LARGE-AMPLITUDE ULTRAVIOLET VARIATIONS IN THE RR LYRAE STAR ROTSE-I J143753.84+345924.8

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ABSTRACT

The NASA *Galaxy Evolution Explorer* (*GALEX*) satellite has obtained simultaneous near-ultraviolet (NUV) and far-ultraviolet (FUV) light curves of the ROTSE-I Catalog RR Lyrae type ab variable star J143753.84+345924.8. A series of 38 *GALEX* Deep Imaging Survey observations well distributed in phase within the star's 0.56432 day period shows an AB = 4.9 mag variation in the FUV (1350–1750 Å) band and an AB = 1.8 mag variation in the NUV (1750–2750 Å) band, compared with only a 0.8 mag variation in the broad, unfiltered ROTSE-I (≈4500–10,000 Å) band. These *GALEX* UV observations are the first to reveal a large RR Lyrae amplitude variation at wavelengths below 1800 Å. We compare the *GALEX* and ROTSE-I observations to predictions made by recent Kurucz stellar atmosphere models. We use published physical parameters for the comparable period (0.57433 days), well-observed RR Lyrae star WY Antliae to compute predicted FUV, NUV, and ROTSE-I light curves for J143753.84+345924.8. The observed light curves agree with the Kurucz predictions for [Fe/H] = −1.25 to within AB = 0.2 mag in the *GALEX* NUV and ROTSE-I bands and to within 0.5 mag in the FUV. At all metallicities between solar and 1/100 solar, the Kurucz models predict 6–8 mag of variation at wavelengths between 1000 and 1700 Å. Other variable stars with similar temperature variations, such as Cepheids, should also have large-amplitude FUV light curves, observable during the ongoing *GALEX* imaging surveys.

Subject headings: stars: atmospheres — stars: individual (ROTSE-I J143753.84+345924.8) —
stars: variables: other — ultraviolet: stars

1. INTRODUCTION

RR Lyrae stars vary in brightness primarily because of radial pulsations, such that the contraction and expansion of their stellar surface produce a temperature variation that is observed as a change in their apparent stellar magnitude. This cyclic behavior has been well observed for many thousands of these Population II stars, with an apparent magnitude variation of ~0.3 mag when observed at near-infrared wavelengths and a variation of ~1.0 mag at visible wavelengths (Skillen et al. 1993). Since the physical mechanism causing the brightness variation is the same for each RR Lyrae star, it follows that their absolute magnitudes are also similar, and thus they provide a useful tool for determining stellar distances. In addition, observation of their periodic variability can also provide important empirical tests of stellar pulsation and stellar atmosphere theory (Kurucz 2002; Mihalas 2003).

Although the variation in apparent magnitude in the ultraviolet (UV) regime is far more pronounced (i.e., >2 mag), observations of RR Lyrae stars for wavelengths less than 3000 Å are surprisingly sparse. The first observation of the UV light curve of an RR Lyrae star was reported by Hutchinson et al. (1977) using photometry at 1550 Å gained with the *OAO 2* satellite. Since then, similar observations in the UV have been reported for RR Lyrae, X Arietis, W Virginis, and several other bright variables using the *ANS* and *IUE* satellites (Bonnell et al. 1982; Bonnell & Bell 1985; Bohm-Vitense et al. 1984). In general, most of these data have been recorded at λ > 1750 Å with an incomplete sampling over the whole phase of the stellar light curves. In this Letter, we present observations well distributed in phase of the UV light curve of an RR Lyrae star, cataloged by the first Robotic Optical Transient Search Experiment (ROTSE-I) as J143753.84+345924.8 (Akerlof et al. 2000). The *Galaxy Evolution Explorer* (*GALEX*; Martin et al. 2005) obtained simultaneous light curves in the wavelength ranges 1350–1750 and 1750–2750 Å.

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GALEX Field NGPDWS_00	Julian Day +2,452,800	Phase[a]	Exposure (s)	AB$_{NUV}$	σ_{NUV}	AB$_{FUV}$[b]	σ_{FUV}[b]
1	5.605636	0.443042	222	17.375	0.021	...	...
2	5.655968	0.532231	27	17.559	0.065	...	...
3	5.724452	0.653587	25	17.405	0.063	...	...
4	5.802598	0.792066	1693	17.537	0.008	22.421	0.172
5	5.871100	0.913452	1692	16.789	0.006	20.992	0.076
6	5.939589	0.034818	1691	15.874	0.004	18.613	0.024
7	6.008085	0.156194	1691	16.522	0.005	20.625	0.064
8	6.076574	0.277560	1690	16.947	0.006	21.413	0.099
9	6.145075	0.398947	1689	17.302	0.008	21.994	0.132
10	6.214676	0.522281	1496	17.422	0.008	23.010	0.268
11	6.285092	0.647062	1164	17.439	0.010	22.420	0.193
13	6.424456	0.894019	752	17.241	0.011	21.862	0.161
14	6.493773	0.016851	608	15.788	0.006	18.296	0.035
15	6.563513	0.140432	393	16.487	0.011	20.447	0.116
16	6.632969	0.263511	225	16.915	0.017	21.675	0.270
17	6.683429	0.352927	24	17.151	0.057	...	...
18	6.830012	0.612678	1680	17.447	0.008	22.558	0.173
19	6.898507	0.734054	1680	17.421	0.008	21.839	0.135
20	6.966997	0.855420	1679	17.539	0.008	22.869	0.203
21	7.035498	0.976806	1678	15.916	0.004	18.832	0.027
22	7.103987	0.098172	1677	16.254	0.005	19.634	0.039
26	14.159219	0.600288	1439	17.438	0.009	22.418	0.183
27	14.573721	0.334800	827	17.120	0.010	22.022	0.203
28	15.118443	0.300067	1383	17.042	0.007	21.634	0.117
29	15.598090	0.150018	1354	16.502	0.006	20.338	0.062
30	16.077755	0.000000	1322	15.751	0.004	18.202	0.023
31	16.557448	0.850033	1289	17.565	0.010	22.646	0.210
32	17.517454	0.551197	1134	17.440	0.010	23.081	0.274
33	18.750671	0.736501	1148	17.399	0.010	22.556	0.214
34	18.819213	0.857960	1144	17.518	0.010	21.757	0.159
35	19.093409	0.343844	1131	17.138	0.009	21.878	0.151
36	19.161956	0.465312	1126	17.394	0.010	22.243	0.183
37	19.573252	0.194143	1106	16.659	0.007	20.753	0.085
38	19.641800	0.315612	1103	17.066	0.008	21.878	0.151
39	20.053119	0.044484	1089	15.917	0.005	18.734	0.032
40	20.121673	0.165963	1087	16.571	0.007	20.486	0.075
41	20.533009	0.894866	1078	17.228	0.009	21.682	0.140
42	20.601557	0.016335	1075	15.772	0.005	18.372	0.027

[a] The phase was computed with the ROTSE-I period of 0.564323 ± 0.000058 days, using *GALEX* maximum light at JD 2,452,816.077755.

[b] An ellipsis indicates that the star was not detected in the FUV observation.

2. OBSERVATIONS AND DATA REDUCTION

GALEX observations of the star ROTSE-I J143753.84+345924.8 (hereafter R-J14+34.5) were obtained serendipitously during a 15 day interval in 2003 July. The 38 exposures, most between 1000 and 1700 s duration, were part of the mission's Deep Imaging Survey program to map a region named NGP_DWS_00 near the north Galactic pole. Data were collected in the form of time-tagged photon events in the far-UV (FUV; 1350–1750 Å) and near-UV (NUV; 1750–2750 Å) channels. These photons were then processed by the *GALEX* science data analysis pipeline (Morrissey et al. 2005) to produce a 3840 × 3840 pixels^2 image (1″5 pixel^{-1}) for each of the UV detectors. Automated Source Extractor software (Bertin & Arnouts 1996) subsequently detected sources and computed aperture photometry on them, resulting in an AB magnitude (Oke 1974) in both the *GALEX* FUV and NUV wave bands. Table 1 details the date, exposure time, and *GALEX* magnitude for each observation.

The ROTSE-I visible light curve consists of 76 observations recorded over a 95 day interval, in 1999 March–June (Akerlof et al. 2000). ROTSE magnitudes are derived from unfiltered CCD images with a broad 4500–10,000 Å bandpass (Wozniak et al. 2004), and we note that Blazhko amplitude modulation is not evident in the ROTSE-I data.

To estimate the distance to R-J14+34.5, we first convert the mean m_{ROTSE} to an m_V, using the conversion factors of Amrose & McKay (2001). The distance to R-J14+34.5 is estimated to be 3.6 ± 0.5 kpc, derived using $m_{ROTSE} = 13.78$, $m_V = 13.64$, an absolute magnitude of $M_V = 0.6$, and $E(B-V) = 0.09$, taken from the reddening maps of Schlegel et al. (1998).

3. DISCUSSION

In Figure 1, we compare ROTSE-I and *GALEX* NUV and FUV observed light curves, phased using the Akerlof et al. (2000) period of 0.564323 ± 0.000058 days. In the NUV, a variation of AB = 1.8 mag is observed, whereas in the FUV this variation is much more pronounced and reaches ~5 mag. Measurement errors for these magnitudes are given in Table 1 and are typically $\sigma \leq 0.01$ mag at NUV wavelengths and rise to $\sigma = 0.3$ mag at AB = 23 mag in the FUV.

In order to model these observed light curves, we require values of the stellar temperature and radius as a function of phase, together with values for stellar metallicity and surface gravity (g). Here we assume a mean log $g = 2.80$, which Skillen et al. (1993) has derived for WY Antliae. Instrument response functions of both the *GALEX* (Morrissey et al. 2005) and ROTSE-I (Wozniak et al. 2004; Apogee Instruments, Inc. 2004) instruments are required to convert the calculated light curves to observed magnitudes.
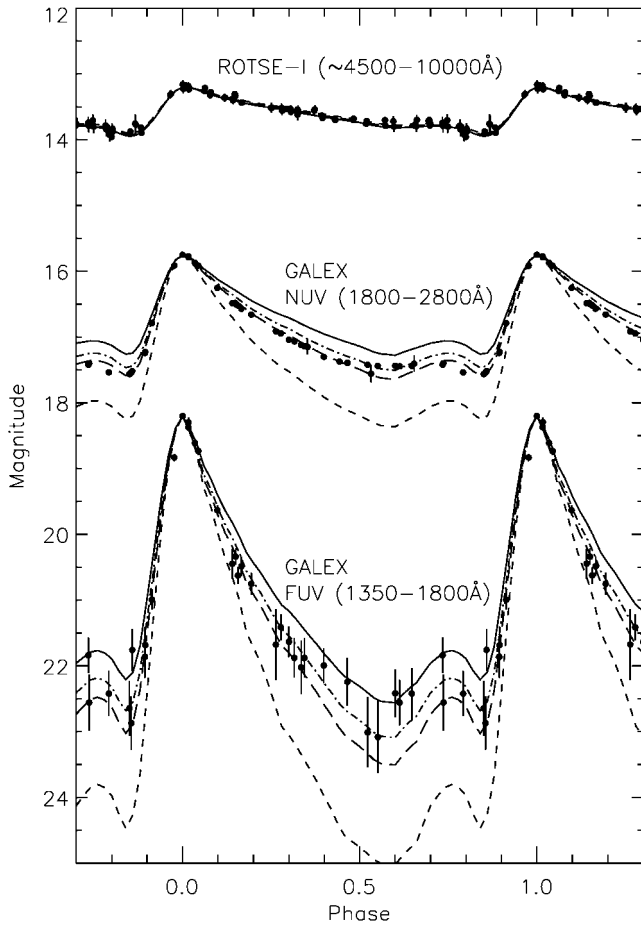
FIG. 1.—Observed ROTSE-I and *GALEX* light curves of J143753.84+ 345924.8 (*filled circles*). The vertical bars show 2 σ errors. Predicted light curves are overlayed for [Fe/H] = −2.0 (*solid line*); [Fe/H] = −1.25 (*dot-dashed line*); [Fe/H] = −1.0 (*long-dash ed line*); and [Fe/H] = 0.0 (*short-dashed line*). All four curves are nearly coincident in the ROTSE-I wave band.

FIG. 2.—*Top panel:* Kurucz model spectra at maximum light (7300 K) and minimum light (5900 K), for [Fe/H] = −1.25 and log g = 2.80. The vertical axis is logarithmic. *Bottom panel:* Predicted amplitude of RR Lyrae light curve as a function of wavelength, for [Fe/H] = −2.0 (*thick line*); [Fe/H] = −1.0 (*medium line*); and [Fe/H] = 0.0 (*thin line*).

The values of stellar temperature and radius are normally derived using visible and infrared photometry and spectroscopy using the Baade-Wesselink method. Such empirical data are unfortunately not available for R-J14+34. Instead, we use temperature and radius curves derived for the well-observed RR Lyrae star WY Antliae (Skillen et al. 1993), which has a period of 0.574330 days, very close to that of R-J14+34. Furthermore, the Two Micron All Sky Survey (2MASS; Cutri et al. 2003) observed the ROTSE star near maximum light, when the $V-K$ color of 0.62 was very close to the $V-K$ of 0.59 measured by Skillen et al. (1993) for WY Antliae at maximum light, a confirmation that the two stars are physically similar.

We used the model atmosphere grid of Kurucz (2003) to compute the theoretical UV and visible light curves shown in Figure 1. These models use the updated OPAL opacities of Iglesias & Rogers (1996) and include the effects of quasi-molecular absorption by hydrogen (Castelli & Kurucz 2001) that occur near the center of the *GALEX* FUV band. The models, designated ODFNEW on the Kurucz Web site, incorporate the "no convective overshoot" treatment of Castelli et al. (1997).

In Figure 2 (*top panel*), we show the Kurucz-predicted UV and visible spectra at minimum and maximum brightness (i.e., T_{min} = 5900 K and T_{max} = 7300 K). We use the WY Antliae metallicity of [Fe/H] = −1.25 from Skillen et al. (1993) for the model atmosphere. In Figure 2 (*bottom panel*), we show the predicted difference between maximum and minimum
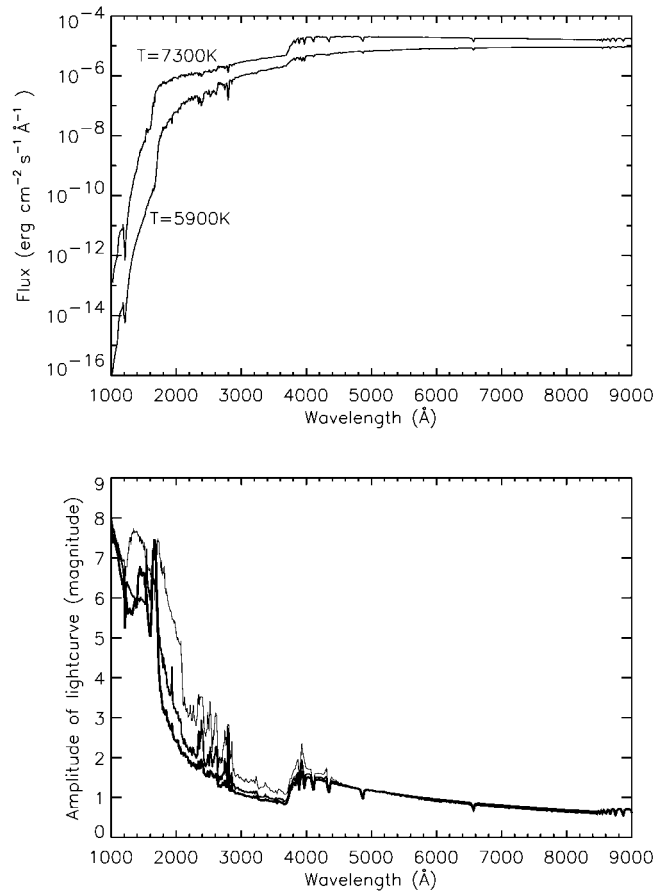
brightness for the 1000–9000 Å region. We note a dramatic increase in amplitude in the UV region shortward of 1700 Å that rises to AB > 7 mag. The steep increase in flux between 1500 and 1800 Å is due to the photoionization edge of silicon at 1656 Å and means that *GALEX* FUV observations of RR Lyrae stars are dominated by 1750 Å photons where the amplitude is AB ∼ 5 mag. The *GALEX* NUV band is dominated by photons at wavelengths longer than 2700 Å.

In Figure 2 (*bottom panel*), we also show the effect of metallicity on the amplitude of the predicted light curve. It is immediately noticeable that the *GALEX* NUV and FUV bands are a far more sensitive indicator of metallicity than either the ROTSE-I visible or λ < 1300 Å observations. This effect can also be seen in Figure 1, in which we have compared the observed ROTSE-I and *GALEX* light-curve magnitudes with those derived from Kurucz model atmospheres using three values of metallicity. We see that the best fit to the FUV light curve occurs for [Fe/H] = −1.25, which is the value chosen by Skillen et al. (1993) for the star WY Antliae. The small residual differences between the observed and predicted UV light curves are probably due to temperature differences between R-J14+34.5 and WY Antliae.

We emphasize that the derived FUV flux is highly sensitive to a change in the Kurucz model atmosphere temperature of only 100–200 K, particularly around 6000 K at minimum brightness. A smaller temperature range experienced during the star's oscillation cycle would require a larger value of metallicity to fit

the observed UV light curves. Our assumption of a constant surface gravity introduces far smaller errors: varying log *g* from 2.5 to 3.0 makes a difference of less than 0.1 mag in the ROTSE-I and GALEX NUV light curves. The largest effect is in the FUV, where the difference is less than 0.25 mag, compared with the amplitude of ≈5 mag, which is largely caused by the temperature variation. Other potential sources of error in this analysis are the uncertainty in the *GALEX* FUV magnitudes at AB > 22.0 mag and the uncertainty in the physical parameters derived by Skillen et al. (1993).

Finally, we note that the high sensitivity and wide field of view of the *GALEX* instrument will result in many more detections of variable sources during its UV imaging survey of the sky. In fact, preliminary detections have already been made for the RR Lyrae stars UU Indi and HL Herculis, in which respective variations in the NUV magnitude of AB = 2.5 mag and AB = 1.8 mag have been recorded. Kurucz model spectra suggest that Cepheids and other instability strip (T = 6000–8000 K) variable stars should also have large-magnitude variations in the FUV. However, the advantage of observing this large flux variation in the FUV is unfortunately offset by the corresponding faintness in the FUV magnitude of these stars.

Hence, their potential use as cosmic distance scale indicators may well be of limited practical value.

REFERENCES

Akerlof, C., et al. 2000, AJ, 119, 1901
Amrose, S., & McKay, T. 2001, ApJ, 560, L151
Apogee Instruments, Inc. 2004, AP10 Cooled CCD Camera (http://www.ccd.com/AP10.PDF)
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bohm-Vitense, E., Proffitt, C., & Wallerstein, G. 1984, in Future of Ultraviolet Astronomy Based on Six Years of *IUE* Research, ed. J. M. Mead, R. D. Chapman, & Y. Kondo (NASA CP-2349; Washington, DC: NASA), 348
Bonnell, J., & Bell, R. 1985, PASP, 97, 236
Bonnell, J., Wu, C.-C., Bell, R., & Hutchinson, J. 1982, PASP, 94, 910
Castelli, F., Gratton, R. G., & Kurucz, R. L. 1997, A&A, 318, 841
Castelli, F., & Kurucz, R. L. 2001, A&A, 372, 260
Cutri, R. M., et al. 2003, Explanatory Supplement to the 2MASS All Sky Data Release (http://www.ipac.caltech.edu/2mass/releases/allsky/doc/explsup.html)
Hutchinson, J., Hill, S., & Lillie, C. 1977, ApJ, 211, 207

Iglesias, C. A., & Rogers, F. J. 1996, ApJ, 464, 943
Kurucz, R. L. 2002, in New Quests in Stellar Astrophysics: The Link between Stars and Cosmology, ed. M. Chavez, A. Bressan, A. Buzzoni, & D. Mayya (Dordrecht: Kluwer), 3
———. 2003, Grids of Model Atmospheres (http://kurucz.harvard.edu/grids.html)
Martin, D. C., et al. 2005, ApJ, 619, L1
Mihalas, D. 2003, in ASP Conf. Ser. 288, Stellar Atmosphere Modeling, ed. I. Hubeny, D. Mihalas, & K. Werner (San Francisco: ASP), 471
Morrissey, P., et al. 2005, ApJ, 619, L7
Oke, J. B. 1974, ApJS, 27, 21
Schlegel, D., Finkbeiner, D., & Davis, M. 1998, ApJ, 500, 525
Skillen, I., Fernley, J., Stobie, R., & Jameson, R. 1993, MNRAS, 265, 301
Wozniak, P. R., et al. 2004, AJ, 127, 2436