DI

MP

SIMULATING THE CIRCUMGALACTIC MEDIUM: THE NEED FOR ROBUST COSMIC RAY TRANSPORT

Iryna Butsky, University of Washington
2016–2017 Graduate Fellow

EXECUTIVE SUMMARY

The majority of galactic baryons reside outside of the galactic disk in the diffuse gas known as the Circumgalactic Medium (CGM). While state-of-the-art simulations excel at reproducing galactic disk properties, many struggle to drive strong galactic winds or to match the observed multiphase structure of the CGM with thermal supernova feedback. To remedy this, recent studies have included nonthermal cosmic ray (CR) stellar feedback prescriptions to drive strong outflows and to better match observed low-ion column densities in the CGM. However promising, these results depend strongly on the choice of CR transport mechanism and its constant parameter values, thus weakening the predictive power of such simulations. This work uses a suite of simulated isolated disk galaxies to demonstrate that the invoked approximation of CR transport affects the predicted temperature and ionization structure of the CGM and motivates the need for a detailed parameter study.

RESEARCH CHALLENGE

The majority of baryonic matter exists as the diffuse gas that surrounds galaxies, commonly referred to as the CGM. Recent observations, such as those from the Cosmic Origins Spectrograph on board the Hubble Space Telescope, have revolutionized our understanding of the CGM. The new picture of the CGM is that of a dynamic, multiphase gas shaped by the interplay of metal-rich galactic outflows and pristine inflows from the intergalactic medium. The inferred gas properties deduced from absorption features in the spectra paint a picture of a CGM with gas clouds spanning wide ranges of temperatures and pressures, spatially coexisting [1].

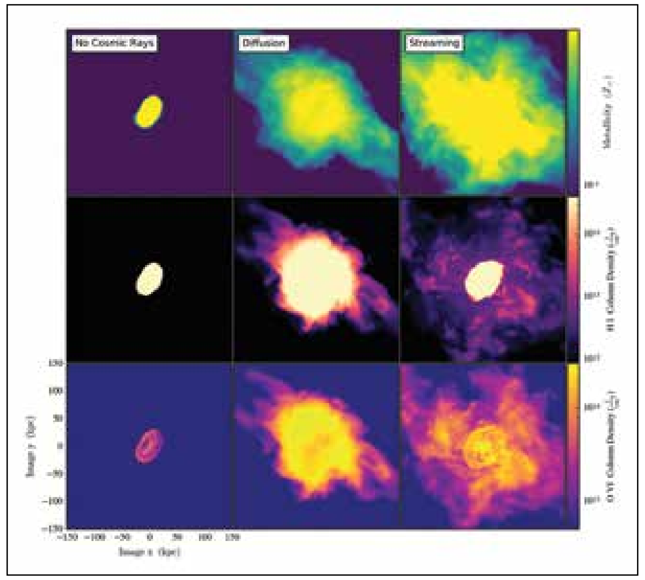

Figure 1: The metallicity (metal-enriched gas that traces galactic outflows) and the line-of-sight densities of H I and O VI (tracing cool and warm gas respectively) for galaxy models with differing CR transport prescriptions, taken after 13 Gyr of evolution.

While state-of-the-art simulations excel at modeling galactic disk structures, they struggle to reproduce the observed ionization structure of the CGM. Particularly puzzling is the presence of two gas states out of pressure equilibrium: low-density, cool (10^4K) and warm gas that originates in the disk and hot (10^6K) gas native to the halo. A possible explanation for this is that the CGM is constantly being replenished by strong galactic winds and is being collisionally ionized by cosmic rays therein.

Cosmic rays are charged particles that have been accelerated to relativistic velocities in extreme shocks such as supernovae. As they travel around magnetic field lines, the induced current exerts an effective pressure on the thermal gas. Simulations of galaxy evolution that include cosmic rays in supernova feedback have been more successful at driving strong outflows and reproducing the observed CGM ionization structure than those with purely thermal supernova feedback [2]. However promising, these simulations lack predictive power because the parameters of simulating cosmic ray physics are poorly constrained. In fact, there is no consensus on the preferred approximation of cosmic ray transport: streaming or diffusion.

METHODS & CODES

Bulk cosmic ray motion is simulated as a relativistic fluid that is coupled to the thermal gas. In this approach, cosmic ray motion relative to the gas is restricted to either diffusion or streaming. Physically, this choice depends on the source of turbulence in the magnetic field lines that is scattering the cosmic rays. During my time as a Blue Waters Graduate Fellow, I implemented cosmic ray diffusion and streaming in the astrophysical simulation code Enzo [3]. We used Enzo to simulate a suite of isolated Milky Way-type galaxies in which supernova feedback injects 10% of its energy as cosmic ray energy. The galaxy models differ in their cosmic ray transport mechanism.

RESULTS & IMPACT

The CGM in the isolated galaxy models is enriched solely by the outflows that expel gas from the disk. Models with cosmic ray feedback drive strong galactic winds that populate the CGM with metals (Fig. 1). However, the cosmic ray transport models predict different ionization structures for the warm and cool gas components. Only the galaxy model with cosmic ray streaming develops the patchy, multiphase CGM structure inferred from observations.

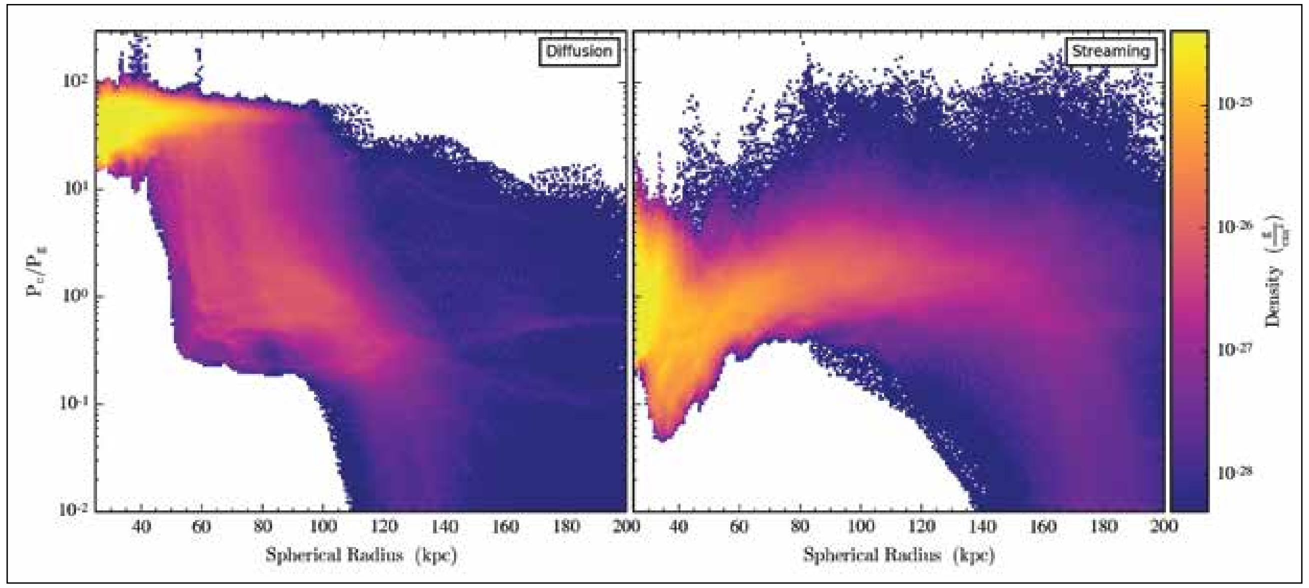

Figure 2: The distribution of the ratio of cosmic ray pressure to thermal pressure as a function of spherical radius from the galaxy center. The pixels are colored by the density of the thermal gas.

The primary differences between the galaxy models stem from the distribution of cosmic ray pressure, which is responsible for driving outflows and for altering the temperature and ionization structure of the CGM (Fig. 2). In the diffusion model, cosmic ray pressure is most influential near the disk, at high gas densities. In the streaming model, the cosmic ray pressure support is most effective at large radii and low gas densities. This fundamental difference between the two CR transport prescriptions cannot be reconciled by trivially altering constant parameter values of CR transport.

Cosmic rays are observed to be a dynamically important component of galaxies [4] and likely play a significant role in shaping the observed ionization structure in the CGM. However, in order for galaxy simulations with cosmic ray physics to hold predictive power, they must first develop robust models of cosmic ray transport.

WHY BLUE WATERS

Although the CGM spans hundreds of kiloparsecs (1kpc = 3.09×10^{16} km), its structure is shaped by gas interactions on subparsec scales. Even with adaptive mesh refinement, capturing this dynamic range of physical and temporal scales is a formidable task and galaxy simulations have yet to resolve the CGM in such detail. Furthermore, realistic simulations of cosmic ray transport must include magnetic fields, which are computationally expensive compared to purely hydrodynamic simulations. Therefore, these simulations require the use of massively parallel, high-performance supercomputers such as Blue Waters. In addition to Blue Waters' computational resources, I have benefited from the help of the User Support team and my point of contact, Roland Haas.

PUBLICATIONS & DATA SETS

Butsky, I., and T. Quinn, The Role of Cosmic Ray Transport in Shaping the Simulated Circumgalactic Medium. Submitted to *The Astrophysical Journal* (2018), arXiv:1803.06345

Iryna Butsky is a third-year PhD student in astronomy. She is working under the supervision of Tom Quinn at the University of Washington, and she plans to graduate in 2021.