M-dwarf Eclipsing Binaries from the SDSS-II Supernova Survey: Testing Low Mass Stellar Evolution Models

Waqas Bhatti

GBO Exam Committee:
Holland Ford, Adam Riess, Bruce Barnett, I. Neill Reid, Cila Herman

November 26, 2008

1 Introduction

A large fraction (nearly 70%) of the stellar population of our Galaxy is made up of low mass stars, such as M-dwarfs. These stars burn their hydrogen fuel slower, so they live longer on the main sequence (the hydrogen-burning phase of a star's lifetime) as depicted on a color-magnitude diagram. Despite their large numbers, we know relatively little about these stars, largely due to their intrinsic faintness, which makes it difficult to observe them.

The best way to learn about a stellar population is to observe its members in binary systems, preferably those that have their orbital planes aligned edge-on to our line of sight. Such systems will be observed to eclipse periodically: a distinct signal that can be picked up by photometric and spectroscopic monitoring. The photometric information enables the calculation of the period of orbit for the eclipsing system, the relative luminosities of the two components of the system, their relative sizes, and finally, their relative temperatures. Spectroscopic observations provide yet more information about these stars. The presence and strength of various emission and absorption spectral lines give constraints on temperatures, chemical compositions, ages, chromospheric activity, and stellar rotation, among other properties. The radial velocities of these binary systems can also be precisely measured, and in conjunction with Kepler's 3^{rd} Law and the orbital period, provide precise estimates of the masses of the components.

Due to the observational difficulties mentioned earlier, very few low mass eclipsing binary star systems have been studied in depth so far (see reviews by Ribas [1, 2] and references therein). Comparing the properties of these stars to the predictions from theoretical models of low mass stellar structure and evolution by Baraffe, Chabrier, and others (see [3], [4], and [5]) reveals discrepancies in the stellar radii and surface temperatures. The disagreement between the observed and predicted mass-radius relationship for the 16 well-characterized low mass eclipsing binary systems is illustrated in Figure 1. The predicted radii are smaller by about 10%. In addition, the models predict surface temperatures nearly 5% hotter than those observed in these low mass eclipsing binary systems.

Explanations for these disagreements between theory and observations involve taking into account the effects of tidal interactions between the two components of the binary system, and the presence of star spots. Chabrier et al. [6] conclude that stars in tight binary systems are forced to

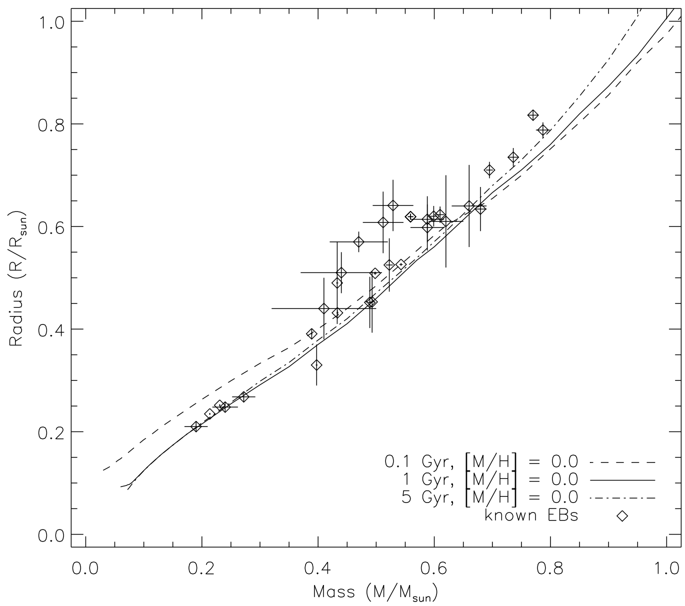

Figure 1: Stellar mass vs. radius for 16 well-characterized low mass eclipsing binary systems from [1, 2] and references therein. The measured masses and radii of these stars differ systematically from those of solar abundance models [3] that are representative of their ages (0.1–5 Gyr).

rotate with periods synchronized to their (small) orbital periods and thus have significant magnetic activity. This magnetic activity, coupled with the fact that the surfaces of low mass stars are often covered by large star spots, may alter stellar radii and temperatures enough to account for the differences between theory and observations.

Systems composed exclusively of low mass stars, such as M-dwarf/M-dwarf binaries, provide the best direct tests of theoretical models of structure and evolution. Increasing the observed number of such systems would provide more estimates of masses, radii, luminosities, and surface temperatures, all of which would help clarify the divergence of these observed parameters from those predicted by theory. The advent of large scale photometric surveys, such as the Sloan Digital Sky Survey (and Pan-STARRS and LSST in the future), has recently made it possible to find and characterize many of these objects in a uniform and systematic manner. In addition, the development of powerful spectroscopic instruments has enabled precise measurements of the fundamental properties of these stars.

Here, we propose to use existing photometric data collected over many epochs by the SDSS-II Supernova Survey [7] to find and characterize M-dwarf eclipsing binary candidates. We intend to perform intensive photometric and spectroscopic follow-up on these objects with the aim of obtaining precise estimates of their properties, especially their masses, radii, and luminosities. The goal will be to obtain several well-characterized binary systems, which can then be compared to existing theoretical models.

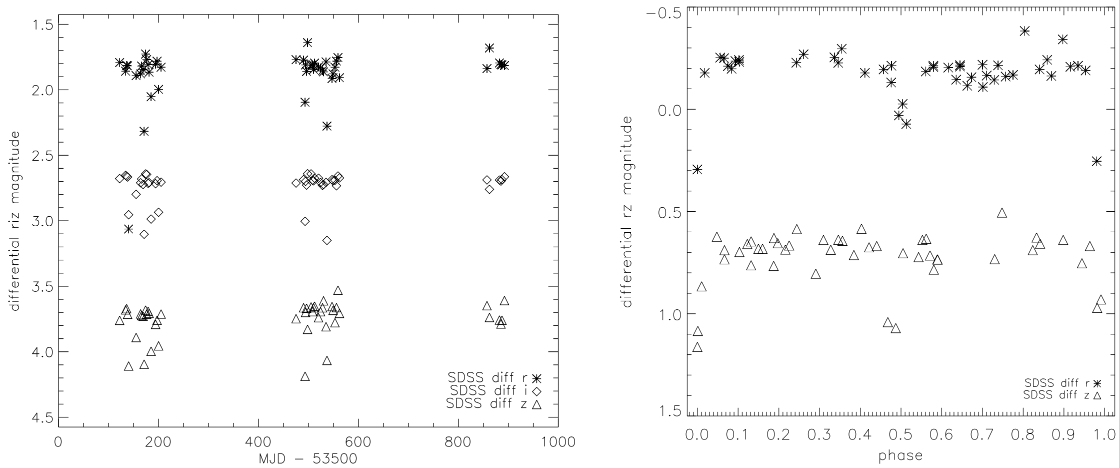

Figure 2: The left panel shows the SDSS r, i, and z differential magnitude light-curves of the M1 dwarf eclipsing binary candidate SDSS J000557.61+005246.2, with the r, i, and z differential magnitudes shifted on the y axis for clarity. The multiple eclipses are clearly visible. The right panel shows phase-folded r and z differential magnitude light-curves for the same object using a first-order period estimate of 2.14 days. The i band light-curve could not be phase-folded because none of our period-finding algorithms converged to a single solution, and it is not shown above.

2 Research Plan

2.1 Eclipsing Binary Candidates from the SDSS-II Supernova Survey

The SDSS-II Supernova Survey monitored a 300 square degree area of the sky known as SDSS Stripe 82 for three consecutive months from 2005 to 2007. The survey took observations in two overlapping 'strips' (the 'north strip' and the 'south strip') over two nights, translating into one full observation run of the entire Stripe every two nights. The goal of the survey was to identify and obtain light-curves of objects that appeared to be supernovae, enabling tests of cosmology with a large and uniform sample of object redshifts. Calibrated object catalogs for all sources detected over all epochs are available at the SDSS Data Archive Server[1].

We downloaded these catalogs and processed them through a multi-stage pipeline designed to detect and classify possible variable point sources. We first extracted objects that were classified as point sources with clean photometry by the SDSS photometric pipeline, enforcing a faint magnitude limit of $z = 21.0$ mag. Next, we matched object detections over 174 observation runs to build up a complete light-curve catalog. From this catalog, we then selected objects that had been observed at least 10 times over the three Survey seasons, leaving us with about 1.1 million point sources. To compensate for changing photometric conditions or small changes in photometric zero-points from night to night, we generated differential magnitude light-curves for all of these sources using inhomogeneous ensemble photometry techniques [8]. This resulted in an average photometric precision of about 30 mmag at $i = 19.0$ mag, which is adequate for the detection of M-dwarf eclipsing binary systems.

[1] `http://das.sdss.org/www/html/imaging/dr-byRun-74.html`

We used SDSS $r - i$, and $i - z$ color-cuts defined by West et al. [9] to select about 690,000 likely M-dwarfs from our sample. The Stetson variability index [10] was employed to find periodic variables among these objects; this removed from consideration a large number of faint objects that appeared variable because of photometric noise. We then inspected the differential magnitude light-curves of identified M-dwarf periodic variables, looking for repeated eclipse-like events that appeared simultaneously in the SDSS r, i, and z filters. Finally, to find initial estimates of the periods, we used three 'string length' methods (all related to the original Lafler-Kinman method) [10, 11, 12]. We also made use of the Lomb-Scargle periodogram [13, 14] as an additional check on the periods obtained by these three methods.

Unfortunately, the periods we obtain from these algorithms are not very precise, largely due to the poor (and uneven) phase coverage of the Survey light-curves, which miss multiple eclipse events for many of our candidate objects. We can, however, use the first order ephemerides generated by these methods to narrowly target a range of future observation dates for several photometric monitoring campaigns to precisely determine these objects' periods and obtain high quality light-curves. As of November 2008, we have identified 37 objects that are good candidates for M-dwarf eclipsing binary systems. Figure 2 shows the differential magnitude and phase-folded light-curves for one of these candidates.

2.2 Photometric and Spectroscopic Followup

We have recently formed a collaboration with Dr. Laurence Marschall of Gettysburg College, which is part of the National Undergraduate Research Observatory (NURO). The Lowell Observatory 0.8-m telescope, which has guaranteed observing time for NURO, will be used to refine the initial-guess periods of our eclipsing binary candidates. Once we have more precise ephemerides for our targets, we will use the Apache Point Observatory (APO) 3.5-m telescope to obtain high time resolution observations of these systems' primary and secondary eclipses. These will be used to establish the components' relative sizes, temperatures, and luminosities.

The final step in the observational program will be the measurement of radial velocities of these eclipsing binary systems. We plan to take spectra using the R-C spectrograph at the Kitt Peak National Observatory (KPNO) 4-m telescope, the GMOS instrument on the Gemini North telescope, and finally the HIRES instrument on the Keck 10-m telescope. The most challenging of our eclipsing binary candidates are expected to be of spectral type M4, with component masses of ~ 0.2 $M_\odot$, in orbits with periods of about 3 days. The peak-to-peak radial velocity signature of such objects is ~ 110 km/sec, which will be observable using our planned instruments and telescopes. To improve the estimates of radial velocities from our spectral observations, we intend to use cross-correlation techniques (see [15, 16]) that involve the comparison of our target spectra to those of well-characterized stars that are similar in spectral type.

2.3 Fundamental Properties of M-dwarfs

We now briefly describe the steps involved in obtaining the fundamental properties (especially masses, radii, and luminosities) of our eclipsing binary candidates using photometric and spectroscopic observations.

1. The relative temperatures of the two binary components can be estimated by looking at the ratio of primary to secondary eclipse depth. Converting these relative temperatures to

absolute temperatures requires knowledge of the spectral type (which we currently have), or precise determination of the colors of the binary during and out of primary and secondary eclipse (which we will obtain).

2. The ratio of light loss to light remaining at the bottom of a total eclipse gives the monochromatic luminosity ratio of the smaller to the larger binary component. If we assume that the stars are spherical in nature, and have circular orbits, this also provides the relative radii of the binary components.

3. The light-curves of primary and secondary eclipse provide an estimate of the inclination (angle between the orbital axis and line-of-sight); systems with higher inclinations (closer to edge-on) will have deeper and wider eclipses.

4. The radial velocities for the two components in the binary system can be measured over several epochs, and provide precise estimates of the masses. If the target system is not a double-lined spectroscopic binary, the mass function can still be calculated. The orbital period (determined by photometric observations), in conjunction with the total mass of the system, and Kepler's 3^{rd} Law, provides the semimajor axis. Once this has been determined, the absolute radii of the stars in the binary system can be calculated.

5. The luminosity of each star can be calculated using the already obtained estimates of the temperature and absolute radius. Comparing the total luminosity of the binary system to the observed flux then gives a measure of its distance, using the inverse-square law.

We note that the steps outlined above assume many simplifications (circular orbits, spherical stars, no limb darkening, and no star spots), and much of our actual light-curve analysis will be carried out by sophisticated binary system modeling programs such as those by Wilson and Devinney [17], Prša and Zwitter [18], and Popper and Etzel [19].

3 Expected Results

As described in Section 2.1, we have generated a differential photometry light-curve catalog of all ~ 1.1 million point sources in the SDSS-II Supernova Survey with at least 10 observations over the three observing seasons. During the course of analyzing potential M-dwarf eclipsing binaries to obtain first guess estimates of their periods, we will also apply our period finding algorithms to all other objects that appear to be variable, as quantified by large values of their Stetson variability indices. This will enable time-series studies of many different variable populations, such as Cepheids, RR Lyrae, cataclysmic variables, flare stars, and long period variables.

Finally, we expect to obtain the masses, radii, and luminosities of at least 10 new M-dwarf eclipsing binary systems. As discussed in Section 1, Chabrier et al. [6] have calculated new models for low mass stars that take into account the presence of large magnetic fields in these fast rotating stars, as well as the effects of large star spots. With increased numbers of stars on the mass-radius diagram (Figure 1), we will be able to determine and characterize the influence of these added second-order effects on the existing stellar structure and evolution models of low mass stars.

References

[1] I. Ribas, "Masses and Radii of Low-Mass Stars: Theory Versus Observations," *Astrophysics and Space Science*, vol. 304, pp. 89–92, Aug. 2006.

[2] I. Ribas, J. C. Morales, C. Jordi, I. Baraffe, G. Chabrier, and J. Gallardo, "Fundamental properties of low-mass stars.," *Memorie della Societa Astronomica Italiana*, vol. 79, p. 562, 2008.

[3] I. Baraffe, G. Chabrier, F. Allard, and P. H. Hauschildt, "Evolutionary models for solar metallicity low-mass stars: mass-magnitude relationships and color-magnitude diagrams," *Astronomy and Astrophysics*, vol. 337, pp. 403–412, Sept. 1998.

[4] G. Chabrier and I. Baraffe, "Theory of Low-Mass Stars and Substellar Objects," *Annual Review of Astronomy and Astrophysics*, vol. 38, pp. 337–377, 2000.

[5] G. Chabrier, I. Baraffe, J. Leconte, J. Gallardo, and T. Barman, "The mass-radius relationship from solar-type stars to terrestrial planets: a review," *ArXiv e-prints*, Oct. 2008.

[6] G. Chabrier, J. Gallardo, and I. Baraffe, "Evolution of low-mass star and brown dwarf eclipsing binaries," *Astronomy and Astrophysics*, vol. 472, pp. L17–L20, Sept. 2007.

[7] J. A. Frieman, B. Bassett, A. Becker, C. Choi, D. Cinabro, *et al.*, "The Sloan Digital Sky Survey-II Supernova Survey: Technical Summary," *Astronomical Journal*, vol. 135, pp. 338–347, Jan. 2008.

[8] R. K. Honeycutt, "CCD ensemble photometry on an inhomogeneous set of exposures," *Publications of the Astronomical Society of the Pacific*, vol. 104, pp. 435–440, June 1992.

[9] A. A. West, L. M. Walkowicz, and S. L. Hawley, "Updated Colors for Cool Stars in the Sloan Digital Sky Survey," *Publications of the Astronomical Society of the Pacific*, vol. 117, pp. 706–710, July 2005.

[10] P. B. Stetson, "On the Automatic Determination of Light-Curve Parameters for Cepheid Variables," *Publications of the Astronomical Society of the Pacific*, vol. 108, p. 851, Oct. 1996.

[11] M. M. Dworetsky, "A period-finding method for sparse randomly spaced observations of 'How long is a piece of string?'," *Monthly Notices of the Royal Astronomical Society*, vol. 203, pp. 917–924, June 1983.

[12] J. Lafler and T. D. Kinman, "An RR Lyrae Star Survey with Ihe Lick 20-INCH Astrograph II. The Calculation of RR Lyrae Periods by Electronic Computer.," *Astrophysical Journal Supplement Series*, vol. 11, p. 216, June 1965.

[13] J. H. Horne and S. L. Baliunas, "A prescription for period analysis of unevenly sampled time series," *Astrophysical Journal*, vol. 302, pp. 757–763, Mar. 1986.

[14] J. D. Scargle, "Studies in astronomical time series analysis. II - Statistical aspects of spectral analysis of unevenly spaced data," *Astrophysical Journal*, vol. 263, pp. 835–853, Dec. 1982.

[15] I. N. Reid and S. Mahoney, "Low-mass spectroscopic binaries in the Hyades: a candidate brown dwarf companion," *Monthly Notices of the Royal Astronomical Society*, vol. 316, pp. 827–844, Aug. 2000.

[16] S. M. Rucinski, "Radial Velocity Studies of Close Binary Stars. VII. Methods and Uncertainties," *Astronomical Journal*, vol. 124, pp. 1746–1756, Sept. 2002.

[17] R. E. Wilson and E. J. Devinney, "Realization of Accurate Close-Binary Light Curves: Application to MR Cygni," *Astrophysical Journal*, vol. 166, p. 605, June 1971.

[18] A. Prša and T. Zwitter, "A Computational Guide to Physics of Eclipsing Binaries. I. Demonstrations and Perspectives," *Astrophysical Journal*, vol. 628, pp. 426–438, July 2005.

[19] D. M. Popper and P. B. Etzel, "Photometric orbits of seven detached eclipsing binaries," *Astronomical Journal*, vol. 86, pp. 102–120, Jan. 1981.