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 2000 days of 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. 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 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 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 actually 2 or more times the actual period. Our results are not surprising, given the very complex behaviour of PRGs.

AAVSO keywords = Photometry, CCD; pulsating variables; giants, red; period analysis; amplitude analysis

ADS keywords = stars; stars: late-type; techniques: photometric; methods: statistical; stars: variable; stars: oscillations

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 complicated. Some stars are multiperiodic; both the fundamental and first overtone modes are excited (e.g. Kiss et al. 1999). About a third show long secondary periods (LSPs), 5-10 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 20-30 pulsation periods (Percy and Abachi 2013). There are also very slow variations in mean magnitude (Percy and Qiu 2018). 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 \((\text{Shappee et al. (2014), Jayasinghe et al. (2018)})\). It has been doing so for over 2000 days (since about JD 2456500). ASAS-SN has identified over 50,000 variable stars, classified these using machine learning, determined periods and amplitudes for those that are periodic, and made this information, and the data on-line (asas-sn.osu.edu/variables). It has also used machine learning to uniformly classify 412,000 known variables (Jayasinghe et al. 2018).

The purpose of the present project was to look at 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. 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 2875 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. A study of smaller-amplitude ASAS-SN stars would be the subject of a future project. The datasets were approximately 2000 days in length, significantly shorter than visual datasets from the AID. For each of the SR and M stars, ASAS-SN provides a period and amplitude, and 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. For one star, we also used a new self-correlation (e.g. Percy et al. 2003) program written by author LF.

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 radial pulsator such as a PRG. Figure 2 shows an example with 3 cycles per unit phase.

For 5 stars, the light curve also showed periodic variability on a time scale 5-10 times shorter than the ASAS-SN period. The latter was clearly a “long secondary period”, whereas the shorter
period was the pulsation period. Figures 3-5 show an example in which the LSP is actually half the ASAS-SN period of 1022 days. The shorter pulsation period of 55±2 days is clearly visible.

For a very few stars, the light curve included some highly-discordant data, and it appeared that ASAS-SN had used all the data for analysis. Figure 6 shows an example. These discordant photometric points are probably due to astrometry problems, and their effect on the image-subtraction process (Kochanek and Jaysinghe, private communication, April 2, 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 (artificial) 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 7 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. Bimodal pulsators can be useful for determining the physical properties of the stars.

Figure 8 shows the light curve of a star which ASAS-SN classifies as irregular (L type) but which clearly shows some periodicity; we obtain a best period of 121 days.

Figure 9 shows a star with a very unusual light curve. There are two maxima which take the form of slow “eruptions”. They may, however, be maxima of a faint Mira star which has a 15.3-magnitude non-variable companion.

Table 1 lists the results of the initial project. It gives: the ASAS-SN name of the star, minus ASAS-SN-V J; the period PA in days given by ASAS-SN; the pulsation period PP in days obtained by us; the V amplitude ∆V; the mean V magnitude \(<V>\); the (J-K) color; the ASAS-SN classification; and the following notes: x2, x3, x4: the ASAS-SN period is 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 “Notes on Individual Stars” below. This Table, and Figures 1-9 show the remarkable diversity of results 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 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 ∆VA; and the following notes: x2, x3, x4, x5: the ASAS-SN period is 2, 3, 4, or 5 times the correct pulsation period; dd: the analysis seems to have been complicated by discordant data (see above); spp: the pulsational phase curve is more sawtooth than sinusoidal; OK: the ASAS-SN analysis is correct; *: see “Notes on Individual Stars”, below.

3.1 Notes on Individual Stars in Table 1

Figures 1-9 and their captions provide both light/phase curves and notes about seven illustrative stars in the sample.

\textit{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.

\textit{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 J052011.96-694029.4*: The light curve (Figure 9) seems to show outbursts, but they may be maxima of a faint Mira star which has a non-variable companion.

*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 1/5 of the ASAS-SN period.

*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 2457850-2457896 which are four magnitudes fainter than the rest, which are almost constant; these are presumably due to instrumental effects, as discussed above. 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. For the rest, the highest peak is at 423.9 days (half the ASAS-SN period) with an amplitude of 0.09 mag; the second-highest is at 66.9 days, with an amplitude of 0.07 mag. These may be an LSP and a pulsation period. The ASAS-SN amplitude is given as 2.5 magnitudes.

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

*ASAS-SN-V J182346.68-363942.1*: There are discordant points. For the rest, periods of 158±8 days and 83±4 days are present, with small amplitudes (Figure 10). 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 11). The ASAS-SN period of 641.8 days is unlikely.

### 4. Discussion

The ASAS-SN data begin about JD 2456500 so, as of the time of carrying out this project, there is 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. Only the visual data can presently do that. Nevertheless, these new data provide a remarkable resource for studying these and other variable stars.

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 certainly a challenge for automated analysis and classification. Jayasinghe (private communication, April 10, 2019) has been refining the analysis and classification procedure, and has provided a list of updated periods for the stars in Table 1. About two-thirds now agree with our values, so a detailed inspection and analysis of the light curve is still recommended for individual SR and Mira stars.

It is not surprising that a few of these stars, especially the longer-period stars, have sawtooth phase curves. The same was found by Percy and Qiu (2018), from AAVSO visual data.
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, quality, and variety. We can envision a large number and variety of projects which could be carried out by students, using the 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, because the ASAS-SN phase curve contains two or more cycles of variability, rather than one. In other cases, the ASAS-SN period is a long secondary period, and the shorter pulsation period is visible in the light curve. In a few stars, the ASAS-SN analysis is complicated by the presence of data which are discordant, 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, 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 a few of the problems with the PRG analysis and classification have been fixed.

The ASAS-SN data on PRGs can be exceptionally useful for analyzing these stars, and is invaluable for both scientific and educational purposes. But the data for individual PRGs in the ASAS-SN catalogue should still be confirmed by careful inspection of the light curve, and by detailed analysis if necessary.

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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.

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Table 1: Table 1. Analysis of ASAS-SN Observations of 29 Pulsating Red Giants

| Name - ASAS-SN-V | Type | PA(d) | P(d) | ∆V | <V> | J-K | Notes (see text) |
|------------------|------|-------|------|-----|-----|-----|-----------------|
| J053227.48-691652.8 | SR   | 469   | 227  | 1.2 | 12.7 | 1.112 | x2?, Fig. 7     |
| 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, Fig. 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, Fig. 9, * |
| J052323.99-694445.8 | SR   | 636   | 400  | 1.2 | 16.38 | 1.228 |               |
| J054036.77-692620.6 | M    | 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, Fig. 1     |
| J171247.59+265024.8 | M/SR | 889   | –    | 0.0 | 13.4  | 0.785 |               |
| J195424.95-114932.2 | M/SR | 848   | 424  | 0.2 | 13.5  | 1.269 | lsp, Fig. 6    |
| 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, Fig. 8     |
| 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, Fig. 3-5, * |
| J082819.18-143319.3 | SR   | 1020  | 78/128 | 0.63| 11.66 | 1.251 | tpp            |
Table 2: Analysis of ASAS-SN Observations of 20 Long-Period Mira Stars

| Name - ASASSN-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 | 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 | Fig. 10, * |
| J185653.55-392537.4 | 645.0 | 13.76 | 2.29 | x3, AB CrA, * |
| J144304.69-753418.9 | 641.8 | 12.25 | 2.5 | Fig. 11, * |
| 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 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 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 – half the ASAS-SN period. Source: ASAS-SN website.
Figure 4: Self-correlation diagram for ASAS-SN-V J042630.05+255344.6 for $\Delta t = 0$ to 800 days. The minimum at about 520 days is the long secondary period. The curve does not go to zero at minimum because of the combined effect of observational error, and the presence of the pulsation period.
Figure 5: Self-correlation diagram for ASAS-SN-V J042630.05+255344.6 for $\Delta t = 0$ to 100 days. The rising curve is due to the 520-day period; the shallow minimum (or inflection) at about 50 days is due to the pulsation period.
Figure 6: 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. 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 7: 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 8: 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 9: 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 a constant companion with magnitude 15.3. Source: ASAS-SN website.
Figure 10: 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 11: 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. There are variations on time scales from 100-300 days. Source: ASAS-SN website.