

HIGH RESOLUTION PROFILES OF CHROMOSPHERIC LINES IN M DWARF STARS

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ABSTRACT

We show 46 hydrogen and sodium line profiles for 17 selected dwarf M and dwarf M emission line stars. These profiles, derived from echelle spectrograms, typically have 0.25 Å spectral resolution. Most of the dMe stars show hydrogen emission lines with central reversals. Central emission features in the cores of the Na D lines are often observed, and the presence of these emission features is strongly correlated with hydrogen line emission.

Subject headings: line profiles — stars: chromospheres — stars: emission-line — stars: flare — stars: late-type

I. INTRODUCTION

M dwarf stars are an important class of objects for several reasons. From estimates of their space density (Luyten 1968), they comprise at least 50% of the stellar mass in the Galaxy (Coleman and Worden 1976). An interesting subset of the M dwarfs are the flare stars or UV Ceti stars. These stars show frequent flaring, principally in the Johnson *U* photometric band, of up to 6 mag. Most flare stars also show strong hydrogen Balmer, calcium H and K, helium, and sodium emission lines in their quiescent (nonflaring) spectra (the “dwarf M emission line” or dMe phenomenon). These lines are considerably enhanced during flares. For a review of flare star properties, see Linsky (1977). Although not conclusively studied, the dMe phenomenon and stellar flaring are almost certainly related. A few flare stars do not show emission lines (i.e., SZ UMa), while others seem to show variable emission lines (i.e., BY Dra, see Bopp 1974).

Many dMe stars show quasi-periodic photometric variations attributable to the rotation and evolution of solar-type spots and active regions on the stellar surface (Kron 1952; Chugainov 1966; Krzeminski 1969; Bopp and Evans 1973; Torres and Ferraz-Mello 1973). This is known as the BY Draconis syndrome.

Recently, sophisticated analysis schemes have been developed for probing stellar surface activity. Mullan (1976) has derived flare models which adequately match flare light curves. Linsky and his collaborators at JILA have developed methods to analyze Ca II H and K line spectra to provide models for lower chromospheric levels in all late-type stars (cf. Kelch, Linsky, and Worden 1979; Giampapa 1980). In addition, Fosbury (1974) has shown that the H α source function is collisionally controlled (and therefore a chromospheric diagnostic) in dMe stars. Furthermore, Cram and Mullan (1979) and Kelch *et al.* have shown that H α emission lines in dMe stars may be successfully modeled. An interesting aspect of this work is the result that Balmer line *absorption* in some M dwarfs is also evidence for nonradiative chromospheric heating.

This paper will provide an atlas of high resolution line profiles for dM and dMe stars. These data, predominately of Na D, H α , and some other Balmer lines, provide a source for chromospheric models. The data, covering 17 stars, were obtained with the Kitt Peak National Observatory 4 m echelle spectrograph (14 stars) and the Steward Observatory 2.3 m echelle spectrograph (6 stars). The spectral resolution for most of the data is ~ 0.25 Å, although there are some data with 0.1 Å resolution, and some lower quality data at 0.5 Å resolution.

II. DATA REDUCTION

Table 1 lists the log of observations, including exposure times, instrument, spectral region, and spectral widening. Table 2 lists observational data for the stars which we observed. The data were reduced in a method

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TABLE 1
LOG OF OBSERVATIONS

Object	Spectral Region	Instrument ^a	Plate Number	UT Data	UT Time	Exposure Time (min)	Spectral Resolution (Å)	Spectral Widening (mm)
SZ UMa	H α	KP	740	1975 Nov 19	12:21	50	0.24	0.3
SZ UMa	Na D	KP	740	1975 Nov 19	12:21	50	0.20	0.3
61 Cyg A	H α	KP	741	1975 Nov 20	01:16	2	0.24	0.6
61 Cyg A	Na D	KP	741	1975 Nov 20	01:16	2	0.20	0.6
EV Lac	H α	KP	743	1975 Nov 20	01:31	40	0.24	0.4
GT Peg	H α	KP	744	1975 Nov 20	02:19	100	0.24	0.15
Ross 614 A ^b	H α	KP	753	1975 Nov 20	10:11	60	0.24	0.15
DM+5°1668 ...	H α	KP	754	1975 Nov 20	11:10	35	0.60	0.15
DM+36°2147 ..	H α	KP	755	1975 Nov 20	12:04	7	0.24	0.15
DM+36°2147 ..	Na D	KP	755	1975 Nov 20	12:04	7	0.20	0.15
YY Gem	H α	KP	757	1975 Nov 20	12:34	12	0.60	0.15
YY Gem	H α	KP	758	1975 Nov 20	12:48	4	0.60	0.15
Ross 614 A ^b	H α	KP	795	1975 Nov 23	08:25	60	0.24	0.3
Ross 614 A ^b	Na D	KP	795	1975 Nov 23	08:25	60	0.20	0.3
EV Lac	H α	KP	790	1975 Nov 23	03:30	30	0.24	0.15
EV Lac	Na D	KP	790	1975 Nov 23	03:30	30	0.20	0.15
FF And	H α	KP	792	1975 Nov 23	05:26	10	0.24	0.15
FF And	Na D	KP	792	1975 Nov 23	05:26	10	0.20	0.15
YY Gem	H α	KP	796	1975 Nov 23	09:35	5	0.24	0.3
YY Gem	H α	KP	797	1975 Nov 23	09:44	7	0.24	0.15
YY Gem	H α	KP	798	1975 Nov 23	09:54	7	0.24	0.15
YY Gem	Na D	KP	798	1975 Nov 23	09:54	7	0.60	0.15
CN Leo ^c	H α	KP	799	1975 Nov 23	10:17	137	0.24	0.15
AU Mic	H α	KP	1345	1976 Sep 08	05:22	9	0.24	0.3
AU Mic	H β	KP	1344	1976 Sep 08	04:48	27	0.18	0.3
AU Mic	H γ	KP	1344	1976 Sep 08	04:48	27	0.16	0.3
AU Mic	H δ	KP	1344	1976 Sep 08	04:48	27	0.15	0.13
AU Mic	He, Ca II H	KP	1344	1976 Sep 08	04:48	27	0.14	0.3
EV Lac	H α	KP	737	1976 Nov 18	02:46	80	0.12	0.3
EV Lac	Na D	KP	737	1976 Nov 18	02:46	80	0.10	0.3
61 Cyg B	H α	KP	731	1976 Nov 18	01:44	1	0.12	0.3
61 Cyg B	Na D	KP	731	1976 Nov 18	01:44	1	0.10	0.3
EV Lac	Na D	SO	75	1976 Jul 09	09:51	82	0.20	0.3
EV Lac	H β	SO	75	1976 Jul 09	09:51	82	0.17	0.3
AU Mic	H α	SO	73	1976 Jul 09	08:41	50	0.23	0.6
AU Mic	Na D	SO	73	1976 Jul 09	08:41	50	0.60	0.6
DM+16°2708 ..	H α	SO	71	1976 Jul 09	04:31	54	0.23	0.3
DM+16°2708 ..	Na D	SO	71	1976 Jul 09	04:31	54	0.60	0.3
AD Leo	H α	SO	115	1978 Feb 17	09:15	30	0.23	0.6
AD Leo	Na D	SO	115	1978 Feb 17	09:15	30	0.20	0.6
DM-7°3646 ^d ..	H α	SO	118	1978 Feb 17	10:22	30	0.23	0.6
DM-7°3646 ^d ..	Na D	SO	118	1978 Feb 17	10:22	30	0.20	0.6
SZ UMa	H α	SO	117	1978 Feb 17	11:59	30	0.23	0.6
SZ UMa	Na D	SO	117	1978 Feb 17	11:59	30	0.20	0.6
Ross 248	H α	KP	791	1975 Nov 23	04:22	60	0.24	0.15
V1285 Aql	H α	KP	1545	1977 Mar 30	12:17	19	0.24	0.9

^aKP=Kitt Peak National Observatory 4 m echelle telescope; SO=Steward Observatory, University of Arizona 2.3 m echelle telescope.

^bV577 Mon.

^cWolf 359.

^dEQ Vir.

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TABLE 2
DATA FOR STARS OBSERVED

Star	Spectral Type	<i>V</i>	α 1950	δ 1950
FF And	dM0e	10.38	0 ^h 40 ^m 5 ^s	+3516.4
Ross 614 A (V577 Mon) ...	dM4.5e	11.07	6 26 51	-246.2
DM+5°1668 ^a	dM4	9.82	7 24 43	+522.7
YY Gem	dM1e	9.07	7 31 26	+3158.8
AD Leo	dM3.5e	9.43	10 16 54	+20 7.3
CN Leo (Wolf 359)	dM6.5e	13.53	10 54 6	+1619.2
DM+36°2147 ^a	dM2(e?)	7.50	11 00 37	+3618.3
SZ UMa.....	dM1.5(e?)	9.32	11 17 29	+66 7.0
DM-7°3646 (EQ Vir).....	dK5e	9.34	13 32 7	-8 5.1
DM+16°2708 (CE Boo) ...	dM2e	10.20	14 52 8	+1618.3
V1285 Aql	dM3e	10.07	18 53 3	+820.3
AU Mic.....	dM2.5e	8.61	20 42 4	-3131.1
61 Cyg A ^b	dK5	5.22	21 04 40	+3830.2
61 Cyg B ^b	dK7	6.03	21 04 40	+3830.0
EV Lac.....	dM4.5e	10.24	22 44 40	+44 4.6
GT Peg ^a	dM3.5e	11.8	22 49 30	+3129.4
Ross 248 ^a	dM5.5(e?)	12.29	23 39 26	+4355.2

NOTE.— Unless noted, data from Kunkel (1975).

^aData from Joy and Abt (1974).^bData from Veeder (1974).

similar to data reduction procedures used by Linsky *et al.* (1979). Both echelle spectrographs have image-tube cameras such that the maximum image-tube resolution is $\sim 40 \mu\text{m}$, and slit widths were set so that their projected widths matched this resolution. Kitt Peak data were obtained on baked IIIa-J plates, and Steward Observatory data on Ila-O plates. Individual spectra were scanned using the Kitt Peak microdensitometer with a $40 \mu\text{m} \times 40 \mu\text{m}$ scanning aperture, digitizing every $20 \mu\text{m}$ in order to obtain maximum information down to the $40 \mu\text{m}$ resolution limit. We show a typical spectrum in Figure 1 (Plate 5). We digitized 500×200 element arrays centered on the spectral regions of interest. Density to intensity conversion was based on spot sensitometer plates taken the same night as the observations and scanned in a similar manner. We removed the scattered light background by measuring and subtracting the mean background between echelle orders. Since S-distortion inherent in echelle spectrographs is small over the restricted spectral range near the emission lines, we approximated this distortion by a straight line and removed it in subsequent digital processing. To produce a single one-dimensional scan from each spectrum, we averaged the data across the spectral widening (i.e., perpendicular to the dispersion).

Some of the spectra were of lower quality because of underexposures and/or insufficient widening. To make these spectra easier to interpret, we Fourier filtered them following Brault and White (1971). Typically, this degraded spectral resolution by about a factor of 3. The resolution listed in Table 1 reflects this degradation.

In Table 3 we list the final equivalent widths for the hydrogen lines. We also give the measured intensity

minima for absorption lines and maxima for emission lines, as well as the measured full width at half-minimum (maximum). In Table 4 we list only the measured line minima for the sodium lines. In the cases where line emission is present, we give both red and violet minima, emission maxima, and wavelength separation of minima for the lines. Because of the great variation in quality for the spectra, it is difficult to consistently derive errors. However, we believe the dominant form of error for somewhat noisy photographic spectra, often with many unresolved, or poorly resolved, weak absorption lines, is in fitting the continuum. We have fitted the continuum at wavelengths 10–50 Å away from the features, and well away from other strong absorption or emission features with a linear least-squares line, and our error estimate for equivalent widths is based on the 1σ uncertainty in this fit. Error estimates for the other parameters should correspond to the relative accuracy of the equivalent width and on the spectral resolution quoted in Table 1.

There are several ways to check the validity of assuming that errors are dominated by continuum fitting. Since the emission lines probably arise in patchy surface distributions of activity, it is not possible to compare emission lines and corresponding equivalent widths obtained on time scales long compared to a stellar rotation rate (a few days) as a measure of repeatability. However, YY Gem was observed three times on 1975 November 23 and twice on 1975 November 20. The rotation period of YY Gem based on the “BY Dra Syndrome” is 0.^d814 (Torres and Ferraz-Mello 1973); thus, the November 23 and November 20 results are each comparable among spectra from the same night. The average equivalent

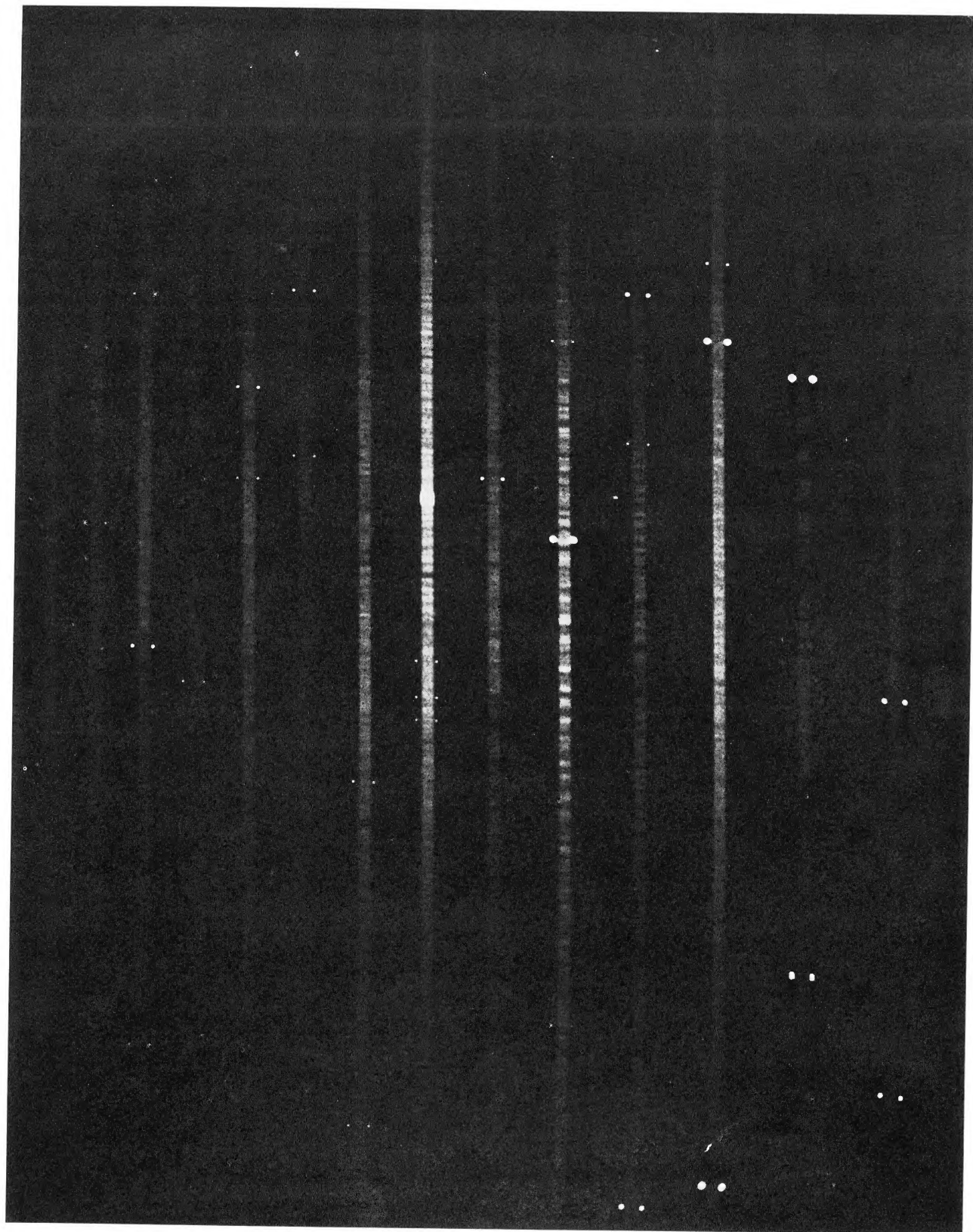


FIG. 1.—Sample Kitt Peak 4 m echelle spectrum for the $H\alpha$ region in the dMe star Ross 614 A

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TABLE 3
 HYDROGEN LINE EQUIVALENT WIDTHS

Object	Line	Date (UT)	Equivalent Widths ^a (Å)		Full Width At Half Maximum (Minimum) (Å)	Maximum/ Minimum Value Continuum = 1.0
SZ UMa	H α	19 Nov 75	-.39	$\pm$.03	.93	.46
	H α	17 Feb 78	-.29	$\pm$.01	.92	.68
61 Cyg A	H α	20 Nov 75	-.58	$\pm$.04	1.04	.36
61 Cyg B	H α	18 Nov 75	-.59	$\pm$.06	.82	.28
EV Lac	H α	18 Nov 75	5.50	$\pm$.77	.92	4.85
	H α	20 Nov 75	6.79	$\pm$.77	1.34	5.25
	H α	23 Nov 75	3.66	$\pm$.28	1.36	3.23
GT Peg	H β	09 Jul 76	8.39	$\pm$ 1.17	1.05	6.60
	H α	20 Nov 75	4.78	$\pm$.50	1.34	3.88
Ross 614 A ^b	H α	20 Nov 75	6.79	$\pm$.99	1.16	5.47
	H α	23 Nov 75	5.84	$\pm$.65	1.22	4.81
DM+5°1668	H α	20 Nov 75	-.16	$\pm$.02	.58	.62
DM+36°2147	H α	20 Nov 75	-.35	$\pm$.03	.64	.55
YY Gem ^c	H α (Total)	20 Nov 75	4.00	$\pm$.40	----	----
	H α (Weak)	20 Nov 75	1.76	$\pm$.20	1.68	1.72
	H α (Strong)	20 Nov 75	2.24	$\pm$.22	1.80	1.94
	H α (Total)	20 Nov 75	4.40	$\pm$.52	----	----
	H α (Weak)	20 Nov 75	1.83	$\pm$.14	1.73	1.82
	H α (Strong)	20 Nov 75	2.57	$\pm$.30	2.09	2.06
	H α (Total)	23 Nov 75	4.30	$\pm$.24	----	----
	H α (Weak)	23 Nov 75	1.49	$\pm$.08	1.75	1.60
	H α (Strong)	23 Nov 75	2.81	$\pm$.16	2.10	1.83
	H α (Total)	23 Nov 75	3.74	$\pm$.29	----	----
	H α (Weak)	23 Nov 75	1.69	$\pm$.14	1.72	1.54
	H α (Strong)	23 Nov 75	2.05	$\pm$.16	1.94	1.61
	H α (Total)	23 Nov 75	2.96	$\pm$.15	----	----
	H α (Weak)	23 Nov 75	1.18	$\pm$.06	1.63	1.65
	H α (Strong)	23 Nov 75	1.78	$\pm$.10	1.85	1.74
Ross 248	H α	23 Nov 75	-.24	$\pm$.03	.56	.60
FF And	H α	23 Nov 75	2.27	$\pm$.12	1.54	2.28
CN Leo ^d	H α	23 Nov 75	10.46	$\pm$ 1.63	1.08	8.99
AU Mic	H α	09 Jul 76	8.70	$\pm$.90	1.51	6.47
	H α	08 Sep 76	1.56	$\pm$.20	1.23	2.18
	H β	08 Sep 76	3.68	$\pm$.57	.75	4.69
	H γ	08 Sep 76	3.63	$\pm$ 1.08	.51	5.72
	H δ	08 Sep 76	1.68	$\pm$.25	.42	4.40
^e	He	08 Sep 76	2.66	$\pm$.64	.46	3.77
DM+16°2708	H α	09 Jul 76	3.58	$\pm$.53	1.32	2.95
AD Leo	H α	17 Feb 78	9.00	$\pm$.63	1.29	6.57
V1285 Aql	H α	30 Mar 77	2.99	$\pm$.26	1.29	2.89

^aNegative values for absorption line, positive values for emission line.^bV577 Mon.^cValues listed for total hydrogen emission line and the two component stars, where the stronger and weaker components are identified.^dWolf 359.^eCa II H line Max value 28.70, FWHM 0.30 Å.

width uncertainty for the total H α emission derived from uncertainty in continuum fitting is ± 0.32 Å. The combined 1 σ departure from the nightly average is ± 0.45 Å, in reasonable agreement with the above. An alternate approach for estimating errors is to compare nonchromospheric, presumably nonvariable, absorption lines in several spectra for the same star. Using the Ca I line at 6572.9 Å, we derive an equivalent width of 0.14 ± 0.01 Å for SZ UMa on plate SO117 (1978 Feb 17) and 0.16 ± 0.02 Å for the same star in plate KP740 (1975 Nov 19). The errors have been, as described, based on continuum uncertainty. Similarly, the Ca I line for EV Lac was measured to be 0.28 ± 0.03 Å, 0.29 ± 0.03

Å, and 0.20 ± 0.03 Å for the three spectra, respectively, KP790 (1975 Nov 23), KP743 (1975 Nov 20), and KP737 (1975 Nov 18). Ignoring our continuum-based errors, these values give an average and standard deviation value of 0.26 ± 0.04 Å. The standard deviation error is again in reasonable agreement with the error estimates based on continuum fitting. Although these results are not conclusive, they suggest that our method of error determination is valid for both strong emission lines and weaker absorption lines.

The resulting spectral traces are shown in the figure section. The spectra which were filtered have been identified by an asterisk on the plot. We have normalized the

TABLE 4
 Na I LINE PARAMETERS

Star	Date	Na I λ 5890				Na I λ 5896			
		MIN _{BLUE}	MIN _{RED}	MAX	$\Delta \lambda$ (Å)	MIN _{BLUE}	MIN _{RED}	MAX	$\Delta \lambda$ (Å)
		(Continuum = 1)				(Continuum = 1)			
SZ UMa	19 Nov 75		.136				.147		
	17 Feb 78		.343				.273		
61 Cyg A	20 Nov 75		.106				.143		
61 Cyg B	18 Nov 75		.193				.250		
DM+36°2147	20 Nov 75		.010				.135		
Ross 614	23 Nov 75	.401	.443	.949	1.35	.440	.538	1.333	1.30
EV Lac	18 Nov 75	.375	.502	1.053	1.16	.610	.563	.799	1.00
	23 Nov 75	.341	.310	.461	1.30	.347	.339	.356	1.35
	09 Jul 76	.442	.521	1.455	1.59	.517	.494	1.179	1.94
FF And	23 Nov 75		.200				.265		
AU Mic	09 Jul 76	.350	.468	.581	.87	.499	.502	.617	1.02
DM+16°2708	09 Jul 76	.315	.324	.537	.92	.370	.298	.479	.87
AD Leo	17 Feb 78	.446	.380	.761	1.44	.492	.378	.599	1.30
DM-7°3646	17 Feb 78		.420				.283		

* $\Delta \lambda$ (Å) if given is the separation between the two minima in the cases of stars with central emission.

relative intensity so that the continuum value is equal to one. The plots are also identified by the plate numbers, KP prefix referring to Kitt Peak data and SO referring to Steward Observatory data.

III. DISCUSSION

Our data show several general features. The central emission line reversal in H α lines noted by Worden and Peterson (1976) is a prevalent phenomenon in dMe stars, particularly among those dMe stars which are single. This implies that the H α reversals are optical depth effects in the emission line formation region as suggested by Worden and Peterson. Cram and Mullan (1979) and Kelch, Linsky, and Worden (1979) have subsequently calculated hydrogen emission line profiles with just such reversals. Other dMe stars that apparently do not show the central emission line reversal (such as GT Peg and AD Leo) either show evidence of the feature in the original plates or in other publications (see Giampapa *et al.* 1978). We note that the H α profile in dMe stars which are members of spectroscopic binary systems will be affected. This is illustrated by the two dMe stars FF And and YY Gem, each of which are spectroscopic binaries and do not show a central reversal. The dMe star V1285 Aql also does not show a central emission line reversal in H α . However, the H α profile for this object is very similar to that of FF And. Hence, this may indicate that V1285 Aql is an undiscovered spectroscopic binary.

The theoretical calculations mentioned above show that hydrogen absorption lines are also indicative of stellar chromospheric activity. Since several absorption line stars are flare stars, such as SZ UMa, this fact is underscored. Although the spectrum for DM 7° 3646

(EQ Vir) is very poor, we include it because this spectrum shows no evidence for a strong H α emission line, while H α spectra of EQ Vir reported in Kelch, Linsky, and Worden (1979) and Hartmann and Anderson (1977) show a definite H α emission feature. Several other lower quality spectra have been included. The equivalent width for H α in +5° 1668 (KP754) has an estimated error of $\pm 12\%$, which appears small considering the noisy character of the spectrum. However, the continuum used to fit these data was outside the displayed spectra, and less noisy, and our error estimation method may begin to break down for extremely noisy data such as shown here. The noisy Na I line data for EV Lac, KP737, and SO75, while noisy, are included as a point of comparison and model constraint for the much better H α line profiles from the same plates.

Evidence for line profile variability is obtained by comparing several spectra observed on different nights for the same star and by comparing our AD Leo data with the results of Giampapa *et al.* (1978). These comparisons reveal variations in the absorption and emission lines which are larger than the errors. This result is consistent with the findings of Bopp (1974), where profile variations on time scales as short as 4 hrs were observed.

Giampapa *et al.* (1978) showed that the Na D emission features in the spectrum of AD Leo are stellar in origin, rather than night sky emission. The present observations strongly suggest that this is true for all the stars observed with Na D emission features, since Na D emission is observed only in those stars with hydrogen emission.

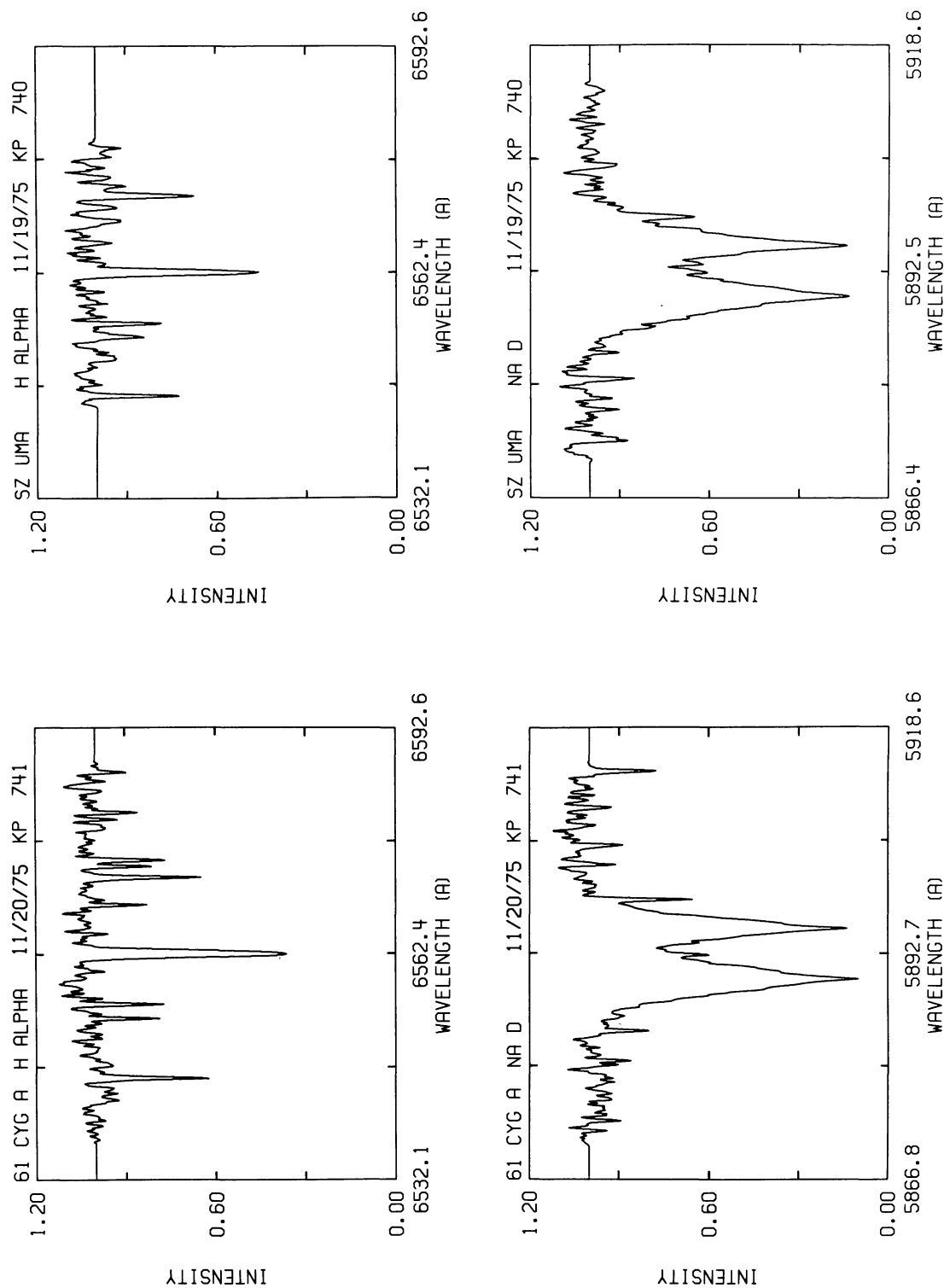


FIG. 2

FIG. 3

FIGS. 2-24.—The star name, spectral region, UT date (month/day/year), and instrument/plate number are given at the top of each plot. KP denotes Kitt Peak 4 m echelle observations, and SO denotes Steward Observatory 2.3 m echelle observations. Fourier-filtered data are marked by an asterisk in the upper right corner. The flat segments at the beginning and end of each plot indicate unit relative intensity, or “continuum”, based on fitting data on either side of the plotted spectral region. Note that the strongest feature in the AU Mic H ϵ spectrum is Ca II H. The two H α features in YY Gem spectra are due to the two component stars.

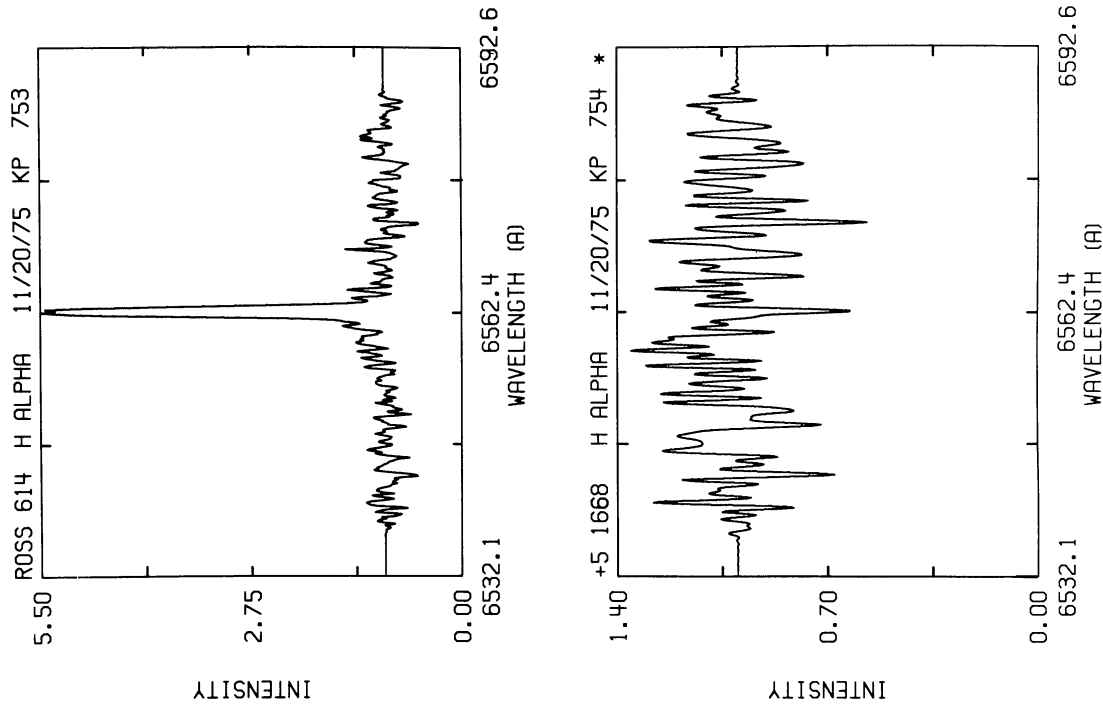


FIG. 5

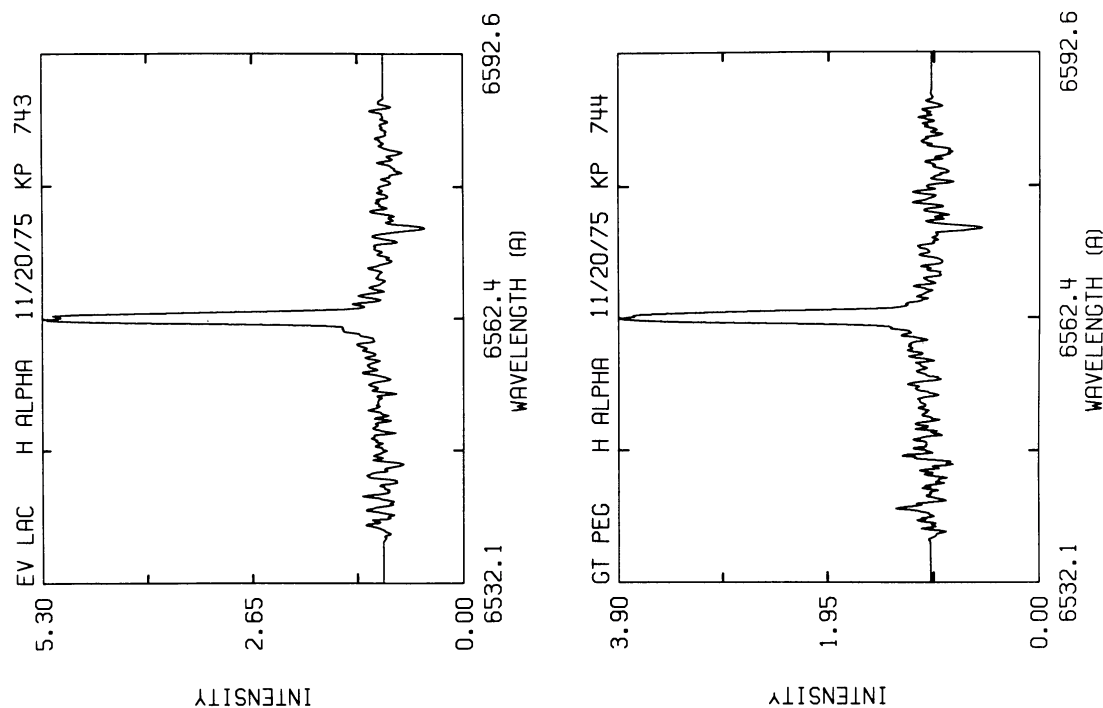


FIG. 4

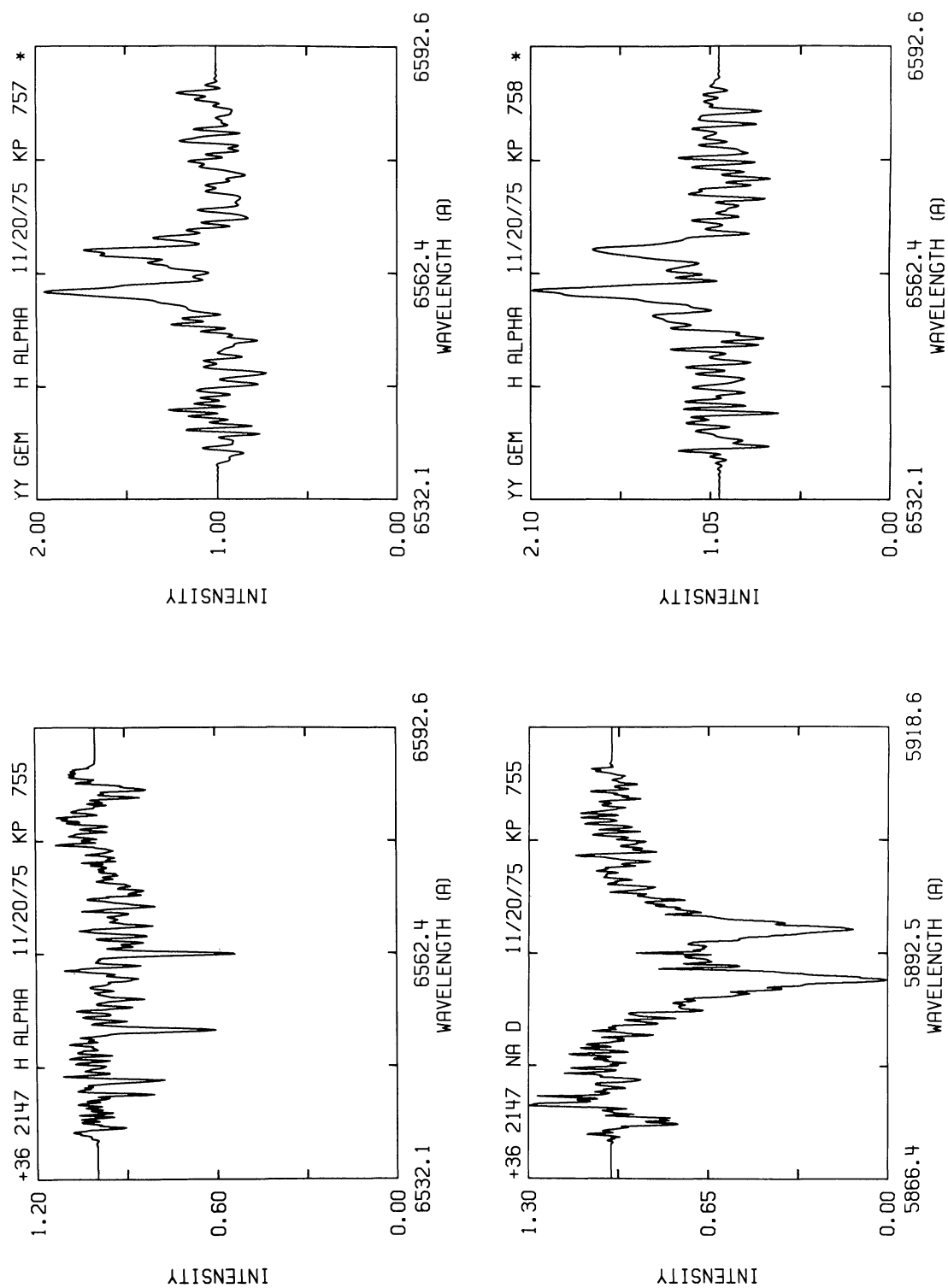


FIG. 7

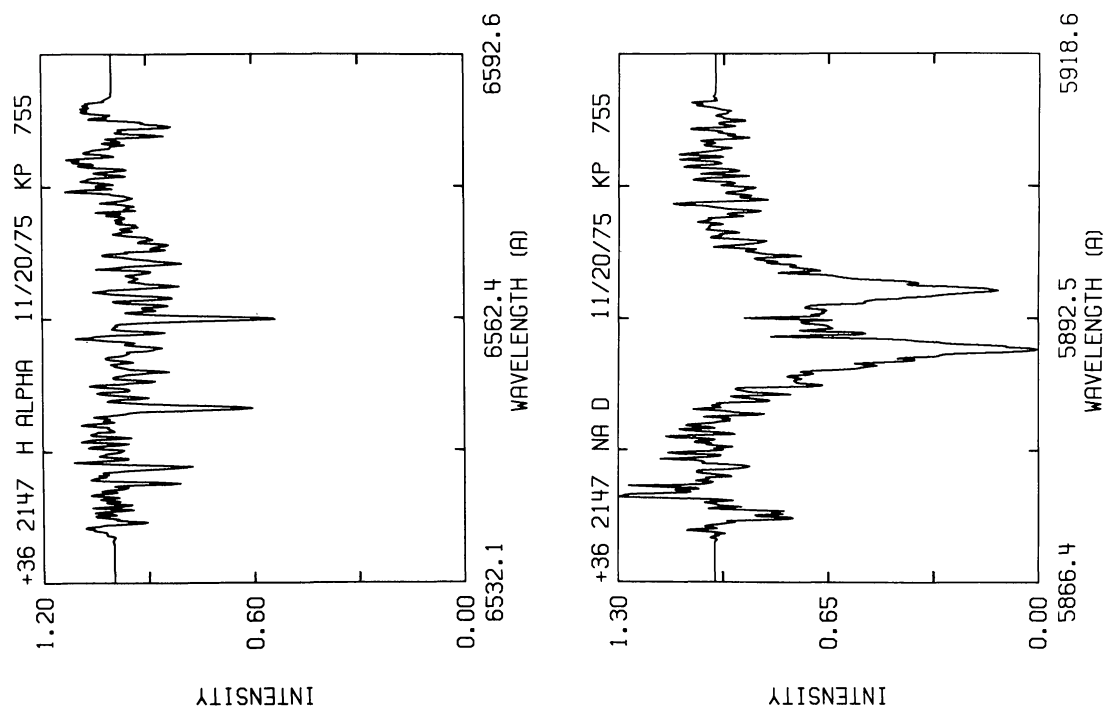


FIG. 6

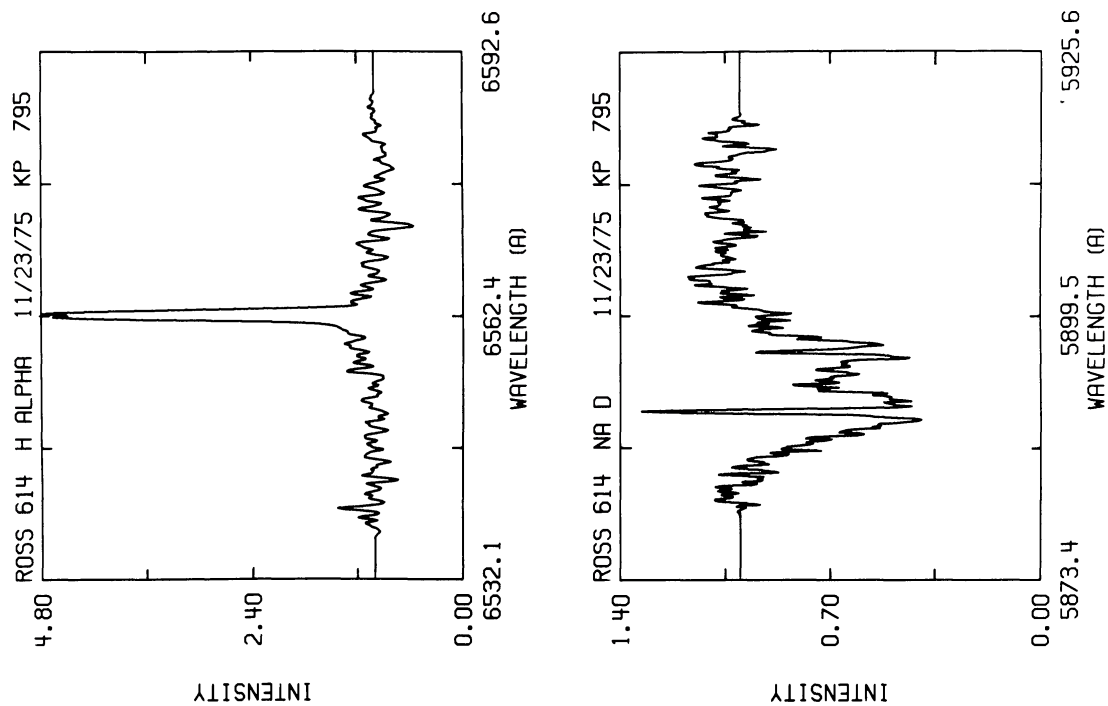


FIG. 8

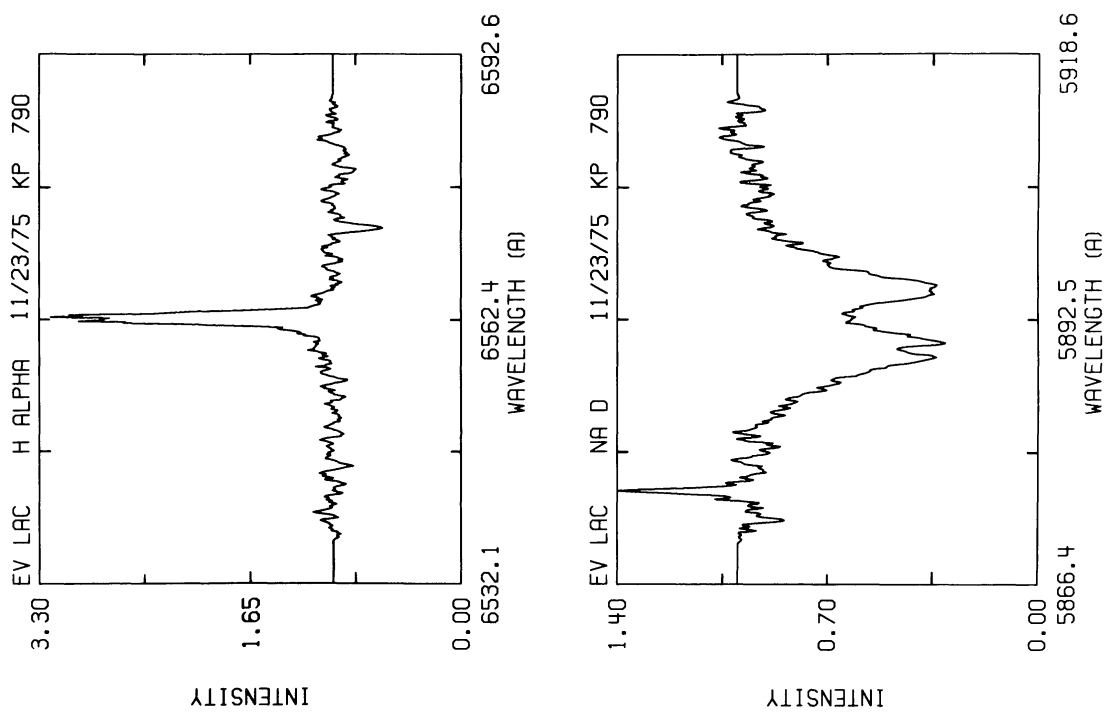


FIG. 9

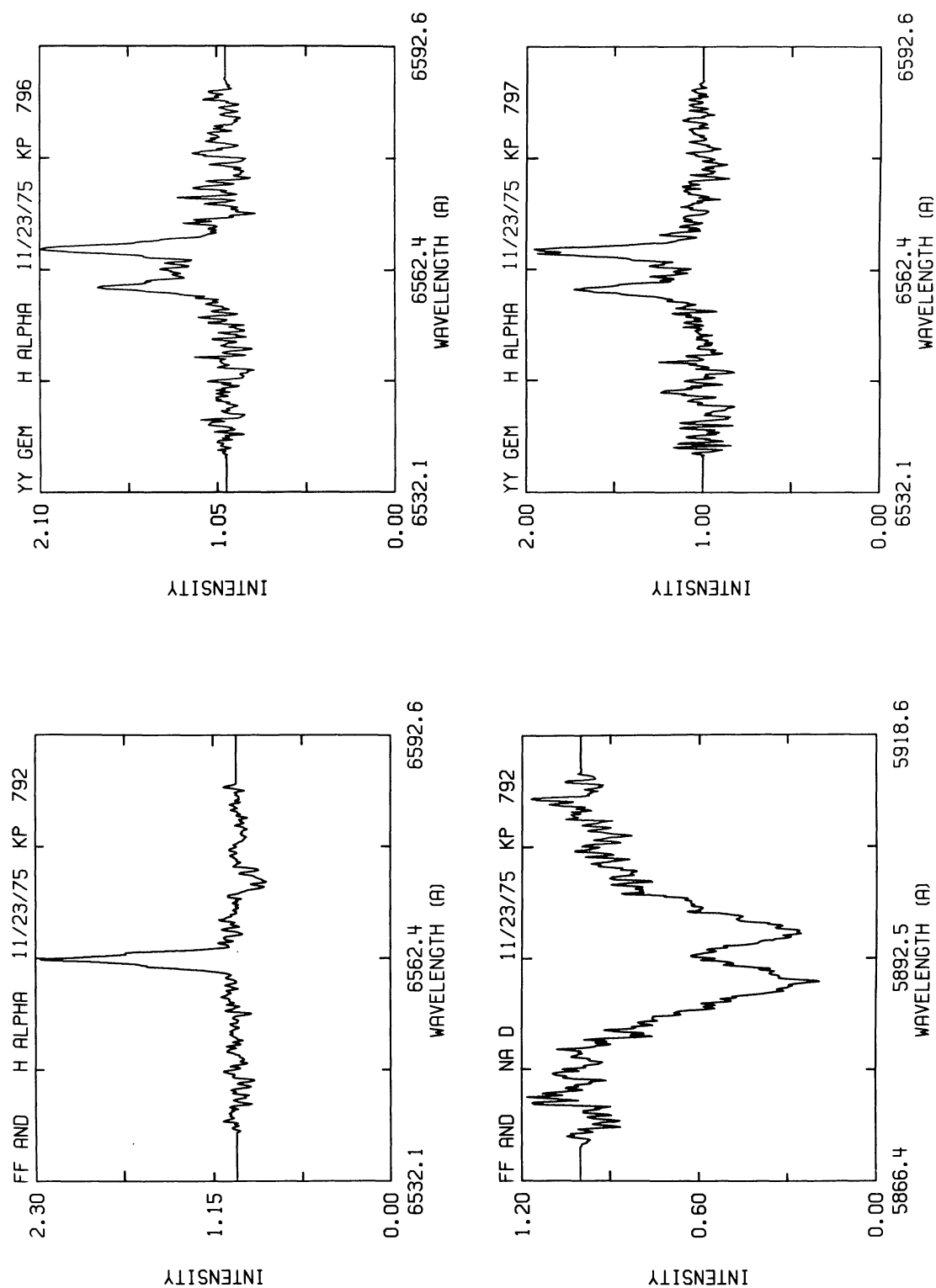


FIG. 10

FIG. 11

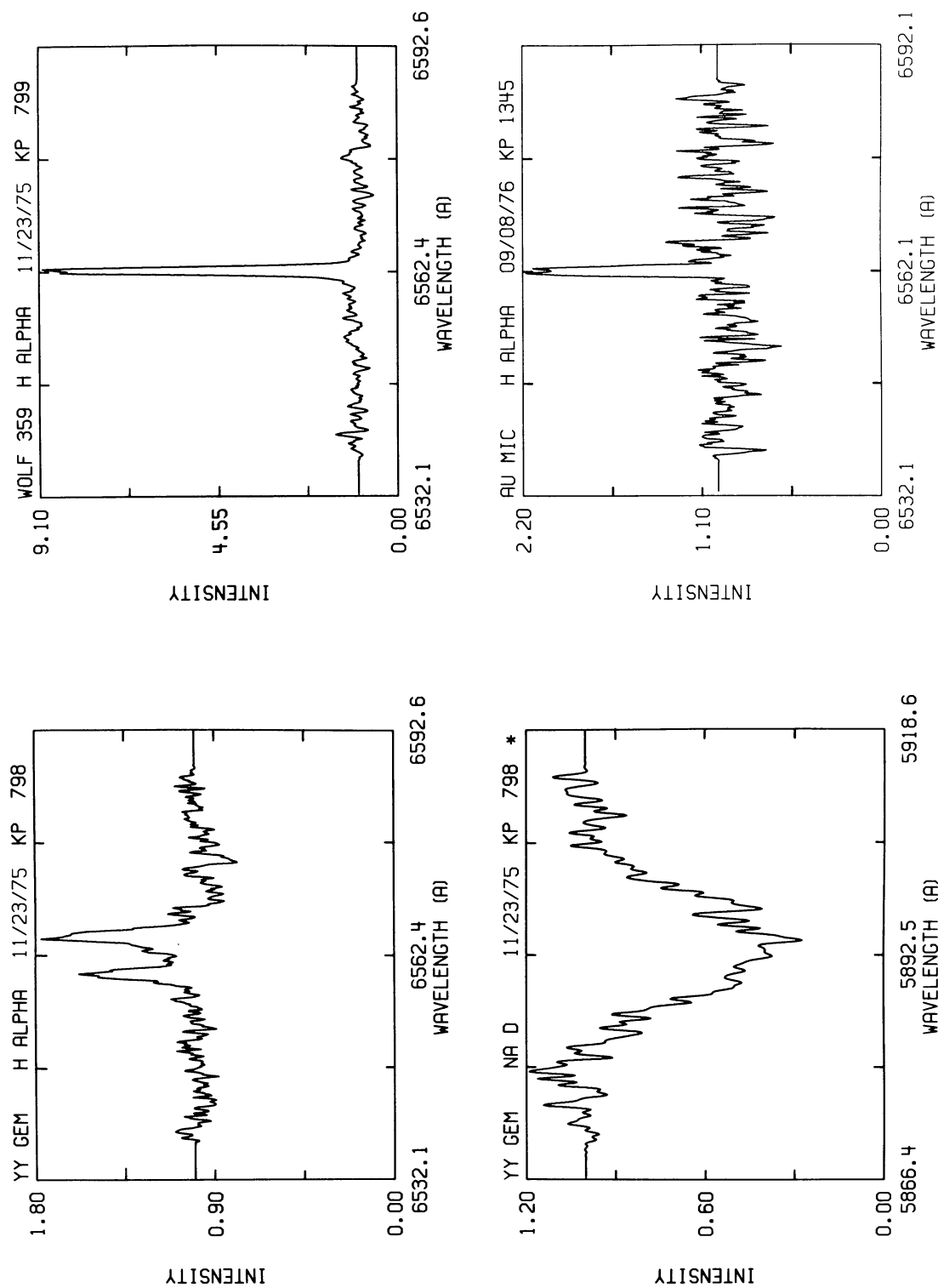


FIG. 13

FIG. 12

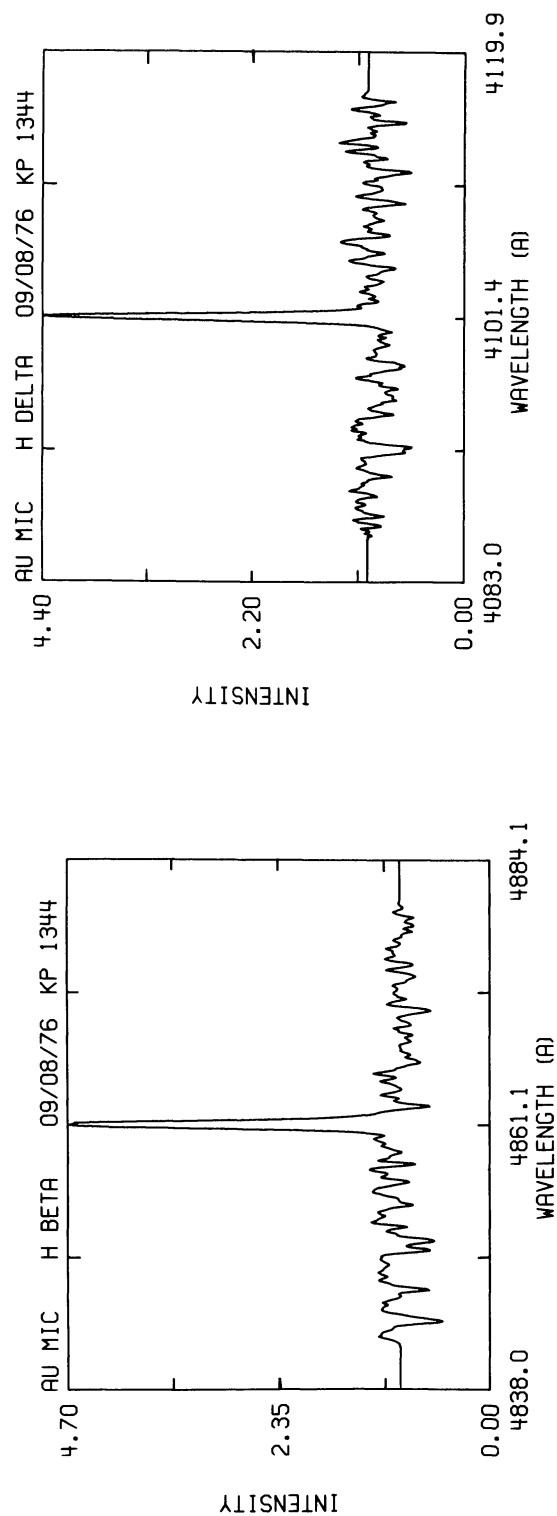


FIG. 14

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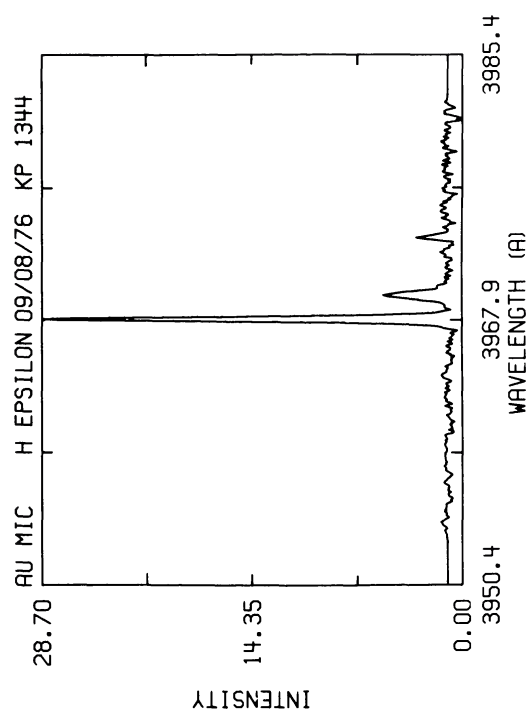
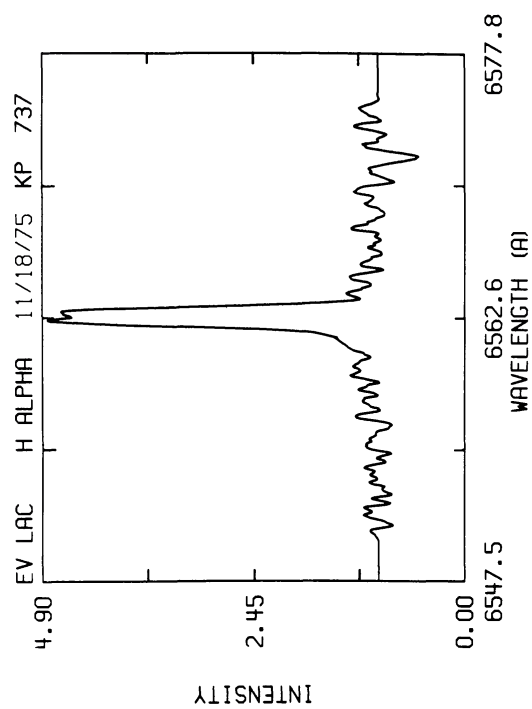


FIG. 15



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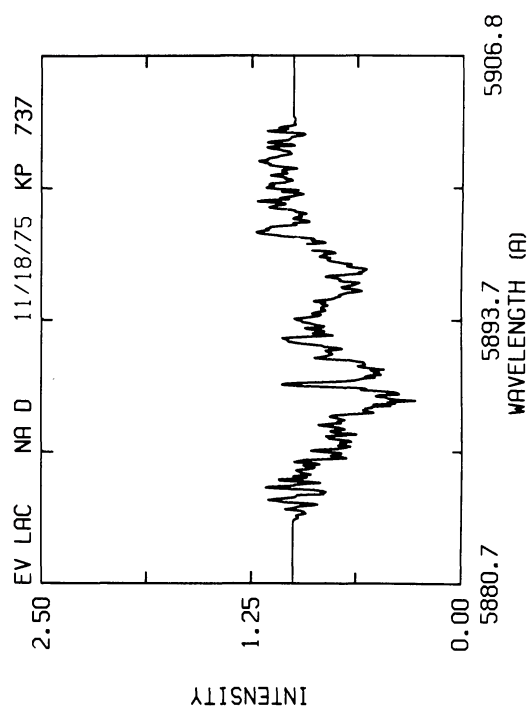


FIG. 16

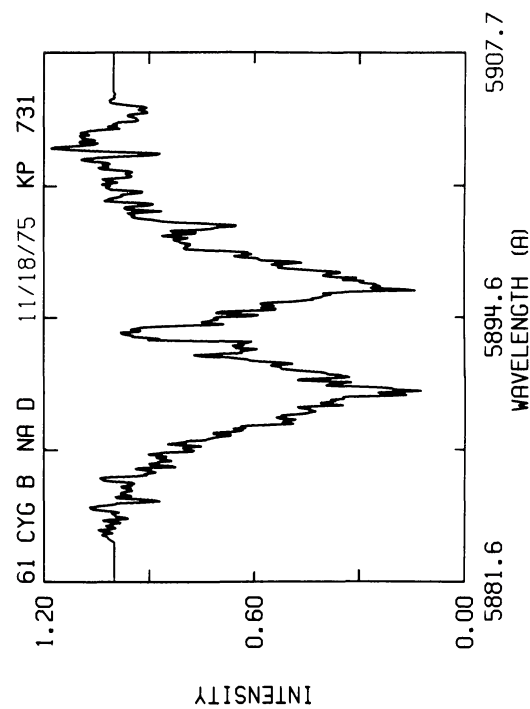
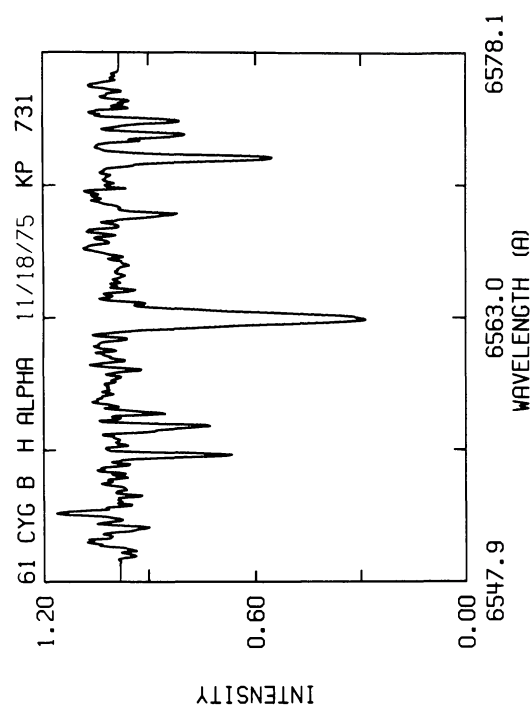


FIG. 17

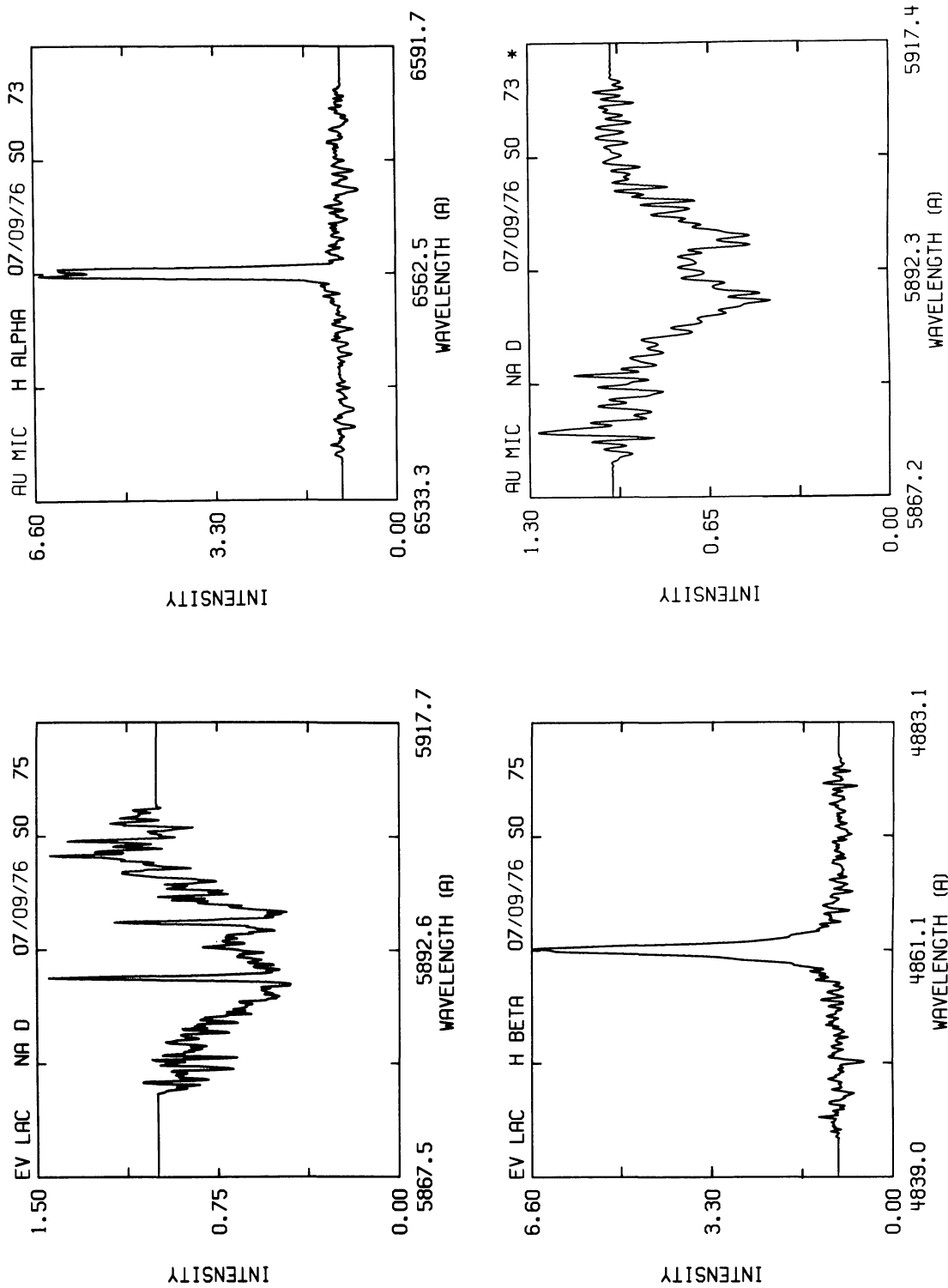


Fig. 19

Fig. 18

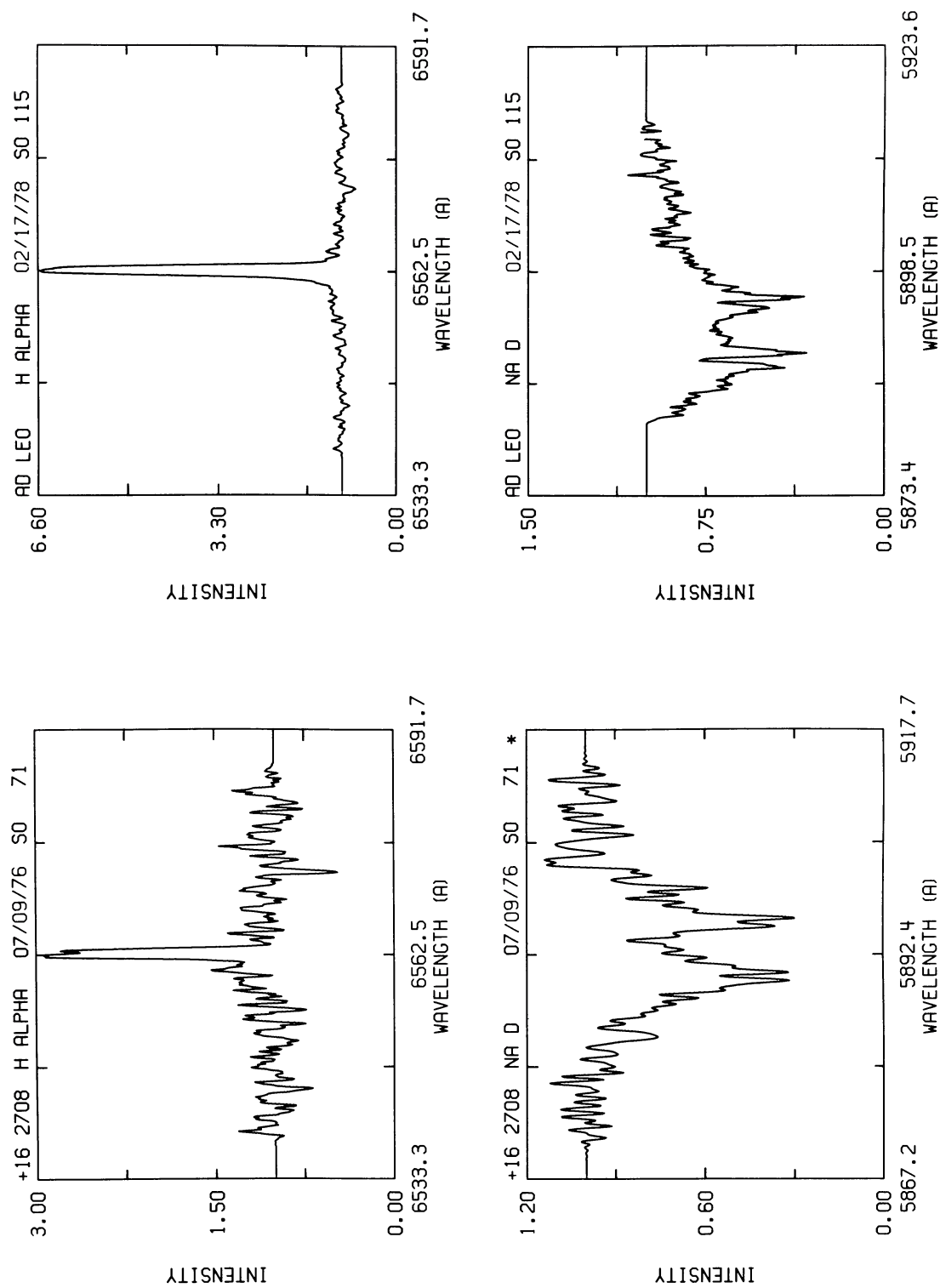


FIG. 21

FIG. 20

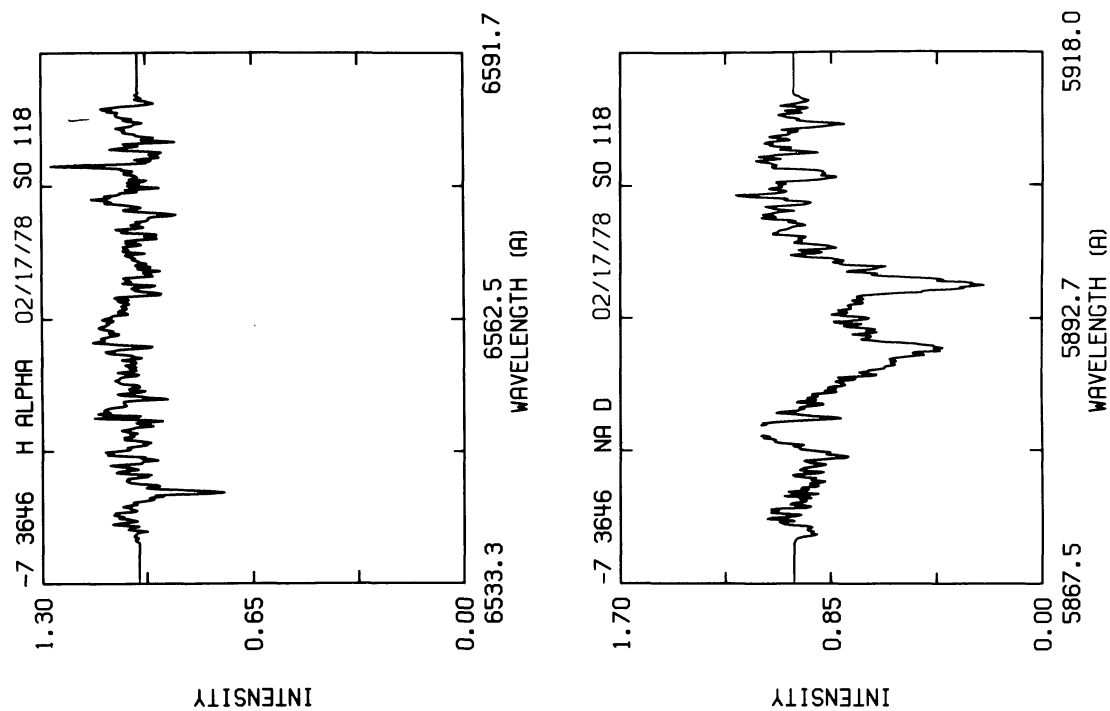


FIG. 22

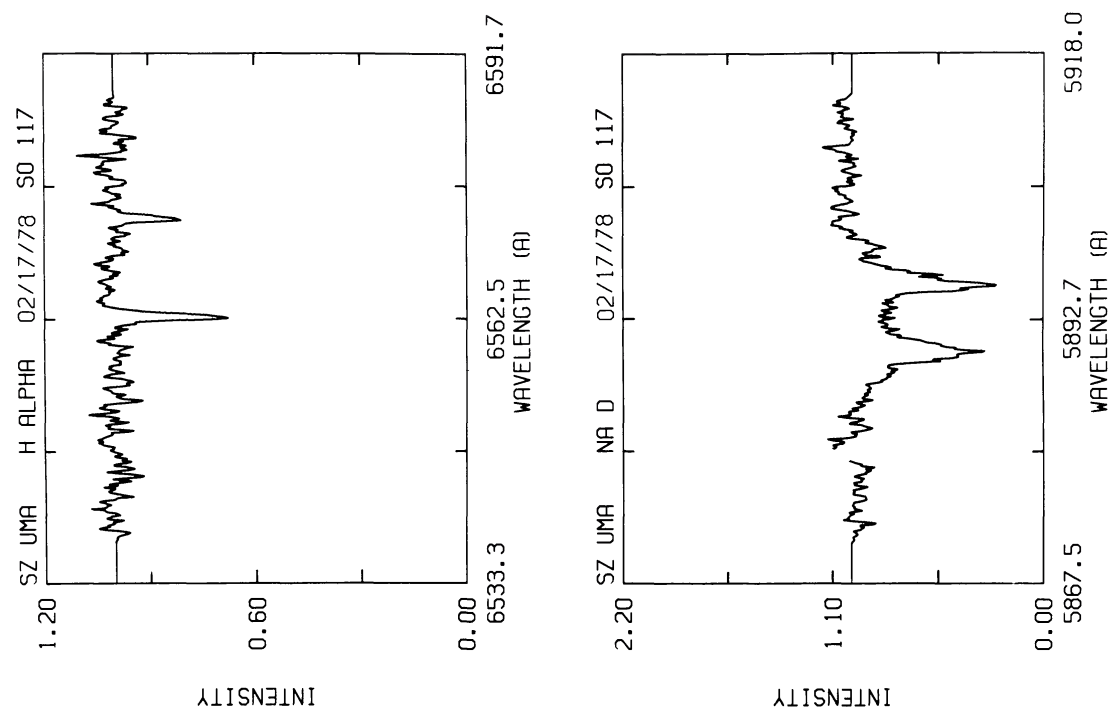


FIG. 23

LINE PROFILES FOR 17 M DWARF STARS

175

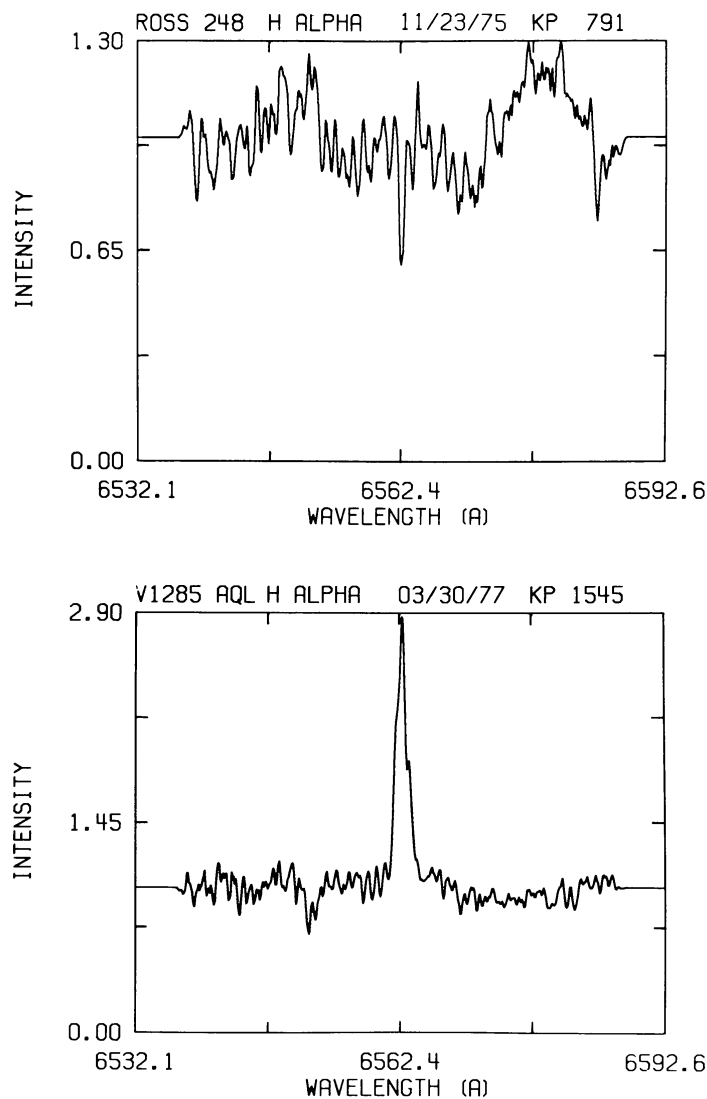


FIG. 24

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