UCRL-PROC-220911

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April 27, 2006

NASA Laboratory Astrophysics Workshop
Las Vegas, NV, United States
February 14, 2006 through February 16, 2006

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ABSTRACT

We discovered a class of lines that are sensitive to the strength of the ambient magnetic field, and present a measurement of such a line in Ar IX near 49 Å. Calculations show that the magnitude of field strengths that can be measured ranges from a few hundred gauss to several tens of kilogauss depending on the particular ion emitting the line.

1. Introduction

The emission from high-temperature plasmas, such as stellar coronae, is dominated by spectral lines in the EUV and soft X-ray range. These lines provide accurate information on temperature, density, and emission volume. So far, none of the lines has provided information on the strength of the ambient magnetic field, even though the fields may quite high. Magnetic field measurements using the Zeeman effect in optical lines (Zeeman 1897) from neutrals or singly charged ions reveal kilogauss fields in certain types of stars, and magnetospheric accretion models predict fields in excess of 10,000 gauss (Johns-Krull et al. 1999). Fields in cataclysmic variables may even achieve values of several megagauss. Instead of direct measurements, magnetic fields in high-temperature plasmas, which may play an important role for constraining evolutionary models of astrophysical objects, must be estimated rather imprecisely from equipartition arguments.

During the past years we have been engaged in laboratory measurements at the University of California Lawrence Livermore National Laboratory EBIT-I and SuperEBIT electron beam ion trap facility, which systematically have established catalogues of astrophysically relevant lines in the extreme ultraviolet. Our measurements, for example, have produced line lists of the $n \geq 3 \rightarrow 2$ L-shell transitions of Ar, S, and Si (Lepson et al. 2003, 2005; Lepson & Beiersdorfer 2005). These measurements have included a class of lines that are sensitive to the strength of the ambient magnetic field. In particular, the intensity of these lines increases as the magnetic field strength increases. As a result, the ratio of the intensity of this line to those of neighboring lines represents a diagnostic of the magnetic field strength.

The principle of our magnetic field diagnostic is based on the fact that the presence of a magnetic field spoils the spherical symmetry of the Coulomb potential, thereby removing the degeneracy of the magnetic sublevels and allowing mixing among sublevels associated with levels of different total angular momentum as long as they have the same magnetic quantum number and parity. Such mixing in many cases is irrelevant, as it typically is weak, and both levels are likely to have strong radiative decay channels. In other words, a few parts per million change in the radiative decay rates will hardly be noticeable given the present accuracy of calculations and measurements. However, if one of the levels has no or only a very weak radiative channel while the other has a strong channel, magnetic field mixing can result in the apportioning of a finite radiative rate and thus the appearance of a line that would otherwise not exist. The intensity of the new line depends on the mixing and thus on the magnetic field.

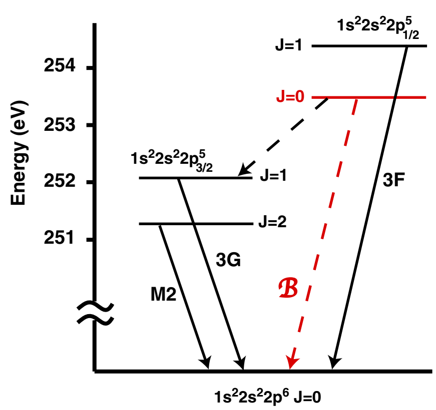

Fig. 1.— Grotrian diagram showing the lowest four excited levels in Ar IX. Transitions are labeled in common notation; the magnetic field sensitive line is labeled $\mathcal{B}$.

Levels with total angular momentum $J = 0$ are strictly forbidden to decay to another level with zero total angular momentum (in the absence of hyperfine structure). These levels, therefore, represent an ideal case to study magnetic-field induced transitions. A diagram of the four lowest levels in neonlike Ar IX is shown in Fig. 1. The two levels that are best suited for magnetic-field mixing are the $(1s^2 2s^2 2p^5_{1/2} 3s)_{J=0}$ $^3P_0$ level and the close-by $(1s^2 2s^2 2p^5_{1/2} 3s_{1/2})_{J=1}$ $^1P_1$ level. In the absence of an external field, the $^3P_0$ level exclusively decays via a magnetic dipole (M1) transition to the $(1s^2 2s^2 2p^5_{3/2})_{J=1}$ $^3P_1$ level, but because of the small energy separation does so only very weakly with a rate of 58 1/s. By contrast, the neighboring $(1s^2 2s^2 2p^5_{1/2} 3s_{1/2})_{J=1}$ $^1P_1$ level rapidly decays to the ground state via an electric-dipole transition, commonly labeled $3F$, at a rate of 1.4×10^{11} 1/s. Mixing with the $^1P_1$ level allows the $^3P_0$ level to decay to the $^1S_0$ ground state with a finite, albeit small, radiative rate. Although closeness is a prerequisite for mixing, the two levels are sufficiently far apart so that the presence of a line resulting from the magnetic field induced decay of the $^3P_0$ level can be observed and resolved from the decay of the neighboring $^1P_1$ level. We note that in strict LS-coupling such mixing would not be possible. However, mixing occurs because the triplet and singlet levels themselves are not pure states.

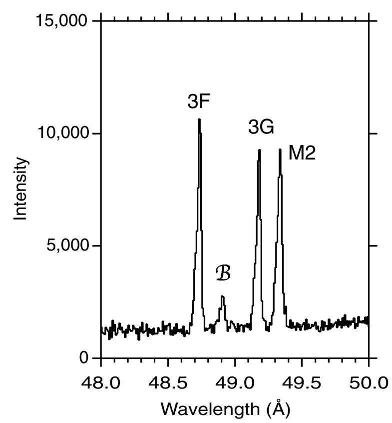

Fig. 2.— Spectrum of the Ar^{8+} $3s \rightarrow 2p$ emission obtained with the new high-resolution grating spectrometer. Lines are labeled in the same notation as in Fig. 1.

Our measurements were performed using the EBIT-I electron beam ion trap at the University of California Lawrence Livermore National Laboratory. Initial measurements utilized a broadband grazing-incidence spectrometer (Beiersdorfer et al. 2003). We have since implemented a very high-resolution grazing-incidence spectrometer based on a 44 m variable line spacing reflective grating (Beiersdorfer et al. 2004). This increased the resolving power by a factor of eight and clearly isolates the line produced by the presence of the magnetic field, as illustrated in Fig. 2.

The variation of the intensity of the field-induced line with magnetic field strength is shown in Fig. 3 for the three neonlike ions Si V, Ar IX, and Fe XVII. The figure shows that the line reaches 20 % of its final strength at 500 G in Si V, at 2500 G in Ar IX, and at about 25,000 G in Fe XVII. These ions thus cover a wide range of magnetic field strengths.

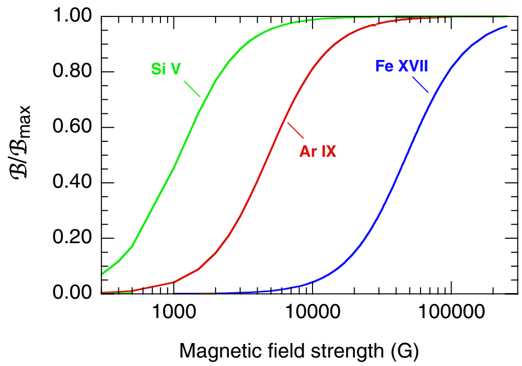

Fig. 3.— Intensity variation of the B line as a function of magnetic field strength in three astrophysically abundant neonlike ions.

This work was supported by NASA Astronomy and Physics Research and Analysis program work order NNH04AA751, and was performed under the auspices of the Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

REFERENCES

Beiersdorfer, P., Magee, E. W., Träbert, E., Chen, H., Lepson, J. K., Gu, M.-F., & Schmidt, M. 2004, Rev. Sci. Instrum., 75, 3723

Beiersdorfer, P., Scofield, J. H., & Osterheld, A. L. 2003, Phys. Rev. Lett., 90, 235003

Johns-Krull, C. M., Valenti, J. A., & Koresko, C. 1999, Astrophys. J., 516, 900

Kochukhov, O. P., Piskunov, N. E., Valenti, J. A., & Johns-Krull, C. M. 2001, in *Cool Stars, Stellar Systems and the Sun, Eleventh Cambridge Workshop*, Astronomical Society of the Pacific Conference Series Vol. 223, ed. by R. J. García López, R. Rebolo, and M. R. Zapatero Osorio (ASP, San Francisco, 2001), p. CD-985

Lepson, J. K. & Beiersdorfer, P. 2005, Phys. Scripta, T120, 62

Lepson, J. K., Beiersdorfer, P., Behar, E., & Kahn, S. M. 2003, Astrophys. J., 590, 604

—. 2005, Astrophys. J., 625, 1045

Zeeman, P. 1897, Phil. Mag., 43, 226