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Coronal Gas in Magellanic-Analog Dwarfs: Insights from the HESTIA Simulations

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ABSTRACT

We characterize the warm circumgalactic medium (CGM) of a dwarf galaxy pair with properties similar to the Magellanic Clouds in the Hestia cosmological simulations. The system consists of a massive dwarf ($M_{\rm halo} \sim 10^{11.5} M_{\odot}$) and a lower-mass companion ($M_{\rm halo} \sim 10^{10} M_{\odot}$), dynamically evolving in isolation before infall into a Milky Way-mass halo. The massive dwarf hosts a warm coronal gas envelope with a temperature of $T \sim 3 \times 10^5$ K, consistent with expectations for virialized CGM in dwarf halos. Tidal interactions produce a neutral gas stream that extends over ~ 150 kpc, with an H I mass of $M_{\rm HI} \sim 10^8 M_{\odot}$, similar to the Magellanic Stream. Furthermore, in the Hestia simulation suite, we find that coronal gas is ubiquitous in all halos with $M_{\rm halo} > 10^{11} M_{\odot}$, implying that massive dwarfs generically develop extended gaseous envelopes prior to accretion. This result has significant implications for the survival of neutral tidal structures, and suggests that current and future high-ion UV absorption-line observations are indicative of warm coronae surrounding LMC-mass dwarfs, independent of their environment.

Keywords: Circumgalactic medium (1879), Galaxy structure (622), Magellanic Clouds (990)

1. INTRODUCTION

The Magellanic System, consisting of the Large and Small Magellanic Clouds (LMC and SMC) as well as a variety of associated gaseous structures, represents a compelling example of an interacting dwarf galaxy pair in the Local Group (see D'Onghia & Fox 2016). This system is dynamically complex, with a prominent gaseous stream, the Magellanic Stream, that extends 200° across the sky (Nidever et al. 2010). Recent mass estimates suggest that the LMC is significantly more massive than previously thought, with a halo mass of the order of $10^{11.3} - 10^{11.5} M_{\odot}$ (e.g., Erkal et al. 2019; Patel et al. 2020; Besla et al. 2007; Peñarrubia et al. 2016; Cavieres et al. 2024; Shipp et al. 2021). These revised estimates raise new questions about the circumgalactic medium (CGM) of the LMC, including the role of a warm coronal gas envelope that may have influenced the evolution of the Magellanic Stream (Lucchini et al. 2020, 2021, 2024; Krishnarao et al. 2022); the existence of such a coronal gas halo around the LMC has been supported both theoretically and observationally.

Recent ultraviolet absorption line studies have revealed an extended, ionized gas envelope around the LMC, extending up to 35 kpc from its disk (Krishnarao et al. 2022; Mishra et al. 2024). These studies confirmed that this gas is kinematically consistent with an LMC-associated truncated corona and the ionized component of the Magellanic Stream rather than being part of the Milky Way's CGM, indicating that massive dwarf galaxies can sustain their own gaseous halos even in the presence of a larger host galaxy. This result is consistent with previous studies that indicate that massive dwarf halos, such as the LMC, should host warm virialized coronal gas (e.g., Nuza et al. 2014; Jahn et al. 2022). More recent high-resolution hydrodynamical simulations have shown that the presence of such a corona can significantly alter the evolution of tidally stripped gas, potentially influencing the formation of the Magellanic Stream (Lucchini et al. 2020, 2024). However, most previous numerical studies of the Magellanic system have focused on its interaction with the Milky Way (e.g., Moore 2004; Mastropietro et al. 2005) or modeled the LMC and SMC in isolation (Besla et al. 2012;

Pardy et al. 2018), neglecting the cosmological environment that shapes their early evolution. These findings raise key questions regarding the properties and evolution of the LMC corona prior to its accretion by the Milky Way; specifically, the role of this circumgalactic gas in shielding the Magellanic Stream from ionization and regulating gas accretion onto the LMC remains an open issue.

In this work, we leverage the Hestia (High-Resolution Environmental Simulations of the Immediate Area) cosmological simulations to study the CGM of a Magellanic-analog system within a full cosmological context. These simulations offer a unique opportunity to investigate the formation and properties of a warm coronal envelope in an isolated dwarf galaxy pair before its accretion onto a Milky Way-mass host. Unlike previous studies, our analysis is the first to resolve a Magellanic-analog corona in a high-resolution cosmological simulation suite, allowing us to track its evolution dynamically, assess its impact on gas stripping processes, and determine its ubiquity in halos of similar mass. By characterizing the CGM of a massive dwarf (with $M_{\rm halo} \geq 10^{11.5}$ M$_\odot$) interacting with a lower-mass companion, we aim to provide new insights into the pre-infall state of the Magellanic System and the physical conditions that shaped its gaseous environment before its encounter with the Milky Way.

2. METHODOLOGY

2.1. HESTIA *simulations*

The Hestia project consists of a suite of constrained cosmological zoomed-in simulations designed to reproduce the local universe with high fidelity (Libeskind et al. 2020). Low resolution, dark-matter only simulations are run with initial conditions constrained by the observed peculiar velocity of nearby galaxies, groups, and clusters to accurately simulate the local cosmography. Halo pairs that resemble the Local Group are identified and then selected for higher-resolution magnetohydrodynamical simulation runs using Arepo (Springel 2010; Weinberger et al. 2020), with baryonic physics following the Auriga galaxy formation model (Grand et al. 2017). This includes prescriptions for star formation, supernova and AGN feedback, metal enrichment, and radiative cooling.[1] The zoom-in regions achieve a mass resolution of $\sim 2 \times 10^4$ M$_\odot$ and a spatial resolution of $\sim$ 220 pc for the gas cells, within a total zoomed-in simulated box size of $\sim$ 3.5 Mpc, allowing us to resolve detailed circumgalactic structures such as the warm corona and tidally stripped neutral gas at unprecedented precision.

Within the simulation suite, we identify an interacting dwarf galaxy pair consisting of a massive dwarf $M_{\rm host} \sim 10^{11.5}$ M$_\odot$ and a smaller companion with mass $M_{\rm satellite} \sim 10^{10}$ M$_\odot$. This system is dynamically isolated at $z = 0$, located at a distance $d \gtrsim 1$ Mpc from both Milky Way and M31 analog halos, making it an ideal candidate for studying the pre-infall phase of a Magellanic analog system.

2.2. *Identifying the CGM components*

To analyze the circumgalactic medium of the massive dwarf, we classify its gas content into distinct physical phases based on temperature and density thresholds, following previous studies of the CGM structure (e.g., Tumlinson et al. 2017; Stern et al. 2021):

- **Coronal Gas:** Defined as a metal-poor gas with temperatures $T > 10^5$ K and densities $n_{HII} < 10^{-4.5}$ cm^{-3}. This phase corresponds to the predicted virialized corona in a massive dwarf halo (Lucchini et al. 2020).

- **Neutral Gas Stream:** Identified using a combination of angular momentum and metallicity selection criteria. Specifically, we select gas that is kinematically linked to the smaller dwarf, excluding cosmological inflows, and has a neutral hydrogen fraction $f_{HI} > 10^{-2}$. This phase corresponds to the cold H I rich component of a structure similar to a Magellanic Stream.

- **Cool CGM:** Defined as a dense, cool gas with $T < 10^{4.5}$ K that typically traces filamentous accretion flows into the dwarf's halo (Keres 2007).

The H I content of the neutral stream is determined by summing the neutral hydrogen mass of selected gas cells. These classification criteria allow us to quantify the extent and properties of the warm corona and assess its interaction with the neutral gas stream. The approach ensures consistency with both theoretical models of dwarf galaxy CGM evolution and observational constraints on the LMC's circumgalactic environment.

3. RESULTS

3.1. *Identification of a Magellanic-Analog System*

Within the Hestia cosmological simulation suite, we visually identify an interacting dwarf galaxy pair that

[1] In addition to the friends-of-friends (FOF), post-processing of the simulation output was performed by the publicly available *Amiga* halo finder (Knollmann & Knebe 2009), which can be found at http://popia.ft.uam.es/AHF/index.html.

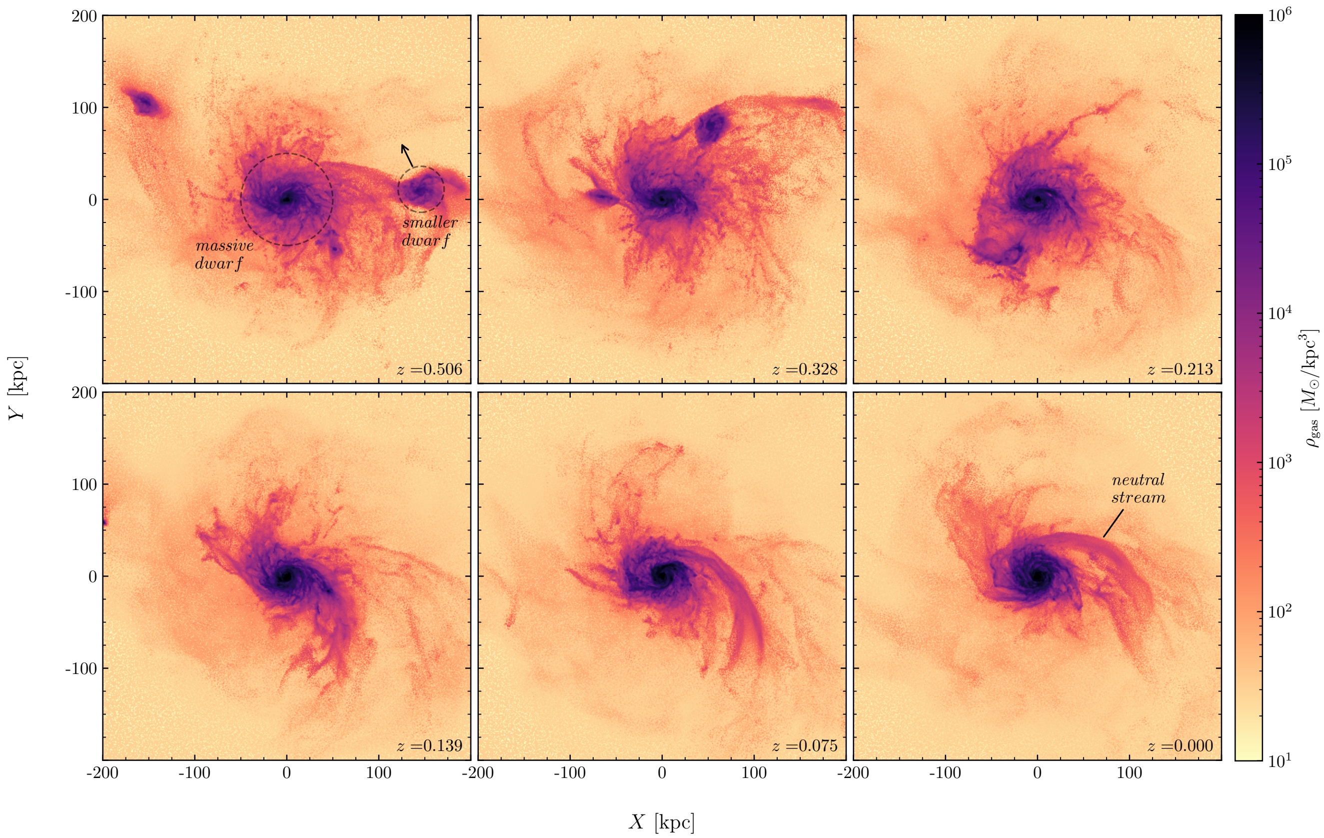

Figure 1. Face-on projections of the simulated Magellanic-analog system at various redshifts, illustrating the evolution of the interacting dwarf galaxy pair. The color scale represents the total gas mass density; each image spans 400 × 400 kpc, with a column depth of 100 kpc. The dwarfs are denoted in the upper-left panel, as well as the smaller dwarf's approximate relative velocity; the neutral stream formed from the smaller dwarf is denoted in the lower-right panel.

	z	Object	$\log(M_{\rm halo}/M_\odot)$	$\log(M_{\rm gas}/M_\odot)$	$\log(M_*/M_\odot)$	$\log(n_{\rm H}/{\rm cm}^{-3})$	$\log(T/K)$	References
Hestia	0.506	Massive Dwarf	11.48	10.60	9.76	-	-	
		Smaller Dwarf	10.10	9.44	8.58	-	-	
		H II Corona	-	9.57	-	-5.10	5.48	
		H I Stream	-	-	-	-	-	
	0.0	Massive Dwarf	11.52	10.57	10.21	-	-	
		Smaller Dwarf	9.58	8.10	6.88	-	-	
		H II Corona	-	9.32	-	-5.15	5.45	
		H I Stream	-	8.15	-	-4.38	4.15	
Observations		LMC	11.3(1)	8.64(1)	9.4	-	-	[1,2,3]
		SMC	≥ 9.8	8.60(1)	8.5	-	-	[4,2,5]
		H II Corona	-	9.10(2)	-	-	~ 5.5	[6,6]
		H I Stream	-	8.69	-	-2.0(2)	< 4.2	[2,7,8]

Table 1. Properties of the various components in the Magellanic-analog dwarf pair immediately following virialization of the halo of the massive dwarf ($z = 0.506$), and at present day. References: [1] Shipp et al. (2021); [2] Brüns et al. (2005), *assuming a distance of* 50 *kpc,* 60 *kpc, and* 55 *kpc for LMC, SMC, and Stream, respectively*; [3] van der Marel et al. (2008); [4] Bekki & Stanimirović (2009), [5] Stanimirović et al. (2004); [6] Krishnarao et al. (2022); [7] Fox et al. (2014), *50 kpc model* [8] Hsu et al. (2011).

serves as a compelling analog to the Magellanic System prior to its accretion by the Milky Way. The system consists of a massive dwarf with a halo mass of 3.02×10^{11} $M_\odot$ and a lower-mass satellite with halo mass of 1.26×10^{10} $M_\odot$, prior to interaction with one another (at $z \sim 0.5$), similar to the LMC and SMC pair. The pair is at a distance $d \gtrsim 1$ Mpc from both the MW- and M31-analogs at present-day.

This pre-infall configuration provides a unique window into the circumgalactic medium (CGM) properties of a massive dwarf galaxy before environmental interactions with a larger host can influence its structure (D'Onghia & Lake 2008). Additionally, tidal interactions between the two dwarfs generate a neutral gas stream stretching over ~ 150 kpc, with an H I mass of $M_{\rm HI} \sim 10^8 M_\odot$, comparable to the Magellanic stream (Brüns et al. 2005; Fox et al. 2014). Face-on projections of the total gas of the system in various snapshots, in which the angular momentum vector of all gas was aligned perpendicular to the image plane, can be seen in Figure 1.

The larger dwarf possess a halo mass only slightly larger than upper-bound estimates of the LMC (Cavieres et al. 2024), and the smaller dwarf within mass estimates for the SMC (Bekki & Stanimirović 2009). This, combined with the interaction's similarities to existing paradigm LMC-SMC interaction histories (Besla et al. 2012)[2] provides an opportunity to explore the properties and dynamics of a Magellanic system-analog prior to its interaction with the Milky Way halo, where they are implied to be more massive than present day (Pardy et al. 2018). The properties of the system are summarized in Table 1.

3.2. *Coronal Gas Properties in a Massive Dwarf Halo*

The massive dwarf galaxy in our Magellanic-analog system exhibits a well-defined, coronal gas envelope that extends to approximately its virial radius. The density of this coronal CGM follows a declining power-law relation, with $n_{\rm H} \sim 10^{-5}$ cm^{-3} near the disk and decreasing to $\sim 10^{-6}$ cm^{-3} at large radii. The temperature of the corona, $T \sim 3 \times 10^5$ K, is in agreement with expectations from the virial theorem for a halo of this mass (Mo et al. 2010) and is consistent with constraints from observational studies of the LMC's coronal gas (Krishnarao et al. 2022). A comparison of the simulated temperature profile with previous theoretical models is shown in Figure 2 (*left panel*). Our results closely match the idealized isolated simulations and LMC corona model of Lucchini et al. (2024, 2020), as well as the hydrostatic equilibrium model of Salem et al. (2015) for the CGM of an LMC-mass halo.

[2] The impact parameter of the first interaction $\rho_{\rm initial} \sim 95$ kpc and mass of the larger halo, is $\sim 2\times$ that of the initial conditions of Besla et al. (2012)'s *Model 2*, but the morphology of the interactions remain highly similar.

3.3. *Formation and Evolution of the Neutral Gas Stream*

Tidal interactions between the two dwarf galaxies lead to the formation of a coherent neutral gas stream extending over 150 kpc. This H I-rich structure primarily originates from the lower-mass companion and contains a total neutral hydrogen mass of $M_{\rm HI} \sim 10^8 M_\odot$, similar to the observed Magellanic Stream, with a distance assumption of ~ 55 kpc (Brüns et al. 2005). A key question regarding the Magellanic Stream is its long-term survival against interaction with the surrounding CGM. In our simulation, the neutral gas stream retains a relatively low velocity with respect to the coronal gas, $v_{\rm rel} \sim 30$ km s^{-1}, which minimizes the impact of ram-pressure stripping and instabilities such as Kelvin-Helmholtz and Rayleigh-Taylor instabilities (Murray et al. 1993; Bland-Hawthorn et al. 2007). Over a timescale of ~ 1.5 Gyr, we find no significant decline in the total H I mass of the stream, suggesting that a neutral gas stream embedded in a warm corona under these conditions can remain stable extended periods of time.

This result is consistent with prior theoretical work indicating that neutral structures can survive within a hot CGM if the relative velocity remains sufficiently low (Murali 1999; Tepper-García et al. 2019). It also reinforces observational findings that the Magellanic Stream has likely persisted for a few Gyr despite interactions with the Milky Way's CGM (Fox et al. 2014).

3.4. *Ubiquity of Coronal Gas surrounding Massive Dwarf Galaxies*

Beyond the Magellanic-analog system, we investigate the presence of coronal gas in all 45 halos within the HESTIA simulations with $M_{\rm halo} > 10^{11} M_\odot$. We find that every such halo hosts a warm-hot circumgalactic corona, with a mass-temperature relationship following the expectations of the virial theorem (Figure 2, *right panel*).

The remaining isolated dwarfs exhibit CGM temperatures of $T \sim 3 \times 10^5$ K, consistent with theoretical predictions for hydrostatic equilibrium (Mo et al. 2010). However, some massive dwarfs residing within the virial radius of a larger halo exhibit higher temperatures, likely due to the interactions with the CGM of the more massive host. This suggests that environmental effects—such as pressure confinement and hydrodynamic mixing—may alter the thermal properties

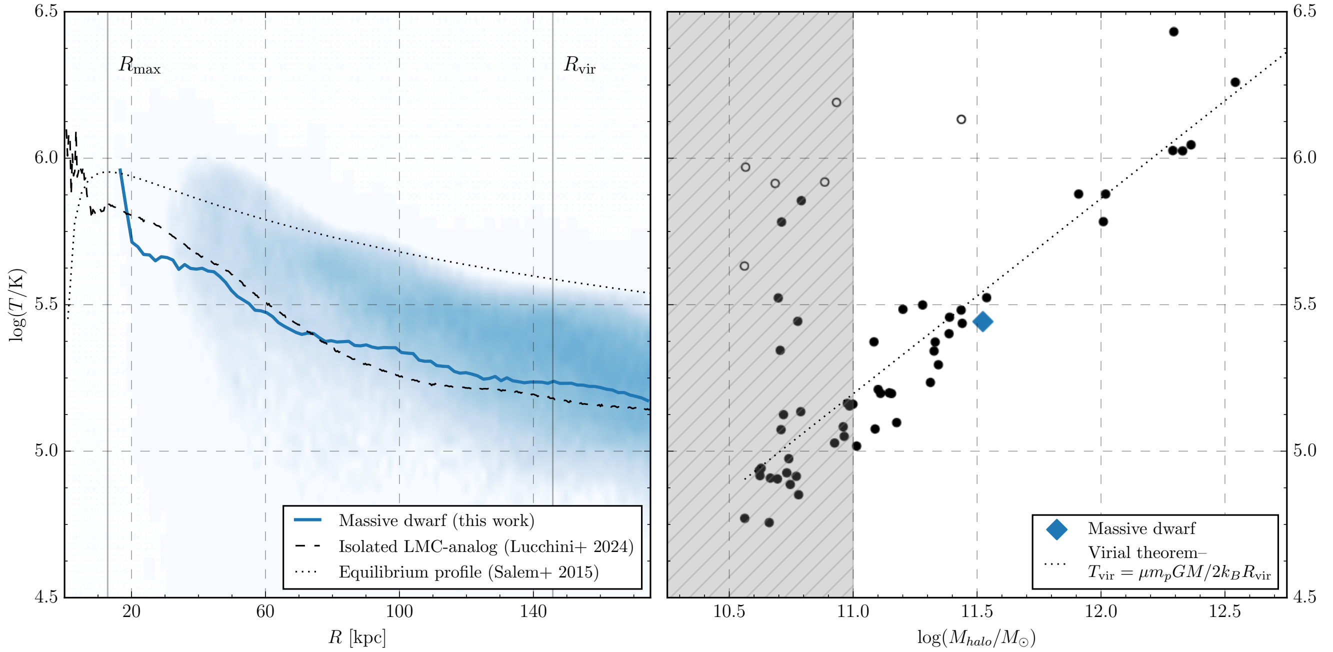

Figure 2. Temperature profile of the coronal gas surrounding the simulated Magellanic-analog system. The left panel shows the temperature distribution of the massive dwarf as a function of radius, overlaid on a heatmap of the volume-unweighted H II gas cells. The equilibrium profile from Salem et al. (2015) for the massive dwarf (dotted) and the isolated LMC corona model from Lucchini et al. (2024) (dashed) are also displayed, along with the radius of the peak of the rotation curve R_{max} and the virial radius of the massive dwarf R_{vir}. The right panel shows the temperature of the coronal gas as a function of halo mass for the most massive halos in the Hestia simulations. Solid points denote isolated halos, while hollow points denote halos within the virial radius of a more massive host. The dashed line indicates the expected virial temperature scaling with halo mass, and the blue diamond denotes the massive dwarf. The shaded region to the left indicates approximately where cooling effects dominate and precludes the formation of a corona.

of dwarf galaxy coronae, a hypothesis that should be tested in future observational studies.

To our knowledge, this is the first systematic study to demonstrate the ubiquity of warm coronae around LMC-mass dwarfs and their properties in cosmological simulations, with prior observations noted by Jahn et al. (2022). This result is consistent with recent UV-absorption-line surveys which detect coronal gas surrounding massive dwarf galaxies, independent of their location within a group or cluster environment (Bordoloi et al. 2014; Johnson et al. 2017; Zheng et al. 2024). The presence of such coronae likely also has significant consequences for gas accretion and star formation regulation in dwarf galaxies, similar to the role of coronal gas in Milky Way mass halos (Tumlinson et al. 2017; Stern et al. 2021).

4. CONCLUSION

Using the Hestia cosmological simulations, we have identified an interacting dwarf-galaxy pair evolving in isolation prior to infall into a MW-mass host; this provides a close analogy to the pre-infall Magellanic Clouds. The massive dwarf ($M_{\mathrm{halo}} \sim 10^{11.5} M_\odot$) hosts a warm-hot circumgalactic corona with a temperature of $T \sim 3 \times 10^5$ K and a total ionized hydrogen mass of $M_{\mathrm{HII}} \sim 2.1 \times 10^9 M_\odot$, consistent with theoretical predictions and recent observational constraints on the LMC's CGM.

Tidal interactions between the two dwarfs produce a neutral gas stream extending over ~ 150 kpc, with a H I mass of $M_{\mathrm{HI}} \sim 10^8 M_\odot$. The persistence of this stream over ~ 1.5 Gyr suggests that an extended warm corona can shield stripped gas from ionization and hydrodynamic instabilities, supporting its long-term survival.

More broadly, we find that warm-hot coronae are ubiquitous in all Hestia halos with $M_{\mathrm{halo}} > 10^{11} M_\odot$, following the expected scaling of the virial temperature. This suggests that extended coronal gas is a fundamental property of massive dwarf galaxies, independent of their location within a group or cluster environment.

These results have important implications for the role of the CGM in shaping the evolution of dwarf galaxies. Future UV absorption-line observations targeting LMC-mass dwarfs—particularly with facilities such as HST-COS will provide a direct test of these predictions and further constrain the thermodynamic structure of the CGM in massive dwarfs.

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