PREDICTIONS ABOUT THE INVISIBLE GAS IN GALAXY CLUSTERS

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EXECUTIVE SUMMARY

Quasar absorption-line studies in the ultraviolet (UV) can uniquely probe the nature of the multiphase cool–warm gas in and around galaxy clusters, promising to provide unprecedented insights into the interactions between infalling galaxies and the hot X-ray-emitting intracluster medium (ICM). This work resulted in a high-resolution simulation of a galaxy cluster used to study the physical properties and observable signatures of the cool ICM gas. The PI extracted synthetic spectra to demonstrate the feasibility of detecting and characterizing the thermal, kinematic, and chemical composition of this cool gas and demonstrated the feasibility of observations with the existing Cosmic Origins Spectrograph aboard the Hubble Space Telescope.

RESEARCH CHALLENGE

Galaxy clusters are the largest structures in the universe, composed of thousands of galaxies that are gravitationally bound to a massive central galaxy. Compared to isolated galaxies, cluster galaxies are more likely to have stopped forming stars—becoming "quenched." The cluster environment plays a critical role in governing the gas cycle that fuels star formation in galaxies.

There are several ways in which the cluster environment can deprive galaxies of gas, causing them to quench. For example, galaxies in a crowded cluster environment can lose gas during galaxy mergers or owing to tidal forces from close encounters. Additionally, the space between galaxies in a galaxy cluster is composed of a hot, dense gas known as the intracluster medium (ICM). Galaxies simply moving through the cluster experience a headwind force from the ICM that can be strong enough to remove all of the galaxy's gas. The gas that has been stripped from galaxies enriches the ICM with heavy elements and contributes to its unique density, temperature, and chemical structure. Therefore, studying the structure of the ICM in detail places stringent constraints on the mechanisms responsible for quenching galaxies.

Traditionally, cluster galaxies have been observed directly through X-ray emission. Although this method is ideal for studying the hot (T > 106K) and dense inner ICM, it cannot detect the diffuse, cool (T = 104-6K) gas that makes up a large fraction of the ICM at the cluster outskirts. Although the diffuse, cool ICM gas is virtually invisible to X-rays, it can be observed indirectly through UV absorption. This research uses an extremely high-resolution simulation of a galaxy cluster, RomulusC (Fig. 1; [1]) to perform a detailed characterization of the properties of the cool ICM gas and to make predictions for its observational signature using existing and future UV telescopes.

Figure 1: The projected gas density in the RomulusC simulation at a redshift of 0.3. This density map shows the distribution of galaxies within the cluster. X-ray observations are most sensitive to gas within the dashed circle. UV absorption is necessary to study the structure of the cluster outskirts.

METHODS & CODES

The RomulusC cluster simulation was run on Blue Waters using the modern astrophysical hydrodynamics simulation code, ChaNGa [2]. ChaNGa is parallelized through the Charm++ parallel infrastructure framework [3] and scales up to 500,000 cores on Blue Waters.

Postprocessing of the simulation was done using the Python analysis tool, yt [4]. The PI generated realistic, instrument-specific synthetic absorption spectra from the simulation using Trident [5]. The synthetic spectra were then analyzed in an analysis pipeline developed for observers, using the Veeper software [6]. The unique combination of state-of-the-art simulations with observational analysis techniques is the key strength of this work.

RESULTS & IMPACT

Using the extremely high-resolution RomulusC simulation, the PI found that the cool ICM phase comprised a significant fraction of the total gas mass at the cluster outskirts. This cool gas (observable through UV absorption) traces a highly complementary structure to that traced by the hot ICM gas that is traditionally studied through X-ray emission. Furthermore, the results found that although the hot phase of the ICM has a uniform distribution of heavy elements, the cool phase of the ICM has a more clustered distribution of "metals" that traces gas stripping from cluster galaxies.

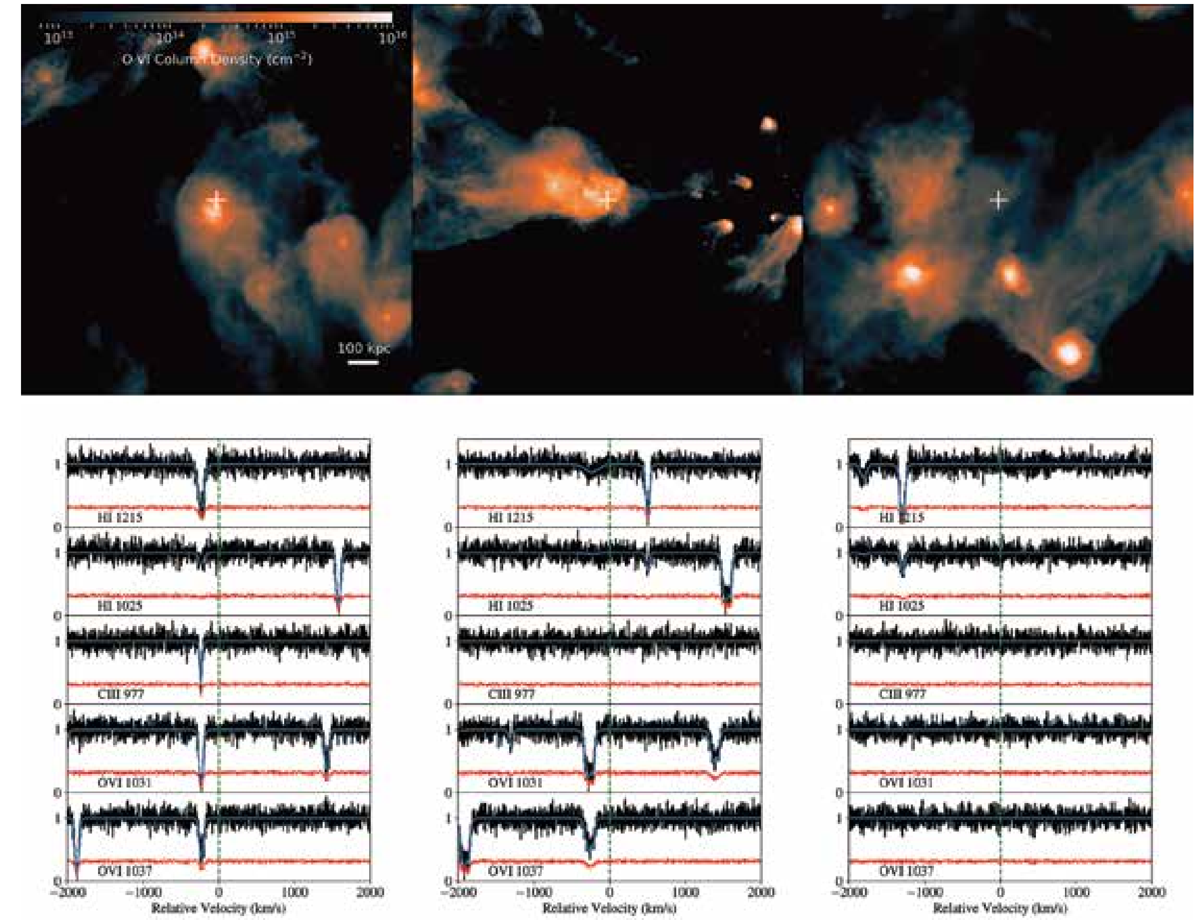

Figure 2: (top) The oxygen VI (O VI) column density (tracing cool gas abundance) at several zoomed-in regions of the RomulusC cluster, and (bottom) the corresponding predicted spectra obtainable by the Cosmic Origins Spectrograph on board the Hubble Space Telescope. Although the O VI signal is strongest around cluster galaxies, there is sufficient signal to observe the ICM between galaxies as well.

The use of synthetic spectroscopy allowed for detailed predictions for the observational signature of this cool ICM gas in clusters using the currently available Cosmic Origins Spectrograph on board the Hubble Space Telescope (Fig. 2). The results showed that random sightlines throughout a galaxy cluster should have a 40% chance of detecting cool gas (traced by hydrogen I absorption) and a 15% chance of detecting warm gas (traced by oxygen VI absorption). Future UV space telescopes such as LUVOIR will increase both the probability of detecting absorption features and the number of possible sightlines probing each galaxy cluster to revolutionize our understanding of galaxy evolution.

WHY BLUE WATERS

While galaxy clusters span several million parsecs in size, their structure is dictated by star formation and feedback processes that happens on subparsec scales. Capturing this large span of physical scales requires detailed subgrid models and significant computational resources. Therefore, these simulations require the use of massively parallel, high-performance supercomputers such as Blue Waters.

PUBLICATIONS & DATA SETS

I. Butsky, J. Burchett, D. Nagai, M. Tremmel, T. Quinn, and J. Werk, "Ultraviolet signatures of the multiphase intracluster and circumgalactic media in the RomulusC simulation," MNRAS, in press, 2019, doi: 10.1093/mnras/stz2859.

A fourth-year Ph.D. candidate in astronomy at the University of Washington, Iryna Butsky works under the direction of Tom Quinn and Jessica Werk, and plans to graduate in June 2021.