

Magnetic Fields Near and Far

**Galactic and Extragalactic Single-Dish Radio Observations of the
Zeeman Effect**

Timothy Robishaw

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*Magnetic Fields Near and Far:
Galactic and Extragalactic Single-Dish Radio Observations of the Zeeman Effect*

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by

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Cover Image:

Zeeman, Lorentz en Zeeman

A triptych of stained glass windows designed by Harm Henrick Kamerlingh Onnes. The three panels depict: Pieter Zeeman's experimental discovery of the broadening of a spectral line by a magnetic field as reported by Heike Kamerlingh Onnes (uncle of the artist) on October 31, 1896 (*top*), the theoretical explanation of the broadening and the prediction of polarization in the broadened line wings by Hendrik Antoon Lorentz (*center*), and Zeeman's experimental confirmation of the polarization as reported on November 28, 1896 (*bottom*). Image used with permission through the courtesy of the Leiden Institute of Physics, Leiden University.

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Abstract

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Doctor of Philosophy in Astrophysics

University of California, Berkeley

Professor Carl Heiles, Chair

According to astrophysical theory, magnetic fields should play an important role in the structure and dynamics of the interstellar medium. While astronomical observations confirm this directly, the observational record is sparse. This is because magnetic fields can only be measured via polarimetric methods, and most of these methods can only provide an indirect inference of the magnetic field strength. The Zeeman effect, however, is the only method by which in situ measurements of astrophysical magnetic fields can be made.

The spectral signature of Zeeman splitting is imprinted in the circular polarization spectrum of radiation received from an astronomical source. In order to make a reliable detection at radio frequencies, one must employ careful calibrations and account for instrumental effects. We begin this dissertation by covering the fundamentals of radio spectropolarimetry. We then offer historical details regarding the Zeeman effect and its use in single-dish radio observations. We present an outline of how one accurately measures the Zeeman effect using large single-dish radio telescopes. We follow this with results from an assessment of the polarization properties of the 100 m Green Bank Telescope (GBT).

We then present magnetic field detections made via the Zeeman effect from the Galactic scale to cosmological distances. We begin with GBT observations of 21 cm emission toward the Taurus Molecular Cloud (TMC) complex. Recent observations have suggested that fields stronger than $20 \mu\text{G}$ are located at the distance of the TMC. Our Zeeman observations rule out fields of this strength, but do show a clear $\sim +5 \mu\text{G}$ detection from H I emission at the velocity of the TMC. More surprisingly, we have discovered multiple detections of a line-of-sight magnetic field of

strength $\sim +40 \mu\text{G}$ in a filament near -50 km s^{-1} . We then present a windfall of detections of milligauss-strength magnetic fields in starburst galaxies. Detected by means of Zeeman splitting of 1667 MHz hydroxyl megamaser emission, these Arecibo and GBT results represent the first extragalactic Zeeman measurements to probe the field inside an external galaxy. Finally, we climb the cosmological distance ladder, and present a dramatic GBT detection of a magnetic field in a damped Ly α absorber at a redshift of 0.692. We discuss possible scenarios for the creation of an 84 μG field at a look-back time of 6.4 Gyr.

Professor Carl Heiles
Dissertation Committee Chair

*To my parents and brother,
who supported me while I avoided the real world.*

*In memoriam — Lillian A. Cashman 1911–2008
Richard C. Spillane 1946–1997*

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Acknowledgments

You might be smart up in space, but here on Earth: no common sense.

MARY ROBISHAW

My residency in Campbell Hall began in 1996, when I took my first astronomy lab course with Carl Heiles. During our first observing session, Carl made us point our theodolites at the North Star. However, we had a great deal of trouble keeping the star in the field of view, until our TA pointed out that the star was not, in fact, Polaris. Carl explained that while this was an *optical* astronomy course, he had good reason to not know which star is at the pole: because he was a *radio* astronomer, and he had been educated at *Princeton*. We had so much fun in that class that a group of us took Carl's radio astronomy lab course the next year. We worked harder than was reasonable for a two unit course, but it was only because of the challenge: when you finished a physics problem set, you dropped it in a box; when you finished one of Carl's do-it-yourself projects, you had looked out into a universe that was invisible to the naked eye. I was hooked. I then worked for a few years with Leo Blitz, who taught me a great deal about how exciting real astrophysical research could be. If it weren't for Leo, I wouldn't have chosen astronomy as a career path, and I'm extremely grateful to him for his support and guidance. I then began the work that became this dissertation back under Carl's wing.

Carl provided me with a unique opportunity to do extremely exciting research using the two biggest telescopes on Earth; I have found this work extremely rewarding. Writing, unfortunately, and to Carl's certain dismay, has not come so easily. I was recently comforted to read that the great historian Barbara Tuchman also found that, "Research is endlessly seductive; writing is hard work." I'm hoping it gets easier; at the very least, this thesis was good practice.

From the start, Carl has treated me like a colleague rather than a student, even when I ask questions that clearly expose my lack of understanding of some fundamental astronomical concepts. Every day I'm amazed by how much he can accomplish and how well he understands so

many aspects of observational radio astronomy. Carl has taught me how to be an expert observer, and in this age of email-it-in observing, I feel extremely lucky to have had so much hands-on observing experience. The most important thing that I've learned from Carl is the desire to make sure a job gets done right. He's a great teacher, a great astronomer, and an even greater pal. Above all, I can't thank Carl enough for his understanding and support when my family went through a severely difficult period.

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live at the hacienda with Mother, who decided being feral isn't where it's at. Not long after, another stray showed up at my door, when my old pal Matt/Buck Prentiss came to California to fill Steve's vacancy. His low-stress philosophy helped me maintain an even strain during some absurdly stressful times. And he's been a great help, reminding me to take a break now and then.

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Most importantly, I would like to thank my family. Without the love and support of my mother and father, Mary and Arthur Robishaw, I would not have been able to pursue a career doing something that I love. They gave me everything I could ever need, and I truly appreciate it. Thanks to Uncle Tim for having me over so often and keeping me well fed, and for hipping me to Coppa Mista, Deadwood, and the Sopranos. Thanks to Uncle Richie for letting me use his computer to observe and get work done when back in Boston. I wouldn't have made it this far without the love and support of my brother, Art; he's the best friend a guy could have. He's also the one who told me to take physics instead of chemistry. Above all, I thank my Nana, Lillian Cashman, who I miss very much. She isn't here to see this final product, but I know she's proud all the same.

Finally, as I finish the 24th grade, I thank the great decider, George W. Bush. There were many times over the last eight years when I thought that I might not have the right stuff to earn a PhD in astrophysics. During these dark times, George was always there for me, reminding me that if he could be President of the United States, then *anything* is possible. As we are both getting ready to leave office (mine is 751B Campbell Hall), I begin this dissertation by following his lead, and stealing his words:

I'm going to try to see if I can remember as much to make it sound like I'm smart on the subject.

The argument in the past has frequently been a process of elimination: one observed certain phenomena, and one investigated what part of the phenomena could be explained; then the unexplained part was taken to show the effects of the magnetic field. It is clear in this case that, the larger one's ignorance, the stronger the magnetic field.

LODEWIJK WOLTJER, 1966

Chapter 1

Introduction

I hate quotations. Tell me what you know.

RALPH WALDO EMERSON, 1849

Magnetic fields play an important role in the structure and dynamics of the interstellar medium (ISM). The energy density of magnetic fields is roughly 1 eV cm^{-3} ; this is identical to the energy density of cosmic rays, gas motions, starlight, and the cosmic microwave background. It is assumed that the first three are connected, and that the latter two are just a coincidence. However, it is clear that magnetic fields cannot be ignored in the study of the ISM.

Unfortunately, there is a difficulty in directly quantifying their importance observationally: they are notoriously hard to measure. Magnetic fields interact with matter in space in such a way that they leave a fingerprint on radiation that is either emitted or absorbed by this matter. This fingerprint is embedded in the polarization of the received astronomical radiation. For example, one can infer the magnetic field in the plane of the sky by measuring the polarization of starlight or dust emission. Synchrotron radiation also allows the observer to indirectly estimate the plane-of-sky field at the location where the radiation was generated.

A more direct observational method is that of Faraday rotation, which allows the observer to probe the line-of-sight component of the magnetic field. Partially linearly polarized radiation passing through an ionized medium that is immersed in a magnetic field will have its polarization position angle rotated by different amounts at different frequencies. One can measure the linear polarization at multiple frequencies and estimate the field strength. There are a number of caveats when using this method. First, Faraday rotation takes place inside the source where the radiation is generated. In addition, polarized sources are often variable, so one must be careful that multi-wavelength estimates of the polarization are measured relatively close in time. Most importantly,