Missing Ba. M-Dwarfs; Insights from 40 Eridani C

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1 Introduction:

The presence of barium in the atmospheres of main-sequence stars present a unique astrophysical paradox. Unlike elements formed through nuclear fusion in stellar cores or supernova explosions, barium is a heavy element primarily formed during the asymptotic giant branch (AGB) phase of low- to intermediate-mass stars (1–8 $M_\odot$) by the slow neutron-capture process (s-process) which is the union of the capture of free-neutrons and beta-decay building heavier and heavier elements over hundreds of thousands of years. Main-sequence stars, by their inherent nature, lack the internal conditions to produce elements heavier than iron-peak group elements.

Through the years, the most likely answer to this anomaly was found to be the Binary Mass Transfer Hypothesis, leading to "contamination". In this scenario, an evolved AGB star, having produced s-process elements (such as barium, strontium, cerium, yttrium, zirconium, etc.) in its helium-burning layer, sheds this enriched material onto a nearby companion still residing on the main sequence, as it evolves from an AGB to P.N. then WD, the outer layers are shed onto its surroundings and in close enough binaries, onto the companion. Through gravitational interactions involving roche lobe overflows and stellar winds, the companion accretes the s-processed enriched material, with detectable peculiar chemical signatures, most notably enhanced barium spectral abundances can be detected in the spectrum in two widened absorption lines within the 6495- 6500 Å range. The AGB star collapses into a white dwarf (WD), serving as a relic of the process that enriched its companion. The Binary Mass Transfer Hypothesis therefore suggests that every barium main-sequence star should have a white dwarf companion [1, 2, 3], which can be found through, primarily, UV-excess measurements and long term radial velocity monitoring to find the mass and period, and estimate the T_{eff} of the unseen WD companion given its separation.

Barium star research began with the identification of broadened Ba II lines by Keenan & Bidelman [4] in the late 1940s, publishing in 1951. The groundwork for the s-process was laid by the Burbidge team in 1957 [5]. The Binary Mass Transfer Hypothesis gained significant validation with McClure et al. (1983) [3], who showed that all known barium giants were binaries, and was later supported by Gray et al. (2011) [6], who provided direct evidence of white dwarf companions to barium dwarfs.

Through advancements in cataloging efforts throughout the past 30 years, which have brought the confirmed count of barium dwarfs to approximately 71 systems (predominantly F and G spectral types) [7, 8, 9, 10, 11], a striking observational gap is brought to light: the complete absence of confirmed M-type barium dwarfs. This is particularly puzzling given that M dwarfs are the most common stellar type in the Milky Way and frequently occur in binary systems. Potential explanations for this include severe observational challenges, such as their low luminosity hindering high resolution spectroscopic observations to identify incredibly faint barium lines. Alternatively, it could suggest fundamental astrophysical differences in mass-transfer efficiency or surface enrichment patterns in lower-mass binary systems.

- Severe observational challenges: M dwarfs have low luminosity, hindering high-resolution spectroscopic observations needed to identify incredibly faint barium lines.

- Astrophysical differences: There could be fundamental differences in mass-transfer efficiency or surface enrichment patterns in lower-mass binary systems, or an M dwarf might not remain in its spectral class after accreting significant mass.

To address this gap, the 40 Eridani (GJ 166) triple star system (composed of a K-type primary 40 Eri A, a white dwarf 40 Eri B, and an M dwarf 40 Eri C) emerges as a unique valuable laboratory for study due to its proximity (approximately 5 pc). At this proximity with high spectral resolution spectral instruments such as HARPS, M-dwarf Ba II broadening may be possible to detect. Recent high-precision interferometric observations from the CHARA Array have revealed a significant anomaly in 40 Eri C: its radius is approximately 34% larger than predicted by standard stellar evolutionary models. Our hypothesis for this discrepancy lies in binary mass transfer from 40 Eri B, which would imply C had been both chemically contaminated with s-process elements and structurally altered in its evolutionary history. If confirmed spectroscopically through analysis against reference M-stars, this would be the first detection of a "barium M dwarf" and the closest barium dwarf, offering insights into the evolution of binary systems and the impact of mass transfer on very low-mass stars, the most common type in the Milky Way, M-types.

2 Comparison Groups

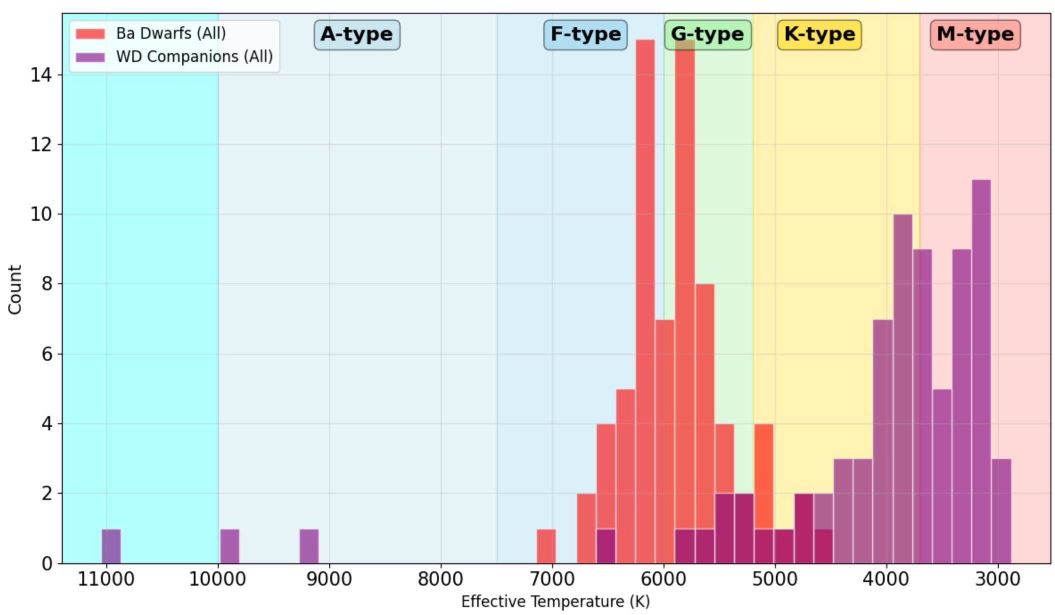

Figure 1: Mamajek's [12] Spectral Type classification used, histogram comparing the inherent temperature differences in Ba. Dwarfs and Local Stars with WD Companions within 40 pc.

Group 1: Confirmed Barium Dwarfs. Our barium dwarf sample was constructed from literature sources with modern spectroscopic validation ensuring accurate classification. Following Bond's criterion, CEMP-s and CH subgiant stars with $\log g > 3.5$ are classified as barium dwarfs. These objects are F/G-type dwarfs or subgiants enriched in carbon and s-process elements, typically through mass transfer from a companion.

The sample was assembled as follows:

1. **Base catalog:** We adopt the 59 confirmed barium dwarfs compiled by Kong et al. (2018) [7], which consolidated prior identifications from Allen & Barbuy (2006) [13] , Pereira & Drake

(2011) [14], Porto de Mello & da Silva (1997) [15], Gray & Griffin (2007) [16], Pereira (2005) [17], Pereira & Junqueira (2003) [18], Smith et al. (1993) [19], Luck & Bond (1991) [20], Karinkuzhi & Goswami (2014, 2015) [21, 22], Reddy et al. (2003) [23], Edvardsson et al. (1993) [24], and North et al. (1994) [25].

2. **Additions since 2018:**
   - Purandardas et al. (2019) [8] and Liu (2019) [26]: HD 123701, 176021, 87853, 2946
   - Shejeelammal et al. (2020) [9]: HD 154276, HD 207585, HD 94518
   - Karinkuzhi et al. (2021) [10]: TYC 2250−1047−1, 3423−696−1, 591−1090−1
   - Roriz et al. (2024) [11]: HD 15096, 37792

The final catalog contains 71 confirmed barium dwarfs, as described by Roriz [11].

Where available, orbital parameters from Escorza et al. [27]were also cross-matched to identify the subset with known binary orbits.

Table 1: Barium Dwarfs - Group Selection Statistics

Statistic	Distance (pc)	$T_{\mathrm{eff}}(K)$	BP-RP	G-Magnitude	Abs. Mag	Sep.
Max	745.54	7057	1.32	11.63	6.51	19
Min	12.89	4502	0.46	3.94	-0.06	1.03
Mean	144.05	5867	0.78	8.40	3.36	4.64

The barium dwarf population is dominated by F & G stars, consistent with observational biases against cooler, less luminous M dwarfs where barium lines are harder to detect.

Table 2: Barium Dwarfs with Separations

Name	Sp. Type	Sp. Type Ref.	Parallax (mas)	Separation (AU)
HD 182274	F6V	[28]	17.454	9.6
HD 50264	G1.5II-III:Ba2CH0.5	[29]	14.014	2.1
HD 224621	G0III/IV	[30]	13.110	1.03
HD 12739	G2IIIBa4	[2]	10.739	3.1
HD 216219	G1II-IIIFe-1CH0.5	[29]	9.694	6.2
HD 123585	G0III Ba3 CH	[2]	6.192	1.41
BD−11°3853	Fwl	[31]	5.991	19
HD 107574	F3IV/V	[32]	5.278	2.99
HD 87080	G6IIIBa5.5CH	[2]	5.187	1.05
HD 202400	ApSr	[33]	5.090	2.9
HD 207585	G2II:Ba1.5CH1Fe-1	[29]	4.844	1.72

Note: All parallaxes are from GAIA DR3 [34] or DR2. All separations are from the [27] catalog.

Group 2: Local Main-Sequence Stars with White Dwarf Companions. This comparison sample encompasses both nearby M dwarfs and local main-sequence stars known to have white dwarf companions. The local star sample with WD companions was primarily drawn from O'Brien et al. (2024) [35], who compiled Gaia-based companions within 40 pc and with projected separations of <1000 AU. This provided 25 resolved stellar systems. To ensure completeness and reproducibility, we additionally included one unique M dwarf, LP 380−6, identified exclusively by Pass et al. (2022) [36], and the benchmark Sirius system, which is absent from Gaia DR3 due to brightness saturation.

For Sirius A, an effective temperature of 9845 K and a distance derived from Hipparcos parallax (379.21 mas, 2.64 pc) were adopted.

In addition, 19 unresolved binaries from O'Brien's [35] catalog were incorporated using the same distance and separation criteria, where separations were estimated assuming a typical 1 arcsecond seeing limit. Three bright main-sequence stars falling into the distance and separation criteria with their WD (Regulus A, Procyon A, HD 149499A) lacked Gaia photometry and were excluded from Gaia-based CMD plots, though retained in the master catalog.

Resolved Systems from O'Brien (2024) [35]: **G** 233−42, 106−51, 218−7, 244−37, 175−34, 212−45, 242−15, 148−6, 142−B2A, 141−10, 169−46, 242−54, 181−37, **HD** 34865, 13445, 218572, 27442A (Eps Ret), 100623 (20 Crt), 140901 (GJ 599 A), **BD** −18 3019, +44 2555, +76 614, +24 32, +52 570, **CD** −51 13128, −27 9236, **LP** 649−66, 552−48, 783−2, 888−63, 530−22, 203−55, 159−33, 844−25, 101−15, **2MASS** J21513828+5917383, J20564846-0450490, J13360209+4828472, J13173072+4833343, J19293859+1118050, **L** 577−72, 923−22, 51−48, 447−10, 170−14, 395−13, **UCAC4** 395−088811, 412−090312, **WT** 766, 1136, **Other:** 40 Eri C, PM J17386−3427, LSPM J1743+1434N, LSPM J1820+1739, UPM J1430−2520

Unresolved Systems from O'Brien (2024) [35]: PM J06157−1247, G 147−65 (WD 1133+358), 12 Psc, tet Hya, V De CVn, EG UMa, HD 114174B, Regulus A, SCR J1848−6855, HD 159062B, WD 0419−487 (RR Caeli), WD 2003+542 (Wolf 1130), LHS 1817, GJ 207.1, G 203−47, Procyon A, 2MASS J11233127+0701213, HD 169889, HD 149499A.

Pass M (2022) [36]: LP 380−6

Benchmark Addition: Sirius A

Table 3: Local Stars - Group Selection Statistics

Statistic	Distance (pc)	$T_{\text{eff}}(K)$	BP-RP	G-Magnitude	Abs. Mag	Sep.
Max	39.38	11000	4.38	18.77	15.83	965
Min	2.61	2931	-0.03	3.88	1.04	0.01
Mean	26.25	4150	2.34	11.79	9.79	258.56

Table 4: Stars with WD Companions within 10 pc

Name	GJ	Sp. Type	Sp. Type Ref	Parallax (mas)	Separation (AU)
Sirius A	244 A	A0mA1Va	[37]	379.21	19.8
Procyon A	280 A	F5IV-V+DQZ	[38]	284.56	15
40 Eri C.	166 C	M4.5V	[39]	199.45	42.1
G 175-34	169.1	M4.0V	[40]	181.24	56.61
G 203-47	3991	M3.5V	[41]	131.60	0.05
IRAS 21500+5903	None	dM4.0	[42]	123.06	123.92
LP 783-2	283 B	M6.5Ve	[43]	109.25	186.00
HD 10063	432 A	K0V	[44]	104.61	146.03

Note: All parallaxes are from GAIA DR3 [34] & DR2 when necessary. All separations are from the [35] catalog.

This sample of nearby stars with WD companions provides a robust comparison/control group, including many M dwarfs, allowing for a potential targeted search for missing barium M dwarfs.

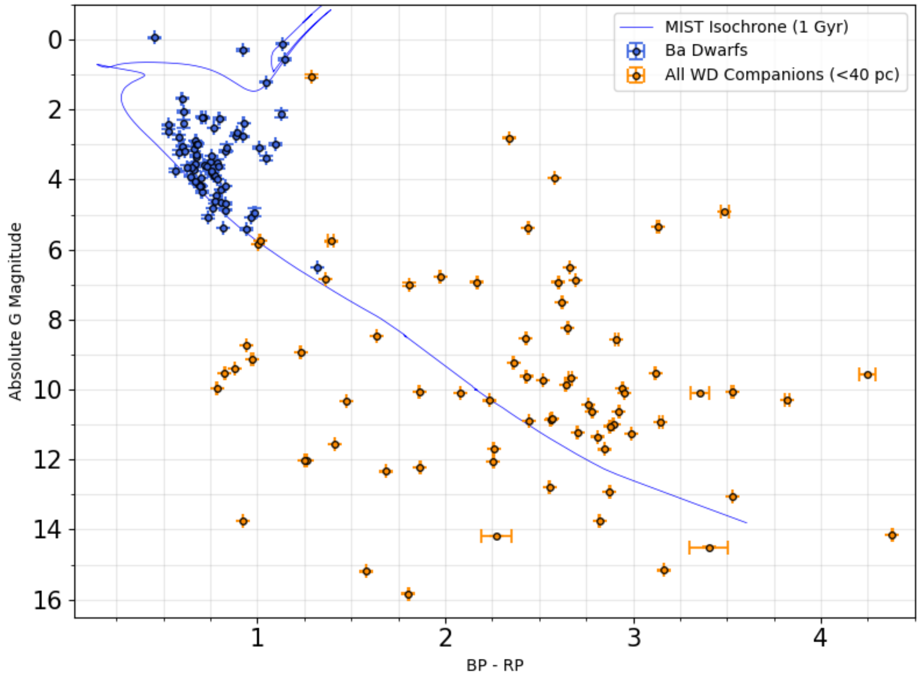

Figure 2: Color-Magnitude Diagram comparing the Ba. Dwarfs and the Local Stars with W.D. Companions, along a 1 Billion Year MIST Solar Metallicity Isochrone. Calculated Errors in BP-RP and Absolute Magnitude in G-band have been included in the form of error-bars.

3 40 Eridani

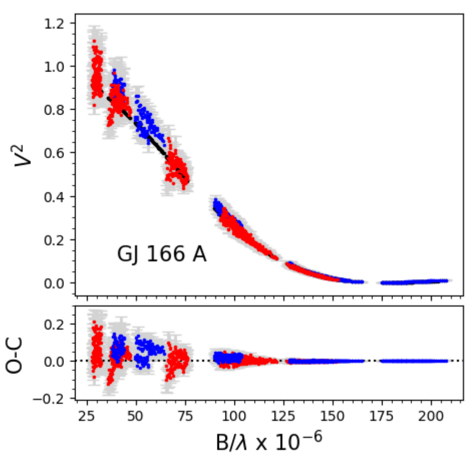

Figure 3: An angular diameter of $0.807 \pm 0.0017 R_{\odot}$ was recorded by CHARA measurements and observed by Becky Flores on two nights in September, 2024.

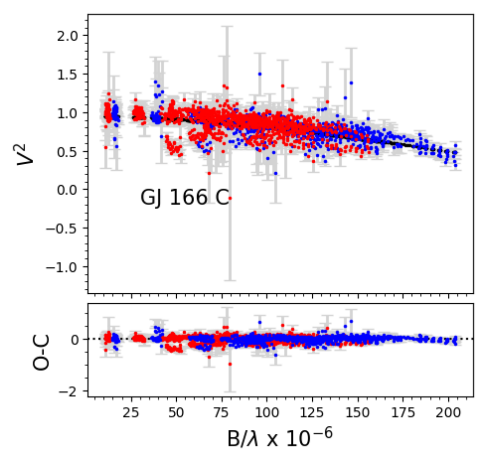

Figure 4: Four nights were combined in order to record a diameter of $0.278 \pm 0.05 R_{\odot}$ by Becky Flores two nights in October, 2023, combined with two nights in September, 2024.

The 40 Eridani triple system (A, B, C) provides an ideal case study for investigating the absence of barium M dwarfs. In particular, 40 Eridani C, an M4.5V dwarf, stands out because of its proximity (~ 5 pc) and well-characterized white dwarf companion. High-precision interferometric observations with the

CHARA Array in the H and K bands have yielded the most accurate angular diameter measurements to date. For 40 Eridani A, the derived radius of $0.807 \pm 0.0017\, R_\odot$ is fully consistent with theoretical models for a K-type dwarf, validating the accuracy of both CHARA and Gaia parallaxes. In contrast, 40 Eridani C shows a significant anomaly: its measured radius of $0.278 \pm 0.050\, R_\odot$ is inflated by approximately 34% relative to model predictions.

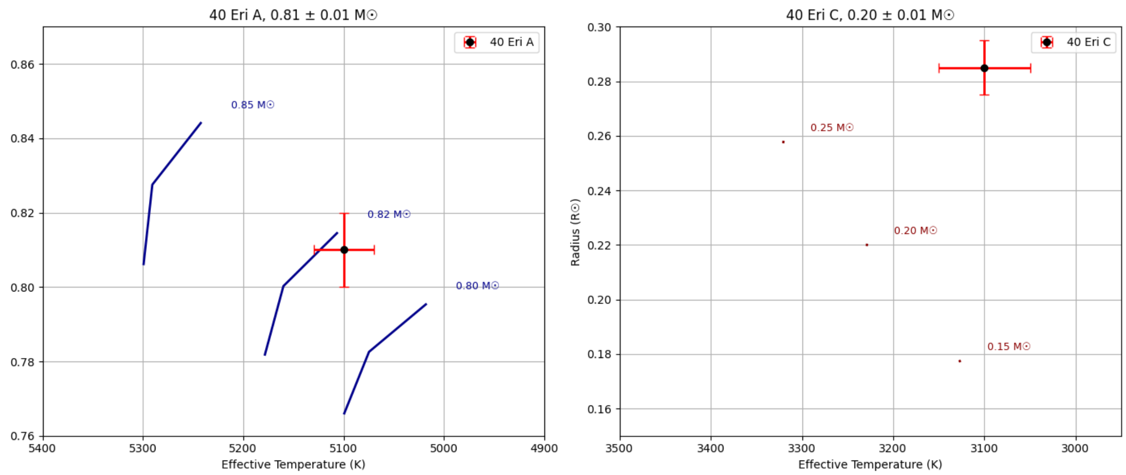

Figure 5: 40 Eri A compared to Eri C with CHARA Radius data on the y axis vs. Gaia DR3 $T_{\rm eff}$ along the mass tracks of the star. Inflation is visible on 40 Eri C, while A lies along the mass track.

While M dwarfs are known to display modest inflation from magnetic activity, the magnitude observed here is far greater than can be explained by magnetism alone. A compelling explanation is past mass transfer from 40 Eridani B during its AGB and planetary nebula phases, which could have deposited s-process enriched material onto 40 Eridani C and altered its internal structure. If spectroscopic follow-up confirms chemical enrichment, 40 Eridani C would represent the first identified "barium M dwarf", offering crucial insights into binary mass transfer and resolving the long-standing absence of such stars.

Table 5: Barium Dwarf Catalog

Name	T_{eff} (K)	Distance (pc)	BP-RP	G-Mag.	Abs. G-Mag.
HR 6094	5724	12.89	0.81	5.22	4.66
HD 164922	5342	21.98	0.96	6.80	5.09
HR 5338	6186	22.03	0.72	3.94	2.23
HR 2906	6168	26.22	0.70	4.31	2.21
HD 15096	5304	29.24	0.94	7.75	5.42
HD 89668	4502	32.00	1.32	9.04	6.51
HD 26367	6218	37.92	0.67	6.44	3.54
HR 107	6368	38.09	0.60	5.94	3.04
HD 89948	6056	40.24	0.70	7.37	4.35
HD 6434	5776	42.25	0.78	7.57	4.44
HR 80218	6105	42.35	0.68	6.49	3.35
HR 4395	6445	45.37	0.60	4.96	1.68
HR 4285	5764	46.68	0.77	5.88	2.53
HD 48565	5950	49.95	0.72	7.07	3.58
HD 176021	5781	51.68	0.77	7.47	3.90
HD 126681	5602	56.13	0.82	9.12	5.38
HD 182274	6221	57.29	0.65	7.69	3.90
HD 140324	5822	57.51	0.75	7.27	3.47
HD 36667	5804	59.00	0.76	7.17	3.32
HD 21922	6020	59.76	0.70	8.08	4.19
BD+80°670	5650	64.62	0.83	8.93	4.88
HD 220842	5826	64.94	0.76	7.85	3.79
HD 88446	5898	66.70	0.73	7.74	3.62
HD 50264	5792	71.36	0.78	8.90	4.63
HD 94518	5902	72.45	0.78	8.19	3.89
HD 37792	6463	74.87	0.58	7.60	3.22
HD 224621	5977	76.28	0.74	9.48	5.07
HD 188985	6023	78.19	0.70	8.42	3.96
HD 8270	6080	81.83	0.69	8.70	4.14
HD 204613	5770	82.90	0.79	8.12	3.52
HD 154276	5667	86.51	0.81	8.96	4.28
BD+68°1027	5814	87.48	0.76	9.52	4.81
HD 141804	6142	88.46	0.70	8.93	4.19
HD 4395	5748	89.08	0.89	7.51	2.76
HD 127392	5686	93.12	0.83	9.52	4.69
HD 150862	6181	102.45	0.67	9.11	4.06
HD 216219	5743	103.16	0.80	7.31	2.25
HD 11377	6123	104.63	0.68	8.39	3.29
HD 222349	6171	119.51	0.66	9.09	3.70
RE J0702+129	5082	119.76	0.96	10.33	4.94
HD 221531	6482	122.40	0.59	8.24	2.80
BD+17°2537	5634	123.95	0.83	8.66	3.20
HD 2946	5863	127.54	0.93	7.92	2.39
BD−10°4311	5558	127.67	0.83	9.71	4.18

Name	$T_{\rm eff}$ (K)	Distance (pc)	BP-RP	G-Mag.	Abs. G-Mag.
HD 92545	6135	127.83	0.67	8.43	2.89
HD 202020	5811	128.24	0.79	9.17	3.63
HD 13551	6222	129.37	0.65	9.22	3.67
BD+18°5215	6313	153.61	0.63	9.60	3.67
HD 123585	6157	161.51	0.66	9.16	3.12
HD 147609	6123	166.42	0.67	9.09	2.99
BD−11°3853	5704	166.93	0.79	10.09	3.98
HD 106191	5906	168.70	0.76	9.88	3.75
HD 76225	6169	169.01	0.68	9.11	2.97
HD 22589	5527	171.51	0.89	8.83	2.66
BD−18°255	6567	188.05	0.56	10.11	3.74
HD 107574	6413	189.45	0.61	8.44	2.06
HD 87080	5397	192.77	0.92	9.19	2.77
HD 87853	6365	192.92	0.61	9.60	3.17
HD 15306	6779	192.95	0.53	8.85	2.43
HD 202400	6701	196.46	0.53	9.10	2.63
HD 207585	5591	206.44	0.84	9.66	3.09
TYC 3423-696-1	5129	237.22	1.05	10.26	3.38
HD 122202	6379	237.65	0.61	9.28	2.40
HD 125079	5103	282.75	1.05	8.47	1.21
HD 123701	4778	344.28	1.15	8.25	0.57
HD 177645	7057	349.04	0.46	7.65	-0.06
TYC 2250-1047-1	5158	445.91	1.01	11.33	3.08
BD−03°3668	4962	479.62	1.13	10.52	2.12
TYC 591-1090-1	5427	536.28	1.09	11.63	2.98
HD 219116	4810	608.53	1.13	9.04	0.12
CPD−62°6195	5447	745.54	0.92	9.66	0.30

Table 6: Local Stars with W.D. Companions, within 40 pc Catalog

Name	$T_{\rm eff}$ (K)	Distance (pc)	BP-RP	G-Mag.	Abs. G-Mag.
Sirius A	9845	2.67	–	–	–
Procyon A	6582	3.51	–	–	–
40 Eri C	3567	5.01	2.99	9.78	11.27
G 175-34	3330	5.52	2.90	9.70	10.99
G 203-47	3668	7.60	2.88	10.45	11.05
IRAS 21500+5903	3552	8.13	2.64	9.41	9.86
LP 783-2	3290	9.15	4.38	13.96	14.15
20 Crt	5225	9.56	1.00	5.74	5.84
L 923-22	3300	10.51	2.56	10.97	10.86
HD 13445	5153	10.76	1.01	5.89	5.73
LP 380-5	3480	11.87	3.53	13.44	13.07
WT 766	3837	13.43	2.81	11.98	11.34
CM Dra	3321	14.86	2.92	11.49	10.63
CD-51 13128	3655	14.86	2.43	9.41	8.55
HD 140901	5540	15.25	0.88	5.83	4.92
GJ 91183	3144	15.78	2.43	10.38	9.39
Ross 193	3054	16.17	2.70	10.66	9.62

Name	T_{eff} (K)	Distance (pc)	BP-RP	G-Mag.	Abs. G-Mag.
LHS 1817	4116	16.28	2.87	12.30	11.24
G 233-42	2931	16.41	3.53	13.99	12.91
Wolf 1130 A	4002	16.58	2.08	11.17	10.07
LP 649-66	3662	16.68	2.36	11.19	10.08
G 244-37	3237	17.29	2.34	10.41	9.22
HD 27442 A	4677	18.44	1.23	4.13	2.81
BD-18 3019	3583	18.81	1.97	10.29	8.92
HD 218572	4544	21.06	1.26	8.38	6.76
RR Caeli	4134	21.19	1.87	13.64	12.01
G 106-51	3684	21.37	3.13	13.88	12.23
HD 159062 A	5383	21.65	0.92	7.03	5.35
SCR J1848-6855	3788	22.77	3.15	15.55	13.76
G 218-7	3825	22.87	2.78	12.73	10.94
LP 888-63	3912	23.03	2.76	12.44	10.63
L 577-72	3172	23.19	2.66	12.25	10.42
HD 34865	4632	23.76	1.25	8.39	6.51
UCAC4 395-088811	3096	24.17	3.05	13.94	12.02
Regulus A	11000	24.31	–	–	–
LP 844-25	3304	25.76	3.82	15.80	13.74
HD 114174	5648	26.40	0.83	6.63	4.52
G 141-10	3220	29.99	2.58	11.73	9.57
BD+24 32	4658	28.13	1.29	9.17	6.92
EG Uma	4122	28.61	1.81	12.57	10.29
L 51-48	3161	28.78	2.85	14.11	11.82
BD+52 270	4234	29.07	1.58	9.83	7.51
LP 159-33	3135	29.80	2.94	14.06	11.69
BD+44 2555	4465	30.43	1.36	9.27	6.86
V* DE CVn	3485	30.51	2.26	11.96	9.54
L 395-13	3739	30.95	1.80	12.55	10.10
G 148-6	3809	31.61	2.69	12.81	10.31
UPM J1430-2520	3888	31.63	2.56	12.02	9.52
L 447-10	3913	33.36	1.68	11.10	8.48
BD+76 614	4412	33.48	1.41	9.50	6.87
G 142-B2A	3977	33.71	2.26	11.78	9.14
LSPM J1820+1739	3928	34.22	2.65	13.00	10.33
LSPM J1743+1434N	3124	34.39	2.57	12.65	9.96
G 169-46	3860	34.79	2.17	11.28	8.58
UCAC4 412-090312	3663	34.94	2.24	11.44	8.73
Wolf 692	3412	34.98	2.45	12.69	9.97
HD 169889	5287	35.36	0.94	8.11	5.37
G 242-54	3391	35.68	3.95	14.12	11.36
HD 149499	5001	35.80	0.97	8.52	5.75
2MASS J14061314-6957172	3296	35.91	4.25	16.96	14.19
12 Psc	5737	36.31	0.78	6.74	3.94
GJ 9445	4423	36.39	1.47	9.73	6.92
2MASS J19293859+1118050	3875	36.47	2.62	12.91	10.10
2MASS J13360209+4828472	3121	36.78	2.91	14.87	12.044
tet Hya	9164	36.94	-0.04	3.88	1.04

Name	$T_{\rm eff}$ (K)	Distance (pc)	BP-RP	G-Mag.	Abs. G-Mag.
2MASS J00442484-1148399	3228	37.00	2.52	13.65	10.81
LP 552-48	4172	37.00	1.64	9.83	6.99
G 242-15	4124	37.50	1.86	11.11	8.24
PM J09598-5027B	–	38.47	–	18.09	15.16
2MASS J15493700-3954588	–	38.49	3.35	17.44	14.51
2MASS J00294996-5441354	3707	38.53	3.16	13.00	10.08
G 147-65	3739	38.59	2.67	14.64	11.70
PM J17386-3427	3194	38.64	2.82	13.82	10.89
PM J06157-1247	–	38.69	2.27	18.13	15.19
2MASS J13173072+4833343	–	38.72	3.40	18.77	15.83
LP 530-22	3674	38.76	3.49	15.74	12.80
UCAC4 106-1000428	3988	38.94	2.60	12.68	9.73
G 212-45	3090	38.99	3.12	13.50	11.55
LP 203-55	3040	39.32	3.21	15.31	12.34
2MASS J09073358-3609149	3737	39.38	2.44	12.64	9.66
PM J11235+0701	–	–	1.39	17.51	–

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