High Velocity Clouds, Magnetic Fields, and Foreground Removal

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

Olivia Walters
26 June 2024

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] ...

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The question of galactic gas accretion is a puzzle that has perplexed Astronomers for decades. Due to the complexities in the structures of star-forming galaxies, there are many factors and potential sources of accretion. What Astronomers do know, at least, is that star-forming galaxies require a continuous supply of fresh gas to continue their star formation.

Due to observational constrains, Astronomers are required to attempt to answer this question by examining the behaviours of our own Milky Way and Local Group environment. This is under the expectation that the Milky Way is typical of a star-forming galaxy.

A major factor to consider when answering this question is where fresh pristine gas comes from, and by what mechanism it takes to enter the disks of star-forming galaxies. The intention of this paper is to continue the examination of one explanation for galactic gas accretion – High Velocity Clouds (HVCs).

1.1 High Velocity Clouds

HVCs are clouds of gas found in the Milky Way's Circumgalactic Medium (CGM) and Galactic Halo and are notable primarily for their high peculiar velocity relative to the Galactic Frame of Rest (GSR), typically 70-90 kms^{-1} [Wakker, 1991; Wakker and van Woerden, 1997; Blitz et al., 1999]. This increased speed, as will be shown in section 1.2.1, is hypothesized to allow the HVC to survive as it travels through the CGM and halo and reach the Galactic disk and Interstellar Medium (ISM) of the Milky Way.

The origin of HVCs is still unknown, with a few hypothesises as to where they originate. Blitz et al. [1999] suggests that HVCs originate from the Intergalactic Medium (IGM) surrounding the local group. However, there is also a belief that some HVCs likely 'tore off' from satellites like the Magellanic Clouds, due to the presence of their own dark matter subhaloes, and the existence of HVCs in the Magellanic Stream and Leading Arm Kaczmarek et al. [2017]; McClure-Griffiths et al. [2010].

HVCs typically have a neutral mass gas content of $3 \times 10^7 M_\odot$ and a dark matter content of $3 \times 10^8 M_\odot$. They are generally shaped like comets, with a primary bulb that is approximately 0.5-25 kpc in diameter - a value that is highly dependent on distance to the Galactic midplane with the lower bound corresponding to approx. 50 kpc and

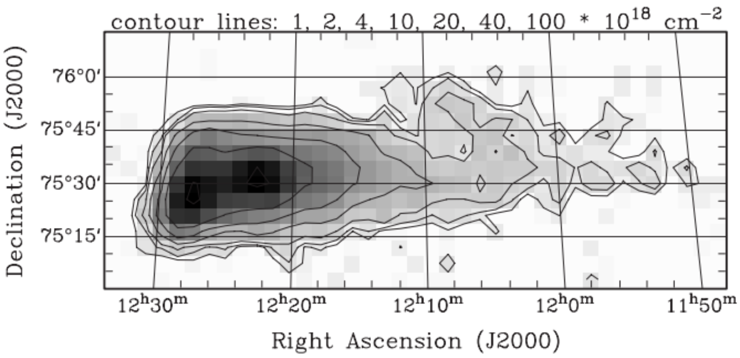

Figure 1.1: From [Konz et al., 2002], figure 2. An example of a typical HVC shape and structure, specifically that of HVC125+41-207. The contour lines and shading indicate N_{HI} column density.

an upper bound of approx. 1 Mpc [Blitz et al., 1999; Konz et al., 2002]. Furthermore, HVCs have tail-like structures that account for one eighth the baryonic mass of the HVC [Konz et al., 2002]. These tails leave behind long streams of gas that remain after collision with the Galactic disk [Putman et al., 2012]. This high distance dependence on size, comet-like structure, and long streaming tails suggest quite conclusively that HVCs shed a lot of material as they make their journey to the ISM.

Figure 1.1 is from [Konz et al., 2002], which provides a typical example of what a HVC looks like in HI, specifically using the example of HVC125+41-207.

1.1.1 Chemical Properites and Emission

HVCs have several characteristics that allow them to be both detected and analysed. Due to their hypothesised extragalactic source, HVCs contain mostly neutral gas such as HI, which can be seen with 21 cm emission [Wakker, 1991; Wakker and van Woerden, 1997; Westmeier, 2018]. HVCs also typically contain molecular gas that emits H-alpha, however due to extinction effects, it is difficult to observe H-alpha emission correctly [Bland-Hawthorn and Maloney, 1999; Finkbeiner, 2003]. Another difficulty for H-alpha analysis is that HVCs typically do not contain CO in significant quantities [Blitz et al., 1999].

Despite HVCs supposed gas purity, there is evidence that HVCs can contain alpha group elements. Hill et al. [2009]; Madsen et al. [2006] found the presence of [NII] 6583Å, [SII] 6716Å, and [OIII] 5007Å emission lines – with a conclusion that Nitrogen abundance is 0.15-0.44 times solar abundance levels. The observation of these emission lines can help constrain the metallicity of any HVC [Hill et al., 2009]. Metallicity is important in both answering the capacity for HVCs to supply fresh gas for star formation, and the mechanism by which HVCs can survive [Grønnow et al., 2018]; more on the latter in section 1.2.1. While HVCs can contain heavier elements Hayakawa and

Fukui [2024] finds that these concentrations are low enough that HVCs can remain as viable candidates for fuelling star formation via gas accretion.

HVCs additionally have a temperature relationship. With an average HVC temperature of 10000 K and a range of temperatures ranging from 8000 – 12000 K [Hill et al., 2009; Madsen et al., 2006]. The temperature of a HVC is just around the region in which atomic hydrogen transitions from neutral (HI) to ionised (HII), suggesting that HVCs may be partly ionised [Hill et al., 2009; Madsen et al., 2006; Kawaguchi, 1952]. This temperature relationship is dependent on their position to the Galactic midplane, with HVCs closer to the midplane generally being cooler [Madsen et al., 2006].

1.2 Magnetic Fields

The primary issue facing HVCs as an explanation for gas accretion is its capacity to survive as it travels through the CGM and Galactic halo. As discussed, in section 1.1, HVCs can loose a lot of size and mass as it approaches towards the Galactic disk, with the long trails it leaves behind being evidence for ram-pressure stripping as the HVC collides with the gas present in the halo [Jones et al., 1996; Grønnow et al., 2017, 2022]. Heitsch and Putman [2009] demonstrates that without anything to counter this effect, HVCs with masses under $10^{4.5} M_{\odot}$ would completely disperse within 10 kpc of halo travel.

Additionally, HVCs are subject to Kelvin-Helmholtz (K-H) instabilities, which is triggered by the nature of the HVC being a cloud of warm gas travelling at high speeds through a medium. These K-H instabilities are a significant factor that would lead a to HVCs collapsing before it reaches the Galactic disk [Jones et al., 1996; Grønnow et al., 2017, 2022].

1.2.1 Draping

The proposed solution to handle this problem is magnetic fields. The Galactic halo is magnetised to some degree in a generally turbulent manner [Hill et al., 2010]. It is hypothesised that these magnetic fields accumulate the existing magnetic fields and ionised gas in the Galactic halo, causing them to coax the HVC with a shield that protects against ram pressure stripping and supresses K-H instabilities [Dursi and Pfrommer, 2008; Jones et al., 1996; Konz et al., 2002; Grønnow et al., 2017, 2018; Jung et al., 2022]. This phenomenon is referred to as 'magnetic draping'.

However, there is not enough evidence to support the magnetic draping hypothesis beyond simulations. As most of the past research, instead, was focused on: technological improvements to surveys [Gaensler et al., 2010; Vanderwoude et al., 2024; Moss et al., 2013; Westmeier, 2018; Taylor et al., 2009; Finkbeiner, 2003; Hutschenreuter and

Enßlin, 2020; Hutschenreuter et al., 2022]; the analysis of physical phenomena such as ram pressure stripping [Jones et al., 1996; Grønnow et al., 2017, 2022]; the development of magnetic field derivation techniques [Betti et al., 2019; Grønnow et al., 2017; Hill et al., 2010; Jones et al., 1996; Hill et al., 2013; Schnitzeler, 2010]; and simulations of HVCs [Konz et al., 2002; Grønnow et al., 2017, 2018, 2022; Jung et al., 2022] – all of which lay the groundwork for a proper investigation of magnetic draping.

Previous and recent simulations involve reports produced by Grønnow et al. [2017, 2018, 2022] (henceforth referred to as the "Grønnow simulations") that provide detailed insight onto how a magnetic draping protects HVCs from collapse, complementing earlier work by Konz et al. [2002]; Jones et al. [1996]. It is shown from the Grønnow simulations that magnetic fields of about 0.3-1 μG can provide stability to HVCs.

However, increasing magnetic field strength beyond a certain threshold can result in more instability; magnetic fields can accelerate the effects of Rayleigh-Taylor (R-T) instabilities and the magnetic pressure applied by the draped fields can also slow down a HVC to the point that it no longer is fast enough to sweep up these magnetic fields. From the Grønnow simulations, the upper threshold where these effects start increasing instability is about 1 μG, thus HVCs should ideally have a "Goldilocks" magnetic field strengths on the order of magnitude of 0.1μG, with 1μG being too high, and 0.01μG being too low.

The effectiveness of magnetic draping is affected by the morphology of these fields and the physical properties of the HVC. The Grønnow simulations state that both the orientation of the magnetic field with respect to the direction of motion of the HVC, and where the magnetic field is located are important considerations. It is expected that not the entire HVC is to be covered in a magnetic field, only the part that is front facing in the direction of travel. While it is possible to draw conclusions about the survivability of a HVC from the strength of the magnetic field, modelling is required to confirm the accuracy of such conclusions [Betti et al., 2019]. The Grønnow simulations also predict that metallicity can affect the HVC's survivability, with high-density metal-rich clouds and low-density metal-poor clouds being more unstable than their counterparts.

1.2.2 Faraday Rotation

Magnetic fields cannot directly be imaged by a telescope. Instead, researchers can use the phenomenon of Faraday Rotation to quantify the line-of-sight magnetic field strength. Low-frequency polarised radiation tends to rotate as it travels through a medium with a magnetic field present. Thus, by recording the stokes parameters of incoming light from distant radio sources, one can derive the Rotation Measure (RM) of incoming radiation, which is a statistical quantifier of Faraday Rotation [Vanderwoude et al., 2024; Brentjens and de Bruyn, 2005]. The polarisation angle can be derived from the two orthogonal linear stokes parameters, Q and U, and where ϕ is the polarisation angle:

$$\phi = \frac{1}{2}\arctan\left(\frac{Q}{U}\right) \tag{1.1}$$

Vanderwoude et al. [2024] describes the method by which this report's main source, the Polarisation Sky Survey of the Universe's Magnetism (POSSUM), obtained it's RMs from raw stokes parameters. The value of the RM is derived by establishing a linear relationship between the polarisation angle, $\delta\phi$, and the square of the wavelength of passing radiation, λ, shown in Equation 1.2:

$$\delta\phi = \mathrm{RM}\lambda^2 \tag{1.2}$$

There is a direct connection between RM and line-of-sight magnetic field strength, quantified by the below equation [Betti et al., 2019; Vanderwoude et al., 2024; Hill et al., 2013; Kaczmarek et al., 2017; Hill et al., 2010].

$$\mathrm{RM} = 0.812\int_{s_{\mathrm{observer}}}^{s_{\mathrm{source}}} \frac{n_e(s)}{\mathrm{cm}^{-2}}\frac{B_{\|}}{\mu\mathrm{G}}\frac{ds}{\mathrm{pc}}\mathrm{radm}^{-2} \tag{1.3}$$

In which, $B_{\|}$ is the magnetic field strength, RM is the Faraday Depth a.k.a. the value of the RM, and n_e is the electron density of the medium as a function of line-of-sight distance s. The analysis of this equation, its solutions, and the use of it in calculating the magnitude of draped magnetic fields is discussed in section 4.

Faraday Rotation also occurs in the ISM, due to the slight magnetisation of the ISM [Ferrière, 2001; Hill et al., 2010; Schnitzeler, 2010]. In addition to this there are many smaller sources of Faraday Rotation that can cause interference with the desired object observations being made. Hence it is also important to remove the foreground from RM observations.

1.2.2.1 Noise Interference

When making radio observations of RMs, a principal factor to consider is signal to noise ratio and detector sensitivity. Radio sources tend to appear in the field after high exposure times, and when they do, they appear as point-like sources. These point-like sources are then collated into an "RM grid" which has a particular density measured in sample points per square degree. The sensitivity of a detector is related to the number of grid points as seen in figure 1.2 [Loi et al., 2019]. At grid densities that are too high, RM sources can bleed into each other, leading to confusion noise. However, no modern radio telescope can reach the confusion limit [Loi et al., 2019].

Signal to noise is of primary concern when measuring the effect of Faraday Rotation. At low enough signal-to-noise ratios, it is possible to encounter 'phantom RMs' which do not accurately represent the real RM [Macquart et al., 2012]. Figure 1.3 gives

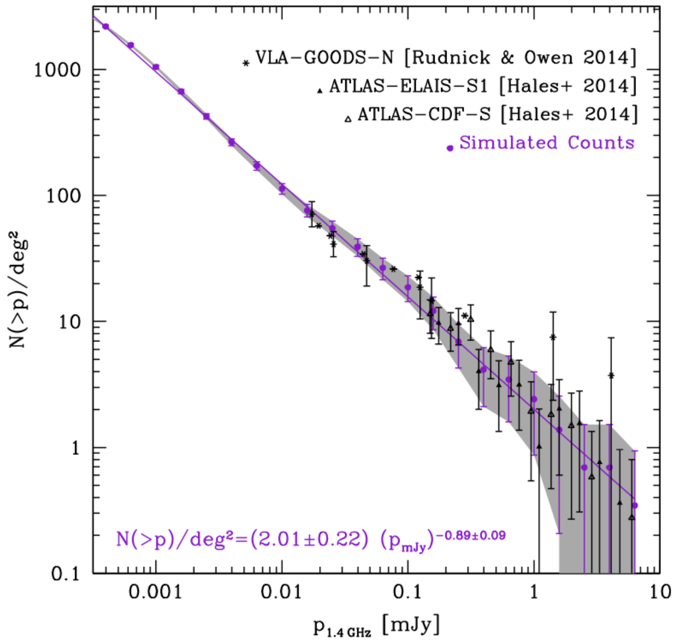

Figure 1.2: From [Loi et al., 2019], figure 4. A graph of the relationship between the 1.4 GHz sensitivity of a radio detector array (x-axis) and the mimumum number of RM sample points per square degree (y-axis). The black points are not relevant to the report, but the purple line and equation describe the determined relationship.

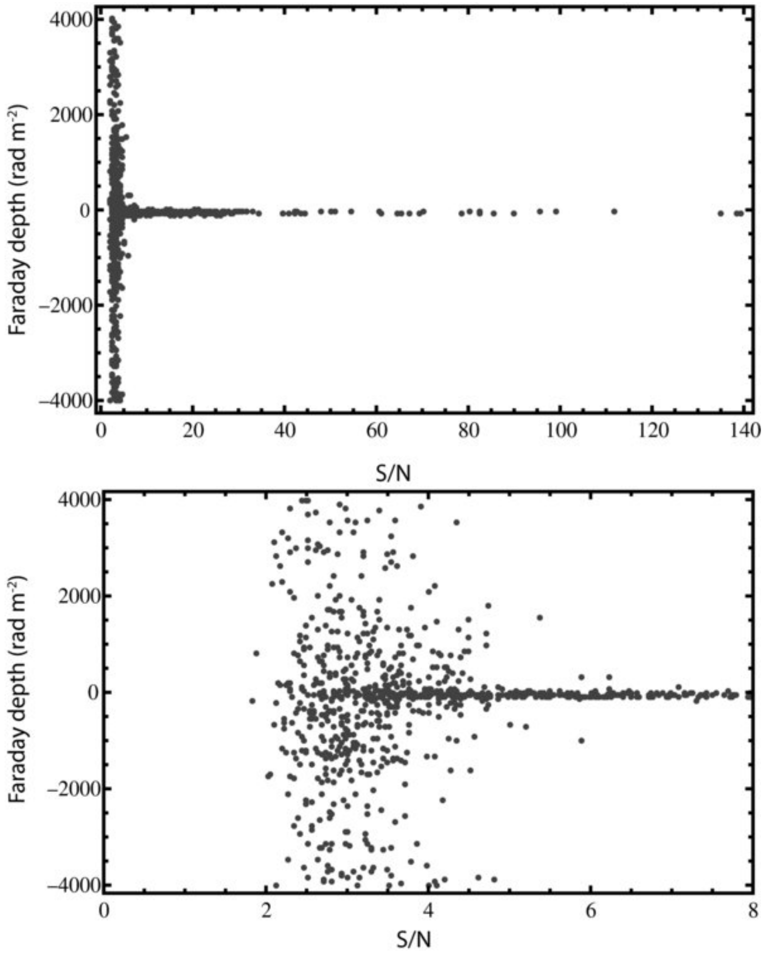

Figure 1.3: From [Macquart et al., 2012], figure 1. A graph displaying the effect of observational (stokes parameters) signal-to-noise ratio the resultant faraday depth on a sample set of observations.

a visual illustration of this phenomenon. The issue in question is that any observation of RM grids is going to dip below the signal-to-noise threshold of approx. 6, which can introduce an intrinsic scatter in collected RM grid data. There is not much that can be done outside of avoiding regions where the signal-to-noise is likely to be lower (i.e. the Galactic midplane), or to account for it with statistical methods more resistant to large errors.

1.3 Smith Cloud

The Smith Cloud is a large HVC that is in the process of colliding with the Galactic disk [Lockman et al., 2008; Tepper-García and Bland-Hawthorn, 2017; Lockman, 2008]. Unlike most HVCs it is quite large in both mass (at least $10^6 M_\odot$ in HI mass) and an-

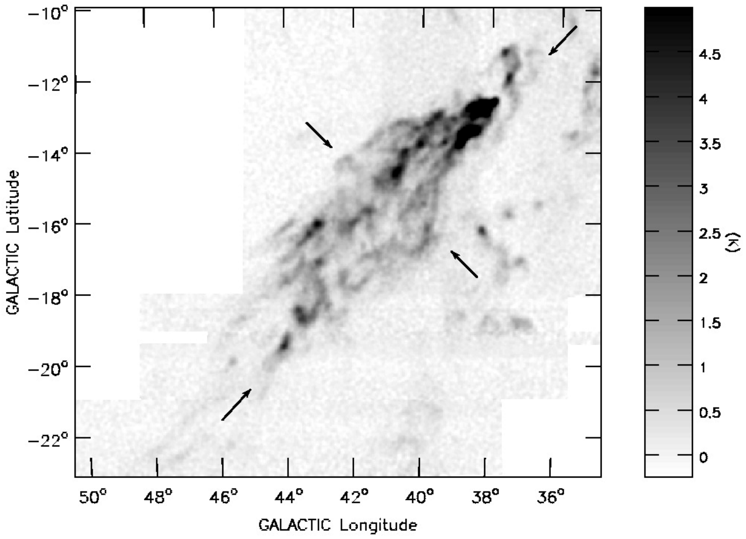

Figure 1.4: From [Lockman et al., 2008], figure 1. A HI image of the Smith Cloud taken from the Green Bank Telescope at a local standard of velocity rest of 100 kms^{-1}. The purpose of the arrows are not meaningful to this paper.

gular size [Lockman et al., 2008; Tepper-García and Bland-Hawthorn, 2017; Lockman, 2008]. It has a predicted physical size of 3 square kpc, which is large for a HVC close to the Galactic disk [Lockman et al., 2008]. Due to its proximity and size, the Smith Cloud has been used as a source point of analysis for most of the properties already discussed. For example, metallicity tracers and alpha-group elements in Madsen et al. [2006]; Hill et al. [2009] were determined by analysing the Smith Cloud. Figure 1.4 provides an image of the Smith Cloud in HI from Lockman et al. [2008].

The Smith Cloud has additionally already had its magnetic draping effect analysed. Simulations by [Grønnow et al., 2017] and observations by [Hill et al., 2013] both agree on an effective magnetic field of $\sim$8 μG. Note that this number is well above the Goldilocks zone mentioned in section 1.2.1 – indicating the exceptionality of the Smith Cloud.

While there are other HVCs that have been sampled in the past, the Smith Cloud has been the main source of HVC information. This is a problem, as the Smith Cloud is an outlier amongst most HVCs – evidenced by its unusual size and magnetic field strength, both factors being related. There is a necessity to analyse more typical nearby HVCs to gain an understanding of the effects of magnetic fields.

1.4 Report Outline and Objectives

The primary objective of this report is to (a) construct a rudimentary algorithm for calculating arbitrary HVCs found in the CGM and halo and, (b) use this base algorithm to come up with a *very* rough estimate for the magnetic field strength surrounding typical HVCs. The primary source of data will be POSSUM, which will be used to obtain the primary outcome of the report. Due to the previous lack of robust RM grid data, along with other periphery data and a large level of required assumptions, it is not possible to come up with an accurate estimate of field strength for any HVC. The best-case scenario is an estimate that is accurate within a single order of magnitude. Hence, why the aim of this report is to lay the foundations for a future, more detailed analysis, of HVCs i.e. it is easier to modify a derivation pipeline than to create one from scratch.

A secondary objective report is integral to completing the primary objective and in future research for all observations of Faraday Rotation: that of foreground removal. Past research, specifically within the analysis of HVCs, has relied on the technique of interpolation to obtain a RM foreground to use in corrections [Schnitzeler, 2010; Moss et al., 2013; Hill et al., 2013]. However, as researchers move onto measurements of magnetism that demand more accuracy, foreground removal needs to equally match that that growing need for accuracy – thus this report also aims to investigate avenues for improving foreground subtraction techniques.

This report is split into eight sections. Section 2 describes the process of how and which data was obtained to achieve the research question, and how this data was collated together. Section 3 summarises the investigation into foreground removal, which is the secondary aim of the research. Section 4 describes how the magnetic fields for HVCs were derived, and the level to which morphology was involved in the analysis. Section 5 provides the results of the scientific investigation and data analysis. Section 6 discusses the viability of the methods described in the report, along with broader scientific and statistical considerations. Lastly section 7 concludes and outlines the many possible directions for future research. Appendix A (8.1) lists information on how to obtain the program data and algorithms used in research.

Chapter 2

Data Collection

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Chapter 3

Foreground Subtraction

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Chapter 4

Magnetic Field Derivation

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Vanderwoude et al. [2024]

Chapter 5

Results

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Chapter 6

Discussion

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Chapter 7

Conclusions

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Chapter 8

Appendix

8.1 A - Developed code and data

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