THE ROLE OF COSMIC RAYS IN ISOLATED DISK GALAXIES

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EXECUTIVE SUMMARY

Cosmic ray feedback in cosmological simulations is integral to creating robust models of stellar feedback and to reproducing galactic structure that is consistent with observations. Unlike thermal gas, relativistic cosmic rays retain more pressure under adiabatic expansion and cool on significantly longer time scales. Cosmic rays stream along magnetic field lines and drive instabilities that initiate strong outflows. The goal of this project is to use simulations of isolated disk galaxies for which cosmic rays are dynamically important to study how cosmic ray-driven outflows shape the structure and kinematics of the circumgalactic medium. In order to model realistic cosmic ray behavior, it is necessary to employ a fully anisotropic, magnetohydrodynamic (MHD) treatment, which I have implemented in Enzo, a publicly available cosmological simulation code.

RESEARCH CHALLENGE

The circumgalactic medium (CGM) is a dynamically complex and diffuse multiphase gas that extends to the outer edges of galactic halos and contains the majority of a galaxy's baryons. The interplay in the CGM between outflows from the star-forming disk and inflows from the intergalactic medium provides constraints to theories of galaxy formation and evolution. Recent observations, such as those from the COS-Halos survey on the Hubble Space Telescope (HST), show that the CGM of distant galaxies contains a substantial amount of metal-enriched, cool gas [1]. Cooling times of such a gas are very short compared to galactic timescales, and it is unclear how this material survives in such abundance. The data seem to imply an additional unknown source of nonthermal pressure—for which cosmic rays are a candidate—that supports the cool gas against evaporation. Furthermore, although metals are produced within galactic disks, galaxies retain only 20–25% of these metals in their stars and interstellar medium [2]. Data from the Sloan Digital Sky Survey suggest that metals have been lost to outflows [3], which strongly affect the mass structure and kinematics of the CGM.

Recent studies have shown that including cosmic ray stellar feedback can drive stronger and more mass-loaded galactic winds than thermal stellar feedback alone [4]. Cosmic rays are relativistic charged particles accelerated by shocks (such as supernovae). Unlike thermal gas, cosmic rays retain pressure under adiabatic expansion better and cool on significantly longer time scales. Because cosmic rays are charged particles, they do not move freely through space but propagate along magnetic field lines. This streaming drives instabilities in the magnetic field lines, which contribute to the exponential growth of the galactic magnetic field and drives strong outflows. Because magnetic fields vary greatly in strength and shape between the galactic disk and the CGM, implementing anisotropic cosmic ray transport is crucial to improved accuracy and predictive power within simulations. Therefore, the goal of this project is to employ realistic cosmic ray physics in simulations of isolated disk galaxies in order to study galactic outflows and their effects on the CGM structure and composition.

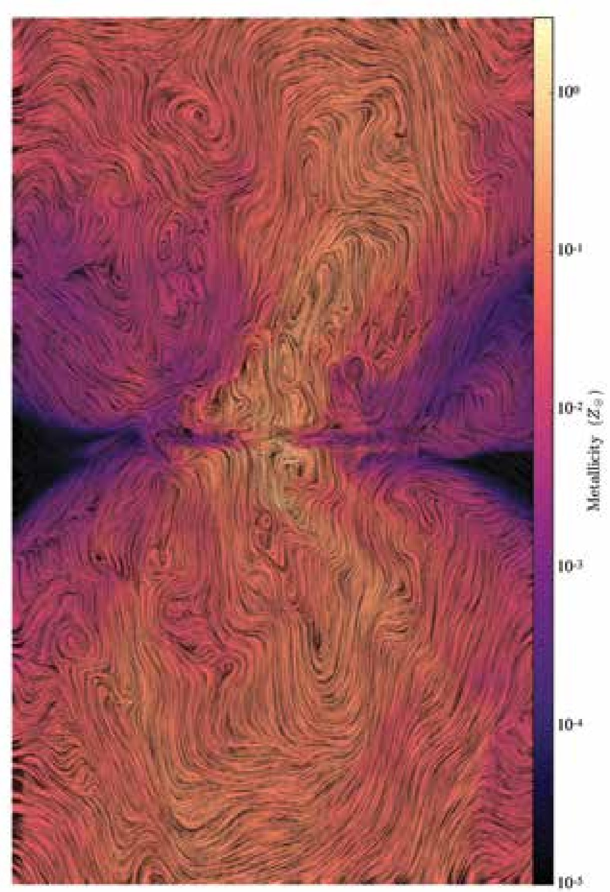

Figure 1: An edge-on view of outflows from an isolated disk galaxy after 1.5 Gyr. The color depicts the metallicity (metal enrichment relative to solar abundances) of the gas, and the streamlines follow the topology of the magnetic field. The dimensions of the image are 90 kpc x 150 kpc.

METHODS & CODES

The challenge of this project was in implementing a new cosmic ray fluid that is compatible with the Riemann solvers in Enzo, a multi-physics astrophysical simulation code. In addition to cosmic ray advection, I implemented several different modes of cosmic pray propagation along magnetic field lines, including anisotropic diffusion, streaming, and gas heating. The new cosmic ray physics will soon be publicly available to all Enzo users.

After extensive testing, I've begun running a suite of isolated disk galaxies following initial conditions prescribed by the AGORA [5] project. In these galaxy models, supernovae inject thermal, magnetic, and cosmic ray energy into the surrounding gas. I will systematically compare models of varying resolution and cosmic ray transport to the control model with no cosmic rays to isolate the effects of the different propagation modes.

RESULTS & IMPACT

Initial results show evidence of strong, mass-loaded outflows that enrich the CGM out to the virial radius of the halo when cosmic rays are present. Fig. 1 shows an edge-on view of the metal-enriched CGM after only 1.5 Gyr (gigayears). The contours of the magnetic field lines in black show the turbulent nature of the outflowing gas. Follow-up work will focus on comparing the simulated CGM structures to existing COS-Halos observations. I will use the new Trident tool to create synthetic spectra that are tuned to the specifications of the COS-Halos instrument. Directly comparing the simulations to existing data is a state-of-the-art approach that will place better constraints on theories pertaining to the CGM and make predictions for the structure and metallicity distribution of the CGM for future COS-Halos observations.

WHY BLUE WATERS

The universal challenge faced by galaxy simulations is reconciling the great dynamic range in physical and temporal scales. Although a galaxy's CGM scales hundreds of kiloparsecs (1kpc = 3.09e16 km), its evolution is dictated by stellar feedback, which happens on subparsec scales. Even with adaptive mesh refinement, this is a formidable task, and galaxy simulations have yet to resolve the scale of individual stars. Furthermore, each cell in the simulation contains many different fluid properties and follows a complicated set of interaction rules in order to capture the equally complicated physics governing galaxy evolution. Therefore, galaxy simulations require the use of massively parallel, high-performance supercomputers such as Blue Waters. In addition to Blue Waters' computational resources, I have benefited greatly from the support of its staff, who are admirably dedicated to resolving issues in a timely manner.

Iryna Butsky is in the second year of a Ph.D. program in astronomy at the University of Washington (UW). Her advisor is Tom Quinn, also of UW; she plans to graduate in June 2021.