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COMBINED NSVS/2MASS DATABASE SEARCH FOR COOL ALGOLS AND ECLIPSING SUBDWARF B STARS

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ABSTRACT

Combining both the Northern Sky Variability Survey (NSVS) and the Two Micron All Sky Survey (2MASS) has allowed us to search for rare types of eclipsing variable stars based upon their light curves and V, J, H and K colors. We have found 10 new cool algols as well as 52 new giant star (GS) eclipsing binary systems. Using the two surveys we have found 8 new possible subdwarf B star (sdB) eclipsing binaries. Six are systems with periods longer than one day and contain a companion star of M2 or later. The 2 others have short periods and contain an earlier main sequence companion.

Subject headings: binaries – binaries: eclipsing

1. INTRODUCTION

The data from the Northern Sky Variability Survey (NSVS; Wozniak et al. 2004), obtained with the Robotic Optical Transient Search Experiment telescopes (ROTSE), contains positions, light curves and V magnitudes for 14 million objects ranging in magnitudes from 8-15.5. The Two Micron All Sky Survey (2MASS; Strutskie et al. 2006) database contains positions and magnitudes J (1.25 μm), H (1.65 μm), and K (2.17 μm) for 300 million stars. We have used the merged database to search for two rare types of binary systems: cool algol systems and binary systems containing an M dwarf and a subdwarf B star (sdB).

2. PROCEDURE

2.1. *2MASS/NSVS database merge*

We used only 2MASS stars containing quality flags of A, B and C for their three infrared magnitudes. For each NSVS star we found the closest 2MASS star within the NSVS/2MASS combined error box. If there was no 2MASS star within that box, then no match was made for that NSVS star.

2.2. *Search for Cool Algols*

Cool algols have been defined as semi-detached eclipsing systems in which both stars are late-type G or K subgiants and one star has filled its Roche lobe (Popper 1980). They have very distinct light curves with wide eclipses and large curvature outside of eclipse because one star fills its Roche lobe. The periods are usually longer than two days.

Prior to the database merge, the NSVS stars had been searched for variability and tentatively classified by visual inspection. Provisional periods had been found for each light curve and were verified or corrected while being classified. For the cool algols, we searched for a $J-K$ greater than 0.3 (Houdashelt 2000) and a period greater than two days. From this search, 62 possible cool algol candidates were selected. For each of those candidates, we used Eclipsing Light Curve (ELC; Orosz 2000) to fit a solution. ELC is a modeling program for finding a solution of best fit for binary systems using the chi-squared method. We used a version of ELC which determines the best fit of a solution with a genetic algorithm. The method fits random solutions within each generation and uses the lowest chi-squared value in the next generation. Random mutations are used throughout each generation to guarantee that the best possible solution is found. We would increase the number of generations until we found the best fit to the light curve with a reasonable astrophysical solution. We used the corresponding $V-K$ color to set the temperature for the hotter star using Tokunaga's (2000) color table. We solved for the temperature of the cooler star, mass ratio, fill factors for both stars, separation, and inclination.

2.3. *Subdwarf B binary Search*

We undertook a more challenging search using the combined databases to hunt for subdwarf B eclipsing binaries. Subdwarf B stars (sdB) are defined as having temperatures ranging from 20,000–42,000 K, masses of about 0.5 $M_\odot$, and radii of about 0.2 $R_\odot$ (Randall et al. 2005). SdB stars belong to the extended horizontal branch (EHB) with higher surface gravity and lower luminosities than main sequence stars (Saffer et al. 1994). Assuming near total eclipses for the binary system, we found the theoretical eclipse width and color indices for all binary systems containing a sdB and a main sequence star for various periods. For almost all main sequence +sdB systems, the light curve does not reveal the presence of the sdB star, but for a sdB+M2 (or later) system, the system distinguishes itself by being bluer than a system containing two M2 stars but having the same very narrow eclipses seen in binaries with both components smaller than 0.5 solar radii. Thus the sdB+M2 (or later) system can be detected using color and eclipse width as search criteria. We searched through our merged database for stars with $J-H$ less than 0.3 and $J-K$ less than 0.35. We looked at light curves with periods from 0.1 to 50 days that contained narrow eclipses. The minimum eclipse depth had to be at least 0.4-0.5 magnitudes (Green, private communication). Also, there could not be a secondary eclipse due to temperature differences between the two stars. However, for periods shorter than one day, we looked at everything with very blue color indices and narrow eclipses. In these systems, a strong reflection effect can reveal the presence of a sdB star.

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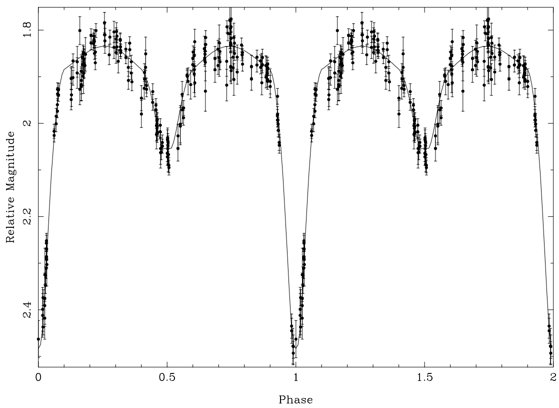

FIG. 1.— Light Curve and Solution for NSVS08044036

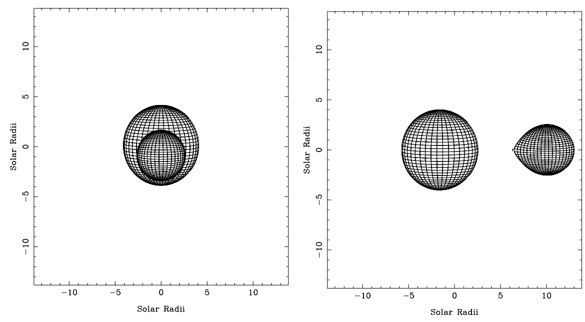

FIG. 2.— ELC model of NSVS08044036

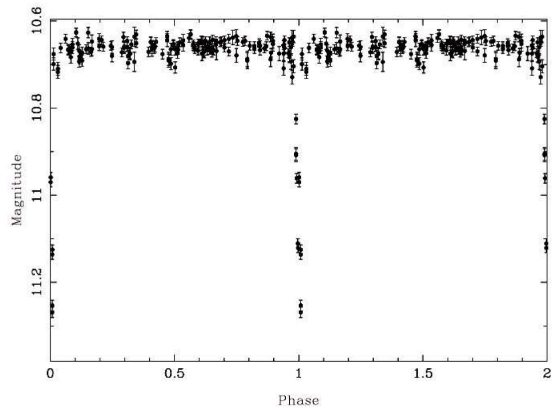

FIG. 3.— Light Curve of NSVS02335765.

3. RESULTS AND DISCUSSION

3.1. *Cool Algol Search Results*

The ELC program found solutions for all 62 cool algol candidates. There were 10 systems in which at least one component was filling its Roche lobe. In the absence of a spectroscopic analysis, the mass ratio was based upon photometric data outside of the eclipse and thus is not of the best accuracy. Table 1 lists our cool algols. The temperature of the hotter start (star 2 for ELC) was derived from Tokunaga (2000) and was set constant in ELC. All other parameters were found as the best chi-squared solution to the given light curve by ELC. The fill of the star is given as the fraction of the Roche lobe filled by its star. The effective radius is the radius of each star divided by the separation of the centers of the two stars.

For every star except NSVS01667524, the cooler star (Star1) fills, or nearly fills it Roche lobe. With NSVS01667524, the hotter star (Star2) fills its lobe. The two stars only differ in temperature by 70 Kelvin and appear to be almost the same size. This would imply that they are two K subgiant stars, one of which is filling its lobe, with the other not far from its lobe. NSVS10081872 is UZ Cnc and has already been classified as a possible cool algol (Popper 1996). NSVS05168710 is YY Boo, previously classified as a F9IV star in the SIMBAD database, but not known as a cool algol.

In Figure 1, a sample light curve solution imposed over the NSVS data is given for NSVS08044036. Figure 2 contains an ELC model for the same star. All light curves and solutions for the ten cool algols, along with ELC models, can be found at `physast.uga.edu/~jss/coolalgols`.

As for the other 52 systems that have large, cool components we present a list of giant star (GS) binaries in Table 2. These systems did not have one star filling its Roche lobe, however at least one star has filled over fifty percent of its lobe. All light curves and solutions for all fifty-two GS binaries can be found at `physast.uga.edu/~jss/GSbinaries`.

3.2. *Search for SdB+cool star system Results*

The initial search for possible sdB binaries, based upon period, color and light curve shape yielded 385 hits. After a closer inspection of each eclipse, requiring that the widths be equal to or less than the combined width of a theoretical sdB+M2 star, only 8 candidates remained. We then used the Palomar-Green catalog (Green et al. 1986) to search for known sdB stars in our databases which exhibited variability and found one star. Table 3 contains 9 eclipsing systems that possibly contain sdB stars.

The three bold stars in Table 3 are stars with periods shorter than one day, narrow eclipses, and a strong reflection effect. The widths given for the short period stars are approximations due to the fact that these systems were not selected using eclipse width as a criteria. NSVS15972828 is an already-know eclipsing sdB star, HW Vir, which was found during our search. Although we included it in the table we did not count it as one of the new 8 systems found. NSVS04818255 is a known sdB star according to the Palomar-Green catalog that we found to have a possible eclipse. The third short period star, NSVS07826147 was selected because it exhibits reflection effect with a narrow eclipse and has a negative color index. The other stars were selected due to the appropriate eclipse narrowness, color and light curve shape. The non-bold stars are for sdB systems with a companion star that is M2 or later. Due to the imperfections of the data, the non-existence of a secondary eclipse and the ability to pick an accurate temperature for the system, the ELC program could not successfully solve these light curves. Therefore the stars listed in Table 3 are only the most likely candidates that we found for eclipsing sdB systems. Accurate solutions for the systems must wait on more thorough photometry. Figure 3 is the light curve of NSVS02335765. All light curves can be seen at the website `physast.uga.edu/~jss/sdB`.

4. CONCLUSIONS

Using the combined 2MASS and NSVS databases has allowed us to successfully find 10 new cool algols, 52 GS binary systems, and 8 new possible sdB binary systems. Based upon the data available to us, we have found systems which in every way meet the criteria of systems found prior to ours.

TABLE 1
COOL ALGOLS

NSVS Star	V Mag.	Period (days)	Fill Star1	Fill Star2	Q M_2/M_1	T_{eff} (K) Star1	T_{eff} (K) Star2	R_{eff} Star1	R_{eff} Star2
01667524	12.77	2.199	0.75	0.94	0.92	4229	4300	0.35	0.38
01690749	10.28	11.723	0.99	0.33	2.19	4868	5750	0.32	0.20
04239237	10.56	5.570	1.00	0.49	1.52	5339	5800	0.35	0.27
05168710	11.99	3.932	0.99	0.33	3.34	4058	5500	0.28	0.21
05873479	12.74	8.229	0.98	0.52	0.78	4109	4250	0.41	0.24
06983718	12.84	4.413	0.97	0.47	0.75	3887	5000	0.41	0.22
08044036	11.95	3.502	1.00	0.53	6.25	4413	5200	0.24	0.36
10054338	12.86	2.720	1.00	0.71	3.74	3927	5750	0.28	0.43
10081872	10.81	11.582	0.97	0.39	1.07	4263	5000	0.38	0.20
14139046	13.04	7.240	1.00	0.45	2.74	4127	4700	0.30	0.27

TABLE 2
GIANT STAR BINARIES

NSVS Star	V Mag.	Period (days)	Fill Star1	Fill Star2	Q M_2/M_1	T_{eff} (K) Star1	T_{eff} (K) Star2	R_{eff} Star1	R_{eff} Star2
00179833	13.45	2.375	0.77	0.53	2.79	3862	5200	0.27	0.32
01134199	13.14	8.565	0.81	0.22	2.64	3863	4900	0.28	0.14
01285912	13.18	8.562	0.87	0.20	2.48	3772	4900	0.30	0.12
01817114	11.14	2.126	0.87	0.65	4.51	4579	6000	0.26	0.41
01903339	12.44	55.435	0.90	0.39	8.61	4139	4330	0.21	0.28
02048376	12.90	2.839	0.84	0.10	4.60	3016	4500	0.25	0.07
02090150	12.13	6.366	0.58	0.66	1.19	4579	5750	0.27	0.33
02441618	12.71	2.524	0.70	0.51	1.87	3738	5100	0.28	0.28
02727033	12.32	4.669	0.76	0.43	3.35	4355	5000	0.26	0.27
02815225	12.52	3.772	0.74	0.31	4.53	4006	4900	0.23	0.20
03073937	12.61	4.287	0.79	0.46	6.31	4946	5800	0.22	0.31
04151529	12.32	7.277	0.53	0.21	3.45	4285	5700	0.20	0.13
04238859	11.92	2.779	0.83	0.64	3.91	4730	6000	0.26	0.40
04325494	13.43	35.569	0.79	0.64	1.99	3565	3700	0.30	0.35
04342609	12.60	3.297	0.81	0.52	1.09	3840	5100	0.35	0.26
04522029	12.42	5.413	0.91	0.18	2.83	3721	5000	0.29	0.11
04651034	13.19	2.308	0.78	0.32	2.97	4217	5900	0.27	0.20
04680862	11.53	5.353	0.63	0.32	1.34	4379	5600	0.28	0.17
05075475	12.26	4.669	0.78	0.43	1.73	4306	5100	0.31	0.24
05728562	12.51	2.448	0.87	0.57	4.57	3738	3800	0.25	0.36
05743393	9.67	10.597	0.70	0.85	6.39	3429	3800	0.21	0.52
06222336	11.91	4.241	0.74	0.68	8.66	4127	4800	0.19	0.47
06386066	12.92	4.401	0.85	0.23	3.60	4082	5800	0.27	0.14
06623348	12.41	4.155	0.84	0.58	8.80	3974	4100	0.21	0.41
06707761	12.71	3.199	0.67	0.56	0.51	3795	4600	0.36	0.24
06742676	11.68	11.037	0.83	0.50	9.98	4296	4600	0.20	0.36
06809672	11.78	4.528	0.80	0.30	2.52	3595	4700	0.29	0.18
06841177	12.85	4.119	0.87	0.62	6.33	3514	4600	0.23	0.42
06841510	10.31	13.617	0.89	0.48	3.68	3784	5000	0.27	0.30
07228035	11.51	4.688	0.59	0.32	4.18	4227	5000	0.20	0.21
07431417	11.71	2.290	0.84	0.71	2.06	4361	5700	0.31	0.38
07741436	10.92	3.197	0.73	0.70	5.32	4691	5000	0.22	0.45
08544767	10.31	45.498	0.93	0.38	3.37	3698	4000	0.28	0.24
09450723	12.79	3.929	0.82	0.56	2.85	3986	4000	0.28	0.34
09728354	12.04	5.476	0.81	0.35	4.20	3783	5000	0.25	0.22
09839705	13.11	11.290	0.21	0.68	0.48	4203	4400	0.12	0.27
10223113	10.90	3.393	0.88	0.53	6.87	4076	5750	0.23	0.36
11461057	11.85	7.240	0.61	0.50	0.53	4215	4600	0.33	0.21
11814354	11.20	2.374	0.75	0.63	3.92	4039	4900	0.25	0.39
11835300	10.45	15.767	0.57	0.47	0.83	3415	4400	0.29	0.22
12387669	10.58	4.634	0.53	0.59	1.91	3629	4500	0.23	0.33
13158483	11.93	2.387	0.86	0.34	1.94	3836	5600	0.32	0.20
13638229	12.12	4.197	0.83	0.30	3.76	3627	4400	0.26	0.19
14440503	12.71	5.376	0.90	0.34	4.03	4252	5700	0.27	0.22
14449011	12.59	2.518	0.73	0.48	1.99	4046	5200	0.29	0.27
14932154	13.67	3.356	0.78	0.43	2.31	4199	5000	0.29	0.25
15011390	12.07	8.323	0.83	0.37	6.95	4410	4800	0.22	0.26
15121376	11.42	3.375	0.85	0.66	1.35	3933	5200	0.35	0.34
15984457	11.78	5.157	0.83	0.33	1.21	3885	5200	0.35	0.17
16154232	11.14	20.968	0.33	0.71	1.40	4766	4800	0.15	0.36
17100401	12.22	6.394	0.76	0.31	2.01	4047	5200	0.29	0.18
17329412	13.14	4.892	0.81	0.48	1.54	4191	5200	0.33	0.26

TABLE 3
POSSIBLE sdB ECLIPSING BINARIES

NSVS Star	V Mag.	Period (days)	Eclipse Width/Phase	V-K	J-H
02335765	10.69	9.744983	0.026	1.5555	0.224
03259747	11.22	1.239805	0.103	1.6656	0.274
04818255	**12.10**	**0.1600359**	**0.046**	**1.407**	**0.343**
04963674	10.63	3.6390769	0.040	1.5546	0.297
07826147	**13.61**	**0.16177**	**0.115**	**-0.273**	**-0.084**
08086052	11.94	1.853631	0.075	1.56	0.255
09729507	11.77	4.740887	0.042	1.045	0.094
15864165	12.65	1.232349	0.075	1.29	0.111
15972828	**11.21**	**0.116719**	**0.108**	**0.0895**	**-0.119**

Further research will be needed to confirm our results. By having a merged database, we can now search for other binary systems. The results found from these searches can be a launch point to the further study of other rare eclipsing systems.

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REFERENCES

Carroll, B. W., & Ostlie, D. A., An Introduction to Modern Astrophysics, Addison-Wesley Publishing, 1996, 52, 68, 81-82
Green, E. 2006, private communication
Green R.F., Schmidt M., & Liebert J. 1986, ApJS, 61, 305
Houdashelt, Bell, & Sweigart. March 2000, AJ (FIX REF!)
Orosz, J.A., & Hauschildt, P.H. 2000, A&A, 364, 265
Popper, D. M. 1980, AJ, 96, 1040
Popper, D. M. 1996, ApJS, 106, 133
Randall, S.K., Fontaine, G., Brassard, P., & Bergeron, P. 2005, AJ, 161, 456-479
Saffer, R., Bergerson, P., Koester, D., & Liebert, J. 1994, ApJ, 432, 351
Skrutskie, M. F. et al. 2006, AJ, 131, 1163
Tokunaga, A.T., Allen's Astrophysical Quantities, 4th edition, Springer-Verlag, 2000, p. 143
Torres, G., Neuhauser, R, & Wichmann, R. 1998, ASP, 154, 1644
Wozniak, P.R., et al., 2004, AJ, 127, 2436
Zacharias, N., Monet, D. G., Levine, S. E., Urban, S.E ., Gaume, R., & Wycoff, G.L. 2004, AAS 205, San Diego meeting, January 2005