A Physical Model for AGN Feedback: Improvement through BH Spin and Magnetic Field

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The Working Group

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Outline

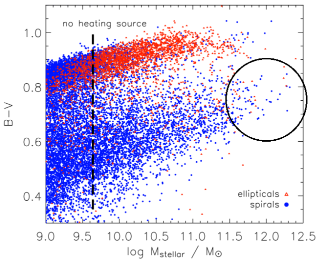
1. Introduction and Motivation.
2. Semi-analytic Modelling as a tool for studying cosmological samples of galaxies.
3. A model for the Black Hole Magnetosophere: Magnetic Coupling between the accretion disc and BH.
4. Dual AGN Feedback from the accretion disc and the jet.
5. Galaxies under the effects of the new model: Luminosity Functions and BH-Bulge mass relation.
6. Summary and Future Work.

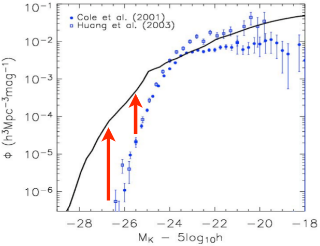
AGN Feedback

- Correlations between $M_{\rm BH}$ and the properties of the host galaxy suggests that evolution of galaxy and BH are connected.
- The BH regulates the growth of the galaxy and the amount of gas accreted.
- Feedback between the infalling material and the AGN
  $\Rightarrow$ winds from the accreting BH push the gas.
  $\Rightarrow$ regulates the accretion and star formation when the SMBH reaches some critical mass.
- The form of feedback could be either energy injection or momentum injection

AGN Feedback in SAMs

- Problems: massive blue galaxy population and an excess in the bright end of the LFs
- Introduction of "super winds" $\Rightarrow$ not completely successful
- AGN Feedback reduces the cooling of gas
- The physics of AGN is poorly understood
  $\Rightarrow$ A phenomenological model of feedback, e.g. powers of the virial velocity of the halo





Croton et al. (2006)

Why a physical model instead a phenomenological model?

- More reliable predictions
- Better understanding of the physics behind the phenomena

Objetive

Eliminate some of the non-physical dependences in the feedback and accretion process.

Method

We propose a new model for the luminosity of the BH (accretion disc and jet) which depends on the BH spin.

The cosmological simulation

- ΛCDM cosmology.
- Parameters consistent with the WMAP5 + SDSS observations:

$$\Omega_\Lambda = 0{,}73 \quad \Omega_m = 0{,}27 \quad \sigma_8 = 0{,}82 \quad H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

- Periodic cubic box of $67{,}68h^{-1}$ Mpc which contains 256^3 DM particles with mass $1{,}38 \times 10^9 M_\odot h^{-1}$.
- Redshift range from $z = 20$ to $z = 0$.
- FOF algorithm to indentify DM haloes.
- SUBFIND algorithm to find self-bound substructures.
- Cosmological merger trees are constructed.

The semi-analytic model of galaxy formation (SAG)

- The best tool for studying the effects of AGN feedback on cosmological samples of galaxies.
- It couples the analytic evolution of baryons to the dynamical evolution of a DM N-body simulation.
- The SAG model that we used is presented by Cora (2006); Lagos, Cora & Padilla (2008); Lagos, Padilla & Cora (2009) and Tecce et al. (2010).
- Radiative cooling of gas, star formation, galaxy mergers, disc instabilities, supernovae feedback, BH evolution of mass and spin, AGN feedback among others.

SAG - BH mass evolution

We have 3 different mechanism of BH growth:

- The QSO mode

$$\dot{M}_{\rm BH} = \frac{f_{\rm BH}}{\Delta T} \times \frac{M^{\rm sat}}{M^{\rm central}} \times \frac{M_{\rm ColdGas}}{1 + (200\,{\rm km\,s^{-1}}/V_{\rm vir})^2}, \quad (1)$$

  with $f_{\rm BH} = 0{,}078$.

- The Radio mode

$$\dot{M}_{\rm BH} = \kappa_{\rm AGN} \frac{M_{\rm BH}}{10^8 M_\odot} \times \frac{f_{\rm hot}}{0{,}1} \times \left(\frac{V_{\rm vir}}{200\,{\rm km\,s^{-1}}} \right)^3, \quad (2)$$

  with $\kappa_{\rm AGN} = 2{,}2 \times 10^{-4}\ {\rm M_\odot\,yr^{-1}}$.

- Mergers of BHs

$$M_{\rm BH}^{\rm final} = M_{\rm BH}^{1} + M_{\rm BH}^{2} \quad (3)$$

SAG - AGN outflows and gas cooling suppression

- The BH luminosity

$$L_{\rm BH} = \eta \dot{M}_{\rm BH}, \tag{4}$$

with $\eta = 0{,}1$.

- The modification of the cooling rate is given by

$$\dot{M}'_{\rm cool} = \dot{M}_{\rm cool} - \frac{L_{\rm BH}}{V_{\rm vir}^2/2} \tag{5}$$

- We limit the luminosity by the “Eddington limit”

$$L_{\rm edd} = \frac{4\pi G m_p}{\sigma_T} M_{\rm BH} \tag{6}$$

MC - The geometry

- Rotating black hole $\Rightarrow$ Kerr space-time
- The physical parameters of the orbits as a function of the radius ($x \equiv \sqrt{r/M}$):

$$\begin{aligned} \Omega &= M^{-1}x^{-3}(1+a_*x^{-3})^{-1}, & (7)\\ E^+ &= (1-3x^{-2}+2a_*x^{-3})^{-1/2}(1-2x^{-2}+a_*x^{-3}), & (8)\\ L^+ &= Mx(1-3x^{-2}+2a_*x^{-3})^{-1/2}(1-2a_*x^{-3}+a_*^2x^{-4}). & (9) \end{aligned}$$

- The innermost marginally stable orbit:

$$r_{\rm ms} = M\left\{3+Z_2-{\rm sgn}(a_*)\left[(3-Z_1)(3+Z_1+2Z_2)\right]^{1/2}\right\}, \quad (10)$$

with

$$\begin{aligned} Z_1 &\equiv 1+(1-a_*^2)^{1/3}[(1+a_*)^{1/3}+(1-a_*)^{1/3}],\\ Z_2 &\equiv (3a_*^2+Z_1^2)^{1/2}. & (11) \end{aligned}$$

MC - The accretion disc

Weak magnetic field ⇒ quasi-steady state ⇒ solve the conservation equations

$$(\dot{M}_0 L^+ - g)_{,r} = 4\pi r (F L^+ - H), \quad (12)$$

$$(\dot{M}_0 E^+ - g\Omega)_{,r} = 4\pi r (F E^+ - H\Omega), \quad (13)$$

$$\dot{M}_0 = -2\pi r \Sigma u^r = \text{cte.} \quad (14)$$

We obtained the flux

$$F(r) = \frac{\dot{M}_0}{4\pi r} f + \frac{1}{r} \frac{-\Omega_{,r}}{(E^+ - \Omega L^+)^2} \int_{r_{\rm ms}}^{r} (E^+ - \Omega L^+) H r dr, \quad (15)$$

with

$$f \equiv \frac{-\Omega_{,r}}{(E^+ - \Omega L^+)^2} \int_{r_{\rm ms}}^{r} (E^+ - \Omega L^+) L^+_{,r} dr. \quad (16)$$

By integrating the flux we obtained the luminosity

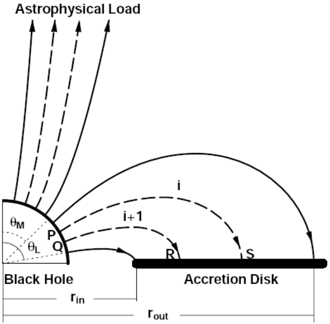
$$\begin{aligned} L_{\rm BH} &\equiv 2\int_{r_{\rm ms}}^{\infty} F E^{+} 2\pi r dr \\ &= \dot{M}_0(1 - E^{+}_{\rm ms}) + 4\pi \int_{r_{\rm ms}}^{\infty} H\Omega r dr \\ &= \epsilon_0 \dot{M}_0 + L_{\rm MC} \end{aligned} \quad (17)$$

Since the luminosity cannot be negative

$$L_{\rm MC} \geq -\epsilon_0 \dot{M}_0 \quad (18)$$

MC - The magnetic field

We use the model of Wang, Xiao & Lei (2002), with the improvement of Wang et al. (2003)



This model allows the coexistence of the BZ and MC processes (CEBZMC).

The magnetic field on the horizon

$$B_{\rm H}^2 = \frac{2\dot{M}_0}{r_{\rm H}^2} \tag{19}$$

Assuming that the magnetic field on the disc varies as a power law, and applying continuity of the magnetic flux they obtained

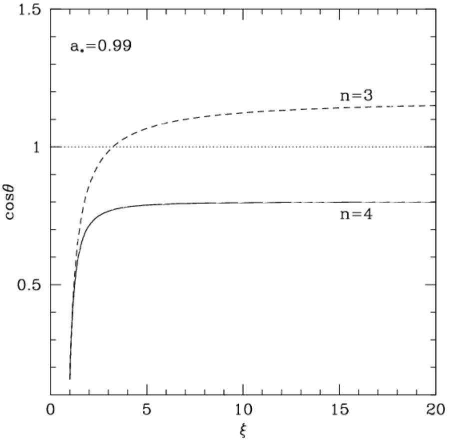
$$B_z = B_{\rm H} \left[\frac{r_{\rm H}}{\tilde{\omega}(r_{\rm ms})} \right] \xi^{-n} \quad \text{with} \quad \xi \equiv \frac{r}{r_{\rm ms}}, \tag{20}$$

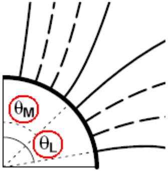
and the mapping relation

$$\cos\theta - \cos\theta_L = \int_1^{\xi} G(a_*, \xi, n) d\xi. \tag{21}$$

The mapping relation determines θ_M and the outer radius

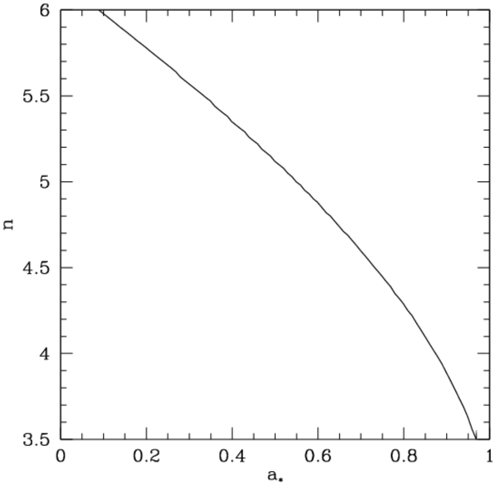
$$\cos\theta_M = \cos\theta_L + \int_1^{\xi_{\rm out}} G(a_*, \xi, n) d\xi. \quad (22)$$





Following Wang et al. (2003) we set $\theta_L = 0{,}45\pi$

The CEBZMC state depends on the combination of a_* and n



The angular momentum flux derived from the magnetic field

$$\frac{H(a_*,\xi,n)}{H_0} = \begin{cases} A(a_*,\xi)\xi^{-n}, & 1 < \xi < \xi_{\rm out} \\ 0, & \xi > \xi_{\rm out} \end{cases}, \quad (23)$$

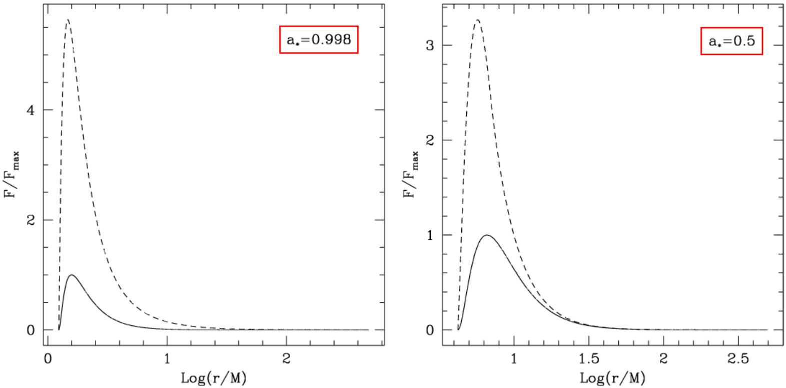
with

$$A(a_*,\xi) = \frac{a_*(1-\beta)(1+q)}{2\pi x_{\rm ms}^2[2\csc^2\theta-(1-q)]} F_A(a_*,\xi), \quad (24)$$

$$F_A(a_*,\xi) = \frac{\sqrt{1+a_*^2 x_{\rm ms}^{-4}\xi^{-2}+2a_*^2 x_{\rm ms}^{-6}\xi^{-3}}}{\sqrt{(1+a_*^2 x_{\rm ms}^{-4}+2a_*^2 x_{\rm ms}^{-6})(1-2x_{\rm ms}^{-2}\xi^{-1}+a_*^2 x_{\rm ms}^{-4}\xi^{-2})}}. \quad (25)$$

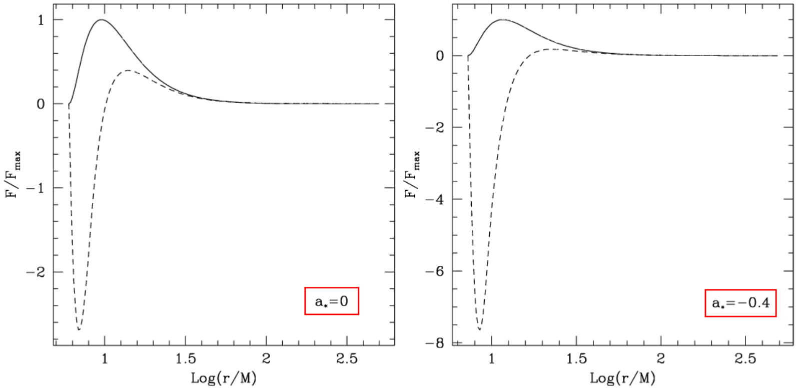
Radiation Flux - High spins

Using $n = 4$ we obtain

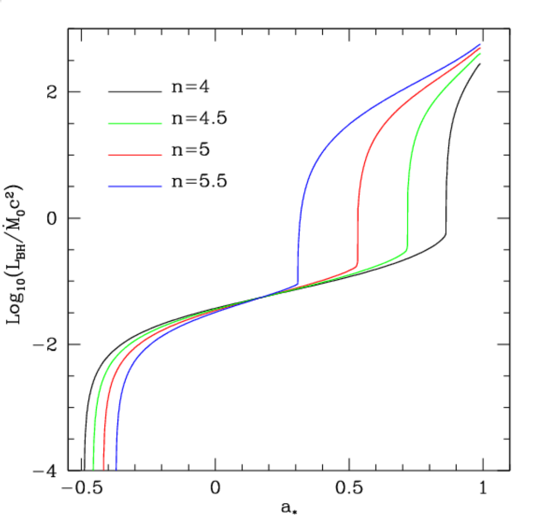


Radiation Flux - Low spins

Using $n = 4$ we obtain



Disc Luminosity



Jet Power - The BZ mechanism

The total poloidal magnetic flux in the jet

$$\Phi_{\rm tot} = 4\pi r_{\rm H}^2 (1 - \cos\theta_M) B_{\rm H} \tag{26}$$

and the angular frequency of the BH

$$\Omega_{\rm H} = \frac{a}{2 r_{\rm H}(a)} \tag{27}$$

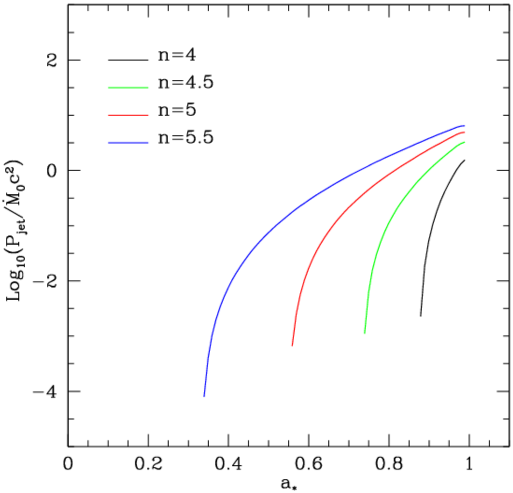
Then the power output is

$$P_{\rm jet} = k \Phi_{\rm tot}^2 \Omega_{\rm H}^2 \tag{28}$$

where $k (\approx 0{,}05)$ is a constant weakly dependent on the field geometry.

Tchekhovskoy et al. (2010)

The Jet power



Feedback in the Radio Mode

In the SAG, the accretion rate in this mode is estimated as

$$\dot{M}_{\rm BH} = \kappa_{\rm AGN} \frac{M_{\rm BH}}{10^8 M_\odot} \times \frac{f_{\rm hot}}{0{,}1} \times \left(\frac{V_{\rm vir}}{200\,{\rm km\,s^{-1}}} \right)^3 , \tag{29}$$

We allow the existence (if possible according the BH spin) of a jet that reduces the cooling rate

$$\dot{M}'_{\rm cool} = \dot{M}_{\rm cool} - \eta_{\rm FB} \frac{P_{\rm jet}}{V_{\rm vir}^2/2} \tag{30}$$

and a disc luminosity that reheates the cold gas

$$(\Delta M_{\rm reheated})_{\rm AGN} = \eta_{\rm BH} \frac{L_{\rm BH}}{V_{\rm vir}^2/2} \Delta T \tag{31}$$

Feedback in the QSO Mode

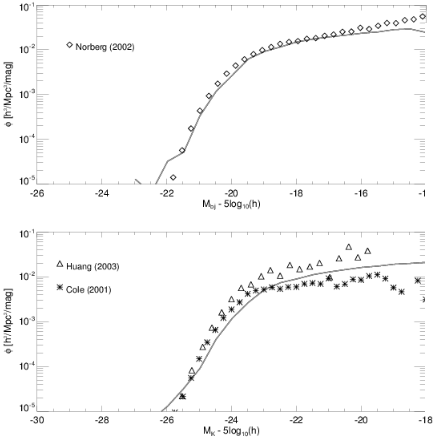
In the SAG, the accretion rate in this mode is estimated as

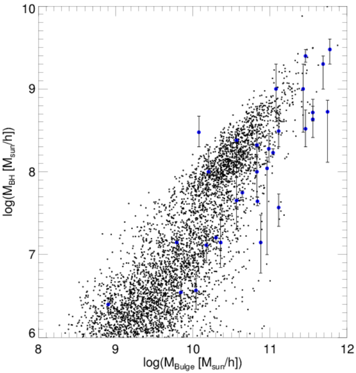
$$\dot{M}_{\rm BH} = \frac{f_{\rm BH}}{\Delta T} \times \frac{M^{\rm sat}}{M^{\rm central}} \times \frac{M_{\rm ColdGas}}{1 + (200\,{\rm km\,s^{-1}}/V_{\rm vir})^2}, \quad (32)$$

In this case we only have the luminosity of the disc that reheates the cold gas

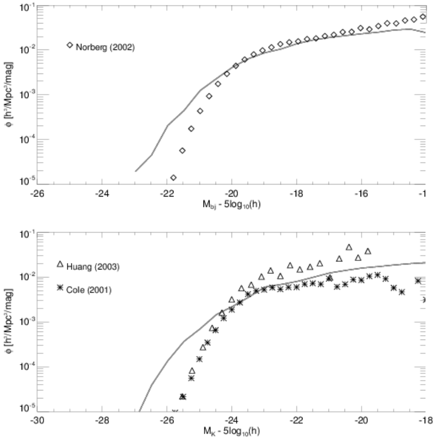
$$(\Delta M_{\rm reheated})_{\rm AGN} = \eta_{\rm BH} \frac{L_{\rm BH}}{V_{\rm vir}^2/2} \Delta T \quad (33)$$

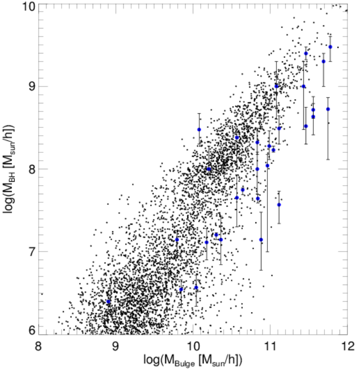
The old SAG model



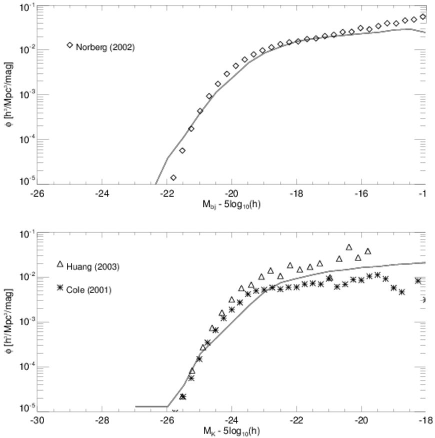


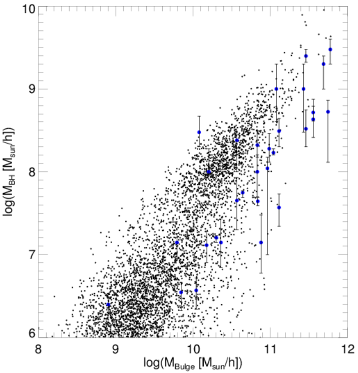
New AGN feedback - $n = 4$ - $\eta_{\rm BH} = 0{,}5$ - $\eta_{\rm FB} = 0{,}5$





New AGN feedback - $n = 5{,}5$ - $\eta_{\mathrm{BH}} = 0{,}5$ - $\eta_{\mathrm{FB}} = 0{,}5$





Summary

- We study the effects of AGN feedback on cosmological samples of galaxies using a semi-analytic model of galaxy formation (SAG) within a dark matter N-Body simulation.
- We propose a new model for the BH magnetosphere which invokes the magnetic coupling between the BH and its surrounding disc and allows the existence of the Blandford-Znajek effect, associated with jet production.
- With our model the AGN processes depend strongly on the BH spin, through the disc luminosity and the jet power.

Summary

- In the SAG, we implement our model as a 'dual AGN feedback':
  - The jet reduces the gas cooling during the radio mode.
  - The disc luminosity reheates the cold gas during the radio and the QSO mode.
- We were able to reproduce the galaxy LFs in the b_j and K band, and the BH mass-Bulge mass relation in a very good agreement with the observational data.
- Because of these results, our model presents a more physical way of describing the AGN feedback process.

Future Work

1. Improve the following of the angular momentum of DM halos and galaxies (S. Contreras)
   $\Rightarrow$ Distribution of BH spin.
   $\Rightarrow$ Prolonged or Chaotic accretion?
2. Include MC and BZ in the BH spin evolution.
3. Compare with more observations: QSO LF's, SFH, Radio Loudness, Fundamental Plane, etc.
4. Physical model for BH accretion rate?
5. More and more...