

# HIGH-PRECISION 2MASS $JHK_s$ LIGHT CURVES AND OTHER DATA FOR RR LYRAE STAR SDSS J015450 + 001501: STRONG CONSTRAINTS FOR NONLINEAR PULSATION MODELS

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Received 2013 September 27; accepted 2013 November 4; published 2013 December 13

## ABSTRACT

We present and discuss an extensive data set for the non-Blazhko ab-type RR Lyrae star SDSS J015450+001501, including optical Sloan Digital Sky Survey *ugriz* light curves and spectroscopic data, LINEAR and Catalina Sky Survey unfiltered optical light curves, and infrared Two Micron All Sky Survey (2MASS)  $JHK_s$  and *Wide-field Infrared Survey Explorer* *W1* and *W2* light curves. Most notable is that light curves obtained by 2MASS include close to 9000 photometric measures collected over 3.3 yr and provide an exceedingly precise view of near-infrared variability. These data demonstrate that static atmosphere models are insufficient to explain multiband photometric light-curve behavior and present strong constraints for nonlinear pulsation models for RR Lyrae stars. It is a challenge to modelers to produce theoretical light curves that can explain data presented here, which we make publicly available.

**Key words:** infrared: stars – stars: atmospheres – stars: individual (SDSS J015450+001501) – stars: oscillations – stars: variables: RR Lyrae – techniques: photometric

**Online-only material:** color figures, machine-readable tables

## 1. INTRODUCTION

RR Lyrae stars are old low-mass (around half the Sun’s) pulsating horizontal branch stars of spectral class A and F. They are important both as stellar evolutionary probes and as tracers of Galactic structure. For these reasons, accurate pulsational models for RR Lyrae stars are crucial in a large number of astrophysical applications. Marconi (2009) recently pointed out that a nonlocal time-dependent treatment of convection in nonlinear (i.e., without small oscillation approximation) pulsation models for RR Lyrae are needed to explain the morphological characteristics of the variation along a pulsation cycle of luminosity, radius, radial velocity, effective temperature, and surface gravity: “the comparison between theoretical and observed variations represents a powerful tool to constrain the intrinsic stellar parameters including the mass” (Marconi 2009, p. 226).

Precise multiband light curves provide strong constraints for pulsation models. Bono et al. (2000) performed simultaneous fitting of multiband (*UBVK*) light curves of an RRc star (U Comae). They transformed the bolometric magnitudes supplied by a hydrocode to standard magnitudes using bolometric corrections and empirical color–temperature relations on the basis of ATLAS9 model atmospheres (Castelli et al. 1997). Dorfi & Feuchtinger (1999) carried out detailed frequency-dependent radiative transfer computations to obtain *UBVI* light curves of both RRab and RRc stars. Motivated by their results, in this work we present light curves for an RR Lyrae star pulsating in the fundamental mode (RRab) obtained over 15 yr in 10 photometric bandpasses that span more than a factor of 10 in wavelength, and bracket the wavelength range where most of its luminosity is emitted. Most notable is that light curves obtained by Two Micron All Sky Survey (2MASS) include close to 9000 photo-

metric measures obtained over 3.3 yr and, after data averaging, provide an exceedingly precise view of near-infrared variability. While quasi-continuous, extreme precision optical light curves have recently become available because of the *Kepler* mission (e.g., ~140,000 short-cadence data points were analyzed for RRab stars FN Lyr and AW Dra in Nemeč et al. 2011 and half a million points per star were discussed in Nemeč et al. 2013), we believe that a data set of similar completeness, precision, and wavelength and temporal coverage does not exist for any other RR Lyrae star in the near-infrared bandpasses. Hence, data presented here will provide unprecedented observational constraints for nonlinear pulsation models of RR Lyrae stars and will stimulate modelers to include a self-consistent and frequency-dependent treatment of radiation hydrodynamics in the outer parts of these pulsators.

In Section 2, we present and analyze the available data, which we make public, and discuss and summarize our findings in Section 3.

## 2. DATA ANALYSIS

We first describe optical Sloan Digital Sky Survey (SDSS) *ugriz* light curves and spectroscopic data, LINEAR and Catalina Sky Survey (CSS) unfiltered light-curve data, infrared 2MASS  $JHK_s$  and *Wide-field Infrared Survey Explorer* (*WISE*) *W1* and *W2* light-curve data, and then perform their joint analysis. The temporal coverage and sizes of these data sets are summarized in Table 1.

As photometric data for RR Lyrae stars have been historically taken predominantly in the *UBVRI* system, it might be interesting to note that Ivezić et al. (2007) provide a set of nonlinear transformation between *BVRI* and SDSS *griz* magnitudes. For

**Table 1**  
Photometric Data Analyzed in This Work

Survey	MJD <sub>min</sub> <sup>a</sup>	MJD <sub>max</sub> <sup>b</sup>	<i>N</i> Epochs <sup>c</sup>	<i>N</i> Data <sup>d</sup>
2MASS	50660	51869	2969	8907
SDSS	51075	54412	64	320
LINEAR	52608	54817	225	225
CSS	53627	56297	270	270
WISE	55209	55575	43	86

**Notes.**<sup>a</sup> Earliest MJD in the survey.<sup>b</sup> Latest MJD in the survey.<sup>c</sup> The number of photometric epochs.<sup>d</sup> The number of photometric data points (the number of epochs times the number of bandpasses).

a linear transformation between the *U* and *u* magnitudes, refer to Jester et al. (2005).

**2.1. SDSS Data**

The SDSS (Abazajian et al. 2009) has repeatedly imaged about 300 deg<sup>2</sup> large equatorial strip limited by 309° < R.A. < 60° and |decl.| < 1°26, and known as Stripe 82. The properties of this data set and its impact on variability studies are discussed in detail by Ivezić et al. (2007), Sesar et al. (2007), and Bramich et al. (2008). An extensive study of light curves for RR Lyrae stars found in Stripe 82 was undertaken by Sesar et al. (2010).

The star discussed here was identified in SDSS Stripe 82 data with coordinates (J2000.0): R.A. = 28.709054 and decl. = +0.250206 (decimal degrees). Following standard SDSS nomenclature, hereafter we refer to it as SDSS J015450+001501. All SDSS data for this star are publicly<sup>8</sup> available, as well as electronically published along with this paper for convenience. Table 2 shows the form and content of the data. Images show a distinctively blue isolated point source, with the nearest brighter object more than 30'' away. Its SDSS *r*-band magnitude varies from ∼14.6 to ∼15.5 and, according to Sesar et al. (2010), this star is at a heliocentric distance of  $D = 7.59$  kpc.

**2.1.1. Imaging Data**

SDSS imaging data for this star were obtained 64 times and include nearly simultaneous *ugriz* photometry precise to 0.01–0.02 mag. To construct phased light curves, we use the period and epoch of maximum determined using better sampled LINEAR data (see Section 2.2). Phased and normalized SDSS *urz* light curves are shown in Figure 1. Following Sesar et al.

<sup>8</sup> <http://skyserver.sdss3.org/dr9/en/tools/explore/obj.asp?sid=788271533805037568>

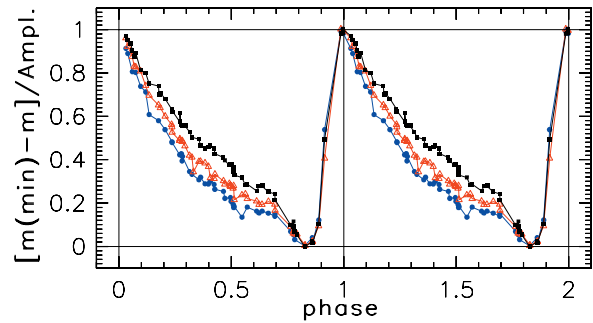
**Table 2**  
SDSS *ugriz* Light Curves for RR Lyrae Star SDSS J015450+001501 (64 Epochs)

R.A. <sup>a</sup> (deg)	Decl <sup>a</sup> (deg)	MJD <sub><i>u</i></sub> (day)	<i>u</i> (mag)	<i>u</i> <sub>err</sub> (mag)	MJD <sub><i>g</i></sub> (day)	<i>g</i> (mag)	<i>g</i> <sub>err</sub> (mag)	MJD <sub><i>r</i></sub> (day)	<i>r</i> (mag)	<i>r</i> <sub>err</sub> (mag)
28.709058	0.250204	51075.379381	16.603	0.008	51075.381047	15.412	0.005	51075.377714	15.161	0.006
28.709058	0.250204	51818.349055	16.921	0.009	51818.350721	15.715	0.006	51818.347388	15.447	0.006
...	...	...	...	...	...	...	...	...	...	...

**Notes.** Magnitudes are not corrected for ISM dust extinction and set to -99.999 if unreliable. See Sesar et al. (2010) for more details.

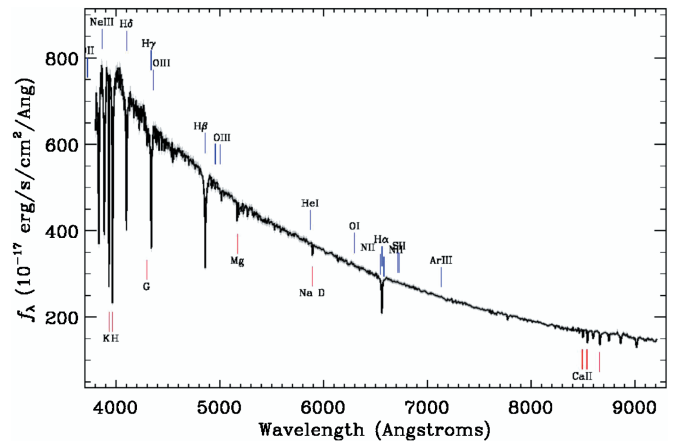
<sup>a</sup> Equatorial J2000.0 right ascension and declination.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)



**Figure 1.** Phased and normalized SDSS *urz* (bottom to top, respectively) light curves for SDSS J015450+001501. Data points are shown by symbols and connected by straight lines. The scatter is due to random photometric errors (0.01–0.02 mag).

(A color version of this figure is available in the online journal.)



**Figure 2.** Default SDSS visualization of the SDSS spectrum for SDSS J015450+001501. The spectrum is classified as an A0 star.

(A color version of this figure is available in the online journal.)

(2010), we normalized light curves by their amplitude (with minimum and maximum brightness determined using *B* splines) and shifted so that minimum brightness is 0 and maximum brightness is 1. As evident from Figure 1, light curves are typical for ab RR Lyrae stars and greatly vary with wavelength.

**2.1.2. Spectroscopic Data**

SDSS J015450+001501 was spectroscopically targeted by SDSS as a quasar candidate. Its SDSS spectrum (identifiers: plate = 700, fiber = 515, MJD = 52199) is consistent with that for an A0 star (see Figure 2). The spectroscopic parameters determined by the SEGUE Stellar Parameter Pipeline (Lee et al. 2011) include  $[\text{Fe}/\text{H}] = -1.31 \pm 0.03$ ,  $\log(g) = 2.97 \pm 0.20$ ,  $T_{\text{eff}} = 6580 \pm 104$  K, and radial velocity  $-135.1 \pm 1.8$  km s<sup>-1</sup>.

**Table 3**  
LINEAR Light Curve for RR Lyrae Star  
SDSS J015450+001501 (225 Epochs)

MJD	Mag	Mag <sub>err</sub>
52608.145642	15.559	0.257
52608.175414	15.424	0.024
...	...	...

**Notes.** For details, see Sesar et al. (2011, 2013).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

We note, however, that the spectrum of this star is a coadd of five individual exposures, and the time between the start of the first and the end of the last exposure is 1.03 days. Thus, the parameters derived from this spectrum might contain much higher systematic errors because the individual exposures span a wide range of pulsational phases.

### 2.2. LINEAR and CSS Light-curve Data

The asteroid survey LINEAR was photometrically recalibrated by Sesar et al. (2011) using SDSS stars acting as a dense grid of standard stars. In the overlapping  $\sim 10,000$  deg<sup>2</sup> of sky between LINEAR and SDSS, photometric errors for unfiltered (white light) photometry range from  $\sim 0.03$  mag for sources not limited by photon statistics to  $\sim 0.20$  mag at  $r = 18$  (here  $r$  is the SDSS  $r$ -band magnitude). LINEAR data provide time domain information for the brightest 4 mag of SDSS survey, with 250 unfiltered photometric observations per object on average. The public access to the recalibrated LINEAR data is provided through the SkyDOT Web site (<https://astroweb.lanl.gov/lineardb/>) and is also available as auxiliary material with this paper (see Table 3). RR Lyrae stars from this data set have been analyzed by Sesar et al. (2013).

The CSS uses three telescopes to search for near-Earth objects. Each of the survey telescopes is run as separate subsurveys, including the Catalina Schmidt Survey and the Mount Lemmon Survey in Tucson, Arizona, and the Siding Spring Survey in Siding Spring, Australia. CSS is similar to LINEAR in that it uses unfiltered observations and delivers similar photometric precision (but is deeper by several magnitudes). RR Lyrae stars from this data set have been analyzed by Drake et al. (2013).

SDSS J015450+001501 was observed by LINEAR and CSS about 500 times over 10 yr. Both light curves are shown in Figure 3 and are barely distinguishable. Using only LINEAR data, Sesar et al. (2013) have determined a best-fit period,  $P = 0.636985$  days, and the epoch of maximum,  $MJD_{\max} = 53675.299080$ . Based on Sesar et al. (2011) photometric transformations between LINEAR and SDSS  $r$ -band data, a great degree of similarity is expected between unfiltered LINEAR/CSS light curves and the SDSS  $r$ -band light curve. This expectation is verified by data, as illustrated in Figure 3. CSS observations of SDSS J015450+001501 are collected in Table 4.

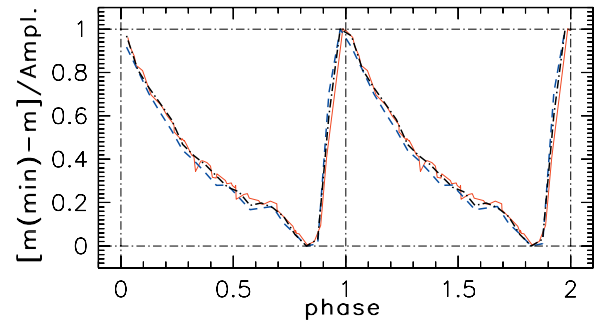
### 2.3. 2MASS Light-curve Data

The most extensive data set presented here comes from the 2MASS survey (Skrutskie et al. 2006). SDSS J015450+001501 falls in one of the 35 2MASS calibration fields that were imaged repeatedly in the  $J$ ,  $H$ , and  $K_s$  bandpasses during each night of the 3.5 yr survey. Full details are given in the online

**Table 4**  
CSS Light Curve for RR Lyrae Star  
SDSS J015450+001501 (270 Epochs)

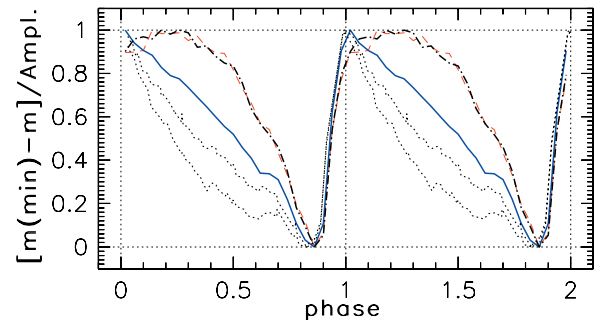
MJD	Mag	Mag <sub>err</sub>
53710.18424	15.44	0.06
53710.19176	15.46	0.06
...	...	...

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)



**Figure 3.** LINEAR (dashed), CSS (dot-dashed), and SDSS  $r$ -band (solid) light curves for SDSS J015450+001501. LINEAR and CSS data (225 and 270 data points, respectively) were smoothed by taking the median in 0.05 wide phase bins, with resulting random errors at most 0.01 mag. SDSS light curve corresponds to 64 data points (with random errors of 0.01–0.02 mag) connected by straight lines (same curve as in Figure 1). Note that all three light curves barely differ from each other.

(A color version of this figure is available in the online journal.)



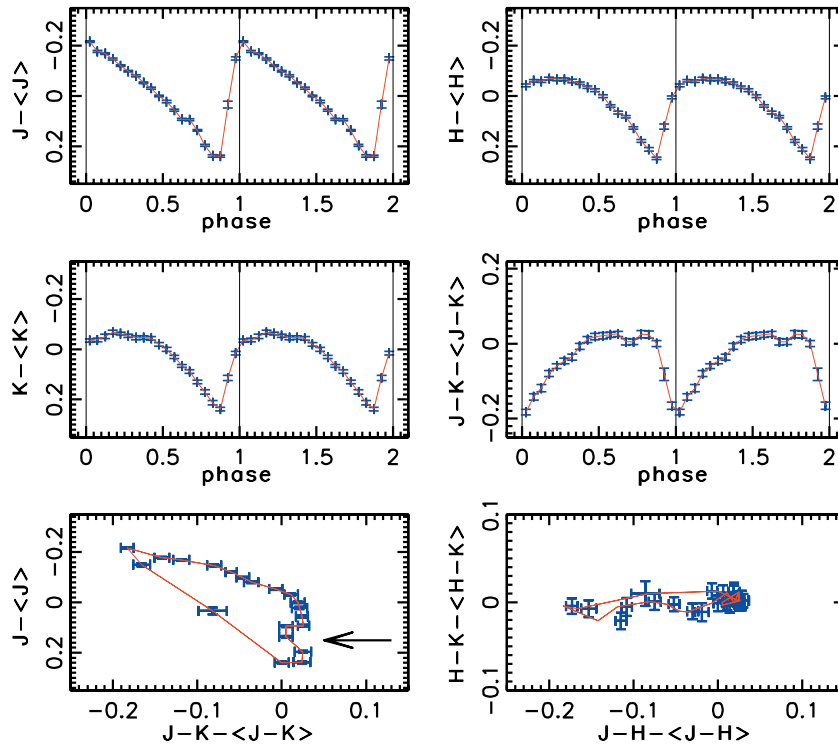
**Figure 4.** Phased and normalized SDSS  $gi$  and 2MASS  $JHK$  (bottom to top, respectively) light curves for SDSS J015450+001501. Phased 2MASS light-curve data ( $\sim 3000$  data points per band) were smoothed by taking the median in 0.04 wide phase bins, with resulting random errors well below 0.01 mag. SDSS light curves correspond to 64 data points each (with random errors of 0.01–0.02 mag), connected by straight lines. Note that the shapes of  $H$  and  $K$  light curves are barely distinguishable.

(A color version of this figure is available in the online journal.)

Explanatory Supplement<sup>9</sup> and Cutri et al. (2003). An analysis of various variable stars contained in this data set was presented by Plavchan et al. (2008), Becker et al. (2008), and Davenport et al. (2012), where more technical details can be found.

SDSS J015450+001501 was observed about 3000 times in each of the three bandpasses (see Tables 1 and 5). Phased and normalized 2MASS light curves are shown and compared to SDSS  $gi$  light curves in Figure 4. Because the 2MASS data set is so large and we see no sign of Blazhko-modulation in the light curves, data were smoothed by taking the median in 0.04 wide phase bins, with resulting random errors well below 0.01 mag.

<sup>9</sup> [http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec3\\_2d.html](http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec3_2d.html)



**Figure 5.** Top four panels display phased and normalized 2MASS  $JHK$  and color  $J-K$  light curves for SDSS J015450+001501. Phased 2MASS light-curve data ( $\sim 3000$  data points per band) were smoothed by taking the median in 0.05 wide phase bins, with resulting random errors well below 0.01 mag. The median value of these averaged data points is subtracted from each curve, and points are connected by straight lines. Random errors are derived from scatter in each phase bin. The bottom two panels show color–magnitude (left) and color–color (right) hysteresis curves (the motion is clockwise). Note that between phases 0.65 and 0.70 the  $J-K$  color becomes bluer despite the decreasing brightness (see the middle right and bottom left panels, and arrow in the latter panel). The  $H-K$  color does not show any variation (rms of  $\sim 0.01$  mag, consistent with measurement errors).

(A color version of this figure is available in the online journal.)

**Table 5**  
2MASS  $JHK$  Light Curves for RR Lyrae Star SDSS J015450+001501 (2969 Epochs)

SourceID	R.A. <sup>a</sup> (deg)	Decl <sup>a</sup> (deg)	BJD	$J$ (mag)	$J_{\text{err}}$ (mag)	$J_q^b$	$H$ (mag)	$H_{\text{err}}$ (mag)	$H_q^b$	$K$ (mag)	$K_{\text{err}}$ (mag)	$K_q^b$
10038165	28.709000	0.250413	51003.4463211	14.257	0.030	A	14.007	0.041	A	13.947	0.075	A
10038255	28.708985	0.250394	51003.4466211	14.219	0.031	A	13.949	0.040	A	13.941	0.077	A
...	...	...	...	...	...	...	...	...	...	...	...	...

#### Notes.

<sup>a</sup> Equatorial J2000.0 right ascension and declination.

<sup>b</sup> Reliability flag. Single character flag that is related to the probability ( $P$ ) that the extraction is a valid detection of a near-infrared source on the sky at the time of the observation. “A” means  $P > 90\%$ .

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

The variation of the light-curve shape with bandpass wavelength seen in SDSS data (see Figure 1), continues into near-infrared, but only to the  $H$  band—the light curves in the  $H$  and  $K$  bands are barely distinguishable despite the high precision of 2MASS data. We proceed with a more detailed analysis of the  $JHK$  variability, which reveals interesting light-curve features.

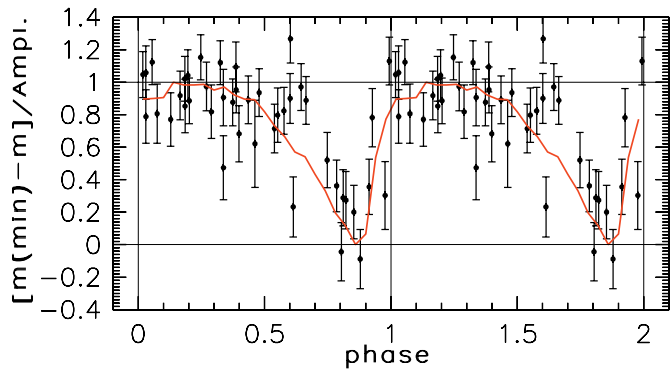
#### 2.3.1. Phase-resolved Near-infrared Color–Magnitude Hysteresis Loops

The phased  $JHK$  light curves, the  $J-K$  color variation with phase, and phased-resolved color–magnitude and color–color diagrams constructed with 2MASS data that were smoothed by taking the median are shown in Figure 5. A notable feature is that the time of maximum light in  $H$  and  $K$  bandpasses does not coincide with the time of maximum light at shorter wavelengths, but lags in phase by about 0.25. Unlike the  $J-K$  color, which

varies with an amplitude of  $\sim 0.2$  mag, the  $H-K$  color does not appear to vary: Its rms scatter is only 0.01 mag, and consistent with photometric noise (compare to 0.075 mag for the  $J-K$  color).

Perhaps the most interesting feature revealed by the high-precision 2MASS data is seen in the  $J$  versus  $J-K$  color–magnitude diagram (bottom left panel of Figure 5). In addition to the clearly seen “hysteresis” (for an illustration of a similar behavior in the  $ugr$  bandpasses, see Figure 9 in Sesar et al. 2010), the  $J-K$  color becomes bluer between phases 0.65 and 0.70 despite the decreasing brightness (see the middle right and bottom left panels and arrow in the latter panel). Given the short duration ( $\sim 45$  minutes) and a small amplitude (0.03 mag) of this feature, it is unlikely that it was well observed for other stars. We return to an interpretation of this behavior in Section 2.5.





**Figure 6.** *WISE* W1-band phased and normalized light curve for SDSS J015450+001501 is shown as symbols with error bars (as computed by the *WISE* photometric processing pipeline). The line shows phased and normalized 2MASS *K*-band light curve (same curve as in Figure 4).

(A color version of this figure is available in the online journal.)

**Table 6**

*WISE* Light Curves for RR Lyrae Star SDSS J015450+001501 (43 Epochs)

MJD	W1	W1 <sub>err</sub>	W2	W2 <sub>err</sub>
55209.272845	13.853	0.047	14.016	0.126
55209.405150	13.828	0.052	13.770	0.119
...	...	...	...	...

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

#### 2.4. *WISE* Light-curve Data

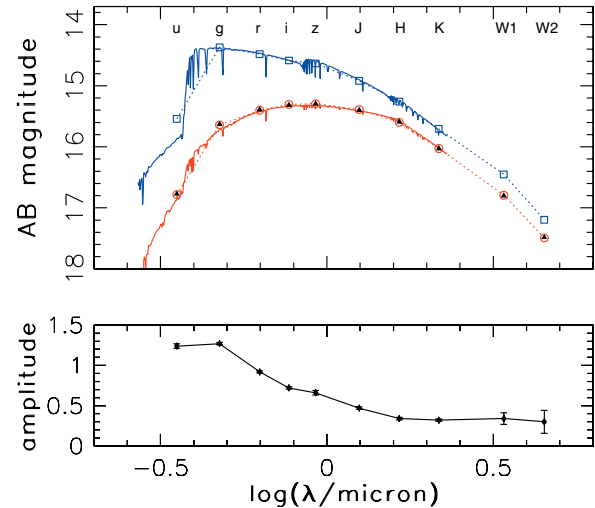
The *WISE* (Wright et al. 2010) mapped the sky at 3.4, 4.6, 12, and 22  $\mu\text{m}$ . *WISE* imaged each point on the sky multiple times to achieve its sensitivity goals and to reject transient events such as cosmic rays. SDSS J015450+001501 was measured 43 independent times, during two epochs approximately 6 months apart. The single-exposure photometric signal-to-noise ratio is high enough for light-curve analysis in the *W1* (3.4  $\mu\text{m}$ ) and *W2* (4.6  $\mu\text{m}$ ) bands: the median photometric errors are 0.05 mag for *W1* and 0.15 mag for *W2*. These two light curves (43 data points per band) are compiled in Table 6.

Although *WISE* data are noisy, it is possible to make a rough comparison with 2MASS data. As shown in Figure 6, the phased and normalized light curve in the *W1* band is fully consistent with the corresponding 2MASS light curve in the *K* band (including the amplitude). A more detailed comparison of data across all 10 bandpasses is described next.

#### 2.5. Simultaneous Analysis of Optical and Infrared Data

As shown earlier, the shape of light curves varies greatly with wavelength. Another way to look at the same data set is to construct phase-resolved spectral energy distributions (SED). SEDs at minimum and maximum phases, and at phase = 0.5, are compiled in Table 7 and shown in the top panel in Figure 7. When the SED at phase = 0.5 is scaled to a fainter flux level by 0.25 mag, it is indistinguishable from the SED at minimum phase (0.86). Assuming identical effective temperatures, this scaling factor implies that the effective radius of the star decreases by 12% between these two phases.

The variation of light-curve amplitude with wavelength is shown in the bottom panel in Figure 7. Between the SDSS *g* band (0.476  $\mu\text{m}$ ) and the 2MASS *H* band (1.65  $\mu\text{m}$ ), the amplitude steadily decreases from  $\sim 1.3$  mag to  $\sim 0.3$  mag. At



**Figure 7.** Top panel: 10 band SEDs at maximum (top) and minimum (bottom) light for SDSS J015450+001501. Data are shown by symbols and connected by dotted straight lines. Open squares correspond to maximum light and open circles to minimum light (phase = 0.86). Solid triangles, inside open circles, correspond to phase = 0.50, shifted fainter by 0.25 mag. The SED shape at phase = 0.50 is nearly indistinguishable from the SED at minimum light. The solid lines show Kurucz models for  $[\text{Fe}/\text{H}] = -1.5$ ,  $\log(g) = 3.0$ , and  $T_{\text{eff}} = 7500$  K (top) and  $T_{\text{eff}} = 6000$  K (bottom). Bottom panel: light-curve amplitude, in magnitudes, as a function of wavelength.

(A color version of this figure is available in the online journal.)

longer wavelengths there is very little change of light-curve amplitude, if any. The *u*-band and the *g*-band amplitudes are similar, which implies that the *u* – *g* color stays approximately constant over the pulsational cycle. This is easily understood as the consequence of the fact that the *u* – *g* color primarily depends on metallicity (see Marconi et al. 2006).

The overall SED shapes are well described by static model atmospheres computed by Kurucz (1979). The solid lines in the top panel in Figure 7 show Kurucz models for fixed  $[\text{Fe}/\text{H}] = -1.5$  and  $\log(g) = 3.0$ , and best-fit  $T_{\text{eff}} = 7500$  K (maximum light) and  $T_{\text{eff}} = 6000$  K (minimum light). The effective temperature step in the model library was 250 K. A slight discrepancy between the measured *u*-band magnitude at maximum light and the best-fit model can be reconciled as due to the impact of the steep SED in that region.

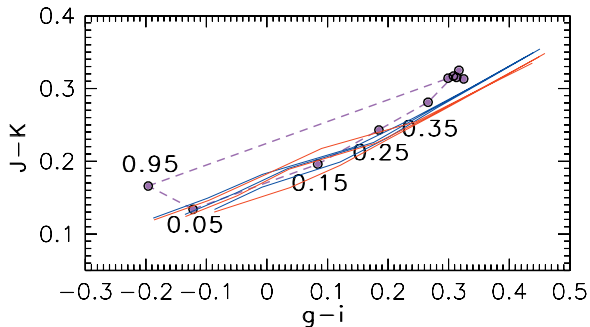
Despite this apparent success of static atmosphere models, it is easy to demonstrate that they cannot provide a complete description of the data. Figure 8 shows a phase-resolved *J* – *K* versus *g* – *i* color–color diagram. Both of these colors are largely driven by effective temperature, and Kurucz models show that the impact of  $\log(g)$  is only minor (at most a few hundredths of a magnitude in the *J* – *K* color at a given *g* – *i* color; for a detailed discussion, see Ivezić et al. 2008). Therefore, if static atmosphere models are sufficient to describe the data, then the data should follow a single line in this diagram, with the position along that line controlled by the effective temperature. In contrast, data in this color–color diagram show a similar hysteresis effect as the *J* versus *J* – *K* color–magnitude diagram (bottom left panel in Figure 5). This color–color hysteresis, however, cannot be described as the result of different stellar radii at a given effective temperature, as in the case of color–magnitude diagram.

To provide a precise quantitative estimate of the discrepancy between observed colors and colors predicted by Kurucz models, we compare a set of models for three values of  $\log(g)$  and

**Table 7**  
Spectral Energy Distribution Data for RR Lyrae Star SDSS J015450+001501

Band	$\lambda_{\text{eff}}$ ( $\mu\text{m}$ )	Mag <sub>min</sub>	Err	Mag <sub>max</sub>	Err	Amplitude	Mag <sub><math>\phi=0.5</math></sub>	Extinction Corr.
<i>u</i>	0.3540	16.96	0.02	15.72	0.02	1.24	16.70	0.179
<i>g</i>	0.4760	15.78	0.01	14.51	0.01	1.27	15.52	0.139
<i>r</i>	0.6280	15.50	0.01	14.58	0.01	0.92	15.24	0.099
<i>i</i>	0.7690	15.38	0.01	14.66	0.01	0.72	15.14	0.075
<i>z</i>	0.9250	15.35	0.02	14.69	0.02	0.66	15.10	0.056
<i>J</i>	1.25	15.42	0.01	14.95	0.01	0.47	15.18	0.031
<i>H</i>	1.65	15.62	0.01	15.28	0.01	0.34	15.36	0.020
<i>K</i>	2.17	16.04	0.01	15.72	0.01	0.32	15.79	0.013
<i>W1</i>	3.4	16.80	0.05	16.46	0.05	0.34	16.56	0.008
<i>W2</i>	4.5	17.50	0.10	17.20	0.10	0.30	17.24	0.007

**Notes.** The table lists 2MASS and *WISE* magnitudes on AB scale. The following Vega-to-AB magnitude offsets ( $m_{\text{AB}} = m_{\text{Vega}} + \text{offset}$ ) were used: 0.89, 1.37, 1.84 in *JHK*, and 2.6, 3.3 in *W1* and *W2*. Magnitude values are not corrected for interstellar medium (ISM) dust extinction. Plausible extinction corrections (Schlegel et al. 1998, SFD) are listed in the last column and are derived using the SFD value for the *r*-band extinction quoted by SDSS for this star:  $A_r = 0.099$ , and coefficients listed in the first row of Table 1 from Berry et al. (2012) for the *ugrizJHK* bands. For the *WISE* bands, the coefficients taken from Yuan et al. (2013) ( $A_{W1}/A_r = 0.084$ ,  $A_{W2}/A_r = 0.074$ ).



**Figure 8.** Symbols connected by dashed lines show 2MASS  $J - K$  color vs. SDSS  $g - i$  color for SDSS J015450+001501. Data were binned in 0.1 wide equidistant phase bins, and the bin centers are marked for a few data points (the motion during pulsational cycle is counterclockwise in this diagram). Although both colors are good estimators of the effective temperature, a hysteresis is easily seen (e.g., at  $g - i = 0$ , about 0.05 mag difference in  $J - K$  color). Note that both colors are essentially constant for phase bins from 0.45 to 0.85. The six thin, solid lines are predictions made on the basis of Kurucz static model atmospheres with effective temperatures in the range 6000–7500 K. At the blue end, they bifurcate into the groups of three tracks—they correspond to models with  $[\text{Fe}/\text{H}] = -1.5$  (the top three curves) and  $[\text{Fe}/\text{H}] = -1.0$ . For each metallicity, the three curves correspond to  $\log(g) = 2.5, 3.0$  and  $3.5$ . Note that at the blue end, the models bifurcate according to  $\log(g)$ , rather than  $[\text{Fe}/\text{H}]$  (at  $J - K \sim 0.13$ , the  $g - i$  color becomes bluer by  $\sim 0.1$  mag as  $\log(g)$  increases from 2.5 to 3.5).

(A color version of this figure is available in the online journal.)

two values of  $[\text{Fe}/\text{H}]$  that bracket the values expected for this star (see Figure 8). Models provide a fairly good agreement, to within a few hundredths of a magnitude) for the descending branch of the light curve (phases between the light curve maximum and minimum, the lower branch in Figure 8). However, all models fail to explain the observed colors during the ascending branch, as the light curve goes from the minimum light to the maximum light (note that ascending portion of the light curve is about five times shorter than the descending portion). At a given  $J - K$  colors, the discrepancy can be as large as  $\sim 0.2$  mag!

Note that this model failing cannot be simply attributed to inadequacy of Kurucz models: whatever static atmosphere model library is invoked, it should produce much smaller hysteresis in this diagram, if any. For example, at a fixed  $J - K = 0.2$ , the difference in the  $g - i$  color at the descending and ascending branches is over 0.2 mag. Similarly, at a fixed

$g - i = 0$  color, the  $J - K$  color differs by  $\sim 0.05$  mag. Such large color differences are unlikely to be explained by the impact of  $\log(g)$  parameter on static atmosphere models. It is unclear whether dynamic models can explain these data.

### 3. DISCUSSION AND CONCLUSIONS

Essentially by coincidence, the nonmodulated (non-Blazhko) RR Lyrae star SDSS J015450+001501 has been extensively observed by several major sky surveys: SDSS, 2MASS, CSS, LINEAR, and *WISE*. We have compiled data from these surveys and made the compilation publicly available in a user-friendly form. The light curves for this star are available in 10 photometric bandpasses that span more than a factor of 10 in wavelength and bracket the wavelength range where most of its luminosity is emitted. Light curves obtained by 2MASS stand out: they include close to 9000 photometric measures and provide an unprecedentedly precise view of near-infrared variability. A data set of similar completeness, precision, and wavelength and temporal coverage likely does not exist for any other RR Lyrae star.

The data for SDSS J015450+001501 presented here provide strong observational constraints for nonlinear pulsation models of RR Lyrae stars. Sesar et al. (2010) already pointed out (see their Figure 8) that there are discrepancies between the *ugriz* RR Lyrae light curves obtained by SDSS and theoretical light-curve predictions from Marconi et al. (2006). Here, we further demonstrated that static atmosphere models are insufficient to explain multiband photometric light-curve behavior. Barcza (2010) demonstrated that the quasi-static approximation is not valid for all phases during an RR Lyrae pulsational cycle. Pulsation models computed by Fokin & Gillet (1997) with a large number of mass shells in the stellar atmosphere show that the  $s3'$  and/or the merging  $s3+s4$  shockwaves might be at work at the pulsational phase range of 0.65–0.70, where we found the “kink” in the  $J - K$  color progression (Figure 5). We caution, however, that a large model survey should be conducted in a broad range of RR Lyrae physical parameters to verify the existence and the influence of these shockwaves, in particular in SDSS J015450+001501.

Another complication is that in different passbands, we observe the integrated light of different atmospheric layers. Therefore, a frequency-dependent, dynamical atmosphere model coupled to a state-of-the-art hydrocode is needed to consistently

handle the violent, shock-permeated outer parts of such large-amplitude pulsators. Frequency-dependent treatment of radiation hydrodynamics developed by Dorfi & Feuchtinger (1999) is very promising in this respect. They found good agreement between the synthetic optical RR Lyrae light curves and observations. An extension of such calculations to the near-infrared passbands would be most beneficial for comparison with the data presented here.

Ž. Ivezić thanks the Hungarian Academy of Sciences for its support through the Distinguished Guest Professor grant No. E-1109/6/2012. A.C.B. and J.R.A.D. acknowledge support from NASA ADP grant NNX09AC77G. This project has been supported by the “Lendület-2009 Young Researchers” Program of the Hungarian Academy of Sciences, the HUMAN MB08C 81013 grant of the MAG Zrt, the Hungarian OTKA grant K83790, and the KTIA URKUT\_10-1-2011-0019 grant. R. Szabó was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This publication also makes use of data products from the *Wide-field Infrared Survey Explorer* and *NEOWISE*, which are joint projects of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is <http://www.sdss.org>. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermi-

lab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

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