1998; Brandt et al 1997; Halpern et al 1999), so it might seem that highly obscured objects are only of low luminosity. This could be a serious problem for the growth of black holes of mass $10^9 \text{ M}_\odot$ or more, which might have luminosities considerably more than that. The second b) requires large column densities to obscure most of the Sky as seen from the sources, in order that most accretion power in the Universe is absorbed (Fabian & Iwasawa 1999 estimate that about 85 per cent is absorbed). We have previously argued that a circumnuclear starburst is responsible for the obscuration in nearby objects (Fabian et al 1998), but in its simple form could be difficult to sustain if the central black hole takes a Gyr or more to grow to its present mass.

A model is presented here in which a black hole grows with its surrounding stellar spheroid by the accretion of hot gas. The gas is also cooling and forming a distributed gaseous cold component within which stars slowly form. In the central regions the cold component provides the required column density for absorption of the quasar radiation from
the accreting black hole. The quasar is assumed to make a slow wind, which eventually becomes powerful enough to blow away the absorbing gas, probably due to a wind, and an unobscured quasar is seen (see Silk & Rees 1998 and Blandford 1999 for a similar wind model). Because the fuel supply for the black hole has also been ejected however, the quasar dies when its accretion disc is exhausted. The high obscuration phase occurs only during the growing phase and thus at redshifts greater than unity which have not been explored yet in the hard X-ray band. Reprocessing of the radiation by the absorbing gas into far infrared emission may make these objects detectable in the sub-millimetre band.

2 GROWTH OF THE BLACK HOLE

Magorrian et al (1998) find from the demographics of nearby massive black holes that the mass of the hole $M_{\text{BH}}$ is proportional to the mass of the surrounding spheroid $M_{\text{sph}}$ or bulge; $M_{\text{BH}} \approx 0.005 M_{\text{sph}}$. There is considerable scatter about this relation of order $\pm 1$ dex. This can be combined with the mass function of galactic bulges, where most of the mass resides. Salucci et al (1999) use the Schechter function luminosity function of bulges to obtain the local mass function of black holes. Most of the mass lies in black holes of individual mass around the break in the function, i.e. $3 \times 10^8 M_\odot$.

Taking this as a typical mass, and assuming growth by accretion with a radiative efficiency of $\eta = 0.1 \eta_1$, the bolometric luminosity of the final object $L_B = 3 \times 10^{46} - 3 \times 10^{44} \text{erg s}^{-1}$ if it is at one and 0.01 times the Eddington limit $L_{\text{Edd}}$ respectively. The Salpeter time for the growth of the black hole, i.e. the mass doubling time, $t_s = 3 \times 10^7 (L_{\text{Edd}}/L_B)^{1/2} \text{yr}$. If we now assume that the initial mass of all massive black holes is less than that of the central black hole in our Galaxy, say $\sim 10^6 M_\odot$, and has grown to $3 \times 10^6 M_\odot$ within 3 Gyr, which corresponds to $z \sim 2$, then $8t_s \sim 3 \times 10^8 \text{yr}$ and the black hole must have grown at a rate of about 10 per cent of the Eddington rate or more. Thus over the final $3 \times 10^8 \text{yr}$, $L_B > 3 \times 10^{45} \text{erg s}^{-1}$. From the work of Elvis et al (1994) the observed 2–10 keV luminosity is about 3 per cent of the bolometric one for a quasar so we can conclude that $L(2 - 10 \text{keV}) > 10^{44} \text{erg s}^{-1}$ during the growth of a typical black hole and we are dealing with powerful, obscured quasars.

It is clear that the objects making up the X-ray background, and the radiative growth phase of most of the mass in nearby black holes are not represented by any object observed so far.

3 THE OBSCURATION

The spectrum of the X-ray Background requires that most accretion power is absorbed. This means that some absorption (say $N_H > 10^{22} \text{cm}^{-2}$) occurs in 90 per cent of objects and heavy absorption ($N_H > 10^{24} \text{cm}^{-2}$) in 30–50 per cent of them. 10 per cent are unabsorbed and are the quasars identified in blue optical surveys or are bright in the soft X-ray band of ROSAT. So far these could be distinct different populations of quasars or different phases in the growth of all quasars.

Such high absorbed fractions mean that the covering fraction of the sky by high column density material seen from a growing black hole must approach $4 \pi r^2$. This cannot be provided by any thin disc or by the standard torus of unified models. The absorbing matter is probably concentrated within the innermost few 100 kpc, or its total mass becomes high. It must presumably be cold and fairly neutral, or it will not absorb the X-rays. At first sight this is at variance with it being space covering, especially if it must be so for a Gyr or more. Such matter should collide and dissipate into a disclike structure.

Following our earlier work on a circumnuclear starburst (Fabian et al 1998), it is plausible that collisions do take place leading to dissipation but that some massive star formation occurs in the shocked and cooled dense gas. The winds and supernovae from those stars then supply the energy to keep the rest of the cold matter in a chaotic and space covering state.

A more detailed model can be developed by assuming that the black hole is growing at the same time as the galaxy does. The stellar spheroid continues to grow by cooling of the gas heated by gravitational collapse of the protogalaxy. It is likely that the hot phase density while the galaxy continues to grow is the maximum possible, which means that the radiative cooling time of the gas equals the gravitational infall time. This condition has been studied in the context of quasar fuelling and growth by Nulsen & Fabian (1999). The gas accretes in a Bondi flow, probably forming a disc well within the Bondi radius. The accretion rate is such that it can typically be 10 per cent of the Eddington value.

The situation as envisaged here is essentially a maximal cooling flow and we can use the properties of observed cooling flows (Fabian 1994 and references therein) to indicate how the cooled gas is distributed and how it may lead to absorption. X-ray observations of cluster cooling flows show that the mass deposited by cooling is distributed with $M(< r) \propto r$, where $r$ is the radius. The density distribution of the cooled gas is therefore $\rho \propto r^{-2}$. If the gravitational potential of the galaxy is isothermal it remains so. X-ray absorption with column densities of the order of $10^{23} \text{cm}^{-2}$ is also observed in many cluster cooling flows. Although not observed in other wavebands, it could represent very cold, dusty gas (Fabian et al 1994).

It is therefore proposed that the cooled gas in protogalaxies does not all rapidly form stars but that much of it forms long-lived cold dusty clouds. As discussed above, energy from the massive stars helps to prevent the clouds rapidly dissipating into a large disc. The inner regions of protogalaxies are therefore highly obscured.

The column density through the cold clouds is obtained from integration of the cold gas density distribution, assumed to be

$$n = n_0 r_0^2 r^{-2}. \quad (1)$$

If the cold clouds are a fraction $f$ of the total mass within radius $r$, $M(< r) = 2r^2 f/G$, then

$$n_0 r_0^2 = \frac{f}{2 \pi G M_{\text{tot}}} \quad (2)$$

and the column density in to radius $r_n$

$$N_H = \frac{\rho^2}{2 \pi G m_p} \frac{f}{r_n} = 10^{24} \frac{f v_2^2}{r_2} \text{cm}^{-2}. \quad (3)$$

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Here the (line of sight) velocity dispersion of the (isothermal) spheroid is 300+7,5 km s\(^{-1}\) and \(v_{\text{rms}} = 100\) pc. It is therefore reasonable to assume that column densities at the level required by X-ray Background models can be produced in this manner, provided that \(f\) is fairly high.

It is interesting that the mass within the radius where the column density becomes Thomson thick \((N_T = \sigma_T^{-1} \sim 2 \times 10^{24} \text{cm}^{-2})\), where \(\sigma_T\) is the Thomson electron scattering cross section, is given by

\[
M_T = \frac{\nu^4 f}{2 \pi G^2 M_p N_T}.
\]

for which the enclosed mass

\[
M_T = \frac{\nu^4 f}{2 \pi G^2 M_p N_T}.
\]

\(M_T\) is thus approximately proportional to the mass of the whole spheroid, \(M_{\text{sph}}\), since approximately \(M_{\text{sph}} \propto \nu^4\), as suggested by the Faber-Jackson relation and any galaxy modelling (Salucci & Persic 1997). The last authors note that \(\tau_c \propto L_{\text{bol}}^{0.5}\) and \(M_{\text{sph}} \propto L_{\text{bol}}^{0.35}\), which with \(\nu \propto (M/r)^{0.5}\) yields a result very close to \(M_{\text{sph}} \propto \nu^4\). As the stellar content of the galaxy and the central black hole grow, the accretion radius of the hole also grows. When \(M_{\text{BH}} \sim M_T\) the accretion radius is at \(r_T\) and the Thomson depth of the obscuring matter around the quasar has dropped to unity.

The growth of the quasar continues until it runs out of gas. This could be because all the gas has cooled and formed stars. More likely it is connected with the central quasar (Silk & Rees 1998; Blandford 1999). Consider the possibility that as well as radiation the quasar produces a wind at velocity \(v_{\text{w}} \ll c\) and with a kinetic power \(L_w\) which scales with the radiated power \(L_{\text{rad}}\) as \(L_w/L_{\text{rad}} = L_{\text{bol}}/L_{\text{Edd}}\). Thus when the bolometric power is 10 per cent of the Eddington value the power of the wind is 10 per cent of the radiated power. Note that winds and outflows are observed from many classes of accreting objects (see e.g. Livio 1997).

The ratio of wind to (optically-thin) radiation pressure is then

\[
P_{\text{w}}/P_{\text{rad}} = 1 \frac{L_w}{L_{\text{rad}}} \frac{c}{v_w} = \frac{L_{\text{bol}}}{L_{\text{Edd}}} \frac{c}{v_w}.
\]

For an optically-thin medium of Thomson depth \(\tau_T\), the effective Eddington limit

\[
L_{\text{Edd}}^w = L_{\text{Edd}} \frac{\tau_T v_w}{c}.
\]

This means that if \(v_w \sim 15,000\) km s\(^{-1}\) and \(L_{\text{bol}} / L_{\text{Edd}} \sim 0.1\) then the wind pressure balances gravity. A wind force slightly in excess of this can therefore eject the gas. Since \(\tau \propto r^{-1}\) and \(M \propto r\), this condition applies throughout the galaxy and all the gas is ejected. (The assumption here that the mass is in a thin shell is applicable to the gas as it is swept up.)

This result can be placed on a surer footing by noting that the force balance between gravity acting on a column of matter at radius \(r\) of total mass \(N_H 4 \pi r^2 m_p\) and the outward force due to a wind \(2L_w/v\) yields the limiting luminosity

\[
L_{\text{Edd}}^w = 2 \pi G M_p N_H v_w.
\]

Substituting for \(M\) and \(N_H\) in the model galaxy we obtain

\[
L_{\text{Edd}}^w = 2 \nu^4 f v_w / G.
\]

The gas is ejected by the wind when the wind power exceeds this limit, i.e. when

\[
L_w > L_{\text{Edd}}^w.
\]

If \(L_w = aL_{\text{Edd}}\) then the limit occurs when

\[
a = \frac{4 \pi G M_p m_e c}{\sigma_T} \frac{v^4 f v_w}{2 G}.
\]

or at the critical mass

\[
M_c = \frac{v^4 f v_w}{2 \pi G^2 M_p N_T} \frac{c}{2 a c}.
\]

Thus if \(v_w \sim 0.1 c\) and \(a \sim 0.1\) then \(M_c \sim M_T / 2\). Assuming that most of the mass within \(r_T\) lies in the central black hole again means that \(M_{\text{BH}} \sim M_T \propto M_{\text{sph}}\). Most of the power during the main growth phase of a massive black hole is then radiated into gas with a Thomson depth of about unity, as required for modelling the X-ray Background spectrum.

Clearly \(f\) cannot equal unity if a galaxy is to be formed. In practice it will be a function of time. The important issue here is that it cannot be small, i.e. it probably lies in the range of \(0.1 \sim 0.5\).

The black hole mass is therefore proportional to the spheroid mass, as observed (Magorrian et al. 1998). The quasar is now unobscured and is observable as an ordinary blue excess object for as long as it has fuel. A reasonable estimate would be about a million yr for the disc to empty. The ejection phase is tentatively identified with broad absorption line quasars (BAL quasars; see e.g. Weymann 1997).

The normalization for the relation between \(M_{\text{BH}}\) and \(M_{\text{sph}}\) is obtained by using the Faber-Jackson relation given by Binney & Tremaine (1992), where \(v = 220 (L/L_\odot)^{0.25}\) km s\(^{-1}\) and \(L_\odot = 4 \times 10^{10} L_\odot\) in the V-band, and a mass-to-light ratio in that band of 6 (both for a Hubble constant of 50 km s\(^{-1}\) Mpc\(^{-1}\)). The result is

\[
M_{\text{BH}} / M_{\text{sph}} \approx 0.005,
\]

for the values of \(a\) and \(v_w\) above. This is in good agreement with the relation found by Magorrian et al. (1998). In detail, the weak variations in \(M/L\) such as summarized by Salucci & Persic (1997) could shift the observed relation from being strictly linear.

Note that the ordinary quasar phase marks the end of the main growth phase of both the black hole and its host spheroid. The central black hole in galaxies therefore has a profound effect on the whole galaxy, in providing a limit to the stellar component. In this context, Silk & Rees (1998) have shown that a powerful quasar wind could end the formation of a galaxy and Blandford (1999) has noted that it could prevent the formation of a galactic disc.
Eddington limit for the black hole, is released as a sub-relativistic wind, then, as suggested by Silk & Rees (1998) the cold, and accompanying hot, gas components are ejected from the galaxy when the Thomson depth to the outside $\tau_T$ drops to about unity. The central accretion source then appears as an unobscured quasar which lasts until its disc empties. The growth of both the central black hole and the stellar body of the galaxy then terminate, unless fresh gas and stars are brought in from outside, for example by a merger. Assuming that most of the mass within the region where $\tau_T \sim 1$ has been accreted into the black hole, it is found that its mass $M_{BH} \propto M_{sph}$, the mass of the spheroid of the galaxy.

The rough explanation for the proportionality is that a more massive galaxy has more cold gas and so requires a more powerful wind to eject the gas. A stronger wind requires a more massive black hole. The normalization results by relating the wind power to the Eddington limit.

The model accounts for the bulk of the X-ray Background which requires that most accretion power, resulting from the growth of massive black holes, is obscured. Also, such obscured accretion leads to agreement with the local mass density of black holes (Fabian & Iwasawa 1999). Most of the absorbed radiation will be reradiated in the far infrared/sub-mm bands and contribute to the source counts and backgrounds there. It can plausibly account for some of the sub-mm sources recently discovered by SCUBA (Barger et al. 1998; Hughes et al. 1998, Blain et al. 1999).

Indeed it predicts a population of distant Ultra-Luminous Infrared Galaxies (ULIRGs; Sanders & Mirabel 1996) associated with the main growth phase of massive black holes and distinct from the nearby population, which is probably due to mergers briefly fuelling central starbursts and fully grown black holes. (Whether radiation from the black hole can then dominate the ULIRG emission depends on the Eddington limit, i.e. the mass of the black hole, relative to the strength of the starburst; see e.g. Wilman et al. 1999.) The bolometric power of a typical growing black hole must be high, $L_{bol} > 10^{46}$ erg s$^{-1}$; which means an observed 2–10 keV luminosity when $N_H \sim 2 \times 10^{24}$ cm$^{-2}$ of about $3 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. Current ASCA (e.g. Ueda et al. 1998) and BeppoSAX (Fiore et al. 1999) hard X-ray surveys have not probed deep enough to reveal these objects, although they should be obvious in the deeper surveys planned for Chandra and XMM. These surveys will enable the major growth phase of black holes and, with optical/infrared identifications, their redshift distribution to be studied.

Note that the obscured growth phase of a massive black hole represents a distinctly different phase from the brief unobscured phase predicted after the gas is ejected and the quasar dies or any later phase, obscured or unobscured, when the quasar is revived by a merger or other transient fuelling event. These last phases are the ones which have been observed so far; the major growth phase has not. It is unlikely therefore that the properties of the major growth phase are obtainable by any simple extrapolation from observations of any transient recent phases, i.e. from studies of the properties of active galaxies at low redshift ($z < 0.5$).

It is important that the cold gas in the young galaxy, which provides the X-ray (and other waveband) obscuration, be metal enriched, and probably dusty. This is likely to be a consequence of continued star formation, particularly of massive stars, throughout the galaxy. The energy of stellar winds and supernovae help to keep the cold gas space covering. Note that the injected metals and stellar mass loss will be distributed both as assumed for the stars and the cold gas. Indeed the metallicity of the obscuring gas closest to the black hole may be higher than the solar values, which leads to better fits to the X-ray Background spectrum (Wilman & Fabian 1999). This also accounts for the high metallicity inferred in the broad-line region gas for many quasars (Hamann & Ferland 1999).

The column density distribution of the gas obscuring the radiation from the growing black hole will be such that most power is emitted just before the gas is ejected, which happens around $\tau_T \sim 1$. The fraction of the power radiated at optical depths greater than $\tau_T$ scales roughly as $\tau_T^{-1}$. Angular momentum and other factors may cause the gas in the young spheroidal galaxy, and the wind, to not be completely spherical. Thus when the wind ejects the gas it may do so most along one axis and only later eject gas in other directions (if at all). This means that the column density distribution for $\tau_T < 1$ is complicated to predict and is best found from the shape of the X-ray Background spectrum.

An important consequence for the stellar radiation in young growing galaxies is that most of it too is obscured. This agrees with recent evidence for the star formation history of the Universe from sub-mm and other observations.

The ejection of the metal-rich cold gas in the young galaxy should terminate its stellar growth, as well as growth of the black hole. The final appearance of a galaxy is thus significantly affected by its central black hole. How far the gas is ejected depends on how long the unobscured quasar phase lasts and what the surrounding gas mass and density is; whether for example the galaxy is in a group or cluster. The most massive black holes will be in the most massive galaxies and may last longest in the unobscured quasar phase. They might also be surrounded by a hot intragroup medium which could prevent much of the hotter space-filling phase from being ejected. If a surrounding hot phase is a necessary ingredient for a radio source then such objects might be more likely to be radio galaxies.

During the ejection phase the quasar might be classed as a BAL and later it might be seen to be surrounded by extended metal-rich filaments, depending on the velocity of ejection of the cold gas. The metal-rich gas, if mixed with surrounding hot intracluster gas, will enhance the local metallicity, providing one source for the extensive metallicity gradients found by X-ray spectroscopy around many cD galaxies in clusters (Fukazawa et al. 1994).

Finally, it is noted that the model requires a significant power output in the form of a wind associated with the growth of black holes. This wind power is dissipated as heat in the surrounding medium. It may have a marked effect on surrounding intracluster gas (Ensslin et al. 1998; Wu, Fabian & Nulsen 1999), possibly contributing to the heating required to change the X-ray luminosity–temperature relation, $L_x \propto T_x^\alpha$, from the predicted one with $\alpha \sim 2$ to the observed one with $\alpha \sim 3$. The estimates of Wu et al (1999) indicate that it will also heat the general intergalactic medium to a temperature of $\sim 10^7$ K at $z \sim 1 - 2$.

In summary, the growth of both massive black holes and galactic bulges is a highly obscured, and related, process, best observed directly in the hard X-ray band and indirectly,
through radiation of the absorbed energy, in the sub-mm band.

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REFERENCES

Almaini O., Lawrence A., Boyle B., 1998, MNRAS, 305, 59
Almaini O., Boyle B., Griffiths R.E., Shanks T., Stewart G.C., Georgantopoulos I., 1995, MNRAS, 277, L31,
Barger A.J., et al 1998, Nature, 394, 248
Blain A.W., Kneib J.-P., Ivison R.J., Smail I., 1999, ApJ, 512, L87
Boyle B.J., Almaini O., Georgantopoulos I., Blair A.J., Stewart G.C., Griffiths R.E., Shanks T., Gunn K.F., 1998, MNRAS, 297, 53
Binney J., Tremaine S. 1987, Galactic Dynamics, Princeton Univ. Press, Princeton
Blanford R., in ASP Conference Series, ed. D. Meritt, Valluri and J. Sellwood in press (astro-ph 9906025)
Brandt W.N., Fabian A.C., Takahashi K., Fujimoto R., Yamashita A., Inoue H., Ogasaka Y., 1997, MNRAS, 290, 617
Celotti A., Fabian A.C., Chisellini G., Madau P., 1999, ApJ, 512, L87
Comastri A., Setti G., Zamorani G., Hasinger G., 1995, AaA, 296, 1
Elvis M. et al 1994, ApJS, 95, 1
Ensslin T.A., Wang Y., Nath B.B., Biermann P.L., 1998, A&A, 333 L47
Fabian AC, 1994, ARAA, 32, 277
Fabian A.C., Barcons X., Almaini O., Iwasawa K., 1998, MNRAS, 297, L11
Fabian A.C., Iwasawa K., 1999, MNRAS, 303, L34
Fabian A.C., Johnstone R.M., Daines S.J., 1994, MNRAS, 271, 737
Fiore F., et al 1999, MNRAS, 306, L55
Fukazawa, Y., Ohashi, T., Fabian A.C., Canizares C.R., Ikebe Y., Makishima K., Mushotzky R.F., Yamashita K., 1994, PASJ, 46, L55
Halpern J.P., Turner T.J., George I.M., 1999, MNRAS in press (astro-ph 9905342)
Hamann F., Ferland G., 1999, ARAA in press (astro-ph 9904223)
Hughes D.H., et al 1998, Nature 394, 241
Livio M., 1997, in ASP Conference Series 121, eds D.T. Wickramasinghe, L Ferrario, G.V. Bicknell, p845
Madau P., Ghisellini G., Fabian A.C., 1994, MNRAS, 270, L17
Magorrian J., et al 1998, AJ, 115, 2285
Matt G., Fabian A.C., 1994, MNRAS, 267, 187
Nulsen P.E.J., Fabian A.C., 1990, MNRAS, in press
Richstone D., 1998, Nature, 395, 14
Salucci P., Persic M., Salucci P., Danese L., 1998, MNRAS in press (astro-ph/9811102)
Salucci P., Persic M., 1997, in ASP Conference Series 117, 1, eds Persic M., Salucci P., p1
Sanders D.B., Mirabel I.F., 1996, ARAA, 17, 477
Silk J., Rees M.J., 1998, A&A, 331, L1
Setti G., Woltjer L., 1989, A&A, 224, L21
Ueda Y., et al 1998, Nature 391, 866
Weymann R.J., 1997, in ASP Conference Series 128, eds N. Arav, I Shlosman, R.J. Weymann, p3
Wilman R.J., Fabian A.C., 1999, MNRAS submitted
Wilman R.J., Fabian A.C., Cutri R.M., Crawford C.S., Brandt W.N., 1999, MNRAS, 300, L7