RS Sagittae: the Search for Eclipses

Jerry D. Horne
3055 Lynview Drive, San Jose, CA 95148; jdhorne@hotmail.com

Presented at the 100th Annual Meeting of the AAVSO, October 8, 2011; received November 9, 2011; revised January 3, 2012; accepted February 13, 2012

Abstract New V-, B-, I_c-, and R-band photometry of RS Sge has been obtained for 2010 and 2011. These new observations, when combined with previous observations, provide clear verification of RS Sge as an RVb-type variable. The observations also allowed development of B–V, V–I, and V–R color indexes for RS Sge and an examination of calculated vs. observed minima. The light curve shows evidence of both a primary and secondary eclipse with a period of 55.427 days, although the eclipse is difficult to detect because of the intrinsic short and long period variation of the star. The eclipse data have been analyzed following the principles of the Wilson-Devinney method resulting in development of a binary model for the RS Sge system.

1. Introduction

The designation for RS Sge in the *General Catalogue of Variable Stars* (GCVS; Samus *et al.* 2011) is RVB+EA. That is, this star is a RV Tauri, type b star (RVb). It is the only RV Tauri star in the GCVS which is also labeled as an eclipsing binary (EA) (GCVS 2011), since two "Algol-like" fades have been previously reported (Kardopolov and Filip'ev 1985). Since then, there have been no published reports of eclipses for this star.

As part of its *Eyepiece Views* notices, periodic observations of RS Sge were recommended by the AAVSO (Broens 2007). In part because of this recommendation, and other discussions at the AAVSO annual meeting in 2009, a detailed multi-year study of RS Sge was begun in 2010, utilizing both AAVSOnet and the author's telescopes in order to detect eclipses for RS Sge.

RV Tauri stars are giant or supergiant stars, having masses close to that the Sun, of spectral types of F or G at maximum light and G or early K at minimum light (Fokin 1994), and typically have periods between 30 and 150 days (Sterken and Jaschek 1996). Most have low metal abundances (Fokin 1994). RV Tauri stars are known to be strong infrared sources (Jura 1986) from substantial amounts of dust surrounding them (Fokin 1994). It has also been postulated that it is common for RV Tauri stars to be part of binary systems (Van Winckel *et al.* 1998). The majority of RV Tauri stars are in the RVa subclass, while a smaller percentage of these stars, the RVb subclass, also show a long term variation of hundreds to thousands of days (Pollard *et al.* 1996).

Because of the alternating shallow and deep minima of RV Tauri stars, the usual method of determining the period from adjacent minima is not used. The established convention for these types stars places the primary or deepest minima at phase 0.0, and the secondary, or shallow minimum at phase 0.5. Additionally, the primary or fundamental period is defined to be the time between the deepest minima. The period between adjacent minima is then designated as the half-period (Fokin 1994).

2. Previous observations

RS Sge first appears as a variable in the German publication A*stronomiche Nachrichten* in 1905 (Wolf and Wolf 1905). It was also noted as a variable by Walter Baade, who provided more precise coordinates (Baade 1928).

The first detailed study of the star was published by Tsessevich in 1977. He reported both "fast" and "slow" fluctuations in the light curve over an approximately twenty-year period. Between JD 243600 and 2443000, Tssesevich noted the "fast" period, corresponding to the time between adjacent minima, as 41.1975 days. Tsessevich noted that "slow" fluctuations had a period of 1123 days. This first full light curve, generated for the long term variation in RS Sge, is shown in Figure 1.

Kardopolov and Filip'ev (1985) focused on the short term variability of RS Sge and observed two types of minima, one deep (11.1 to 12.0 V mag.), one more shallow (11.25 to 11.70 V mag.), and noted the fundamental period between deep minima was approximately 90 days. As was mentioned previously, they also noted two "Algol-like" fades on JD 2444837.22 and 2444865.17 of approximately 0.15 V magnitude. These fades appear as single data points on their light curve of RS Sge, and measurement of the eclipse width and depth is somewhat uncertain. It is solely from these two reported fades that the apparent eclipse period for RS Sge is given as 27.95 days. This short term variability and the apparent eclipses are shown in Figure 2.

A query of the current ASAS project database, (Pojmański 2000), shows that more than 350 observations of RS Sge were made between 2003 and 2008. The long and short term variation of RS Sge from these ASAS observations is shown in Figure 3.

Likewise, a query of the AAVSO database (AAVSO 2011) returns a number of observations were made by both CCD and visual observers over a longer period, approximately twenty years. A corresponding graph of those observations shows a long term variation of RS Sge that is very similar to the ASAS light curve in Figure 3 (bottom).

A period analysis was conducted using the software package PERANSO (Vanmuster 2007) for both the AAVSO and ASAS observations of RS Sge, and this analysis indicates that the long period variation is 1193.49 ± 0.9 days, the fundamental period as 80.90 ± 0.7 days, and the half period as 40.55 ± 0.3 days. It does not reveal any significant period of approximately 28 days corresponding to the eclipse period reported by Kardopolov and Filip'ev (1985).

Self-correlation analysis, (Percy and Mohammed, 2004) also illustrates the approximately 40- and 80-day half and full period respectively (Figure 4, top), and an approximately 1,200-day long term variation (Figure 4, bottom). Similar to the period analysis, a self-correlation analysis does not indicate the presence of a twenty-eight day eclipse period for RS Sge in the ASAS and AAVSO data.

3. Current observations

For 2010 and 2011, observations of RS Sge were carried out using a number of telescopes:

- W28—a 28-cm Celestron, part of the AAVSOnet, located at the Astrokolkhoz telescope facility near Cloudcroft, New Mexico;
- W30—a 30-cm Meade LX200, part of the AAVSOnet, also located at the Astrokolkhoz telescope facility;
- SRO50—a 0.5-m telescope, part of the AAVSOnet, located at the Sonoita Research Observatory in Arizona;
- a 0.25-m Meade LX200, located in San Jose, California.

Depending on the specific instrument and filter, exposures ranging from 60 to 300 seconds were made using Johnson B, V, R, and Cousins I filters. Each recorded image was processed using established procedures. Photometric measurements were made using the AAVSO VPHOT application, using the corresponding AAVSO photometric sequence for RS Sge. The air mass for observations ranged from 2.17, for those few observations made earlier in the year, to 1.02, when RS Sge was at higher elevations during the night. Uncertainties for the photometric measurements averaged 0.08 mag. for B band, 0.03 mag. for V and R band, and 0.05 mag. for I band.

3.1. Light curves and color indexes

BVRI light curves from 2011 are shown in Figure 5. The overall variation for the B band is approximately 1.1 magnitude, and 0.6 for the other color curves. While the minima are fairly well aligned among the color curves, the maxima occur at different time periods, with the B-band maxima being well in advance of the V- or I-band maxima. The color indexes from the 2011 observations are shown in Figure 6. Examination of the V–I and B–V color indexes shows that these color indices have a saw-tooth type pattern, with the index values rising to a sharp peak at the maxima, while the V–R color index shows a more rounded maxima. The largest range of differences occur in the B–V index, almost 0.6 magnitude, while the V–I and V–R indexes show range differences on the order of 0.4 magnitude.

3.2. Observed vs. calculated minima

Examination of the 2011 RS Sge light curves in Figure 5 shows the typical RV Tauri-type alternating deep and shallow minima in their light curves, (Pollard *et al.* 1996). For RS Sge, this effect is most pronounced in the V band, also shown in Figure 10, when one compares the minima at JD 2455763 (14.1 V mag.) , JD 2455820 (14.25 V mag.), and JD2455846 (14.08 V mag.).

Additionally, it is typical for RV Tauri stars to generally show random fluctuations in period from one cycle to the next, (Percy *et al.* 1997). RS Sge follows this tendency, as the difference between minima is not constant, and did vary by as much as twelve days during the 2010 and 2011 observations. It was noticed that RS Sge apparently also has short bursts of fairly regularly spaced minima. If the average magnitude of each minima cycle is calculated and subtracted from the magnitude of each data point, the long term variation can be extracted from the light curve and the minima of 2010 and 2011 can be directly compared. Additionally, using the half period, 40.55 days, obtained from the period analysis of the ASAS data for RS Sge, the observed vs. calculated minima from 2010 and 2011 can be graphed. As shown in Figure 7, RS Sge had a number of minima that closely match the calculated date for the minima in 2010 and 2011.

4. Evidence of eclipses

An important aspect of the RS Sge light curve is that the segments between maxima and minima are sections of time where the star's magnitude is changing very rapidly, at times more that 0.1 magnitude in a single day. While this change is small in comparison to other variable stars, such a change is sufficient to effectively mask an eclipse of 0.15 magnitude in depth over perhaps several days, as was reported for RS Sge (Kardopolov and Filip'ev 1985). One of the perhaps fortuitous aspects of the 1985 eclipses was that they happened during a relatively slow period of change in RS Sge's light curve, as seen in Figure 2.

The challenge then, in finding evidence of eclipses in the current set of data from 2010 and 2011, is to separate where possible, any effects from an eclipse from the overall long and short term variability of RS Sge.

4.1. Eclipse evidence from 2010

Although the ASAS data are generally too sparse to use for eclipse detection, certain segments are useful for light curve comparisons. If a comparison is made for RS Sge between a segment of ASAS data from 2007, Figure 8 (top), and the other 2010 data, in Figure 8 (bottom), it can be noted that almost every cycle is fairly smooth, with a rapid rise to maxima, then a more gradual decline to the minima. In the 2010 data, Figure 8 (bottom) a discrepancy is noted around JD 2455370, in that after reaching the maxima, the light curve immediately drops 0.15 magnitude, then has a short segment of minor variability before resuming the normal gradual decline at JD 2455380.

If it assumed that this maximum around JD 2455370 has been altered by an eclipse, it is possible to recalculate the star's light curve for this segment. By also assuming that the light curve should have been following a more constant slope between JD 2455370 and 2455410, a possible eclipse can be revealed by subtracting out the expected slope of the light curve for this segment. The result of modifying the observational data in such a manner is shown in Figure 9. This residual light curve shows good evidence of an eclipse centered on JD 2455376.81393, which is also 377 27.95-day cycles from the first 1985 eclipse. This eclipse is approximately 0.15 V mag., in depth, and occurs over multiple days. In examining both the residual and the observed light curve for 2010 in Figures 8 and 9, there is additional evidence of eclipses at JD 2455321 and 2455404, which are multiples of this same 27.95 day cycle, prior to, and after the JD 2455375 event, although these eclipses appear more shallow.

4.2 Eclipse evidence from 2011

The light curve from 2011, shown in Figure 10, also shows evidence of an eclipse around JD 2455763, which is fourteen 27.95-day cycles from the 2010 eclipse at JD2455375. In this case, the eclipse appears to last approximately five days and reaches a depth of at least 0.11 V mag. In examining the overall light curve for 2011 in Figure 10, there is additional evidence of an eclipse around JD 2455848, also separated by multiples of 27.95 days, from the other 2011 eclipse event. The apparent eclipse at JD 2455848 is definitely shallower, only about 0.04 V mag. in depth.

4.3 Eclipse discussion

This evidence, the case of the presence of more shallow eclipses, is slightly different than what was reported by Kardopolov and Filip'ev (1985). In examining their light curve in Figure 2, it can be noted that the second eclipse at JD 2444865.17 is only partially recorded. Plus, its overall depth is even more uncertain than the first eclipse at JD 2444837.22, so the interpretation that there were two similar "Algol-like" fades in 1985 may be incorrect.

Additionally, while there is evidence of eclipse activity happening in multiples of approximately twenty-eight days for RS Sge, this difference in depth raises the possibility that the actual eclipse period might actually be approximately 56 days. The difference in depth obviously could represent a primary and secondary eclipse. In fact, if a period analysis is performed on the RS Sge 2010 and 2011 data, there is a small, but apparently significant period found in the PERANSO (Vanmunster 2007) period diagram corresponding to 55.86 ± 0.54 days, which is very close to twice the 27.95 period from 1985. The theta value, or calculated Schwarzenberg-Czerny value from the ANOVA analysis method (Schwarzenberg-Czerny 1996) is 11.53 for this 55.86-day period. This compares to a theta value of 28.12 for an ANOVA analysis of the 40.55-day half period, and 37.4 for the 80.9-day full period of RS Sge from the ASAS data.

5. System modeling

There is some concern that despite some observational evidence, the fact that RV Tauri stars are supergiant stars (Jura 1986), the corresponding stellar radius of such a star might make the existence of such a stable eclipsing system with an orbital period of 27.95 or 55.86 days, with eclipses lasting multiple days, somewhat improbable.

5.1. Astrophysical considerations

A simple astrophysical calculation can be performed to test the orbital possibilities of such an RS Sge system. It can be assumed that RV Tauri stars have luminosities (L_{RV}) of 10^3 to 10^4 $L_\odot$ (Fokin 1994) and RV Tauri stars vary from F to G, or G to K (Samus *et al.* 2011). This corresponds to a T_{eff} range of 4800–6500 K, so it is possible to calculate a range of possible stellar radii (R_{RV}) for RV Tauri stars by using the formula for stellar luminosity:

$$L = 4\pi R^2 \sigma T^4 \qquad (1)$$

Using the luminosity of an RV Tauri star, L_{RV}, then dividing by the luminosity of the sun, $L_\odot$, and cancelling the constants, this becomes:

$$L_{RV} / L_\odot = T^4_{RV} R^2_{RV} / T^4_\odot R^2_\odot \qquad (2)$$

Utilizing the range of T_{eff} and luminosities for RV Tauri stars, the range of possible radii is then:

$$R_{RV} = 15 - 100\ R_\odot \qquad (3)$$

In terms of Astronomical Units (A.U.), this range is: $R_{RV} = 0.07 - 0.46$ A.U.

For an eclipse period of 27.95 days, Kepler's Third Law gives us the semi-major axis of a possible secondary component of RS Sge as:

$$a = 0.18 \text{ A.U.} \qquad (4)$$

A companion star is possible if the luminosity of RS Sge is constrained to the lower end of the assumed range. If the primary eclipse period is closer to 56 days, the size of the semi-major axis is of course correspondingly larger, as is the possible range of luminosities.

5.2. Binary stellar modeling

A more rigorous method of modeling the RS Sge system is possible through an examination of the RS Sge light curves via a binary star modeling program such as PHOEBE (Prsa and Zwitter 2005), which utilizes the methods of the Wilson-Devinney code (Wilson 1994).

A difficulty in using such a modeling program like PHOEBE for RS Sge is that the star exhibits complex light curve changes outside of any possible eclipse activity. The net effect is that different eclipse events, on approximately 28-day centers, happen at very different magnitudes, ranging from approximately 11.5 to 14.0 V magnitude. While filtering for these eclipse data, some care must be taken to minimize any data selection bias, and these data, must, in turn, be converted to a common base magnitude so that the PHOEBE program can make sense of them. Nonetheless, as the JD 2455763 eclipse is the best defined, prior to input into PHOEBE, the magnitude of all eclipse V-band data from 2010 and 2011 was re-scaled to that JD 2455763 magnitude base of 14.02 V mag.

The best fit for the 2010 and 2011 RS Sge V-band data from PHOEBE is shown in Figure 11. This fit is for a detached binary system, based upon a 55.33-day orbital period with both primary and secondary eclipses, of 0.14 and 0.05 V magnitude, respectively. While the data are a good fit to the primary eclipse, there is some scatter about the secondary eclipse. The corresponding modeling of the RS Sge system is listed in Table 1.

The outputs from the binary model for RS Sge are consistent with the previous astrophysical calculations, in terms of stellar radius and effective temperature of RS Sge. The orbital period from the PHOEBE model is shorter than the one from the 2010 and 2011 period analysis, by about a half a day, but within the degree of uncertainty (0.54 day). It is also important to point out that because of limitations in the accuracy of the photometry, the small amount of eclipse data, and the inherent limitations of the binary models, the results offered here are from simply one solution, consistent with the available observational data, but it is not necessarily a mathematically unique solution.

6. Conclusions

This paper has reviewed previous and recent observations of RS Sge, including BVRI light curves, color indexes, period and self-correlation analyses, and an examination of observed versus calculated minima. There is good verification of the classification of RS Sge as a RVb-type variable star. The half-period of RS Sge was found to be 40.55 days, while the full period between the deep minima is 80.9 days. As is typical for RV Tauri stars, RS Sge shows some cycle-to-cycle variations in the timing of the minima. The long term variation of RS Sge was found to be 1193.5 days and spans more than 3.0 V magnitudes.

There is evidence of eclipse activity for RS Sge in the 2010 and 2011 data, seemingly confirming the eclipses first published in 1985. Because in some cases, the eclipse data are wrapped within the overall complex variation of this RV Tauri-type star, this confirmation is not totally unambiguous. Additional observations are needed to gather additional data and refine the nature of the RS Sge eclipses. Binary modeling of the current data does show a reasonable fit to a system with an orbital period of 55.33 days, with both primary and secondary eclipses being present.

7. Acknowledgements

This research has made use of the SIMBAD data base, operated at Centre de Données astronomiques de Strasbourg, the ASAS database, managed by Grzegorz Pojmański of the Warsaw University Observatory, and the GCVS databases, operated by the Sternberg Astronomical Institute, Moscow, Russia. Special acknowledgement is given for the data and resources of the American Association of Variable Star Observers (AAVSO), especially the telescopes and their operator at its Astrokolkhoz facility.

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Table 1. Output from PHOEBE for the RS Sge data from AAVSOnet and the author's observations in 2010 and 2011.

Parameter	*Value*
Mass Ratio: q	0.95999
Primary Radius: R_p	13.02 $R_\odot$
Secondary Radius: R_s	5.92 $R_\odot$
Primary T_{eff}	6400 K
Secondary T_{eff}	5020 K
Semi-major axis: a	76.0 $R_\odot$
Inclination: i	81.1°
Eccentricity: e	0.05
Period: p	55.33 d
Epoch (HJD)	2455765.1008

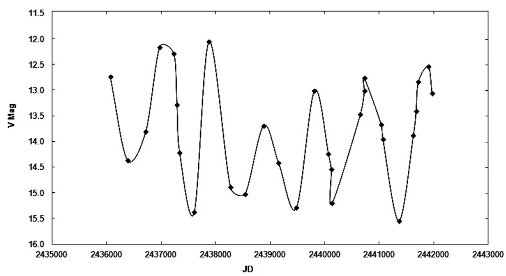


Figure 1. Long-term variability of RS Sge. From observations by Tsessevich (1977).

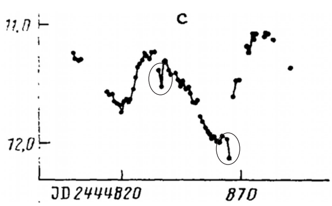


Figure 2: Short-term variability of RS Sge. The Algol-like fades are identified with a circle. From photoelectric observations by Kardopolov and Filip'ev (1985); light curve published in Kardopolov and Filip'ev (1988).

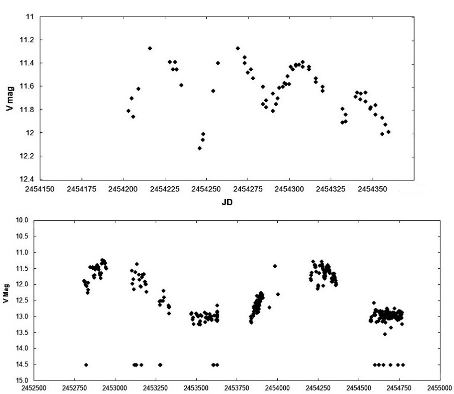


Figure 3. Short-term, April–September 2007 (top graph, black dots), and long-term (bottom graph, black dots) variability of RS Sge. From ASAS observations 2003–2008.

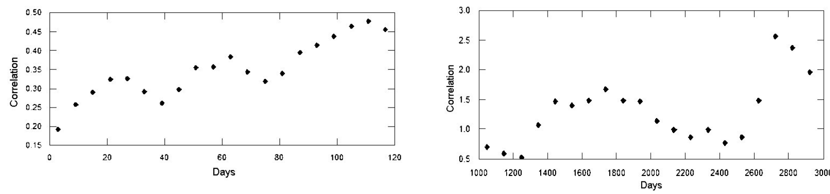


Figure 4: Short period (left graph, black dots) and long period (right graph, black dots), self-correlation analysis of the ASAS Data. From ASAS observations 2003–2008.

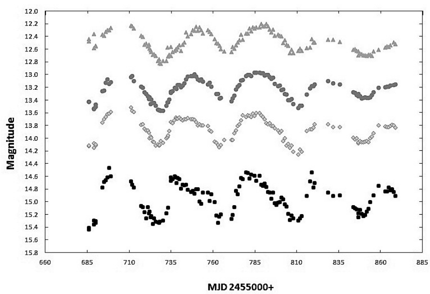


Figure 5: BVRI magnitudes of RS Sge (top to bottom: B, gray squares; V, gray diamonds; R, black dots; I, light gray triangles). From AAVSOnet and the author's observations in 2011.

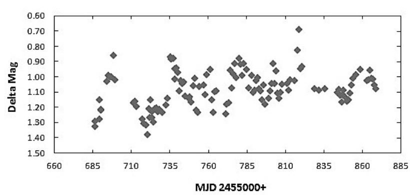
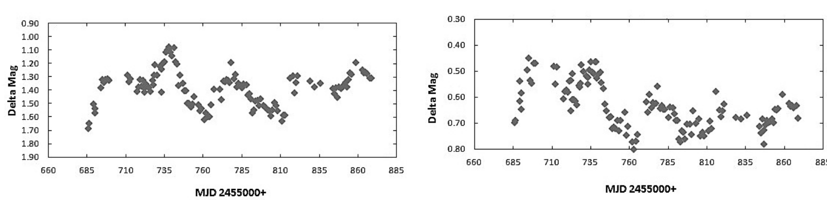


Figure 6: Color Indices of RS Sge: B–V, top left; V–I, bottom left; V–R, bottom right. From AAVSOnet and the author's observations in 2011.



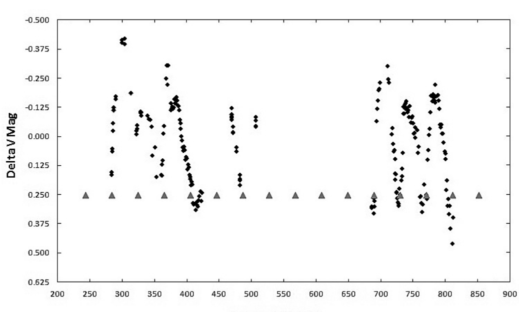


Figure 7: Calculated light curve (gray triangles) using a period of 40.55 days, and observed (black diamonds) minima for RS Sge. From AAVSOnet and the author's observations in 2010 and 2011.

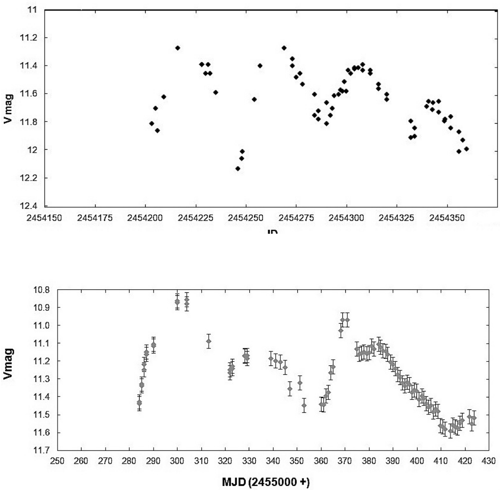


Figure 8: A comparison of RS Sge short term variability from ASAS data in 2007 (top graph) and from AAVSOnet and the authors observations in 2010 (bottom graph).

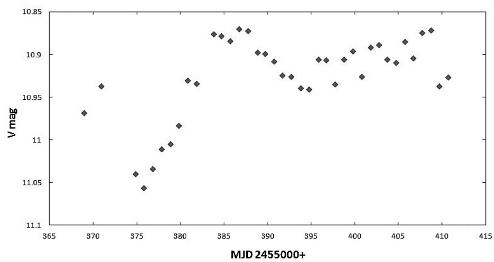


Figure 9: A residual light curve of RS Sge from AAVSOnet and the author's observations in 2010.

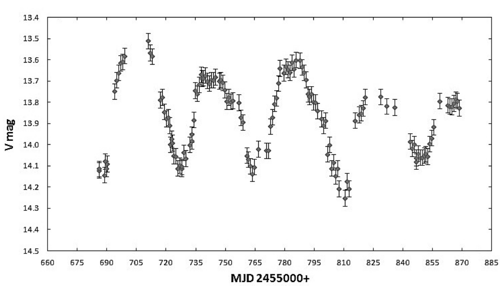


Figure 10: The V-band light curve of RS Sge from AAVSOnet and the author's observations in 2011.

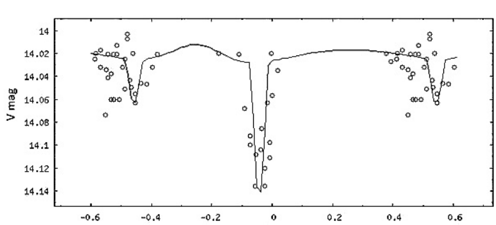


Figure 11: The calculated V-band light curve (line) from PHOEBE and the observed eclipse data of RS Sge from AAVSOnet and the author's observations in 2010 and 2011.