Search for faint companions to O-stars using the AEOS 3.6 meter telescope

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Abstract

O stars are the most massive and luminous main sequence stars in the sky. They are frequently found in clusters of other O and B type stars. Due to the intrinsic brightness of these stars and their typical large distances, physical companions found by traditional techniques (spectroscopy, speckle interferometry, etc.) tend to be similar in mass and brightness to the primary. Adaptive optics observations allow one to probe for the fainter physical companions, further testing star formation scenarios and neighborhood conditions of O and B star clusters.

We present the results of a multi-year survey of O stars using the Advanced Electro-Optical System (AEOS) 3.6 meter telescope, specifically searching for additional companions. Starting with a list of 171 O stars accessible to AEOS, we were able to observe 116 of these objects at least once, using the facility Visible Imager camera at I band. Under good atmospheric conditions, the analysis indicates that we can detect, and measure, a differential magnitude of at least 8 at I band, with indications that we may be doing better. Of these 116 systems, we have detected 39 new companions in 31 O star systems.

1 Introduction

Reference [1] performed a speckle interferometry survey of Galactic O-type stars for close companions, specifically looking for differences in the multiplicity frequencies amongst the cluster, field and runaway O-type star populations. They did their survey in the V-band, being able to detect a companion when the projected separation was in the range $0''.035 < \rho < 1''.5$ and the magnitude difference $\Delta m_V \lesssim 3$. Using the Advanced Electro-Optical System (AEOS), a 3.6 meter telescope and adaptive optics (AO) system, we have extended the detection phase space of their work. Using the I band (which will slightly emphasize a redder companion), we can reliably detect a companion with a magnitude difference of $\Delta m_I \lesssim 6$ in the projected separation range of $0''.5 < \rho < 1''.0$, and $\Delta m_I \lesssim 9.5$ in the $1''.0 < \rho < 5''.0$ range.

2 Object Selection

The object list started out as all the components in the 228 systems listed in [1]. They were then culled for the effective magnitude limit of the AEOS AO system (about $m_V = 8$), and then for the declination limit of

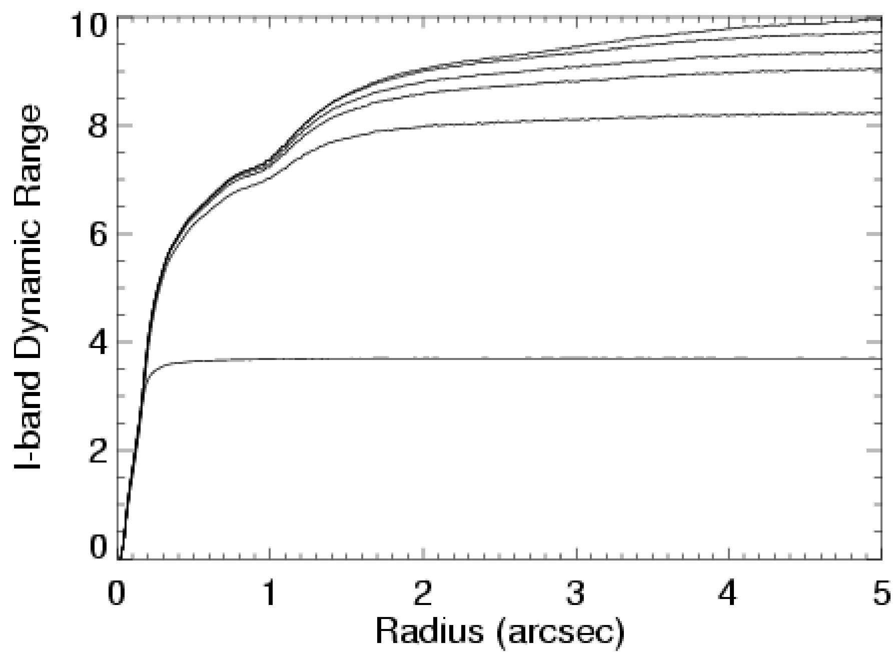

Fig. 1: Assuming that a gaussian-shaped peak, 3σ detection above background constitutes a positive detection of a companion, this plot shows the rough dynamic range of the AEOS AO system as a function of radius for different numbers of summed images. From top to bottom, the curves represent the results of 1000, 250, 100, 50, 10, and 1 summed frame(s). The "shelf", most apparent in the upper curves from about 0.7 to 1 arcsec in radius, is due to AO system artifacts.

acceptable AO correction (objects that at some time during the year get above 30° elevation at Haleakala – a declination greater than about $-45°$). This brought the list to 164 objects. When the Galactic O Star Catalog[1] [2] went on line, an additional 7 objects, not in the [1] list, were discovered to be within the above mentioned magnitude and declination limits and were therefore added to the list. This brings the list total to 171 members. Of these 171 objects, 116 have been observed at least once. These observations are fairly consistently distributed among the three O-star populations, sampling 63 percent of the cluster membership stars, 78 percent of the field stars, and 88 percent of the runaway stars.

3 Observations

The data were taken using the AO system and Visible Imager (VisIm) camera of AEOS at the Maui Space Surveillance System, located on Haleakala. The data were collected during four separate observing runs between February 2001 and September 2002. In addition to the dedicated observing runs, some observations were taken as part of the queue-scheduled observation program between May 2001 and November 2005.

Since VisIm is only a 12-bit camera (described in detail in [3]), a stellar image can overflow the digitizer with a rather short exposure time. If the frame saturates, it can't be a part of the final image. Frequently, this saturated frame will represent a period of particularly good seeing. In order to keep as many of these "good seeing" frames as possible, we set the exposure time such that the average peak value was about 75 percent of the full-well depth. We then built up the signal-to-noise ratio by taking many frames, weighting them, and summing them. Fig. 1 shows the effect of this summing on the detectable magnitude difference for 1, 10, 50, 100, 250, and 1000 frame(s). On the basis of this plot, we aimed to take at least 1000 frames

[1] The catalog can be found at http://www-int.stsci.edu/~jmaiz/GOSmain.html

of each object, though time constraints, weather, and object brightness occasionally limited us to a lower frame count.

4 Data Reduction

The VisIm is a frame transfer camera and is therefore unable to take a bias frame. To compensate, a bias frame was created by taking many dark exposures at a variety of exposure times ranging from 10 ms to several minutes. A linear fit was made to each pixel as a function of exposure time – the y-intercepts became the bias frame while the slopes became the dark frame. Prior to 2005, flat-field frames were created using the twilight sky to evenly illuminate the VisIm detector. Reference [4] found that sky flat-field frames varied at about the 1 percent level, so after 2005, flat-field frames were generated using an internal calibration sphere, which lowered the frame-to-frame variation below the 0.01 percent level. From this point, all data frames were debiased, dark-subtracted and flat-fielded in the conventional way.

For a given sequence of data frames, a weighted shift-and-add algorithm was used to create the final image. The weighted shift-and-add algorithm [5] is a modification of the traditional image-stacking algorithm that takes the seeing conditions in each individual frame into account. The frames with higher peak values (which represent better seeing) influence the final image (by means of weighting) more than frames with lower peak values.

The fitting algorithm is described in detail in [6]. In short, the point-spread function (PSF) used to represent the system performance is that of the primary star in the image, with a few modifications; near the primary, the PSF is a pixel-for-pixel table of numbers, while farther out, the PSF is a radially symmetric series of values. The radius at which the functional form of the PSF changes is dynamically determined from the first guess component separation and intensity ratio. This composite PSF is then fitted to the primary and secondary components and iterated until the intensity ratio converges.

5 Measurements

Table 1 shows the 39 new companions found. Table 1 contains 6 columns. The first column is a discoverer designation, where we have anticipated the Washingtion Double Star (WDS) catalog[2] [7] assignment. The second through sixth columns list (respectively): the Henry Draper (HD) catalog number of the primary (the brightest star in the field of view); the epoch of observation in units of Besselian year; the position angle (P.A.) of the new discovery in degrees east of north; the separation between the new discovery and primary in seconds of arc; and the magnitude difference at I band between the new discovery and the primary. Values of the P.A. for which there are dots indicate that the P.A. was unknown for that particular measurement. There was a period of time during 2001 when the derotator in front of the VisIm camera malfunctioned.

Table 2 lists the measurements of the previously known pairs. Column 1 lists the discoverer designation for a given pair, while column 2 lists the WDS coarse coordinate. Columns 3 through 7 match columns 2 through 6 in Table 1.

Table 3 lists the measurements of stellar systems in which no companion, either new or known, showed up in the vicinity, typically, within a 5 arcsec radius. The table has 6 columns, the last 3 of which are duplicates of the first 3. Columns 1 and 4 list the HD number, columns 2 and 5 list the epoch of observation in units of Besselian year, and columns 3 and 6 list the measured full-width half maximum (FWHM) of the main star in the image in seconds of arc. In columns 1 and 4, a missing value indicates a second observation of the star immediately preceding the missing HD number. In columns 3 and 6, the FWHM gives a measure of the combination of the seeing conditions and AO system performance. The lower the value, the fainter a companion one can detect. The typical FWHM is about 0.15 arcsec, though we have had values as small as 0.08 arcsec, and as large as 0.49 arcsec.

[2]The catalog can be found at http://ad.usno.navy.mil/wds/

Table 1: New Discoveries. The column description is given in the text, section 5.

Disc. Des.	WDS	HD	Epoch	P.A.	Sep.	Δm_I
		Bess. Yr.	deg.	arcsec		
TRN 7	00061+6341	108	2001.7450	...	3.24	9.47
TRN 8	00177+5126	1337	2001.7341	...	2.75	9.30
TRN 9	02158+5600	13745	2004.7924	29	4.55	10.04
TRN 10	02229+4129	14633	2001.7451	...	2.18	10.31
TRN 11 AF	02327+6127	15558	2001.7450	261	4.45	6.59
			2002.6845	261	4.48	6.38
			2005.6962	262	4.44	6.42
TRN 11 AG			2001.7450	221	2.99	9.94
TRN 11 AH			2001.7450	211	5.79	11.03
TRN 12 AD	02407+6117	16429	2005.6963	112	2.94	7.39
TRN 13 AH	02511+6025	17505	2001.7450	142	4.59	6.72
			2002.6845	140	4.62	7.01
			2004.9648	143	4.59	7.15
TRN 14	02594+6034	18326	2001.7451	...	2.38	7.45
TRN 15	03141+5934	19820	2001.7452	...	2.81	10.37
TRN 16	03590+3548	24912	2001.7342	...	2.40	9.81
TRN 17 Aa	05163+3419	34078	2004.7873	171	0.35	4.97
TRN 18 Aa	05207+3726	34656	2002.7257	279	0.35	3.77
			2003.7360	280	0.35	4.09
			2003.8917	280	0.34	4.13
TRN 18 AC			2003.7360	126	2.96	10.57
TRN 18 AD			2003.7360	247	5.75	10.39
TRN 19 AF	05387−0236	37468	2001.7456	18	3.13	8.07
TRN 20	06322+0450	46223	2001.8661	...	0.46	4.37
TRN 21	06364+0605	46966	2002.8023	210	3.19	9.97
TRN 22 AB	06374+0608	47129	2002.2404	240	1.15	5.10
			2005.0144	251	1.16	4.94
TRN 22 AC			2005.0144	203	0.78	5.14
TRN 23	06386+0137	47432	2005.0134	206	0.78	4.95
TRN 24 AB	17175−2746	156212	2001.4959	...	4.04	8.05
TRN 24 AC			2001.4959	...	7.31	7.40
TRN 25	17595−3601	163758	2001.4960	...	1.70	8.05
TRN 26 AH	18024−2302	164492	2002.4516	342	1.48	5.12
TRN 27	18181−1215	167971	2001.7447	...	4.70	8.12
TRN 28 AB	20191+3916	193514	2001.7367	78	4.75	5.80
			2002.6730	79	4.79	6.18
TRN 28 AC			2001.7367	157	3.20	7.23
			2002.6730	158	3.22	7.44
TRN 29 AC	20205+4351	193793	2001.7363	202	2.29	9.62
			2001.7447	...	3.23	9.32
TRN 30	20566+4455	199579	2001.7338	...	3.76	9.79
TRN 31	21079+3324	201345	2001.7367	...	7.38	9.31
TRN 32	21185+4357	203064	2001.7337	...	3.84	9.48
TRN 33 AC	21449+6228	207198	2001.7364	...	2.96	10.43
TRN 34	22021+5800	209481	2001.7341	...	2.75	9.92

Table 1, continued						
Disc. Des.	WDS	HD Bess. Yr.	Epoch deg.	P.A. arcsec	Sep.	Δm_I
TRN 35 AD	22051+6217	209975	2001.7367	...	4.14	9.98
TRN 35 AE			2001.7367	...	3.79	10.03
TRN 36 AC	22393+3903	214680	2001.7339	...	3.56	9.94
TRN 37 AC	22568+6244	217086	2001.7369	164	3.15	7.14
			2002.6843	165	3.17	6.79
			2004.7598	165	3.12	7.03

Table 2: New Measures of Previously Known Systems. The column description is given in the text, section 5.

Disc. Des.	WDS	HD	Epoch Bess. Yr.	P.A. deg.	Sep. arcsec	Δm_I
STF 306 AB	02511+6025	17505	2001.7450	91	2.09	1.71
			2002.6845	89	2.11	1.71
			2004.9648	92	2.10	1.64
HDS 494	03556+5238	24431	2001.7455	176	0.71	2.86
SEI 201	05207+3726	34656	2002.7257	48	1.88	6.98
			2003.7360	47	1.90	6.94
			2003.8917	47	1.89	7.28
HU 217	05297+3523	35921	2004.7873	253	0.61	2.23
STF 738 AB	05351+0956	36861	2001.7428	...	4.25	2.29
			2001.7456	41	4.23	2.04
STF 748 Ca,F	05353−0523	37022	2001.7456	118	4.39	4.89
			2003.0045	120	4.46	4.73
CHR 249 Aa	05354−0525	37041	2004.8666	292	0.39	2.97
BU 1032 AB	05387−0236	37468	2001.7456	106	0.24	1.22
STF 774 Aa-B	05407−0157	37742	2001.7455	160	2.36	2.24
GAN 3 AB	06319+0457	46150	2001.0989	...	3.47	4.87
STF 950 Aa-B	06410+0954	47839	2001.7457	202	2.88	3.31
STF 956 AB	06427+0143	48279	2004.0478	199	6.63	2.57
B 1623	08392−4025	73882	2004.1190	256	0.65	1.25
I 576	16550−4109	152408	2001.4030	...	5.30	5.67
B 894	17065−3527	154368	2002.6730	357	2.57	6.28
SEE 322	17158−3344	155889	2003.6041	285	0.19	0.68
HDS2480 Ab	17347−3235	159176	2003.3280	59	0.70	3.14
RST 3149 AB	18026−2415	164536	2002.4627	62	1.65	4.49
B 376	18061−2412	165246	2002.4819	98	1.90	3.68
BU 276 AB	18152−2023	167263	2005.6545	216	5.93	5.62
STF 2624 Aa-B	20035+3601	190429	2001.7337	172	1.92	0.84
STF 2666 Aa-B	20181+4044	193322	2001.6683	244	2.69	2.51
			2001.7364	243	2.67	2.11
BU 1207	20205+4351	193793	2001.3400	209	4.77	8.44
			2001.7337	209	4.77	6.75
			2001.7363	209	4.77	6.75
			2001.7447	...	4.79	6.43
			2002.6731	210	4.81	6.93
			2002.6731	210	4.81	6.58
BU 1143 AB	21390+5729	206267	2001.7338	317	1.78	5.65
MLR 266	22568+6244	217086	2001.7369	353	2.79	3.41
			2002.6843	354	2.83	3.34
			2004.7598	354	2.78	3.79

Table 3: Single Star FWHM measures. The column description is given in the text, section 5.

HD	Epoch Bess. Yr.	FWHM arcsec	HD	Epoch Bess. Yr.	FWHM arcsec
14947	2001.7455	0.12	157857	2002.2383	0.22
15137	2004.7923	0.18	162978	2001.7446	0.12
25638	2004.8665	0.12	163758	2001.5179	0.17
30614	2004.8665	0.12	163800	2001.4960	0.13
36879	2003.8944	0.11		2001.5176	0.16
37042	2004.8667	0.12	163892	2005.3404	0.21
37043	2001.7455	0.08	164438	2002.3204	0.16
37366	2005.0200	0.34	164794	2002.6729	0.10
39680	2002.2404	0.22	164816	2001.6709	0.14
41161	2001.8659	0.16		2002.4817	0.11
42088	2001.8660	0.21	165052	2001.6711	0.14
45314	2001.0989	0.11	165319	2001.6711	0.16
46149	2001.8660	0.36	167771	2002.4843	0.20
46966	2002.2377	0.25		2002.4950	0.19
48099	2002.2405	0.13	175876	2001.7447	0.14
52266	2001.9754	0.12	186980	2001.7366	0.19
53975	2005.0196	0.12	188001	2001.7338	0.12
54662	2002.0218	0.16		2001.7447	0.17
	2002.2404	0.12	188209	2004.7646	0.08
55879	2005.0170	0.19	190864	2001.7365	0.14
57061	2004.0807	0.21	190918	2001.7421	0.18
57682	2001.9290	0.45	191612	2001.7365	0.13
60848	2001.0990	0.16	191978	2002.6786	0.33
66811	2004.0861	0.48	192281	2001.7365	0.12
69648	2004.0451	0.26	192639	2001.7366	0.17
75211	2004.1432	0.23	193443	2001.7366	0.19
75222	2005.0197	0.49	195592	2005.6549	0.19
93521	2001.0992	0.19	198846	2005.3843	0.12
148546	2005.3482	0.28	202124	2005.6549	0.19
149404	2001.3893	0.12	203064	2001.7342	0.12
149757	2002.2243	0.22		2001.7448	0.12
151003	2004.2590	0.23	207538	2005.7180	0.22
151515	2004.3384	1.93	210809	2001.7369	0.21
152003	2001.3893	0.12	210839	2001.7342	0.16
152219	2004.5265	0.22	214680	2001.7369	0.19
152314	2001.4029	0.17	216898	2001.7451	0.10
153919	2003.5247	0.16	218915	2004.7597	0.18
155806	2002.6730	0.12			

6 Conclusion

This O star survey is the first step toward expanding the work of [1] to a different detection realm. Since it is only a single color band survey, taken over a relatively short period of time, it is difficult to determine which of the detections listed in Table 1 are actually physically bound to the main star, which are simply optical superpositions, and which are AO system artifacts. At this point, we do not have enough data to make a determination. However, the 39 new detections in Table 1 provide a "short list" for a follow-up survey.

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