Magnetic Fields Near and Far

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

Timothy Robishaw

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Committee in charge:
Professor Carl Heiles, Chair
Professor James R. Graham
Professor William L. Holzapfel

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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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Timothy Robishaw
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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 μG are located at the distance of the TMC. Our Zeeman observations rule out fields of this strength, but do show a clear $\sim$+5 μG 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 μG 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 Lyα 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.

I got to know two of my favorite people, Tom Troland and Josh Simon, via long, long observing runs at Green Bank and Arecibo, respectively. Tom is an incredibly meticulous observer, a source of good advice, a great maker of popcorn, and a great guy. I learned everything I know about booze from Tom. Josh amazes me with his fearlessness in tackling observational projects all over the spectrum, and I hope I get to work with him again. He's alright for a Stanford fan.

A number of folks in Campbell Hall made my infrequent daylight operating hours really enjoyable: Mike Cooper, Snežana Stanimirović, Alberto Bolatto, Karin Sandstrom, John Johnson, and Marijke Haverkorn. Thanks to Jon Swift for having the right attitude about this astronomy gig, and to Danny Jones for looking out for me: he's alright for a Yankees fan. And the biggest thanks go to Mike Fitzgerald and Doug Finkbeiner: whenever I've needed to know something, about anything, at any strange hour, these guys have always provided a timely answer. I'm lucky to have met some new friends when astronomy took me away from Berkeley, and they are all extremely reliable folks: Kayhan Gultekin, Neil Nagar, Jeremy Darling, Crystal Brogan, Dick Crutcher, Bryan Gaensler, Loris Magnani, Peter Teuben, Dap Hartmann, and Tom Bania.

Now and then, my real-world friends made sure life wasn't all work. Thanks to: Kevin Cuff for the #55s and stickball, Pat Mahoney for the hegna, Sarah Adams for gabbing, Julie Walters for being awesome, and, especially, Elena Cotto, whose Red Pen of Justice keeps me in line.

Steve Dawson was a great roommate, and became a prize of a friend. There were some long nights in the living room wondering out loud what the hell we could do with a PhD in astrophysics if we were to split for the real world. Thanks to Steve, now I know: have your weekends off, enjoy your life, and make money.

Thanks to Colleen Henry for being such a great friend. She has made my life extremely bright since I met her. She's going to be the best PhD social welfarologist in the world. And thanks to her family, and Darcy, who have treated me like one of their own. I really appreciate their kindness and love.

Thanks, I guess, to Mother, the stray cat from my hood, who brought seven kittens into my closet one hot afternoon last July. Five were adopted, and two, Choo Choo and Coco, still 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.

I had the great fortune to be able to spend many months of my life in Green Bank, West Virginia. While it *is* a little out of the way, the Green Bank staff made me feel right at home. I made a lot of friends down there, and miss them quite a bit. First of all, the most important people to thank are the cafeteria girls because they always brought a smile to my face and kept me from going hungry: Barbara Taylor, Amy Thompson, Sue Roberts, Ashley McCarty, Sylvia Warner, Shirley Riggsby, and Rosie Slaven. I always enjoy my long conversations with Max Gum and Daryl Shinaberry on the way from, then back to, Dulles. The telescope operators are top-notch. I really enjoyed all the conversations and the time that we spent together (cumulatively, over 1500 hours): Eric Knapp, Greg Monk, Kevin Gum, Dave Rose, Barry Sharp, and Donna Stricklin. Whenever I had a software problem that needed fixing, Bob Garwood, Paul Marganian, Amy Shelton, Mark Clark, and Melinda Mello were all quick to solve it. The scientific staff was incredibly helpful in assisting in the implementation of our extremely non-standard observing methods. In particular, Toney Minter, Dana Balser, Rick Fisher, Frank Ghigo, and Ron Maddalena all invested a lot of time helping me out. Roger Norrod and Rich Lacasse were invaluable in sorting out the heavy details. Thanks a ton to Sue Ann Heatherly and Bill Saxton for helping me get some of our results out into the real world. Shirley Curry, Sherry Sizemore, and Becky Warner are organizational experts and were always looking out for me. Our observations were aided by the organizational work of Bob Anderson, Pete Chestnut, and especially Carl Bignell, who does an extremely hard job extremely well. Our polarization work was only possible due to the full support of Phil Jewell and Richard Prestage. Some other Green Bank friends who made my stays more enjoyable include Jim Braatz, Mike Stennes, Mary Meeks, Maggie Morgan, Don Nelson, and Brian Mason, who came through for me in a big way by finding the IAU definition of Stokes V hidden in a time capsule behind a secret panel in the Charlottesville library.

I met Karen O'Neil on my first trip to Arecibo. Within the first hour, she became an invaluable telescope pal. Like an angel at the side, she moved to Green Bank just as I switched my observing from Puerto Rico to West Virginia. She, and her husband Paul, couldn't have been more helpful. In addition to solving a lot of telescope mysteries for me, Karen has also given me a lot of great professional advice. I really appreciate everything.

Sadly, the development of remote observing has ended my visits to Puerto Rico, but my observations have been, and still are, made easier by the help of Phil Perillat, Chris Salter, and Arun Venkataraman. Edith Alvarez, Willie Portalatin, and Norberto Despiau were all very helpful to me during my time in Arecibo.

There are a few people who certainly influenced my life path along the way, and I thank them here: Bill Barrett, Chet Raymo, Don Goldsmith, and Dave Cudaback. Most especially, I thank Richard Spillane, my physics teacher for two years at Boston Latin. He passed away far too early at the age of 51. His classes, which I never paid a dime for, set me on this course; it has been disheartening to me that not one of my college courses, which I'm still repaying loans for, was as inspirational as his.

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,