The ASAS-SN Catalog of Variable Stars IX: The Spectroscopic Properties of Galactic Variable Stars

T. Jayasinghe\textsuperscript{1,2\star}, C. S. Kochanek\textsuperscript{1,2}, K. Z. Stanek\textsuperscript{1,2}, B. J. Shappee\textsuperscript{3}, T. W. -S. Holoien\textsuperscript{4}, Todd A. Thompson\textsuperscript{1,2}, J. L. Prieto\textsuperscript{5,6}, Subo Dong\textsuperscript{7}, M. Pawlak\textsuperscript{8}, O. Pejcha\textsuperscript{8}, G. Pojmanski\textsuperscript{9}, S. Otero\textsuperscript{10}, N. Hurst\textsuperscript{11}, D. Will\textsuperscript{1,11}

\textsuperscript{1}Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA
\textsuperscript{2}Center for Cosmology and Astroparticle Physics, The Ohio State University, 191 W. Woodruff Avenue, Columbus, OH 43210, USA
\textsuperscript{3}Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
\textsuperscript{4}Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA
\textsuperscript{5}Núcleo de Astronomía de la Facultad de Ingeniería y Ciencias, Universidad Diego Portales, Av. Ejército 441, Santiago, Chile
\textsuperscript{6}Millennium Institute of Astrophysics, Santiago, Chile
\textsuperscript{7}Kavli Institute for Astronomy and Astrophysics, Peking University, Yi He Yuan Road 5, Haidian District, China
\textsuperscript{8}Institute of Theoretical Physics, Faculty of Mathematics and Physics, Charles University, Czech Republic
\textsuperscript{9}Warsaw University Observatory, Al Ujazdowskie 4, 00-478 Warsaw, Poland
\textsuperscript{10}The American Association of Variable Star Observers, 49 Bay State Road, Cambridge, MA 02138, USA
\textsuperscript{11}ASC Technology Services, 433 Mendenhall Laboratory 125 South Oval Mall Columbus OH, 43210, USA

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The All-Sky Automated Survey for Supernovae (ASAS-SN) provides long baseline (~4 yrs) V-band light curves for sources brighter than $V \lesssim 17$ mag across the whole sky. We produced V-band light curves for a total of $\sim 61.5$ million sources and systematically searched these sources for variability. We identified $\sim 426,000$ variables, including $\sim 219,000$ new discoveries. Most (~74\%) of our discoveries are in the Southern hemisphere. Here we use spectroscopic information from LAMOST, GALAH, RAVE, and APOGEE to study the physical and chemical properties of these variables. We find that metal-poor eclipsing binaries have orbital periods that are shorter than metal-rich systems at fixed temperature. We identified rotational variables on the main-sequence, red giant branch and the red clump. A substantial fraction ($\gtrsim 80\%$) of the rotating giants have large $v_{\text{rot}}$ or large NUV excesses also indicative of fast rotation. The rotational variables have unusual abundances suggestive of analysis problems. Semi-regular variables tend to be lower metallicity ($[\text{Fe}/\text{H}] \sim -0.5$) than most giant stars. We find that the APOGEE DR16 temperatures of oxygen-rich semi-regular variables are strongly correlated with the $W_{\text{RP}} - W_{\text{JK}}$ color index for $T_{\text{eff}} \lesssim 3800$ K. Using abundance measurements from APOGEE DR16, we find evidence for Mg, O and N enrichment in the semi-regular variables. We find that the Aluminum abundances of the semi-regular variables are strongly correlated with the pulsation period, where the variables with $P \gtrsim 60$ days are significantly depleted in Al.

Key words: stars:variables – stars:binaries:eclipsing – stars:rotation – stars:AGB and post-AGB – catalogues – surveys

\textsuperscript{\star} E-mail: jayasinghearachchilage.1@osu.edu

© 2020 The Authors
Variable stars are useful astrophysical tools that can be used to study the lives and deaths of stars. Pulsating variables, including Cepheids, RR Lyrae stars and Mira variables are used as distance indicators as they follow distinct period-luminosity relationships (e.g., Leavitt 1908; Mateu et al. 2006; Beaton et al. 2018; White洛克 et al. 2008, and references therein). Eclipsing binary stars allow for the derivation of dynamical information and fundamental stellar parameters, including the masses and radii of the stars (Torres et al. 2010). The precise measurements afforded by eclipsing binaries allow for tests of stellar theory across the Hertzsprung-Russell diagram. Variable stars are also used to study stellar populations and Galactic structure (Mateu & Vivas 2018; Matsuungan 2018; Feast & White洛克 2014).

Modern large scale sky surveys such as the All-Sky Automated Survey (ASAS; Pojmanski 2002), the All-Sky Automated Survey for SuperNovae (ASAS-SN, Shappee et al. 2014; Kochanek et al. 2017; Jayasinghe et al. 2018), the Optical Gravitational Lensing Experiment (OGLE; Udalski 2003), the Northern Sky Variability Survey (NSVS; Woźniak et al. 2004), MACHO (Alcock et al. 1997), EROS (Derue et al. 2002), the Catalina Real-Time Transient Survey (CRTS; Drake et al. 2014), the Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al. 2018a; Heinze et al. 2018), Gaia (Gaia Collaboration et al. 2018; Holl et al. 2018; Gaia Collaboration et al. 2019), and the Zwicky Transient Facility (Bellm et al. 2019; Chen et al. 2020) have revolutionized the study of stellar variability. Amateur astronomers have also contributed to these discoveries over the years. As of May 2020, the International Variable Stars Index (VSX; Watson et al. 2006) hosted by the American Association of Variable Star Observers (AAVSO) lists $\sim 1.4 \times 10^6$ variable stars.

In addition to these modern photometric surveys, large-scale wide-field spectroscopic surveys such as the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Gunn et al. 2006; Blanton et al. 2017; Wilson et al. 2019), Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST; Cui et al. 2012), GALactic Archaeology with HERMES (GALAH; De Silva et al. 2015; Buder et al. 2018) and the RA dial Velocity Experiment (RAVE; Casey et al. 2017) have been making medium/high resolution spectroscopic observations of millions of Galactic stars. Spectroscopic observations of Galactic stars are invaluable for deciphering the chemical evolution of our Galaxy (see for e.g., Weinberg et al. 2019; Griffith et al. 2019), and for evolved stars they also provide clues to understanding chemical enrichment caused by dredge up episodes (see for e.g., Salaris et al. 2015; Shetrone et al. 2019). Variable stars that have both extensive time-series data and spectroscopic observations will allow for the study of stellar evolution to great detail.

ASAS-SN monitored the visible sky to a depth of $V \lesssim 17$ mag with a cadence of 2-3 days using two units in Chile and Hawaii each with 4 telescopes from 2014-2018. Since then, ASAS-SN has expanded to 5 units with 20 telescopes and is currently monitoring the sky in the g-band to a depth of $g \lesssim 18.5$ mag with a cadence of $\sim 1$ day. The ASAS-SN telescopes are hosted by the Las Cumbres Observatory (LCO; Brown et al. 2013) in Hawaii, Chile, Texas and South Africa. The primary focus of ASAS-SN is the detection of bright supernovae and other transients (e.g., tidal disruption events, cataclysmic variables, AGN flares, stellar flares, etc.) with minimal bias (e.g., Holoien et al. 2014, 2016, 2017), but its excellent baseline and all-sky coverage allows for the characterization of stellar variability across the whole sky.

In Paper I (Jayasinghe et al. 2018), we discovered $\sim 66,000$ new variables that were flagged during the search for supernovae, most of which are located in regions that were not well-sampled by previous surveys. In Paper II (Jayasinghe et al. 2019b), we homogeneously analyzed $\sim 412,000$ known variables from the VSX catalog, and developed a versatile random forest variability classifier utilizing the ASAS-SN V-band light curves and data from external catalogues. As data from The Transiting Exoplanet Satellite (TESS; Ricker et al. 2015) became available, we have explored the synergy between the two surveys. In Paper III (Jayasinghe et al. 2019a), we characterized the variability of $\sim 1.3$ million sources within 18 deg of the Southern Ecliptic Pole towards the TESS continuous viewing zone and identified $\sim 11,700$ variables, including $\sim 7,000$ new discoveries. We have also explored the synergy between ASAS-SN and large scale spectroscopic surveys using data from APOGEE (Holtzman et al. 2015) with the discovery of the first likely non-interacting binary composed of a black hole with a field red giant (Thompson et al. 2019) and the identification of 1924 APOGEE stars as periodic variables in Paper IV (Pawlak et al. 2019). In Paper V, we systematically searched for variable sources with $V < 17$ mag in the southern hemisphere and identified $\sim 220,000$ variable sources, of which $\sim 88,300$ were new discoveries (Jayasinghe et al. 2019c). In Paper VI, we derived period-luminosity relationships for $\delta$ Scuti stars (Jayasinghe et al. 2020a). We studied contact binaries in Paper VII (Jayasinghe et al. 2020b). In Paper VIII, we identified 11 new “dipper” stars in the Lupus star forming region (Breddall et al. 2020).

Here, we summarize the results of our V-band variability search based on $\sim 61.5$ million ASAS-SN light curves of sources from the AAVSO Photometric All-Sky Survey (APASS; Henden et al. 2015) DR9 catalog with $V < 17$ mag and the ATLAS All-Sky Stellar Reference Catalog (refcat2; Tonry et al. 2018b) catalog with $g < 17$ mag. In this work, we describe our V-band variability catalog of $\sim 426,000$ variable sources, of which $\sim 219,000$ are new discoveries. In Section §2, we discuss the ASAS-SN observations, our variable star identification and classification procedure and summarize the final V-band catalog. Section §3 discusses the cross-matches made to various spectroscopic catalogs and the general spectroscopic properties of the ASAS-SN variable stars. In Section §4, we discuss the eclipsing binaries, rotational variables and semi-regular variables in greater depth and present a summary of our work in Section §5.
Figure 1. Projected distribution of the ~219, 200 new ASAS-SN discoveries in Equatorial coordinates (Lambert projection). The points are colored by the variability type.

the pixel scale is 8′0 and the FWHM is typically ~2 pixels. ASAS-SN tends to saturate at ~10−11 mag, but we attempt to correct the light curves of saturated sources for bleed trails (see Kochanek et al. 2017). The V-band light curves were extracted as described in Jayasinghe et al. (2018) using image subtraction (Alard & Lupton 1998; Alard 2000) and aperture photometry on the subtracted images with a 2 pixel radius aperture. We corrected the zero point offsets between the different cameras as described in Jayasinghe et al. (2018). The photometric errors were recalculated as described in Jayasinghe et al. (2019a).

As we did in Paper V, we started with the APASS DR9 catalog (Henden et al. 2015) as our input source catalog for the northern hemisphere. We selected ~23.1M APASS sources with $V < 17$ mag in the northern hemisphere ($\delta > 0$ deg). However, there are regions towards the Galactic plane that are missing in the APASS DR9 catalog (Henden et al. 2015; Marrese et al. 2019). To address the issue of incomplete sky coverage, we used the refcat2 catalog (Tonry et al. 2018b) to produce light curves for the sources missing from APASS DR9. From the refcat2 catalog, we selected ~7.1M sources with $r_1 > 30''$ and $G < 17$ mag, where $r_1$ is the ra-
We applied the trained random forest classifier from Jayasinghe et al. (2019c) to identify candidate variables. From this sample, blended sources were identified and removed as described in Jayasinghe et al. (2019c). Following these procedures, we used the variability classifier implemented in Jayasinghe et al. (2019b), which consists of a random forest classifier plus several refinement steps, in order to classify the candidate variables. We applied additional quality checks to improve the purity of our catalog (summarized in Table 4 from Jayasinghe et al. 2019c). We previously noted that light curves that are contaminated by systematics tend to be classified as irregular or generic vari-
ables. Thus, we visually reviewed all the sources that were classified as L, VAR, GCAS, or YSO to improve the purity of our catalog. Following this, we identified ~124,000 and ~40,000 variables among the northern APASS sources and the refcat2 sources, respectively. As described in Jayasinghe et al. (2019c), we cross-matched these variables to the and the refcat2 sources, respectively. As described in Jayasinghe et al. (2019c), we cross-matched these variables to the 2MASS (Skrutskie et al. 2006) and GALEX (Bianchi et al. 2017) catalogues using a matching radius of 5′′. We used TOPCAT (Taylor 2005) for this process. For each source, we also calculate the total line of sight Galactic reddening $E(B-V)$ from the recalibrated ‘SF’ dust maps (Schlafly & Finkbeiner 2011; Schlegel et al. 1998). We calculated the absolute, reddening-free Wesenheit magnitudes (Madore 1982; Lebzelter et al. 2018)

\begin{align*}
W_{RP} &= M_{GSP} - 1.3(G_{BP} - G_{RP}), \\
W_{JK} &= M_{K_s} - 0.686(J - K_s),
\end{align*}

and

for each source, where the $G_{BP}$ and $G_{RP}$ magnitudes are from Gaia DR2 (Gaia Collaboration et al. 2018) and the $J$ and $K_s$ magnitudes are from 2MASS (Skrutskie et al. 2006). The Wesenheit magnitudes are important for refining variable type classifications (see Jayasinghe et al. 2019b).

The near-infrared (NIR) $M_{K_s}$ vs. $J-K_s$ color-magnitude diagram and the $M_{K_s}$ period–luminosity relationship (PLR) diagram for all the variables with variable type classification probabilities Prob $> 0.95$, $A_V < 2$ mag and Gaia DR2 parallaxes better than 20% are shown in Figure 3. Generic and uncertain variable types are not shown. We have sorted the variables into groups to highlight the different classes of variable sources. Rotational variables in our catalog consist of spotted stars on the main-sequence (MS) as well as evolved stars on the red-giant branch (RGB). Semi-regular variables and Mira variables lie on the asymptotic giant branch (AGB). Several PLR sequences are seen in Figure 3. We studied the PLR sequences for the δ Scuti variables and contact binaries in Papers VI and VII respectively. The slight deficits of variables at the aliases of a sidereal day (e.g., $P \approx 1$ d, $P \approx 2$ d, $P \approx 30$ d, etc.) are due to the quality checks from Jayasinghe et al. (2019c).

### 3 ASAS-SN VARIABLES IN WIDE-FIELD SPECTROSCOPIC SURVEYS

ASAS-SN significantly overlaps with modern major wide-field spectroscopic surveys owing to its all-sky coverage and the magnitude range of the survey. We cross-matched our catalog with the APOGEE DR16 catalog (Holtzman et al. 2015; García Pérez et al. 2016; Alomada et al. 2019), the RAVE-on catalog (Casey et al. 2017), the LAMOST DR5 v4 catalog (Cui et al. 2012) and the GALAH DR2 catalog (De Silva et al. 2015; Buder et al. 2018) using a matching radius of 5′′. LAMOST only reports $T_{\text{eff}}$, log(g), and [Fe/H] for A, F, G and K stars. We identified 39811 (39036) total (unique) matches to the catalogs from the LAMOST (17381), GALAH (3067), RAVE (15050) and APOGEE (4313) spectroscopic surveys.

These spectroscopic surveys differ in their targeting strategy, spectral resolution and data reduction. APOGEE is a NIR survey with a spectral resolving power of $R \sim 22,500$. LAMOST, RAVE and GALAH are optical surveys with $R \sim 1,800$, $R \sim 7,000$ and $R \sim 28,000$ respectively. The different pipelines that are used in the data reduction process can result in survey specific offsets in the spectroscopic parameters for similar stars. However, efforts have been made to compare the various spectroscopic parameters amongst these surveys, and the parameters are generally similar for most stars (Casey et al. 2017; Buder et al. 2018). The targeting
strategies are also different, with APOGEE focusing more on observing red stars than the other surveys. Additionally, variability might impact the derivation of spectroscopic parameters, particularly when sources are in double-lined spectroscopic binaries (eclipsing binaries). Thus, we cannot rely on a single survey to study all the different classes of variable stars.

We illustrate the distribution of the ASAS-SN variable stars with classification probabilities $\text{Prob} > 0.95$ in $T_{\text{eff}}$ and $\log$(g) (Kiel Diagram) across these surveys in Figure 4. We will only consider sources with $\text{Prob} > 0.95$ in all of our examinations of spectroscopic properties. We have generally not implemented any cuts on the various flags that are available across these data sets. The LAMOST survey provides the only data set that samples all the major variability classes in our catalog. Most of the cross-matches to APOGEE come from the semi-regular variables and rotational variables. If we implement the data quality cut $\text{ASPCAPFLAG}=0$, ~65% of the APOGEE sources remain. We note that some fraction of the SR variables with temperatures $T_{\text{eff}} < 3800$ K in the RAVE data set have values of $\log$(g) that are inconsistent with being evolved stars on the AGB. If we implement the quality cut $\text{QC}=0$ from Casey et al. (2017), ~95% of the RAVE sources remain, but this issue with the location of the giants persists. It is also clear that the vast majority of the semi-regular variables in GALAH have incorrect spectroscopic parameters as they populate a non-physical locus in the Kiel diagram. Buder et al. (2018) noted this issue with their pipeline for cool giants with $T_{\text{eff}} < 4500$ K. Implementing the data quality cut $\text{FLAG}_C\text{ANNON}=0$ suggested by Buder et al. (2018), eliminates all but ~5% of the GALAH sources, which suggests that the GALAH data set is sub-optimal for our purpose of studying variable stars. We find that the data from the LAMOST and RAVE surveys are best suited to characterizing pulsators, eclipsing binaries and rotational variables. APOGEE data are excellent for the characterization of the cooler semi-regular and irregular variables.

The distribution of the variables in $T_{\text{eff}}$ and $[\text{Fe/H}]$ is shown in Figure 5. We note that the eclipsing binaries in the GALAH sample have metallicities that are largely inconsistent with the eclipsing binaries in the other catalogs. However, only a tiny fraction of this sample passes the quality cut $\text{FLAG}_C\text{ANNON}=0$. In order to improve the accuracy of our work, we will only consider GALAH sources with $\text{FLAG}_C\text{ANNON}=0$. We also restrict the RAVE sample of semi-regular variables to those stars with $\log$(g) < 2.

The combined distributions of the variables in $T_{\text{eff}}$, $\log$(g), $[\text{Fe/H}]$ and $\log_{10}$(P/days) are shown in Figure 6. The median and standard deviation of the spectroscopic parameters for variable types with sample sizes $N > 10$ are also summarized in Table 2. On average, eclipsing binaries have sub-solar metallicities ($[\text{Fe/H}]$~−0.2). Cepheid variables have metallicities consistent with Solar metallicity. $\delta$ Scuti variables and rotational variables have metallicites that are slightly sub-Solar ($[\text{Fe/H}]$~−0.1). Semi-regular variables are strongly peaked at $[\text{Fe/H}]$~− 0.5, with very few having Solar or super-Solar metallicities. The population II RRAB stars have very low metallicities with $[\text{Fe/H}]$~− 1. The average metallicity of the overtone RR Lyrae (RRC) variables in our sample is $[\text{Fe/H}]$~− 0.3 and has a large dispersion of $\sigma$~0.8 dex. Walker & Terndrup (1991) found that, on average, both RRAB and RRC variables in Baade’s window had $[\text{Fe/H}]$~− 1. This suggests that some fraction of the sources classified as RRC variables are in fact EW-type eclipsing binaries with higher metallicities ($[\text{Fe/H}]$~ − 0.2). Without spectroscopic information, there can be non-negligible confusion between these two variable groups during the classi-
fication process due to their very similar and symmetrical light curve shapes.

The temperatures and surface gravities of the semi-regular/irregular variables are consistent with these stars being highly evolved AGB stars. Classical pulsators, such as the RR Lyraes, Cepheids and δ Scuti variables, have temperatures that fall within the instability strip for pulsations. Overtone Cepheids and RR Lyrae are hotter than the fundamental mode pulsators at fixed temperature. The eclipsing binaries in this sample mostly have surface gravities consistent with main sequence (MS) or slightly evolved stars. Figure 5 shows that the eclipsing binaries span a large range in effective temperature with $4000 \text{ K} < T_{\text{eff}} < 8000 \text{ K}$ (A-K spectral types). On average, β Lyrae-type semi-detached binaries (EB) have hotter effective temperatures than both contact binaries and detached eclipsing binaries. The surface gravities of the rotational variables peak near the MS, but the dispersion of $\sigma \sim 0.8$ dex is large because it is a much more diverse population of sources, including spotted stars on the RGB. We will further investigate the populations of eclipsing binaries and rotational variables in §4.

Figure 7 shows the correlation between APOGEE and GALAH estimates of $v \sin(i)$ and the ASAS-SN log$_{10}(P$/days) for the variables in the spectroscopic sample. As expected for the rotational variables, $v \sin(i)$ decreases with the period. For the 32 semi-regular variables with $v \sin(i)$ measurements from GALAH (APOGEE does not report $v \sin(i)$ for very evolved stars), the median was $v \sin(i) \sim 8$ km/s. δ Scuti variables have a broad distribution in $v \sin(i)$, consistent with previous measurements (Solano & Fernley 1997). Most short period ($P < 1$ d) eclipsing binaries have $v \sin(i) \lesssim 20$ km/s.

**Table 2.** Distribution of [Fe/H], $T_{\text{eff}}$, and log(g) for variable types with at least 10 members with classifications. The variable types are defined in Table 1. The median, and standard deviation for each spectroscopic parameter is shown.

| VSX Type | $N$ | $T_{\text{eff}}$ | log(g) | [Fe/H] |
|----------|-----|----------------|--------|--------|
| DCEP     | 40  | 6094±453       | 1.5±0.8| -0.02±0.28 |
| DCEPS    | 17  | 6618±428       | 2.9±0.8| 0.01±0.16  |
| DSCT     | 537 | 7194±408       | 4.0±0.2| -0.09±0.27 |
| HADS     | 267 | 7256±538       | 4.1±0.2| -0.24±0.34 |
| EA       | 3115| 6283±851       | 4.1±0.3| -0.13±0.27 |
| EB       | 1948| 6725±771       | 4.1±0.3| -0.16±0.27 |
| EW       | 6388| 5905±656       | 4.2±0.2| -0.17±0.32 |
| SR       | 7232| 3777±158       | 0.6±0.3| -0.51±0.24 |
| L        | 371 | 3773±212       | 0.5±0.4| -0.47±0.24 |
| ROT      | 2748| 4616±503       | 4.1±0.8| -0.14±0.28 |
| YSO      | 27  | 4188±497       | 4.0±0.9| -0.21±0.25 |
| RRAB     | 1086| 6477±297       | 4.2±0.2| -1.01±0.37 |
| RRC      | 161 | 6960±554       | 4.2±0.3| -0.33±0.60 |
| VAR      | 17  | 5811±1262      | 4.1±1.8| -0.90±0.63 |

**Figure 3.** NIR color-magnitude (left) and period-luminosity (right) diagrams for the ASAS-SN V-band variable stars with Prob > 0.95, $A_V < 2$ mag and parallaxes better than 20%. MIST isochrones (Choi et al. 2016; Dotter 2016) for single stars with [Fe/H] = 0 at 1 Gyr, 5 Gyr and 10 Gyr are shown for comparison.
Figure 4. Distributions of the ASAS-SN V-band variables in log(g) and $T_{\text{eff}}$ across the LAMOST, APOGEE, RAVE and GALAH datasets. The points are colored by the variable type. Spectroscopic data quality cuts are not included. MIST isochrones (Choi et al. 2016; Dotter 2016) for single stars with [Fe/H] = −0.50 at 1 Gyr, 5 Gyr and 10 Gyr are shown for comparison.
Figure 5. Distributions of the ASAS-SN V-band variables in $T_{\text{eff}}$ and [Fe/H] across the LAMOST, APOGEE, RAVE and GALAH datasets. The points are colored by the variable type.
Figure 6. Distributions of the ASAS-SN V-band variables in $T_{\text{eff}}$, $\log(g)$, $[\text{Fe}/\text{H}]$ and $\log_{10}(P/\text{days})$. The histograms are colored by the variable type.

Figure 7. Distributions of the ASAS-SN V-band variables in $v\sin(i)$ vs. $\log_{10}(P/\text{days})$. The points are colored by the variable type.
Here we discuss eclipsing binaries, rotational variables and semi-regular variables using both the photometric information from ASAS-SN and other surveys (including Gaia, WISE, 2MASS and GALEX) and spectroscopic information from the cross-matching in §3 in more detail. In Section 4.1, we study the temperature and metallicity dependences of the periods of eclipsing binaries. In Section 4.2, we examine our catalog of rotational variables and particularly the rapidly rotating evolved stars. In Section 4.3, we discuss the semi-regular variables and their chemical properties using the measurements from APOGEE DR16.

4 DISCUSSION

4.1 Eclipsing Binaries

Eclipsing binaries are useful astrophysical tools that can be used to measure the masses and radii of stars across the Hertzsprung-Russell diagram (see Torres et al. 2010, and references therein). We classified ~136,000 eclipsing binaries in our catalog based on the VSX types: EW (W UMa), EB (β-Lyrae) and EA (Algol). EW binaries have light curves with similar primary/secondary eclipse depths whereas EB binaries tend to have eclipses with significantly different depths. Both the EW (contact) and EB (contact/semi-detached) binaries transition smoothly from the eclipse to the out-of-eclipse state. EA (Algol) binaries are detached systems where the exact onset and end of the eclipses are easily defined. These detached systems may or may not have a secondary minimum.

Figure 8 shows the distributions of the eclipsing binaries in log(g), T_{eff}, log(t_0(P)/days) and M_{Ks}. The surface gravity distributions of the three sub-types are very similar. The biggest differences between the different sub-types are in their effective temperatures. On average, EW type contact binaries are significantly cooler (T_{eff}~5900 K) than both the semi-detached EB binaries (T_{eff}~6700 K) and the detached EA systems (T_{eff}~6300 K). EW binaries peak at log(t_0(P)/days)~−0.5 and drop sharply at both longer and shorter periods. There are very few EW systems with log(t_0(P)/days) > 0. EB systems peak at log(t_0(P)/days)~−0.8 and span a larger range in period. The detached EA systems peak at log(t_0(P)/days)~0.4 and are more evenly distributed in their orbital periods than the EB and EW systems. EW systems are fainter, with a peak at M_{Ks}=2.4 mag, whereas the EB and EA systems peak at a similar M_{Ks}=1.6 mag.

In Paper VII (Jayasinghe et al. 2020b), we analyzed a sample of ~71,000 EW systems, and noted a clear dichotomy between the early and late-type EW systems. We found that the period distribution had a clear minimum at log(P/d) = −0.30 which also corresponded to a break in the slope of the period-luminosity relation. The distinction between the populations was even clearer in the case of period and effective temperature, with a gap along the line T_{eff} = 6710K − 1760K log(P/0.5d). The median temperature of the early-type contact binaries (T_{eff}~6900 K) was significantly hotter than the late-type contact binaries (T_{eff}~5800 K). We further noted that the Kraft break (Kraft 1967) appeared to determine the observed dichotomy of the contact binaries. Early-type systems form due to stellar evolution and the subsequent expansion of a more massive component that is above the Kraft break (~1.3 M_{⊙}). In contrast, the less massive late-type systems can come into contact due to efficient angular momentum loss during the detached phase (Yildiz 2014).

Figure 9 shows the different sub-types of eclipsing binaries in the space of log(P/d) and T_{eff}. There is significant overlap in period-temperature space between the EW and EB binaries, with most EB binaries falling above the cut defined in Jayasinghe et al. (2020b) for the early-type EW systems. The overlap between the EW and EB binaries is most significant in the period—temperature space above this cut. The detached binaries are distributed randomly in this space. The distribution of EB binaries peaks at a similar temperature to the early-type EW binaries (T_{eff}~6900 K, see Figure 8), which suggests that the early-type EW are drawn from the population of EB binaries. However, these two populations differ in the ratio between the primary and secondary light curve minima. The degree of thermal equilibrium between the two stars dictates the difference in eclipse depths (Paczynski et al. 2006), and the very similar eclipses seen in EW binaries suggest that these stars are in better thermal contact than the EB binaries that have different eclipse depths.

In our previous work, we hypothesized that the early-type EW systems have a massive component above the Kraft break (~1.3 M_{⊙}) that is in thermal contact with the secondary. The EB systems are likely to have similar massive components, but the two components in these systems diverge significantly from thermal contact, unlike those in the late-type EW systems. Models of thermal relaxation oscillations (TRO, see, for e.g., Lucy 1976; Flannery 1976; Yakut & Eggleton 2005) predict a population of EB eclipsing binaries with unequal minima that overlap in period and temperature with the EW systems (Webbink 2003). In the TRO cycle, an eclipsing binary oscillates between the contact and semi-detached states. The semi-detached phase spans a period and temperature range that is comparable to the contact phase, and the two components develop different effective temperatures during the EB stage of the cycle (Webbink 2003). The overlap between the early-type EW and the semi-detached EB systems appear to be consistent with the predictions of the TRO models for contact binaries.

The orbital period at which a star overflows its Roche Lobe in a binary consisting of two equal mass stars with a mass ratio of q = 1 is approximately (Eggleton 1983)

$$\frac{P}{\text{days}} \approx 0.351 \left( \frac{R_{*}}{R_{\odot}} \right)^{-3/2} \left( \frac{M_{1}}{M_{\odot}} \right)^{1/2} \left( \frac{M_{2}}{M_{\odot}} \right)^{-1/2}.$$

We used the MIST single star isochrones (Choi et al. 2016; Dotter 2016) to predict the period-temperature relationship at metallicities of [Fe/H] = −0.5, 0 and 0.25 for a MS population with an age of 10^8 yr. The predicted minimum period-temperature relationship depends on metallicity—binaries at lower metallicities can have a shorter minimum orbital period at fixed temperature. This relationship is steep for binaries with T_{eff} \leq 7000 K and flattens at higher temperatures. Figure 10 shows the median and 5% to 95% ranges for the periods of eclipsing binaries as a function of temperature. We selected sources with log(g) > 4 to restrict the sample to MS binaries. As one would expect, contact EW binaries at fixed T_{eff} have shorter periods than semi-detached EB binaries which have shorter periods than detached EA binaries. We see that the lower edge of the EW distribution
hugs the Roche limit as expected. They do not all lie at this limit because the minimum period for one of the stars to be in Roche contact becomes lower as we reduce the mass-ratio $q$. We illustrate this for a mass ratio of $q = 0.1$.

In the MIST model shown in Figure 10, we see that the low metallicity binaries can be more compact before reaching the Roche limit. In Figure 11, we divide each class of eclipsing binaries into metallicity bins of $[\text{Fe/H}] < -0.5$, $-0.5 < [\text{Fe/H}] < 0$ and $[\text{Fe/H}] > 0$, and show the period ranges as a function of temperature for each bin. Most ($\sim 63\%$) eclipsing binaries have metallicities in the range $-0.5 < [\text{Fe/H}] < 0$. Similarly, Pawlak et al. (2019) found that the ASAS-SN eclipsing binaries had a median $[\text{Fe/H}]$ 0.2 dex lower than the entire APOGEE DR14 sample. In general, we see that the lower metallicity binaries have shorter periods than the binaries that are metal-rich at fixed temperature.

Figure 8. Distributions of the EW (red), EB (blue) and EA (black) binaries in log$(g)$, $T_{\text{eff}}$, log$_{10}(P/$days) and $M_K$. The distributions in $T_{\text{eff}}$ for the early (orange) and late-type (purple) EW binaries from Jayasinghe et al. (2020b) are shown as the dashed histograms.
Figure 9. $T_{\text{eff}}$ vs. $\log(P/$days) for EW (red), EB (blue) and EA (black) binaries. The yellow line in $T_{\text{eff}}$ and $\log(P/$days) that separates early and late-type EW binaries is derived in Jayasinghe et al. (2020b).
Figure 10. The median $\log(P/d)$ as a function of $T_{\text{eff}}$ distributions for EW (left), EB (center) and EA (right) binaries. The shaded regions correspond to the 5% to 95% ranges of the periods. The predicted period-temperature relationships for MS Roche contact binaries with mass ratios $q = 1$ (light blue) and $q = 0.1$ (orange) is derived using the MIST isochrones (Choi et al. 2016; Dotter 2016) and are shown for metallicities of $[\text{Fe/H}] = -0.50$ (dashed), $[\text{Fe/H}] = 0$ (straight) and $[\text{Fe/H}] = 0.25$ (dot dashed) for a 10$^8$ yr old stellar population.
Figure 11. The distribution of the 5th percentile in log(P/d) vs $T_{\text{eff}}$ for EW (left), EB (center) and EA (right) binaries in metallicity bins of $[\text{Fe/H}] < -0.5$ (black), $-0.5 < [\text{Fe/H}] < 0$ (red) and $[\text{Fe/H}] > 0$ (blue). The shaded regions correspond to the 5% to 95% ranges of the periods. The predicted period-temperature relationships (light blue) for equal mass MS binaries overflowing their Roche Lobes is derived using the MIST isochrones (Choi et al. 2016; Dotter 2016) and are shown for metallicities of $[\text{Fe/H}] = -0.50$ (dashed), $[\text{Fe/H}] = 0$ (straight) and $[\text{Fe/H}] = 0.25$ (dot dashed) for a 10$^8$ yr old stellar population.
4.2 Rotational Variables

The ~33,000 Rotational (ROT) variables in our V-band catalog are drawn from a variety of rotational variable types, including Ω2 Canum Venaticorum variables (ACV), RS Canum Venaticorum-type (RS) binary systems, BY Draconis-type variables (BY), FK Comae Berenices-type variables (FKCOM), rotating ellipsoidal variables (ELL) and spotted T Tauri stars showing periodic variability (TTS/ROT). Rotational variables are distributed across the Hertzsprung-Russell diagram, but the detectability of a rotational signal largely depends on their evolutionary state. Cellier et al. (2017) studied ~17,400 Kepler red giants and noted that ~2% of these sources had a detectable rotational signal in their light curves. They also studied ~600 red clump stars in their sample and found that ~15% of these sources had a detectable rotational signal. In contrast, McQuillan et al. (2013) detected rotational signals in the Kepler light curves of ~38% of main-sequence planet hosts.

Figure 12 shows the distributions of the ROT variables in log(g), $T_{\text{eff}}$, log$_{10}(P/\text{days})$ and $M_K$. The rotational variables in LAMOST are shown separately, as most spectroscopic cross-matches to the rotational variables come from this catalog. The LAMOST catalog is incomplete for the M-dwarf rotational variables with log(g) > 4.8, $T_{\text{eff}} < 3800$ K. As expected, there are three distinct classes of rotational variables in the log(g) and $M_K$ distributions. These correspond to sources on the MS/pre-MS (log(g) -4.5, $M_K$ -4), the RGB (log(g) -3.5, $M_K$ -1) and the red clump (log(g) -2.6, $M_K$ -1.5) evolutionary states. These three classes of rotational variables have been characterized in previous surveys (see for e.g., McQuillan et al. 2013; Cellier et al. 2017. The color-magnitude diagram shown in Figure 3 suggests that sources with $M_K$ > 2 mag are likely to be evolved stars on the lower RGB. Red clump (RC) stars have an absolute magnitude of $M_K$ = -1.61 ± 0.01 mag (Hawkins et al. 2017), which is consistent with the peak in the $M_K$ distribution.

Figure 13 shows the distribution of rotational variables in log(g) and luminosity as a function of $T_{\text{eff}}$. We use the calibrations from Torres et al. (2010) to derive the radii of the rotational variables using $T_{\text{eff}}$, log(g) and [Fe/H]. The Torres et al. (2010) scalings agree with asteroseismic estimates (Yu et al. 2018). The luminosities are then derived using the radius and $T_{\text{eff}}$. We find that the rotational variables are largely distributed along the MS and the RGB. Sources on the red clump are also seen in both of these spaces. There are also many sources above the MS, which are likely spotted stars in binary systems or pre-MS spotted T Tauri stars (TTS/ROT).

The distribution of the rotational variables in log$_{10}(P/\text{days})$ or $v_{\text{rot}}$ and log(g) are shown in Figure 14. We estimate the rotational velocities as

$$v_{\text{rot}} = \frac{2\pi R}{P_{\text{phot}}}$$

where $R$ is estimated using the Torres et al. (2010) calibrations. Regions corresponding to the red clump (1.8 ≤ log(g) ≤ 2.8) and the RGB (2.9 ≤ log(g) ≤ 3.9) are shaded in red and blue, respectively. The stars in the RGB region have a median radius of $R$ - 3.4 $R_\odot$, whereas the red clump variables have a median radius of $R$ - 13.5 $R_\odot$. RGB stars have shorter rotational periods than sources in the red clump, with ~62% (~42%) of the RGB (RC) rotators having periods $P_{\text{rot}} < 10$ d. 78 evolved stars on the RGB had spectroscopic measurements of $v$ sin(i) from APOGEE (~86%), or GALAH (~14%) (see Figure 7). The majority (~81%) of these stars were fast rotators with $v$ sin(i) > 10 km/s. We find that ~80% of the rotating giants have $v_{\text{rot}} > 10$ km/s, consistent with the rapid rotators from the sample with spectroscopic $v$ sin(i). In contrast, ~98% of the rotational variables on the red clump have $v_{\text{rot}} > 10$ km/s. If we impose a more conservative cut on the red clump sample to minimize contamination from RGB stars by restricting our sample to stars with $2.3 < log(g) < 2.6$, we find that nearly all of these stars have $v_{\text{rot}} > 10$ km/s, implying that rapid rotation is more common for red clump stars than for stars on the RGB.

Of the rapidly rotating red clump stars, ~30% are metal-poor with [Fe/H] < ~0.5, whereas only ~8% are metal-rich with [Fe/H] > 0. The multiplicity fraction is anti-correlated with metallicity (see e.g., Moe et al. 2019), and the prevalence of metal-poor rapid rotators maybe a consequence of higher binary fractions at lower metallicity. Similarly, Tayar et al. (2015) found a large fraction of rapidly-rotating stars on the red clump. This enhancement probably appears because stars are more likely to interact as they expand going up the giant branch, and stop interacting as they descend the giant branch to the red clump. The clump stars then retain the “memory” of the interactions allowed by the expansion. The multiplicity fraction at the red clump is also lower than that of the RGB, and is comparable to the multiplicity fraction at the tip of the RGB (Badenes et al. 2018; Price-Whelan et al. 2020). The reduced multiplicity fraction could be a sign of companion engulfment and spin up during a common envelope phase (Ivanova et al. 2013; Price-Whelan et al. 2020).

Dixon et al. (2020) identified an empirical relationship between the near-UV (NUV) excess estimated by combining GALEX+2MASS data and $v$ sin(i) for giant stars in the APOGEE survey. Figure 15 shows the distribution of ~2,500 evolved rotational variables with $M_K < 2$ mag (see Figure 3) for which we could calculate the Dixon et al. (2020) NUV excess. Of the sources with GALEX detections, ~58% have periods $P_{\text{rot}} < 10$ d. Dixon et al. (2020) derived an empirical rotation-activity relation for giants of NUV excess $= (-1.43 ± 0.12) log(v$ sin(i) $) + (0.647 ± 0.131)$. (5)

So, giants with $v$ sin(i) > 10 km/s will have an NUV excess $< -0.78$ mag. We find that ~87% of the rotating giants have NUV excesses $< -0.78$ mag, which is consistent with our other estimates of the fraction of sources with rapid rotation ($v$ sin(i) > 10 km/s). If we restrict the sources to $M_K < 0$ mag, the fraction of sources with NUV excesses $< -0.78$ mag drops to ~80%.

Dixon et al. (2020) argued that the dependence of the NUV excess on period could be divided into a saturated and a linear regime in activity with a break at $P_{\text{rot}} = 10$ d. Our sources follow a similar trend, with the median NUV excess decreasing with increasing period beyond $P_{\text{rot}} = 10$ d (Figure 15). The median NUV excess is roughly flat between 4 < $P_{\text{rot}}$ d < 10, as also found by Dixon et al. (2020). In the super-saturated regime ($P_{\text{rot}} ≈ 4$ days for typical giants), active giant stars are expected to have decreased activity compared to giants in the saturated regime. We see some evidence for this super-saturated regime in Figure 15.

Figure 16 shows the distribution of all the 248 rotational
variables in APOGEE with \texttt{ASPCAP\_FLAG=0} in the [Mg/Fe]—[Fe/H] plane as compared to the ~248,000 APOGEE DR16 giants with log(g) < 3.8 and \texttt{ASPCAP\_FLAG=0}. We also show the division from Weinberg et al. (2019) between the “high-\(\alpha\)” and “low-\(\alpha\)” sequences. The high-\(\alpha\) population is older, kinematically hotter and is located in the thick disk, whereas the low-\(\alpha\) population is located in the thin disk (Prochaska et al. 2000; Fuhrmann 1998; Weinberg et al. 2019). The plateau in the high-\(\alpha\) sequence at [Mg/Fe]=0.4 is the average yield of core collapse supernovae and the drop to lower values of [Mg/Fe] is due to later Fe production in type II supernovae (Weinberg et al. 2019). The rotational variables are low-\(\alpha\) stars strongly clustered towards [Mg/Fe]~ −0.1, and [Fe/H]~ −0.1. Their distribution in Figure 16 is very different from the typical giant stars or the SR variables and AGB stars we discuss in §4.3.3. The rotational variables occupy a sparsely populated area in the [Mg/Fe]—[Fe/H] plane and this odd clustering of the rotational variables is very likely due to systematics in the ASPCAP abundance pipeline when dealing with rapidly rotating stars. We also highlight 2M05215658+4359220, the candidate giant star-black hole binary identified by Thompson et al. (2019) in Figure 16. 2M05215658+4359220 is a rapidly rotating giant with \(v\sin(i) \approx 14.1\pm 0.6\ \text{km/s}\) and is a clear outlier in the [Mg/Fe]—[Fe/H] plane, even compared to the ROT variables. The ASPCAP pipeline includes the flag \texttt{ROTATION\_WARN} to warn of the presence of broadened lines in the APOGEE spectrum, suggesting that the abundances derived for this object could be suspect. The [C/N] abundance of this giant is unusual for a giant with \(M_{\text{giant}} \approx 3.2 \pm 1.0M_{\odot}\) and is more typical of a lower mass giant with \(M_{\text{giant}} \sim 1M_{\odot}\) (Thompson et al. 2019). Thompson et al. (2020) cautions against the use of the APOGEE [C/N] abundance in claiming a lower mass for the giant based on the systematic uncertainties in the determination of abundances for rapidly rotating giants. The distribution of the ASAS-SN rotational variables in Figure 16 supports this argument, as their abundances are unusual and suggestive of systematic issues in the ASPCAP pipeline when dealing with rapidly rotating stars. Indeed, if we examine the individual element abundances ([Fe/Mg], [C/Mg], [Mn/Mg] and [Ni/Mg]) of the rotational variables, they are almost all peculiar, and those of 2M05215658+4359220 are more peculiar than most.

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{asas-sn-distributions.png}
\caption{Distributions of the rotational variables for the complete spectroscopic sample (blue) and the LAMOST sample (red) in log(g), \(T_{\text{eff}}\), log(\(P/\text{days}\)) and M\(_{\text{Ks}}\). The log(\(P/\text{days}\)) and M\(_{\text{Ks}}\) distributions of the rotational variables in the entire ASAS-SN sample are shown in black.}
\end{figure}
Figure 13. 2-D histograms of the rotation variables in log(g) (left) and luminosity (right) as a function of $T_{\text{eff}}$. The bins are colored by the number density. Solar metallicity MIST isochrones (Choi et al. 2016; Dotter 2016) for single stars at 5 Gyr and 10 Gyr are shown for comparison.

Figure 14. $\log_{10}(P/\text{days})$ (left) and $v_{\text{rot}}$ (right) as a function of log(g) for the rotational variables. The points are colored by metallicity. Regions corresponding to the red clump ($1.8 \lesssim \log(g) \lesssim 2.8$) and the RGB ($2.9 \lesssim \log(g) \lesssim 3.9$) are shaded in red and blue, respectively. The red dashed line corresponds to the division between fast ($v_{\text{rot}} > 10 \text{ km/s}$) and slow rotating giants.
Figure 15. Distributions of the NUV excess (left) and its dependence on period (right) for the rotational variables with $M_{Ks} < 2$ mag. The blue dashed line is the expected NUV excess (~0.78 mag) for rotating giant stars with $v \sin(i) = 10$ km/s from Dixon et al. (2020). The red dashed line represents the break in the period-NUV excess relationship at $P_{rot} = 10$ days from Dixon et al. (2020). The period at which rotating giants reach super-saturation is shown as a black dashed line at $P_{rot} \approx 4$ days.

Figure 16. The distribution of all the rotational variables in APOGEE DR16 (red) and a reference sample of giants from APOGEE DR16 (2-d histogram) in the $[\text{Mg/Fe}]$ vs. $[\text{Fe/H}]$ plane. The blue line shows the division between the low-\(\alpha\) and high-\(\alpha\) populations from Weinberg et al. (2019). The candidate giant star-black hole binary (2M05215658+4359220) from Thompson et al. (2019) is shown as an orange star.
4.3 Long Period Variables on the Asymptotic Giant Branch

Low and intermediate mass stars end their lives after reaching the asymptotic giant branch (AGB). During the AGB phase, stellar evolution is characterized by hydrogen and helium shell burning on top of a degenerate carbon/oxygen core (see for e.g., Herwig 2005). AGB stars are cool, luminous objects that contribute significantly to the metallicity of the interstellar medium through nucleosynthetic processes and strong mass loss (Herwig 2005; Lebzelter et al. 2018). In particular, the thermally pulsing AGB (TP-AGB) stars are characterized by long-period pulsational variability and heavy mass loss rates (Marigo & Girardi 2007).

The long-period variables on the TP-AGB are broadly classified into the semi-regular (SR) variables and the Mira variables. Mira variables are thought to be located at the tip of the AGB (Iben & Renzini 1983) and have large variability amplitudes ($A > 2.5$ mag in the V-band). Semi-regular variables are separated from the Mira variables on the basis of their variability amplitudes ($A < 2.5$ mag in the V-band). Previous surveys have argued that TP-AGB stars start off as pulsating semi-regular variables with small amplitudes and later evolve into the high amplitude Mira variables as they reach the tip of the AGB (Wood et al. 1999; Marigo & Girardi 2007; Sozrnski et al. 2009). Mira variables follow a period-luminosity relationship (Glass & Evans 1981; White-lock et al. 2008), although some Mira variables can undergo changes in their period over time (Percy & Colivas 1999).

SR variables are less strictly periodic and can show multiple periods that can be used to study the dynamics of stellar interiors (Kiss et al. 1999). Microlensing surveys of the Magellanic clouds have shown that semi-regular variables fall along five distinct period-luminosity sequences (A-E; Wood et al. 1999; Wood 2000). More recent work by the OGLE survey has shown that the five Wood’s sequences are a result of an overlap of 14 or more period-luminosity sequences (Soszynski et al. 2007; Soszynski et al. 2009).

During the TP-AGB, numerous nuclides are produced during H and He burning. The surfaces of AGB stars are chemically enriched primarily through the third dredge up (TDU) events that follow a thermal pulse. AGB nucleosynthesis depends on the efficiency of the TDU, the minimum core mass at which TDU begins, the size of the convective envelope, and the mass of the He intershell (Karakas et al. 2002). The efficiency of TDU increases with increasing stellar mass and decreasing metallicity (Karakas et al. 2002). In particular, the surface abundances of CNO elements are enhanced by an order of magnitude or more following a TDU episode (Iwamoto et al. 2004). The surfaces of AGB stars are also enriched in heavy elements that are produced by the s-process (e.g., Zr, Sr, Ba, etc., Smith & Lambert 1986, 1988). Hot-bottom burning (HBB) in the more massive AGB stars can also further enhance the surface N abundances (Scalo et al. 1975; McSaveney et al. 2007). Thus, the surface abundances of intermediate-mass AGB stars are dependent on both the TDU and HBB processes.

In this section, we use APOGEE DR16 data (Ahumada et al. 2019) to study the spectroscopic and chemical properties of pulsating AGB stars. The abundances come from the APOGEE Stellar Parameters and Chemical Abundances Pipeline (ASPCAP; Nidever et al. 2015). For comparison with the semi-regular variables, we selected a set of RGB stars ($T_{\text{eff}} \leq 5200$ K, $2 \leq \log(g) \leq 3.5, N \sim 160,000$) and likely AGB stars ($T_{\text{eff}} \leq 4000$ K, $\log(g) \leq 1, N \sim 15,000$). The sample of candidate AGB stars is likely contaminated with some lower mass stars on the upper RGB. For detailed studies of the APOGEE DR16 abundances, we required the flags ASPCAP_FLAG=0 and X_FE_FLAG=0, where X= Mg, Al, C, N or O. We calculate the $[X/Mg]$ metallicities as $[X/Mg] = [X/H] - [Mg/H]$. Following Weinberg et al. (2019), we chose Mg as the reference element because it is produced almost exclusively by core-collapse supernovae and is thus a simpler tracer of chemical enrichment than Fe.

In §4.3.1, we study the various TP-AGB period-luminosity sequences. We identify an APOGEE temperature—$W_{\text{RP}} - W_{\text{JK}}$ color index fit to the oxygen-rich AGB stars in §4.3.2. We examine the α enhancements of the SR variables in §4.3.3. In §4.3.4, we study the Aluminum abundances of the semi-regular variables and characterize the pulsation period dependent Al depletion as a result of mass loss and dust production. We look at the Nitrogen abundances of the semi-regular variables in §4.3.5 and identify a sample of likely intermediate-mass AGB stars undergoing hot-bottom burning.

4.3.1 Period-luminosity sequences

Figure 17 shows the distributions in $\log(g)$, $T_{\text{eff}}$, $\log(10(P/\text{days})$ and $M_\text{K}$ of the SR variables. The SR variables in APOGEE are shown separately. The spectroscopic parameters confirm the highly evolved nature of these stars, with the SR variables having a median surface gravity of $\log(g)$-$0.6$, and a median effective temperature of $T_{\text{eff}}$-$3750$ K. The subset of SR variables in APOGEE DR16 is skewed towards cooler, more evolved SR variables when compared to the SR variables in other surveys. We will only consider the SR variables from APOGEE in the discussions below.

The Gaia DR2 parallaxes of these luminous giants are poor, so we cannot directly assign them to the Wood (2000)’s A-E period-luminosity relations. However, we can use the periods to roughly group them. There are 3 distinct peaks in the period distribution shown in Figure 17 at $\log(10(P/\text{days})$-1.4, 1.7, and 2.7. SR variables with $1 \lesssim \log(10(P/\text{days}) \lesssim 1.5$ (hereafter group I) fall on the Wood (2000) sequence A and have low variability amplitudes. Due to the overlap between the PLR sequences A and B, SR variables with $1.5 \lesssim \log(10(P/\text{days}) \lesssim 1.9$ (hereafter group II) consist of sources on both sequences A and B. In addition, SR variables on sequence E also have periods in this range, even though they are less luminous than the variables on sequences A and B. The OGLE small amplitude variable red giants (OSARGs; Soszynski et al. 2004) consist of both RGB and AGB stars, and follow a unique set of period-luminosity relations (Soszynski et al. 2007). OSARGs have periods that span group I and have amplitudes as small as -3 mmag (Soszynski et al. 2007; Auge et al. 2020). Note that we are not considering the much lower variability amplitudes of ASAS-SN OSARGs used by Auge et al. (2020) to determine the feasibility of ground-based asteroseismology of luminous giants. There is a paucity of SR variables with periods in the range $1.9 \lesssim \log(10(P/\text{days}) \lesssim 2.3$ (hereafter group III) which spans the PLR sequence C corresponding to the Mira variables. It is thought that the PLR sequence C corresponds to...
A large fraction of the semi-regular variables with reported periods $\log_{10}(P/\text{days}) \geq 2.3$ are examples of semi-regular variables with long secondary periods (LSPs) of $P_{\text{LSP}} \approx 300 - 1500 \text{d}$ that are $\sim 10 - 15$ times longer than their actual pulsation period (Wood et al. 2004). The origin of the long secondary periods is debated (Wood et al. 2004; Pawlak et al. 2019). These LSPs can complicate our analysis of the pulsational properties of these variables. Thus, we re-derived the periods of the SR variables using the Generalized Lomb-Scargle (GLS; Zeidmer & Kürster 2009; Scargle 1982) periodogram implemented in astrobasis (Bhatti et al. 2018). From the 5 best periods in the periodogram, SR variables with LSPs were identified if there was a significantly shorter period $P$ in the range $8 \leq P_{\text{LSP}}/P \leq 30$ relative to the primary period. For SR variables identified as LSPs, we assign the shorter period as the pulsation period. Of the SR variables with $\log_{10}(P/\text{days}) \geq 2.3$, $\sim 36\%$ were LSPs. This estimate of the LSP fraction at these periods agree with the estimates ($\sim 25\% - 50\%$) from previous studies (see for e.g., Wood et al. 2004; Sozzyński 2007; Nicholls et al. 2009). Of the LSPs, $\sim 60\%$ had pulsational periods in the range $1.5 \leq \log_{10}(P/\text{days}) \leq 1.9$ and the LSP was on average $\sim 11$ times longer than the actual pulsation period. The period distribution of the semi-regular variables after correcting for LSPs is shown in Figure 17. We assign the LSPs into a separate group (group V) for comparison with the other SR variables.

Figure 18 shows the distribution of the SR variables in $M_{\text{Ks}}$ (left) and $\log(g)$ with period. SR variables on the PLR sequences A, B and D are prominent, with sources on sequence C largely absent from this sample. The SR variables in these sequences overlap in both the period-luminosity and period-surface gravity spaces. It is difficult to disentangle the PLR sequences given the distance uncertainties — only $\sim 15\%$ ($\sim 9\%$) of these sources have Gaia DR2 parallaxes better than $20\%$ ($10\%$). The various spectroscopic parameters and chemical abundances from APOGEE DR16 for the four groups (I-V, defined above) are summarized in Table 3.

The median effective temperatures are similar for all the groups, however the median surface gravity for group I is larger than the other groups, suggesting that these sources might be less evolved. Sources in group I might be contaminated with some sources on the upper RGB or are relatively new to the TP-AGB phase. Sources in group III and IV have the largest median $V$-band amplitudes. This is not too surprising as these stars are fundamental-mode pulsators. Sources in group I have the smallest amplitudes, which is consistent with them being overtone pulsators. The metallicities of the sources in groups II, III and IV are largely similar. However, group I has a slightly different chemical profile, with median metallicities higher than for the other groups. However, the $[\text{X}/\text{Mg}]$ metallicities are consistent across these groups given the reported dispersions. The biggest difference ($\sim 0.2$ dex) is seen in $[\text{Al}/\text{Mg}]$, with the median metallicity trending from $[\text{Al}/\text{Mg}] \sim -0.1$ for $\log_{10}(P/\text{days}) < 1.5$ to $[\text{Al}/\text{Mg}] \sim -0.3$ for $\log_{10}(P/\text{days}) > 1.5$. The LSPs are less evolved than the SR variables in group IV with $\Delta \log(g) < 0.1$, and are more similar to the SR variables in group I and II in their properties. This is not surprising given that the pulsation periods of the LSPs are consistent with the periods of SR variables in groups I and II.

We compare the periods, amplitudes, bolometric luminosities and radii of the Mira and semi-regular variables with $A_V < 2$ mag and parallaxes better than $50\%$ in Figure 19. Very few Miras were in the spectroscopic sample. We calculate the bolometric luminosities as

$$\log(L/L_\odot) = 0.4(M_{\text{bol,0}} - M_{\text{Ks}} - B_{\text{C}}).$$

where $B_{\text{C}} = -6.75\log(T_{\text{eff}}/9500)$ is the K-band bolometric correction for stars with $3300 \leq T_{\text{eff}}/K \leq 5000$ from Buzzoni et al. (2010). The $M_{\text{Ks}}$ magnitudes were corrected for extinction using the SFD estimates (Schlafly & Finkbeiner 2011; Schlegel et al. 1998). The radii are then calculated as

$$\frac{R}{R_\odot} = \left(\frac{T}{T_\odot}\right)^{-2/3} \left(\frac{L}{L_\odot}\right)^{1/2}.$$

The bolometric corrections and radii of the SR variables were calculated using the spectroscopic temperatures, whereas we used temperature estimates from Gaia DR2 for the Mira variables. The Mira variables have a median period of $\log_{10}(P/\text{days}) \sim 2.5$ ($P \sim 320$ days). The amplitudes of the Mira variables range from $\sim 2$–$6$ mag, whereas most SR variables have amplitudes $< 1$ mag. The luminosity distributions of the Mira and SR variables are different, with the Mira variables being more luminous. The median luminosities of the SR variables and Mira variables are $\log(L/L_\odot) \sim 3.0$ and $\log(L/L_\odot) \sim 3.3$ respectively. Some Mira variables are very luminous, with $\log(L/L_\odot) > 4$. Paczynski (1970) calculated the maximum luminosity of AGB stars as $\log(L/L_\odot) = 4.74$ based on the core-mass luminosity relationship derived for AGB stars that go through third dredge up. In our sample, all the Mira and SR variables had luminosities below this limit. The median radius of the Mira variables ($R \sim 132 R_\odot$) is almost twice that of the SR variables ($R \sim 72 R_\odot$), confirming the more evolved nature of the Mira variables when compared to the SR variables.

### 4.3.2 A multi-band photometric calibration for the temperatures of oxygen-rich AGB stars

Most AGB stars lack spectroscopic information, but well calibrated temperatures are useful for studying these evolved stars. Here, we develop a temperature calibration based on the APOGEE temperatures, and a combination of Gaia and 2MASS photometry. Lehzelter et al. (2018) developed a multi-band approach using the Wesenheit magnitudes, $W_{RP}$ and $W_{JK}$, to distinguish between the various types of AGB stars. The intrinsic spread of red giants in the NIR colors is small, and the Wesenheit magnitudes adequately correct for the interstellar extinction. The visual colors of red giants are more sensitive to their surface temperatures and chemical compositions, resulting in a bigger spread in their optical colors. In their work, Lehzelter et al. (2018) found that the color index $W_{RP} - W_{JK}$ traces the temperature and molecular features in the stellar spectra of AGB stars and that the $W_{RP} - W_{JK}$ index can be used to distinguish between carbon-rich and oxygen-rich AGB stars, with the
Figure 17. Distributions of the semi-regular variables for the complete spectroscopic sample (blue) and the APOGEE sample (red) in \( \log(g) \), \( T_{\text{eff}} \), \( \log_{10}(P/\text{days}) \) and \( M_{K_s} \). The \( \log_{10}(P/\text{days}) \) and \( M_{K_s} \) distributions of the semi-regular variables in the entire ASAS-SN sample are shown in black. The period distribution of the semi-regular variables after correcting for LSPs is shown in green.

Figure 18. 2-D histograms of \( M_{K_s} \) (left) and \( \log(g) \) (right) as a function of period for the SR variables in APOGEE DR16 after correcting for LSPs. The bins are colored by the number density.
carbon-rich (oxygen-rich) stars having $W_{RP} - W_{JK} \gtrsim 0.8$ mag ($W_{RP} - W_{JK} \lesssim 0.8$ mag), Arnold et al. (2020) used the $W_{RP} - W_{JK}$ index and the 2MASS $J - Ks$ colors to study long period variables in the KELT survey (Pepper et al. 2007).

We illustrate the distribution of ASAS-SN Mira and semi-regular variables in the ($W_{RP} - W_{JK}$) -- ($J - Ks$) plane in Figure 20. For reference, we also show the sources from the Catalog of Galactic Carbon Stars (Allksnis et al. 2001). The carbon stars form a sharp, linear locus in this color-color space and have a median $W_{RP} - W_{JK} \sim 1.5$ mag. In contrast to the carbon rich stars, the oxygen rich sources form a broader and bluer distribution in this plane. The vast majority of the ASAS-SN Mira and semi-regular variables have values of $W_{RP} - W_{JK}$ consistent with oxygen-rich stars. Of the Mira variables and semi-regular variables, ~97% and ~95% appear to be oxygen-rich AGB stars, respectively. The carbon-rich semi-regular variables follow the tight carbon-star locus in the $W_{RP} - W_{JK} - J - Ks$ plane at 1 mag $\lesssim W_{RP} - W_{JK} \lesssim 2$ mag. In general, the carbon-rich semi-regular variables with $W_{RP} - W_{JK} \gtrsim 0.8$ mag have longer median periods ($\log_{10}$(P/days)-2.1) than the oxygen-rich stars ($\log_{10}$(P/days)-1.9). The Mira variables have a distinct distribution in $W_{RP} - W_{JK}$ that skews lower than that of the semi-regular variables.

To investigate the dependence of temperature on the $W_{RP} - W_{JK}$ index, we show the distribution of 1639 semi-regular variables in APOGEE DR16 in the NIR $J - Ks$ color and $T_{\text{eff}}$ against the $W_{RP} - W_{JK}$ index in Figure 21. These are essentially all oxygen-rich semi-regular variables because there are few carbon-rich semi-regular variables in the APOGEE data. The temperatures of the oxygen-rich semi-regular variables are remarkably well correlated with the $W_{RP} - W_{JK}$ index for $T_{\text{eff}} \lesssim 3800$ K. The semi-regular variables with $T_{\text{eff}} \gtrsim 3800$ K have significantly more scatter. We fit a linear relationship of

$$T_{\text{eff}} = 3548(\pm2) K + 312(\pm4) K \left( W_{RP} - W_{JK} \right)$$

(8)

to the 1191 sources with $T_{\text{eff}} \lesssim 3800$ K and $-0.7$ mag $\lesssim W_{RP} - W_{JK} < 0.8$ mag. On average, this fit returns temperatures that are within ±0.7% of the APOGEE temperatures. The fit is only done for $-0.7$ mag $\leq W_{RP} - W_{JK} \leq 0.8$ mag due to the lack of semi-regular variables with $W_{RP} - W_{JK} < -0.7$ mag.

As a test, we use this relation to estimate the temperatures of the Mira variables shown in Figure 20. The majority of these sources have $W_{RP} - W_{JK} < -0.7$ mag, thus they lie outside the parameter space of the sources used in the fit. Applying equation 8 to these Mira variables, we find the median temperature to be $T_{\text{eff}} \sim 3230$ K (M5 spectral type), with the 1$^{\text{st}}$ percentile being $T_{\text{eff}} \sim 2800$ K (M8 spectral type) and the 99$^{\text{th}}$ percentile being $T_{\text{eff}} \sim 3687$ K (M1 spectral type). Mira variables have spectral temperatures that range
from M0-M10 (Yao et al. 2017), which is entirely consistent with the extrapolation. Furthermore, the median Gaia DR2 temperature for these Mira variables is $T_{\text{eff}} \sim 3290$ K, which is very similar to the median temperature estimated using equation 8.
Figure 20. Distributions of the semi-regular variables (black) and Mira variables (red) in \( W_{RP} - W_{KS} \) vs. \( J - K_s \) (left) and \( W_{RP} - W_{JK} \) (right). The sources from the Catalog of Galactic Carbon Stars (Alksnis et al. 2001) (light blue) are also shown for reference. The orange dashed line corresponds to the \( W_{RP} - W_{JK} \) index used to separate oxygen-rich (\( W_{RP} - W_{JK} \leq 0.8 \) mag) and carbon-rich (\( W_{RP} - W_{JK} \geq 0.8 \) mag) AGB stars.

Figure 21. Distributions of the semi-regular variables in APOGEE DR16 in \( W_{RP} - W_{JK} \) vs. \( J - K_s \) (left) and \( W_{RP} - W_{JK} \) vs. \( T_{eff} \) (right). The blue dashed line corresponds to the \( W_{RP} - W_{JK} \) index (0.8 mag) used to separate oxygen-rich and carbon-rich AGB stars. The red line shows the linear fit to the sources with \( T_{eff} < 3800 \) K and \( W_{RP} - W_{JK} < 0.8 \). The green dashed line corresponds to the temperature cutoff of \( T_{eff} = 3800 \) K used in the fit.
4.3.3 \(\alpha\)-enhancements on the TP-AGB

We show the distribution of the semi-regular variables in the \([\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]\) plane as compared to the distribution of a reference sample of \(\sim 238,000\) giants in APOGEE DR16 with \(\log(g) < 3.8\) in Figure 22. In the reference sample, \(\sim 27\%\) of the sources belong in the high-\(\alpha\) sequence. The bimodality in \([\text{Mg}/\text{Fe}]\) at sub-solar \([\text{Fe}/\text{H}]\) is clearly seen for the semi-regular variables as well, but \(\sim 38\%\) of the semi-regular variables lie in the high-\(\alpha\) sequence, which is an enhancement of +41\% compared to the overall APOGEE sample.

While the morphology of the SR distribution is similar to the APOGEE giants, the actual distributions are shifted, as shown in Figure 23. SR variables tend to be more metal poor (peak \([\text{Fe}/\text{H}] \sim -0.6\) instead of \([\text{Fe}/\text{H}] \sim -0.2\)) and \(\alpha\) rich (median \([\text{Mg}/\text{Fe}] \sim 0.16\) instead of \([\text{Mg}/\text{Fe}] \sim 0.07\)). The low-\(\alpha\) SR variables peak at \([\text{Mg}/\text{Fe}] \sim +0.12\), compared to \([\text{Mg}/\text{Fe}] \sim +0.03\) for the low-\(\alpha\) APOGEE giants. We illustrate the shifts in the distribution of the \([\alpha/\text{M}], [\text{Mg}/\text{Fe}], [\text{O}/\text{Fe}]\) and \([\text{Si}/\text{Fe}]\) abundances in Figure 24. We see significant shifts for both the low-\(\alpha\) and high-\(\alpha\) stars in all but the \([\text{Si}/\text{Fe}]\) abundances. The enhancements in Mg and O relative to Fe are likely due to the third dredge up enhancing the surface abundances of AGB stars in species like O, Ne, Na and Mg (Herwig 2005). The efficiency of dredge up increases with decreasing metallicity (Karakas et al. 2002; Marigo & Girardi 2007), consistent with the larger shifts relative to the reference sample seen on the low-\(\alpha\) branch.

We illustrate the distributions of various surface abundances of the semi-regular variables, APOGEE RGB stars and APOGEE AGB stars in Figure 25. The semi-regular variables and the AGB stars are significantly metal-poor in both \([\text{Fe}/\text{H}]\) and \([\text{Mg}/\text{H}]\). Semi-regular variables with \([\text{Fe}/\text{H}] > 0\) or \([\text{Mg}/\text{H}] > 0\) are rare (\(\sim 3\%\) and \(\sim 7\%\)). The APOGEE AGB stars populate the super-solar metallicity bins significantly more than the semi-regular variables, but this maybe due to the contamination from metal-rich upper RGB stars. The distributions of \([\text{Na}/\text{Mg}], [\text{P}/\text{Mg}],\) and \([\text{Mn}/\text{Mg}]\) for the three samples are mostly similar. The semi-regular variables and the AGB stars have lower \([\text{C}/\text{Mg}], [\text{N}/\text{Mg}]\) and \([\text{O}/\text{Mg}]\) abundances than the RGB stars. The biggest deviation from the RGB stars is in the distribution of \([\text{Al}/\text{Mg}]\), with the semi-regular variables peaking \(\sim -0.3\) dex below the peak of the RGB stars. There are virtually no RGB stars with \([\text{Al}/\text{Mg}] < -0.25\). There are more semi-regular variables than AGB stars in these lower metallicity bins, perhaps suggesting a pulsational dependence to the \([\text{Al}/\text{Mg}]\) abundances. We will further investigate this phenomenon in §4.3.4. The semi-regular variables and AGB stars also show substantial shifts relative to the RGB stars in the \([\text{Si}/\text{Mg}](\Delta\sim 0.1\text{ dex}), [\text{Ni}/\text{Mg}](\Delta\sim 0.1\text{ dex})\) and \([\text{Co}/\text{Mg}](\Delta\sim 0.1\text{ dex})\) metallicities.

Figure 22. The distribution of the semi-regular variables in the APOGEE DR16 \([\text{Mg}/\text{Fe}]\) vs. \([\text{Fe}/\text{H}]\) plane. The contours show the distribution of a reference sample of APOGEE giants. The red line shows the division between the low-\(\alpha\) and high-\(\alpha\) populations from Weinberg et al. (2019).
**Figure 23.** The distribution of the SR variables (blue) and giant stars from APOGEE DR16 with log($g$) < 3.8 (black) in [Mg/Fe] (left) and [Fe/H] (right).

**Figure 24.** The distribution of the SR variables (blue) and giant stars from APOGEE DR16 in [$\alpha$/M], [Mg/Fe], [O/Fe] and [Si/Fe]. The median abundances of the high-$\alpha$ and low-$\alpha$ SR variables (APOGEE giants) are shown as red (purple) dashed (dot-dashed) lines.
Figure 25. [Fe/H], [Mg/H] and [X/Mg] abundances, where X = C, N, O, Al, Si, P, Na, Ni, Co, and Mn, for the semi-regular variables (blue), APOGEE AGB stars (red) and APOGEE RGB stars (black).
4.3.4 Surface Aluminium depletion on the TP-AGB

Al is a light, odd Z element that is almost entirely produced due to core-collapse supernovae (see for e.g., Weinberg et al. 2019; Griffith et al. 2019). The oxygen-rich atmospheres of most AGB stars are conducive to the formation of dust seeds close to the stellar surface, including Al$_2$O$_3$, SiO$_2$ and TiO$_2$ (Gail et al. 2013; Decin et al. 2017). The presence of alumina (Al$_2$O$_3$) dust around oxygen-rich AGB stars is well known (Onaka et al. 1989). Banerjee et al. (2012) reported the near-IR detection of several AlO bands in the wavelength range 1.0 − 1.35 μm and rotational transitions of this molecule have also been reported (De Beck et al. 2017; Decin et al. 2017). It is thought that AlO is efficiently depleted from the gas around oxygen-rich AGB stars to form alumina dust seeds (De Beck et al. 2017). AGB stars lose mass through a slow wind (<10 km/s) driven by radiation pressure on dust grains (Iben & Renzini 1983; Khouri et al. 2015). Understanding the formation of dust seeds like alumina and silicate is a crucial consideration when studying mass loss in AGB stars.  

In §4.3.3, we noted that the semi-regular variables and a sample of likely AGB stars in APOGEE DR16 had lower [Al/Mg] abundances than the APOGEE RGB stars. We investigate the [Al/Mg] and [Al/C] abundances for the semi-regular variables, APOGEE AGB and RGB stars in Figure 26. In the [Al/Mg] − [Mg/H] plane, both the semi-regular variables and APOGEE AGB stars form two distinct sequences at [Al/Mg] = −0.15 and [Al/Mg] = −0.35. There is an additional peak in the distribution of [Al/Mg] at [Al/Mg] = −0.5, however, we do not see an associated sequence in the [Al/Mg] − [Mg/H] plane. The median [Al/Mg] abundances for the semi-regular variables, AGB stars and RGB stars are −0.25, −0.16 and −0.01, respectively. In general, the AGB stars have higher [Al/Mg] abundances than the semi-regular variables. The [Al/Mg] abundances of the RGB stars appear to follow a Gaussian distribution centered at [Al/Mg] = 0. Of the RGB stars, only ~3% have [Al/Mg] < −0.2, whereas ~61% of the semi-regular variables and ~42% of the AGB stars have [Al/Mg] < −0.2. This suggests that Al is being depleted on the AGB, with the pulsating TP-AGB stars depleting more Al than other AGB stars.

The two Al sequences (hereafter the “high-Al” and “low-Al” sequences) are even more distinct in the [Al/C] − [Mg/H] plane (Figure 26). The “high-Al” and “low-Al” populations are centered on [Al/C] = 0 and [Al/C] = −0.15. The RGB stars again appear to follow a Gaussian distribution in [Al/C], centered at [Al/C] = +0.05. However, both the semi-regular variables and AGB stars have a bi-modal distribution in [Al/C]. The semi-regular variables populate the “low-Al” sequence relatively more than the AGB stars, with ~40% of the semi-regular variables having [Al/C] < −0.1 compared to only ~23% of the AGB stars. This again hints at a correlation between Al depletion and pulsations in AGB stars.

We investigate the dependence of [Al/X], where X = Mg, C, Si, and O, with the pulsation period in Figure 27. The reference elements C, Si and O, were chosen due to their significant presence in dust grains. Previous studies have established that strong mass loss and increased dust formation first occurs for pulsation periods of P > 60 days for Galactic AGB stars (Glass et al. 2009; McDonald et al. 2018). The [Al/X] metallicities of the semi-regular variables are strongly correlated with the pulsational period. On average, the [Al/X] abundances decrease with period up until P > 60 days and then flatten. The most striking dependence is seen in the distribution of [Al/O] with period. The [Al/O] trend largely plateaus at [Al/O] ~ 0.3 beyond P > 60 days. The fraction of sources with [Al/O] < −0.22 varies between the PLR groups (see §4.3.1), with ~16% in group I, ~54% in group II, ~74% in group III and ~69% in group IV. The fraction of sources with [Al/O] < −0.1 follow a similar trend, with ~14% in group I, ~45% in group II, ~62% in group III and ~63% in group IV. Of the LSPs, ~44% and ~41% had [Al/O] < −0.22 and [Al/C] < −0.1, respectively. These period trends were far less obvious when we assigned stars their LSPs, which strongly supports the argument that the shorter periods are more physically important.

Figure 28 shows the dependence of [Al/X], where X = Mg, C, Si, and O, with effective temperature for the semi-regular variables. The high-Al and low-Al sequences that were identified in the [Al/Mg] − [Mg/H] and [Al/C] − [Mg/H] planes are also apparent in temperature−metallicity space. Furthermore, we see evidence of the period dependence on the Al abundances, with short period sources falling into the high-Al sequence. Cuts of [Al/Mg] = −0.25, [Al/C] = −0.1, [Al/O] = −0.22 or [Al/Si] = −0.13 roughly separate the high-Al and low-Al sequences. Separating based on their [Al/C] abundance ratio, we find that the high-Al variables have a median period of log$_{10}$(P/days)~1.5, whereas the low-Al variables have a median period of log$_{10}$(P/days)~1.8. The median period of the low-Al variables falls below the period at which dust formation and mass loss is significant for AGB stars (log$_{10}$(P/days)~1.75), whereas the median period of the high-Al variables exceeds this limit. After separating these sources into the high-α and low-α sequences based on the division in Weinberg et al. (2019), we find that ~54% of the low-Al variables are high-α stars, whereas only ~34% of the high-Al variables are on the high-α sequence. The low-Al sequence is likely the result of significant Al depletion through the formation of dust grains containing Al (for example, alumina) in the stellar winds of AGB stars.

The various APOGEE DR16 spectroscopic parameters and chemical abundances for the high-Al and low-Al sequences are summarized in Table 4 for these two groups. The low-Al sources are slightly cooler and more evolved (ΔTeff~50 K, Δ log(g)~0.1) than the high-Al sources. The median V-band amplitudes of the low-Al stars are more than twice that of the high-Al stars. The high-Al stars have [α/M] abundances that are consistent with being on the low-α sequence, whereas the low-Al stars have [α/M] consistent with being high-α stars. The low-Al stars have larger Mg abundances (Δ[Mg/Fe]<0.1dex) than the high-Al stars, which likely indicates enrichment due to dredge up. The high-Al stars have enhanced N, Na, P, Cr, Mn, Ni and Ti abundances when compared to the low-Al stars.
Figure 26. [Al/Mg] (top left) and [Al/C] (top right) vs. [Mg/H] for the semi-regular variables (P < 60d: black, P > 60d: purple) and APOGEE AGB stars (orange). The distributions of the APOGEE RGB stars in these planes are shown as contours. The distributions of [Al/Mg] (bottom left) and [Al/C] (bottom right) for the semi-regular variables (black) APOGEE AGB (orange) and RGB (blue) stars are shown as histograms.
Figure 27. $[\text{Al}/\text{Mg}]$, $[\text{Al}/\text{C}]$, $[\text{Al}/\text{Si}]$ and $[\text{Al}/\text{O}]$ vs. $\log_{10}(P/\text{days})$ for the semi-regular variables. The binned median metallicities are shown in blue. The red dashed line shows the period at which increased dust formation first occurs for Galactic AGB stars ($P \geq 60$ days). These correlations are far less clear if we use the LSP periods.
Figure 28. The dependence of $[\text{Al}/\text{Mg}]$, $[\text{Al}/\text{C}]$, $[\text{Al}/\text{Si}]$ and $[\text{Al}/\text{O}]$ on $T_{\text{eff}}$ for the semi-regular variables. The points are colored by $\log_{10}(P/\text{days})$ with the changes in hue at periods near 60 days. The black dashed line shows the suggested metallicity cuts ($[\text{Al}/\text{Mg}]=−0.25$, $[\text{Al}/\text{C}]=−0.1$, $[\text{Al}/\text{O}]=−0.22$ or $[\text{Al}/\text{Si}]=−0.13$) for separating the high-Al and low-Al sequences.
The SR variables are sorted into these groups based on their [Al/O] and [N/O] abundances. The median, and standard deviation for each parameter is shown.

|                  | High-Al | Low-Al | High-N | Low-N | HBB |
|------------------|---------|--------|--------|-------|-----|
| [Al/O] > -0.22   | 874     | 812    | 872    | 728   | 86  |
| N                | 1.5±0.4 | 1.8±0.5| 1.6±0.5| 1.6±0.5| 2.0±0.6|
| log₁₀(P/days)    | 0.13±0.13| 0.26±0.23| 0.15±0.19| 0.20±0.21| 0.17±0.21|
| T eff [K]        | 3730±126| 3683±139| 3727±126| 3677±120| 3822±194|
| log(g)           | 0.54±0.29| 0.42±0.25| 0.46±0.28| 0.55±0.21| 0.07±0.55|
| [M/H]            | -0.50±0.26| -0.68±0.29| -0.57±0.31| -0.63±0.28| -0.52±0.31|
| [α/M]            | 0.08±0.09| 0.22±0.11| 0.07±0.05| 0.25±0.06| -0.03±0.07|
| [Fe/H]           | -0.52±0.25| -0.69±0.28| -0.59±0.30| -0.64±0.27| -0.56±0.30|
| [Mg/Fe]          | 0.14±0.10| 0.24±0.12| 0.13±0.07| 0.30±0.08| 0.03±0.09|
| [C/Mg]           | -0.14±0.09| -0.15±0.16| -0.14±0.13| -0.15±0.14| -0.22±0.18|
| [N/Mg]           | 0.08±0.16| -0.07±0.18| 0.10±0.08| -0.13±0.09| 0.36±0.19|
| [O/Mg]           | -0.03±0.04| -0.04±0.05| -0.04±0.05| -0.04±0.05| -0.05±0.05|
| [Si/Mg]          | -0.11±0.05| -0.12±0.06| -0.11±0.05| -0.12±0.05| -0.08±0.06|
| [Ca/Mg]          | -0.07±0.07| -0.10±0.10| -0.06±0.06| -0.14±0.08| 0.05±0.08|
| [Al/Mg]          | -0.16±0.09| -0.34±0.11| -0.20±0.14| -0.31±0.14| -0.31±0.14|
| [Na/Mg]          | -0.04±0.15| -0.14±0.24| -0.02±0.16| -0.17±0.20| 0.10±0.17|
| [P/Mg]           | -0.01±0.15| -0.07±0.25| 0.01±0.17| -0.11±0.20| 0.18±0.23|
| [K/Mg]           | 0.02±0.10| -0.01±0.11| 0.03±0.10| -0.02±0.11| 0.09±0.11|
| [Cr/Mg]          | -0.11±0.11| -0.21±0.15| -0.08±0.11| -0.25±0.09| 0.02±0.12|
| [V/Mg]           | -0.04±0.09| -0.07±0.13| -0.03±0.12| -0.09±0.09| -0.05±0.13|
| [Co/Mg]          | -0.08±0.09| -0.12±0.11| -0.06±0.10| -0.14±0.08| -0.09±0.12|
| [Mn/Mg]          | -0.04±0.16| -0.17±0.18| -0.02±0.14| -0.24±0.14| 0.02±0.16|
| [Ni/Mg]          | -0.13±0.08| -0.20±0.09| -0.11±0.07| -0.23±0.06| -0.12±0.10|
| [Ti/Mg]          | -0.06±0.14| -0.10±0.12| -0.07±0.16| -0.09±0.11| -0.04±0.11|
| [C/N]            | -0.20±0.18| -0.11±0.24| -0.23±0.12| -0.02±0.14| -0.60±0.32|
| [C/O]            | -0.10±0.07| -0.11±0.14| -0.10±0.11| -0.11±0.11| -0.17±0.17|
| [N/O]            | 0.11±0.15| -0.03±0.17| 0.13±0.06| -0.09±0.07| 0.41±0.19|
| [Al/O]           | -0.12±0.07| -0.29±0.10| -0.14±0.12| -0.27±0.12| -0.27±0.20|

Table 4. Distribution of the APOGEE DR16 spectroscopic parameters and chemical abundances for the SR variables grouped by their abundances. The SR variables are sorted into these groups based on their [Al/O] and [N/O] abundances. The median, and standard deviation for each parameter is shown.
Nitrogen production during the AGB phase is dominated by hot bottom burning (HBB) in intermediate mass stars with \( M \geq 3M_\odot \) (Scalo et al. 1975; McSavey et al. 2007). During hot-bottom burning, proton-capture nucleosynthesis occurs at the base of the outer envelope, favoring the conversion of C to N through the CN cycle (Boothroyd & Sackmann 1992). This can only happen if the temperature at the bottom of the envelope exceeds \( \sim 5 \times 10^6 \) K (Garcia-Hernández et al. 2013). In these intermediate mass stars, the combination of third dredge-up and hot-bottom burning results in increased C and N abundances (McSavey et al. 2007). At the onset of the thermal pulses, hot-bottom burning reduces the \(^{12}\text{C}\) abundance to \(-1/15\) of the MS value and increases the \(^{14}\text{N}\) abundance to \(-5 - 6\) times the MS value (Lattanzio & Wood 2004). Both the C and N abundances steadily increase over many pulsation cycles as \(^{12}\text{C}\) is dredged up during the thermal pulses and HBB continues.

We investigate the \([\text{C}/\text{Mg}]\) and \([\text{C}/\text{N}]\) abundances for the semi-regular variables, APOGEE AGB and RGB stars in Figure 29. The \([\text{C}/\text{Mg}]\) abundances for both the semi-regular variables and AGB stars are positively correlated with \([\text{Mg}/\text{H}]\). The \([\text{C}/\text{Mg}]\) abundances for the semi-regular variables and AGB stars peak at \([\text{C}/\text{Mg}] - 0.15\) whereas the RGB stars peak at \([\text{C}/\text{Mg}] - 0.05\). This could be a result of the Mg enhancements of the semi-regular variables (see §4.3.3). The APOGEE AGB stars form three distinct clusters in the \([\text{C}/\text{N}]/\text{[Mg/H]}\) plane at \((-0.4, -0.25), (-0.25, 0)\) and \((0.25, -0.25)\). However, the vast majority of the semi-regular variables only populate the two clusters with \([\text{Mg}/\text{H}] < 0\). This is not too surprising as semi-regular variables with \([\text{Mg}/\text{H}] > 0\) are rare in our catalog. The distribution of the RGB stars overlapped the metal-rich cluster of AGB stars at \((0.25, -0.25)\), which suggests that the sample of AGB stars is likely contaminated with stars on the RGB. The distribution of the \([\text{C}/\text{N}]\) abundances is strongly bi-modal for both the semi-regular variables and the AGB stars \((\text{[C}/\text{N}] - 0.2\) and \([\text{C}/\text{N}] < 0)\), whereas the RGB stars form a continuous distribution in \([\text{C}/\text{N}]\), peaking at \([\text{C}/\text{N}] - 0.2\). Compared to the RGB stars, there is a small enhancement in the distribution of AGB stars and semi-regular variables with \([\text{C}/\text{N}] < 0.5\). These are potentially sources with significant N enhancement due to HBB.

In the \([\text{N}/\text{Mg}]/\text{[Mg/H]}\) plane (Figure 29), the AGB stars and semi-regular variables form a cluster with the \([\text{N}/\text{Mg}]\) abundances positively correlated with \([\text{Mg}/\text{H}]\). However, there is an additional cluster of Nitrogen-rich sources with \([\text{N}/\text{Mg}] - 0.1\) at \([\text{Mg}/\text{H}] - 0.5\). We also note the presence of some stars with even larger \([\text{N}/\text{Mg}]\) abundances \((\text{[N}/\text{Mg}] - 0.25)\). The distribution of \([\text{N}/\text{Mg}]\) abundances of the semi-regular variables and AGB stars is bi-modal, peaking at \([\text{N}/\text{Mg}] - 0.15\) and \([\text{N}/\text{Mg}] - 0.1\). There are more semi-regular variables with \([\text{N}/\text{Mg}] < 0\) \((45\%)\) than AGB stars \((36\%)\). The distribution of RGB stars in \([\text{N}/\text{Mg}]\) also appears to be bi-modal, with peaks that are similar to those seen for the semi-regular variables and AGB stars. Unlike the RGB stars, semi-regular variables and AGB stars with \([\text{N}/\text{Mg}] < 0.3\) are very rare.

The AGB stars form three distinct clusters in the \([\text{Mg/H}]/\text{[N/O]}\) plane at \((-0.25, -0.1), (-0.4, 0.15)\) and \((0.25, 0.15)\). The semi-regular variables populate the two clusters with \([\text{Mg}/\text{H}] < 0\). Again, the distribution of the RGB stars overlap the metal-rich cluster of AGB stars at \((0.25, 0.15)\), hinting at RGB contamination in the sample of APOGEE AGB stars. Unlike the RGB stars, the distribution in \([\text{N}/\text{O}]\) is strongly bi-modal for both the semi-regular variables and AGB stars. There is a small enhancement in the distribution of semi-regular variables with \([\text{N}/\text{O}] < 0.3\). These N-rich variables are likely intermediate-mass AGB stars. There is a sharp cutoff in \([\text{N}/\text{O}]\) for both the semi-regular variables and AGB stars at \([\text{N}/\text{O}] - 0.3\). -0.7\% of the semi-regular variables and \(-0.5\%\) of the AGB stars have \([\text{N}/\text{O}] < 0.3\), whereas \(-4.7\%\) of the RGB stars have \([\text{N}/\text{O}] < 0.3\). A similar cutoff was seen in the \([\text{N}/\text{Mg}]\) distribution. This low-metallicity cutoff is most likely due to the third dredge up events that occur during the AGB, enriching the surface abundances of these stars with CNO elements. Based on their \([\text{N}/\text{O}]\) abundances, we group the semi-regular variables into the “high-N” group \((0.02 \leq [\text{N}/\text{O}] < 0.3)\), “low-N” group \(([\text{N}/\text{O}] < 0.02)\) and intermediate-mass AGB stars that are candidates for HBB \([\text{N}/\text{O}] > 0.30\).

The HBB candidates with \([\text{N}/\text{O}] > 0.30\) are distinct from the high-N and low-N stars. They have significantly lower \(\log(g)\) -0.07, when compared to the high-N \((\log(g) -0.46)\) and low-N \((\log(g) -0.55)\) groups. They also have a median temperature of \(T_{\text{eff}} = 3822K\) which is \(100\) K hotter than the median temperatures of the high-N and low-N groups. The HBB candidates have a median period of \(\log(P/\text{days})\) -2, which is consistent with these stars pulsating in the fundamental mode (Fadeyev 2017). Much like the high-N stars, the HBB candidates also have low \([\alpha/\text{M}]\) metallicities \([\alpha/\text{M}] - 0.04\) consistent with the low-\(\alpha\) sequence.

The HBB stars have average \([\text{Al}/\text{Mg}]\) and \([\text{Al}/\text{O}]\) abundances \([\text{Al}/\text{Mg}] - 0.3, \text{[Al}/\text{O}] - 0.3\) that are consistent with the low-\(\text{Al}\) sequence identified in §4.3.4. Compared to both the high-N and low-N groups, the HBB candidates are poor in Mg and C and they have enhanced N, Ca, Na, P, K, Cr, Mn and Ti abundances compared to both the high-N and low-N groups. The HBB stars have slightly lower \([\text{C}/\text{O}]\) abundances \([\text{C}/\text{O}] - 0.06\) than the low-N and high-N groups. The \([\text{C}/\text{N}]\) abundances of the HBB candidates are significantly different—these HBB candidates have \([\text{C}/\text{N}] - 0.6, \text{compared to} [\text{C}/\text{N}] - 0.2\) for the high-N and \([\text{C}/\text{N}] < 0\) for the low-N stars.

The high-N and low-N stars have similar periods, temperatures and \(\log(g)\). The slight differences in these measures \(\Delta T_{\text{eff}} -50 K, \Delta \log(g) -0.1\) might suggest that the high-N stars are somewhat more evolved and hotter than the low-N stars. The high-N stars have \([\alpha/\text{M}]\) abundances that are consistent with them being on the low-\(\alpha\) sequence, whereas the low-N stars have \([\alpha/\text{M}]\) consistent with them being high-\(\alpha\) stars. The low-N stars have larger Mg abundances \(\Delta \text{[Mg/Fe]} -0.2\) than the high-N stars. The \([\text{Al}/\text{Mg}]\) and \([\text{Al}/\text{O}]\) abundances of the low-N stars are lower than that of the high-N stars and possibly indicate that these stars are undergoing mass loss. The high-N stars have enhanced N, Ca, Na, P, K, Cr, V, Co, Mn, and Ni abundances when compared to the low-N stars.
Figure 29. [C/Mg] (top left) and [C/N] (top right) vs. [Mg/H] for the semi-regular variables (black) and APOGEE AGB stars (orange). The distributions of the APOGEE RGB stars in these planes are shown as contours. The distributions of [C/Mg] (bottom left) and [C/N] (bottom right) for the semi-regular variables (black) APOGEE AGB (orange) and RGB (blue) stars are shown as histograms.
Figure 30. [N/Mg] (top left) and [N/O] (top right) vs. [Mg/H] for the semi-regular variables (black) and APOGEE AGB stars (orange). The distributions of the APOGEE RGB stars in these planes are shown as contours. The distributions of [N/Mg] (bottom left) and [N/O] (bottom right) for the semi-regular variables (black) APOGEE AGB (orange) and RGB (blue) stars are shown as histograms.
5 CONCLUSIONS

We systematically searched for variable sources with $V < 17$ mag in the $V$-band light curves of $\sim 61.5$ million sources. Through our search, we identified $\sim 426$ million variable sources, of which $\sim 219$ million are new discoveries. The $V$-band light curves of all the $\sim 61.5$M sources studied in this work are available online at the ASAS-SN Photometry Database (https://asas-sn.osu.edu/photometry). The $V$-band light curves and other information on the variable stars identified in our work are available on the ASAS-SN variable stars database (https://asas-sn.osu.edu/variables). ASAS-SN has significantly improved the census of semi-regular/irregular variables ($\sim 237\%$), $\delta$ Scuti variables ($\sim 81\%$), rotational variables ($\sim 115\%$) and detached eclipsing binaries ($\sim 90\%$) with $V < 17$ mag. Most ($\sim 74\%$) of our discoveries were in the Southern hemisphere.

Due to the overlap between ASAS-SN and modern major wide-field spectroscopic surveys, we are able to utilize spectroscopic information to closely study various variable types. We cross-matched our catalog of variables with the APOGEE DR16 catalog, the RAVE-on catalog, the LAMOST DR5 v4 catalog and the GALAH DR2 catalog, and identified $\sim 219$ million unique cross-matches. We find that data from the LAMOST and RAVE surveys are best suited to the characterization of pulsators, eclipsing binaries and rotational variables. APOGEE data is excellent for the characterization of the cooler semi-regular and irregular variables. Our main results for eclipsing binaries, rotational variables and semi-regular variables are summarized below.

Eclipsing binaries:

(i) EW type contact binaries are significantly cooler ($T_{\text{eff}} \sim 5900$ K) than both the semi-detached EB binaries ($T_{\text{eff}} \sim 6700$ K) and the detached EA systems ($T_{\text{eff}} \sim 6300$ K).

(ii) There is significant overlap in period—temperature space between the early-type EW and EB binaries. This overlap is consistent with the predictions of the thermal relaxation oscillation (TRO) models for contact binaries, where systems can transition between the semi-detached and contact phases.

(iii) Most ($\sim 63\%$) eclipsing binaries have metallicities $\sim 0.5 < [\text{Fe}/\text{H}] < 0$. This is consistent with recent findings of higher binary fractions at lower metallicity (Badenes et al. 2018; Moe et al. 2019; El-Badry & Rix 2019).

(iv) The period—temperature distributions depend on metallicity, with lower metallicity binaries having shorter periods at fixed temperature.

(v) Contact binaries have an observed period—temperature relationship that falls below that of the semi-detached and detached binaries at any given temperature and tracks Roche expectations.

Rotational variables:

(i) We find rotational variables on the MS/pre-MS (log(g)$<4.5$, $M_K\sim4$ mag) rotational giant branch (log(g)$<3.5$, $M_K\sim1$ mag) and the red clump (log(g)$>2.6$, $M_K\sim-1.5$ mag).

(ii) $\sim 81\%$ of the rotating giants with spectroscopic $v \sin(i)$ were rapid rotators with $v \sin(i) > 10$ km/s.

(iii) $\sim 80\%$ of the giants have $v_{\text{rot}} > 10$ km/s, consistent with the estimate of rapid rotators with spectroscopic $v \sin(i)$.

(iv) $\sim 98\%$ of the rotational variables on the red clump have $v_{\text{rot}} > 10$ km/s.

(v) $\sim 30\%$ of the rapidly rotating red clump stars are metal-poor with [Fe/H] $< -0.5$, whereas only $\sim 8\%$ are metal-rich with [Fe/H] $> 0$.

(vi) $\sim 87\%$ of the rotating giants had NUV excesses from Dixon et al. (2020) consistent with $v \sin(i) > 10$ km/s. This is consistent with our other estimates of the fraction of sources with rapid rotation ($v \sin(i) > 10$ km/s).

(vii) The NUV excesses of these rotating giants follow a similar trend with period to the work of Dixon et al. (2020).

(viii) The rotational variables in APOGEE are low-$\alpha$ stars strongly clustered towards [Mg/Fe] $= -0.1$, and [Fe/H] $< -0.1$, distinct from the typical giant stars or the SR variables and AGB stars. These abundances are unusual and suggestive of systematic issues in the ASPCAP pipeline when dealing with rapidly rotating stars.

Semi-regular variables and Miras:

(i) Semi-regular variables tend to be lower metallicity ([Fe/H] $\sim -0.5$) than most giant stars.

(ii) Of the semi-regular variables with log(10$P$/days) $\geq 2.3$, $\sim 36\%$ were LSPs. $\sim 60\%$ of the LSPs had pulsational periods in the range $1.5 \lesssim \log(10P$/days) $\lesssim 1.9$. The LSP was on average $\sim 11$ times longer than the actual pulsation period.

(iii) Many semi-regular variables have LSPs, and while it seems clear that the shorter period rather than the LSP is more closely related to the physical properties of the star, we could identify no spectroscopic property ($T_{\text{eff}}$, log(g), abundances etc.) which distinguished SR variables with LSPs from those without.

(iv) The vast majority of the ASAS-SN Mira ($\sim 97\%$) and semi-regular variables ($\sim 95\%$) are oxygen-rich AGB stars.

(v) We fit a temperature—$W_{\text{RP}} - W_{\text{JK}}$ relation that returns temperatures that are, on average, within $\pm 0.7\%$ of the APOGEE temperatures for the oxygen-rich SR variables with $T_{\text{eff}} < 3800$ K and $-0.7$ mag $\leq W_{\text{RP}} - W_{\text{JK}} \leq 0.8$ mag. We tested an extrapolation of this temperature—$W_{\text{RP}} - W_{\text{JK}}$ relation to estimate the temperatures of the Mira variables with $W_{\text{RP}} - W_{\text{JK}} < -0.7$ mag. We find the results of our extrapolation consistent with the expected temperatures of Miras (Yao et al. 2017).

(vi) The peak shifts in the $[\text{Mg}/\text{Fe}]$, $[\text{O}/\text{Fe}]$ and $[\alpha/\text{M}]$ abundances for the high-$\alpha$ and low-$\alpha$ stars relative to the APOGEE giants indicate $\alpha$-enhancements and are likely due to the effects of the third dredge up in AGB stars.

(vii) The $[\text{Al}/\text{X}]$ metallicities of the semi-regular variables are correlated with the pulsation period. These metallicities decrease with period and plateau beyond the canonical period of $P \sim 60$ days where dust formation first occurs.

(viii) We identified a “high-$\text{AI}$” and a “low-$\text{AI}$” sequence amongst the SR variables. The Al depleted “low-$\text{AI}$” sequence likely corresponds to AGB stars with significant dust production and mass loss. Cuts of $[\text{AI}/\text{Mg}] = -0.25$, $[\text{AI}/\text{C}] = -0.1$, $[\text{AI}/\text{O}] = -0.25$ or $[\text{AI}/\text{Si}] = -0.13$ roughly separate the high-$\text{AI}$ and low-$\text{AI}$ sequences.

(ix) We identified a “high-$\text{N}$” group ($0.02 \leq [\text{N}/\text{O}] \leq 0.3$), and a “low-$\text{N}$” group ([N/O] $< 0.02$) amongst the SR variables. The high-N stars have enhanced Ca, N, Na, P, K, Cr, V, Co, Mn, and Ni abundances when compared to the low-N stars.

(x) We identified a sample of likely intermediate-mass...
AGB stars going through significant hot-bottom burning (HBB) using the cutoff [N/O] > 0.30. The HBB candidates are poor in Mg and C (\[C/N\] ≈ 0.6), but have enhanced N, Ca, Na, P, K, Cr, Mn and Ti abundances compared to both the high-N and low-N groups.

This work is a first exploration of the powerful synergy between wide-field photometric and spectroscopic surveys towards deciphering the various properties of variable stars. As the number of stars with spectroscopic measurements increases by orders of magnitude over the coming years, it will be possible to study much larger samples of variable stars in greater detail. While we have not examined it here, larger samples with models of selection effects can be used to examine the detailed fractions of variable types as a function of their spectroscopic properties, similar to the recent studies of the dependence of binary fraction on metallicity (Badenes et al. 2018; Moe et al. 2019; El-Badry & Rix 2019).

ACKNOWLEDGEMENTS

This work is dedicated to the memory of our friend and colleague David Will, whose enduring support enabled the success of the ASAS-SN project. We thank Dr. Jamie Tayar for her help with interpreting the APOGEE data used in this analysis. We thank the Las Cumbres Observatory and its staff for its continuing support of the ASAS-SN project. We also thank the Ohio State University College of Arts and Sciences Technology Services for helping us set up and maintain the ASAS-SN variable stars and photometry databases.

ASAS-SN is supported by the Gordon and Betty Moore Foundation through grant GBMF5490 to the Ohio State University, and NSF grants AST-1515927 and AST-1908570. Development of ASAS-SN has been supported by NSF grant AST-0908816, the Mt. Cuba Astronomical Foundation, the Center for Cosmology and AstroParticle Physics at the Ohio State University, the Chinese Academy of Sciences South America Center for Astronomy (CAS- SACA), the Villum Foundation, and George Skestos.

K2S and CSK are supported by NSF grants AST-1515927, AST-1814440, and AST-1908570. BJS is supported by NSF grants AST-1908952, AST-1920392, and AST-1911074. TAT acknowledges support from a Simons Foundation Fellowship and from an IBM Einstein Fellowship from the Institute for Advanced Study, Princeton. Support for JLP is provided in part by the Ministry of Economy, Development, and Tourism’s Millennium Science Initiative through grant IC120009, awarded to The Millennium Institute of Astrophysics, MAS. Support for MP and OP has been provided by INTER-EXCELLENCE grant LTUAS18093 from the Czech Ministry of Education, Youth, and Sports. The research of OP has also been supported by Horizon 2020 ERC Starting Grant “Cat-In-hAT” (grant agreement #803158) and PRIMUS/SCI/17 awarded from Charles University. This work was partly supported by NSFC 11721303.

Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss.org.

SDSS-IV is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, the Chilean Participation Group, the French Participation Group, Harvard-Smithsonian Center for Astrophysics, Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU) / University of Tokyo, the Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional / MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium. This publication makes use of data products from the Two Micron All Sky Survey, as well as data products from the Wide-field Infrared Survey Explorer. This research was also made possible through the use of the AAVSO Photometric All-Sky Survey (APASS), funded by the Robert Martin Ayers Sciences Fund.

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 research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France. This research also made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration, 2013).

DATA AVAILABILITY

The ASAS-SN photometric data underlying this article are available on the ASAS-SN Photometry Database (https://asas-sn.osu.edu/photometry) and the ASAS-SN variable stars database (https://asas-sn.osu.edu/variables). The external photometric data underlying this article were accessed from sources in the public domain: Gaia (https://www.cosmos.esa.int/gaia), 2MASS (https://old.ipac.caltech.edu/2mass/overview/access.html), AllWISE (http://wise2.ipac.caltech.edu/docs/release/allwise/) and GALEX (https://archive.stsci.edu/missions-and-data/galex-1/). The spectroscopic datasets underlying this article were accessed from sources in the public domain: APOGEE (https://www.sdss.org/dr16/), LAMOST (http://dr5.lamost.org/), GALAH
