Stellar Collisions, Mergers and Their Consequences
ASP Conference Series, Vol. 263, 2002
Michael M. Shara, ed.

A Spectroscopic Search For Massive Thorne-Żytkow Objects

Marc J. Kuchner and David Vakil

Palomar Observatory, California Institute of Technology, Pasadena, CA 91125

Verne V. Smith

Department of Physics, University of Texas at El Paso, El Paso, TX 79968

David L. Lambert

Department of Astronomy, University of Texas at Austin, Austin, TX 78712

Bertrand Plez

Université de Montpellier II, 34095 Montpellier Cedex 5, France

E. Sterl Phinney

Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125

Abstract. Sometimes, in a collision or merger between a massive star and a neutron star, the neutron star might sink to the core of the massive star and form a Thorne-Zytkow Object (TŻO). Massive TŻOs (> 12 $M_\odot$) could appear as red supergiants enriched in exotic elements formed by proton capture (the p-process) in the unique nucleosynthetic environments just outside their degenerate cores. We performed a spectroscopic survey of 59 red supergiants to look for absorption lines of p-process elements—to search for TŻOs. Our survey uncovered two stars, BD+55 388 and IO Per, that appear to be enriched in Rb, a possible signature of the p-process.

1. Introduction

Some galactic red supergiants may contain degenerate neutron cores, planted there during a collision or merger. The notion that stars could have degenerate cores originated with Gamow (1937) and Landau (1938) who suggested that the sun might generate its energy by accretion onto a such a core. Later, Thorne and Żytkow (1975; 1977) calculated equilibrium models for stars with degenerate neutron cores and found that they would necessarily have lofty convective envelopes, and would more closely resemble a red giant or supergiant than a dwarf. These hypothetical giants and supergiants with degenerate neutron cores are called Thorne-Żytkow Objects (TŻOs).

Especially massive TŻOs (> 12 $M_\odot$) can not support themselves with accretion power alone. Cannon (1993) and Biehle (1994) suggested an alternative energy source for these models as a remedy: proton capture nucleosynthesis via the interrupted rapid p-process, occurring in a thin shell just above the degenerate zone. They argued that the products of this nucleosynthesis, p-process elements like Zn, Br, Rb, Zr, Mo, and Ru, would be convected to the photosphere in large quantities, where they would reveal themselves in absorption-line spectra. Hence, the presence of absorption lines from p-process elements in the spectrum of an otherwise ordinary red supergiant might indicate that that star is actually a TŻO.

If they exist, TŻOs may be the most luminous stars in the Galaxy. They could also be important sources of galactic p-process elements. Deciding whether TŻO formation is a possible or likely evolutionary pathway for high-mass binaries could have wide ramifications, from the origins of neutron star-neutron star binaries (Brandt & Podsiadlowski 1995), pulsar planets (Podsiadlowski, Cannon & Rees 1995), pulsating X-Ray sources (Coe & Pightling 1998) and high-energy cosmic explosions (Fryer, Benz & Herant 1996) to the sources of the gravitational-radiation background (Nazin & Postnov 1995; Bethe & Brown 1998). No objects have yet been conclusively determined to be TŻOs, though a few interesting objects have been examined as TŻO candidates (van Paradijs et al. 1995; Vanture, Zucker, & Wallerstein 1999).

We undertook a systematic search for Thorne-Zytkow objects following the path drawn by Cannon (1993) and Biehle (1994). We surveyed 59 red supergiants to search for the signatures of p-process elements in their optical spectra. Some estimates of the formation rates and lifetimes of TŻOs (Biehle 1994; Podsiadlowski et al. 1995) suggest that there are as many as 20-200 TŻOs in the Galaxy. In that case, our sample should be expected to contain a few of these hypothetical objects.

2. Observations

We observed 59 red supergiants using the Sandiford Cassegrain Echelle Spectrograph on the 2.1 meter Struve telescope at McDonald Observatory (McCarthy et al. 1993). The observations were made over the course of three observing runs: July 24–26 and September 27–29, 1994, and January 21–23, 1995. The spectra cover the region from 6230 to 8230 Å at a resolution of $R \approx 60{,}000$. Our stars were mostly as bright as V=7–10, so with integrations of 30 minutes or less, we obtained spectra with the signal to noise ratios of 80 or greater, limited by systematics, not photon noise.

The strongest relatively un-blended p-process element line in the spectral region covered by our observations cover is the Rb I 7800.23 Å line. Figure 1 shows a region of our spectrum of KN Cassiopeiae (M1 Ib) near 7800 Å compared to two synthesized spectra generated using a MARCS model atmosphere (Gustafsson et al. 1975) and a version of the MOOG spectral synthesis code introduced by Sneden (1973). One synthesized spectrum is a model with roughly

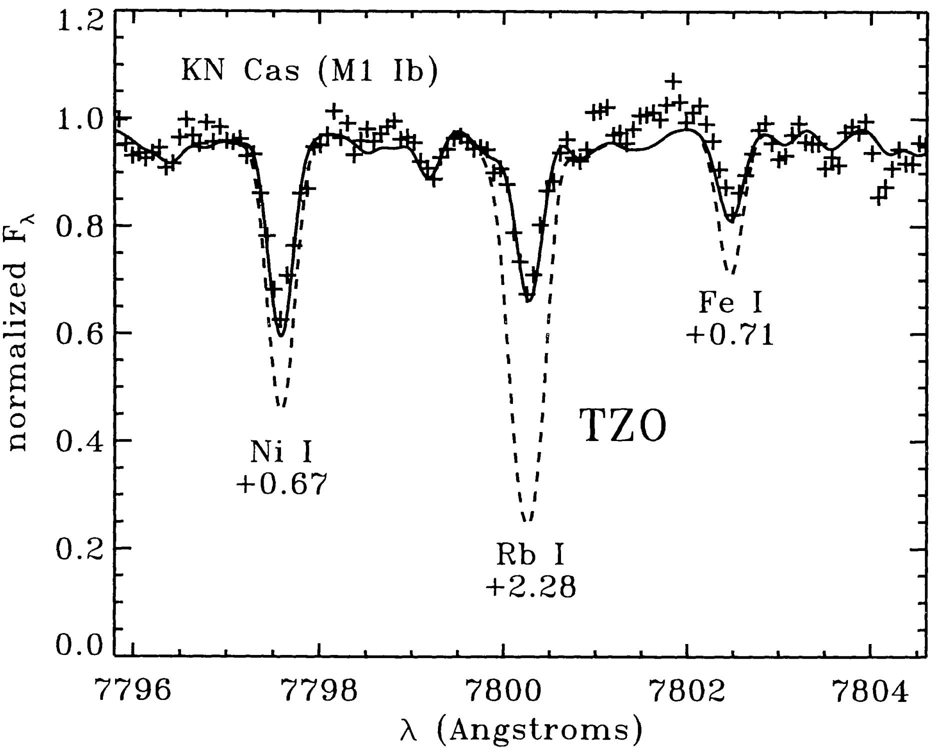

Figure 1. Our spectrum of KN Cassiopeiae (the crosses) compared to two synthetic spectra. The solid line is a synthetic spectrum with roughly solar abundances. The dashed line shows how the spectrum would appear if the abundances of Rb, Ni and Fe were enhanced to the levels expected in a TŻO (Biehle 1994).

solar abundances, tweaked slightly to match the observed spectrum; the other is the same model with Rb, Ni and Fe abundances enhanced by +2.28 dex, +0.67 dex, and +0.71 dex, respectively. These enhancements are based on Table 2 (column 3) of Biehle (1994), a model for a massive TŻO that has burned one sixth of its p-process fuel. As Figure 1 shows, the spectrum of a massive TŻO could be dramatically different than the spectrum of an ordinary red supergiant, and the Rb I line at 7800 Å could be a useful indicator of p-process enhancement.

The spectra of cool M supergiants are notoriously difficult to model. So instead of attempting to perform a thorough abundance analysis of our 59 supergiants, we simply measured the Rb I 7800 Å line in each star and compared it to the nearby Ni I 7798 Å line and looked for spectra with unusual equivalent-width ratios. The only problem with this approach is that for supergiants cooler than type M3, the absorption lines are so dense that the continuum level is completely obscured. This severe line blanketing makes measuring traditional equivalent widths of absorption features impossible. Instead, we resorted to measuring "pseudo-equivalent widths" of the relevant lines by fitting low-order polynomials to the highest peaks in the spectra, and using those fitted "pseudo-continua" to measure the integrated line strengths.

Figure 2 shows a plot of the ratios of the pseudo-equivalent widths of the Rb and Ni lines: Rb I 7800/Ni I 7798. Since equivalent widths are functions of temperature as well as concentration, the stars are sorted by spectral type and only stars of roughly the same spectral type should be compared with one another. The solid line shows measurements of the Rb I 7800/Ni I 7798 pseudo-equivalent width ratio for a set of synthesized spectra with solar metallicity.

The biggest source of error in our measurements is the choice of the pseudo-continuum. For example, if we chose an algorithm that places the continuum especially high, the measured pseudo-equivalent widths will all be especially large, and the measured ratios will be forced to be closer to one. To indicate the range of possibilities, we drew error bars on Figure 2, showing the ratios that result from two extreme but not unreasonable algorithms for chosing the pseudo-continua. In all but a few poor-quality spectra, which we discarded, our measurements of line-strength ratios appear to be fairly robust with regard to the choice of pseudo-continuum.

3. Discussion

Two stars, IO Per and BD +55 358 stand out from among other stars with roughly the same temperature. Rb can be formed via the s-process, so by itself, Rb enrichment does not guarantee that a star is a TŻO. To improve our test for whether a star is a TŻO we would look for signs of enrichment of other p-process elements, like Mo and Zn which are not produced in large quantities by the s-process. We are examining our spectra for further signs of p-process enrichment, and planning further observations of BD+55 388 and IO Per.

References

Bethe H. A. & Brown, G. E., ApJ, 506, 780

Biehle, G. T. 1994, ApJ, 420, 364

Brandt, N., Podsiadlowski, P. 1995, MNRAS, 274, 461

Cannon, R. C. 1993, MNRAS, 263, 817

Cannon, R. C., Eggleton, P. P., Zytkow, A. N. & Podsiadlowski, P. 1992, ApJ, 386, 206

Coe, M. J. & Pightling, S. L. 1998, MNRAS, 299, 223

Fryer, C. L., Benz, W. & Herant, M. 1996, ApJ, 460, 801

Gamow, G. 1937, Structure of Atomic Nuclei and Nuclear Transformations. Oxford Univ. Press, Oxford

Gustafsson, B., Bell, R. A., Eriksson, K., & Nordlund, Å. 1975, A&A, 42, 407

Landau, L. D. 1938, *Nature*, 141, 333

McCarthy, J. K., Sandiford, B. A., Boyd, D., & Booth, J. 1993, PASP, 105, 881

Nazin, S. N., Postnov, K. A. 1995, A&A, 303, 789

Podsiadlowski, P., Cannon, R. C. & Rees, M. J. 1995, MNRAS, 274, 485

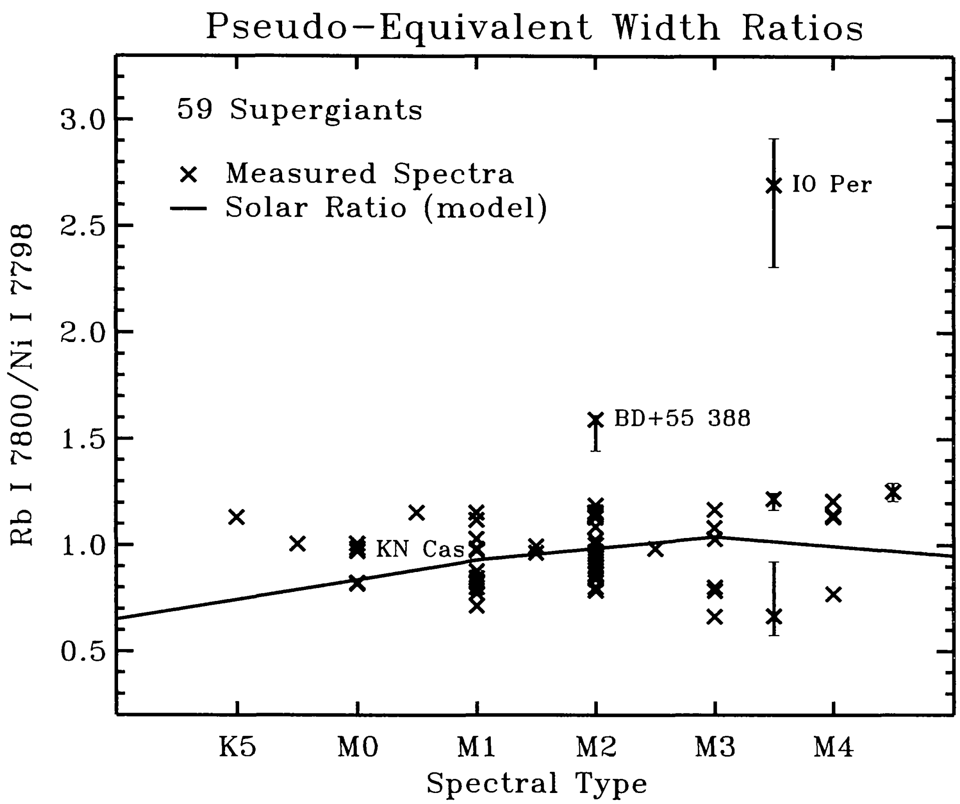

Figure 2. The pseudo-equivalent widths of the Rb I 7800 lines divided by the pseudo-equivalent widths of the Ni I 7798 lines for all of the stars we observed, grouped by spectral type. By this measure, IO Per and BD +55 358 stand out from other stars which have roughly the same temperature. The solid line indicates the pseudo-equivalent width ratio for a set of models of solar abundance.

Sneden, C. 1973, ApJ, 184, 839
Thorne, K. S. & Zytkow, A. N. 1975, ApJ, 199, L19
Thorne K. S. & Zytkow, A. N. 1977, ApJ, 212, 832
Vanture, A. D., Zucker, D., Wallerstein, G. 1999, ApJ, 514, 932