ASTAC LARGE PROGRAM PROPOSAL: SCIENCE JUSTIFICATION

UTILISING A DIVERSE SET OF HYDRODYNAMICAL SIMULATIONS TO STUDY THE ANGULAR MOMENTUM JOURNEY TO GALAXIES

MOTIVATION AND OBJECTIVES

In our current model of the universe galaxies form at the centre of enormous dark matter haloes. It is therefore natural to question the relationship between the host halo and its natal galaxy. In particular, do the properties of the halo (mass, rotation) set the corresponding properties in the galaxy?

We know that in a closed system angular momentum (or rotation) is conserved. In other words, the rotation of the galaxy needs to come from what was there initially (or from extreme tidal torques). Is it therefore correct to say the angular momentum of the halo sets the rotation of the galaxy?

This pivotal theoretical question is challenging to answer, in part due to the large dynamic range of scales involved; galaxies form on 10s of kpc (kpc = 10^3 pc) scales, while dark matter haloes interact on Mpc (Mpc = 10^6 pc) scales. Further, when we consider the internal galaxy evolution processes such as the formation and evolution of stars, we really need to push the spatial resolution to scales of a few pc – making the ideal dynamic range ~ 10^6. Our best hope of coming anywhere close to resolving both small-scale galaxy evolution physics and large-scale dark matter interactions lies in state-of-the-art cosmological zoom simulations. Now is the perfect time address this question, since the chemical and stellar modelling within zoom simulations has never been more advanced. Further, there has never been a wider breadth of public hydrodynamical simulation codes available to tackle this problem.

This project aims to leverage the breadth of state-of-the-art hydrodynamical codes and chemical models out there and conduct high resolution cosmological zoom simulations that follow the co-evolution of both galaxies and their host haloes.

BACKGROUND

Simulations offer an excellent way to study the journey of angular momentum since they can explicitly track dark matter alongside the stellar and gaseous components of a galaxy during its formation and evolution. Further, different simulations can be used to track the different stages of the journey.

Broadly, within a hierarchical ΛCDM universe, we can split the journey of angular momentum from halo-scales to galaxy-scales into two;

1. The interplay between gas and dark matter on halo scales (~ 100s of kpc) as structures form in the universe.
2. The journey of angular momentum from gas on halo scales (in other words, the circumgalactic medium) into the central galaxy.

In this section we will discuss the insights we can gain from simulations on both stages. We will then explain where this project fits in, along with our requirement for supercomputing resources.

THE ANGULAR MOMENTUM JOURNEY

STAGE 1: THE DARK MATTER-GAS INTERPLAY ON HALO-SCALES

In the well-established ΛCDM model of our universe, density perturbations lead to the clustering of dark matter and gas, first in small spherical haloes, then when these haloes merge hierarchically, into more massive haloes and finally into large-scale clusters of haloes. During this process, the dark matter and gas gain angular momentum through tidal torques (e.g. Peebles 1969, White 1984, Barnes & Efstathiou 1987).

Simulations offer a way of directly investigating the interplay between the angular momentum of gas and dark matter on large-scales by removing galaxy formation/evolution altogether. Known as non-radiative simulations, this type of hydrodynamical simulation models gas adiabatically and does not include radiative cooling/star formation. As such, it will follow the formation of dark matter and gaseous haloes, however galaxies will not form at the halo centres.

From early non-radiative hydrodynamical simulations onwards, it was clear the mapping between the angular momentum of the diffuse halo gas and the dark matter was non-linear; there is an enhancement in the angular momentum of the halo/circumgalactic gas in relation to that of the dark matter (e.g. van den Bosch et al. 2002, Gottlöber & Yepes 2007). The angular momentum of the gas is then enhanced further with respect to the dark matter once cooling/galaxy evolution physics is included (e.g. Stewart et al. 2017, Zjupa & Springel 2017).

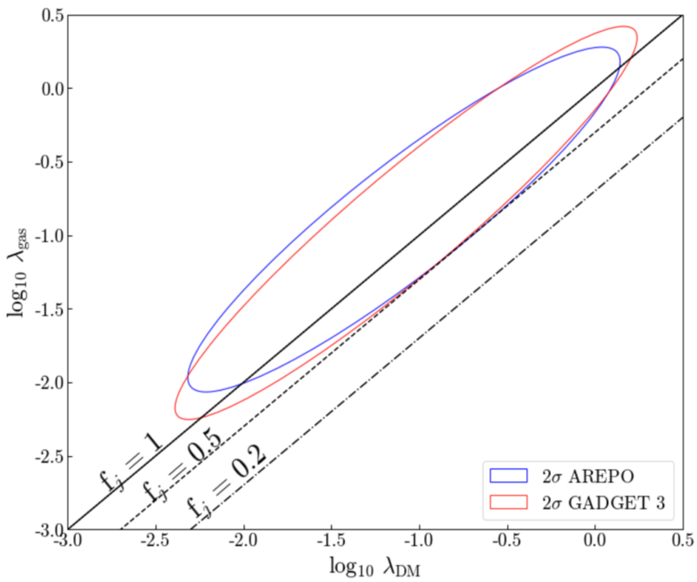

Figure 1: gas spin (λ_{gas}) versus dark matter spin (λ_{dm}) calculated for haloes taken from two cosmological simulations that use identical initial conditions, however different hydrodynamic codes; AREPO (in blue) and GADGET 3 (in red). The 2-σ distribution is indicated by the solid ovals, while the diagonal lines indicate different f_j (or $\lambda_{gas}/\lambda_{dm}$) values.

To complicate matters further, it is evident that the type of hydrodynamic scheme employed in the hydrodynamical simulation (e.g. smoothed particle hydrodynamics or SPH, adaptive mesh refinement or AMR) impacts this result; in Fig. 1 we show the relative spins of the gas and dark matter in haloes taken from two cosmological non-radiative simulations which have exactly the same initial conditions, however utilise different hydrodynamic schemes. Here spin is a measure of the angular momentum in each component; it is defined as

$$\lambda \propto \frac{j}{M^{2/3}};$$

where j is the specific angular momentum of the component (gas or dark matter) and M is the total mass of the system. It is clear that altering the hydrodynamic scheme from SPH (GADGET-3 code; a modified version of GADGET-2, presented in Springel 2005) to AMR (AREPO code; Weinberger et al. 2020) results in an increase in the mean $\frac{\lambda_{gas}}{\lambda_{dm}}$ (or f_j) ratio, indicating an increase in the angular momentum of the halo gas compared with the dark matter.

These differences motivate the use of different hydrodynamic schemes when studying the journey of angular momentum to the galaxy.

STAGE 2: THE JOURNEY OF ANGULAR MOMENTUM FROM THE CIRCUMGALACTIC MEDIUM (CGM) TO THE GALAXY

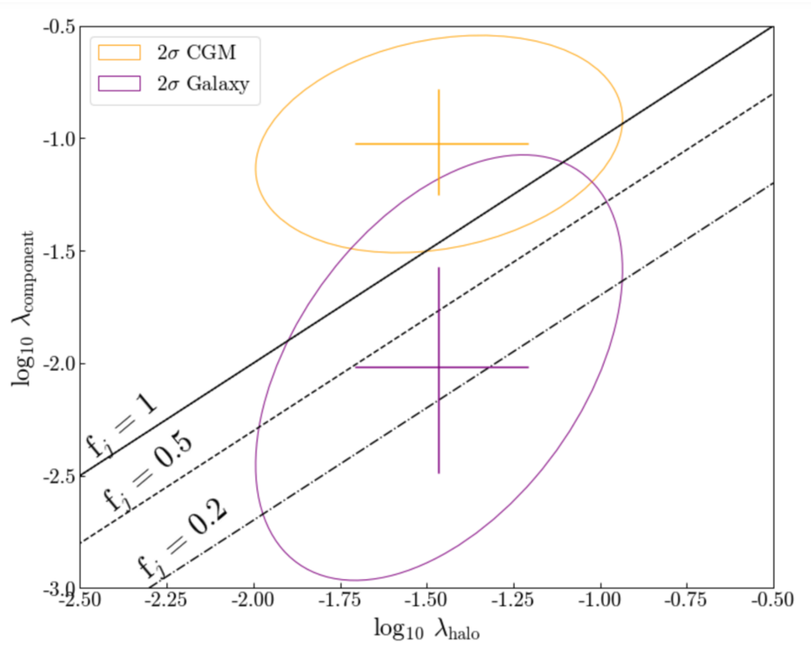

Figure 2: galaxy (purple) and CGM (orange) spin versus dark matter spin calculated for haloes taken from the full-physics cosmological simulation RecalL0025N0752. The 2-σ distributions are indicated by the solid ovals, while the diagonal lines indicate different f_j (or $\lambda_{gas}/\lambda_{dm}$) values. The straight lines indicate the 16th-84th percentiles.

Moving from non-radiative simulations to simulations that also include cooling and galaxy formation/evolution physics, we can now follow the journey from diffuse, CGM gas to the central galaxy. Fig. 2 shows the spins of both the CGM and galaxy plotted against the dark matter halo spins for systems taken from the cosmological hydrodynamical simulation EAGLE Recal-L0025N0752 (an SPH simulation that includes cooling/galaxy physics, described in Schaye et. al 2015) It is clear there is a significant disparity between the angular momentum of the CGM gas and the galaxy – **it is not a simple case of angular momentum conservation.**

How galaxy evolution physics sets the relative angular momentum of the CGM gas and the galaxy is a pivotal question that we will address with this project.

THIS WORK: INNOVATION

This project proposes to use cosmological zoom simulations (such as the example given in Fig. 3) to bridge the gap between the two stages in the angular momentum journey presented above. These simulations will simultaneously follow the formation and evolution of galaxies at high resolution, alongside the interactions of dark matter haloes on Mpc scales. We will then be able to map the journey of angular momentum throughout the galaxy life-cycle. We will use the state-of-the-art initial conditions generator genetIC (Stopyra et al., 2021) to set up both the base cosmological N-body simulation and the subsequent zoom simulations of particular (Milky Way-mass) systems taken from this box.

Figure 3: sample cosmological zoom simulation of a Milky Way-mass halo, taken from a 50 Mpc/h cosmological volume. The simulation was run using GADGET 3, and the initial conditions were generated using genetIC. Gas is shown in red, while dark matter is in blue. The side length of the image is 750 kpc.

The project will be unique both in terms of its scientific scope and the breadth of hydrodynamic codes used to tackle the problem. We will leverage the expertise on multiple hydrodynamical schemes within our research team. The four hydrodynamic codes we will apply to the problem are: GADGET 3 (modified version of Springel at al. 2005), GADGET 4 (Springel et al. 2021), SWIFT (Schaller et al. 2018) and AREPO (Weinberger et al. 2020). In this way, we will be applying three different SPH codes to the problem (GADGET 3, GADGET 4 and SWIFT), along with the AMR code AREPO. All codes differ in their treatment of gas mixing and converging gas flows, key ingredients to any simulation hoping to follow galaxy evolution processes such as stellar feedback-generated outflows. This is also particularly key when attempting to follow the journey of angular momentum from the CGM to the galaxy.

THIS WORK: JUSTIFICATION FOR THE USE OF RESOURCES

In order to cover the vast dynamic range required to follow the journey of angular momentum from large to small scales, cosmological zoom simulations are required. Further, since this problem requires a multi-code approach, a suite of simulations is needed.

Cosmological zoom simulations require a massively parallel approach and consequently all four hydrodynamic codes we are using are optimised to be run on a supercomputer across a large number (256-512) of CPUs. We are therefore unable to complete this work without the use of a supercomputer such as Gadi.

Each simulation requires 256 - 512 processors across a 120-hr period (each software code also has restart capability). The computational requirement arises from the fact we are simulating over 10^8 N-body particles (representing dark matter) and over 10^7 SPH particles. Such a resolution is necessary to study detailed galaxy evolution physics. In order to follow both the gravitational and (in the case of SPH particles) hydrodynamical interactions, rigorous time-stepping and gravitational force computation algorithms are needed. All four software codes we will be using satisfy this requirement.

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