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Revisiting Galactic Fountain Kinematics with an Updated Galactic Corona Model

Abstract

This paper seeks to continue the work of Marinacci et al. (2011, hereafter referred to as M11) in determining by simulation a constraint on the rotational velocity of the Milky Way corona relative to the galactic disc. Modern parameters and changes to the accepted warm/hot galactic corona model can inform an updated simulation that should produce a more accurate threshold rotational velocity, above which momentum transfer between cool H I clouds and the ambient corona becomes inefficient and ceases to replicate observed dynamics. This constraint will facilitate a better understanding of galactic coronae morphology, star formation mechanisms, and galaxy formation mechanisms.

1. Introduction

Modern cosmological models of the Milky Way include a galactic corona, an extended region of warm/hot gas extending out to a virial radius of about 250 kpc (Troitsky 2017). The galactic corona has been indirectly observed through the absorption lines of highly ionized species of oxygen (Sembach et al. 2003; Williams 2005). These species lie at the boundary of cool gaseous clouds a few kpc outside of the galaxy interacting with a hot corona. Since its conception, theorists have aimed to place constraints on various properties of the corona, such as temperature distributions, metallicity, cooling time, and rotational velocity (M11). Most of the constraints result from data such as observed column densities of OVI, OVII, and OVIII as calculated from absorption lines seen during observations of AGNs (Williams 2005). A constraint on rotational velocity relative to that of the galactic disk of $v_{th} \sim 75$ km s^{-1} has been calculated from a simulation regarding momentum transfer between the gaseous corona and the cold clouds ejected from the galactic disk (M11). The constraint was calculated assuming a homogeneous, isothermal galactic corona. Newer models suggest the galactic corona is inhomogeneous as a mixture of warm/hot gas (Faerman et al. 2017). The constraint also contained inherent uncertainty due to uncertainty in coronal density. A coronal density of $n_e \sim 10^{-4}$ cm^{-3} for the relevant region and a density profile of $n_e \propto r^{-0.9-1.1}$ (where r is galactocentric radius) has since been calculated (Martynenko 2022). Given the importance of relative rotational velocity on the corona's morphology and implications for star formation and galactic evolution, this constraint deserves recalculating with an updated corona model.

2. Galactic Fountains

Roughly 10% of H I gas in star-forming disc galaxies is outside the galactic disc, likely ejected from the disc by supernovae (M11). A galactic fountain model explains this observation, suggesting that cool clouds (~ 10^4 K) of outgoing gas interact with a hot corona and fall back in on a timescale of ~ 4.7×10^7 yr (Houck & Bregman 1990; M11). Observed dynamics of the H I clouds are best explained by accretion of the hot coronal gas (Fraternali & Binney 2008). The metallicity of the cool clouds is modeled as $Z \sim Z_\odot$, with the subscript ⊙ representing solar metallicity (M11). The trajectory of the cool clouds leaves behind a wake which facilitates radiative cooling for the coronal gas (M11). Without this cooling mechanism, there is no meaningful relative rotational velocity threshold. Some theorists propose that the observed cool clouds are due to locally cooling regions within the hot corona, but this framework of thermal instability has been disproven by analyzing the effect of the galaxy's gravitational field on the corona (Fraternali & Binney 2008).

3. Warm/Hot Galactic Corona

Locally observed absorption lines of O VI, O VII, and O VIII at the outer layer of high-velocity and intermediate-velocity H I clouds imply interactions with a warm/hot corona (Williams et al. 2005, M11). The O VII and O VIII lines are explained by a homogeneous hot corona, but the observation of O VI absorption necessitates the inclusion of a warm gas phase as well. The warm gas exists as approximately spherical clumps of radius $a \sim 36$ kpc (Faerman 2017). This corona can explain all of the "missing" baryons theorized by modern cosmology (Maller & Bullock 2004; Fraternali & Binney 2008; Faerman 2017). A fiducial model for the corona predicts 80% hot gas by mass fraction at $T \sim 1.5 \times 10^6$ K and 20% warm gas by mass fraction at $T \sim 3.0 \times 10^5$ K (Faerman 2017). The local warm gas mass fraction within the corona increases with radius. Other studies predict 40-60% for the warm gas mass fraction, but do not seem as likely (Maller & Bullock 2004; Faerman 2017). The density of the warm gas is expected to be 3 times the density of the hot gas (Faerman 2017). The density in the region $r < 60$ kpc is $n_e \sim 10^{-4}$ cm^{-3}, while the density in the region $r > 60$ kpc is $n_e \sim 10^{-5}$ cm^{-3} (Martynenko 2022). The corona's metallicity is widely constrained as $Z \sim 0.1\text{-}0.7\ Z_\odot$ (Martynenko 2022). Considerations of the galactic baryonic budget lead to an estimated metallicity of $Z \sim 0.5\ Z_\odot$ (Faerman 2017). The galactic corona provides a mechanism for steady stellar formation in star-forming galaxies and most likely has ties to the early stages of galaxy formation (Faerman 2017). Assuming the H I gas has rotational velocity aligned with the galactic disc, the galactic corona must be within a threshold relative rotational velocity. A steadily lagging corona rotational velocity could not persist: if the corona were rotating far slower than the fountain clouds, it would rapidly accelerate from interactions with them and quickly approach the cool cloud's rotational velocity (Fraternali & Binney 2008).

4. Simulation Code

The original simulation detailed by M11 used ECHO, a high-order, shock-capturing Eulerian hydrodynamical code. The code has the capability to simulate time dependent and three-dimensional general relativistic magnetohydrodynamics and magnetodynamics (Del Zanna et al. 2007). M11 used a modified version of the code, ECHO++, which included metallicity evolution and mean molecular weight μ, both relevant for the consideration of radiative cooling. For efficient computing, M11 only simulated two dimensions, effectively modeling ejected fountain gas as cylinders of infinite height. This approximation is later corrected for in calculations. ECHO++ could be further modified to consider an inhomogeneous warm/hot galactic corona. Rather than attempting to model localized warm regions within the hot corona, the code would only need to include the capability to distinguish between two individually homogeneous regions at a given galactocentric radius. The physical logic behind this simplification is discussed in §5.

5. Possible Findings

The updated capabilities of ECHO++ would provide new constraints for the rotational velocity of the warm/hot galactic corona relative to the galactic disc. To compare a rough modern estimate of the constraint with that calculated in M11, the original ECHO++ code assuming homogeneity should be ran again for initial fountain cloud velocities of 100 km s^{-1} and 200 km s^{-1} with updated parameters: density n_e ~ 10^{-4} cm^{-3} as opposed to 0.5-2 x 10^{-3} cm^{-3}, temperature $T \sim 1.5 \times 10^6$ K as opposed to 2 x 10^6 K, and initial coronal metallicity $Z \sim 0.5\ Z_\odot$ as opposed to 0.1 $Z_\odot$. Considerations of warm gas clumps can then be added to investigate fountain gas dynamics and changes in the corona's relative rotational velocity threshold. The cool clouds are found within a few kiloparsecs of the galactic disc, a far smaller distance than the expected radii of warm gas clumps (a ~ 36 kpc). As a result, the warm gas clumps need not be simulated as localized environments enclosed within the greater hot corona. Instead, the region of the corona close to the disc could be approximated as two individually homogeneous regions representing the hot gaseous phase and warm gaseous phase. Based off of the current warm/hot galactic corona model, it should be possible for an ejected cloud to interact with only hot gas, only warm gas, or hot gas first and then warm gas—but never warm gas and then hot gas, as the warm gas clump radius is far larger than the distance clouds travel outside of the galactic disc. Thus, the code should simulate cool clouds travelling through various lengths of hot gas before transitioning into a region of warm gas, ranging from 0 kpc to 3 kpc of initial hot gas at small intervals of 0.25 kpc before changing the density and temperature profile of the coronal region. Similarly to M11, the code should investigate varying initial cloud velocities—100 km s^{-1} and 200 km s^{-1}. The possibility of cold clouds interacting with warm gas clumps could lead to potentially interesting results. The simulation could investigate if the corona can rotate at a velocity higher than the relative threshold calculated using an assumption of hot homogeneous coronal gas and still demonstrate efficient momentum transfer. This interaction could result from the fountain gas passing through hot material above the velocity threshold—without transferring momentum efficiently—and then beginning to transfer momentum and following observed trajectories upon entering a region of warm gas. This could be possible since the relative rotational velocity threshold increases with density and the warm coronal gas has a higher density than the hot gas. Changes to constraints on relative rotational velocity can allow for better-informed models of galactic coronae morphology, star formation mechanisms, and galaxy formation mechanisms.

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