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A 3D hydrodynamic simulation of a black hole outflow in a dwarf spheroidal galaxy

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Abstract. We present results from a non-cosmological, three-dimensional hydrodynamic simulation of an outflow from an intermediate-mass black hole in Dwarf Spheroidal Galaxies. Assuming an initial baryonic-to-dark-matter ratio derived from the CMB radiation and a cored, static dark matter potential, we evolved the galactic gas distribution over 3 Gyr, taking into account the outflow of a black hole. Our results indicate that in a homogeneous medium the outflow propagates freely in both directions with the same velocity and its capable of removing a fraction of the gas from the galaxy (it depends on the initial conditions of the outflow). When the SNe are taken into account, the effect of the outflow is substantially reduced. It is necessary an initial velocity around 1000 km/s and a density larger than 0.003 particles.cm^{-3} for the outflow to propagate. In these conditions, the removal of gas from the galaxy is almost negligible at the end of the 3 Gyr of the simulation.

Keywords. galaxies: dwarf - galaxies: evolution - galaxies: outflow - hydrodynamics - methods: numerical

1. Introduction

Recently, several observations suggested that dwarf galaxies host black holes in their center, the so-called intermediate-mass black holes (IMBH). In the Ursa Minor Dwarf Spheroidal Galaxy, for instance, there are indications suggesting the presence of a IMBH of $M \sim 10^{4-6}$ $M_\odot$ at or near its center (Moran *et al.* 2014; Lora *et al.* 2009). The effects of these objects in the evolution of the dSphs have been so far not properly analyzed. Could the outflow of the IMBH be one of the mechanisms responsible for the total absence of gas in local dSph? In order to analyze the possible role played by the outflow from a IMBH in the removal of gas from a typical dSph, we adopted a 3D hydrodynamic code already adjusted to the dSph galaxy Ursa Minor in Caproni*et al.* (2015); Caproni *et al.* (2017). The initial setup of the code is the same as in these works. We first explored the space-parameter of the main properties of the outflow in order to determine in which physical conditions it can develop and propagate through the interstellar medium of the galaxy. After that, we started analyzing its impact in the gas loss of the galaxy.

2. Methodology and Results

The differential equations for the mass, momentum and energy quantities associated with an ideal gas under influence of a cored, static dark matter gravitational potential were treated with the numerical code PLUTO (Mignone *et al.* 2007). Starting with a interstellar medium in hydrostatic equilibrium with the dark matter gravitational potential, we evolved the galactic gas distribution over 3 Gyr in a cubic region of 3 kpc × 3 kpc × 3 kpc, using a grid with 150 points in each Cartesian direction. Starting from the equilibrium, an outflow is simulated by the injection, in the central cell of

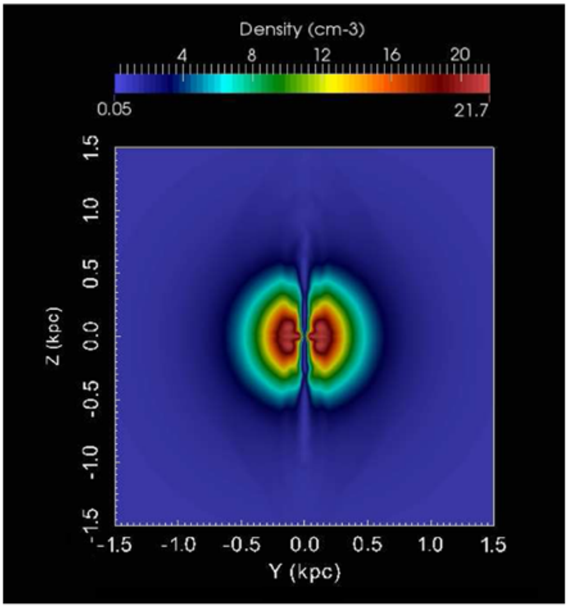

Figure 1. Density profile in the YZ plane in t = 75 Myr for the case with $\rho = 0.005$ part.cm^{-3} and v = 1000 km/s in an homogeneous medium.

the computer domain, of a certain density with a velocity in both directions of one of the axis, for a time interval of 250 Myr. The outflow will propagate in a scenario with an homogeneous medium and in another one with the feedback of types Ia and II supernovae.

First, the density and velocity of the outflow were varied to constrain the physical conditions that allows the outflow to develop and propagate through the ISM of the galaxy. All chosen values for these two quantities are consistent with an IMBH mass ($M \sim 10^4$ to 10^6 M$_\odot$). A low density outflow (below 0,001 part.cm^{-3}) is not able to propagate neither in the homogeneous medium and in a disturbed one. As its density is increased, the impact in the medium is larger and the outflow pushes the gas creating a jet in the direction of the velocity (see Figure 1). An outflow with a higher density causes a stronger impact in the ISM. The outflow can propagate more easily and reach the outer regions of the galaxy faster. At 75 Myr after the beginning of the simulation, the outflow has already reached the 1 kpc radius of the galaxy in the case of $\rho_{outflow} = 0.005$ part.cm^{-3}, whereas it is still inside 0,5 kpc when its density is lower (0.003 part.cm^{-3}). It also seems to remove more gas and to affect the gas distribution on its vicinity. The initial velocity of the outflow, on the other hand, has a lower impact. In both cases it was adopted an initial velocity of 1000 km/s.

When an outflow is simulated in an homogeneous medium, it propagates in both directions of the axis (Figure 1) with the same velocity, much below the initial one (Figure 2). After almost 100 Myr, it reaches the outskirts of the galaxy removing a fraction of the gas of the ISM. In the density profile, it is possible to see that the outflow almost does not disturb the ISM, unless in the axis of its propagation (Figure 1). After the outflow ends, gravity pulls the gas to its original distribution. The temperature profile, however, shows imprints of the outflow for a longer period and reveals that it heats also the gas in the vicinity of its propagation.

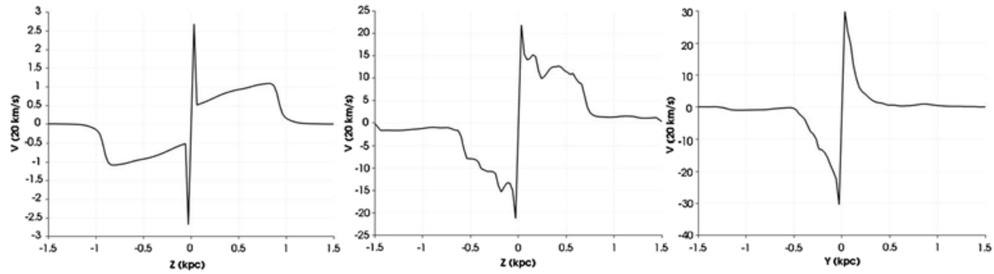

Figure 2. velocity (in 20 km/s) in the axis of the outflow in t = 125 Myr for the case of homogeneous medium with v = 1000 km/s and $\rho = 0.003$ and 0.005 part.cm^{-3} (left and middle panels, respectively) and the perturbed medium with v = 1000 km/s and $\rho = 0.005$ part.cm^{-3} (right panel).

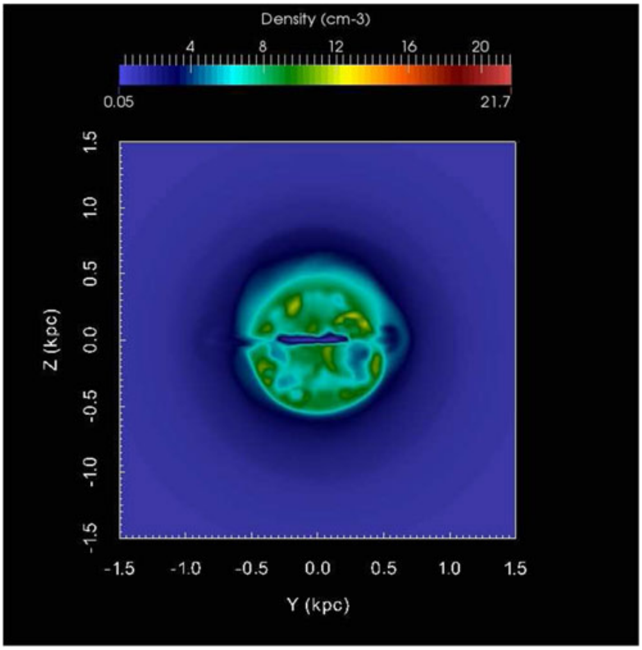

Figure 3. Density profile in the YZ plane in t = 75 Myr for the case with $\rho = 0.005$ part.cm^{-3} and v = 1000 km/s in an perturbed medium.

In the case of a perturbed medium, the energy of each SNe is inserted in the ISM following the procedure described in Caproni *et al.* (2017). The SNe rate is the one from the chemical evolution model of Lanfranchi & Matteucci (2007). When the energy of SNe is released, a shock wave associated with a region of high density, temperature and pressure is created. The velocity of the gas in this region is also high. These features cause turbulence in the medium that affects the development of the outflow. Its velocity is reduced substantially, reaching zero in some positions and epochs (Figure 2), the symmetry in the axis is lost (Figure 3), and it takes longer to leave the galaxy. After 75 Myr, the outflow is still inside the 500 pc radius of the galaxy (when the medium is homogeneous, the outflow at this time has already reached more than 1 kpc). It seems

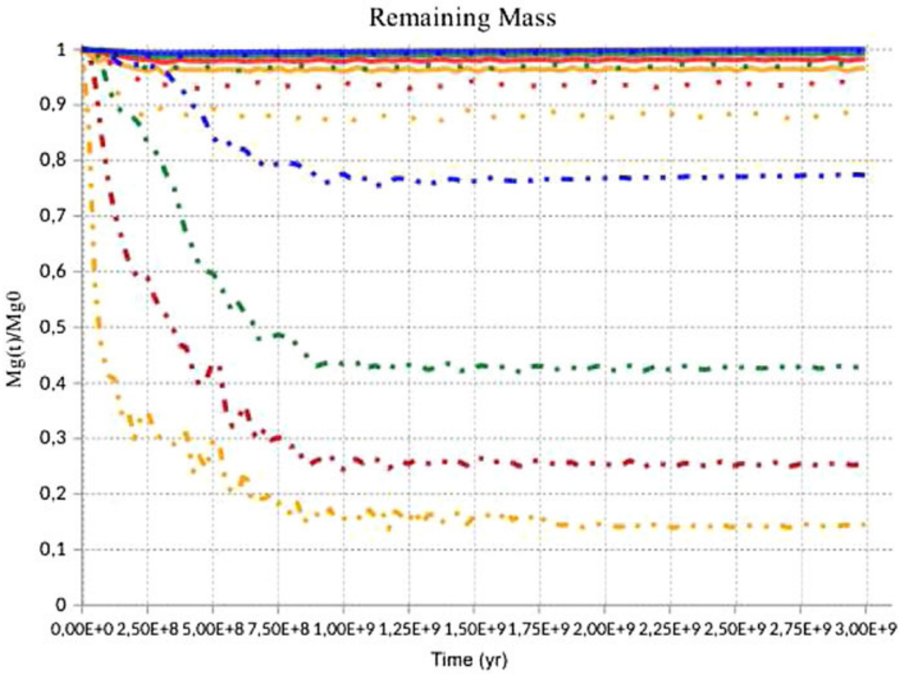

Figure 4. Remaining mass fraction inside different regions of the galaxy (300 pc - orange line; 600 pc - red line; 950 pc - red line, and 1500 pc - blue line) for the case with an outflow with v = 1000 km/s and $\rho = 0.003$ and 0.005 part.cm^{-3} (solid line and dotted lines, respectively) and the perturbed medium with and outflow with v = 1000 km/s and $\rho = 0.005$ part.cm^{-3} dot-dashed line).

also in this case that the outflow does not carry any gas out of the system (Figure 4). At 500 Myr, only the effects of the SNe in the temperature profile can be noticed, whereas the density of the gas is much lower due to the SNe energy that expels the gas out of the galaxy (Caproni *et al.* 2017).

By comparing the fraction of the initial mass that remains inside different regions of the galaxy in different scenarios for the outflow and the medium, one can quantify the effects of the outflow on the gas loss of the galaxy. On Figure 4, it is possible to see that an outflow with a higher density removes more gas from the central region of the galaxy (around 15% inside the 300 pc), whereas with $\rho = 0.003$ part.cm^{-3} around 5% of the gas is lost. When the energy of SNe is also taken into account, the amount of mass that is lost from the galaxy is much higher, however very similar to the case when only the SNe is considered (see Caproni *et al.* 2017 for details). In both cases, at the end of the simulation (3 Gyr) the remaining mass inside the 300 pc region is close to 15%. The difference is that rate of gas loss when a high density outflow is taken into account is higher during the epoch when its active (until 250 Myr).

3. Final Remarks

Our main results can be summarized as follows: 1) an IMBH outflow with v = 1000 km/s and $\rho = 0.003$ part.cm^{-3} (or higher) propagates in the ISM of a dSph galaxy and contributes to the gas loss of the galaxy; 2) outflows with higher densities have a larger impact in the ISM and remove more gas: $\sim$ 15% of the gas inside 300 pc; 3) in a medium

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perturbed by the energy of SNe, the effect of the outflow is reduced drastically: the amount of mass that is lost from the galaxy is very similar to the case when no outflow is considered; 4) the outflow seems to affect the rate of gas loss only when its active, making the rate higher.

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