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LETTER

Letter to the Editor

Black hole energy release to the Gaseous Universe

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Abstract. We estimate the energy release of black hole formation to the intra-cluster medium of the Coma cluster and find that this is comparable to the present day energy content. Therefore an energetic and maybe hydrostatic influence is possible. Our calculations rely on the assumption of an universal black hole to galaxy mass ratio (more exactly: spheroidal mass component of the stellar population), for which there is growing evidence. On a cosmological scale, there is also an energy release of black hole formation comparable to what is expected to be present within the thermal gas, caused by the process of structure formation. This indicates an important dynamical influence, neglected by present day structure formation simulations. This estimate of cosmological black hole energy release is independent of the black hole to galaxy mass ratio, but consistent with its value.

Key words: black hole physics – intergalactic medium – galaxies: jets – galaxies: clusters: individual: Coma – cosmology: large-scale structure of the Universe

1. Introduction

There is growing evidence for the existence of black holes (BHs) in all galaxies, being remnants of the strong quasar activity in the young Universe (Lynden-Bell 1969; Rees 1989; Haehnelt & Rees 1993; van der Marel 1997; Ford et al. 1997; Hasinger 1998; and references therein). Estimates of the ratio of the BH mass to that of the spheroidal component of the stellar population of the host galaxy seem to converge to $\eta_{\rm bh} \approx 0.002 - 0.006$ (Kormendy & Richstone 1995; Faber et al. 1997; Magorrian et al. 1997; Silk & Rees 1998; Wang & Biermann 1998). This allows to estimate the total BH mass within a population of galaxies. The former BH growth was accompanied by an output of large amounts of energy by radiation, heating of the ambient medium and outflows of relativistic particles, which can influence the environment of the host galaxies energetically and dynamically. In this Letter we present a comparison of the BH energy release and the thermal energy of the quasar environment in order to demonstrate the possible importance of this influence. The efficiency of energy dissipation of the accreting matter to a Schwarzschild BH is $\varepsilon \approx 0.06$, whereas to a maximal rotating BH $\varepsilon \approx 0.3$ (Thorne 1974; Laor & Netzer 1989). We assume $\varepsilon_{\rm light} \approx 0.1$ to be the mass-to-light conversion rate, and $\varepsilon_{\rm th+nth} \approx 0.1$ for the production efficiency of thermal and nonthermal energy release in relativistic particles and magnetic fields. Therefore we use an intermediate value of $\varepsilon \approx 0.2$. We adopt a conservative value of $\eta_{\rm bh} \approx 0.002$, since we like to include the fraction of galaxies containing massive BHs into this number. If $\eta_{\rm bh} \approx 0.006$ our estimate of energy release to the Coma cluster is still correct if only one third of all galaxies contain massive BHs. But the cosmological estimate is not affected, since it depends only on the ratio $\varepsilon_{\rm th+nth}/\varepsilon_{\rm light}$ and the observed quasar light. Further, we use $H_{\rm o} = 50\, h_{50}\, {\rm km\, s^{-1}\, Mpc^{-1}}$, $\Omega_{\rm o} = 1$, $\Lambda = 0$, and indicate the scaling of all quantities with the Hubble constant.

2. The Coma cluster

First, we estimate the thermal energy content of the Coma cluster. The electron density of the intra-cluster medium of the Coma cluster can be described by a β-model: $n_{\rm e}(r) = n_{\rm e,o}[1 + (r/r_{\rm core})^2]^{-3\beta_{\rm e}/2}$, where $n_{\rm e,o} = 3 \cdot 10^{-3}\, h_{50}^{1/2}\, {\rm cm^{-3}}$ is the central electron density, $r_{\rm core} = 400\, h_{50}^{-1}\, {\rm kpc}$ the core radius, and $\beta_{\rm e} = 0.75$ gives the slope (Briel et al. 1992). The gas extends to a radius of $R_{\rm cluster} \approx 5\, h_{50}^{-1}\, {\rm Mpc}$, where an accretion shock of the infalling matter marks the cluster boundary (Enßlin et al. 1998). The integrated gas mass within this radius is $4.2 \cdot 10^{14}\, h_{50}^{-5/2}\, {\rm M_\odot}$. The central temperature of the cluster is $8.2\, {\rm keV}$ (Briel et al. 1992), but there is evidence for a temperature decrease from the center to the boundary by a factor of two (Fusco-Femiano & Hughes 1994; Honda et al. 1996), which seems to be typical for clusters (Markevitch et al. 1997). We therefore describe the temperature with a β-profile with the same core radius, but with $\beta_{kT} = 0.09$, leading to a temperature drop by two within $5\, h_{50}^{-1}$ Mpc. The resulting thermal energy content within $R_{\rm cluster}$ is $1.3 \cdot 10^{64}\, h_{50}^{-5/2}\, {\rm erg}$.

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This has to be compared with the energy release of BH formation. Since the galaxies in Coma are mainly ellipticals, only their total mass has to be estimated and multiplied with $\eta_{\rm bh}$ in order to get the mass of BHs in Coma. The mass of the ellipticals can be derived from their luminosity function and their mass to light ratio. The R-band luminosity function of early type galaxies in the central $700\,\rm arcmin^2$ of Coma is given in Secker & Harris (1996). The complete luminosity function can be estimated by assuming these galaxies to be within a cylindrical volume, and correcting to the whole cluster volume, with the help of the spatial distribution of galaxies. The radial distribution of galaxies within Coma is given by $n_{\rm gal} \sim (1+(r/r_{\rm gal})^2)^{-\alpha_{\rm gal}}$, with $\alpha_{\rm gal} = 0.8$ and $r_{\rm gal} = 160\,h_{50}^{-1}\,\rm kpc$ (Girardi et al. 1995). Including into this the luminosities of NGC 4874 and NGC 4889 (Strom & Strom 1978), which were not included into this luminosity function, and applying a correction of V-R = 0.85, which is typical for ellipticals (Tinsley & Gunn 1976), we get the V-band luminosity function. The galactic mass can now be integrated with the help of the mass to (V-band) light ratio given by Magorrian et al. (1997). It is $M_{\rm gal} = 2.9\cdot 10^{13}\,h_{50}^{-1}\,\rm M_\odot$, giving a total BH mass of $M_{\rm bh} = 5.8\cdot 10^{10}\,h_{50}^{-1}\,(\eta_{\rm bh}/0.002)\,\rm M_\odot$. The gravitational energy, which was freed during the BH formation, is therefore $E_{\rm bh} = \varepsilon M_{\rm bh} c^2 = 2.1\cdot 10^{64}\,h_{50}^{-1}\,(\varepsilon/0.2)\,(\eta_{\rm bh}/0.002)\,\rm erg$. The thermal plus nonthermal energy release (one half of the total) is therefore comparable to the present day thermal energy content of Coma within a $5\,h_{50}^{-1}$ Mpc radius.

A different approach to the nonthermal energy release of BH formation to clusters of galaxies was taken by Enßlin et al. (1997) by an estimate of the jet-power of radio galaxies, integrated over cosmological epochs. A comparison with the typical thermal energy content of cluster showed, that both numbers could be comparable on cluster scale, if a considerable amount of energy is ejected by the not radio-emitting and therefore invisible relativistic protons. Our above estimate of the nonthermal energy release is completely independent of this calculation, and therefore demands such energetic protons, having energy densities much higher than the electrons within the relativistic plasma flowing out of radio galaxies, consistent with theories of the origin of the observed ultra-high-energy cosmic rays (Rachen & Biermann 1993; Biermann 1997) and recently discovered TeV γ-rays from blazars (Mannheim 1998).

Since also the nonthermal energy should be stored in the intra-cluster medium for at least a Hubble time, we expect a large nonthermal energy content of Coma and similar clusters. Discussions of the storage of relativistic particles in clusters can be found in Völk et al. (1996) (who estimate the supernovae energy release into the Perseus cluster), Enßlin et al. (1997), and Berezinsky et al. (1997). We note, that details of the injection of relativistic plasma from quasars into the intra-cluster medium and also the later evolution of this plasma need further investigations. E.g. in speculative scenarios of dwarf galaxy formation induced by violent expansion of quasar outflows in the early Universe large fractions of the released energy are transformed to heat in the ambient medium by shocks and adiabatic compression (Natarajan et al. 1997; Silk & Rees 1998; and references therein). The question if the nonthermal plasma influences the hydrostatics of the cluster, and should be taken into account into (uncertainties of) X-ray mass determinations, can not be answered yet, since this depends on the amount and also crucial on the spatial distribution of the nonthermal phases.

At the location of the radio outflow from Perseus A an X-ray hole is present in the thermal emission of the Perseus cluster (Böhringer et al. 1993), demonstrating that the radio plasma rather displaces the thermal gas, driven in this case with a power of probably more than $10^{46}\,\rm erg\,s^{-1}$ (Heinz et al. 1998), than mixes with it. Thus the radio plasma might remain within the intra-cluster medium, invisible since the electrons cool down in a cosmologically short time, and might be reactivated when a cluster merger event reaccelerates the electron population, as it could be the case for the $3\,h_{50}^{-1}$ Mpc sized, diffuse radio halo of Coma (Deiss et al. 1997; and references therein). Also the peripherally located cluster radio relics (e.g. 1253+275 in Coma) can be understood in terms of old reactivated radio plasma, having passed through a cluster accretion- or merger shock wave (Enßlin et al. 1998). Evidence for the existence for a necessary, old, but large relativistic electron population within the intra-cluster medium, having energies below what is visible in the radio, can be seen in the recently detected EUV excess of the Coma cluster (Lieu et al. 1996), if this is explained by inverse-Compton scattered microwave background photons (Hwang 1997; Enßlin & Biermann 1998; Sarazin & Lieu 1998).

3. The Universe

It is also possible to compare the BH formation energy release to that of the thermal gas on a cosmological scale. The integrated energy density in quasar light emitted during (and estimated for) the epoch of quasar activity is $(0.9-1.3)\cdot 10^{-15}\,\rm erg\,cm^{-3}$ (Chokshi & Turner 1992; an earlier, more conservative estimate can be found in Soltan 1982). This number is given per comoving volume, and it is independent of cosmology. Chokshi & Turner (1992) assumed an efficiency of light production of $\varepsilon_{\rm light} \approx 0.1$, and got a present day BH mass density of $(1.4-2.2)\cdot 10^5\,\rm M_\odot\,Mpc^{-3}$, consistent with the above used BH to spheroidal mass ratio $\eta_{\rm bh}$, even if all galaxies contain BHs (Faber et al. 1997).

A large fraction of the energy output is injected into clusters, roughly $f_{\rm cl} = 0.3-0.5$ (Enßlin et al. 1997), which contain less than 10% of all baryons, and therefore get more energy per baryon from BHs than the gas outside clusters. Distributing 60% of the BH energy release onto the 90% of the gas which is outside clusters gives an average temperature of $kT(z_{\rm inj}) \leq (0.9-1.3)\,\rm keV\;(\varepsilon_{\rm th+nth}/\varepsilon_{\rm light})\;((1-f_{\rm cl})/0.6)\;(\Omega_{\rm b} h_{50}^2/0.05\,)^{-1}$ at the redshift of injection. This estimate assumes complete dissipation of the nonthermal energy in magnetic fields and relativistic particles. This is not realistic, but gives us upper limits to the heating and Comptonization parameter. The true thermal heating might only be some fraction of this number.

In a homogeneous universe comoving energy densities have to be redshifted by $(1+z_{\rm inj})^{-\alpha}$ due to adiabatic expansion losses, with $\alpha = 3(\gamma - 1)$ and γ the adiabatic index. This correction has to be applied for the quasar light, which has $\gamma_{\rm light} = 4/3$ and therefore $\alpha_{\rm light} = 1$. The average injection redshift of the luminosity function used in Chokshi & Turner (1992) is $z_{\rm inj} = 2.34$, giving a present day quasar light density of $(0.3-0.4) \cdot 10^{-15}\,{\rm erg\,cm^{-3}}$. The redshift correction for BH thermal energy release should be different, due to $\gamma_{\rm gas} = 5/3$, but also since this heat is injected into the environment of the quasar host galaxies, which is the inter-galactic medium of the filaments and sheets of the large scale structure and therefore partly decoupled from the Hubble flow. We assume that the density in sheets and filaments decreases with $(1+z)^d$ only due to the action of the Hubble flow in the direction of these structures of dimension d: we adopt $d = 2$ for sheets and $d = 1$ for filaments. Since most galaxies are located in filaments, we use $d = 1$, but give the scaling for different values. This is conservative, since these structures are forming, and the ongoing infall of matter could lead to compression, whereas the Universe still expands. Thus, $\alpha_{\rm gas} = d(\gamma_{\rm gas} - 1) = 2/3$ gives a present day average heat (from BHs) outside clusters of

$$kT(z=0) \;\leq\; (0.4-0.6)\;{\rm keV}\,\frac{\varepsilon_{\rm th+nth}}{\varepsilon_{\rm light}}\,\frac{1-f_{\rm cl}}{0.6}\,\frac{(1+z_{\rm inj})^{-\alpha}}{3.34^{-2/3}}\,\left(\frac{\Omega_{\rm b} h_{50}^2}{0.05}\right)^{-1},$$

(independent of cosmology) again assuming complete dissipation of nonthermal phases (therefore $\leq$). The corresponding Comptonization parameter $y \leq (0.7-1.2)\cdot 10^{-5} h_{50}^{-1}$, estimated for this adiabatic cooling history and an Einstein-de-Sitter Universe (using $\Omega_{\rm o} = 0$ increases y by only 50%), does not violate the present day upper limit of $y < 1.5\cdot 10^{-5}$ (Fixsen et al. 1996). Additional to the dependence on h_{50}, y scales with $(1+z_{\rm inj})^{3/2}$ $(3/2+\alpha_{\rm gas})^{-1}$ $(\varepsilon_{\rm th+nth}/\varepsilon_{\rm light})$ $(1-f_{\rm cl})$ in an Einstein-de-Sitter Universe, and $(1+z_{\rm inj})^2$ $(2+\alpha_{\rm gas})^{-1}$ $(\varepsilon_{\rm th+nth}/\varepsilon_{\rm light})$ $(1-f_{\rm cl})$ if $\Omega_{\rm o} = 0$. Our result also satisfies constraints from HeII absorption in the IGM (Sethi & Nath 1997).

The true cosmological BH heating of gas in cosmological filaments might be lower than this heat, due to the non-negligible fraction of nonthermal energy which does not dissipate, and which is mainly invisible to Comptonization measurements. But this phase cools slower than the thermal gas, due to a smaller adiabatic index. The present day BH energy release should therefore be slightly higher than the thermal energy given above (present day BH released thermal and nonthermal energy outside clusters per cosmological volume: $(2.5-4.0)\cdot 10^{-16}\,{\rm erg\,cm^{-3}}$). This is large enough in order to be energetically and dynamically important. For comparison: numerical simulation for the evolution for IGM assumes only photoionization from quasars and get a temperature increase of several eV (e.g. Miralda-Escudé et al. 1996; and references therein). Simulations of structure formation predict temperatures of $0.1-0.5$ keV within filaments, resulting from shock heating at the accretion shocks of filaments (Kang et al. 1996). This demonstrates the need for simulations of structure formation, which take into account the back reaction of galaxy formation induced BH growth onto the inter-galactic medium.

4. Conclusions

We estimate the contribution of energy release of black hole formation during the quasar active epoch of the Universe for the energy budget of the Coma cluster of galaxies and also on a cosmological scales in order to investigate their possible energetical and dynamical influence. Although uncertainties are large, we find, that these energies are comparable to that of the thermal gas of the environment. In the case of galaxy clusters a possible hydrostatic influence of nonthermal phases was proposed as a possible systematic effect for mass determinations of clusters, and therefore for $\Omega_{\rm o}$ (Loeb & Mao 1994; Enßlin et al. 1997). This Letter shows that sufficient energy seems to be injected (depending on the black hole efficiency and black hole to spheroidal mass ratio), but the unknown details of thermalization and spatial distribution of nonthermal phases within the intra-cluster medium do not allow a final answer to this question. Since large amounts of magnetized plasma should have flown out of quasars, this scenario also can help to explain the origin of the observed intra-cluster magnetic fields. On larger scales, the black hole energy release can influence the large-scale structure formation by the feed back reaction during galaxy formation and black hole growth. This cosmological estimate is quite robust against changes in the unknown parameters of black hole energy release, since it depends only on the ratio of the thermal plus nonthermal to light production efficiency.

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