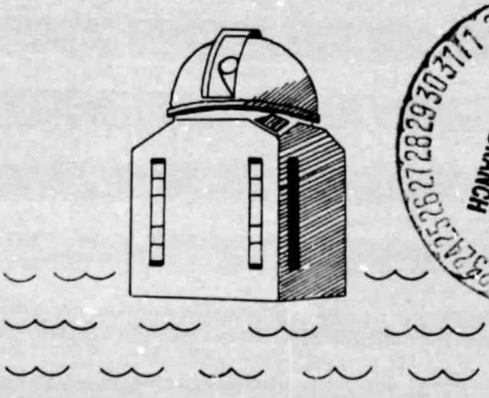
NGR- 05-002-03

CALIFORNIA INSTITUTE OF TECHNOLOGY

BIG BEAR SOLAR OBSERVATORY

HALE OBSERVATORIES



(NASA-CR-145974) FURTHER OBSERVATIONS OF THE LAMBDA 10830 He LINE IN STARS AND THEIR SIGNIFICANCE AS A MEASURE OF STELLAR ACTIVITY (Hale Observatories, Pasadena, Calif.) 28 p HC $4.00 CSCL 03A G3/89

N76-14992

Unclas
07726

FURTHER OBSERVATIONS OF THE λ10830 HE LINE IN STARS AND THEIR SIGNIFICANCE AS A MEASURE OF STELLAR ACTIVITY

H. Zirin

HALE OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

BBSO #0150
November, 1975

ABSTRACT

Measurements of the λ10830 He line in 198 stars are given, along with data on other features in that spectral range. Nearly 80% of all G and K stars show some λ10830; of these, half are variable and 1/4 show emission. We confirm the results of Vaughan and Zirin (1968) that λ10830 is not found in M stars and is weak in F stars, also that it is particularly strong in close binaries. The line is found in emission in extremely late M and S stars, along with Pγ, but Pγ is not in emission in the G and K stars with λ10830 emissions. Variable He emission along with the Ti I emission is found in the RV Tauri variables R Scuti and U Mon. In R Aqr we find in emission the Fe XIII coronal line λ10747 and a line at λ11012 which may be singlet He or La II, as well as λ10830 and Pγ. There is possibly a 5 year period in the appearance of λ10830 emission in θ Herculis.

The nature of coronas or hot chromospheres in the various stars is extensively discussed without definite conclusion, except that the λ10830 intensity must be more or less proportional to the energy deposited in the chromosphere corona by non-thermal processes.

I. INTRODUCTION

In two earlier papers (Vaughan and Zirin, 1968; Zirin, 1971) we presented results of measurement of the He I 10830 line in 86 late-type (and a few early-type) stars. In this paper we have results on 122 additional stars, bringing the total list to 198 stars of various types, as well as additional spectra of stars in the Vaughan and Zirin lists. The new spectra are mostly of fainter stars made accessible by better image tubes and better techniques. For 40 stars we have multiple observations showing change (or lack thereof). We have also measured the intensity of the CN band heads at 10872 and 10926.

Recent work (Zirin 1975) has shown that helium in the sun is probably excited by coronal ultraviolet. Thus our measures of 10830 absorption may measure the existence of stellar coronas rather than chromospheres; however He 10830 emission can only be produced by denser regions, i.e. stellar chromospheres. Of course, only direct observation of coronal lines like O VI in the stars can resolve the question of chromosphere or corona.

II. MEASUREMENTS

Almost all of the plates were made at the 72" camera of the Palomar coude (dispersion 15.6 A/mm); till 1972 plates were obtained with the same RCA image tube used by Vaughan and Zirin. This tube lost its sensitivity at that point and a new RCA fiber optic tube was purchased, which lasted only a year. The 1974 observations were made with an ITT tube with fiber optic backplate kindly lent by Prof. Guido Munch. This tube permitted a significant gain in speed, permitting spectra of stars down to I = 5.

All spectra were microdensitometered, and the equivalent width of 10830 measured. All values were confirmed by careful visual examination. The line is often very weak, and easily confused with the atmospheric H_2O line at 10832. Possible blending effects were eliminated when possible by comparison with other H_2O lines in the neighborhood on the same spectrum. If 10830 is blended by radial velocity shift with 10832 we use the measured value when the other H_2O lines are weak or absent: sometimes, if the H_2O lines are present, the 10830 line is so strong that a meaningful result is obtained by subtracting the intensity of an unblended H_2O line of strength similar to 10832. This can only be done on the better plates.

We attempted to make a quantitative measurement of the CN band intensities; however blends and water vapor made a visual estimate based on the tracings and the plate more reliable. This is given, when measurable, on a scale of 1 to 4. The value 4 is used for the red stars with especially intense systems.

Table 1 lists all the stars measured. In column 4, we find the equivalent width in angstroms (absorption unless marked E) and in column 5 the intensity of the infrared CN bands on an increasing scale of 1 to 4. If several plates over a period optic tube was purchased, which lasted only a year. The 1974 observations were made with an ITT tube with fiber optic backplate kindly lent by Prof. Guido Munch. This tube permitted a significant gain in speed, permitting spectra of stars down to I = 5.

All spectra were microdensitometered, and the equivalent width of 10830 measured. All values were confirmed by careful visual examination. The line is often very weak, and easily confused with the atmospheric H_2O line at 10832. Possible blending effects were eliminated when possible by comparison with other H_2O lines in the neighborhood on the same spectrum. If 10830 is blended by radial velocity shift with 10832 we use the measured value when the other H_2O lines are weak or absent: sometimes, if the H_2O lines are present, the 10830 line is so strong that a meaningful result is obtained by subtracting the intensity of an unblended H_2O line of strength similar to 10832. This can only be done on the better plates.

We attempted to make a quantitative measurement of the CN band intensities; however blends and water vapor made a visual estimate based on the tracings and the plate more reliable. This is given, when measurable, on a scale of 1 to 4. The value 4 is used for the red stars with especially intense systems.

Table 1 lists all the stars measured. In column 4, we find the equivalent width in angstroms (absorption unless marked E) and in column 5 the intensity of the infrared CN bands on an increasing scale of 1 to 4. If several plates over a period

TABLE 1

Summary of λ10830 data for all observations (including Vaughan and Zirin, 1968).

HD No.	Name	Spectral Type	He	CN	K Int/Width		Date	No. of Plates	Notes
STAR TYPE: O ; B									
149757	ζ Oph	O9n	0	...	...	...	7/70	1	
358	α And	B8p	0	...	...	...	10/65-12/68	2	
19356	β Per	B8p	0	...	...	...	2/66- 2/73	2	
34085	β Ori	cB8ep	1.2	...	...	...	9/65-11/65	2	
37128	ε Ori	B0	0	...	...	...	1/67	1	
116658	α Vir	B2v	0	...	...	...	1/67	1	
120709	3 Cen A	B5	.1	...	...	...	1/67	1	1
			.2 bl				4/75	1	
STAR TYPE: A									
11502	γ Ari	A0p	0	...	...	...	12/68	1	
33904	μ Lep	A0p	0	...	...	...	1/67-12/68	2	
95418	β UMa	A1	0	..	...	...	1/67	1	
112413	α² CVn	A0p	0	...	...	...	2/66- 6/71	4	
172167	α Lyr	A1v	0	...	...	...	8/65-11/65	2	
197345	α Cyg	A2 Ia	0	...	...	...	11/65	1	
STAR TYPE: F									
432	β Cas	dF2	0 bl	...	...	...	/65- 1/67	2	
4614	η Cas	F8 V	0	1	0	...	12/68	1	
11443	α Tri	F5	.38	1	...	...	12/68-10/70	2	
18925	γ Per	cF7	.03	2	...	...	1/69	1	
20902	α Per	cF5	0	...	...	...	9/65-11/65	2	
31964	ε Aur	cF0p	0	1	...	...	9/69	1	
61421	α CMi	dF5	.16	1	...	...	2/66	1	
			.07	...	...	...	5/66	1	
			.06	...	...	...	1/69	1	
			0	...	...	...	9/69	1	
110379	γ Vir	dF0	.09	2	...	...	1/67	1	
159532	θ Sco	F0 I-II	0	...	...	...	5/66	1	
170153	χ Dra	F7 V	0 bl	...	...	...	/65- 5/66	2	
181869	α Sgr	F8	0	1	...	...	5/66	1	
194093	γ Cyg	cF8p Ib	0	...	...	...	11/65-10/70	2	
STAR TYPE: G									
3546	ε And	sgG3	0	2	1	...	9/69	1	
9270	η Psc	G5	.10 bl	...	1	90	12/68	1	
9826	υ And	dG0	0	1	...	...	10/70	1	
13611	ξ Cet	gG4	0	1	1	...	9/69	1	
20630	κ Cet	G5 V	.20	2	3	48	12/68-10/72	2	
21120	ο Tau	G8 III	.03	1	1	72	9/69	1	
26630	μ Per	G0 Ib	.09E, .05A	2	1	158	12/68	1	
28307	θ Tau	gG8	.2 bl	2	2	80	12/68	1	
29094	ι Per	cG2	.62? bl	3	0	...	1/69	1	brd He
31910	β Cam	G0 Ib	1.50	3	3	175	1/67-12/68	3	
34029	α Aur	gG5 III	.50	1	...	...	11/65	1	2
			.70	...	...	...	12/68	1	3
			.30	...	...	...	2/73	1	4
			.70 bl	...	...	...	4/75	2	
36076	β Lep	gG2	0	0	...	...	1/74	1	
41116	1 Gem	gG5	wk. em?	2	...	...	12/68	1	
47731	25 Gem	G5 Ib	.25	1	3	148	1/74	1	
48329	ε Gem	G8 Ib	.2E, .13A	3	4	154	10/65	1	P Cyg
			.15E, .10A	...	...	...	11/65	1	P Cyg
			0	...	...	...	1/67	1	
			.14	...	...	...	12/68	1	
			.07	...	...	...	1/69	1	
			.15	...	...	...	10/72	1	
			.15	...	...	...	2/73	1	
			.06	...	...	...	2/74	1	
54605	δ CMa	G3	wk. em?	2	...	...	1/67	1	
			0	...	...	...	10/72	1	
59693	U Mon	G2ev	0	2	...	...	12/68	1	5
			.05E	...	...	...	10/70	1	
			.15	...	...	...	1/74	1	
63700	ξ Pup	gG6	0	2	2	...	1/67	1	
67594	ζ Mon	G2 Ib	.38 bl	2	3	167	1/67	1	
			.16	1	...	...	1/69	1	
			0	...	...	...	10/72	1	
74395	31 Mon	G2 Ib	.06	2	2	149	1/67- 6/71	2	
74739	ι Cnc	G8 II	0	1	1	...	2/73	1	
84441	ε Leo	G0 II	.36	1	2	117	2/66	1	
			0	2	...	...	1/69	1	
			.27	1	...	...	10/70	1	
			.32	1	...	...	6/71	1	
			.33	1	...	...	1/74	1	
89485	γ² Leo	gG5	.13	2	1	72	4/75	1	
98430	δ Crt	G8 III-IV	0	1	2	...	1/67	1	poor
109379	β Crv	G4	.04?	2	1	89	5/68- 1/69	2	
113226	ε Vir	G6	0	1	1	84	5/66- 2/73	3	
114710	β Com	G0 V	0?	...	...	51	5/66	1	
115659	γ Hya	G8 III	0	1	1	...	2/73	1	
121370	η Boo	G0 IV	0	...	0	...	5/65	1	
123139	θ Cen	gG9 III-IV	0	...	1	...	5/66	1	
131156br	ξ Boo	G8 V	0	1	5	46	5/66	1	
			.20?	1	...	...	6/71	1	
			.26	1	...	...	4/75	1	
133208	β Boo	G8 III	.05	2	2	...	7/70- 2/73	2	
135722	δ Boo	G8 III+	0	1	1	73	5/72	1	
148387	η Dra	G8 III	0	...	1	65	/65	1	
148856	β Her	G8 III	0	...	1	89	5/66	1	
150680	ζ Her	G0 IV	0	...	0	...	5/66	1	
150997	η Her	sgG5	bl-prob no	1	1	...	5/75	1	
159181	β Dra	G2 II	1.00	2	3	186	8/65- 4/75	6	
161797	μ Her	dG5 IV	.04E	2	0	...	7/68	1	
			.03	1	...	...	10/70	1	
			0	1	...	...	5/72	1	6
173764	β Sct	G7	.80	...	2	154	5/66	1	7
			.36	2	...	...	7/68	1	
			.30	1	...	...	7/70	1	
			.40	1	...	...	5/72	1	
185758	α Sge	G0 II	0	...	2	113	5/66	1	
187929	η Aql	G0 V	.07E	1	...	...	6/71	1	8
			0	1	...	...	5/72	1	9
			.15	...	...	...	4/75	1	10
188119	ε Dra	G8 III	0	1	1	80	7/70	1	
188512	β Aql	G8 IV	.05	2	1	...	7/68	1	
202109	ζ Cyg	G8 II	0	...	1	77	5/66	1	
204867	β Aqr	G0 Ib	0	0	2	169	9/65	1	
206859	9 Peg	G5 Ib	.05	2	2	148	10/70	1	
209750	α Aqr	G2 Ib	.15	...	2	182	9/65	1	
			.06	...	...	...	5/66	1	
			0	...	...	...	7/66	1	
			.22	...	...	...	12/68	1	
			.3 bl	2	...	...	10/72	1	
216131	μ Peg	G8 III	0	...	1	79	11/66	1	
222107	And	G8 III-IV	.90	...	5	80	8/65	1	11
			.35	...	...	...	7/68	1	
			.58	...	...	...	9/69	1	
224014	ρ Cas	G0 V	0	...	...	...	11/66	1	
STAR TYPE: K									
28	33 Psc	sgK0	0	3	...	...	12/68	1	12
			.05	2	...	...	10/70	1	
1522	ι Cet	K0	.18	2	2	103	1/69	1	
3627	δ And	gK3	.05	2	2	88	9/69	1	
3712	α Cas	K0 II-III	0	2	2	...	11/65-11/72	7	13
4128	β Cet	gK0	.35	2	2	80	11/65-11/72	5	
4502	ζ And	K0	.76	1	5	...	9/69	1	
4656	δ Psc	gK5	.14E	2	4	...	9/69	1	
6805	η Cet	K3 III	0	1	1	77	9/69	1	
8512	θ Cet	sgK0	.05E, .08A	2	1	...	1/69- 7/70	2	
9927	51 And	K3 III	0	3	2	85	9/69	1	
12533	γ¹ And	K3 III	0	2	3	108	11/65- 1/67	3	
12929	α Ari	K2 III	0	1	2	72	10/65- 9/69	2	
17361	39 Ari	gK1	.08E	2	2	...	9/69	1	
			0	...	...	...	10/70	1	
17506	η Per	K3 Ib	.3E? .3A	...	4	164	9/65	1	
			.05	3	...	...	12/68	1	
			0	3	...	...	10/70	1	
22049	ε Eri	K2 V	.30	...	4	42	1/65	1	
			.30	...	...	...	11/65	1	
			0	3?	...	...	1/67	1	
			.10	...	...	...	9/69	1	
			0	1	...	...	10/70	1	
			.20	1	...	...	1/74	1	

Table 1 (cont.)

HD No.	Name	Spectral Type	He	CN	K		Date	No. of Plates	Notes
					Int	Width			
23249	δ Eri	K0 IV	bl	2	1	50	1/69	1	
25604	37 Tau	gK0	.15	1	1	...	1/74	1	
26965	ο² Eri	K0	.15	1	2	47	12/68	1	
			0	1	...	...	10/70	1	
27371	γ Tau	K0 III	.10	2	1	88	9/69	1	
27697	δ Tau	K0 III	.22	1	1	83	12/68	1	
28305	ε Tau	K0 III	.22	...	1	82	11/65	1	
29139	α Tau	K5 III	0	1	3	86	8/65-1/69	5	
31398	ι Aur	K3 II	.05E,.11A	...	3	113	10/65	1	
			0	2	...	...	1/69	1	
			.1E	2	2	116	9/69	1	
			.1	2	...	...	10/70	1	
			0	2	...	...	10/72	1	
			poss em	2	...	...	2/73	1	
			0	2	...	...	2/74	1	
31767	π⁶ Ori	K2 II	bl	1?	2	113	2/74	1	
32068	ζ Aur	K5 II	.12	...	2	116	10/65	1	
			bl	3	...	...	1/67	1	
32887	ε Lep	gK5	.06	1	4	...	1/69	1	
33856	ξ Ori	gK3	.15 bl	2	1	...	2/74	1	
39400	56 Ori	K2 II	.15	3	3	112	2/74	1	
40035	δ Aur	K0	bl	2	1	76	1/67	1	
			0	2	...	...	9/69	1	
43232	γ Mon	gK2	.05	...	3	...	1/69	1	
50077	ο¹ CMa	K3 Iab	.30	...	3	173	11/65	1	14
			0	3	...	...	1/67- 2/73	2	
			.02	3	...	...	1/69	1	
62044	σ Gem	K1 p	1.0	...	5	108	11/65	1	15
			.87	2	...	...	12/68	1	
			1.6	2	...	...	2/74	1	
62509	β Gem	K0 III	.14	...	1	74	11/65	1	
			.06	2	...	...	12/68	1	
			0	2	...	...	1/75	1	16
69267	β Cnc	K4 III	0	...	3	82	1/67	1	
74442	δ Cnc	K0	0	...	2	...	1/67	1	
80493	α Lyn	K5	?	2	3	93	10/72	1	poor
81797	α Hyd	K3 III	0	...	3	100	2/66	1	
89484	γ¹ Leo	K0 IIIp	0	...	2	83	2/66	1	
			.05	2	...	...	12/68	1	
94264	46 LMi	K0 III	0	1	2	69	1/67	1	
			.07	1	...	...	6/71	1	
95272	α Crt	K0 III	0	2	1	80	1/67- 6/71	2	
95689	α UMa	K0 III	0	...	1	88	5/66	1	
98430	δ Crt	K0 III	0	1	2	...	5/66-1/67	2	
105707	ε Crv	gK3 III	.12E	2	3	...	1/69	1	
			.05E	2	...	...	2/74	1	
			.10E	2	...	...	4/75	1	
124294	κ Vir	gK2 III	0	...	3	...	2/73	1	
124897	α Boo	K2 IIIp	0	1	3	80	8/65- 5/72	3	
127665	ρ Boo	K3 III	0	...	2	92	5/66	1	
129989	ε Boo	K0 II-III	0	1	1	98	7/68- 7/70	2	
			.20	1	...	...	6/71	1	
131873	β UMi	gK4	0	1	3	89	9/65- 7/70	3	
131977	...	K5	.12 bl	...	5	44	5/66	1	
			bl	1	...	...	6/71	1	17
137759	ι Dra	K2 III	.05	...	2	75	5/68	1	
140573	α Ser	K2 III	0	1	2	76	6/71	1	
142257	...	K4 III	0	2	...	...	5/68	1	poor
148856	β Her	K0	.02	...	1	89	5/66	1	
			0	1	...	...	7/70	1	
149661	12 Oph	K0	.20	1	...	...	4/75	1	18
153210	κ Oph	K2 III	.07E	1	1	82	6/71	1	
156283	π Her	K3 II	0	...	3	101	5/66	1	
157999	σ Oph	K3 II	.15E,.25A	2	3	...	2/73	1	P Cyg
161096	β Oph	K2 II	.2E,.2A	...	1	74	5/66	1	
163770	θ Her	K1 III	.2E,.27A	...	3	121	5/66	1	
			.27E,.07A	3	...	...	5/68	1	
			.05A	...	...	...	9/69	1	
			.22A	3	...	...	10/70	1	
			.27E	3	...	...	6/71	1	
			.1E	3	...	...	5/72	1	19
			.16E,.2A	2	...	...	2/73	1	
			.2E,.1A	3	...	...	4/75	1	
164058	γ Dra	K5 III	0	...	3	101	8/65	1	(Prob.
			.05	...	...	...	9/65	1	all 0)
			.10E	...	...	...	5/66	1	
			<.05	...	...	...	7/66	1	
			0	2	...	...	7/68	1	
165341	70 Oph A	K0 V	.26	...	3	48	8/65	1	
			.15	...	...	...	9/65	1	
			.26	...	...	...	5/66	1	
			.15	1	...	...	5/72	1	
168723	η Ser	K0 III-IV	0	1	1	...	/65-5/66	3	
171443	α Sct	K3 III	.15	...	3	84	9/69	1	
173819	R Sct	K0	.09E	2	...	...	5/68	1	20
			0 bl	2	...	...	6/71	1	
180809	θ Lyr	K0 II	.10	1	2	119	7/68	1	narrow
183912	β Cyg	gK Ip	.08	1	...	...	9/69	1	narrow
186791	γ Aql	K2	.1E	2	3	115	7/68	1	
			.07	2	...	...	7/70	1	PY em
			.04	2	...	...	1/69	1	
			.05	2	...	...	10/70	1	
			.10E	2	...	...	4/75	1	21
197989	ε Cyg	K0 III	0	0	2	75	5/66	1	
200905	ξ Cyg	K5 Ib	.5?	...	4	...	9/65	1	
			.47?	...	...	...	11/65	1	22
			.15E?	2	...	...	7/68	1	
			0	2	...	...	10/70	1	
201091	61 Cyg A	K5 V	.2A?	...	5	41	11/65	1	
			.1A	1	5	37	7/68	1	
			.23	1	...	...	6/71	1	
			.05	1	...	...	10/70	1	
206778	ε Peg	K2 Ib	.35	...	4	158	10/65	1	
			.1E	2	...	...	9/69	1	
			poss E	...	...	...	7/70	1	
			.05E	2	...	...	10/70	1	
			0	2	...	...	10/72	1	
207089	12 Peg	K0 Iab	.24E,.08A	...	3	194	10/65	1	
			1.4E	2	...	...	7/68	1	
			.66E,.5A	2	...	...	9/69	1	23
			.47E	2	...	...	5/72	1	24
210745	ζ Cep	K1 Ib	0	3	3	168	8/65- 9/69	2	
212943	35 Peg	K0	bl	1	1	61	10/70	1	
216946	...	K5 Ib	.05E	2	5	169	10/70	1	
218356	56 Peg	cK0	1.1	2	4	116	9/69-10/72	2	
218594	i² Aqr	gK1	0	1	2	...	10/70	1	
222404	γ Cep	sgK1	0	1	1	65	1/67	1	
			.04	1	...	...	1/69	1	
STAR TYPE: M									
6860	β And	M0 III	0	1	4	98	8/65-11/66	4	
14386	ο Cet	M6e	bl	...	...	...	10/65-12/68	3	25
18884	α Cet	M2 III	0	1	5	106	9/65- 2/74	5	
20797	...	M0 II	0	...	5	141	11/69	1	
25025	γ Eri	M0 III	0	1	4	...	10/65	1	
36389	119 Tau	M2 Ib	0	...	3	169	10/65	1	
39801	α Ori	M0 Iab	.1	3	2	186	8/65- 2/73	2	narrow
40239	π Aur	M3 II	0	...	5	130	10/65	1	
...	WY Gem	M2 ep	bl	3	...	...	2/74	1	
44478	μ Gem	M3 III	bl	...	5	104	9/65	1	
44537	ψ¹ Aur	M0 Iab	0	2	3	183	1/69	1	
60414	...	M2 Iab	0	1	...	...	12/68	1	
84748	R Leo	M8e	0	1	...	...	1/69	1	
88230	...	M0	.2?	1	5	42	6/71	1	
95735	...	M2 V	0	...	5	27	2/74	1	
112300	δ Vir	M3 III	0	1	4	90	5/66- 5/72	4	
117287	R Hyd	gM6e	0	...	...	...	5/68	1	
			.23E	1	...	...	7/68	1	26
119228	63 UMa	M2 III	0	...	4	104	5/68	1	
146051	δ Oph	M0	0	...	4	92	5/66	1	
149349	...	M2	0	1	4	85	6/71	1	
148478	α Sco	M0 Ib	0	1	4	168	8/65- 4/75	4	
156014	α Her	M5 II	0	...	4	114	5/66	1	
183439	α Vul	M0 III	0	2	4	94	6/71	1	
206936	μ Cep	M2 Ia	0	...	0	...	11/65	1	
216386	λ Aqr	M2 III	0	...	4	96	5/66	1	
217906	β Peg	M0	0	...	4	109	8/65- 7/66	2	
222800	R Aqr	gM7e	.78E	2	...	...	9/69- 7/70	2	27

Table 1 (cont.)

HD No.	Name	Spectral Type	He	CN	K Int/Width	Date	No. of Plates	Notes
STAR TYPES: R, N, S, C								
1967	R And	S6e	.12E	2	... ...	12/68	1	28
31996	R Lep	N6e	bl	4	... ...	10/70	1	
32736	W Ori	N5	bl	4	... ...	1/69	1	
44984	BL Ori	Nb	0	4	... ...	12/68	1	
53791	R Gem	S3 ev	.12E	2	... ...	12/68	1	29
110914	Y CVn	N3	bl	...	... ...	5/75	1	
...	T Lyr	R6	bl	4	... ...	7/68	1	
187796	χ Cyg	gS7 ev	wk em?	2	... ...	12/68	1	
223075	TX Psc	Na/C6	bl	4	... ...	12/68	1	

NOTES:

1. A Line is seen at 10832, blended with H_2O; on the second plate, which is the best, the blend is far stronger than other H_2O lines normally as strong. (3 Cen A)
2. Double, narrow. (α Aur)
3. Double lines, broad. (α Aur)
4. Narrow > 10827. (α Aur)
5. Broad absorption at 10815 on plates for 12/68 and 2/74. (U Mon)
6. Plates O.K. but all effects small. (μ Her)
7. Change 1966-68 is real; 10830 was >10827 in 1966, weaker afterwards. (δ Sct).
8. Phase .38 (η Aql)
9. Phase .46. (η Aql)
10. Phase .11 (η Aql)
11. Line complex, appears to vary. (λ And)
12. Narrow, weak lines, unlike normal He line. (33 Psc)
13. 1/69 possible emission, but other plates show nothing definite. (α Cas)
14. No H_2O. Plate for 11/65 checked and really show .3A (o^1 CMa)
15. Binary 19d period. (σ Gem)
16. 36" camera plate by G. Munch. (β Gem)
17. Blended by RV. (β UMi)
18. Narrow (< 1A) line. (12 Oph)
19. Red shifted 2A. (θ Her)
20. Ti emission; 5/68 post max, 6/71 min. (R Sct)
21. He 1.5A wide, Pγ emission. (γ Aql)
22. Because all but the last plate are poor, earlier variations may not be real. (ζ Cyg)
23. Emission 3.5A red shifted absorption at 1A. (12 Peg)
24. Emission 2A red shifted, may have blue absorption. (12 Peg)
25. Spectrum is so complex that these values may be due to other lines, especially H_2O, but 10830 less than .20. (o Cet)
26. Pγ emission = 10830 emission; 5/68 on rise, 7/68 max. (R Hyd)
27. 9/69 max, 7/70 on rise; Pγ, Fe XIII 10747 and He I 11012 emission. (R Aqr)
28. Strong Pγ emission. (R And)
29. Strong Pγ emission. (R Gem)

of time show no change, a single value is given. The period of observation is in column 8; if the star varies each observation is listed separately. The typical error of measurement of an equivalent width is around 0.1 Å; <u>measurements of He equivalent width less than .1 Å are not certain</u>, but non-zero values were checked, and only accepted if both microdensitometer and visual evaluation showed a real absorption line to be present. Columns 6 and 7 give K line intensities and widths from Wilson and Bappu (1957) brought up to date with new observations kindly furnished by Dr. Wilson.

Unfortunately, many spectra do not permit a definite conclusion about the 10830 intensity; a question mark is added when there is some problem; bl means the H_2O 10832 line cannot be disentangled.

Table 1 shows the following new results:

(1) Out of 125 G and K stars, 52 show > 100 m Å He equivalent width, and 76 show > 0.

(2) 10830 emission is observed in the declining phase of the cepheid η Aql.

(3) Time variation is established in 20 stars of 40 for which several plates are available.

(4) Variable 10830 emission is observed in the RV Tauri stars U Monocerotis and R Scuti.

(5) 10830 emission, always accompanied by $P\gamma$ emission, is observed in several late red variables, viz.: R Hydrae, R Aquarii, R Andromedae and R Geminorum, and maybe χ Cygni; but no 10830 is found in

ordinary M stars.

(6) Variable 10830 absorption is found in the main sequence stars ε Eridani, 70 Ophiuchi br, 61 Cygni A and ε Bootis.

(7) The 10747 Fe XIII coronal line is observed in R Aquarii.

Vaughan and Zirin found that there was no strong relation between the He equivalent width and the K line intensities given by Wilson and Bappu (1957). Our present data (Fig. 1a) show a modest correlation; the stars of K intensity > 3 all show 10830, and those of small K intensity show little. Correlation of W_{10830} with K line widths (Fig. 1b) gives a weaker relation, and with CN intensity from Griffin and Redman (1960) in Figure 1c, none at all.

It is possible that the reason that the K line and 10830 intensities are not strongly correlated is that the K line intensities measure a <u>chromospheric</u> phenomenon, while 10830 reflects the coronal situation. On the sun, K line emission and 10830 absorption are well correlated; but the stars discussed here have a far higher level of activity. Since the K line emission tends to saturate, while 10830 does not, we may simply be up off the K line intensity scale or the K line is limited by self-absorption. But several stars have low K intensity on Wilson's scale and still show strong 10830. In those cases the corona must be decoupled from the chromosphere; back-conduction may be inhibited or the line formed in an entirely different way. For this reason, our understanding of of the outer atmospheres of these stars would be very greatly enhanced by X-ray or XUV data.

The present data confirm other conclusions reached by Vaughan and Zirin (1968). There is no 10830 in M stars, except for special objects like R Aquarii; close double stars like α Tri, α Aur, σ Gem show strong 10830; and there is little 10830 in F stars.

III. THEORETICAL REMARKS

The rationale for observing 10830 was that this line, lying 20 volts above the ground state, could not be excited in the atmosphere of a normal cool star, and therefore its presence could only be due to the existence of a hot chromosphere on the star However recent work (Zirin 1975) has confirmed earlier suggestions by Goldberg (1939) and by Hirayama (1971) that He is in fact excited by back-radiation from the corona. The hot part of the chromosphere of the sun is not extensive enough to produce observable 10830. If we assume that the same is true of stars, then we in fact are measuring the stellar <u>coronas</u> and not their chromospheres. This would explain the lack of agreement between the K line intensity, which refers to the chromosphere and the 10830 intensity in these stars.

The model of photoexcitation of He by coronal ultraviolet depends on the fact that cm wave radio observations of the sun give a brightness temperature too low to admit collisional excitation of helium, and the fact that He excitation is observed to be greatly weakened in coronal holes. We have no similar evidence in stars, and in fact the presence of 10830 emission in some stars is more easily explained by collisional excitation. Further, the presence of coronas in some of the low-gravity giant stars is as difficult to understand as the existence of hot chromospheres; they could only be contained by magnetic fields. Despite this the solar analogy is worth retaining, as the structure of the K and Hα lines is not dissimilar to the sun.

The corona of the sun appears to arise from the deposition of wave energy of undetermined form at a point in the atmosphere where the density is about $N \sim 10^9$ atoms/cm^3. Why it occurs here is unknown; possibly it occurs because the mean free path exceeds the scale height and energy can no longer flow upward in an organized way. From this deposition and temperature peak, energy flows downward and upward by conduction; upward there are no sinks (emissivity is very low) and the energy is carried out into a stellar wind. Downward, the higher density chromospheric region forms an important sink. The temperature at the input, or peak temperature height, rises until the heat conducted away, proportional to $T^{5/2} \frac{dT}{dr}$, is sufficient (along with the stellar wind) to balance the energy input. On the sun, this occurs with $T \sim 10^6$ deg, $N \sim 10^9$.

The fact that the corona is greatly weakened when the magnetic fields are open implies that the "normal" solar corona with base density $\sim 10^9$ only occurs when the magnetic fields contain it; otherwise the solar wind rapidly carries away the deposited energy. Any reasonable conduction model for the underlying transition zone shows it too thin to produce the observed He. An artificial model which has enough hot material to produce the observed He contradicts the XUV and radio observations. What happens in a star where 10830 has equivalent width not 10 m A as in the sun, but 1000 m A? We have carried out numerical integration of the ionization of helium in stars of different atmospheric scale heights. In every case the He 10830 absorption is directly proportional to the XUV flux from the stellar corona. In supergiants there is a thick overlying He II layer; although most of the radiation is absorbed in the He II continuum, it is converted to λ304, which ionizes He I very nicely upon re-radiation. So a star with $W_{10830} \cong 1000$, such as λ And or β Dra must have an XUV flux beyond 504 A at least 100 times that from the sun. This flux comes from a great range of coronal lines between 170 and 350 A (mostly 170 - 220 A) which, since they cover a great range of ionization, are in sum temperature independent. Since these are mostly Fe lines, the XUV flux is $F_{XUV} = N_e N_{Fe} \cong N_o^2 H$ where H is the coronal scale height. (A star poor in Fe would therefore show no He!) This would imply that for a fixed coronal base height, the XUV flux is proportional to the scale height. However, if the point of energy deposition is fixed by mfp = H as mentioned above, then, since $N \sim \frac{1}{H}$, F_{XUV} might even go as 1/H. Thus the strength of the 10830 line is not necessarily related to scale height, which is in agreement with Figures 1b and 1c.

If the photoexcitation model is correct, an XUV flux below 228 Å is to be expected in the ratio of the star's 10830 equivalent width and apparent diameter to the same quantities in the sun. Of course in some cases the 10830 may be due to a hot chromosphere, and no XUV would be expected. Any star with measured XUV flux would have to show the corresponding 10830, or more, as the photoexcitation invariably results if the flux is present.

There are a number of stars (such as ε Eri, 61 Cyg) with strong 10830 and scale height similar to the sun. In this case, if the increase was uniform over the star, we would have $N_o^2 \propto W_{10830}$. This would result from a great increase in coronal heating, requiring a higher gradient of temperature and thus lowering the level at which coronal temperatures exist and producing a non-supersonic "stellar breeze" instead of wind. The star might simply have more plages; but the fraction of the star covered by plage would have to equal the 10830 central depth which often is over 30%. In solar plages the Ca II K3 reversal is quite weak; although a few stars in the Wilson-Bappu catalog show K line structure suggesting they are covered by plages - most of the stars have deep, broad reversal, suggesting a general intensification over the whole star, but nothing like a standard plage.

It is possible to push the solar analogy too far in demanding photoionization of He. Since we don't really understand chromospheres, we have no reason except the solar analogy to doubt the possible existence of large, dense chromospheres in which 10830 is thermally excited. We can judge the extent of such a chromosphere from the calculations of Milkey et al. (1973) who produce the solar λ584 line with a layer at 25000° 300 km thick and $N_e \sim 1.5 \times 10^{10}$, or $N_eH \sim 4.5 \times 10^{17}$. Since $N(2^3S)/N_e$ peaks around 25000° in a collisional model, the great 10830 absorption lines of 1Å or more equivalent width would require N_eH of 1.35×10^{19} at 25000°. This is possible within the frame of our present knowledge.

Line widths are not useful clues, since our spectroscopic resolution of 0.5Å is too small to resolve the thermal width for narrow lines, while the fact that most of the 10830 absorption observed is an angstrom or more wide must be explained by mass motion anyway (the widths observed correspond to temperatures far too high for 10830).

The case of the 10830 emission line is more difficult still. In order for the line to appear in emission the source function must exceed the value of the Planck function of the stellar surface at that wavelength, which may occur if collisional excitation is comparable to radiative excitation. Using the Born approximation the collisional excitation rate $2^3S \rightarrow 2^3P$ at 10000° is $\langle v\sigma \rangle \sim 1.5 \times 10^{-6}$. Thus at $N_e \sim 10^{13}$ the direct excitation rate equals the spontaneous emission rate ($\sim 10^7$). As long as 10830 is optically deep, emission will occur if the kinetic temperature exceeds the surface temperature. However, the optical depth of such a region ($N_eH > 10^{20}$) makes it optically deep to coronal XUV and the He is not photoexcited by coronal XUV. A thick hot layer of this sort requires a sizeable non-thermal energy input and must incidentally be too hot to show hydrogen emission, for we find that the Pγ line is not in emission in the G and K stars showing 10830, but is in emission in the S stars with He emission. This means the atmospheric situation is considerably different in these types, but detailed models are needed for further progress. It is possible we are seeing a shock wave, or some other phenomenon that produces high temperature low in the atmosphere or a high density in a hotter region. The fact that we often observe the emission with a P Cygni-type blue absorption edge, suggests a deep hot chromosphere with lower density absorbing gas moving outward. It is also possible that we are seeing a high density "solar breeze" which slowly evaporates from the surface. It is doubtful that there is a classical shell, since the emission lines are all broad, and none of the stars with 10830 emission show shell effects in the other lines. In any case the XUV emission in these stars must be very strong, because the emissivity of the thick shell would be sizeable.

IV. STATISTICS

TABLE 2

Frequency of λ10830 and Variations

	No	Yes
10830?...........	47 stars	78 stars (22 with some emission)
10830 >.1A?......	73 stars	52 stars
Variable?........	8 stars (10830) 11 stars (no 10830)	21 stars (2 or more plates obtained)
Variables: No. of observations with 10830......	27 plates	97 plates

In Table 2 we summarize the results of Table 1. Many of the stars observed show changes, and the extent of these may be judged from Table 1. Of the 40 G and K stars for which more than one plate is available, 21, or half, show changes; of the 19 with no change, 11 had no He and 8 had constant (even intense) He lines. This statistic is fraught with observational problems, particularly if the quality of the spectra differs, it is easy to have spurious change. On the other hand, for this reason we tended to ignore changes in measured 10830 intensity if the line had the same visual appearance on the various plates. Despite these problems, the variation is sure in at least half the 21 cases. A certain fraction of the stars with no 10830 absorption were seen by chance at their minima and thus missed. We find that 27 out of 124 observations of variable 10830 show zero intensity. If we correct this to leave out stars with intense 10830 observed many times, we find that about 1/4 of random observations of 10830 variables, and thus 1/8 of all observations correspond to 10830 variables accidentally observed at zero intensity. Of all G and K stars observed, 47 out of 125 show no He; 15 of these might thus be considered as accidentally observed at zero intensity. This leads to the conclusion that 93 of the 125, or 74% of the G and K stars observed have detectable 10830; 62% actually observed and 12% probably caught at zero intensity. Admittedly, our sample of G and K stars is weighted toward giants and stars with known K emission; nonetheless, considering our detectability threshold of about two or three times the solar value, we conclude that 80% of the G and K stars have coronas with emission measure two or three times the sun; even if we limit the statistic to $W_{10830} > .1\mathring{A}$, an easily detected value, we get more than 50% of the stars examined showing a level of activity at least twice the sun. Further, Figure 1b and 1c show there is no connection between absolute luminosity and K intensity, so a similar relation would apply for dwarfs, too. Even for K intensities of 1 or 2, at least 1/3 have $W_{10830} > .1\mathring{A}$ (uncorrected for variables at zero).

V. VARIABILITY

The statistics above indicate that half the stars observed have variable 10830. Even if we admit that the quality of the plates makes some of this doubtful, there is no question that at least 1/4 vary. The nature of 10830 production by coronal XUV makes this quite reasonable; a stellar corona must be due to magnetic activity, and we see on the sun how variable this is. We therefore have an opportunity to examine the general magnetic variability of G and K stars; to see if it is periodic or irregular, and if there is a period, to relate it to size or whatever. Despite the fact that some of our stars have been observed for 10 years, there is no clear-cut activity period for any of these stars. The only possibility is θ Herculis, which shows 3 peaks of emission, separated by five years; we must wait till 1980 to find if this is regular; others have shown a single "cycle" but the generally irregular variation means these may just be pulses of activity. It does appear that the variation is more rapid in main sequence stars.

Despite this lack of regularity, we should view these results in the light of what happens on the sun. There the 11-year period is well-established; and 10830 varies with it. However, the amplitude of the solar 10830 variation is less than the sunspot number; although not measured quantitatively so far (at this point we have better data on integrated 10830 from θ Her than from the sun) examination of plages indicates that it should vary like the 2800 MHz flux. I plotted the Ottawa 2800 MHz flux values for the sun for the dates on which θ Her was observed, and found that such a random selection of 8 values over 9 years clearly showed the rise and fall of the solar cycle (but remember we have no such solar 10830 data). The implication is that if the stellar 10830 was anything like the solar, we should have seen a solar-type cycle. But the stellar variability, when observed, appears to be much greater in amplitude, shorter in period and less regular than the solar. It may be that the intense 10830 lines found in the variables, particularly those in emission, are due to erratic, star-wide outbreaks of activity. An absorption line with central depth of 30% can only be produced by a phenomenon covering at least 30% of the star. We conclude that there are star-wide variations whose relation to the solar sunspot cycle is unclear.

VI. PARTICULAR STARS

A number of interesting special cases have been found, and are described individually below:

(a) η Aquilae. He emission has not previously been observed in cepheid variables. Our three plates show contradictory results (Fig. 2). By accident, two plates were obtained a year apart at almost the same phase. The plate at .38 shows no emission on the trace, but possibly a narrow absorption. The second plate (actually obtained a year earlier) at phase .41, shows a well-defined emission line. The third, at phase 0.69, shows a definite 10830 absorption line and a probably spurious emission at 10831 due to scattering of the He comparison (no He comparison was used on the earlier plates). There are no other obvious changes in the spectrum. Further observations are planned.

(b) R Aquarii. This remarkable star, described in detail by Merrill (1935) has been found by Gregory and Seaquist (1974) to be a radio source. On our two plates, Figure 3, (taken at max and on rise) it shows strong He 10830 and Pγ emission, about equal in strength. The lines are broad and strong on the plate at maximum. Our most interesting result is the observation of the Fe XIII 10747 coronal line in emission on two plates. The

The second Fe XIII line, at 10798, is possibly in emission. Better observations would give the ratio of these lines, which are density sensitive. In addition, we find the redmost emission identified in this program, a line at 11012 Å. This line can be identified either with He I $5^1P - 3^1S$ 11013 or [La II] $b^1D - a^3F$, a forbidden line at 11012 Å. Our wavelength scale is not accurate enough at this point to tell. One would expect the single He line to be fainter than 10830, particularly because electrons arriving in 5^1P will preferentially go to 1^1S and 2^1S. In pure recombination the ratio of 10830 to 11012 would be 300:1. The fact that the $6^3F - 3^3D$ He line at 10997 is not seen implies that recombination is not important for 11013 and only strong singlet resonance lines could produce the excitation. Further, G. Wallerstein (private comm.) reports no 6678 emission in plates taken in 1970-71. Unless there is an enormous flux in the He resonance lines, the line must be La II or something unknown. A check for the other La II line at 9903 Å and for other He lines will be made in the future. The 10830 emission line is 3 Å wide and blue-shifted by about 15 km/sec; the line is broad and complex. Pγ by contrast, is a more normal, peaked emission line.

(c) R Scuti. Besides a strong He 10830 emission line on one plate, R Scuti shows a series of emission lines of Ti I, particularly multiplet 31. The emission lines do not appear on the plate (TPb 10526) which shows He emission, but it is inferior in the region (around 10700 Å) of the Ti lines.

(d) U Monocerotis. The Ti I line at 10726 appears in emission on one plate. Varying 10830 emission and absorption are seen on the other plates.

(d) α Aurigae. Capella shows a strong 10830 line, which varies from time to time as shown by Figure 4. It was found by Catura and Acton (1975) to have X-ray emission, and a calculation (Zirin, 1975) of the coronal soft X-ray emission to be expected if the 10830 is excited by a corona comes out a factor 10 below the observed flux. Since later rocket flights showed no X-ray flux, the matter is in question. But the fact that O VI was observed (Dupree et al., 1975) shows that a corona is definitely present.

(f) θ Herculis. We have followed this remarkable star closely for 9 years. It showed peaked emission in 1966, 1971, and 1975, but only weak absorption in between. The star must now be followed till 1980. Figure 5 shows the variation of the 10830 profile over the years. There is no other variation in the spectrum. The CN bands are strong.

VII. CONCLUSIONS

We have found that a large fraction of G and K stars show chromospheric or coronal activity that considerably exceeds that of the sun. Further, this activity is variable with time in half the stars showing such activity, or at least one fourth of the stars. This activity is essentially limited to G and K stars, with very little in F or M stars (except for close binaries in the former and emission variables in the latter). It is possible to make models for the observed He emission or absorption. In the case of absorption the equivalent width is proportional to the energy deposited in the corona, no matter what the scale height. In the case of emission a chromosphere of density 10^{11}, T = 20,000° is required, which necessitates a much greater input of energy to balance the strong emission.

There is no clear way in which absolute magnitude or atmospheric scale height influences the He equivalent width.

No regularities were found in the spectrum variation so far.

The most interesting observations are the observation of Fe XIII in R Aquarii and of 10830 emission in η Aquilae.

I wish to thank Frances Tang and Betsy Eldridge for work on the microdensitometer and G. Munch for the use of his image tube. This work was supported by NASA under NGR 05-002-034 and NSF under Ga. 24015.

REFERENCES

Catura, R.C., Acton, L.W., and Johnson, H.M. 1975, Ap.J. (Letters) 196, L47.

Dupree, A.K. 1974, Bull. A.A.S. 6, 427.

Goldberg, L. 1939, Ap.J., 89, 673.

Gregory, P.C. and Seaquist, E.R. 1974, Nature 247, 532.

Griffin, R.F. and Redman, R.O. 1960, MNRAS 120, 22.

Hirayama, T. 1971, Solar Phys., 17, 50.

Merrill, P.W., Ap.J. 81, 312.

Milkey, R.W., Heasley, H.N., and Beebe, H.A. 1973, Ap.J. 186, 1043.

Vaughan, A.H. and Zirin, H. 1968, Ap.J. 152, 123.

Wilson, O.C. and Bappu, M.K.V. 1957, Ap.J. 125, 661.

Zirin, H. 1971, Phil. Trans. Roy. Soc. Lond. A. 270, 183.

Zirin, H. 1975, Ap.J. (Letters), 199, L63.

FIGURE CAPTIONS

FIG. 1 (a) - Correlation of λ10830 equivalent width with K intensity. For variables, we always use the highest values. Each letter indicates one star of the spectral class of the letter; circled symbols are in emission; a number preceding the symbols means that many stars are represented. There is a weak correlation.

(b) - Correlation of He equivalent width with K line width from Wilson and Bappu (1957) and Wilson (1975). This is essentially a correlation with absolute magnitude and/or K line self-absorptions and displays a weak correlation.

(c) - Correlation of W_{10830} with CN intensity from Griffin and Redman (1960). No apparent relation.

FIG. 2 (a-b) - Two plates of R Aquarii showing He, H, and Fe XIII emission lines:

(a) Sept. 1968. Phase .01

(b) July 1970. Phase .79.

There are a number of other emission like features in the spectrum (e.g. 10864) but none are identified and they may just be peaks in the continuum.

FIG. 2 (c-d) - R Scuti, showing:

(c) Ti I emission lines at post maximum (June 197[illegible]),

(d) He em, no Ti I at minimum (9 May 1968).

FIG. 2 (e-g) - Three plates of η Aql at various phases:

(e) .38, no λ10830

(f) .41, weak emission

(g) .69, absorption and an emission at λ10831 which may be scattering from the comparison He and needs reconfirmation.

FIG. 2 (h-j) - α Aur, showing changes in λ10830 structure and intensity. The H_2O at λ10800 is weak on all these, so the H_2O line at λ10832 can also be assumed to be unimportant.

(h) 8 November 1965

(i) 5 December 1968

(j) 28 February 1973

FIG. 3 - Microdensitometer tracings of spectra of θ Her over 10 years. The peaks of emission occur in 1966, 1971, and 1975. A five-year period is plausible. There is weaker emission in 1968 and 1972, following the maxima, and absorption in 1970.

TABLE 1 - Summary of λ10830 data for all observations (including Vaughan and Zirin, 1968).

TABLE 2 - Frequency of λ10830 and variations.

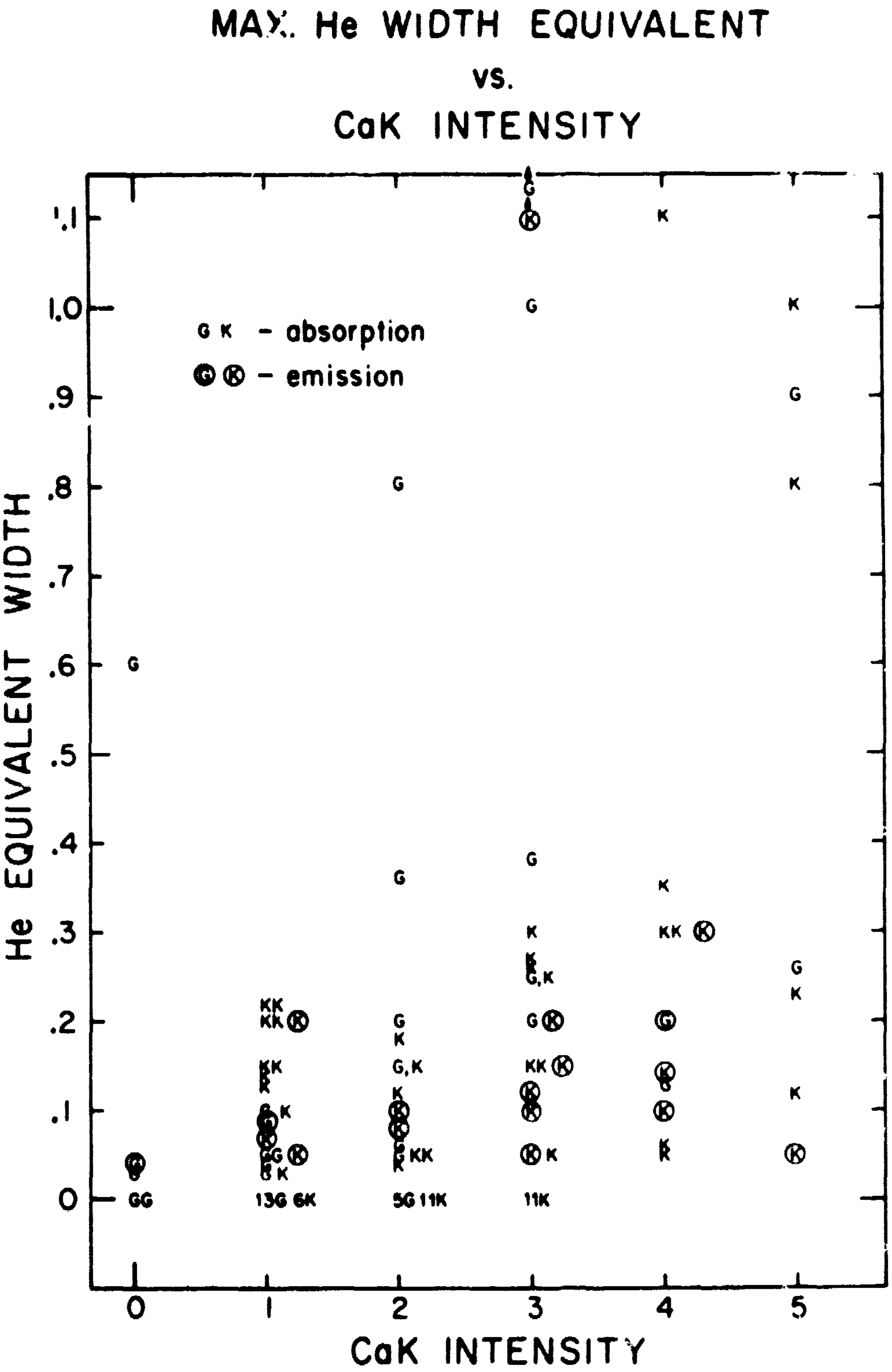

MAX. He WIDTH EQUIVALENT
vs.
CaK INTENSITY
He EQUIVALENT WIDTH
CaK INTENSITY
G K - absorption
Ⓖ Ⓚ - emission
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
0
1
2
3
4
5
GG
13G 6K
5G 11K
11K

Figure 1(a)

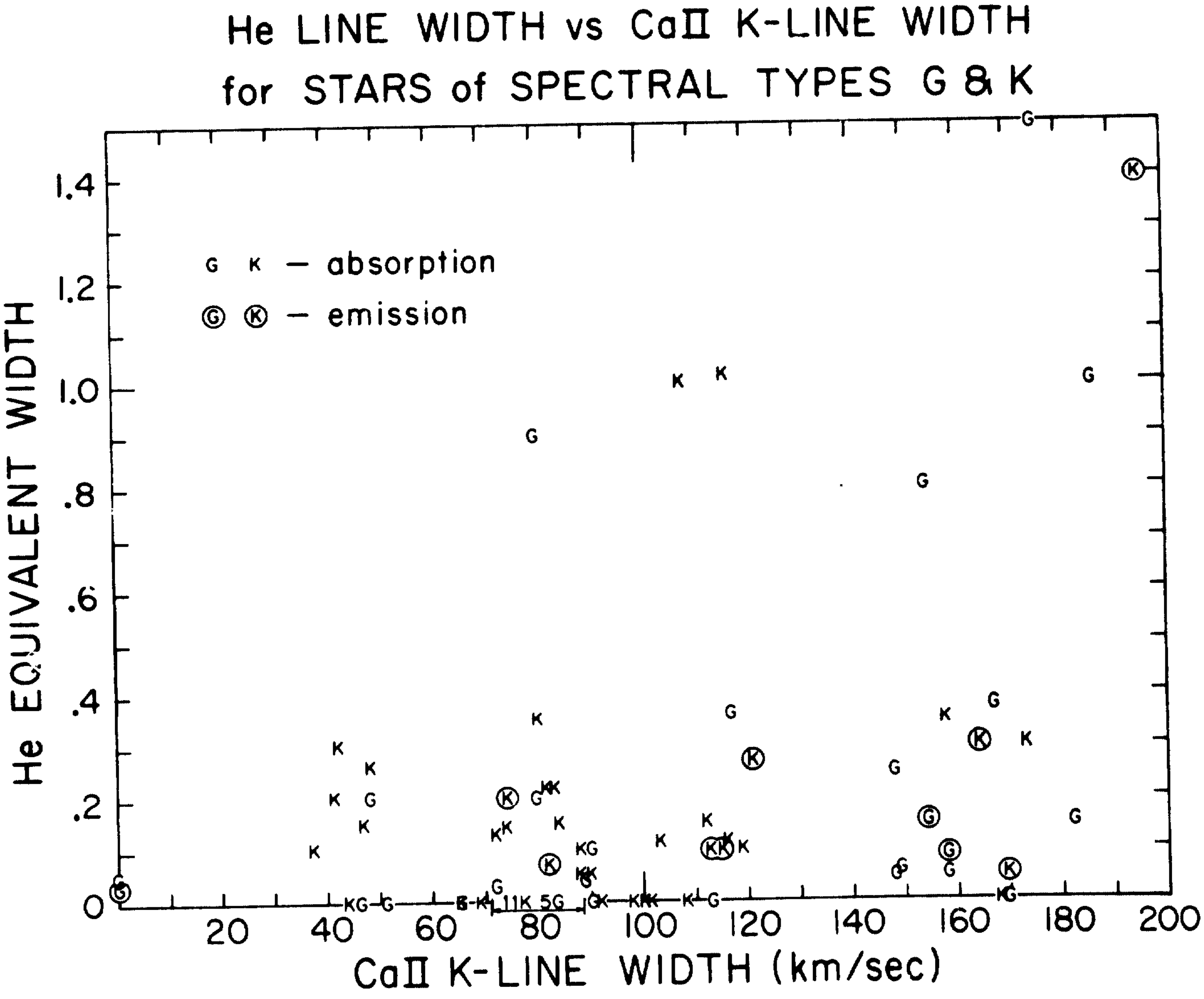

He LINE WIDTH vs CaII K-LINE WIDTH
for STARS of SPECTRAL TYPES G & K
He EQUIVALENT WIDTH
CaII K-LINE WIDTH (km/sec)
G K — absorption
Ⓖ Ⓚ — emission
0
.2
.4
.6
.8
1.0
1.2
1.4
20
40
60
80
100
120
140
160
180
200
11K 5G

Figure 1 (b)

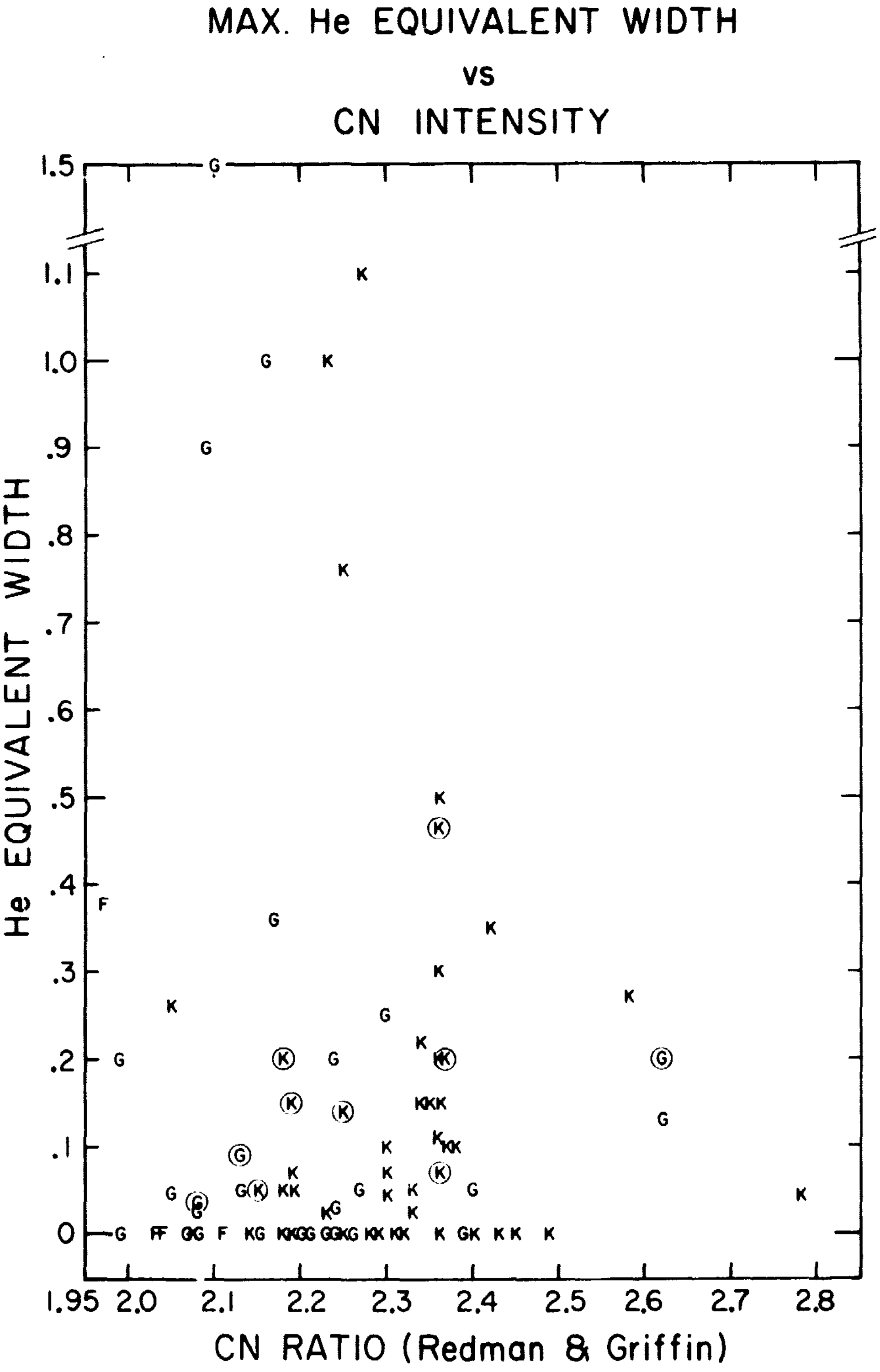

MAX. He EQUIVALENT WIDTH
vs
CN INTENSITY
He EQUIVALENT WIDTH
1.5
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1.95
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
CN RATIO (Redman & Griffin)

Figure 1(c)

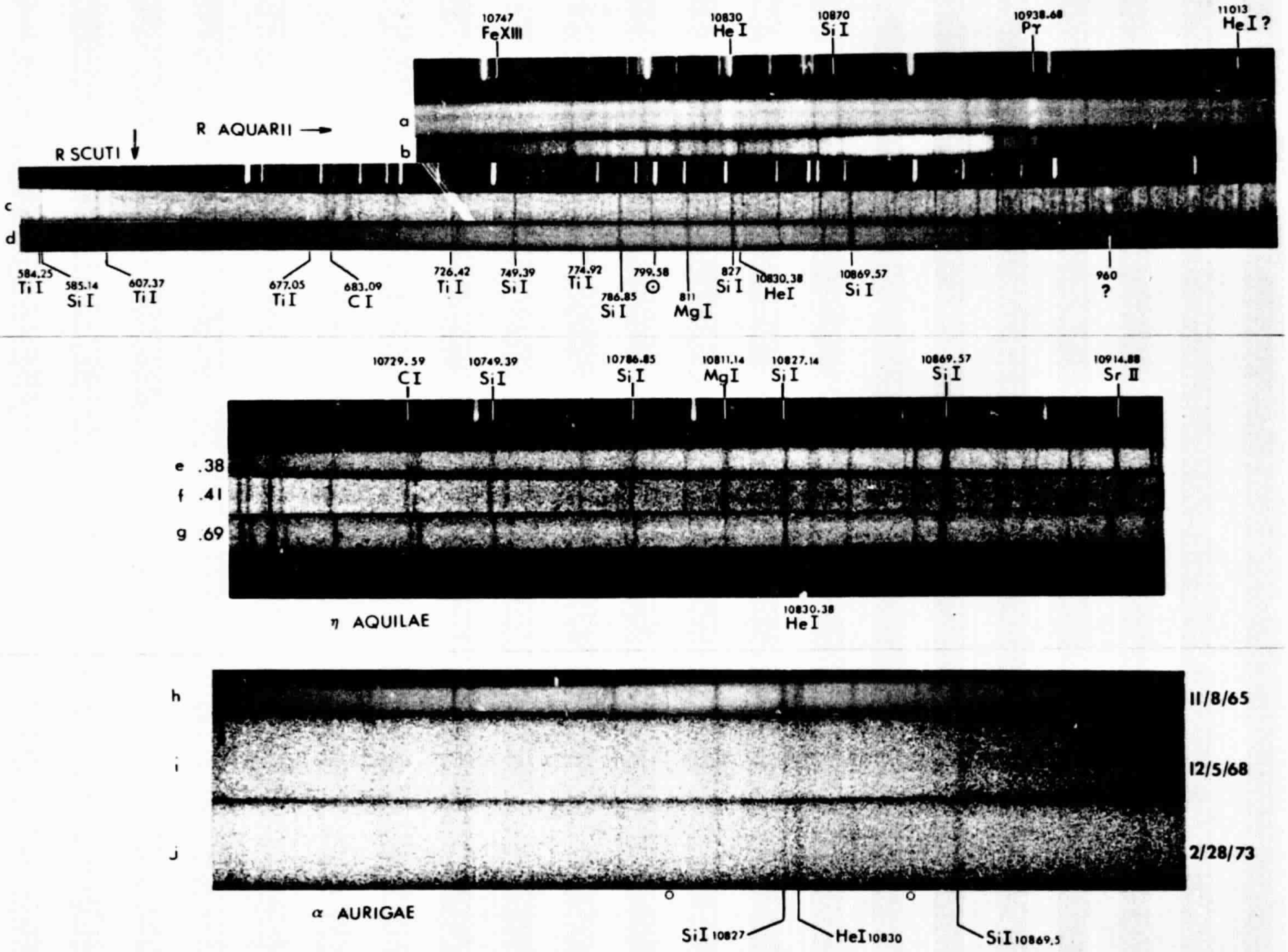

10747
FeXIII
10830
He I
10870
Si I
10938.68
Pγ
11013
He I ?
R AQUARII →
R SCUTI ↓
a
b
c
d
584.25
Ti I
585.14
Si I
607.37
Ti I
677.05
Ti I
683.09
C I
726.42
Ti I
749.39
Si I
774.92
Ti I
786.85
Si I
799.58
⊙
811
Mg I
827
Si I
10830.38
He I
10869.57
Si I
960
?
10729.59
C I
10749.39
Si I
10786.85
Si I
10811.14
Mg I
10827.14
Si I
10869.57
Si I
10914.88
Sr II
e .38
f .41
g .69
η AQUILAE
10830.38
He I
h
i
j
11/8/65
12/5/68
2/28/73
α AURIGAE
Si I 10827
He I 10830
Si I 10869.5

Figure 2

θ Her

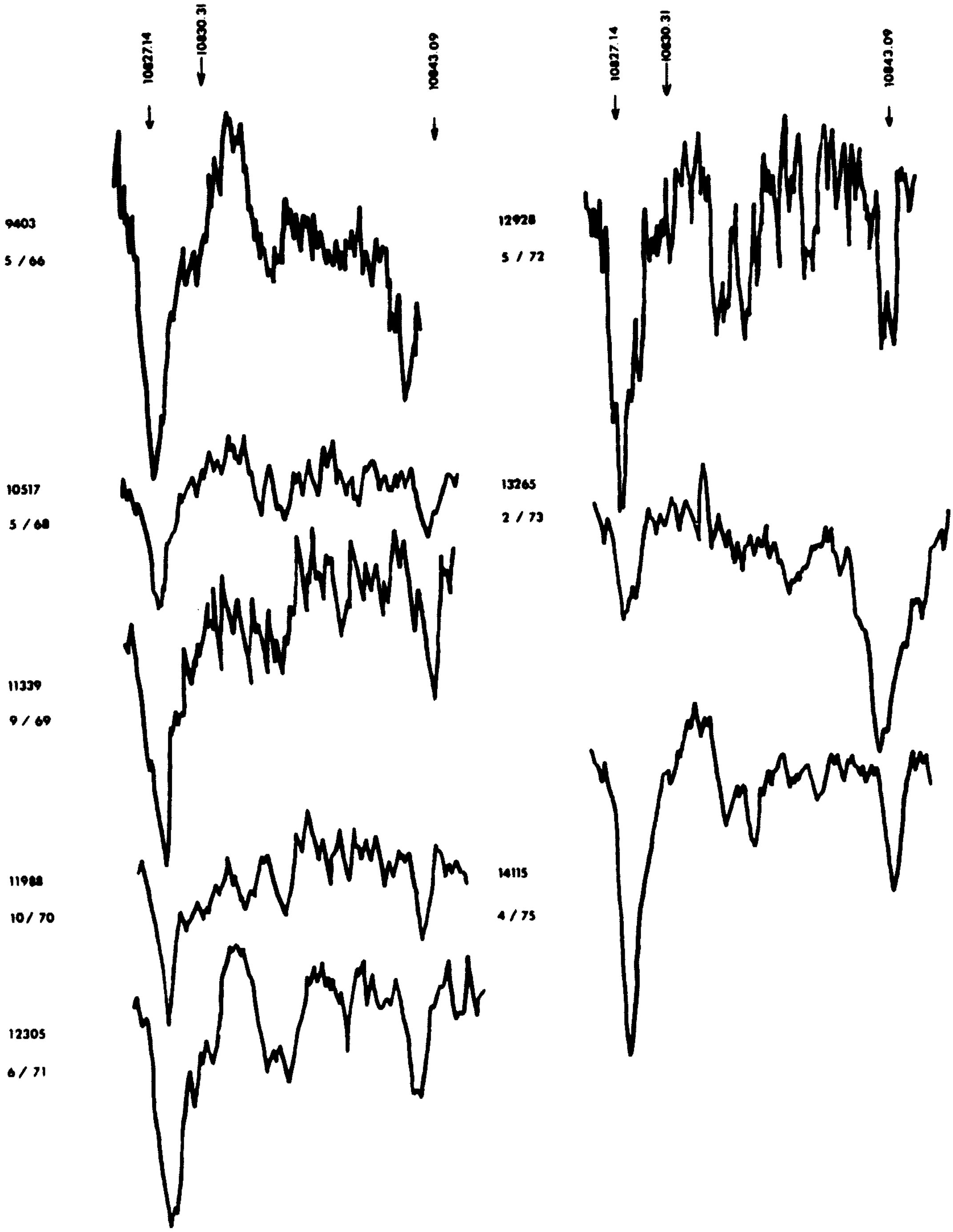


Figure 3