Black Hole Winds at All Scales
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Ram-pressure induced radial inflows of gas to the galaxy centre

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Abstract. Ram-pressure stripping (RPS) is a process known to remove gas from satellite galaxies. Recent observational studies have found an increased ratio of active galactic nuclei (AGN) among the population of RPS galaxies compared to regular galaxies in the field. To test whether ram pressure (RP) can trigger an AGN, we perform a suite of hydrodynamical wind-tunnel simulations of a massive ($M_{\rm star} = 10^{11} M_{\odot}$) galaxy, with inclusion of star formation, stellar feedback and high resolution up to 39 pc. We find that RP increases the inflow of gas to the galaxy centre, which in turn can result in the enhanced BH accretion, as measured by the Bondi-Hoyle model. We also estimate pressure of outflows from our accretion rates and show that AGN feedback would play an important role on the early stages of stripping, while RP itself is not so strong.

Keywords. galaxies: active, galaxies: evolution, methods: numerical

1. Introduction

In a process called ram-pressure stripping (RPS), hot intracluster medium (ICM) pushes and removes the interstellar medium (ISM) of a galaxy infalling in this cluster. Predicted by Gunn & Gott (1972), RPS has since been observed to act on galaxies in a variety of clusters (see review by Boselli et al. 2022). Apart from a more expected inevitable quenching of star formation (SF) due to gas removal, RPS has other effects on a galaxy, among which is a possible triggering of nuclear activity. Studies by Poggianti et al. (2017) and Peluso et al. (2022) show the increased number active galactic nuclei (AGN) among the population of RPS galaxies compared to regular field galaxies.

Here we will tackle the question of AGN-RPS connection through a means of simulations. Our goal is to see whether black hole (BH) accretion is enhanced enough under RP to turn a regular galaxy into an active one.

2. Methods

A detailed description of our simulation set-up is presented in Akerman et al. (2023), and here we briefly summarise it. We use an adaptive mesh refinement code *Enzo*, rendering a box region of 160 kpc on a side. An additional 5 levels of refinement allow us to achieve a maximum resolution of 39 pc.

We input a Plummer–Kuzmin stellar disk (Miyamoto & Nagai 1975) and Burkert profile for the spherical dark matter halo (Burkert 1995) as static potentials, but calculate the self-gravity of the gas and allow it to radiatively cool and form stars. For SF and stellar feedback recipes we follow Goldbaum et al. (2015, 2016). The main parameter of this SF model is the minimum threshold number density (set to $10\,\mathrm{cm}^{-3}$) at which SF can happen in a cell if its mass exceeds Jeans mass. The disk starts with metallicity $Z = 1.0 Z_\odot$ and the ICM has $Z = 0.3 Z_\odot$. In this simulation we do not include a BH seed particle, and, consequently, AGN feedback physics.

The initial conditions are based on galaxy JO201 that is both subject to RP (Bellhouse et al. 2017, 2019) and is an AGN (Poggianti et al. 2017). Several parameters go into the aforementioned static potentials, such as the stellar disk mass, set to $M_{\rm star} = 10^{11} M_\odot$. Parameters of the ICM wind are also based on JO201 falling into its parent cluster (Bellhouse et al. 2019), so that we model a varying wind instead of a constant one (Tonnesen 2019).

We fix a galaxy in the centre of the simulation box and add a moving ICM flowing through it, simulating a RP 'wind'. We define the wind angle as the angle between the direction of the wind and the galaxy rotation axis, and model three wind angles: 0° (face-on wind, W0), 45° (W45), and 90° (edge-on wind, W90). This allows us to study the influence of the wind angle on the centremost gas. We also simulate a fiducial galaxy not subject to RP (no wind, NW).

We let the galaxy evolve for 300 Myr before the wind reaches it. Then we separate the simulation into 4 different runs (NW, W0, W45 and W90) and model RP for 700 Myr.

3. Movement of gas in and out of the galaxy centre

With the focus of this study being BH accretion, let us first answer the question of how RP influences the movement of gas in the galaxy centre, looking closely at the innermost 500 pc. To do this, we measure mass flux though a spherical shell centred around the galaxy centre where we would expect a BH to be located, since we do not have one. The radius of this shell is 500 pc, and the mass flux is calculated as follows:

$$\dot{M} = \sum_i \frac{m_i v_i}{dL}, \tag{1}$$

where m_i is mass of the i-th cell, v_i is its radial velocity and $dL = 200$ pc is the shell's width. We measure the mass flux for cold gas, defined as having temperature $T \leq 10^{4.5}$ K, since this is the gas that might feed a BH.

We plot the results in Fig. 1, where the left and right panels present the same data, but the right one is zoomed-in to better show W0 and W45. Under RP, both inflows and outflows to the galaxy centre are increased. This manifests in the net flux as the growing difference between the peak values of the NW and RPS-galaxies. The effect is especially evident in the asymmetric W90, where the increase is about an order of magnitude during the later stages of stripping. To test for net inflow, we integrate these values and simply sum the total mass within 500 pc of the galaxy centre. We find an increased net mass inflow to, and higher total mass in, the centre of galaxies undergoing RP than the NW galaxy.

4. Black hole accretion

Now that we have shown that more cold gas inflows to the galaxy centre under RP, let us measure whether this gas can make it to the central BH. In Akerman et al. (2023) we go into detail about different BH accretion models that we can test. Here, instead,

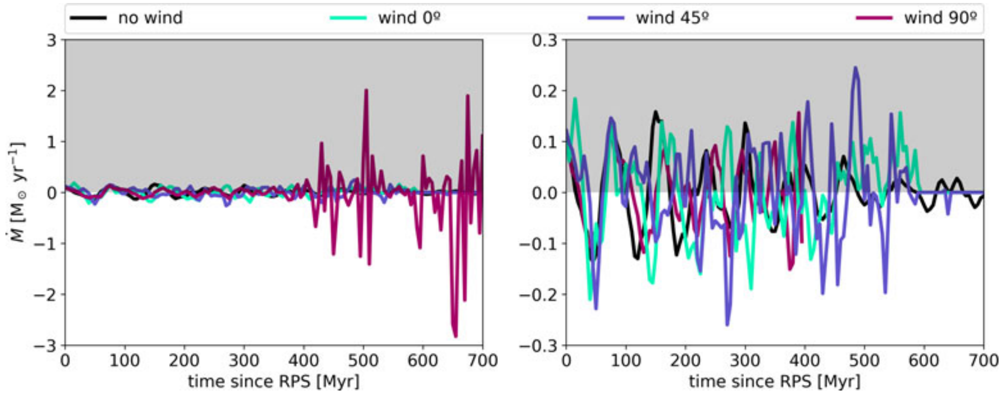

Figure 1. Net mass flux of cold gas ($T \leq 10^{4.5}$ K) though a spherical shell of radius 500 pc centred on the galaxy centre, colour-coded for different wind angles. Left and right panels present the same data, but the right one is scaled down to better show W0 and W45, and W90 is plotted only for the first 400 Myr. The grey area serves to separate inflow (negative) from outflow (positive).

we will focus on one of them, modified Bondi–Hoyle (Tremmel et al. 2017), as it gives us the highest accretion rates that will serve as an upper limit:

$$\dot{M}_{\rm BH} \propto \frac{M_{\rm BH}^2 \rho c_s}{(v_\theta^2 + c_s^2)^2}, \tag{2}$$

where $M_{\rm BH} = 10^7 M_\odot$ is assumed BH mass, ρ is the mean density and c_s is the speed of sound measured in a sphere of radius 700 pc around the galaxy centre, while v_θ is average angular velocity in a thin cylindrical shell of radii 660 pc $< R <$ 740 pc and 50 pc height. Radii of the sphere and the cylindrical shell were chosen so that the resulting accretion rate estimated by the Bondi–Hoyle model for the NW galaxy would match the accretion rate from the other two models in Akerman et al. (2023).

We find that the Bondi–Hoyle model predicts that a BH would accrete more mass under RP. RPS-galaxies also become active, defined as $\dot{M}_{\rm BH} \geq 1\%$ of the Eddington accretion limit, much more often and for longer periods of time.

In particular in face-on stripped galaxies W0 and W45, AGN feedback would 'compete' with RP in removing the gas, assuming that the former would be aligned perpendicularly to the plane of the galaxy. To estimate the relative role of AGN feedback compared to that of RP we find the energy ratio of the two forces acting on the galaxy centre. First, to measure the AGN feedback energy we follow Springel et al. (2005):

$$E_{\rm AGN} = \epsilon_f \epsilon_r \dot{M}_{\rm BH} c^2 \Delta t, \tag{3}$$

where $\epsilon_f = 0.05$ is how much of the accreted mass energy is available as feedback, $\epsilon_r = 0.1$ is radiative efficiency, c is speed of light and $\Delta t = 5$ Myr is our time step.

For the ICM wind energy, we take the kinetic energy of the wind:

$$E_{\rm ICM} = \frac{1}{2} \dot{M}_{\rm ICM} \Delta t v_{\rm ICM}^2, \tag{4}$$

where $v_{\rm ICM}$ is the wind velocity and $\dot{M}_{\rm ICM}$ is mass flux of the ICM. We measure these values in a cylinder centred 16 kpc away from the disk of W0 galaxy, with height of 2 kpc and radius of 1 kpc. We place the cylinder far enough not to catch the bow shock region but close enough so that the measured values resemble the ones immediately experienced by the galaxy disk.

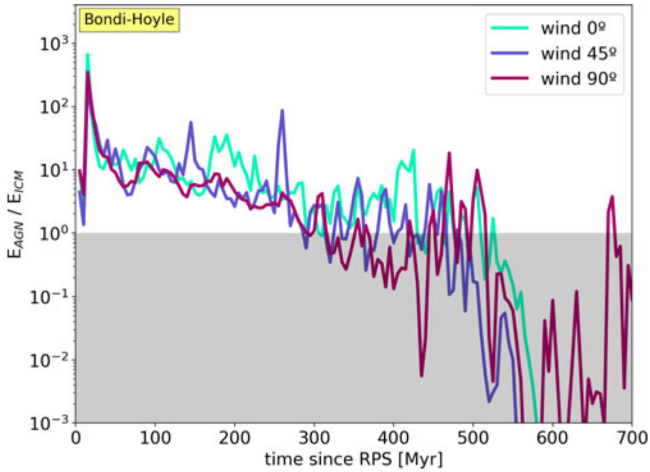

Figure 2. Ratio of energy of an AGN to kinetic energy of ICM, as a function of time, colour-coded for different wind angles. AGN energy is taken for Bondi-Hoyle accretion estimation. The grey area serves to separate AGN-dominated regime from the ICM-dominated one.

We plot the energy ratio as a function of time in Fig. 2, where $\dot{M}_{\rm BH}$ is estimated for the Bondi-Hoyle model, as it gives us the highest accretion rates. For the first 300-400 Myr the feedback energy dominates over the ICM wind, but since in our model RP increases with time, at 400-500 Myr its energy overtakes that of the AGN. This emphasises the importance of AGN feedback during the early stages of RPS. Including BH physics in the simulations could, hence, alter the galaxy evolution by stopping the ICM wind from reaching the disk at low RP.

5. Conclusions

We present the first systematic numerical study on the effect of RP on a galaxy nucleus. We find that RP increases the inflow of gas to the galaxy centre, which in turn, in accordance with observations, can result in the enhanced BH accretion. RPS-galaxies, thus, are more prone to becoming active compared to non-stripped cluster galaxies. We show that AGN feedback would play an important role on the early stages of stripping, while RP itself is not so strong. To study this effect in greater detail would require simulating RPS-galaxy with BH accretion physics and AGN feedback recipes.

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