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Analytical Study of Zeeman effect and spectral splitting in physics and astronomy

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ABSTRACT

In this paper, the author studied an interactive module created through the Wolfram Demonstrations Project that visualizes the Zeeman effect for the small magnetic field strengths present in the interstellar medium. The paper gives an outline of spectral lines and a couple of instances of solid and powerless Zeeman splitting prior to examining the module inside and out. Understudy revelation is helped with model circumstances to examine utilizing the intelligent module, which is focused at the upper undergrad or early alumni level. This module utilizes free programming, can be utilized in study hall exercises or as a methods for acquainting understudies with the Wolfram Demonstrations Project as a learning asset.

1. Introduction

In electricity & magnetism courses, one of the more difficult concepts for students to visualize is magnetic field structure. Researchers can notice the immediate effects of magnetic fields, however not simply the magnetic field. With the end goal for understudies to have a superior comprehension of this subject, it is basic that they see with their own eyes such direct effects (Dori, Hult, Breslow, and Belcher, 2007). While homeroom exhibits are unimaginably valuable, giving a bigger setting is likewise attractive. This can be given by intuitive reenactments, which have been appeared to expand understudy learning in physical science (Weiman, Adams, and Perkins, 2008). This paper will depict one of these unique situations and an intelligent module intended for upper-level students and early-level alumni understudies to use for researching the subject. Probably the biggest setting accessible in material science is application to astronomy. There are a set number of approaches to gauge magnetic field in the interstellar medium. The main uses direct polarization of starlight or dissipated light from dust.

This technique gives a halfway course; like a bolt without a sharpened stone, the vector is limited to two potential headings. The drawback of this strategy is this uncertainty in course, on the grounds that while numerous actual cycles can make arbitrary field headings that may look adjusted, magnetic powers can assume a greater part in districts of room where the field is rational, pointing in a similar bearing over a huge zone. Different techniques that can test the genuine bearing of the magnetic field and decide its intelligence are Faraday turn and Zeeman splitting, the last of which should be possible in undergrad labs (Blue, Bayram, and Marcum, 2010; Olson and Mayer, 2009). Faraday pivot can be utilized when there is a firmly directly captivated foundation source and has numerous applications (Heiles, 1976; Oppermann, Junklewitz, and Robbers, 2012).

The Zeeman effect can gauge both heading and strength of the magnetic field, which is unbelievably helpful. In any case, for use in the interstellar medium (ISM), atoms or particles with huge magnetic minutes should be available in a sufficiently high thickness for it to work. Consequently, as Bryan Gaensler once expressed, "when you can utilize it, it's gold, yet there are without a doubt, exceptionally restricted spots in the universe where Zeeman splitting really works" (colloquium at Harvard-Smithsonian Center for Astrophysics, 21-Mar-2013). This article centers around the utilization of the Zeeman effect in moderately thick bits of the ISM like sub-atomic mists.

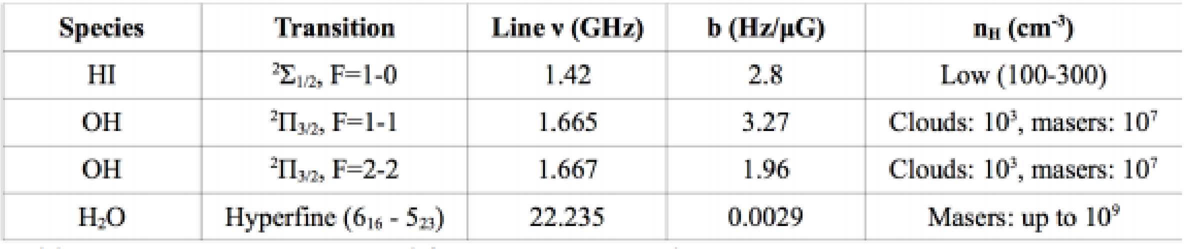
2. Spectral Lines and Zeeman Splitting

At the point when spectral lines come up in space science and physical science courses, teachers are most usually examining the assimilation and discharge lines made when an electron changes energy levels in a particle (Rybicki and Lightman, 2004). There are, nonetheless, subtler cycles that additionally make spectral lines. A notable model in cosmology is made by nonpartisan Hydrogen (HI; Dickey and Lockman, 1990) When the turn of the solitary electron in a HI particle flips from being corresponding with the proton in the core to being against equal, a photon with a frequency at 21 cm is transmitted. The turn flip progress of HI and different particles or atoms are frequently seen in the radio because of the little energy level contrasts, and I will talk about why a portion of these long frequency spectral lines are ideal for noticing the Zeeman effect in the ISM. These unpretentious cycles that can deliver long-frequency spectral lines are regularly enraptured. Parts that are circularly enraptured will be significant for magnetic field estimations of the ISM. The measure of splitting between two precise energy quantum numbers for a solitary line is given by $\Delta \nu Z = (g\ \mu B\ B/h)$, where μB is the Bohr magneton, h is the Planck consistent, and g is the Lande g-factor (Heiles, Goodman, McKee, and Zweibel, 1993).

The Sun is an illustration of the solid Zeeman effect, where splitting of the lines is sufficiently able to be found in the general force and the measure of splitting is straightforwardly estimated from sun oriented spectra utilizing the condition above. This effect is sufficiently able to be quantifiable in undergrad material science labs (Ratcliff, Noss, Dunham, Anthony, Cooley, and Alvarez, 1992). Such noticeable splitting of the field lines is uncommon in other cosmic perceptions, where field qualities will in general be a lot of lower. Perceptions of the magnetic field strength at the Sun's photosphere, ordinarily alluded to as magnetograms, are regularly utilized as limit conditions for codes that model the 3D magnetic field of the Sun out to 1 AU.

The exactness of these limit conditions is fundamental, as the Sun's magnetic field assumes a significant part in the warming of the crown and speeding up of the sunlight based breeze (Woolsey and Cranmer, 2014). At the point when the magnetic field isn't sufficiently able to part the spectral lines totally, the cycle is alluded to as the powerless Zeeman effect. Heiles, Goodman, McKee, and Zweibel (1993) aggregate a broad rundown of contender for perceptions of the powerless Zeeman effect, which I replicate for just the most normally utilized applicants in Table 1. Here, b = (2 g μB / h) Hz/μG such that the equation above can be rewritten as ΔvZ = (b B / 2).

Table 1: Common Species used for ISM Zeeman Observations



Species	Transition	Line v (GHz)	b (Hz/μG)	n_H (cm^{-3})
HI	$^2\Sigma_{1/2}$, F=1-0	1.42	2.8	Low (100-300)
OH	$^2\Pi_{3/2}$, F=1-1	1.665	3.27	Clouds: 10^3, masers: 10^7
OH	$^2\Pi_{3/2}$, F=2-2	1.667	1.96	Clouds: 10^3, masers: 10^7
H_2O	Hyperfine (6_{16} - 5_{23})	22.235	0.0029	Masers: up to 10^9

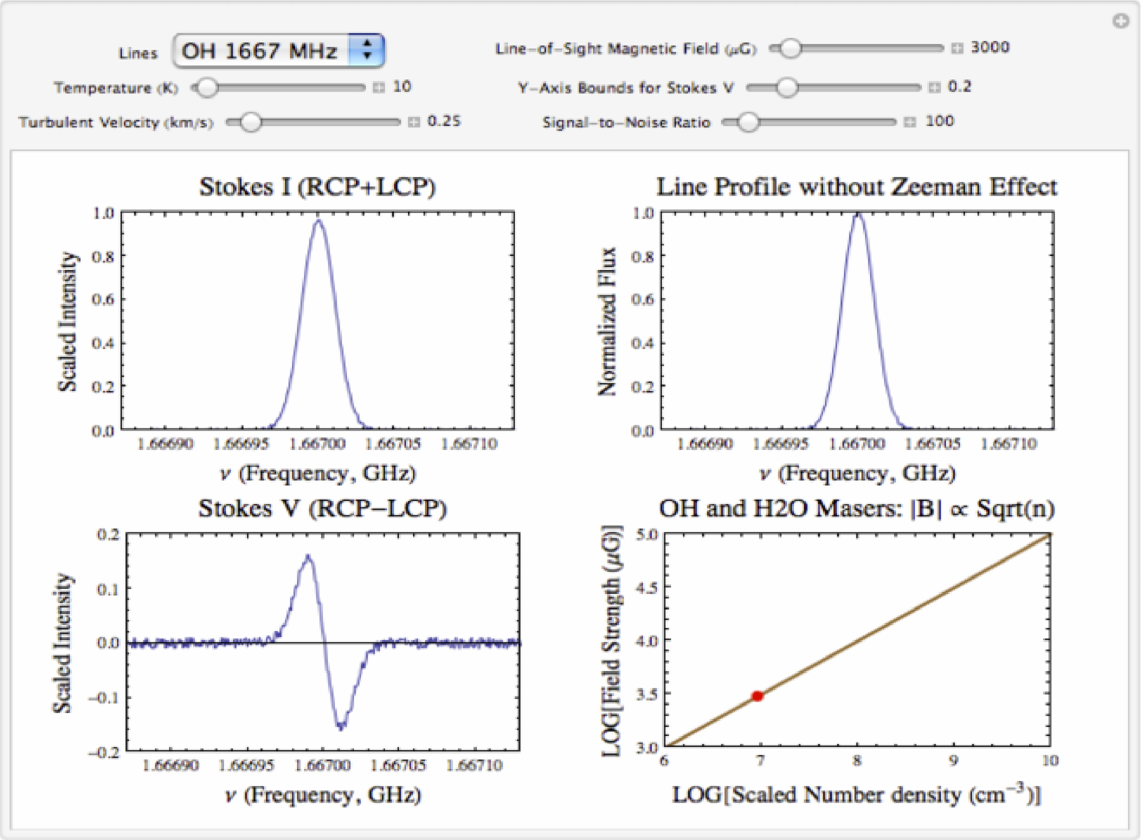
In Table 1, the density nH is representative of the density of the environment in which each species is observable. Note that every one of the lines recorded, which are the best possibility for distinguishing Zeeman splitting, all have frequencies of 22 GHz or lower, which implies long frequency perceptions (noticeable light has frequencies on the request for 500 THz). The conditions that can deliver quantifiable Zeeman effects are denser than a significant part of the ISM. The external pieces of sub-atomic mists are followed by abundance 21-cm emanation for HI and have densities of two or three hundred particles for every cubic centimeter. Goodness is found in atomic mists and is perceptible for densities up to 2500 cm-3. Zeeman splitting in OH outflow has additionally been seen in masers with solid magnetic fields. Hyperfine progress lines of H2O are additionally found in masers (Elitzur, 1992).

In these incredibly high thickness masers, the magnetic field can be sufficiently able to traditionally part the spectral line and the complete magnetic field strength can be noticed similarly concerning sun based magnetograms. In any case, the magnetic fields regularly saw in the interstellar medium in sub-atomic mists are low enough that the splitting of the spectral line isn't sufficiently extraordinary to create a quantifiable effect. For this situation, spectators should go to Stokes boundaries. Right roundabout polarization and left round polarization of spectral lines can be estimated independently; the amount of these is known as the Stokes I boundary and the thing that matters is known as the Stokes V boundary. With no magnetic field present, the Stokes V range ought to be a level line. Be that as it may, if a magnetic field is available, the "V-range" can be fit by the subordinate of the "I-range" scaled up by the strength of the magnetic field along the view as follows: V = (ΔvZ dI/dv) (Heiles, Goodman, McKee, and Zweibel, 1993; Sarma, Brogan, Bourke, Eftimova, and Troland, 2013). The intuitive module I present in this paper plots these Stokes boundaries as stargazers notice them.

3. The Interactive Module

The module I have made to assist understudies with exploring the Zeeman effect has been written in Mathematica, changed over to a Computational Document Format (CDF), and uses free programming from Wolfram to run and utilize. This product, the Wolfram CDF Player can be downloaded at www.wolfram.com/cdf-player/. The module has a few alternatives that the client can change. They are viewed as a draw down menu and five slider bars in Figure 1:

- Lines: the client can pick a spectral line from the rundown introduced in Table 1.
- Temperature: a more smoking climate creates thermally widened spectral lines.
- Turbulent Velocity: disturbance adds non-warm Doppler widening to spectral lines.
- Line-of-Sight Magnetic Field: this is the thing that delivers the Zeeman splitting.
- Y-hub Bounds for Stokes V: the extent of the Zeeman effect ranges relying upon inputs, so this permits the client to "zoom in" to a reach where the effect is detectable.
- Signal-to-Noise Ratio: longer perceptions on a telescope produce a higher sign to-clamor, so the openness time we need to see a reasonable sign for given data sources may contrast, and this mimics the observational imperative.



Lines: OH 1667 MHz
Temperature (K): 10
Turbulent Velocity (km/s): 0.25
Line-of-Sight Magnetic Field (μG): 3000
Y-Axis Bounds for Stokes V: 0.2
Signal-to-Noise Ratio: 100

Figure 1: A screenshot of the complete interactive module.

The module plots Stokes I and Stokes V, discussed in the previous section. There is additionally a plot of the line profile without Zeeman effect, which is intended to give a benchmark to examination with the Stokes I boundary. On the off chance that there is no magnetic field, the main two plots (Stokes I and line profile without Zeeman effect) will be indistinguishable, and the Stokes V line will be level. The motion is standardized to top at a unitless estimation of 1 since we have not made any suspicions about the source brilliance and distance or the telescope utilized. These subtleties are past the extent of this module and are not important to comprehend the Zeeman effect from an overall perspective.

The last plot addresses an unpleasant thought of how the magnetic field strength is identified with the thickness of OH and H2O masers. Perceptions demonstrate a feeble proportionality of the greatness of view magnetic field strength with the square foundation of nH (Crutcher, 2010). The connection emerges from the effect of transition freeze-in, where magnetic field lines are hauled along by the thick medium over a limit thickness. This should fill in as a decent beginning stage to begin playing with the module and finding the trouble of mentioning diverse observable facts of the magnetic field in the interstellar medium. To give extra direction, Table 2 records commonplace estimations of designs in the ISM. The turbulent velocity is approximated by σv ~ 1.1 (L [pc])0.38 km/s (Larson, 1981).

Table 2: Typical Properties of Structures in the ISM

Region	Size, L (pc)	Density, n (cm^{-3})	Temperature (K)	σ_v (km/s)
Giant Molecular Cloud	100	100	50	0.5
Dark Cloud	10	1000	20	0.3
Core	0.3	10000	10	0.2

Students can use the module to experiment with similar values in the interactive module to get a sense of how difficult observations of the Zeeman Effect in the interstellar medium can be. The ISM has magnetic field strengths that typically range from 1 microgauss to tens of milligauss (0.1 nT to several hundred nT). Here are not many model circumstances that understudies may examine independently or during a short homeroom examination, however there are various employments of this module past these inquiries.

- A typical Giant Molecular Cloud (GMC) may be 100 pc across, with a normal temperature of 50 K (- 370 degrees Fahrenheit!) and fierce speed of generally 0.4 km/s (900 mph!). In the event that view magnetic fields are estimated to be on the request for 200 microgauss by noticing impartial hydrogen's 21-cm line, what is the proportion between top power of Stokes V to Stokes I?

- Astronomers set out to notice the OH 1665 MHz line in a maser. On the off chance that the temperature is 300 K (commonplace room temperature on Earth, generally hot for the interstellar medium) and there is no disturbance, at what magnetic field strength would we be able to recognize two totally separate spectral lines in the Stokes I range? Consider the possibility that the tempestuous speed were 0.5 km/s. Consider the possibility that the fierce speed were pretty much as high as 1 km/s.
- Let's perceive how troublesome utilizing the Water line at 22 GHz is for estimating the Zeeman effect. Play around with the five sliding controls until you have the most clear Stokes V sign. What were your qualities? Clarify the effect of changing every slider on the sign you notice.

Understudies should observe the general power of the Stokes V to the Stokes I and the measure of sign to-commotion needed for a reasonable sign in the Stokes V. Districts of the ISM where such perceptions are conceivable make up just a little part of the complete volume. This module can along these lines give understudies a feeling of the challenges looked in perceptions contrasted with the reasonable and clear hypothesis they learn in classes. For cutting edge understudies, the module can likewise be utilized to replicate logical outcomes by deciding the magnetic field strength of a particular area dependent on the state of a deliberate sign and the related ecological properties.

4. Applications of Zeeman effect

Astrophysics

George Ellery Hale was the first to notice the Zeeman effect in the solar spectra, indicating the existence of strong magnetic fields in sunspots. Such fields can be quite high, on the order of 0.1 tesla or higher. Today, the Zeeman effect is used to produce magnetograms showing the variation of magnetic field on the sun.

Laser cooling

The Zeeman effect is utilized in many laser cooling applications such as a magneto-optical trap and the Zeeman slower.

Zeeman-energy mediated coupling of spin and orbital motions

Spin-orbit interaction in crystals is usually attributed to coupling of Pauli matrices to electron momentum which exists even in the absence of magnetic field . However, under the conditions of the Zeeman effect, when a similar interaction can be achieved by coupling to the electron coordinate through the spatially inhomogeneous Zeeman Hamiltonian.

5. Conclusion

The creator has examined an intuitive module that exhibits the Zeeman effect, one of only a handful few different ways that space experts can quantify the strength and bearing of magnetic fields in the interstellar medium. The module is an effective path for understudies to comprehend both the manners in which that magnetic field can be estimated and the strategies that researchers use to find out about the interstellar medium. It can undoubtedly enlarge study hall talks and undergrad labs in spectroscopy. The module was made utilizing Mathematica and the amazing Computing Document Format (CDF) from Wolfram, which can be perused with free programming (Wolfram CDF Player). This module is accessible on the web. While the creator trust the particular module introduced in the paper can discover progressing utilizes in cosmology courses, the creator additionally need this module to fill in to act as an illustration of the capacities of CDF. For understudies alright with Mathematica, the Wolfram Demonstrations Project is an amazing asset for learning modules and can be utilized for in-class projects, which was the root of the module introduced here.

References

[1] Sarma, A. P., Brogan, C. L., Bourke, T. L., Eftimova, M., & Troland, T. H. (2013). VLA OH Zeeman observations of the star forming region S88B. Astrophysical Journal. 767(1).

[2] Woolsey, L. N., & Cranmer, S. R. (2014). Turbulence-driven Coronal Heating and Improvements to Empirical Forecasting of the Solar Wind. Astrophysical Journal. 787(2), 160.

[3] Weiman, C. E., Adams, W. K., & Perkins, K. K. (2008). PhET: Simulations that enhance learning. Science, 322(5902), 682- 683.

[4] Oppermann, N., Junklewitz, H., Robbers, G., et al. (2012). An improved map of the Galactic Faraday sky. Astronomy and Astrophysics. 542, A93.

[5] Blue, J., Bayram, S. B., & Marcum, S. D. (2010). Creating, implementing, and sustaining an advanced optical spectroscopy laboratory course. American Journal of Physics, 78(5), 503-509.

[6] Ratcliff, S. J., Noss, D. K., Dunham, J. S., Anthony, E. B., Cooley, J. H., & Alvarez, A. (1992). High-resolution solar spectroscopy in the undergraduate physics laboratory. American Journal of Physics, 60(7), 645-649.

[7] Heiles, C., Goodman, A. A., McKee, C. F., & Zweibel, E. G. (1993). Magnetic fields in star-forming regions: Observations. Protostars and Planets III. University of Arizona Press.

[8] Woolsey, L. (2013) The Zeeman Effect in the Interstellar Medium. Wolfram Demonstrations Project. Retrieved from http://demonstrations.wolfram.com/TheZeemanEffectInTheInterstellar Medium.

[9] Crutcher, R. M. (2010). Magnetic Fields in Interstellar Clouds from Zeeman Observations: Inference of Total Field Strengths by Bayesian Analysis. Astrophysical Journal. 725(1), 466-479.

[10] Dori, Y. J., Hult, E., Breslow, L., & Belcher, J. W. (2007). How Much Have They Retained? Making Unseen Concepts Seen in a Freshman Electromagnetism Course at MIT. Journal of Science Education and Technology, 16(4), 299-323.

[11] Larson, R. B. (1981). Turbulence and star formation in molecular clouds. Monthly Notices of the Royal Astronomical Society. 194, 809-826.

[12] Olson, A. J. & Mayer, S. K. (2009). Electromagnetically induced transparency in rubidum. American Journal of Physics, 77, 116-121.