Magnetic fields in circumgalactic high velocity clouds

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Except where otherwise indicated, this thesis is my own original work.

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Acknowledgments

Who do you want to thank?

Abstract

High Velocity Clouds (HVCs) are a proposed solution to how extragalactic gas enters into star-forming galaxies. However, the presence of magnetic fields is required to ensure that HVCs can travel through the halo without being torn apart by ram pressure. This report aims to measure the strength of the magnetic fields present within the Milky Way's halo and surrounding circumgalactic HVCs, to determine if they can support HVCs as they travel through the Galactic halo. This report uses data from the ASKAP Polarisation Sky Survey of the Universe's Magnetism (POSSUM) to pull a series of rotation measures (RMs) across the southern sky. These RMs are then converted into magnetic fields using an algorithm, developed using previously collected data from the Smith Cloud. Statistical analysis tools are applied to confirm if hypothesised magnetic fields can support HVCs. The report finds that [Summary of discussion and conclusion] . . .

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Chapter 1

Introduction

1.1 Motivation

High Velocity Clouds (HVCs) are a possible explanation for gas in-fall into galaxies Wakker [1991]. This is primarily due to their high velocities (approx. 70-90 kms^{-1}) being a result of tidal stripping of satellite galaxies like the Magellanic system Wakker [1991]; Wakker and van Woerden [1997]. However, HVCs face a different issue that can prevent them from colliding with disks. When a cloud of gas moves at such speeds, the expectation is that it will collapse due to Kelvin-Helmholtz instabilities and ram pressure stripping Grønnow et al. [2017, 2022]; Jones et al. [1996].

The galactic halo is magnetised to some degree Hill et al. [2010]. It is hypothesised that HVCs, as they travel through the galactic halo, will accumulate magnetic fields, which protect them from collapse Dursi and Pfrommer [2008]; Jones et al. [1996]; Konz et al. [2002]; Grønnow et al. [2017, 2018]; Jung et al. [2022]. However, there has not been substantial evidence to demonstrate that this hypothesis is true. This is because of: a past lack of rotation measure (RM) cataloguing; lower-density RM grid measurements; and foreground obstructions McClure-Griffiths et al. [2010]; Taylor et al. [2009]; Jung et al. [2021]. A majority of past research, instead, has been focused on data collection, and the development of synthesis techniques that allow modern research to begin testing the hypothesis Taylor et al. [2009]; Vanderwoude et al. [2024]; Moss et al. [2013]; Westmeier [2018]; Betti et al. [2019]; Hill et al. [2010, 2013]. This project aims to use the collected data, simulations, and synthesis techniques to produce the first high-quality measurement of magnetic draping phenomena in circumgalactic HVCs - a pivotal turning point in the progression of research.

1.2 Literature Review

HVCs are shaped like comets, with a large central gas cloud (approx. 500 pc in diameter), and a long tail of material that has been stripped from the cloud (which accounts for one eighth the total mass of the cloud) Jung et al. [2022];

Konz et al. [2002]. When HVCs collide with the galactic disk, they generally leave evidence of long trails behind Putman et al. [2012]. HVCs contain hydrogen and helium, however, they can also contain trace amounts of metals Hayakawa and Fukui [2024], and non-metals like nitrogen, oxygen, and sulfur Madsen et al. [2006]; Hill et al. [2009]. The relative metallicity and alpha abundance in HVCs do have an impact on the ability for HVCs to survive as they travel through the medium e.g. [Grønnow et al., 2018] predicts that high-density metal-rich clouds, and low-density metal-poor clouds are generally more unstable. While HVCs can contain heavier elements, [Hayakawa and Fukui, 2024] finds that the concentrations are low enough that HVCs can remain viable candidates for gas in-fall.

Simulations conducted by [Grønnow et al., 2017, 2018, 2022], provide the most detailed insight on how magnetic draping protects HVCs against collapse, in addition to previous work by [Jones et al., 1996; Konz et al., 2002; Heitsch and Putman, 2009]. It is generally shown that magnetic fields around 0.3 - 1 μG are enough to provide stability. Magnetic fields larger than 1 μG produce enough pressure to both slow down HVCs and accelerate Rayleigh–Taylor instabilities. This depends on the size of the HVC.

Determining the magnetic field strength required for a HVC to survive can be done by balancing magnetic pressure with ram pressure Konz et al. [2002], however it is much harder to find a mathematical formulation to determine how high magnetic field strengths affect instabilities. Without any magnetic draping, HVCs with masses under 10^4.5 solar masses will fully disperse within 10 kpc of halo travel Heitsch and Putman [2009].

The morphology of magnetic field lines matters Grønnow et al. [2018]. While it is possible to draw conclusions on the survivability of HVCs by analysing the strength of the magnetic field alone, modelling is needed to confirm those conclusions' accuracy's Betti et al. [2019].

The Smith Cloud is a larger HVC that, in previous research, has had its magnetic field analysed. Simulations from [Grønnow et al., 2017] and observations from [Lockman et al., 2008] agree on the magnetic field strength of the Smith Cloud being approx. 8 μG. This value exceeds the "Goldilocks" zone of stable magnetic fields, acting as an example of how size affects stability. The Smith Cloud is an exceptionally large HVC that has already partially collided with the galactic disk Lockman et al. [2008]; Lockman [2008]. This points to the Smith Cloud being an outlier in regard to most HVCs.

From nitrogen spectral analysis, HVCs are typically at an equilibrium temperature of 8000 - 12000 K, with HVCs at higher galactic latitudes being on-average hotter than at lower latitudes Madsen et al. [2006]; Hill et al. [2009]. These temperatures allow HVCs to be HI and H-alpha emitters. Temperature is an important component of determining the emission measure of a HVC

Betti et al. [2019]; Hill et al. [2013, 2010].

HVCs require a weakly-magnetised halo of approx. 0.3 - 3 μG to have magnetic fields to sweep up Konz et al. [2002]. There is a very broad range of measured halo field strengths, ranging from 0.1 - 5 μG Jung et al. [2023]; Han and Qiao [1994]; Schnitzeler [2010]; Hill et al. [2010]; Ferrière [2001]; Beck et al. [2012]. This suggests that there is not enough data to conclusively determine the halo magnetic field strength and/or that the halo is heterogeneous in magnetic field strength. This primarily is due to interferences from foreground sources obstructing proper measurement of the base halo strength. What is known is that the galactic halo has a galaxy-wide asymmetry in its magnetic field strength Han and Qiao [1994]; Hill et al. [2010]; Schnitzeler [2010].

Therefore, the elimination of foreground objects is an important step in the process of determining RMs. For more see section 2.1. This has had an impact on past determinations of leading arm HVC magnetic field strengths, as shown in [Jung et al., 2021], which challenges the results of [McClure-Griffiths et al., 2010] on the basis that there was a foreground object manipulating the RM data.

1.3 Data Sources

The scientific investigation will require catalogue data to complete its objectives. Firstly, foreground observations, which act as the primary source of invalid measurement, have been catalogued by [Hutschenreuter and Enßlin, 2020; Hutschenreuter et al., 2022]. H-alpha emission is required to determine electron density. [Finkbeiner, 2003] provides combined whole-sky survey of H-alpha measurements.

HI emission is used in the location of HVCs, as they are opaque at the 21 cm line. [Moss et al., 2013; Westmeier, 2018] provides a broad southern sky catalog of HI emission with [Moss et al., 2013] locating points of interest for closer analysis. [Lockman et al., 2008] provides HI emission for the Smith Cloud specifically.

RMs were taken for the whole southern hemisphere in [Vanderwoude et al., 2024] - which is the results of the ASKAP Polarisation Sky Survey of the Universe's Magnetism (POSSUM). POSSUM is of key interest in this report. [Taylor et al., 2009] provides data on the Smith Cloud rotation measures. Due to latitude limits, POSSUM has covered the portion of the sky in which the Smith Cloud belongs to as well.

1.4 Objectives, novelty, and expected outcomes

The objective of this honours thesis is to:

1. Investigate the presence of magnetic fields surrounding circumgalactic HVCs using RMs collected from POSSUM

2. Determine if these magnetic fields, from a "rough estimation" (i.e. is the number in the "Goldilocks zone"), can allow a HVC to travel through a halo relatively undisturbed

3. (if there is time) More in-depth modelling surrounding the specific structure of magnetic fields surrounding HVCs and if this structure is preventing the formation of Kelvin-Helmholtz instabilities

While previous reports exist that have measured magnetic fields surrounding circumgalactic HVCs, most of this data is from HVCs in the Smith Cloud McClure-Griffiths et al. [2010]; Betti et al. [2019]; Grønnow et al. [2017]; Hill et al. [2013]. So far there has not been a substantial analysis of HVC magnetic fields across the entire southern hemisphere. This is important, as it could be the case that the Smith Cloud is exceptional compared to the relatively homogeneous Galactic halo.

Novelty comes in the scope of the analysis, as a broad measuring of HVCs in the southern hemisphere means a much larger data set for future researchers to pull on. This report takes advantage of the fact that only recently has POSSUM catalogued enough data to perform this operation.

The RM Grid analysis is of a higher sensitivity with POSSUM, with 30 reliable measurements per square degree compared to previous surveys only having 1 measurement per square degree Taylor et al. [2009]; Vanderwoude et al. [2024]. This makes the HVC data significantly higher in resolution.

Of course, the report will rely on previous data, as a means of providing a test data set. Previous location and spectral analysis of HVCs, in the measurement of HI and H-alpha emission, is used to not only know where the HVCs are, but also to determine important factors like emission measure Betti et al. [2019]; Hill et al. [2013, 2010].

Because this report is one of the first to measure magnetic fields surrounding numerous HVCs, there are a few potential outcomes that this report needs to anticipate:

- There are magnetic fields that are strong enough to support HVCs. This would mean that HVCs can act as a significant explanation for how galaxies take in external gas. Future research from this would involve more in-depth modelling on magnetic fields, the setup of a northern hemisphere equivalent to POSSUM, investigation of extragalactic HVCs, or determining if the gas content in HVCs can fully account for the fuel demands of star-forming galaxies.

- Magnetic fields exist surrounding HVCs in the halo, however they are only strong enough to partially explain HVC transport, meaning that this report would give a percentage estimation to how much is missing in the explanatory power of collected magnetic fields. Future research would involve investigating other possible sources of stability for HVCs or attempting to find a different method for how gas enters galactic disks.

- The magnetic fields are either non-existent or too weak to support HVCs i.e. a null result. This potentially eliminates HVCs as an explanation for gas in-fall, meaning that we are back at square one. Future research would involve checking to confirm if the null result of the report is correct, or if there is wiggle room in the data for other HVCs in the Milky Way. It may also involve completely abandoning HVCs as a candidate for gas in-fall after more careful analysis is done.

(Future) Methodology

2.1 Data analysis

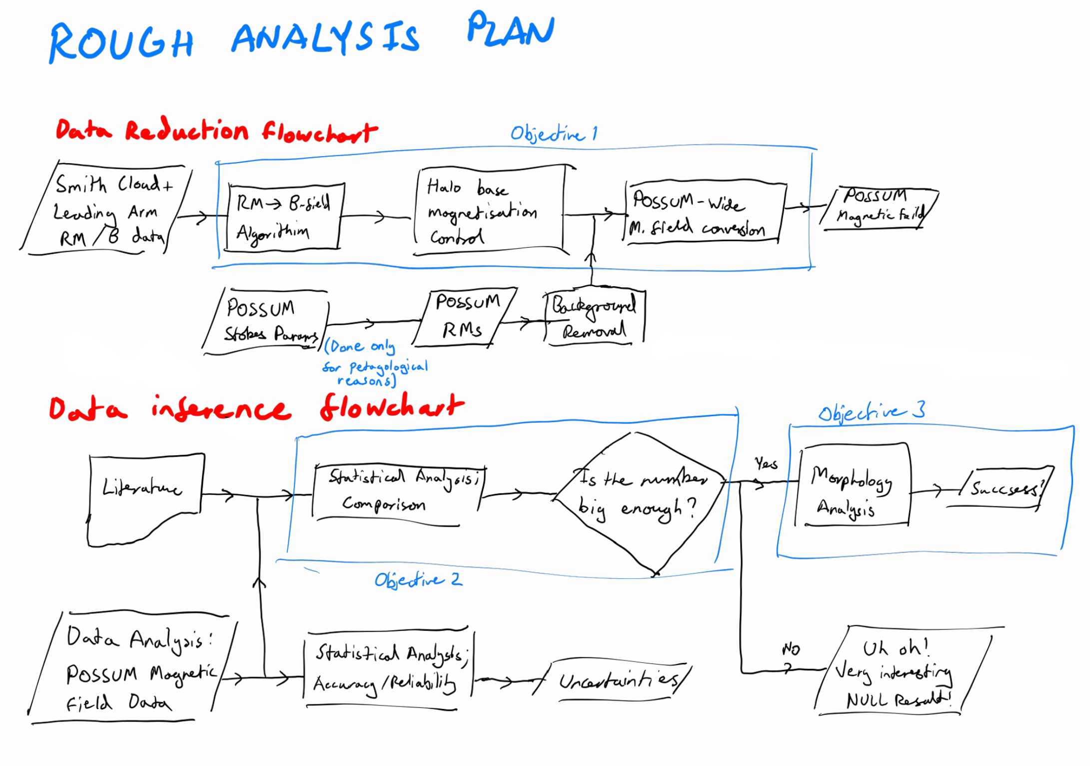

Figure 2.1: A rough flowchart of the data analysis method. A neater version of this flowchart will appear in future iterations of the report as a visual representation of the methodology.

Figure 2.1 represents the rough outline of the pipeline of data analysis as per the three objectives listed in 1.4.

The first point of data reduction is to convert the raw POSSUM data, i.e. stokes parameters in the field, to RMs. A component of research, revision, and programming will be dedicated to doing this. POSSUM as a survey has already condensed the stokes parameters into RMs Vanderwoude et al. [2024]. The purpose of doing it again is purely for pedagogical reasons - so that a better understanding about the nature of RMs is achieved. Purposefully, this part of the data reduction will only appear in perhaps a few sentences in the mid-term and final report, discussing how the POSSUM data was obtained.

Smith Cloud data will be obtained from a secondary source outside of POSSUM Taylor et al. [2009]; Hill et al. [2013]; Lockman et al. [2008]. The purpose of this data is to act as a testing set. Since past research has already determined the magnetic field strengths in HVCs in those regions Hill et al. [2013]. It is important that this data be used to confirm that the algorithm developed is working correctly.

After the program is developed to convert RMs into magnetic fields, data from the non-active components of the halo itself are then fed through the same algorithm. This will act as a control variable, providing a measure of base magnetisation for the Galactic Halo as well as pointing to a default ionisation state of the halo.

The halo control test will also help in the removal of foreground and foreground sources of Faraday rotation [1]. The light used to measure polarisation, comes from extragalactic synchrotron radiation, and is initially unpolarised. However, this radiation will have to travel a far distance before reaching us, at which point it can polarise from ionised gas in the Universe. HVCs will also be ionised. this is where H-alpha and foreground observations are used, as they provide information of the emission measure of the HVCs.

All these sources of interference can make it extremely difficult to determine the actual RMs. A background control run and analysis of the HVC can prevent this issue. Combating RM interference is an active part of the process in radio astronomy, with research that aims to tackle this problem Schnitzeler [2010]. With a larger data set, however, there is more reliability simply because there is more resistance to outliers. In previous examples, HVCs in the can be obscured, which is a way HVCs in the halo can also experience faulty RMs McClure-Griffiths et al. [2010]; Jung et al. [2021].

Techniques for foreground removal include convolutional blurring, binned averages, median filtering, and signal whitening/bandpassing Pulfer [2019]; Huang et al. [1979]; Arias-Castro and Donoho [2009]. Tools which will be investigated in literature while completing the implementation of objective 1.

Once all these processes are done, the algorithm should be fully capable of a simple pass-over across all HVCs in the entire southern sky. This step is the easiest, as it only involves repeatedly running an already completed script on several objects. After the program is developed, applied across all detected HVCs in the field, and the data is catalogued, the next step is to infer

[1] Foreground removal will also be performed using the annulus method

information from this data.

Most of the statistical analysis tools will be basic, as objective 2 simply requires a rough estimate of the magnetic field strengths. Uncertainties will naturally arise from the program's mathematical evaluations. The K-S test will be used to compare magnetic field distributions to theoretical cases and example cases like the Smith Cloud. Simple averages, box plots, and other single-set analysis tools will be used to establish a characterisation of the sample. It is expected, however, that HVCs that are at a higher Galactic latitude will be more resolute as there is less contamination by dust radio emission from the disk. This should be accounted for in the analysis of uncertainties.

Once these tests have been performed, it will be possible to assess if the results align with the initial alternative hypothesis. From there, either a tertiary objective is completed (if there is time), or further research is recommended in the conclusion of the report.

2.2 Timeline of honours project

Table 2.1 displays a rough timeline of both honours program milestones and self-assigned objectives.

As a general summary, the first half of the first semester will be focused on initialising the project, starting the process of research, and planning. The second half will focus on primarily completing objective 1, in which 14 weeks sounds like a realistic timeframe. The midterm report will be worked on as the tasks of objective 1 approach completion, with all the new research discovered over those months being compiled into the incomplete skeleton of the report.

Objective 2 will require less time, and hence only will take the former half of the second semester. The latter half of the semester is dedicated to drafting and finalising the report and its results. After the second semester exams, there will be a bit of time to clean up the project's code for future use, debriefing on the year, and if the research is of enough value, potentially publishing the report.

I do not actually know, according to the honours guidelines, if I am allowed to submit theses for formal publishing after the grading and reviewing of the report internally.

There will inevitably be disruptions, to account for these, several contingency measures are employed:

1. Starting work on tasks 1-2 weeks before their allocated time
2. Spending a portion of the 20 hrs/week on non-focused tasks (i.e. reading for 3 hrs while working on objective 1)

Objective	**Task**	**Period**
Milestone 1 (Semester 1)	Initial Reading Research Period I Proposal	Weeks 0-1 Weeks 1-3 Weeks 1-4
Objective 1 (Semester 1)	Initial Analysis Stokes Parameters Development SC/LA Testing Halo Analysis Background Removal Full POSSUM Analysis	Weeks 3-5 Weeks 5-6 Weeks 6-7 Weeks MS2-7 Weeks 8-9 Weeks 10-11 Weeks 11-12 & Break
Milestone 2 (Semester 2)	Research Period II Compilation of Data Report Construction	Break Break & Weeks 0-1 Break & Weeks 0-1
Objective 2 (Semester 2)	Statistical Analysis Uncertainties Final Evaluation	Weeks 1-4 Weeks 4-6 Weeks 5-6
Milestones 4 & 5 (Semester 2)	Research Period III Seminar Preparation Drafting Finalisation	Weeks 6-7 Weeks 7-9 Weeks 7-10 Weeks 10-12
Post-Submission (Oct-Dec 2024)	Cleanup/Debreif Publishing (Potential)	Week 12 After Semester 2

Table 2.1: A planned timeline of events.

3. Slightly overestimating the time it takes to complete each aspect of the project, to allow room for slow progress

4. Using a flowchart model of progression, so if one aspect of the project cannot be completed, only future contingencies are hindered

5. Regular and premature testing of programs

Chapter 3

Results

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Chapter 4

Discussion

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Chapter 5

Conclusions

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Chapter 6

Appendix

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