Mem. S.A.It. Vol. 79, 1189

Memorie della

Anisotropic AGN outflows filling the cosmological volume

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Abstract. We simulate anisotropic outflows of AGN, and investigate the large-scale impact of the cosmological population of AGN outflows over the Hubble time by performing N-body ΛCDM simulations. Using the observed quasar luminosity function to get the redshift and luminosity distribution, and analytical models for the outflow expansion, AGNs are allowed to evolve in a cosmological volume. By the present epoch, 13 – 25% of the total volume is found to be pervaded by AGN outflows, with 10^{-9} G magnetic field.

Key words. Cosmology: miscellaneous – Galaxies: active – Galaxies: jets – (Galaxies:) intergalactic medium – Methods: N-body simulations

1. Introduction

Outflows from AGN are observed in a wide variety of forms: radio galaxies, broad absorption line quasars, Seyfert galaxies exhibiting intrinsic absorption in the UV, broad emission lines, warm absorbers and absorption lines in X-rays (e.g., Crenshaw et al. 2003; Everett 2007). There have been studies on the cosmological impact of quasar outflows in large scales (Furlanetto & Loeb 2001, hereafter FL01; Scannapieco & Oh 2004, hereafter SO04; Levine & Gnedin 2005, hereafter LG05). Barai (2008) investigated the cosmological influence of radio galaxies over the Hubble time. All these studies considered spherically expanding outflows.

On cosmological scales an outflow is expected to move away from the high density regions of large-scale structures, with the outflowing matter getting channelled into low-density regions of the Universe (Martel & Shapiro 2001). We implement such anisotropic AGN outflows within a cosmological volume. The simulation methodology is given in §2, and the results are discussed in §3.

2. The numerical setup

2.1. N-body simulation and distribution

We simulate the growth of large-scale structures in a cubic cosmological volume of comoving size $L_{\rm box}$=128h^{-1} Mpc. We use the Particle-Mesh (PM) algorithm, with 256^3 equal-mass particles, on a 512^3 grid. A particle has a mass of $1.32\times10^{10}M_\odot$, and the grid spacing is $\Delta = 0.25h^{-1}$ Mpc. We consider a concordance ΛCDM model with the cosmological parameters: $\Omega_M = 0.268$, $\Omega_\Lambda = 0.732$, $H_0 = 70.4\,{\rm km\,s^{-1}Mpc^{-1}}$, $\Omega_b = 0.0441$, $n_s = 0.947$, and $T_{\rm CMB} = 2.725$.

The redshift-dependent luminosity distribution of AGN is obtained from the bolometric quasar luminosity function (QLF) (Hopkins et al. 2007),

$$\phi(L, z) \equiv \frac{d\Phi}{d \log L} = \frac{\phi_\star}{(L/L_\star)^{\gamma_1} + (L/L_\star)^{\gamma_2}}, \quad (1)$$

which gives the number of quasars per unit comoving volume, per unit $\log_{10}$ of luminosity. A fraction $f_{\rm outflow} = 0.2$ of AGN are considered to host outflows (Ganguly & Brotherton 2008). The number of outflows within the simulation box of comoving volume $V_{\rm box} = L_{\rm box}^3$, at epoch z, between $[L, L + dL]$ is,

$$N(L, z) = f_{\rm outflow}\phi(L, z)d[\log_{10} L]V_{\rm box}. \quad (2)$$

The AGN activity lifetime is taken as $T_{\rm AGN} = 10^8$ yr; the maximum and minimum AGN luminosities as $10^8 L_\odot$ and $10^{14} L_\odot$.

Using the QLF, we obtain the entire cosmological population of AGN in the simulation volume starting from $z = 6$, namely the birth redshift ($z_{\rm bir}$), switch-off redshift ($z_{\rm off}$) and bolometric luminosity ($L_{\rm bol}$) of each source. A total of 929805 sources were produced.

At each timestep, we filter the density distribution on the 512^3 grid (from the PM code) using a gaussian filter containing a mass $10^{10} M_\odot$, assumed as the minimum mass of a halo hosting an AGN. We identify the density peaks, or the grid cells where the filtered density exceeds the values at the 26 neighboring grids. We consider the peaks that have a filtered density > 5× the mean density of the box, and each new AGN born during that epoch (whose $z_{\rm bir}$ values fall within the timestep interval) is located at the center of one such peak cell, selected randomly. After their initial distribution, the AGNs are allowed to evolve according to the prescription in §2.2.

2.2. Outflow model

Despite the observational differences between various outflows, we stress that the AGNs hosting outflows constitute a random subset of the whole AGN population, and we simply assume the same outflow model for all AGNs (also FL01, SO04, LG05). We allow each outflow to evolve through an active-AGN life (§2.2.1), when $z_{\rm bir} > z > z_{\rm off}$. After the central engine has stopped activity (when $z < z_{\rm off}$), it enters the late-expansion phase (§2.2.2).

The baryonic ambient gas density, $\rho_g(z, \mathbf{r})$, is considered to follow the dark matter density, $\rho_M(z, \mathbf{r})$, in the N-body simulation: $\rho_g = (\Omega_b/\Omega_M)\rho_M$. The external gas pressure is $p_g(z, \mathbf{r}) = \rho_g(z, \mathbf{r})kT_g/\mu$. The external temperature is fixed at $T_g = 10^4$ K assuming a photoheated ambient medium, and $\mu = 0.611$ amu is the mean molecular mass.

2.2.1. The active life

The AGN activity period is short compared to the Hubble time. So we neglect energy losses and Hubble expansion of the cosmological volume when the quasar is active. We approximate the shape of the outflow as spherical.

An active outflow is inflated by twin collimated relativistic jets (Begelman et al. 1984), each of length R. We consider that the kinetic luminosity carried by each jet is a constant fraction of the bolometric luminosity: $L_K = \epsilon_K L_{\rm bol}/2$, with $\epsilon_K = 0.1$ (FL01; LG05; Shankar et al. 2008). The jet advance speed is obtained by balancing the jet momentum flux with the ram pressure of the ambient medium: $L_K/(A_s c) = \rho_g (dR/dt)^2$. Here, A_s is the area of the shocked "working" surface at the jet head. We use $A_s = 2\pi R^2 \theta_s^2$, assuming that the shock front has a constant half-opening angle of $\theta_s = 5°$ relative to the central AGN (FL01).

All the kinetic energy transported along the jets during an AGN's age $t_{\rm age} = t(z) - t(z_{\rm bir})$ is transferred to the outflow. The outflow energy is $E_0 = 2L_K t_{\rm age}$, and its pressure follows $p_0 V_0 = (\Gamma_0 - 1)E_0$. The adiabatic index of the relativistic outflow plasma is $\Gamma_0 = 4/3$. The outflow volume during this active spherical expansion is $V_0(z) = 4\pi R^3/3$.

2.2.2. The late anisotropic expansion

When AGN activity ends, the left-over high-pressure outflow expands into the large scales of the IGM with an anisotropic geometry. It is represented as a "bipolar spherical cone" with radius R and opening angle α (Pieri et al. 2007), and it follows the direction of least re-

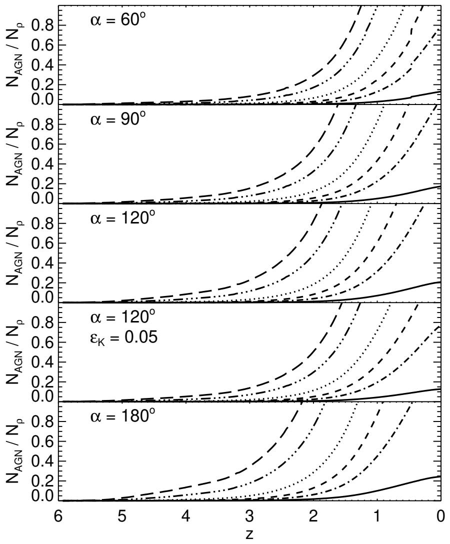

Fig. 1. Volume of the simulation box filled by AGN outflows ($N_{\rm AGN}$) as a fraction of the total volume *(solid)*, and as a fraction of volumes of various overdensities: $N(\rho > \overline{\rho})$ *(dash dot)*, $N(\rho > 2\overline{\rho})$ *(dashed)*, $N(\rho > 3\overline{\rho})$ *(dotted)*, $N(\rho > 5\overline{\rho})$ *(dash dot dot dot)*, $N(\rho > 7\overline{\rho})$ *(long dashes)*.

sistance (DLR). We perform a second-order Taylor expansion of the density around each peak, whose coefficients are determined by performing a least-square fit to all the grid points within a distance 2Δ from the peak. We then rotate the coordinate axes such that the cross-terms vanish to give: $\rho(x', y', z') = \rho_{\rm peak} - Ax'^2 - By'^2 - Cz'^2$. The largest of the coefficients A, B, C gives the DLR.

The Sedov-Taylor adiabatic blast wave model is used to obtain the radius of the overpressured outflow (Castor et al. 1975; SO04; LG05): $R(z) = \xi_0 \left(E_{\rm tot} t_{\rm age}^2 / \overline{\rho_g}(z)\right)^{1/5}$. We obtain $\overline{\rho_g}(z)$ by averaging the gas density of the grid cells occurring within the outflow volume. For a strong explosion in the $\Gamma_g = 5/3$ ambient gas, $\xi_0 = 1.12$. Here the total kinetic energy injected into the outflow by the AGN is $E_{\rm tot} = 2 L_K T_{\rm AGN}$. Adiabatic expansion losses are considered, and the outflow pressure evolves as $p_0 R^{3\Gamma_g}$ = constant, with the constant derived from the values at the end of the active phase.

The outflow follows an anisotropic expansion as long as its pressure exceeds the external pressure of the IGM, i.e., $p_0(z) > p_g(z)$. During this late biconical expansion, $V_0(z) = 4\pi R^3(1 - \cos(\alpha/2))/3$.

When $p_0(z) \leq p_g(z)$, or, the outflow has reached pressure equilibrium with the IGM, it has no further expansion. After this, the outflow simply evolves passively with the Hubble flow of the cosmological volume. Thus an outflow in pressure equilibrium attains a final volume of $V_0 = 4\pi R_f^3(1 - \cos(\alpha/2))/3$, where R_f is the final comoving radius of the outflow.

3. Results and discussion

At each timestep the total volume occupied by the AGN outflows is computed by counting the contributions of all the sources born by then, both the active ones and those in the anisotropic phase. We performed 4 simulations with opening angles of α = $60^{\rm o}, 90^{\rm o}, 120^{\rm o}, 180^{\rm o}$, all with $\epsilon_K = 0.1$, and one with $\alpha = 120^{\rm o}$ and $\epsilon_K = 0.05$, whose results are shown in the figures.

We count the grid cells in the simulation box which occur inside the volume of one or more AGN outflows. The total number of these filled cells, $N_{\rm AGN}$, gives the total volume of the box occupied by outflows. We express the total volume filled as a fraction of volumes of various overdensities in the box, $N_\rho = N(\rho > C\overline{\rho})$, where $\overline{\rho} = (1+z)^3 \Omega_M 3 H_0^2/(8\pi G)$ is the mean matter density of a spatially flat Universe (the box) at an epoch z. So N_ρ gives the number of cells which are at a density C times the mean density. We find N_ρ for $C = 0, 1, 2, 3, 5, 7$; $C = 0$ gives the total volume of the box.

Figure 1 shows the redshift evolution of the volume filling factors for our 5 simulation runs. With 10% kinetic efficiency, 0.13 of the entire Universe is filled at present by AGN outflows with an opening angle of $60^{\rm o}$; the fraction increases to 0.17 with $90^{\rm o}$, 0.21 with $120^{\rm o}$, and 0.25 with $180^{\rm o}$. A 5% kinetic efficiency and $\alpha = 120^{\rm o}$ fills 0.13 of the volume. In all our runs, the outflows fill up all of the regions with $\rho > 2\overline{\rho}$ by $z = 0.3$. With $\epsilon_K = 0.1$ and $\alpha = 90^{\rm o}$ or higher, the outflows permeate all the overdense regions ($\rho > \overline{\rho}$) by $z = 0.1$.

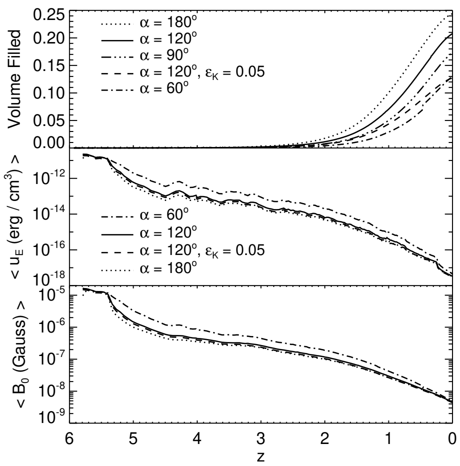

Fig. 2. Volume fraction filled by AGN outflows (*top*), the volume weighted average of the total energy density inside outflow volumes $\langle u_E \rangle$ (*middle*), and the equipartition magnetic field within the filled volumes $\langle B_0 \rangle$ (*bottom*).

It is the overdense regions of the Universe which gravitationally collapse to form stars and galaxies. So evidently the AGN outflows have a profound cosmological impact on the protogalactic regions. We note that the volumes obtained by LG05 (100% filling by $z \sim 1$) are higher than ours.

We perform preliminary estimates of the energy density and magnetic field in the volumes of the Universe filled by the AGN outflows. The energy density inside the outflow behaves similar to the outflow pressure evolving adiabatically (§2.2.2), $u_E = 3p_0$. Assuming equipartition of energy between magnetic field of strength B_0 and relativistic particles inside the outflow, the magnetic energy density is $u_B = u_E/2 = B_0^2/(8\pi)$. We define the volume weighted average of a physical quantity $\mathcal{A}$ as $\langle\mathcal{A}\rangle(z) \equiv \sum(\mathcal{A}V_0)/\sum V_0$, where the summation is over all outflows existing in the simulation box at that epoch.

Figure 2 shows the redshift evolution of the total volume filling fraction, $\langle u_E \rangle$ and $\langle B_0 \rangle$. The energy density and magnetic field decrease with redshift as larger volumes are filled. At $z = 0$, a magnetic field of $\sim 10^{-9}$ G permeates the filled overdense volumes, consistent with the results of Ryu et al. (2008). At a given redshift, the energy density and magnetic field are larger for smaller opening angles of the anisotropic outflows.

We conclude that, using our N-body simulations, the cosmological population of AGN outflows pervade 13 – 25% of the volume of the Universe by the present. A magnetic field of $\sim 10^{-9}$ G is infused in the filled volumes at $z = 0$.

Acknowledgements. All calculations were performed at the Laboratoire d'astrophysique numérique, Université Laval. We thank the Canada Research Chair program and NSERC for support.

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