February 1, 2013 E. Klimek

# Revised Thesis Project Description

## Original Project Summary

My original project as proposed was to generate mock absorption lines through the halos of simulated Milky Way-like galaxies at z=0 from the perspective of the Solar circle, looking outward from the disk. The scientific goal was to quantitatively compare the distribution and kinematics of coronal gas surrounding the simulated galaxies to existing absorption line observations of CIV and OVI in the Milky Way halo. Last Spring, it was discovered that all of the simulation snapshots generated by the ART code for z<1.5 are not useable due to the "halo drift" problem. Several discussions with Daniel Ceverino revealed that the snapshots are safe to use for z>2. As a result, my project must be redefined to focus on questions pertaining to galaxy evolution at and above this redshift.

## Executive Summary of New Project

*Simulation Data*

My galaxy sample consists of four galaxies having a z=0 halo mass ranging from $0.77 \times 10^{12}$ $M_{sol}$ to $2.29 \times 10^{12}$ $M_{sol}$. Each galaxy was simulated twice, using two different star formation prescriptions. The first star formation prescription uses a Miller-Scalo IMF, a star formation efficiency of 5%, and no radiation pressure. The four galaxies run with this prescription have been given the designation MW6a, MW7a, MW8a, and MW9a. The second star formation prescription uses a Chabrier IMF, a smaller star formation efficiency of 1.7%, and a model for radiation pressure. The four galaxies run with this prescription have been given the designation MW6b, MW7b, MW8b, and MW9b. There are 14 snapshots between 2<z<4 for all galaxies except for MW6b, which has 11 snapshots.

*Motivation*

The redshift range 2<z<4 is interesting because it represents the time period leading up to the most active period of star formation in galaxies. Understanding the cycle of baryons during this time is important for understanding galaxy formation and evolution. Gas accretion from the intergalactic medium (IGM) must pass through and interact with the multiphase circumgalactic medium (CGM), which makes up the gaseous halo component of a galaxy. The CGM itself can also serve as a reservoir of gas that could eventually cool and accrete onto the disk. Stellar feedback due to star formation drives winds that carry metals away from the disk and into the halo. If the wind speeds exceed the escape velocity of the galaxy, the outflowing gas will enrich the the IGM. However, if the wind speeds are below the escape speed, the outflowing material could either linger in the halo or rain back down onto the disk in a fountain type flow. The fate of the outflow gas thus has consequences for the evolution of the disk.

*Planned Experiments*

I am proposing a new project that focuses on furthering our understanding of the relationship between the disk and gaseous halo components of Milky Way-like galaxies and how this relationship evolves over time. Specifically:

**(1) How does the gaseous halo respond to physical processes in the disk?**
**(2) How does the ISM of the disk respond to gas accreted from the halo?**

**(1) How does the gaseous halo respond to physical processes in the disk?**

If the halo is sensitive to differences in the feedback prescription, namely through the implementation of radiation pressure, the mass fraction of hot gas and the metal mass in the halo should increase following stronger star formation episodes. The average velocity of the outflowing gas should also be greater, as well as the mass flux of the outflow. Furthermore, if the outflowing material hinders the ability of fresh material to reach the disk, then one would expect to see a corresponding decrease in the mass fraction of cold, low metallicity gas moving toward the disk.

One would expect to see the inner portion of the radial profiles of metal mass and hot gas rise more steeply following episodes of stronger feedback. Such a response signature should be even more pronounced when separating the outflowing from the inflowing gas.

A time series of the radial temperature, neutral hydrogen, and metal mass profiles for each galaxy will show the time evolution of the properties and structure of the gaseous halo and will enable the estimation of time scale on which the halo responds to star formation episodes.

**(2) How does the ISM of the disk respond to gas accreted from the halo?**

Growing galaxy disks at high redshift continuously accrete gas, fueling star formation. The details of how the gas settles onto the disk, however, remain an open question. I will address the question of the time scale on which the disk responds to accretion events by examining expected correlations between accretion events and star formation episodes. If such a signal is detected, I will estimate the mean time delay between the arrival of fresh fuel and the onset of star formation.

If the accretion is dominated by cold gas, one would expect a shorter time delay between the arrival of the gas and the onset of star formation than if the accretion is dominated by warmer gas. This is because warmer gas will need time to cool and collapse before it can begin to form stars.

With respect to the mass flux of inflowing material, if the accretion rate onto the disk region is greater, one would expect a shorter time delay before the onset of star formation. An increase the accretion rate would also be correlated with a stronger episode of star formation, as would appear in the form of a greater increase in the star formation rate.

**Optional Experiment**

Halo mass has been shown to be an important factor in galaxy growth because it determines the accretion mode (Birnboim & Dekel 2003; Keres et al. 2005; Dekel & Birnboim 2006). How the relationship between the gaseous halo and disk processes depends on halo mass for each of the star formation prescriptions constitutes a possible additional component to my dissertation. While such a study is possible, it is beyond the main focus of my dissertation as described above. I will undertake this optional project only if time permits.

*Methodology*

The analysis of the first question will be similar in scope and focus to the work of van de Voort & Shaye (2012), which characterized the CGM of simulated galaxies having different feedback prescriptions. The analysis of the second question will be based on the work of Joung et al. (2012), which studied mass accretion onto the disks of simulated galaxies and the mass flux of gas throughout simulated galaxy halos. In order to study the connection between physical processes within the disk (such as star formation) and processes in the halo (accretion, outflow), the disk region and the CGM must be clearly distinguished. I have already written code to do this. The disk is defined to be a cylindrical region containing 85% of the cold ($T<10^4$ K), dense ($n_H > 1.0$ cm$^{-3}$) gas mass representative of the ISM. All of the gas cells that are within the virial radius but are not within this cylindrical region are defined as being part of the gaseous halo.

To characterize the disk, I will next calculate the total stellar and gas masses and the star formation rate. A star formation episode will be defined as a fractional increase in the star formation rate above some threshold. The duration of such an episode will correspond to the time that elapses until the star formation rate falls below the same threshold. The star formation rate itself is calculated by summing up the initial stellar masses that formed within the last timestep. An accretion event will be defined as an increase in the mass fraction of cold ($T<10^4$ K), low metallicity ($Z< 0.1\ Z_{sol}$) gas in the disk region above some threshold average value. I will not distinguish between gas acquired via merging events or infall, as the goal of the project is to examine how the disk responds to the arrival of new material and not to analyze the specific origins of such material.

The mass flux of gas throughout the halo quantitatively describes the rate (in $M_{sol}$/yr) at which gas is falling toward or being ejected away from the disk. The net mass flux (inflow mass rate minus outflow mass rate) corresponds to the accretion rate of material onto the disk. The halo is divided into thin spherical shells, and the mass flux across each shell in the radial direction is calculated according to the method of Peek et al. (2008).

The physical state of the halo will be characterized in terms of the mass fraction hydrogen gas and of metals in the cold ($T<10^4$ K), warm ($10^4<T<10^5$ K), warm-hot ($10^5<T<10^6$ K), and hot ($T>10^6$ K) temperature regimes. The same mass fractions associated with infalling and outflowing material considered separately will also be calculated. The mass of metals and the mass fraction of gas in the four different temperature regimes for the outflowing gas quantifies how the halo changes as a result of disk processes, while the same mass quantities for the infalling gas enable possible correlations to be made between the physical conditions of newly acquired material and star formation in the disk. Inflowing and outflowing material is distinguished by the sign of the galactocentric radial velocity of each gas cell. The average velocity of the masses of inflowing and outflowing material also provides information about the how the disk and halo respond to each other.

The structure of the halo will be characterized by the radial profile of quantities such as temperature, mass, and density of low/high metallicity gas and of the infalling/outflowing gas. The construction of radial profiles is one method of quantifying the spatial distribution of gas mass in different temperature regimes and of gas mass having different metallicities. The construction of the radial velocity profiles of the gas provide information about the kinematic structure of the halo by revealing how the gas is moving on average throughout the halo as it either falls inward to possibly end up influencing the disk or flows outward as a result of disk processes.

Each of the eight galaxies in my sample will be analyzed at each existing snapshot beween $2<z<4$. I will directly compare galaxies differing in star formation prescription (the "*a*" and "*b*" runs for each galaxy).

## *Chapter Outline*

Chapter 1: Introduction
Chapter 2: Data: The simulations
Chapter 3: Methodology: Characterizing disk and halo components
Chapter 4: Gaseous Halo Response to Disk
Chapter 5: Disk Response to Gaseous Halo
Chapter 6: Discussion of Results: Effects of Different Star Formation and Feedback on Halo Properties
Chapter 7: Conclusion

## *General Timeline*

The bulleted tasks in this timeline refer to each of the eight galaxies in my sample.

Spring 2013:

January:

- Write code to find the disk region (*Done.)*
- Start calculating star formation rates in the ISM of the disk as a function of time.

February:

- Finish calculating star formation rates in the ISM of the disk as a function of time. The code is already 90% complete.
- Determine threshold above which an increase in the star formation rate constitutes a star formation episode.
- Determine threshold value which defines an accretion event of cold gas onto the disk.
- Finish writing code for generating the temperature, mass, and metallicity radial profiles of halo gas.

The code is already 75% complete.

March:
- Generate temperature, mass, and metallicity radial profiles of halo gas.
- Generate temperature, mass, and metallicity radial profiles of inflowing/outflowing halo gas.
- Generate galactocentric radial velocity profiles of halo gas.
- Start writing Chapter 2 (Data)

April:
- Finish writing Chapter 2 (Data)
- Assemble time series of halo property profiles.
- Calculate total mass of neutral hydrogen and metals, as well as mass fractions of gas in different temperature regimes.
- Quantify properties of outflowing gas (total mass in metals, mass fractions of cold, warm, hot material, average outflow velocities)
- Calculate mass flux of outflowing mass (total mass, metal mass, mass in various temperature regimes)

May:
- Start writing Chapter 3 (Methodology)
- Determine how the mass of outflowing gas correlates with the star formation rate.
- Calculate mass flux of inflowing mass (total mass, metal mass, mass in various temperature regimes) throughout the halo.
- Calculate mass accretion rate of gas in various gas phases onto disk.

Summer 2013:

June:
- Measure time delay between accretion events and star formation episodes.
- Determine relationship between accreted mass of cold gas and star formation rate.

July:
- Start writing Chapters 4-5 (Halo Response to Disk, Disk Response to Halo).
- Compare effects of different star formation recipes.

August:
- Continue/Finish writing Chapters 4-5 (Halo Response to Disk, Disk Response to Halo).
- Begin writing Chapter 6 (Discussion of Effects of Different Star Formation Prescriptions).

Fall 2013:

September:
- Finish writing Chapters 3-5 (Methodology, Halo Response to Disk, Disk Response to Halo).
- Write Chapters 1 (Introduction) and 7 (Conclusion).

October:
- Defend.
- The last day to defend next Fall isn't on the Graduate Deadlines Calendar yet. The final date for Fall 2012 was November 9.

*Signatures*

*The undersigned approve of this proposed thesis.*

| *Name* | *Date* |
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