

Quadratic Zeeman effect in hydrogen at 2–3 MG magnetic fields

V. V. Ivanov¹, R. C. Mancini¹, N. A. Huerta¹, K. J. Swanson¹, D. E. Winget², M. H. Montgomery²,
I. E. Golovkin³, H. K. Hariharan¹, and Z. S. Berbel²

¹*Department of Physics, University of Nevada, Reno, Nevada 89557, USA*

²*Department of Astronomy, University of Texas, Austin, Texas 78712, USA*

³*Prism Computational Sciences, Madison, Wisconsin 53711, USA*



(Received 1 April 2022; accepted 23 September 2022; published 19 October 2022)

The Zeeman effect is used for measurement of magnetic fields in astrophysical and laboratory plasmas. Magnetic fields in atmospheres of magnetic white dwarf stars are in the range 40 kG–1 GG. The quadratic Zeeman effect results in the additional split and shift of lines for magnetic fields >2 MG. Hydrogen Balmer lines were studied in magnetic fields delivered by a 1 MA pulse power generator. The magnetic field was generated by rod loads 0.8–1 mm in diameter. A droplet of CH oil on the load center was the source of hydrogen. A low ionized oil layer was backlit by blackbody emission from the rod with a temperature of 0.5–0.6 eV. Zeeman splitting of H -alpha and H -beta absorption lines were with a grating spectrometer. A spectral shift of the central component of the triplet indicated the quadratic Zeeman effect in hydrogen lines.

DOI: [10.1103/PhysRevE.106.045206](https://doi.org/10.1103/PhysRevE.106.045206)

I. INTRODUCTION

Plasma in strong magnetic fields is the object of research in many fields of basic and applied plasma physics as well as astrophysics. Magnetic fields confine fusion plasma in tokamaks and can improve conditions for inertial confinement fusion [1]. Heat trapping due to a strong magnetic field plays a key role in the magnetized liner inertial fusion concept [2]. Magnetic fields significantly change the dynamics of plasma expansion and formation of plasma jets and disks [3–6]. Furthermore, laboratory magnetized plasmas can be scaled to plasmas in astrophysical objects [4,7].

For a long time, the Zeeman effect was the main spectroscopic feature of plasma in a magnetic field. The Zeeman effect has been used for measurements of magnetic fields in Z pinches and liners. Zeeman splitting of emission lines in Na indicated a 2 MG field in liners on the Z machine [8]. The Zeeman effect in indium emission lines was observed in a 5 MG field during the compression of the magnetic flux [9]. The quadratic Zeeman effect appears in hydrogen lines in strong magnetic fields, $B > 2$ MG. The quadratic effect results in the additional fine splitting and spectral shift of Zeeman π and σ components of $H\alpha$ and $H\beta$ triplets [10,11]. Modeling has extended the region of magnetic fields for the Zeeman effect to 1 GG [12], but laboratory plasma experiments were limited by the linear Zeeman effect.

The Zeeman effect has been used to identify magnetic fields in stars via spectroscopy since the beginning of the 20th century [13]. Stellar objects vary widely in magnetic field strength, from the kilogauss level in solar plasmas to the gigagauss level in magnetars. White dwarf stars (WDs) are of particular interest since they are the evolutionary end point of $>97\%$ of all stars, and they often have measurable magnetic fields: Liebert *et al.* [14] found that at least 10%

of WDs have strong magnetic fields over 2 MG, and Ferrario *et al.* [15] found that of the isolated WDs, $13 \pm 4\%$ fall into this high-field regime with magnetic fields from 0.1 MG to 1 GG. In addition, Bagnulo and Landstreet [16] found that the overall incidence of these magnetic WDs is even higher, with 20–25% of all WDs containing fields from 40 kG to 300 MG. Finally, 36% of cataclysmic variable systems (systems in which a WD accretes material from a main sequence binary companion star) contain a magnetic WD with MG fields [17].

WDs with magnetic fields are observed to have systematically higher masses than their nonmagnetic counterparts [18]. This and other evidence suggest that magnetic WDs may be formed through the merger of a WD and another star, with the system passing through a common envelope and/or accretion disk phase. This would naturally account for both their higher masses compared to nonmagnetic WDs as well as their observed MG magnetic fields, though this may not be the only mechanism by which strong magnetic fields can form [17,19].

The masses of magnetic WDs are determined by fitting their spectral lines, and these lines are themselves altered by the presence of a magnetic field. Since $\sim 80\%$ of WDs have hydrogen atmospheres, fits to the Balmer series are used to obtain the temperatures and masses of these stars [20]. Models employed in the fits have been developed from a best theory effort. In order to obtain more reliable temperature and mass determinations from spectroscopic fits, the theoretical treatment of these lines in magnetized dense plasmas needs to be tested and validated. The latter necessitates benchmark laboratory experiments with hydrogen at MG-level magnetic fields where experimentally obtained hydrogen absorption lines can be compared with theory calculations of the absorption lines in the atmospheres of magnetic WDs.

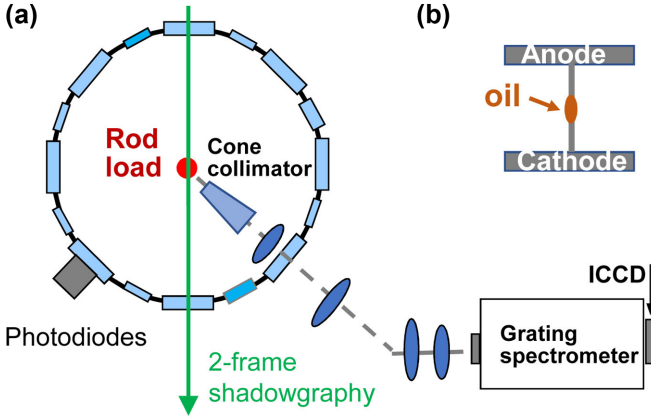


FIG. 1. (a) Vacuum chamber, beam path, and grating spectrometer. (b) A rod load between anode and cathode electrodes.

In this paper, we investigated the linear and quadratic Zeeman effects in hydrogen at magnetic fields of 2–3 MG in a laboratory setting. The Zeeman split was studied in hydrogen Balmer absorption lines in magnetic fields generated by rod loads. A spectral shift measured for the central π component due to the quadratic Zeeman effect was in agreement with theory predictions.

II. EXPERIMENTAL SETUP

The 1 MA Zebra pulsed power generator at the University of Nevada, Reno was used for these quadratic Zeeman effect experiments. A Zebra machine generates a current pulse with a 1 MA amplitude and 80 ns rising edge (10–90%). As well, the Zebra machine can produce strong longitudinal and transverse magnetic fields in coil and rod loads [21]. The magnetic field reaches values of 2–4 MG on the surface of the metal rod loads 0.8–1 mm in diameter. A thin plasma layer arises on the surface at the 30–90% level of the maximum current depending on the rod diameter and material [22]. This surface plasma is confined by the strong magnetic field and slowly expands with a velocity of ~ 3 km/s. The Doppler spectral shift < 0.1 Å is negligible for our experiments. The magnetic field from the load is characterized using Faraday rotation diagnostics and B -dot sensors [23].

The blackbody temperature of the surface of the rod load during the current pulse is 0.4–3 eV. The temperature depends on the rod diameter, material, and a value of current. Photodiodes filtered by narrow-band interference filters at three wavelengths are used to monitor the temperature of the load surface. A droplet of CH oil on the load is used as a source of hydrogen. A thin layer of oil is evaporated and heated on the load surface. The external oil layer stays in a liquid and transparent state during the current pulse. Blackbody emission from the load backlights hydrogen atoms in the evaporated layer. Balmer absorption lines are seen on the blackbody spectra of the load emission.

Figure 1(a) schematically shows the Zebra vacuum chamber with a load, an optical beam path, and a grating spectrometer with two gratings, 1200 and 2400 1/mm. The rod load, 2 cm tall, is installed in the center of the chamber. A cone collimator selects emission only from the center of

the load covered with oil, and a four-lens optical beam path relays emission from the load center to the 50 μm slit of the spectrometer. The rod load between anode and cathode with the oil droplet is shown in Fig. 1(b).

An intensified charge coupled device (ICCD) camera with a matrix of $1\text{ K} \times 1\text{ K}$ pixels and microchannel plate (MCP) was used as a sensor of the grating spectrometer. A 3–6 ns gate of MCP provided temporal resolution of spectral measurements on the 80 ns rising edge of the current pulse. Dispersion of the spectrometer with the ICCD sensor measured at the wavelength of the $H\alpha$ line was -0.4 Å/pixel (px) with the 1200 1/mm grating and -0.16 Å/px with the 2400 1/mm grating. Spectral ranges were 400 and 160 Å for two gratings, respectively. Neon, xenon, and hydrogen lamps were used for spectral calibration in the ranges near $H\alpha$ and $H\beta$ lines at wavelengths of 656 and 486 nm.

The diameter and material of the rod loads were varied to reach the highest magnetic field before the intense evaporation of the load material. Simulations with PRISMSPECT [24] showed that the optimal temperature of hydrogen is in the range 0.5–0.6 eV because the linewidth strongly increases at the temperature > 0.7 eV. Line absorption drops below the noise at temperatures < 0.4 eV. Some materials like titanium and stainless steel were not used due to strong absorption lines generated in the range near $H\alpha$ and $H\beta$ hydrogen lines.

III. ZEEMAN EFFECT AT 2–3 MG MAGNETIC FIELDS

The quadratic Zeeman effect results in the fine splitting and spectral shift of components of Zeeman triplets in magnetic fields > 2 MG. A theoretical approach to the Zeeman effect in MG magnetic fields was presented in reviews [10,12]. For Balmer transition $2S-nP$, the center of mass of the line averaged over π and σ components is shifted to short wavelengths due to the quadratic Zeeman effect [12]:

$$\delta\lambda_Q(2S) = -1.73 \left(\frac{\lambda}{4101\text{Å}} \right)^2 \left(\frac{B}{10^6\text{G}} \right)^2 \left(\frac{n_{\text{up}}}{6} \right)^4 A,$$

where λ is a wavelength, B is the magnetic field, and n_{up} is the upper principal quantum number. The shifts are smaller, $\sim 40\%$ for $2P-nS$ and $2P-nD$ transitions. A detailed table of the quadratic splitting with quantum numbers for transitions is presented in [10].

A series of shots was performed to confirm the viability of experimental methods and diagnostic capability for the observation of the Zeeman effect in MG magnetic fields. Aluminum rod loads, 1 mm in diameter, provided conditions suitable for observation of the $H\alpha$ line for current up to 0.8 MA. Polarization and intensity of the Zeeman components depend on the direction of the magnetic field vector [25]. σ components are too wide and weak for circular cross section loads with azimuthal magnetic fields. A flat center of the load was employed to enhance visibility of the σ components of the Zeeman triplet. The magnetic field was enhanced along the line of sight. This configuration also decreased spanning in a large range of field strengths in cylindrical loads.

Figure 2(a) presents absorption Zeeman spectra from four shots with Al loads at current of 0.78 MA. Spectra fade at higher current due to the fast evaporation of the load material. Spectra in Fig. 2 were recorded with a 1200 1/mm grating,

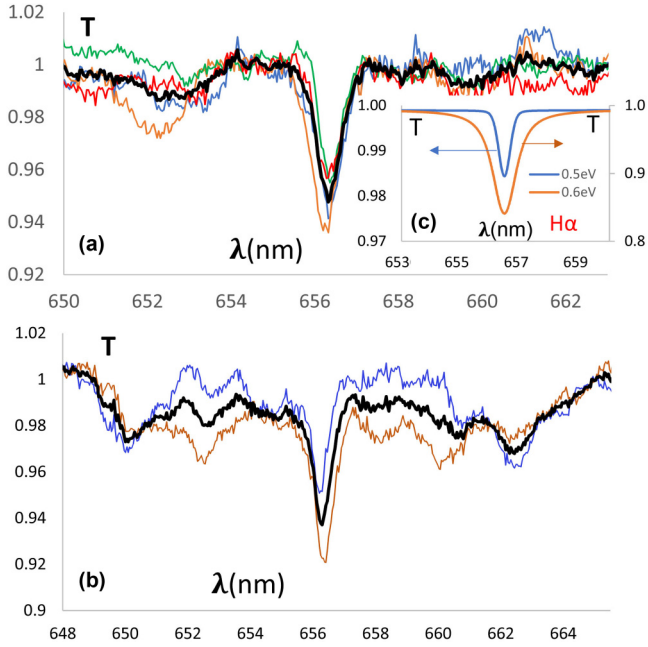


FIG. 2. (a) $H\alpha$ Zeeman triplets from four shots with Al loads 1 mm in diameter. (b) Zeeman triplets from two shots with Cu loads 0.9 mm in diameter. (c) PRISMSPECT simulations of transmission of the $H\alpha$ line at 0.5 and 0.6 eV.

which were calibrated with spectral lamps. Color lines show spectra taken from several shots. Averaging of shots is shown in black and clearly shows a central π component near 656 nm and two wide σ “wings” of the $H\alpha$ Zeeman triplet. Wings are wide compared to the central part due to the strength of components of the B field varying on the load. Zeeman σ components are shifted by 3.8–3.9 nm from the π component to the centers of wings. The magnetic field B can be calculated from the spectral split using a Paschen-Back formula $E = E_0 \pm \mu_B B$, where μ_B is the Bohr magneton and E is the energy level. The magnetic field is $B = 1.9 \pm 0.1$ MG. An additional quadratic shift of σ components is 0.07 nm at 2 MG magnetic fields [11]. Values of magnetic fields taken from the Zeeman splitting agree with measurements of the magnetic field by Faraday rotation and B -dot diagnostics with uncertainty of 5–8%. A shift and width of σ components are measured with an error due to small absorption and shot-to-shot variation of the machine. σ components were not used for further precision measurements. We note that the value of the split represents a value of the local magnetic field seen by hydrogen atoms compared to the integrated magnetic fields taken at the distance from the load with Faraday and B -dot diagnostics.

Figure 2(b) shows $H\alpha$ spectra taken from two shots with Cu loads 0.9 mm in diameter. These loads allow measurements of the Zeeman effect near the maximum of the current pulse. The Zeeman split ~ 6.2 nm in Fig. 2(b) corresponds to the local magnetic field of ~ 3 MG.

Absorption of the central line in Fig. 2 is 5–7% and a linewidth is 0.5–0.7 nm. These parameters of the absorption line are in agreement with PRISMSPECT simulations for hydrogen without magnetic fields with an electron temperature

of 0.5–0.6 eV, density of 10 mg/cm³, and width of the layer of 0.3 mm as shown in Fig. 2(c), and broadens at higher densities. $H\beta$ Zeeman triplets were also observed with Al loads but with weaker absorption. Uncertainties of measurements in Fig. 2 do not allow identification of the quadratic Zeeman effect. Due to small intensities and the large width, σ components cannot be used for precision measurements of the quadratic effect. Apparatus and procedures were improved for investigation of the quadratic effect as shown in the next section.

IV. QUADRATIC ZEEMAN EFFECT

Atomic simulations for hydrogen atoms in strong magnetic fields show that the quadratic Zeeman effect produces an additional fine splitting of lines of the Zeeman triplet and spectral shifts of the π and σ components of $H\alpha$ and $H\beta$ triplets [10,11]. Fine structure of the additional split cannot be resolved in our case. These splitting results in a broadening of the central π line and σ components. The σ components are wide and their absorption is low. The width of the central component includes contributions of temperature and instrumental broadenings. The most promising method to identify the quadratic effect is measuring the spectral shift of the central π line to the shorter wavelength. The spectral shift of the center of mass for hydrogen $H\alpha$ and $H\beta$ Zeeman lines in the magnetic field of 1–5 MG has been calculated by [11]. For example, the shift of the $H\alpha$ central line is expected to be 0.36 Å at $B = 2$ MG. The spectral shift is higher for the $H\beta$ transition at the wavelength of 486 nm, 0.97 Å at the same $B = 2$ MG. The $H\beta$ line has a weaker absorption compared to the $H\alpha$ line due to the smaller oscillator strength for this transition.

Apparatus and procedures were improved to provide higher accuracy and reproducibility of spectral measurements. The spectrometer and ICCD camera were protected against shocks and vibration during operations. A 2400 l/mm grating was used for investigation of the quadratic Zeeman effect. The spectral shift of the minimum of $H\alpha$ or $H\beta$ absorption lines in the magnetic field was compared to the peak of reference $H\alpha$ or $H\beta$ emission lines taken from the hydrogen spectral lamp as shown in Fig. 3. Reference $H\alpha$ and $H\beta$ lines were

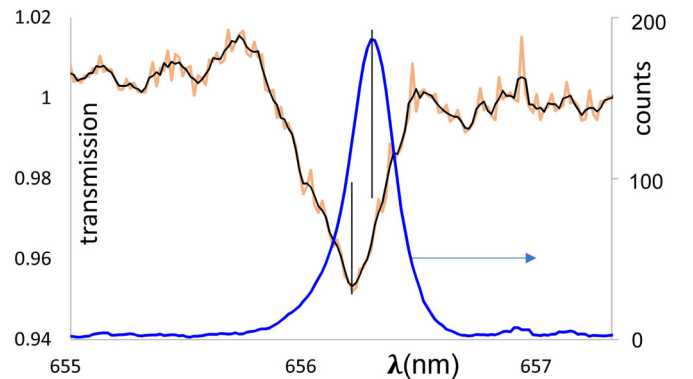


FIG. 3. The blue line is a $H\alpha$ emission reference line from the hydrogen lamp. The red line is an absorption line from hydrogen in the magnetic field of the rod load with the average as the black line.

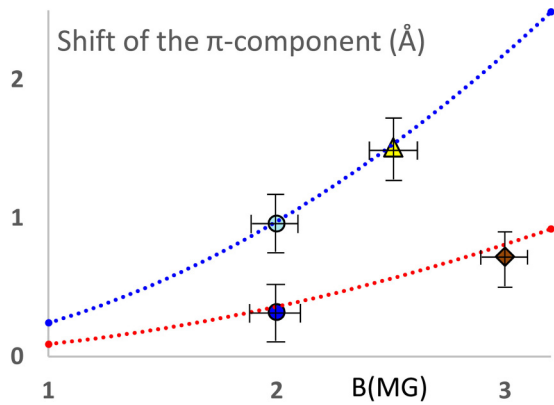


FIG. 4. Dotted lines present calculations of Surmelian and O’Connell [11] of the spectral shift of $H\alpha$ (red line) and $H\beta$ (blue line) central component due to the quadratic Zeeman effect. Experimental points are taken with Al 1 mm loads (circles), Au 1 mm loads (triangle), and Cu 0.9 mm loads (diamond).

recorded right before every shot with the load and magnetic field. The width of reference hydrogen lines was 12–14 pixels, but the peaks of the lines were reproducible with accuracy of 0.5 pixels. The optical beam path was tested with a hydrogen lamp installed in the vacuum chamber on the load position. Accuracy of the spectral shift measurement was better than 1 pixel of the ICCD camera.

We used Al 99.9% rod loads, 1 mm in diameter, at current values of 0.78 MA when the magnetic field was 1.9 MG. Cu 99.99% rod loads, 0.9 mm in diameter, allowed generation of 3 MG fields near the maximum of the current pulse. Copper loads were used for $H\alpha$ line at the wavelength of 6562.8 Å but were not used for the $H\beta$ line because of Cu spectral lines generated near 4862 Å. Au 99.99% rod loads 1 mm in diameter provided 2.5 MG magnetic fields. Au loads generate a strong line at 6562.8 Å but can still be used in the range near the $H\beta$ line. Figures 3 and 4 show results of experiments with these loads. The wavelength of the absorption peak was measured as seen in Fig. 3. The experimental points in Fig. 4 are the laboratory measurements of the quadratic Zeeman effect in hydrogen $H\alpha$ and $H\beta$ lines for magnetic fields of 2–3 MG. Experimental points are placed on dotted lines taken from calculations of [11] for the quadratic Zeeman shift. The dotted lines interpolate calculations for $H\alpha$ and $H\beta$ lines at 1, 2, 3.2, and 5 MG. The diamond marker presents an average value for three shots with Cu loads 0.9 mm in diameter. The triangle marker shows the average for two shots with 1 mm Au loads. Circles represent shots with 1 mm Al loads. The filled circle presents one shot at the $H\alpha$ wavelength. The open circle represents the average of two shots at the $H\beta$

wavelength. Variations of magnetic fields are due to the shot to shot reproducibility of the current pulse on the load. Experimental points are in agreement with interpolated lines.

V. CONCLUSIONS

The quadratic Zeeman effect in hydrogen at magnetic fields of 2–3 MG was studied in a laboratory. An experimental platform based on the 1 MA Zebra pulsed power machine allowed for investigation of plasmas at 1–3 MG magnetic fields. A layer of oil on the rod load was employed as the source of hydrogen. Rod loads generated MG magnetic fields, populated the second level of hydrogen, and backlit hydrogen atoms. We optimized load materials, load diameters, and current in the load and found a regime appropriate for the observation of hydrogen Balmer absorption lines.

Absorption in hydrogen $H\alpha$ central π line is 3–5%. The spectral shift of σ components in the $H\alpha$ Zeeman triplet indicates magnetic fields in the range 2–3 MG in Al, Au, and Cu loads. These values are in agreement with other diagnostics. The width of the central π component of the $H\alpha$ Zeeman triplet is 0.5–0.7 nm. The absorption π line was used for measuring the spectral shift of the line peak due to the quadratic Zeeman effect. The spectral shift of $H\alpha$ and $H\beta$ absorption lines in magnetic fields was measured compared to the reference $H\alpha$ and $H\beta$ emission lines from the hydrogen spectral lamp. The experimental spectral shifts are in agreement with calculations of the quadratic Zeeman effect for these hydrogen lines in this range of magnetic fields.

The influence of the quadratic Zeeman effect in the range 2–3 MG fields can be found in hydrogen spectra of atmospheres of magnetic white dwarf stars if measured and analyzed with high spectral resolution. We note that carbon absorption lines are seen in atmospheres of some magnetic white dwarf stars [26]. Carbon lines can be investigated in the laboratory with the same technique in future experiments.

ACKNOWLEDGMENTS

The authors thank the team of the Zebra generator at UNR for help with experiments. This work was supported by the DOE NNSA under Award No. DE-NA0003991, and partly by NSF Award No. PHY-1903355 through the NSF-DOE Partnership in Basic Plasma Science and Engineering. D.E.W., M.H.M., and Z.S.B. acknowledge support from the Wootton Center for Astrophysical Plasma Properties under U.S. Department of Energy Cooperative Agreement No. DE-NA0003843, and the National Science Foundation under Grant No. AST 1707419.

- [1] P. Y. Chang, G. Fiksel, M. Hohenberger, J. P. Knauer, R. Betti, F. J. Marshall, D. D. Meyerhofer, F. H. Séguin, and R. D. Petrasso, *Phys. Rev. Lett.* **107**, 035006 (2011).
- [2] S. A. Slutz and R. A. Vesey, *Phys. Rev. Lett.* **108**, 025003 (2012).
- [3] V. V. Ivanov, A. V. Maximov, R. Betti, P. P. Wiewior, P. Hakel, and M. E. Sherrill, *Plasma Phys. Control. Fusion* **59**, 085008 (2017).

- [4] B. Albertazzi, A. Ciardi, M. Nakatsutsumi, T. Vinci, J. Béard, R. Bonito, J. Billette, M. Borghesi, Z. Burkley, S. N. Chen *et al.*, *Science* **346**, 325 (2014).
- [5] R. Presura, V. V. Ivanov, Y. Sentoku, V. I. Sotnikov, P. J. Laca, N. Le, Galloudec, A. Kemp, R. Mancini, H. Ruhl, A. L. Astanovitskiy *et al.*, *Astrophys. Space Sci.* **298**, 299 (2005).
- [6] V. V. Ivanov, A. V. Maximov, R. Betti, L. Leal, R. C. Mancini, K. J. Swanson, I. Golovkin, C. J. Fontes,

- H. Sawada, A. B. Sefkow *et al.*, *Phys. Plasmas* **26**, 062707 (2019).
- [7] R. E. Falcon, G. A. Rochau, J. E. Bailey, T. A. Gomez, M. H. Montgomery, D. E. Winget, and T. Nagayama, *Astrophys. J.* **805**, 214 (2015).
- [8] M. R. Gomez, S. B. Hansen, K. J. Peterson, D. E. Bliss, A. L. Carlson, D. C. Lamppa, D. G. Schroen, and G. A. Rochau, *Rev. Sci. Instrum.* **85**, 11E609 (2014).
- [9] W. B. Garn, R. S. Caird, D. B. Thomson, and C. M. Fowler, *Rev. Sci. Instrum.* **37**, 762 (1966).
- [10] R. H. Garstang, *Rep. Prog. Phys.* **40**, 106 (1977).
- [11] G. L. Surmelian and R. F. O’Connell, *Astrophys. J.* **193**, 705 (1974).
- [12] D. T. Wickramasinghe and L. Ferrario, *Astron. Soc. Pac. Conf. Ser.* **112**, 873 (2000).
- [13] G. E. Hale, *Astrophys. J.* **28**, 315 (1908).
- [14] J. Liebert, P. Bergeron, and J. B. Holberg, *Astrophys. J.* **125**, 348 (2003).
- [15] L. Ferrario, D. T. Wickramasinghe, and A. Kawka, *Adv. Space Res.* **66**, 1025 (2020).
- [16] S. Bagnulo and J. D. Landstreet, *Mon. Not. R. Astron. Soc.* **507**, 5902 (2021).
- [17] A. F. Pala, B. T. Gänsicke, E. Breedt, C. Knigge, J. J. Hermes, N. P. Gentile Fusillo, M. A. Hollands, T. Naylor, I. Pelisoli, M. R. Schreiber *et al.*, *Mon. Not. R. Astron. Soc.* **494**, 3799 (2020).
- [18] J. McCleery, P. E. Tremblay, N. P. G. Fusillo, M. A. Hollands, B. T. Gänsicke, P. Izquierdo, S. Toonen, T. Cunningham, and A. Rebassa-Mansergas, *Mon. Not. R. Astron. Soc.* **499**, 1890 (2020).
- [19] D. Stello, M. Cantiello, J. Fuller, D. Huber, R. A. García, T. R. Bedding, L. Bildsten, and V. S. Aguirre, *Nature (London)* **529**, 364 (2016).
- [20] A. Raji, J. Rosato, R. Stamm, and Y. Marandet, *Eur. Phys. J. D* **75**, 63 (2021).
- [21] V. V. Ivanov, A. V. Maximov, R. Betti, L. S. Leal, J. D. Moody, K. J. Swanson, and N. A. Huerta, *Matter Radiat. Extremes* **6**, 046901 (2021).
- [22] K. C. Yates, B. S. Bauer, S. Fuelling, T. J. Awe, T. M. Hutchinson, V. V. Ivanov, J. Mei, and R. S. Bauer, *Phys. Plasmas* **26**, 042708 (2019).
- [23] V. V. Ivanov, K. J. Swanson, G. S. Sarkisov, A. V. Maximov, P. Wiewior, A. Astanovitskiy, V. Nalajala, O. Chalyy, O. Dmitriev, and N. Wong, *Phys. Plasmas* **24**, 112707 (2017).
- [24] J. J. MacFarlane, I. E. Golovkin, P. Wang, P. R. Woodruff, and N. A. Pereyra, *High Energy Density Phys.* **3**, 181 (2007).
- [25] E. Landi Degl’Innocenti and M. Landolfi, in *Polarization in Spectral Lines, Astrophysics and Space Science Library* (Kluwer, Dordrecht, 2004), p. 307.
- [26] K. A. Williams, D. E. Winget, M. H. Montgomery, P. Dufour, S. O. Kepler, J. J. Hermes, R. E. Falcon, K. I. Winget, M. Bolte, K. H. R. Rubin *et al.*, *Astrophys. J.* **769**, 123 (2013).