

5.3 BALMER LINES

Generally, the existence of the emission Balmer lines in an optical spectrum can be used to categorise a normal B type star into a Be star or Be-shell star phase depending on the profile of the emission lines. In addition, the Be stars can be classified as mild, more developed or extreme Be stars by the number of Balmer series, which appear in the emission and also by the existence of other elements, such as *HeI* and *FeII* (Gray et al., 2009). The emission line profiles are also subject to change on a timescale of days, months or decades.

The BeSS database provides a constant monitoring of δ -Sco in the H_α region since 2006. Starting from 2008, the observations have been carried out using an Echelle type spectrograph, which enables a high-resolution spectrum covering the H_γ region simultaneously. Table 5.1 shows the parameters of δ -Sco in the H_α region from 2007 to 2010, whereas Table 5.2 shows the parameters of the H_β and H_γ spectral profiles. Column 1 and 2 are the observation dates represent in Gregorian and Modified Heliocentric Julian Date (MHJD) calendars respectively. Column 3 is *V/R* ratio – ratio of violet to red peaks. Column 4 is for the equivalent width, *EW* measured in Angstroms (\AA) and columns 5 and 6 are *FWHM* in \AA and km/s, respectively. Columns 7 and 8 are the separation of the *V* and *R* peaks, ΔVp , in \AA and km/s, respectively and column 9 is the ratio of the disc radius over the stellar radius and the last column *dw*, is the minimum spectral dispersion of the instruments.

Table 5.1 – List of data of δ -Sco and profile measurements of H_{α} from 2007 to 2010. Column 1 and 2 are observation dates in Gregorian calendar and modified heliocentric Julian Date calendar. Column 3 is V/R ratio, followed by the equivalent width, EW measured in Angstroms (\AA), columns 5 and 6 are FWHM in \AA and km/s, respectively, columns 7 and 8 are the separation of the V and R peaks, ΔV_p , in \AA and km/s, respectively and column 9 is the ratio of the disc radius over the stellar radius and the last column dw, is the minimum spectral dispersion of the spectrograph.

Delta Scorpii : H-alpha 2007-2010

Date	MHJD+ 2454140	V/R	EW (\AA)	FWHM (\AA)	FWHM (km/s)	v sin i (km/s)	ΔV_p (\AA)	ΔV_p (km/s)	Rd/R*	dw
20070216	7.65	-	-15.290	4.255	194.504	116.812	-	-	-	0.25
20070221	12.65	1.10	-14.867	3.901	178.322	107.094	1.432	65.459	25.415	0.12
20070312	31.62	-	-11.038	4.104	187.601	112.667	-	-	-	0.24
20070326	45.62	-	-13.830	4.105	187.647	112.694	-	-	-	0.25
20070408	58.56	-	-15.067	4.063	185.727	111.541	-	-	-	0.24
20070412	62.56	-	-14.801	4.012	183.396	110.141	-	-	-	0.25
20070415	65.57	-	-14.980	4.062	185.681	111.514	-	-	-	0.24
20070416	66.63	1.27	-14.559	3.721	170.094	102.152	1.457	66.602	24.550	0.11
20070419	69.57	1.21	-14.459	3.861	176.493	105.996	-	-	-	0.23
20070420	70.52	-	-14.973	3.920	179.190	107.615	-	-	-	0.25
20070421	71.63	-	-14.655	4.093	187.099	112.365	-	-	-	0.23
20070423	73.58	1.25	-14.441	3.659	167.260	100.450	1.416	64.728	25.992	0.12
20070425	76.51	1.20	-13.951	3.878	177.270	106.462	-	-	-	0.24
20070506	86.54	1.19	-12.163	4.043	184.813	110.992	-	-	-	0.24
20070508	89.46	1.25	-10.694	3.557	162.597	97.650	1.377	62.945	27.485	0.12
20070519	99.66	1.28	-9.259	3.495	159.763	95.948	1.521	69.528	22.527	0.11
20070523	104.48	-	-9.472	3.961	181.065	108.741	-	-	-	0.24
20070601	113.47	-	-12.082	4.288	196.012	117.718	-	-	-	0.24
20070605	117.43	-	-12.425	4.272	195.281	117.279	-	-	-	0.24
20070618	130.44	-	-12.475	4.357	199.166	119.612	-	-	-	0.25
20070621	133.39	-	-14.497	4.346	198.664	119.310	-	-	-	0.24
20070707	149.42	-	-12.181	4.404	201.315	120.903	-	-	-	0.24
20070717	159.40	1.26	-10.411	4.283	195.784	117.581	2.277	104.086	10.052	0.24
20070726	168.41	1.11	-8.962	4.158	190.070	114.149	2.156	98.555	11.212	0.12
20070803	176.36	1.19	-9.882	4.429	202.458	121.589	2.222	101.572	10.556	0.24
20070804	177.36	1.21	-10.570	4.488	205.155	123.209	2.167	99.058	11.098	0.24
20080208	364.68	0.97	-9.810	4.779	218.457	131.197	1.575	71.996	21.009	0.24
20080212	368.69	1.00	-7.757	4.828	220.697	132.543	1.626	74.327	19.712	0.24
20080217	373.67	1.02	-10.493	4.833	220.925	132.680	1.569	71.722	21.170	0.24
20080305	390.63	1.05	-14.090	4.888	223.439	134.190	1.463	66.876	24.349	0.24
20080401	417.61	-	-14.290	4.771	218.091	130.978	-	-	-	0.24
20080408	424.60	-	-11.270	4.499	205.658	123.511	-	-	-	0.24
20080429	445.58	-	-14.730	4.250	194.275	116.675	-	-	-	0.20
20080501	447.54	-	-14.656	4.083	186.641	112.090	-	-	-	0.24
20080501b	448.47	-	-15.490	4.200	191.990	115.302	-	-	-	0.20
20080508	455.50	-	-15.450	4.040	184.676	110.910	-	-	-	0.24
20080509	456.51	-	-13.838	3.718	169.957	102.070	-	-	-	0.24
20080512	459.44	-	-14.823	4.097	187.281	112.475	-	-	-	0.20
20080521	467.51	-	-13.927	4.038	184.584	110.855	-	-	-	0.20
20080524	471.50	-	-14.002	4.060	185.590	111.459	-	-	-	0.24
20080604	482.43	-	-10.287	3.898	178.185	107.011	-	-	-	0.20
20080618	496.39	-	-10.660	4.198	191.898	115.247	-	-	-	0.20
20080621	499.41	-	-10.413	4.169	190.573	114.451	-	-	-	0.20
20080625	503.38	-	-9.953	4.142	189.338	113.710	-	-	-	0.24
20080628	506.39	1.32	-10.584	3.998	182.756	109.757	2.288	104.589	9.955	0.20
20080629	507.44	1.41	-10.929	4.251	194.321	116.702	2.218	101.389	10.594	0.12
20080701	509.40	1.35	-11.140	4.260	194.732	116.949	2.181	99.698	10.956	0.25
20080703	511.41	1.37	-11.101	4.130	188.790	113.381	2.243	102.532	10.359	0.12

Table 5.1 – Continue

Delta Scorpii : H-alpha 2007-2010

Date	MHJD+ 2454140	V/R	EW (Å)	FWHM (Å)	FWHM (km/s)	v sin i (km/s)	ΔVp (Å)	ΔVp (km/s)	Rd/R*	dw
20080709	517.484	1.36	-11.980	4.127	188.653	113.298	2.041	93.298	12.511	0.10
20080717	525.390	1.25	-11.900	4.259	194.687	116.922	1.755	80.224	16.921	0.10
20080717	525.29	1.25	-11.447	4.342	198.481	119.201	2.085	95.309	11.988	0.35
20080723	531.37	1.27	-10.207	4.416	201.863	121.232	2.160	98.738	11.170	0.25
20080724	532.404	1.25	-11.450	4.226	193.178	116.016	1.910	87.310	14.286	0.10
20080724	532.37	1.30	-16.143	5.031	229.976	138.116	2.206	100.840	10.709	0.24
20080830	569.32	1.17	-9.950	3.990	182.390	109.537	2.003	91.561	12.990	0.12
20090215	737.75	-	-10.880	4.068	185.956	111.678	-	-	-	0.26
20090228	750.63	-	-11.377	3.809	174.116	104.568	-	-	-	0.26
20090317	767.66	-	-14.220	4.215	192.675	115.714	-	-	-	0.11
20090318	768.65	-	-12.487	4.747	216.994	130.319	-	-	-	0.24
20090327	777.64	-	-14.810	4.453	203.555	122.248	-	-	-	0.11
20090330	780.63	-	-13.153	4.693	214.526	128.836	-	-	-	0.24
20090415	796.61	-	-11.970	4.104	187.601	112.667	-	-	-	0.25
20090418	800.52	-	-10.533	4.137	189.128	113.584	-	-	-	0.11
20090422	803.55	-	-11.207	4.140	189.247	113.655	-	-	-	0.25
20090424	805.56	-	-10.160	4.109	187.830	112.804	-	-	-	0.25
20090503	814.6	0.78	-10.370	4.215	192.675	115.714	1.309	59.837	30.415	0.11
20090509	821.46	-	-11.233	4.305	196.789	118.185	-	-	-	0.25
20090520	832.52	-	-11.580	4.190	191.533	115.028	-	-	-	0.25
20090529	841.39	0.95	-11.877	4.514	206.343	123.922	-	-	-	0.25
20090612	855.41	0.94	-12.450	4.486	205.063	123.154	-	-	-	0.25
20090704	877.39	0.91	-12.958	4.349	198.801	119.393	1.370	62.625	27.767	0.24
20090712	885.38	0.91	-13.920	4.397	200.995	120.710	1.425	65.139	25.665	0.25
20090718	891.36	0.90	-14.143	4.440	202.961	121.891	-	-	-	0.25
20090804	908.35	-	-14.213	4.697	214.708	128.946	-	-	-	0.25
20090810	914.37	0.88	-14.300	4.060	185.590	111.459	1.531	69.985	22.234	0.12
20090812	916.36	0.88	-14.057	4.145	189.476	113.792	1.518	69.391	22.617	0.12
20090818	923.36	0.93	-13.600	4.418	201.955	121.287	-	-	-	0.34
20090819	923.36	0.92	-13.787	4.702	214.937	129.084	-	-	-	0.34
20100221	1108.72	1.19	-10.282	3.924	179.373	107.725	1.660	75.882	18.913	0.10
20100309	1124.68	1.26	-10.170	3.899	178.230	107.039	2.747	125.570	6.906	0.11
20100325	1140.58	1.13	-10.450	4.087	186.824	112.200	2.935	134.164	6.050	0.11
20100411	1158.51	1.10	-7.514	4.113	188.013	112.914	2.483	113.502	8.453	0.11
20100429	1175.54	1.20	-7.242	3.942	180.196	108.219	2.378	108.703	9.216	0.11
20100519	1195.51	1.10	-9.166	4.161	190.207	114.232	2.570	117.479	7.890	0.11
20100522	1199.46	1.09	-7.200	4.010	183.304	110.086	2.423	110.760	8.877	0.11
20100523	1199.46	1.11	-7.070	3.439	157.203	94.411	2.547	116.428	8.034	0.11
20100530	1207.40	1.05	-5.440	4.018	183.670	110.306	2.034	92.978	12.597	0.11
20100604	1212.39	1.05	-7.527	4.158	190.070	114.149	2.404	109.891	9.018	0.11
20100608	1215.52	1.07	-6.417	4.133	188.927	113.463	2.233	102.075	10.452	0.11
20100626	1234.43	1.03	-7.062	4.396	200.949	120.683	2.179	99.606	10.976	0.11
20100630	1238.41	1.00	-5.835	4.367	199.624	119.887	1.855	84.795	15.145	0.11
20100704	1242.48	1.10	-5.184	4.452	203.509	122.220	2.078	94.989	12.069	0.11
20100707	1245.36	1.01	-6.424	4.704	215.028	129.138	1.750	79.996	17.017	0.34
20100708	1246.42	1.05	-6.167	4.641	212.149	127.409	2.040	93.252	12.523	0.11
20100709	1247.35	-	-7.017	4.710	215.303	129.303	-	-	-	0.34
20100712	1250.02	0.95	-6.149	4.314	197.201	118.432	2.538	116.017	8.091	0.19
20100715	1253.35	1.04	-6.892	4.630	211.646	127.107	-	-	-	0.34
20100718	1256.37	1.03	-6.381	4.488	205.155	123.209	1.644	75.150	19.283	0.10
20100721	1258.95	0.94	-6.957	4.360	199.304	119.695	2.538	116.017	8.091	0.19
20100725	1263.06	0.98	-6.675	4.470	204.332	122.714	1.770	80.910	16.635	0.19
20100726	1263.93	0.98	-6.563	4.550	207.989	124.911	2.519	115.148	8.213	0.19

Table 5.1 – Continue

Delta Scorpii : H-alpha 2007-2010

Date	MHJD+ 2454140	V/R	EW (A)	FWHM (A)	FWHM (km/s)	$v \sin i$ (km/s)	ΔV_p (A)	ΔV_p (km/s)	Rd/R*	dw
20100730	1268.47	1.01	-6.737	4.460	203.875	122.440	2.128	97.275	11.509	0.11
20100809	1277.99	1.01	-6.318	4.400	201.132	120.793	2.529	115.605	8.148	0.19
20100811	1280.39	1.04	-6.573	4.360	199.304	119.695	1.774	81.093	16.560	0.11
20100813	1282.28	1.03	-6.617	4.570	208.903	125.460	2.134	97.549	11.444	0.18
20100815	1284.33	-	-6.254	4.910	224.445	134.794	-	-	-	0.67
20100820	1289.33	1.06	-6.080	4.994	228.285	137.100	2.121	96.955	11.585	0.34
20100821	1290.32	1.03	-6.766	4.538	207.440	124.581	2.261	103.354	10.195	0.20
20100823	1292.32	1.04	-6.665	4.810	219.874	132.048	1.936	88.498	13.905	0.34
20100827	1296.33	1.05	-6.753	4.270	195.190	117.224	1.956	89.412	13.622	0.34
20100830	1299.31	1.02	-6.580	4.612	210.823	126.613	1.821	83.241	15.716	0.10
20100903	1303.30	1.02	-6.900	4.526	206.892	124.252	2.151	98.326	11.264	0.10
20100907	1306.92	0.99	-6.805	4.470	204.332	122.714	2.649	121.091	7.427	0.19
20100910	1309.93	0.94	-7.212	4.410	201.589	121.067	2.704	123.605	7.128	0.19
20101005	1334.93	0.97	-7.593	4.760	217.588	130.676	2.559	116.977	7.958	0.19
20101010	1339.93	1.00	-6.886	4.820	220.331	132.323	2.419	110.577	8.906	0.19
20101019	1348.91	1.01	-6.838	4.840	221.245	132.872	2.419	110.577	8.906	0.19
20101021	1350.91	1.03	-6.636	4.700	214.846	129.029	2.259	103.263	10.213	0.19
20101025	1354.90	1.03	-6.687	4.640	212.103	127.381	2.366	108.154	9.310	0.19

Table 5.2 – List of Echelle data of δ -Sco and spectral profiles of H_β (above) and H_γ (below): column 4 lists the radial velocity of the centre reversal of the line profile RV_{cr} , measured in km/s. The other parameters are the same as in Table 5.1.

Delta-Scorpii : H-beta 2009 - 2010

Date	MHJD+ 2454000	EW (A)	RVcr (km/s)	fwhm (km/s)	V/R	ΔV_p (A)	ΔV_p (km/s)	Rd/R*	dw
20090317	907.66	-2.24	-44.11	192.31	0.53	1.82	112.25	8.64	0.1
20090327	917.64	-2.43	-40.43	191.91	0.48	1.94	119.66	7.61	0.1
20090418	940.52	-1.88	-36.21	221.93	0.58	1.96	121.20	7.41	0.1
20090503	954.60	-1.85	-30.46	219.96	0.64	1.83	112.99	8.53	0.1
20100221	1248.72	-1.57	20.17	229.72	1.81	1.50	92.57	12.71	0.1
20100313	1268.64	-1.79	12.31	272.89	1.75	1.69	104.23	10.02	0.1
20100411	1297.60	-1.37	10.17	240.91	1.27	2.33	143.66	5.28	0.1
20100415	1301.55	-1.24	2.51	234.25	1.29	2.16	133.36	6.12	0.1
20100522	1339.44	-1.37	-2.85	228.75	1.04	1.95	120.15	7.54	0.1
20100604	1352.44	-1.40	-3.17	225.8	0.94	1.93	118.79	7.72	0.1
20100624	1372.40	-1.33	-12.40	219.6	0.74	1.86	114.54	8.30	0.1
20100704	1382.40	-1.14	-10.32	221.36	0.70	1.70	105.09	9.86	0.1
20100707	1385.40	-1.14	-17.62	224.01	0.69	1.82	112.62	8.59	0.1
20100718	1396.37	-1.10	-21.27	217.39	0.73	1.68	103.37	10.19	0.1
20100830	1439.31	-1.10	-20.98	219.53	0.69	1.77	109.11	9.15	0.1
20100903	1443.30	-1.06	-20.76	216.13	0.80	1.72	106.45	9.61	0.1

Table 5.2 – Continue

Delta-Scorpii : H-gamma 2009 - 2010

Date	MHJD+ 2455000	EW (Å)	RVcr (km/s)	V/R	ΔV_p (Å)	ΔV_p (km/s)	Rd/R*	dw
20090317	907.66	-0.57	-35.88	0.48	1.90	131.18	6.33	0.1
20090327	917.64	-0.54	-48.67	0.51	2.12	146.74	5.06	0.1
20090418	940.52	-0.45	-27.28	0.47	1.83	126.42	6.81	0.1
20090503	954.60	-0.40	-31.32	0.60	2.09	144.25	5.23	0.1
20100221	1248.72	-0.26	69.12	1.99	2.99	206.59	2.55	0.1
20100313	1268.64	-0.42	58.10	1.61	2.73	188.34	3.07	0.1
20100411	1297.60	-0.41	25.32	0.93	2.30	158.69	4.32	0.1
20100415	1301.55	-0.33	21.13	1.03	2.30	158.97	4.31	0.1
20100522	1339.44	-0.34	12.35	0.75	2.00	138.23	5.70	0.1
20100604	1352.44	-0.45	7.38	0.82	1.79	123.86	7.10	0.1
20100624	1372.40	-0.36	11.35	0.65	1.61	111.49	8.76	0.1
20100704	1382.40	-0.29	-2.21	0.46	1.89	130.70	6.37	0.1
20100707	1385.40	-0.41	17.25	0.71	1.77	122.13	7.30	0.1
20100718	1396.37	-0.36	23.14	0.65	1.81	124.83	6.99	0.1
20100830	1439.31	-0.35	21.62	0.71	1.95	134.50	6.02	0.1
20100903	1443.30	-0.41	9.95	0.62	2.26	156.48	4.45	0.1

5.3.1 H_α variability behaviour

As shown in Table 5.1, the number of data on H_α from 2007 to 2010 was the highest compared with other lines. This provides us data with which to study the behaviour of the outer emitting disc region of δ -Sco when closing to the next periastron, which occurred in 2011. Figure 5.5a, 5.5b and 5.5c show several types of variation in the H_α profiles that we had identified from the data. Those profiles shown in the figures had a minimum spectral dispersion of $0.1 \text{ \AA}/\text{pixel}$ in which the profiles reveal features that are more detailed compared with higher spectral dispersion data. Based on the speckle interferometric observations, δ -Sco has been confirmed as a binary system with high eccentricity and a period P of ~ 10.6 years (Miroshnichenko et al., 2001), 10.7 years (Tango et al., 2009) and 10.817 years (Tycner et al., 2011). The detection of radial velocity RV variation in the primary's spectra shows that δ -Sco is a single-lined spectroscopic binary. The binary characteristics sometimes can be captured in its spectral profiles depending on the

orientation and physical conditions of the companion relative to the primary. In Figure 5.5a, 5.5b and 5.5c, some of the profiles show a profile with more than two peaks, which could be a sign of the binary or a multiple system of δ -Sco. The following explanation of the behaviour and characteristics of the H_α line profile of δ -Sco refers to Figure 5.5a, 5.5b and 5.5c.

In 2007, the profile on the 21st February and 16th April resembled a class 2 category profile, which is characterised by an asymmetric sharp single peak with blue or red asymmetric flanks (Hanuschick et al., 1988). Hanuschik (1987) suggested that such a profile indicates that the circumstellar envelope of δ -Sco is in a form of elliptical disc or ring. However, the single peak of a class 2 profile appeared probably because of the incapability of the instrument to resolve the double-peak profile very well from a very wide circumstellar disc.