An All-Sky Search For R Coronae Borealis Stars in ASAS-SN

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ABSTRACT

We report the discovery of 19 new R Coronae Borealis (RCB) star candidates with light curves from the All-Sky Automated Survey for Supernovae (ASAS-SN). We examined both an existing set of 1602 near/mid-IR selected candidates and an additional 2615 candidates selected to have near/mid-IR SEDs consistent with those of known R Coronae Borealis stars. We visually inspected the light curves for the characteristic variability of these systems.

Key words: stars: variable

1 INTRODUCTION

The R Coronae Borealis (RCB) stars are a rare class of hydrogen deficient red giants. These stars are characterized by dramatic, unpredictable photometric declines with slow returns to full luminosity caused by clouds of carbon dust forming and flowing away from the star (e.g., Feast et al. 1997, Clayton 2012, Leão et al. 2007). These declines can be as great as 9 magnitudes in V band, and can last from a month to hundreds of days (Tisserand 2012).

There are two possible evolutionary paths for RCBs. RCBs could be the products of a final helium-flash in heavily evolved single stars before they cool to become white dwarfs. Alternatively, they could be merger products of lower mass He white dwarfs with higher mass CO white dwarfs. The abundance of $^{18}$O in cool RCBs heavily favors the latter theory (García-Hernández et al. 2010).

Additionally, the He-rich pre-white dwarf KPD 0005+5106 has the abundances expected for a double degenerate merger. This both confirms that it is the descendant of an RCB star and reinforces the merger model for their origin (Werner & Rauch 2015). However, observations of R Coronae Borealis, the prototype of its class, during a photometric minimum revealed a planetary nebula around the star (Clayton et al. 2011). This is not predicted by the merger model and may support the He flash model. Still, the double degenerate scenario is presently the favored explanation of these stars.

If the double degenerate scenario is correct, merger and lifetime arguments predict between 100 and 500 RCB stars in our galaxy (Tisserand et al. 2013, Saio & Jeffery 2002). At present, only about 100 RCB stars have been identified in the Milky Way, with an additional ~20 in the Magellanic Clouds (Tisserand et al. 2016). The number of known RCB stars has more than doubled in the past decade (Tisserand et al. 2008), and many of these new RCBs were found by searching for a combination of a mid-infrared excess and variability (Tisserand et al. 2013, Nikzat & Catelan 2016, Otero et al. 2014) using techniques developed in Tisserand (2012). Here we expand this approach to the full sky using ALLWISE (Wright et al. 2010) and 2MASS (Skrutskie et al. 2006) to photometrically select candidates, and ASAS-SN (Shappee et al. 2014, Kochanek et al. 2017) to examine their optical variability.

The All-Sky Automated Survey for SuperNovae (ASAS-SN) is a ground based survey hosted by Las Cumbres Observatory (Brown et al. 2013) that has been monitoring the entire sky on a 2-3 day cadence to a depth of V ≤ 17 mag since 2013 using two units consisting of 4 telescopes in a common mount located in Hawaii and Chile. ASAS-SN has recently expanded, adding 3 more units located in Chile, Texas, and South Africa, respectively. ASAS-SN was cre-

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ated to monitor the sky for bright supernovae, but it also continuously monitors for variable stars (Jayasinghe et al. 2018). In this work we search for new RCB stars. In Section 2 we outline the photometric selection of the candidates. In Section 3 we present our list of RCB candidates and their ASAS-SN light curves.

2 TARGET SELECTION

We started with the 2MASS and WISE selected list of 1602 candidates from Tisserand (2012). The selection method required that each source had data in all 7 bands (J, H, K, and W1-W4), and selected for stars with infrared properties similar to known RCBs, taking in to account interstellar reddening by Galactic latitude. Cuts were made to reject other stars with similar infrared colors such as Asymptotic Giant Branch stars and Miras.

Tisserand (2012) selected these candidates before WISE data was available for the full sky. To select across the full sky, we used an alternate approach, simply looking for stars with spectral energy distributions (SEDs) similar to those of known RCBs. We started from the nominal list of “known” RCBs from SIMBAD (Wenger et al. 2000), albeit with the knowledge that some of these classifications were likely problematic, and objects from the ALLWISE (Wright et al. 2010) catalog with defined WISE and 2MASS magnitudes satisfying a somewhat broader version of Tisserand 2012’s first color cut, namely,

\[
W_2 - W_3 > 0.75, \\
W_2 - W_3 < 3.00, \\
W_3 - W_4 < 1.30,
\]

and none of their other criterion. This provided a list of 93 “known” RCBs and roughly 1.3 million WISE sources.

The SED of a new RCB can differ from that of a known RCB due to changes in luminosity, distance and extinction, where the change in extinction can either be due to changes in either Galactic or circumstellar extinction. We do not differentiate between the two sources of extinction since the differences are primarily due to changes in the physics of scattered photons, which are less important in the infrared (see the discussion in Kochanek et al. 2012).

We assume that changes in extinction only modify the 2MASS magnitudes as a simplifying assumption. So for each ALLWISE source and each “known” RCB, we first use the WISE magnitudes to estimate a change in distance and luminosity as

\[
\Delta \mu = \frac{1}{4} \sum_{i=1,4} \left( W_i(WISE) - W_i(RCB_j) \right)
\]

which assumes uniform weighting of the four WISE bands (\(W_i\)) since this exercise is almost certainly dominated by systematic errors. Then, with \(\Delta \mu\) fixed, we determine the change in extinction which would best match the near-IR magnitudes (\(M_i = J, H, K, \) and \(K_s\)),

\[
\Delta E = \left[ \sum_{i=1,3} R_i (M_i(WISE) - M_i(RCB_j) - \Delta \mu) \right]^{-1}
\]

where the \(R_i\) are the extinction coefficients. We then computed the root-mean-square magnitude residual \(\sigma_j\) for each of the trial \(j = 1...93\) RCBs corrected for the number of degrees of freedom after fitting two parameters (\(\Delta \mu\) and \(\Delta E\)). We accepted an object as an RCB candidate if any \(\sigma_j < 0.2\) mag, as this recovered 82 of the 93 “known” RCBs if we used this method to search for each of them after excluding the star being tested from the SED match.

For each of the “known” RCBs we then counted how many candidates were associated with it and iteratively eliminated stars producing too many candidates for new RCBs to be useful. As expected, we found that the SIMBAD listing is contaminated by sources other than RCBs. For example, the worst comparison star was MA-CHO118.18666.100, with 235 thousand (!) matches, which Tisserand et al. (2008) found to be an M giant. In fact, all of the “known” RCBs producing such large numbers of matches are reported to be other sorts of variables (SY Hyi as a semi-regular variable, Lawson et al. 1989 V618 Sgr as a symbiotic star, Kilkenny 1997 V1317 Sco as a Mira, Tisserand et al. 2013 V589 Sgr as a symbiotic star, Menickent et al. 2001 AE Cir as a symbiotic star, Menickent et al. 2008 GM Ser as a Mira, Tisserand et al. 2013 and TYC6283-1417-1 as a Mira, Tisserand et al. 2013). With the last of these, the maximum number of matches had dropped to 11 thousand. We also dropped LT Dra, where the origin of its classification is unclear and whose variability is reported to spurious by the AAVSO (Hesselbach et al. 2002).

Next there were “known” RCBs where we could find no arguments that they were misclassified but which still produced too many matches for a feasible search. Many of these (in order of numbers of matches, Y Mus, SV Sge, XX Cam, MACHO308.38099.66 and EROS2-CG-RCB-12) were also dropped by Tisserand (2012) as falling outside their color selection criteria. We also dropped V409 Nor, HV5637, which is spectroscopically confirmed by Sozzi et al. (2009), oglebul-sc37133492, EROS2-LMC-RCB-8, EROS2-CG-RCB-2, V1405 Cyg, ASAS-RCB-18, and MA-CHO135.27132.51. In total we rejected 24 of the initial list of 93 “known” RCBs. This left us with a list of 2615 candidates from Tisserand et al. (2012). We started with the 2MASS and WISE selected list of 1602 candidates from Tisserand (2012). The selection method required that each source had data in all 7 bands (J, H, K, and W1-W4), and selected for stars with infrared properties similar to known RCBs, taking in to account interstellar reddening by Galactic latitude. Cuts were made to reject other stars with similar infrared colors such as Asymptotic Giant Branch stars and Miras.

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Figure 1. ASAS-SN V-band light curves of the strong RCB candidates from Table 1. All panels have the same dynamic range in magnitude. The different colors represent different ASAS-SN cameras.
3 OPTICAL VARIABILITY

ASAS-SN has been operating since 2013 (Shappee et al. 2014) and provides up to 5 years of data to examine for RCB-like variability. It saturates at $V \sim 10 - 11$ mag and can detect objects down to $V \sim 17$ mag (Kochanek et al. 2017). We extracted light curves for all sources in the two RCB candidates lists from Section 2 as well as for all the RCBs reported by SIMBAD (Wenger et al. 2000).

We began by examining the light curves of known RCBs to understand how they would appear in our data. We then visually scanned each of the 1602 candidates in Tisserand’s original list and the 2615 candidates that we generated using the SED matching approach. We discovered the 15 objects presented in Table 1 as strong candidates for new RCBs. Some of these objects have preexisting classifications in the International Variable Star Index (VSX, Watson et al. 2006), and these are noted in Table 1. We present light curves for each of these objects in Figures 1, 2, and 3.

In Table 2 we present four objects that we discovered while looking through other variables in ASAS-SN data. ASASSN-V J161156.22-575527.2 was included in Tisserand (2012) and was serendipitously discovered in ASAS-SN data by Jayasinghe et al. (2017) before we began the search described in this work. The remaining three objects display strong RCB-like variability, but were not included in either of our candidate lists because of their colors. Two of these objects have preexisting classifications in VSX, and their light curves are presented in Figure 4. We additionally present 13 more objects with peculiar light curves that are weak RCB candidates. These objects are listed in Table 3 with speculative variability types based on their light curve morphologies, and their light curves are presented in Figure 5.

4 DISCUSSION

Figure 6 shows the distribution of RCBs in the Gaia DR2 $G_{BP} - G_{RP}$ vs. $J - K_s$ color-color space (Gaia Collaboration et al. 2018; Skrutskie et al. 2006). We compare the RCBs with a sample of rotational, Mira, and semi-regular/irregular variables from Jayasinghe et al. (2018b, in prep.) and the Catalog of Galactic Carbon Stars (Aksnes et al. 2001). The carbon stars, Mira variables and semi-regular variables all form distinct loci in this color-color space, where the carbon rich sources have redder $J - K_s$ colors for any given $G_{BP} - G_{RP}$ beyond $G_{BP} - G_{RP} \sim 2$. RCBs have carbon rich atmospheres and most known RCBs lie in the same color space as carbon stars. A few known RCBs fall along the semi-regular/Mira loci, making these classifications uncertain, although this distinction becomes hazy towards bluer colors. Most of our RCB candidates are consistent with the distribution of the known red, carbon-rich RCBs. We note that a few of our candidates have bluer colors but are still consistent with the blue end of the known RCB distribution.

The four stars presented in Table 2 were discovered outside of our original search. Other than the RCB candidate ASASSN-V J161156.22-575527.2, the remainder have colors that fail the initial mid-IR color cuts used by Tisserand (2012) and our own procedure (see Figure 7). Their existence suggests that more RCBs should be visually identifiable in ASAS-SN data given a simple method to search for RCB-like variability independent of color information.

These candidates were selected because they have near/mid-IR spectral energy distributions and optical light curves that are fairly typical of RCBs. There are other classes of variables which undergo dust formation episodes (Otero et al. 2014) that might be included in the sample, so spectroscopic observations will be necessary for final confirmation of the classifications.

As we were completing this paper, Tisserand et al. (2018) reported the discovery and spectroscopic confirmation of 45 new RCBs. Four of these systems are on our high confidence list, and one is on the weaker candidate list, as indicated in Tables 1 and 3.

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Figure 2. ASAS-SN V-band light curves of the strong RCB candidates from Table 1.

Figure 3. ASAS-SN V-band light curves of the strong RCB candidates from Table 1 with large amplitude variation. These panels have a larger vertical scale than the other figures.

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Figure 5. ASAS-SN light curves of variable stars that are weak RCB candidates from Table 3.
Figure 6. Gaia DR2 $G_{BP} - G_{RP}$ vs. 2MASS $J - K_s$ color-color diagram. Sources from the Catalog of Galactic Carbon Stars (Alksnis et al. 2001) are colored in black, and sources from the ASAS-SN Catalog of Variable Stars: II (Jayasinghe et al. 2018b, in prep.) are colored by their variability type. RCB candidates from this work are denoted as purple diamonds and peculiar variables in this work are denoted as purple stars. The reddening vector corresponding to an extinction of $A_V = 1$ mag is shown in red.
Figure 7. [12]-[22] vs. [4.6]-[12] ALLWISE color-color diagram. The blue points are the 1602 candidates from Tisserand (2012), with the blue lines showing the initial color cuts used to generate the list. The red points are our new RCB candidates, and the black points are the three RCB candidates we discovered outside the color selection region. The pink points are previously known RCB candidates from Tisserand (2012). Candidates with poor color measurements were not included.
Table 1. Candidate ASAS-SN RCB Stars

| Name               | RA        | Dec       | General Information |
|--------------------|-----------|-----------|---------------------|
| ASASSN-V J053745.71  – 635330.9 | 84.404360 | –63.891918 |                     |
| ASASSN-V J053213.93  + 340601.4 | 83.058029 | +34.100399 |                     |
| ASASSN-V J173819.81  – 203632.2* | 264.582550 | –20.608932 |                     |
| ASASSN-V J191243.07  + 055313.1 | 288.179474 | +05.886981 |                     |
| ASASSN-V J175526.28  – 214214.1 | 268.859497 | –21.703928 |                     |
| ASASSN-V J173737.08  – 072828.2 | 264.404480 | –07.474888 |                     |
| ASASSN-V J174257.20  – 362052.1* | 265.738342 | –36.347805 |                     |
| ASASSN-V J190309.89  – 302037.0* | 285.791229 | –30.343609 |                     |
| ASASSN-V J170737.02  – 341812.5 | 256.904236 | –31.803482 |                     |
| ASASSN-V J175031.71  – 233945.7* | 267.632111 | –23.662706 |                     |
| ASASSN-V J202300.80  + 431111.5 | 305.753330 | +43.186518 |                     |
| ASASSN-V J044531.02  – 683431.3 | 71.379262 | –68.575364 | OGLE-LMC-LPV-02510 |
| ASASSN-V J004822.94  – 734104.6 | 12.095596 | –73.684622 |                     |

Large Amplitude Candidates

| Name               | RA        | Dec       | General Information |
|--------------------|-----------|-----------|---------------------|
| ASASSN-V J174317.53  – 182402.5 | 265.823029 | –18.400686 |                     |
| ASASSN-V J170552.81  – 163416.6 | 256.470062 | –16.571277 |                     |

Note: Large amplitude candidates have variability above 3 mag
* : also discovered in Tisserand et al. [2018]

Table 2. RCB Candidates discovered outside of our search

| Name               | VSX Name | RA        | Dec       | VSX Classification/Notes |
|--------------------|----------|-----------|-----------|--------------------------|
| ASASSN-V J03259.32  + 441584.0 | HH Per | 26.24717 | +41.98168 | long-period variable |
| ASASSN-V J175700.51  – 213934.5 | Miss V0832 | 209.25200 | –21.65972 | semi-regular variable |
| ASASSN-V J201504.29  + 462719.9 | 303.76791 | +46.45553 |                     |

Table 3. Weak RCB Candidates

| Name               | RA        | Dec       | Suspected Variability Type |
|--------------------|-----------|-----------|----------------------------|
| ASASSN-V J195525.11  + 015601.6 | 298.854614 | +1.933783 |                             |
| ASASSN-V J075155.45  – 331057.2 | 117.981049 | –33.182560 |                             |
| ASASSN-V J185316.37  – 271352.7 | 283.318207 | –27.231319 | semi-regular variable       |
| ASASSN-V J174445.73  – 332232.2 | 266.190521 | –36.375629 | semi-regular variable       |
| ASASSN-V J174328.51  – 375029.1* | 265.868774 | –37.841412 | long-period variable        |
| ASASSN-V J163750.78  – 644140.5 | 249.461594 | –64.694595 | semi-regular variable       |
| ASASSN-V J174731.77  – 444501.4 | 266.882360 | –44.750380 | semi-regular variable       |
| ASASSN-V J173257.95  – 180435.6 | 263.244443 | –18.076560 | semi-regular variable       |
| ASASSN-V J211119.06  + 473847.7 | 317.829426 | +47.645767 | irregular variable          |
| ASASSN-V J054551.71  + 350300.0 | 86.465439 | +35.050001 | irregular variable          |
| ASASSN-V J172216.67  – 281656.9 | 260.569464 | –28.282466 | long-period variable        |
| ASASSN-V J174825.52  – 324240.5 | 267.106334 | –32.711251 | irregular variable          |
| ASASSN-V J160407.52  – 508250.6 | 241.031323 | –58.047382 | irregular variable          |
| ASASSN-V J181154.33  – 241827.3 | 272.976308 | –24.307591 | regular variable            |
| ASASSN-V J161424.84  – 655814.2 | 86.103507 | –65.970622 | regular variable            |
| ASASSN-V J181214.33  – 252406.5 | 273.059723 | –25.401814 |                     |

* : also discovered in Tisserand et al. [2018]