Period Analysis of All-Sky Automated Survey for Supernovae (ASAS-SN) Data on Pulsating Red Giants

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Abstract The All-Sky Automated Survey for Supernovae (ASAS-SN) has recently used over 2,000 days of sustained photometric data to identify more than 50,000 variable stars, automatically classify these, determine periods and amplitudes for those that are periodic—part of a remarkable project to classify 412,000 known variable stars and determine their basic properties. This information about the newly-discovered variables, along with the photometric data, is freely available on-line, providing an outstanding resource for both science and education. In this paper, we analyze ASAS-SN V data on two small random samples of pulsating red giants (PRGs) in detail, and compare our results with those found by ASAS-SN. For the majority of a sample of 29 mostly semi-regular (SR) PRGs, the ASAS-SN results are incorrect or incomplete: either the ASAS-SN periods are exactly 2, 3, or 4 times the actual period, or the ASAS-SN period is a "long secondary period" with a shorter pulsation period present, or the star is multi-periodic or otherwise complex, or the star's data and analysis are contaminated by instrumental effects. For almost all of a sample of 20 of the *longest-period* Mira stars (period 640 days or more), the ASAS-SN period is exactly 2 or more times the actual period. The results are not surprising, given the very complex behavior of PRGs.

1. Introduction

Red giant stars are unstable to pulsation. In the *General Catalogue of Variable Stars* (GCVS; Samus *et al.* 2017), pulsating red giants (PRGs) are classified according to their light curves. Mira (M) stars have reasonably regular light curves, with visual ranges greater than 2.5 magnitudes. Semi-regular (SR) stars are classified as SRa if there is appreciable periodicity, and SRb if there is little periodicity. Irregular (L) stars have very little or no periodicity.

Mira stars have periods which "wander" by a few percent; this wandering can be described and modelled as random, cycle-to-cycle fluctuations (Eddington and Plakidis 1929). Their maximum magnitudes vary from cycle to cycle, as observers of Mira itself know. The variability of SR stars is even more complex. Some stars are multiperiodic; two or more pulsation modes are excited (e.g. Kiss *et al.* 1999). About a third show long secondary periods (LSPs), 5 to 10 times the pulsation period (Wood 2000); their cause is unknown. The amplitudes of PRGs vary by up to a factor of 10 on time scales of 20 to 30 pulsation periods (Percy and Abachi 2013). There may also be very slow variations in mean magnitude (Percy and Qiu 2019). In a very few stars, thermal pulses cause large, secular changes in period, amplitude, and mean magnitude (Templeton *et al.* 2005 and references therein).

Our previous studies of PRGs have used long-term visual and sometimes photoelectric observations from the American Association of Variable Star Observers International Database (AID; Kafka 2019). Now, an important and very useful new source of data is available: the All-Sky Automated Survey for Supernovae (ASAS-SN).

ASAS-SN uses a network of up to 24 telescopes around the world to survey the entire visible sky every night down to about 18th magnitude (Shappee *et al.* 2014; Jayasinghe *et al.* 2018, 2019a). It has been doing so for over 2000 days (since about JD 2456500). ASAS-SN has identified over 50,000 variable stars, determined periods and amplitudes for those that are periodic, classified these using machine learning, and made this information and the data available on-line (asas-sn.osu.edu/variables). It has also used machine learning to uniformly classify 412,000 known variables (Jayasinghe *et al.* 2019a).

ASAS-SN used three period-search techniques: Generalized Lomb-Scargle, Multi-Harmonic Analysis of Variance, and the Box Least Squares. For classification purposes, they began with an open-source random forest classifier *Upsilon*, trained using OGLE and EROS-2 data. They note that the performance for the *Upsilon* classifier is low for SR variables—only 36 percent. They then built a new classifier based on ASAS-SN data, using a set of 16 features of the light or phase curve as classification criteria. The precision of the new classifier, for SR variables, is given as 63 percent. They note also that the classifier has difficulty distinguishing between SR and L variables.

The purpose of the present project was to analyze a small, random sample of the PRG data in more detail, and investigate the reliability of the ASAS-SN classifications and periods and amplitudes of PRGs, given our previous knowledge of and experience with such stars. Jayasinghe *et al.* (2018) comment only briefly on the ASAS-SN classification of these very complex variables.

Vogt *et al.* (2016) have recently carried out a related study: analysis of 2,875 Mira stars observed in the original ASAS project, which extended from 2000 to 2009. They used a semi-automatic method based on the observed times of maximum light. They found that, whereas their periods agreed with those in the VSX Catalogue (Watson *et al.* 2014) in more than 95 percent of the stars, their periods agreed with those obtained by Richards *et al.* (2012), who used an automatic machine-learning method, in only 76 percent of the stars. Most often, the latter periods differed from the Vogt *et al.* (2016) periods by a ratio of small whole numbers.

2. Data and analysis

For our initial project, we analyzed a sample of 22 stars classified as SR, five as M, and three as L. They were randomly chosen around a random position on the sky. The SR and L stars were chosen to have ASAS-SN amplitudes of at least 0.5 magnitude (with one accidental exception), so that the results would not be unduly affected by noise, and would therefore be meaningful. The datasets were approximately 2,000 days in length. For each of the SR and M stars, ASAS-SN provides a period and amplitude, a light curve and phase curve, and a quantity T which is a statistical measure of the confidence of the period; lower values indicate higher confidence. The data were downloaded, and analyzed using the AAVSO VSTAR time-series package (Benn 2013), which includes a Fourier analysis routine.

The results were interesting, so we carried out a subsidiary project, to analyze a sample of 20 Mira stars with the *longest* ASAS-SN periods—longer than 639 days. Miras with such long periods would be especially interesting and important, astrophysically.

3. Results

Of the 29 stars in our initial project, 7 were acceptably analyzed (e.g. Figure 1). For 9 stars, the ASAS-SN period was exactly 2, 3, or 4 times the actual period; the phase curve had not one, but 2, 3, or 4 cycles in it. While this is a mathematical possibility, it is unphysical for a pulsator such as a PRG to have such a phase curve. These periods might be considered as "sub-harmonics" of the correct periods. Figure 2 shows an example with three cycles per unit phase. In the figures, we have chosen to show the ASAS-SN light and phase curves as they were when this project was carried out, rather than new plots, since the former are more relevant to the present project.

For five stars, the light curve also showed periodic variability on a time scale 5 to 10 times shorter than the ASAS-SN period. The latter was clearly a "long secondary period," whereas the shorter period was the pulsation period. Figure 3 shows an example in which the LSP is actually half the ASAS-SN period of 1,022 days. The shorter pulsation period of 55 ± 2 days is clearly visible.

For a very few stars, the light curve included some faint, highly-discordant data, and it appeared that ASAS-SN had included these data in the analysis. Figure 4 shows an example. These discordant photometric points are probably due to astrometry problems and their effect on the image-subtraction process (Kochanek and Jayasinghe 2019). The non-discordant data show periods of 423.9 and 66.9 days, with V amplitudes of 0.09 and 0.07, respectively, rather than the (spurious) ASAS-SN amplitude of 2.5. The longer period is probably a long secondary period.

For a few other stars, the variability appears to be either bimodal or more complex. Figure 5 shows an example in which there may be periods of 469 days (the ASAS-SN period) and about half that value—typical of PRGs which are pulsating in the fundamental and first overtone modes (e.g. Kiss *et al.* 1999). Bimodal pulsators can be useful for determining the physical properties of the stars. Figure 6 shows the light curve of a star which ASAS-SN classifies as irregular (L type) but which clearly shows some periodicity, and is SR; we obtain a best period of 121 days. Figure 7 shows a star with an unusual light curve. There are two maxima which take the form of slow "eruptions." They may, however, be maxima of a faint Mira star, with the 15th-magnitude points being background "noise" limits.

Table 1 lists the results of the initial project. It gives: the ASAS-SN name of the star, minus ASAS-SN-V J; the ASAS-SN classification; the period PA in days given by ASAS-SN; the pulsation period PP in days obtained by us; the V amplitude ΔV; the mean V magnitude <V>; the (J–K) color; and the following notes: x2, x3, x4: the ASAS-SN period is exactly 2, 3, or 4 times the correct pulsation period; lsp: the ASAS-SN period is a long secondary period, and a shorter pulsation period can be seen in the light curve; tpp: the star shows evidence of two pulsation periods, differing by a factor of approximately two; dd: the analysis is affected by contamination by discordant data (see above); spp: the pulsational phase curve is more sawtooth than sinusoidal; OK: the ASAS-SN analysis is correct; *: see the figures, or "Notes on individual stars," below. This Table and Figures 1–7 show the remarkable diversity of results and behavior which occur in a sample of less than 30 stars.

In the 20 long-period Mira stars in the subsidiary project, the ASAS-SN period was in almost every case exactly 2, 3, 4, or 5 times the actual period. Table 2 lists the 20 Mira stars with mean V magnitudes between 12 and 14, and with the longest periods. The magnitude range was chosen because it is optimal for ASAS-SN data. They are listed in order of decreasing ASAS-SN period. The columns list: the name of the star, minus ASAS-SN-V J; the period PA in days given by ASAS-SN; the mean V magnitude <V>; the ASAS-SN amplitude ΔVA; and the following notes: x2, x3, x4, x5: the ASAS-SN period is exactly 2, 3, 4, or 5 times the correct pulsation period; dd: the analysis seems to have been complicated by discordant data (see above); OK: the ASAS-SN analysis is correct; *: see the figures, or "Notes on individual stars," below.

3.1, Notes on individual stars in Table 1

Figures 1–7 and their captions provide both light/phase curves and notes about seven illustrative stars in the sample. Sections 3.1 and 3.2 include stars which are not specifically mentioned in the previous section.

ASAS-SN-V J054606.99-694202.8 The light curve is unusual; it is non-sinusoidal, and there are two maxima in the 544-day cycle. It is not clear whether the behavior is periodic.

ASAS-SN-V J053035.52-685923.2 The light curve shows a slow decline, with some cyclic variations superimposed; their time scale is about 200 days. The slow decline could be part of a long secondary period.

ASAS-SN-V J054110.62-693804.1 The star has a double-humped maximum.

ASAS-SN-V J045337.64-691811.2 Unlike the other stars in the sample, this star had a very small amplitude, but it was possible to show that the actual period is exactly 1/5 of the ASAS-SN period.

Table 1. Analysis of ASAS-SN observations of 29 pulsating red giants.

Name—ASAS-SN-V	*Type*	*PA(d)*	*PP(d)*	*ΔV*	*<V>*	*J–K*	*Notes (see text)*
J053227.48-691652.8	SR	469	227	1.2	12.7	1.112	x2?, Figure 5
J055444.75-694714.7	SR	544	264	1.5	12.86	0.951	x2, lsp
J061214.08-694558.6	SR	643	318	1.5	16.82	1.725	x2
J054102.00-704309.9	SR	702	702	1.2	15.78	1.357	OK, spp
J191920.70-195042.1	SR	82	81	0.8	13.43	1.201	OK, tpp?
J054747.21-602210.3	SR	418	139	2.5	13.27	0.944	x3, Figure 2
J191639.10-215848.8	SR	25	38	0.3	11.61	1.245	
J205350.26-593921.1	SR	168	168	1.2	11.81	1.209	tpp
J054606.99-694202.8	SR	544	538	1.5	15.92	1.381	OK, spp, *
J191715.66-200034.1	SR	59	59	0.8	12.75	1.191	OK
J051623.43-690014.3	SR	466	233	0.7	14.95	1.287	x2
J053035.52-685923.2	SR	643	295	0.9	13.13	1.194	lsp?, tpp, *
J052011.96-694029.4	SR	662	662	1.1	15.1	1.494	OK, spp, Figure 7
J052337.99-694445.8	SR	636	400	1.2	16.38	1.228	
J054036.77-692620.6	SR	505	458	1.0	13.39	1.172	tpp
J054110.62-693804.1	SR	702	694	1.4	12.65	1.158	OK, *
J045337.64-691811.2	SR	430	80	0.2	13.3	1.115	x5, *
J045412.77-701708.6	SR	437	204	0.5	13.58	1.181	tpp
J050354.98-721652.3	SR	138	138?	1.5	16.21	0.898	OK, Figure 1
J171247.59+265024.8	M	889	—	0.0	13.4	0.785	
J195424.95-114932.2	M/SR	848	424	0.2	13.5	1.269	lsp, Figure 4
J175514.90+184006.9	M	815	204	2.7	13.68	1.186	x4
J182825.60+171943.2	M	728	243	2.35	13.23	1.538	x3
J185653.55-392537.4	M	645	215	2.30	13.76	1.272	x3, *
J020359.53+141132.4	L/SR	irr	389	1.25	12.01	1.148	SR, lsp?
J181616.35-281634.1	L/SR	irr	121	1.38	13.69	1.149	SR, Figure 6
J194755.85-611127.5	L/SR	irr	400	1.14	13.07	1.151	SR
J042630.05+255344.6	SR	1022	30	0.95	13.66	1.759	x2, lsp, Figure 3
J082819.18-143319.3	SR	1020	78/128	0.63	11.66	1.251	tpp

ASAS-SN-V J 185653.55-392537.4 The pulsation amplitude is slowly decreasing during the time of observation.

ASAS-SN-V J042630.05+255344.6 One-half the ASAS-SN period is a long secondary period. A shorter pulsation period is also present.

3.2, Notes on individual stars in Table 2

ASAS-SN-V J171247.59+265024.8 There are a few points between JD 2457850 and JD 2457896 which are four magnitudes fainter than the rest, which are almost constant; these are presumably due to instrumental effects, as discussed above, rather than due to an eclipse. For the rest of the points, the highest peak has an amplitude of only 0.017 mag.

ASAS-SN-V J195424.95-114932.2 There are discordant points.

ASAS-SN-V J181958.07-395457.8 There are a few discordant points.

ASAS-SN-V J182346.68-363942.1 There are discordant points, which have caused ASAS-SN to classify this as a large-amplitude Mira star. For the rest, periods of 158 ± 8 days and 83 ± 4 days are present, with small amplitudes (Figure 8). They may possibly be the fundamental and first overtone pulsation periods.

ASAS-SN-V J144304.69-753418.9 The light curve is unusual; there are variations on a time scale of about 100 days, superimposed on irregular long-term variations (Figure 9). The ASAS-SN period of 641.8 days is unlikely.

Table 2. Analysis of ASAS-SN observations of 20 long period Mira stars.

Name—ASAS-SN-V	*PA(d)*	*<V>*	*ΔVA*	*Notes (see text)*
J171247.59+265024.8	888.8	13.5	3.05	*
J195424.95-114932.2	848.4	13.6	2.5	Figure 4, lsp?
J175514.90+184006.9	814.7	13.7	2.7	x4
J182825.60+171943.2	814.7	13.2	2.35	x3
J065708.96+473521.9	725.8	13.48	2.02	x2, QX Aur
J202918.27+125429.1	721.0	13.31	2.22	x5, XZ Del
J190214.90+471259.7	716.1	13.49	2.71	x2, WZ Lyr
J175727.78+243018.0	695.1	13.31	2.56	x2
J184802.27-293034.0	675.7	13.27	2.36	dd
J184706.22-314645.6	675.3	13.62	4.61	x3, V962 Sgr
J181958.07-395457.8	665.9	12.75	2.78	*
J082915.17+182307.3	655.8	13.66	2.1	x2
J124209.54-435503.3	645.6	13.93	2.79	OK, V1132 Cen
J182037.28-385833.5	645.5	13.8	2.02	x4
J182346.68-363942.1	645.5	13.73	2.39	Figure 8
J185653.55-392537.4	645.0	13.76	2.29	x3, AB CrA, *
J144304.69-753418.9	641.8	12.25	2.5	Figure 9
J141547.57-480350.7	641.0	13.65	3.02	x3
J175730.94-744810.7	640.5	13.45	2.05	x4
J184614.49-301856.4	639.6	13.64	2.02	x3, V1935 Sgr

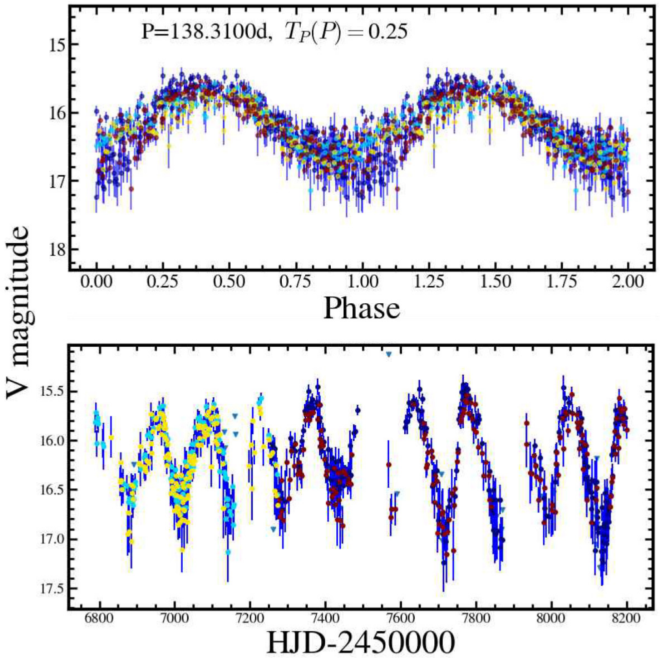

Figure 1. ASAS-SN-V J050354.98-721652.3: Light curve (bottom), and phase curve (top) using the ASAS-SN period of 138.3 days. This period satisfactorily represents the data. In this and the following figures, T is a statistical measure of confidence in the star's period. Source: ASAS-SN website.

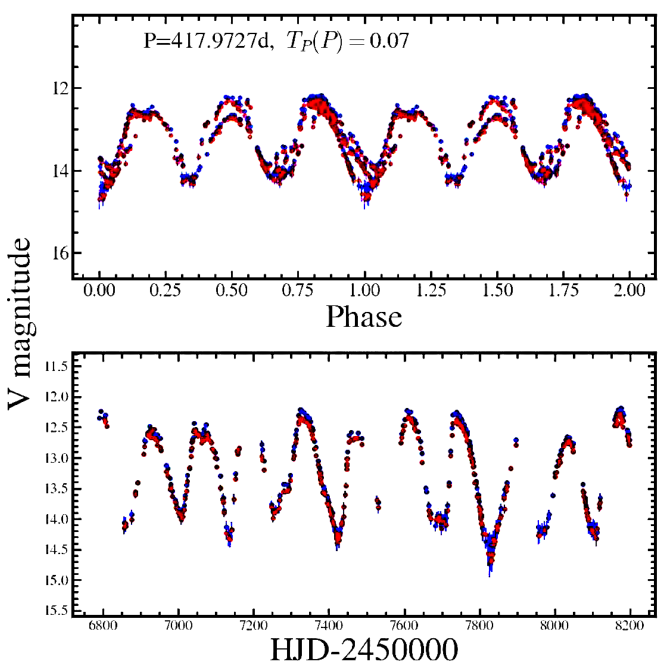

Figure 2. ASAS-SN-V J054747.21-602210.3: Light curve (bottom), and phase curve (top) using the ASAS-SN period of 418.0 days. The actual period is exactly one-third of this; there are three cycles in the phase curve, rather than one. Source: ASAS-SN website.

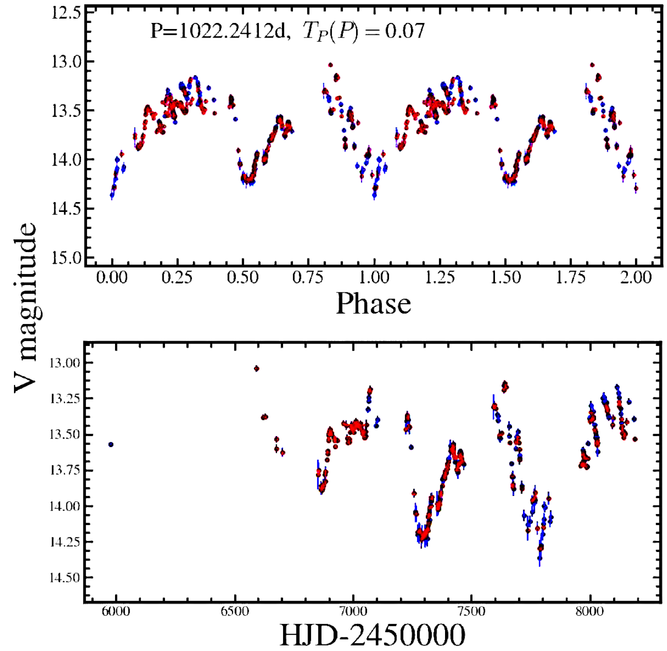

Figure 3. ASAS-SN-V J042630.05+255344.6: Light curve (bottom), and phase curve (top) using the ASAS-SN period of 1022.2 days. There are two (long) cycles in the phase curve, rather than one, and there are also more rapid variations with a period of 55 ± 2 days. This is presumably the pulsation period, and the long secondary period is 511.1 days—exactly half the ASAS-SN period. Source: ASAS-SN website.

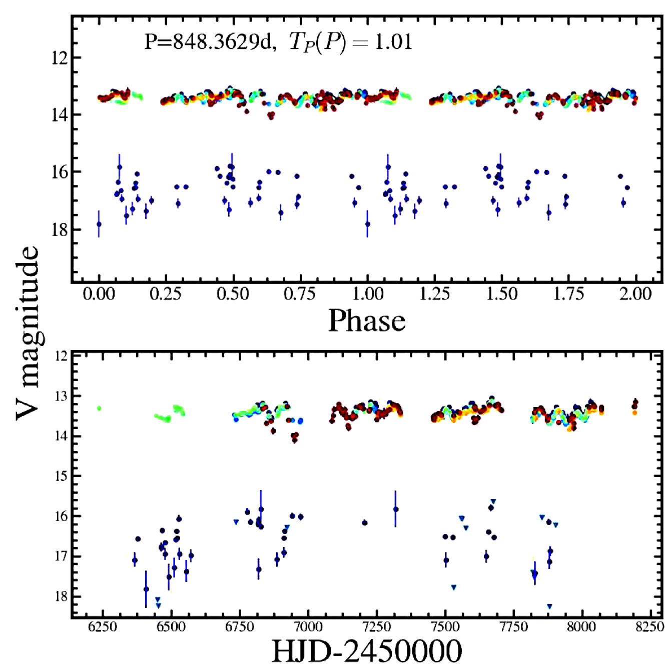

Figure 4. ASAS-SN-V J195424.95-114932.2: Light curve (bottom), and phase curve (top) using the ASAS-SN period of 848.4 days. The ASAS-SN analysis has been complicated by the fainter discordant points, which are spurious. Analysis of the brighter V data gives periods of 423.9 days (V amplitude 0.09) and 66.9 days (V amplitude 0.07). The former period (half the ASAS-SN period) may be a long secondary period, and the latter may be a pulsation period. Source: ASAS-SN website.

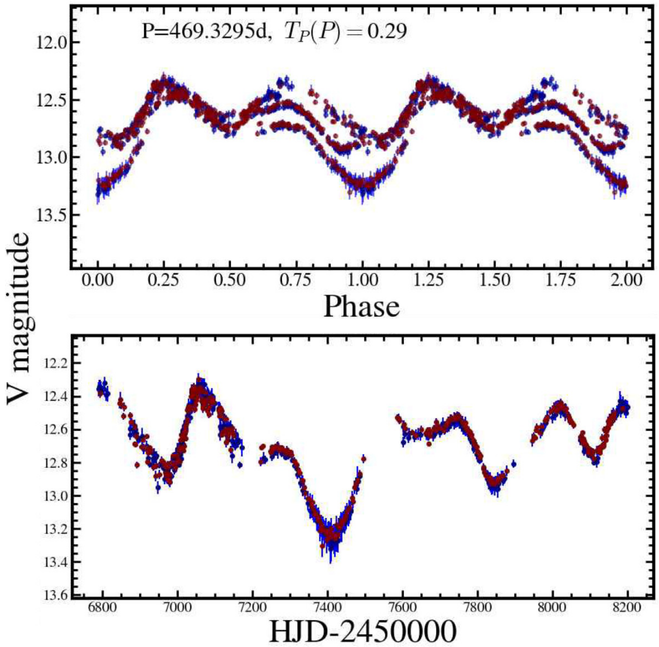

Figure 5. ASAS-SN-V J053227.48-691652.8: Light curve (bottom), and phase curve (top) using the ASAS-SN period of 469.3 days. The star may pulsate in two modes, with the second period being about half of the first period. Source: ASAS-SN website.

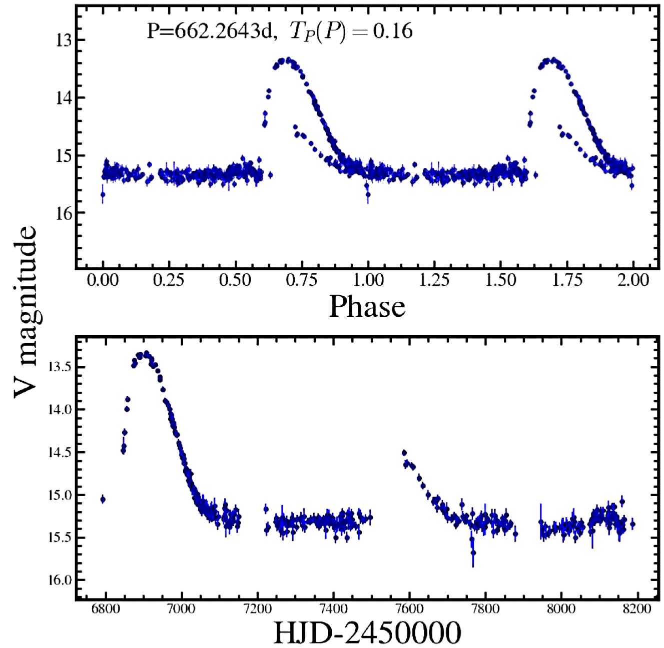

Figure 7. ASAS-SN-V J052011.96-694029.4: Light curve (bottom), and phase curve (top) using the ASAS-SN period of 662.3 days. The light curve shows two "eruptions," 662 days apart. On the other hand, these could be maxima of a faint Mira star, with the 15th-magnitude points being a background noise limit. Source: ASAS-SN website.

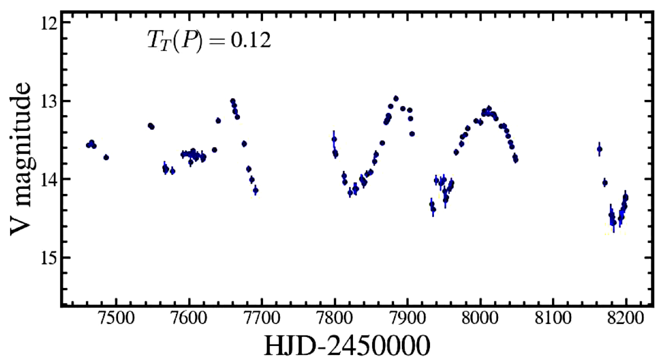

Figure 6. ASAS-SN-V J181616.35-281634.1: This star is considered irregular (type L) in the ASAS-SN catalogue, but the above light curve suggests that it has a period of 121 days, and is therefore an SR star. Source: ASAS-SN website.

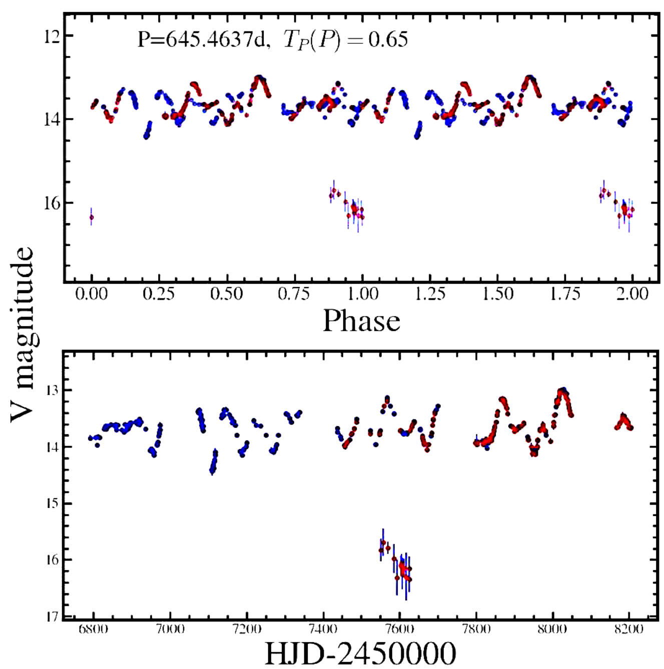

Figure 8. ASAS-SN-V J182346.68-363942.1: Light curve (bottom), and phase curve (top) using the ASAS-SN period of 645.5 days. The ASAS-SN amplitude of 2.39 occurs because of the presence of the fainter discordant data. Our analysis of the rest of the data gives periods of 153 ± 8 and 83 ± 4 days, both with amplitudes of 0.23. This may be a bimodal pulsator. Source: ASAS-SN website.

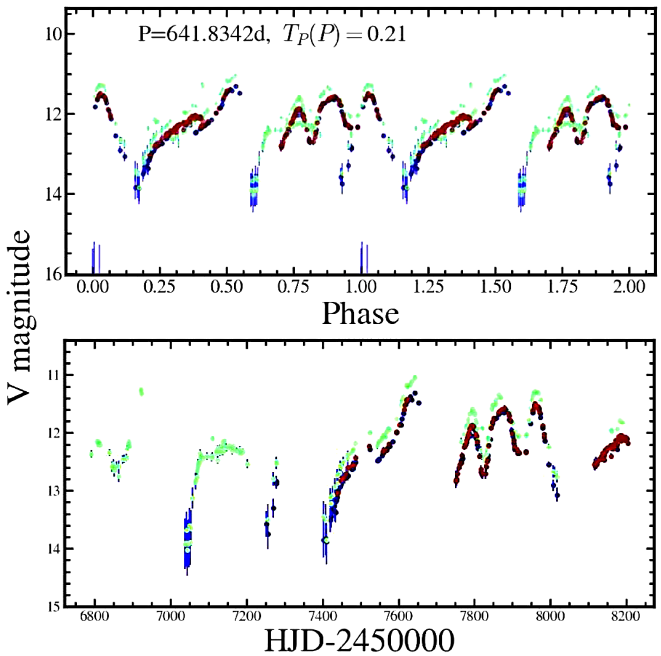

Figure 9. ASAS-SN-V J144304.69-753418.9: Light curve (bottom), and phase curve (top) using the ASAS-SN period of 641.8 days. The light curve is highly unusual and interesting. There are variations on time scales from 100 to 300 days. Source: ASAS-SN website.

4. Discussion

The ASAS-SN data begin about JD 2456500 so, as of the time of carrying out this project (October 2018 to February 2019), there were only about 2000 days of data. This is adequate for studying many aspects of PRG variability, but not the very long-term variations in period, amplitude, and mean magnitude which are known to occur in these stars. Only the visual data can presently do that.

It is interesting to note that, when Vogt *et al.* (2016) compared their results with those of Richards *et al.*'s (2012) results which were obtained using a machine-learning approach, the discrepancy was most often by a ratio of small whole numbers, such as 2 or 1/2. We find a similar result.

Pulsating red giants are understandably a challenge for automated analysis and classification. ASAS-SN carries out a comprehensive search for the best period for each star, and then uses this and other parameters of the light/phase curve to arrive at a final analysis and classification. As noted above, however, SR variables are not strictly periodic; they have "wandering" pulsation periods, variable pulsation amplitudes, additional periods (including LSPs), and residual irregularity. It is difficult to define a single period for these stars, and the phase curve will be constantly variable with time.

Jayasinghe and his colleagues (2019b) have made unspecified refinements to the analysis and classification procedure, and have provided a list of updated periods for the stars in Table 1. About two-thirds now agree with our values. However, 12 of the 20 long-period Mira stars in Table 2 still have incorrect or incomplete analyses and/or classifications.

Most of this project was carried out by undergraduate math major LF. It illustrates the great educational potential of the ASAS-SN data, with its immense quantity and variety. We can envision a large number and variety of projects which could be carried out by students at the college level, and perhaps even at the high school level, using ASAS-SN data. The AAVSO VSTAR time-series analysis package is well-suited for use with these and other data.

5. Conclusions

We have analyzed ASAS-SN observations of pulsating red giants (mostly semi-regular and Mira stars) and compared our results with the periods, amplitudes, and classifications given by ASAS-SN. For many stars, the actual periods are a small integral fraction of the ASAS-SN period ("sub-harmonics"), because the ASAS-SN phase curve incorrectly contains two or more cycles of variability, rather than one. In other cases, the ASAS-SN period is a long secondary period; the shorter pulsation period is visible in the light curve. For a few stars, the ASAS-SN analysis is complicated by the presence of faint data which are spurious and due to instrumental problems. In a few others, the star is bimodal or otherwise complex. The few irregular (type L) stars that we analyzed were probably semi-regular (type SR).

Given the complexity of pulsating red giants as noted above, it is not surprising that the ASAS-SN automatic analysis procedure produced incorrect or incomplete results. Perhaps the procedure can be trained to "solve" these very complex stars! Indeed, the ASAS-SN variable star data and website have been significantly updated and improved in the weeks since we completed this project in February 2019, and some (but not all) of the problems with the PRG analysis and classification have been alleviated.

The ASAS-SN data on PRGs can be exceptionally useful for analyzing these stars, and are invaluable for both scientific and educational purposes. The data for individual PRGs in the ASAS-SN catalogue should, however, be confirmed by careful inspection of the light and phase curves, and by more detailed analysis if necessary, to avoid the types of problems shown in Figures 2–9.

6. Acknowledgements

This paper made use of ASAS-SN photometric data. We thank the ASAS-SN project team for their remarkable contribution to stellar astronomy, and for making the data freely available on-line. Thanks also to Chris Kochanek and especially Tharindu Jayasinghe for helpful comments. We acknowledge and thank the University of Toronto Work-Study Program for financial support. The Dunlap Institute is funded through an endowment established by the David Dunlap Family and the University of Toronto.

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