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MK Morphological Study of Am Stars at 66 Å/mm

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Abstract. The pseudo-luminosity effect in the metallic line A-type stars found by Abt & Morgan (1976) is confirmed in a random sample of 27 Am stars. From a morphological study of their spectra in the wavelength interval 3850–4400 Å at a reciprocal dispersion of 66 Å/mm, revised spectral types are given on the MK system for their K-line and metallic-line spectra. This shows that: (a) our segregation of weak Am from the Am stars largely agrees with that by Cowley *et al.* (1969); (b) all the stars in the sample are dwarfs according to their K-line classification; (c) more than 80 per cent exhibit the pseudo-luminosity effect significantly, with their metallic-line spectra resembling a giant or even a supergiant in the violet (3850–4100 Å), and a giant rather than a dwarf in the blue region (4260-4400 Å); (d) in two-thirds of the stars under (c), the Sr II 4077 Å line is found to have a markedly brighter luminosity class compared to any region, and in more than one-third of the sample it is comparable to that in Ap stars; (e) at least five stars exhibit characteristics which might suggest a spectrum variability: among these, the most striking example is 41 Sex A which was found to show a phase-modulated spectrum variation hitherto unknown in Am stars; (f) the metallic-line spectra of another five stars appear to be similar to A-shell type in differing degrees; (g) less than 20 per cent of the sample comprises stars which do not show any significant differential luminosity effect; these stars might have been misclassified or perhaps they are in a quiescent state.

We also confirm the conclusion arrived at by Böhm-Vitense & Johnson (1978) that all Am stars may vary and our observations suggest that groups may exist among them.

Key words: stars, metallic-line—stars, spectrum classification

1. Introduction

The A-type “metallic lined” stars, which indicate a “pseudo-composite” class with enhanced strength of metals abnormal to their spectral type, were discovered by Titus & Morgan (1940). Morgan, Keenan & Kellman (1943) introduced a dual classification for these stars according to their Ca II K-line and metallic-line types. Roman, Morgan & Eggen (1947) added a third dimension to the above classification by introducing the H type and gave the classical definition of the Am characteristics, namely Sp (K) $\leqslant$ Sp (H) $\leqslant$ Sp (ml) based on the following criteria: (1) The K line would be considerably weaker than that expected for the average metallic-line type. (2) Due to the spurious luminosity effect the spectrum cannot be explained in terms of one or two normal stars; that is, the spectral type inferred from the metallic lines near the K line must be identical to that derived for the same star at longer wavelengths. All these lines, however, give the same radial velocity in a binary system. (3) The metallic-line stars show no obvious similarity to recognized "shell spectrum" types and are readily distinguishable from the "silicon", "strontium" and "europium" groups. The authors also remarked that due to the differential luminosity effect, the metallic-line type could often be matched almost equally well with two different spectral types; for example, in the case of 63 Tau they found it matching well with both F5 IV and F0 II–III.

Greenstein (1949) studied the spectral behaviour of the metallic-line star τ UMa at a dispersion of 2.6 A/mm and estimated a spectral type A3 for its K line, A9 for H and F6 II for its metallic lines. He concluded that metallic-line stars exhibit a false high-luminosity characteristic with respect to their metals compared to the K line. A high dispersion study of a group of Am stars by Smith (1971) confirmed, however, that the spectroscopic gravities of Am stars are dwarf-like. Generally, features like the Sr II line at 4077 Å and the Ti II line at 4315 Å are enhanced in Am stars similar to those in giants and the metallic-line spectrum is often classified as Type III. Abt & Morgan (1976) studied this phenomenon in a group of 9 Am stars at 125 Å/mm. They used two regions to provide luminosity criteria. They found that according to the blue criteria (4260-4340 Å), the star is a dwarf, whereas the violet criteria (3850–4078 Å) correspond to a giant or even a supergiant. In the case of one extreme example in their list, HD 103877, while the K-line spectral type was A7V, the spectral types for blue and violet regions were F5 IV and F5 Ib respectively.

For more detailed studies it is necessary to use a higher reciprocal dispersion than 125 Å/mm. Especially, when peculiar early-type stars are involved, a reciprocal dispersion of about 60 Å/mm is needed to resolve the spectral peculiarities (Lóden 1979; Morgan 1979). This investigation is, therefore, aimed at substantiating the above phenomenology by means of a comprehensive morphological study of a large sample of 27 Am stars observed at a reciprocal linear dispersion of 66 Å/mm.

2. Observations

2.1 *The Data*

Most of the 27 Am stars of our sample were selected from a catalogue compiled by Curchod & Hauck (1979). They are brighter than $m_{pg} = 6.5$ and their projected rotational velocity range is 0–80 km s^{-1}. Among these, 8 each are single- and double-lined spectroscopic binaries with orbits, 8 are single stars and 3 are suspected spectroscopic binaries. This distribution is curious for a randomly selected sample; so also is the fact that more than 30 per cent of the stars in our sample are single Am stars, although, according to Abt (1961, 1965) nearly 100 per cent of the Am stars are expected to be close binaries. Table 1 gives the spectral type, $v \sin i$ and binary nature along with the photometric information for these stars. The metallicity and rotation in Am stars on the main-sequence is a continuously changing phenomenon, and it is a difficult task to acquire a library of standards which adequately represents all the variables in such a multi-dimensional grid. Since Am stars usually have sharp lines,

Table 1. List of Am stars observed for MK morphology.

No.	Name	HR No.	HD No.	V Ref. (3)	$B-V$ Ref. (3)	$U-B$ Ref. (3)	$v \sin i$ km s^{-1} Ref. (1)	Binary nature Ref. (2)	Sp. Class Ref. (3)	Remarks
1	β Ari	553	11636	2.34	+0.13	+0.10	79, 70, 76	SB2 (0)	A5 V	
2	12κ Ari	613	12869	5.03	+0.11	+0.13	29, 0	SB2 (0)	A2 m	
3		723	15385	6.19	+0.15	+0.14	21, 25		A5 m	
4	49 Ari	905	18769	5.90	+0.14	+0.15	43		A3 m	
5	13ξ Ari	984	20320	4.80	+0.23	+0.09	66, 65, 70	SB1 (0)	A5 m	
6		1300	26591	5.79	+0.18	+0.09	30	SB2 (0)	A2 m	
7	63 Tau	1376	27749	5.64	+0.30	+0.13	10, 6, 30	SB1 (0)	A1 m	2 Spectra
8		1645	32667	5.61	+0.10	+0.07	216*	SB*	A3 m	*Ref. (3)
9	59 Ori	2100	40372	5.90	+0.21	+0.17	60	SB1 (0)	A5 m & δ Del	
10	2 Mon	2108	40536	5.03	+0.19	+0.16	23, 25	SB1 (0)	A6 m	
11	61 μ Ori	2124	40932	4.12	+0.16	+0.11	24, 46, 15	SB1 (0)	A2 V	
12	40 Aur	2143	41357	5.36	+0.25	+0.15	26, 41	SB2 (0)	A4 m	
13		2163	41841	5.47	+0.08	+0.09	64, 52		A m	
14		2214	42954	5.88	+0.22	+0.15	47	SB2 (0)	A6 m	
15	WW Aur	2372	46052	5.87	+0.14	+0.15	35, 68	SB2 (0)	A4 m + A5 m	3 Spectra
16		3040	63589	6.03	+0.15	+0.15	40		A2 m	
17	65 α Cnc	3572	76756	4.25	+0.14	+0.15	58, 70, 74	SB*	A5 m	*Ref. (3)
18	15 Uma	3619	78209	4.48	+0.27	+0.12	7, 30, 38		A m	
19	21 Hya	3655	79193	6.11	+0.22	+0.12	<12	SB2 (0)	A3 m	
20			82191	6.59				SB2 (0)	Am + Am	Ref. (2)
21	41 Sex A	4237	93903	5.79	+0.16	+0.13	20, 35	SB1 (0)	A3 m	2 Spectra
22	60 Leo	4300	95608	4.42	+0.05	+0.05	24, 28		A1 m	
23	32 Aqr	8410	209625	5.30	+0.23	+0.15	19, 5, 50	SB1 (0)	A5 m	
24		8708	216608	5.81	+0.26	+0.10	40	SB1 (0)	A3 m + F6 V	
25	14 Psc	8944	221675	5.87	+0.30	+0.16	60		A2 m	
26		8970	222377	5.97	+0.20	+0.13	60, 70		A2 m	
27	21 Psc	9022	223438	5.77	+0.16	+0.12	43	SB*	A5 m	* Ref. 3

(1) Curchod & Hauck (1979), (2) Batten, Fletcher & Mac Carthy (1989), (3) Hoffleit (1982).

Table 2. List of observed MK standards.

No.	HD No.	Sp type	$v \sin i$ km s^{-1}	No.	HD No.	Sp type	$v \sin i$ km s^{-1}
1	36673	F0 I	13	22	62623	A2 I	73
2	20902	F5 I	18	23	59612	A5 I	26
3	*135153	F0 II	0	24	*216627	A2 III	71
4	89025	F0 III	84	25	13161	A5 III	76
5	17584	F2 III	149	26	*70060	A7 III	129
6	432	F2 III/IV	70	27	47105	A0 IV	32
7	21770	F4 III	29	28	89021	A2 IV	48
8	17918	F5 III	120	29	76644	A7 IV	151
9	55052	F5 III/IV	74	30	*41511	A0 V (Shell)	98
10	220657	F8 III	79	31	172167	A0 V	15
11	27397	F0 IV	109	32	140159	A1 V	149
12	*182640	F0 IV	85	33	*176687	A2 V	72
13	11443	F6 IV	93	34	216956	A3 V	100
14	110379	F0 V	28	35	97603	A4 V	181
15	*29992	F2 V	140	36	11636	A5 V	79
16	113139	F2 V	92	37	87696	A7 V	148
17	26015	F3 V	25	38	6961	A7 V	102
18	134083	F5 V	45	39	*49976	A2 P	
19	210027	F5 V	7				
20	30652	F6 V	17				
21	102870	F9 V	3				

* Secondary standards given in Buscombe (1981); $v \sin i$ from Hoffleit (1982).

MK standards of similar rotational velocities were selected for observation. We were, however, restricted in not being able to reach fainter than the 7th magnitude. Thirty of the observed thirty nine MK standards were taken from Morgan, Keenan & Kellman (1943), Yamashita, Nariai & Norimoto (1977), Morgan, Abt & Tapscot (1978), and Jaschek & Jaschek (1977). The remaining nine secondary standards were taken from the catalogue by Buscombe (1981). These are given in Table 2 with their spectral types and projected rotational velocities.

2.2 *Spectroscopy*

All the stars were observed during the early part of the 1987–88 season with the Meinel spectrograph at the Nasmyth focus of the 1.2 m telescope of the Japal-Rangapur Observatory, Osmania University. A Bausch & Lomb reflection grating of size 84 mm × 84 mm, with 600 grooves/mm gave a reciprocal linear dispersion of 66 Å/mm in the blue. The entrance slit width was always kept at 140 μm, corresponding to 1″.7 on the sky, so that the projected slit width would be about 20 μm—approximately equal to the grain size of the Kodak IIa O emulsion. The star was trailed over a slit length of 4 mm so that the spectrum would be widened to 550 μm. The spectrum is imaged by a compact *f*/2 folded Schmidt system of 126 mm focal length. This set-up gave an optimum spectral resolution and remained least affected by small changes in focus, if any, from one observing run to another. The spectrograph is rigidly built and tested for stability and is found to be free from flexure effects and focus changes due to any transient effects. The system is therefore suitable for giving an extremely homogeneous series of spectra over a considerable period of time.

Spectra with different exposures of each star were obtained to get a suitable density for the purpose of spectrophotometry. An Fe–Ne hollow cathode discharge tube of Westinghouse make was used for calibration. Kodak IIa O plates were used throughout without any hyper-sensitization. These were processed in accordance with the prescribed procedures, using a plate rocker for uniform development, in a controlled atmosphere.

2.3 *Spectrophotometry*

The Carl-Zeiss microdensitometer MD 100 of the Department of Astronomy was digitized for an automatic measurement of either transmissivity or density of the spectrum on the plate. The spectrogram is loaded on the carriage of the microdensitometer and synchronized with the direction of the dispersion. The screw of the carriage is coupled to a stepper motor which moves it through 12.7 μm intervals. This is equal to a pixel size of 0.84 Å at 66 Å/mm. The measuring range is selected with the potentiometric recorder. The voltage differences generated by the changing transmissivity of the plate is measured by an inbuilt voltmeter. This is connected to an A to D converter which in turn is connected with an on-line computer. The software generates pixel vs density profile of the spectrum while the plate is being scanned. The instrument was tested for repeatability and was found satisfactory.

The measuring slit of the microdensitometer was adjusted to cut off the edges so as to cover only the central 3/4 of the projected spectrum to produce a fairly uniform density over the length of the slit. The system thus gives a good resolution and remains quite stable against aberrations due to inhomogeneities of the emulsion, vibrations and shocks. The digitized densities are converted into log-intensities by means of a self-calibration method suggested by Sawyer (1963). The spectrum of the Fe–Ne hollow cathode discharge source was used for this purpose. Quantitative photoelectric intensities determined by Crosswhite & Dieke (1963) for sharp and unsaturated Fe lines in its spectrum and their measured densities on several plates were used to generate a mean characteristic curve for the IIa O emulsion. This method was tested for its reliability by measuring equivalent widths of the Ca II K line in six Am stars. Among these, three stars classified as A7 V gave an equivalent width of 4.3 Å and the other three classified as A3 V gave 3 Å. These were in agreement with those estimated by Guthrie (1987) for the same K-line spectral types. The log-intensities were then smoothed by 3-point averaging. This improved the S/N from an estimated 30–35 in raw spectra to 80–90 in the degraded spectra. The smoothed log-intensities were converted into relative intensities (I_v/I_c) by normalizing to the continuum. Finally, the tracing was placed on a linear scale of wavelengths with respect to those of some prominent lines. As many as 100 spectra were scanned on this system and their relative intensity profiles in the region 3850–4400 Å were obtained for morphological studies.

3. MK morphology

For the purpose of classifying the Am stars of our sample based on the morphology of their spectra, we use different spectral ranges as unknown specimens for classification according to the MK system. We simply match the unknown with the MK standard nearest to it in appearance. This match will be made by using the spectrograms obtained with the same spectrograph-camera-telescope system and the same emulsion, identically processed. And in this process we use the language of lines, blends and bands in the standard stars—not the language of stellar atmospheres! In this language, the peculiar category of Am stars exhibit discriminating characteristics suggesting a brighter luminosity class in the violet region than in the region around the G band. We follow here the terminology used by Abt & Morgan (1976): the region for the blue type is 4260–4400 Å; the luminosity criteria are centred around the G band and is shown as the 'm 43' type. The region for the violet type is 3850–4100 Å with the luminosity criteria centred around 3900 Å and is shown as the 'm 39' type. For visual classification, Abt & Morgan have found a marked decrease in luminosity sensitivity for regions shorter than m 39 and longer than m 43. Further, these regions are especially sensitive to luminosity class differences for F2-G0 stars when compared to the region between 4100 Å and 4260 Å.

3.1 *Method*

Table 3 gives all the available spectral types for the selected Am stars in columns 7, 8 and 9 respectively. These are taken from a catalogue of Am stars compiled by Curchod & Hauck (1979). The H type is available only for about 50 per cent of the stars in our sample and evidently, it is associated with a high degree of uncertainty. We are not interested, however, in the reclassification of the H type. The metallic-line type is inconsistent and shows a large scatter. The K-line type, which is easy to determine, is also found to vary by 2 to 3 sub-classes between various authors. In the process of reclassification of the K-line and metallic-line types, the earlier classification for the same, in each star, is taken as the reckoning to find a matching standard.

The K-line type is determined by superposing its digital profile over that of the corresponding line in several standards, and its spectral type is assigned with respect to the best match, as described above, and is given in column 3. This makes it possible to differentiate between dwarfs and giants. In the case of m 39 and m 43 regions, however, a wider range of corresponding regions in the standards had to be consulted before a satisfactory match was found for most of the luminosity sensitive features in the respective regions. The best match obviously is the one which has the maximum number of luminosity sensitive features in both Am and standard stars matching in the same sense, and nearly with the same strength. The spectral types thus assigned are shown in columns 4 and 5. In the violet region, however, the Sr II 4077 Å line exhibits a positive luminosity effect which is not always found to be consistent with the luminosity class assigned to that region. In extreme cases, it resembles that in Ap stars. Therefore, its spectral type is separately given in column 6 whenever it is found to exhibit a brighter luminosity class as mentioned above. The observed resemblance of a few of the Am stars to the A-shell spectrum, discussed in Section 4 (4), is also noted in the remarks column.

The closest match between each Am star and MK standard for the K-line, m 39 and m 43 regions are plotted separately and stacked together, from top to bottom, in Figs 1–27 (see Appendix). The thick line always corresponds to the Am star and the thin line to the MK standard. Similar figures for the Sr II 4077 Å line were generated

Table 3. MK morphological classification of Am stars listed in table 1.

No.	HD No.	Present classification			Sr II	*Earlier Classification			Remarks
		K	m 39	m 43	4077	K	H	M	
1	11636	A7 V	F0 III	F2 III/IV		A5			Sp (m 39) ≈ A-Shell
2	12869	A1 V	F2 III/IV	F2 III/IV	F5 I	A2	A8	A8	
3	15385	A7 IV	F2 III/IV	F2 III/IV	F5 I	A5, 7	A7	F2, 1	
4	18769	A4 V	F2 III/IV	F2 III/IV	F5 III	A2, 3	A8	F0	
5	20320	A7 V	F2 III/IV	F2 III/IV		A2.5, 3.5	A6	F0	Sp (m 39) ≈ A-Shell
6	26591	A0 V	F2 III/IV	F2 III/IV	F5 III	A2			K-line and Sr II 4077 blended
7	27749	A4 V	F5 Ib	F2 III/IV	Ap	A1, 1.5	F0, A8	F5 IV, F II F0 II/III	Fe I 4005 very strong (2spectra); Spectrum variable?
8	32667	A3 V	F0 Ib	F2 III/IV	F5 I	**A3 m			H blended heavily redward; G band resolved
9	40372	A7 V	F5 III/IV	A7 V	Ap	**A5 m & δ Del			
10	40536	A4 V	F0 III	F0 V		A3, 5, 6	A8, 5	F2, F0 III	Ti II 4315 is absent or very weak
11	40932	A7 V	F2 III/IV	F2 III/IV	F5 I	A3	A8	A7	Sp ≈ A-Shell; G-band resolved
12	41357	A7 IV	F5 Ib	F2 III/IV	Ap	A4, 5		F2	Sr II 4077 And Ti II 4315 very strong
13	41841	A2, 3 IV	A2 V	A3 V			A2	A3	Weak Am
14	42954	A5 V	F2 III/IV	F2 III/IV		A6, 5	A7	F0	Sr II 4077 blended
15(a)	46052	A2 V	F5 III/IV	F2 III/IV		A2, 3		A5, F2	
15(b)	46052	A2 V	F2 III/IV	F2 III/IV	F5 I	A2, 3		A5, F2	Sr II enhances, signficant change in blue region; Sp. variable?
15(c)	46052	A2 V	A3 V	F0 V		A2, 3		A5, F2	Sr II 4077 absent or very weak, patchy G-band, quiescent phase
16	63589	A3 V	F2 III/IV	F2 III/IV	F5 III	A2, 3	A7	F0	
17	76756	A7 V	F0 III	F2 III/IV	F5 III	A3, 5	A5	F2, A7	K-line and metals ≈ A-Shell
18	78209	A3 V	F5 Ib	F5 III/IV	Ap	A1, 1.6, 2	F0, FO	F0 II/III, F5 IV, F2, F6 IV, F0 II	Sr II 4077, G-Band very strong; Spectrum variable?

Table 3. Continued.

No.	HD No.	Present classification			Sr II	*Earlier Classification			Remarks
		K	m 39	m 43	4077	K	H	M	
19	79193	A1 V	F5 III	F2 III/IV		A3, 4.2, 5	A7	F0, A9	m 43 ≈ A-Shell
20	82191	A2 V	F2 III/IV	A3 V		A1		F0	Weak Am
21(a)	93903	A2.5 V	F2 III/IV	F0 V	F5 III	A3			Ti II 4315 absent or weak
21(b)	93903	A3 V	A3 V	A3 V		A3			G-band enhanced; quiescent phase; Spectrum variable
22	95608	A1 V	A1 V	A3 V		A1	A4	A5	Weak Am or probably not an Am
23	209625	A7 V	F5 Ib	F0 III	Ap	A3.4, 4.6, 5	A8, 7, 9	A4, F2, 4, 0	Spectrum variable?
24	216608	A3 V	F2 III/IV	F2 III/IV	Ap	A2, 3	A8	F2	
25	221675	A7 V	F5 Ib	F2 III/IV	Ap	A2, 3, 5	A8	F2, 0	
26	222377	A3 V	F5 Ib	F2 III/IV		A3, 2.3, 2		F0	Sr II 4077 broad and strong
27	223438	A7 V	A7 V	A7 V		A5, 5			Weak Am or probably not an Am

* Curchod & Hauck (1979), ** Hoffleit (1982).

Table 4. List of luminosity sensitive features observed in the Am spectra.

Wavelength (Å) (blue region)	Element	Wavelength (Å) (violet region)	Element
4383–6	Fe I, II, Sc II, VI, Cr II	*4077	Sr II
4370–5	Cr I, Sc II	4072–3	Fe I, Cr I
4315	Ti II, I, Fe I	4063–6	Fe I, Fe I
*4305–8	Fe I, I, Ti I, II	*4046	Fe I, VII
*4300–2	Ti II, Fe I, Cr II	4032–4	Fe I, Mn I, VII
*4286	Ti II, Cr I	4005–7	Fe I, Ti I, Cr I
4272–5	Fe I, Ti I, Cr I	*3912–20	Ti I, Fe I, Cr I, VII
4261	Cr II	*3908	Cr I, Fe I, VI
		*3906	Si I, Cr II, Fe II
		*3872–3	Fe I, Fe I
		*3860–5	Fe I, Cr II, VII
		*3856	Fe I, VI

whenever necessary for determining their spectral types. These are not shown here but one can easily discern the behaviour of this line in each star from its corresponding figure. All the figures have been generated using the PS 386 computer of the Department of Astronomy, Osmania University. Table 4 gives some of the spectral features showing a positive luminosity effect in our spectra at 66 Å/mm along with those indicated by Abt & Morgan (1976), seen at 125 Å/mm. The features marked with the asterisks are indicated by them as luminosity sensitive and the remaining ones, in particular, 4383–4386 Å and 4315 Å in the blue and 4032–4034 Å and 4005–4007 Å in the violet, are also found to show a pronounced positive luminosity effect in our spectra. These lines are identified from a finding list given by Moore (1945) and Jaschek & Jaschek (1960).

4. Summary of the results

The results from the MK morphology of our sample of 27 Am stars summarized in Table 3, are described below:

(1) Almost all the stars are dwarfs according to the K-line profiles. They range from A1 V–A7 V in our sample. At least 50 per cent of the spectral types assigned to the K line by us are in agreement with one of the types assigned by different authors. However, for the rest, ours vary by 1 to 3 sub-classes from the earlier classifications which show a scatter of at least two sub-classes. The dwarf nature of Am stars is also confirmed by Smith (1971) from a study of the spectroscopic gravities of these stars.

(2) Nearly 80 per cent of the sample show the pseudo-luminosity effect. The violet region of the metallic-line spectrum gives a spectral type ranging from F0 III to F5 I and in the blue region, more than two-thirds of the stars give a spectral type F2 III/IV while about one-third resemble F and A type dwarfs. The spectral types indicated by the blue region are somewhat different from those of the group studied by Abt & Morgan (1976). This does not appear to be the ‘dispersion effect’ and could perhaps be due to the objective method that we have adopted.

(3) About two-thirds of the stars in (2) exhibit a strong Sr II 4077 Å line giving a brighter luminosity class than for the rest of the spectrum and half of these are as strong as those in the Ap stars. Among these, HD 27749, HD 78209 and HD 209625 might show spectrum variability since the metallic-line spectral types for these as given by various authors show a large scatter. It is significant that these stars are either cooler extensions of the Ap stars or perhaps similar to the "strontium" group. This latter observation, if confirmed, would be in contrast to one of the Am classification criteria given by Roman, Morgan & Eggen (1948), described in Section 1. The scatter in the K-line and metallic-line types, however, does not arise purely from the inadequacies or inconsistencies in classification schemes, but appears to be mainly due to the probable intrinsic spectral variation, associated with these systems.

(4) HD 11636 (also an MK standard), HD 20320, HD 40932, HD 76756 and HD 79193 exhibit, in different spectral regions, the strength and sharpness of metallic lines similar to that of the extreme A-shell spectrum of HD 41511, illustrated by Morgan, Abt & Tapscot (1978). Especially, the entire metallic-line spectrum of HD 40932 and HD 76756, including the K line, resembles that of HD 41511 at JD 244 7131.38, although neither their Sr II 4077 Å and the Fe II, Fe I 4383–4386 Å features show the negative luminosity effect seen in the A-shell spectrum, nor the H lines exhibit cores similar to those in the A-shell spectrum. A good match between the spectra of HD 76756 (65 Cnc) and HD 41511 (17 Lep) is shown in Fig. 28. The low level Ti II lines near 3760 Å, standing out in strength in 17 Lep, are also seen in our spectra besides Ti II 3901–3903 Å, Ti II, Fe II, Y II 4172–4179 Å and Fe II 4233 Å. However, the Sc II 4246 Å line which is quite strong in the shell spectrum is not as strong in Am stars while the Sr II 4078 Å line which is strong in Am stars is almost imperceptible in the A-shell spectrum. But, in some Am stars the Sc II 4246 Å line is not weak according to Jaschek & Jaschek (1960). Also the Ti II, I, blend at 4316 Å is weak and the Ti II 4391–4396 Å is strong in the A-shell spectrum whereas these lines appear strong in some Am stars only. Both these features of the spectrum indicate their shell characteristics as found by us. It may be mentioned that, although HD 4151.1 is classified as A0 V-shell, its K line actually corresponds to an A7 class like HD 40932. The line obviously arises from the shell and cannot be used to classify the underlying star. Also, metallic lines of this star appear to be too sharp for its rotational velocity of 98 km s^{-1} compared to the 15 km s^{-1} of HD 40932.

(5) Less than 20 per cent of the stars in our list do not show any significant differential luminosity effect. Some of these stars are marginal or weak Am stars and some are likely to be at a quiet phase if those are also spectrum variables. For example, WW Aur is listed as a weak Am star by Cowley *et al.* (1969); obviously it was observed at its quiet phase. The segregation of weak Am stars in our list agrees well with that for the same stars by Cowley *et al.* (1969). The three stars, HD 11636, HD 12869, HD 20320, classified as marginal Am by them are, however, found by us to be Am stars; these require a detailed study. It was suggested that weak Am stars are associated with slightly larger rotational velocities (Jaschek & Jaschek 1987), but all the weak Am designates in our list have rotational velocities normal to Am stars. A surprise entry is HD 32667; with a rotational velocity of 200 km s^{-1} this star also shows Am characteristics. According to Jaschek (personal communication) the rotational velocity of this star might have been overestimated. These observations are in conformity with Kurtz's (1978) conclusion that temperature, age and rotation are insufficient to predict whether a particular metallic-line star will have pronounced or mild metallic

line strength anomalies. He, however, invokes pulsation, among other factors, to determine whether a star belongs to one group or the other. According to him Am stars do not pulsate whereas δ Delphini stars and weak Am stars may pulsate.

(6) Our sample covers a wide range of magnitudes, colours, projected rotational velocities, spectral types and binary nature in the Am domain. These parameters and the discriminating characteristics exhibited by this diverse group, described in (l)–(5) above, can be considered as prima facie evidence that the stars constituting this group define various facets of the Am phenomenon. And our classification should be valid even at higher dispersions.

5. Discussion

5.1 *Duplicity*

In our sample at least 30 per cent of the Am stars are either single or yet to be discovered as double. Abt (1961) reported almost 100 per cent duplicity in a sample of 25 Am stars studied by him. Batten (1961) reobserved the same sample and found that only 17 are confirmed doubles. Of the remaining eight, 5 have low amplitude and 3 are found to have constant radial velocities. Abt later clarified that only 16 of the 25 stars show strong Am characteristics. Conti & Barker (1973) studied 5 stars in Coma cluster, all of which showed Am characteristics but only 2 out of these exhibited duplicity. Out of the 4 Am stars (HR 905, HR 3040, HR 5892 and HD 434) studied by us earlier, only one star, HD 434, had turned out to be a binary. This sample is obviously too small for arriving at any definite conclusion and it is not possible to conclude that any specific star is single since its binarity is revealed only at a favourable angle of inclination. However, Conti & Barker (1973) argue that out of many an Am star which have constant velocity at least some are likely to be single. It is therefore certain that although the duplicity among Am stars is high, nearly 30% comprise either single stars or doubles that do not reveal the binary nature due to the unfavourable angle of inclination of their orbits. Some Am stars are members of long period binaries, such as HD 434 (P = 34 days) and β Ari (P = 103 days), which is against the scenario where tidal braking of rotational velocities in a close binary ($P < 10$ days) allows diffusion process to set in for a possible display of Am characteristics. Also, according to Abt (1979) some Am stars in Orion OB 1 association have large rotational velocities of the order of 200 km s^{-1}. Burkhart (1979) concludes that although many peculiar stars have $v \sin i < 55$ km s^{-1}, there is no smooth relation between rotation and metallicity. Therefore, if slow rotation is not a necessary condition for metallicity then it obviates the necessity of their being members of a closely spaced binary as envisaged by Abt (1979).

5.2 *Spectrum Variation*

Those stars, in our sample, for which metallic-line classification between various authors show a large scatter, could be potential candidates for spectrum variation. From scanner observations of Am stars made at different epochs Böhm-Vitense & Johnson (1978) found significant variation in the energy distribution for four Am stars including τ UMa and concluded that all Am stars are probably variable on a long time scale. Lane & Lester (1980) observed several Am stars and did not find any variation except in the case of τ UMa. However, spectrum variation in HD 93903 (41 Sex A) is shown in Figs 21(a) and (b) (see Appendix), where it is seen that the K-line strength reduces while those for the metals, in particular the Sr II 4077 Å line, enhance from its orbital phase 0.37 to 0.54. Another star in our sample, HD 46052 (WW Aur), varies significantly among the three spectra (Figs 15(a), (b) and (c)) taken in a span of a few days. We have found it as a weak Am star at its orbital phase 0.824 and gains in its metallicity around 0.0 phase. The disappearance of the Sr II 4077 Å line at its quiet phase is dramatic, similar to that in 41 sex A, and this is a positive evidence in support of its spectrum variability. Earlier, Kitamura, Tu-Hwan & Kiyokawa (1975) reported 30 per cent variation in the strength of some lines in its spectrum. These changes seem to be correlated with the orbital phase as in 41 Sex A. The classical Am star 63 Tau (HD 27749, Fig. 7), does not show any variation between its two spectra taken on consecutive nights, although it is associated with a large scatter in its metallic-line type as given by various authors. This star, therefore, might show variability on a longer timescale than a few days. Besides the two clear cases of spectrum variation mentioned above, we have also indicated that HD 27749, HD 78209 and HD 209625, all of which display a strong Sr II line, are probable spectrum variables since their metallic-line types assigned by different authors show a large scatter. A detailed study of these systems might show a similar spectral behaviour as in 41 Sex A. Once again HD 78209 is a single Am star and the rotational braking in this system might be due to some other process. If the predicted spectrum variability is confirmed in the above systems then the characteristic discriminant appears to be the strong Sr II 4078 Å line, similar to that in Ap stars, and the resemblance of the violet metallic-line type to that of an F supergiant.

41 Sex A is reported by Sreedhar Rao, Abyankar & Praveen Nagar (1990) as a phase-modulated spectrum variable, a new prototype in the Am class. Its metallic-line spectrum intensifies strongly around its orbital phase 0.25 and 0.75, which coincides with the conjunction. However it is a single-lined star and the estimated secondary spectral type K 5 makes it 7 magnitudes fainter in the blue. So its contribution to the line strength will be negligible and the whole variation appears to be intrinsic to the primary. Also, Greenstein (1949) rules out the possibility of superimposition of spectra of two stars for the observed metallic-line characteristics in similar cases. Hence it is necessary to invoke threshold magnetic fields in 41 Sex A type Am stars so that the degree to which the radiative diffusion process (Michaud 1970; Michaud *et al.* 1981) can occur would be sufficient to drive specific elements selectively upwards, along the vertical magnetic lines of force, to form abundance patches representing the surface magnetic field geometry. Similar arguments may hold good for the variation in another binary WW Aur (HD 46052). However, Borra & Landstreet (1980) showed that the magnetic fields measured in Am stars are near the limit of observing errors and substantially smaller than in Ap stars. About the observed abundance anomalies in 41 Sex A, L. Mestel (private discussion) relates these to the possible presence of dynamically active but optically undetectable fossil magnetic fields. It will be fruitful to look for the magnetic fields in 41 Sex A, WW Aur and other suspected spectrum variables among Am stars.

Now, the degree of abundance anomaly is apparently proportional to the degree to which diffusion occurs which in turn depends upon the strength of the magnetic field which stabilizes mass motions and influences the diffusive separation of elements. Although it appears to be a fragile process in the complex atmospheres of Ap and Am stars, the diffusion hypothesis is in fact the best available one (Cowley 1981) for explaining the abundance peculiarities and spectrum variation in these stars.

5.3 *Shell Characteristics*

The stars in our sample which show shell characteristics have strong Ti II and Fe II lines. Similarity between the Am and the shell spectra is particularly relevant to Böhm-Vitense's (1960) analysis of the outer layers of an Am star which are more distended as a result of nongravitational forces. She concludes that only magnetic fields seem responsible for this effect. Abt & Moyd (1973) suggest that all rapidly rotating A stars can develop shell structures at some time. If this is confirmed, then the star has to slow down in its shell due to some mechanism so as to exhibit the Am characteristics similar to those discussed above. This could perhaps explain the presence of single Am stars. Jaschek, Jaschek & Andrillat (1986) reobserved a part of their sample and did not find new shell stars. According to them, there are rich and poor shells and the shell features are slowly varying with time. However, Greenstein's (1949) analysis of the metallic-line star τ UMa shows that dilution effects are not present when a comparison is made between the strength of lines from normal and excited metastable levels of Fe I. Therefore, the metallic lines do not originate in an extended envelope or circumstellar shell. Smith (1971) studied microturbulence and abundances in Am stars. Of these the lines of HR 1458 (88 Tau) show possible dilution effects associated with extended atmospheres. However, Böhm-Vitense (1980) demonstrated unambiguously that a lower density in the upper layers of the atmosphere cannot be the explanation for the weakening of Ca II since the Mg II h and k lines in Am and normal A type stars are indistinguishable from each other. Although this absence of a shell satisfies one of the Am criteria defined by Roman *et al.,* the problem of circumstellar envelopes in A-type stars and their connection, if any, with the emergence of Am stars deserves a detailed study. From their infrared observations of a sample of Am stars, Professor C. Jaschek confirms our findings that some Am stars look like shell stars (Personal communication).

6. Conclusions

All Am stars should exhibit a pseudo-luminosity effect, perhaps in differing degrees, irrespective of the dispersion at which they are observed. The degree to which this effect is present in an Am star at any time might probably depend on its stage of evolution and the structure of the circumstellar shell, if present. An important spin-off from this study is the emergence of 41 Sex A as the prototype of spectrum variables among Am stars. WW Aur, δ Cap (Kitamura & Okazaki 1977), 3 Oph (Abt & Levy 1985), and 32 Vir (Abt 1961; Eggen 1976), are some of the potential candidates which might belong to this group besides those discussed by us in Section 4 (3).

Greenstein (1949) argues against probable shell structure based on his study of a single Am star τ UMa. It is worthwhile to pbtain its spectra again for a fresh study. Also a detailed study of the objects with shell characteristics in our sample, may see us out of this shell syndrome.

According to Jaschek & Jaschek (1960) and Cowley & Henry (1979), no two Am stars are identical and no families or groups are found among these stars. Our study, however, shows a distinct possibility of the presence of groups among the Am stars like for instance, the weak Am stars without any perceptible spectrum line variation, Am stars with strong Sr line associated with probable phase-modulated spectrum line variation which are the most likely candidates to show abundance patches and finally, those with distended atmospheres exhibiting shell characteristics. It is also evident from this investigation that a morphological study of Am spectra might obviate the necessity to study pulsation for segregating the Am from weak Am stars. It appears that MK morphology of several spectra of the same star, taken at different times, with the same system, might reveal discriminating characteristics of these enigmatic stars, which might have otherwise escaped attention.

This analysis has brought to light various manifestations of Am phenomenology which have to be studied in detail for further confirmation and a better understanding of the Am phenomena.

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Appendix

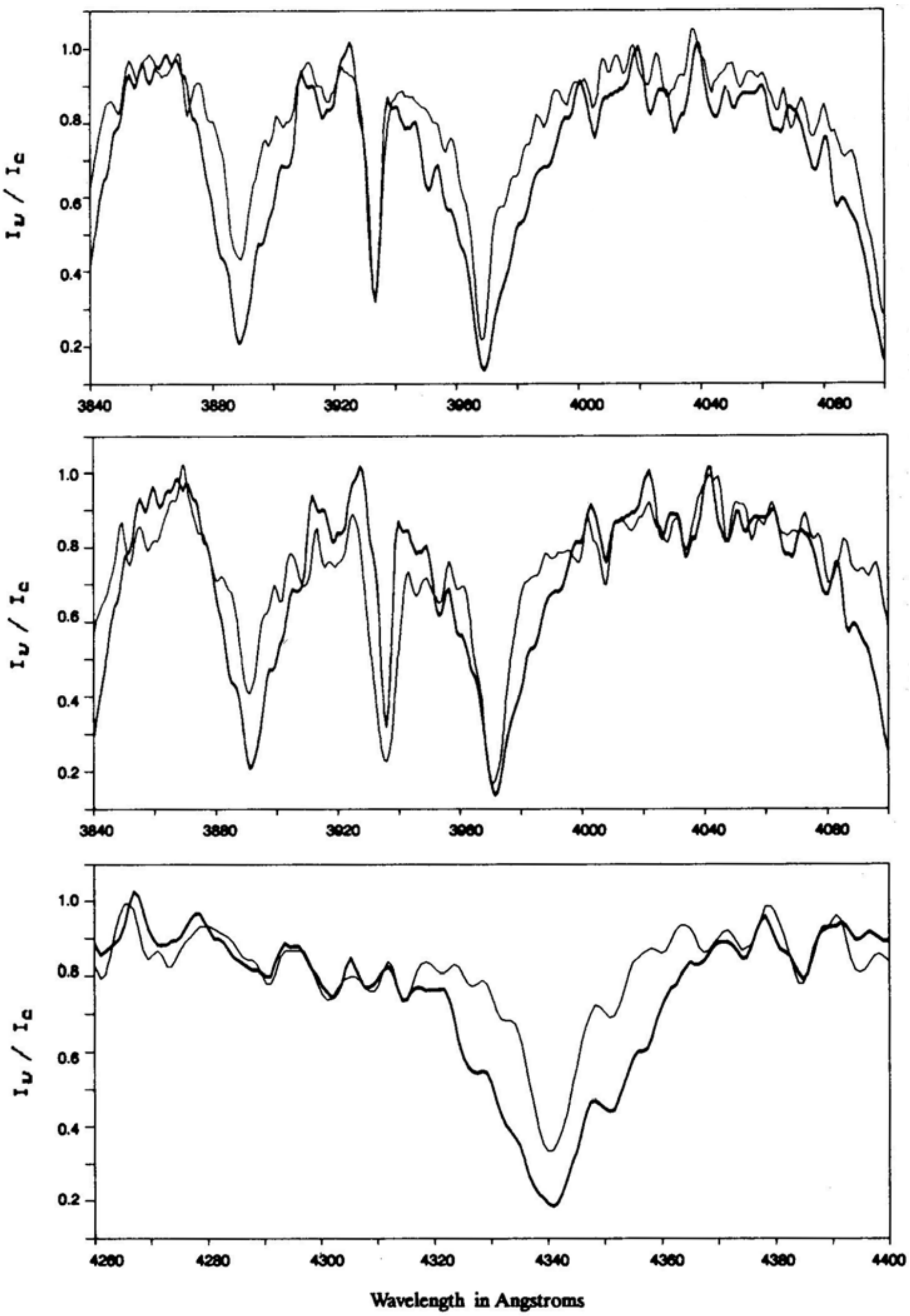

Figure 1. K-line (top) *m* 39 (middle) and *m* 43 (bottom) regions of HD 11636 (thick line) compared with the MK standards given in Table 3.

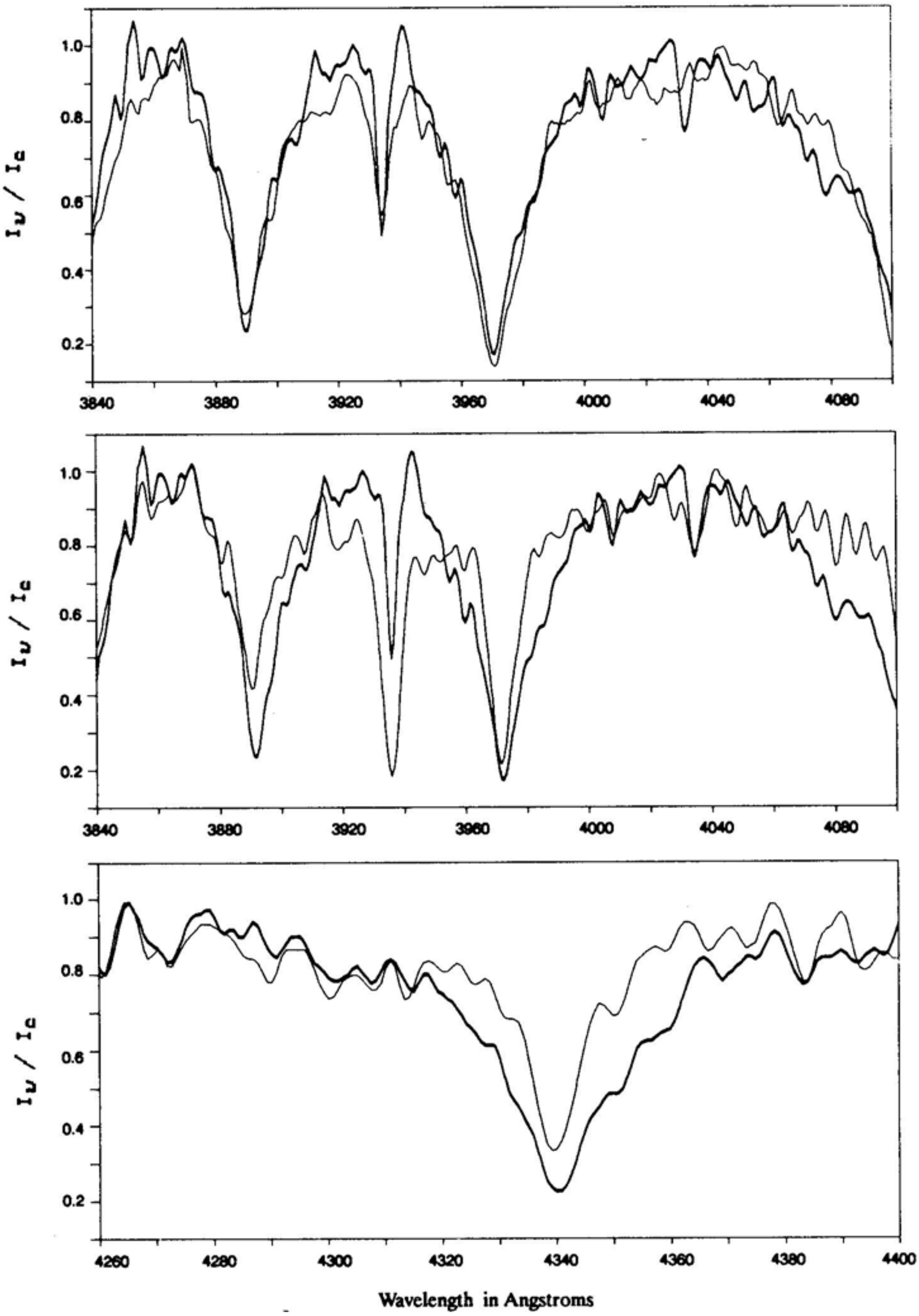

Figure 2. Same as Fig 1 for HD 12869.

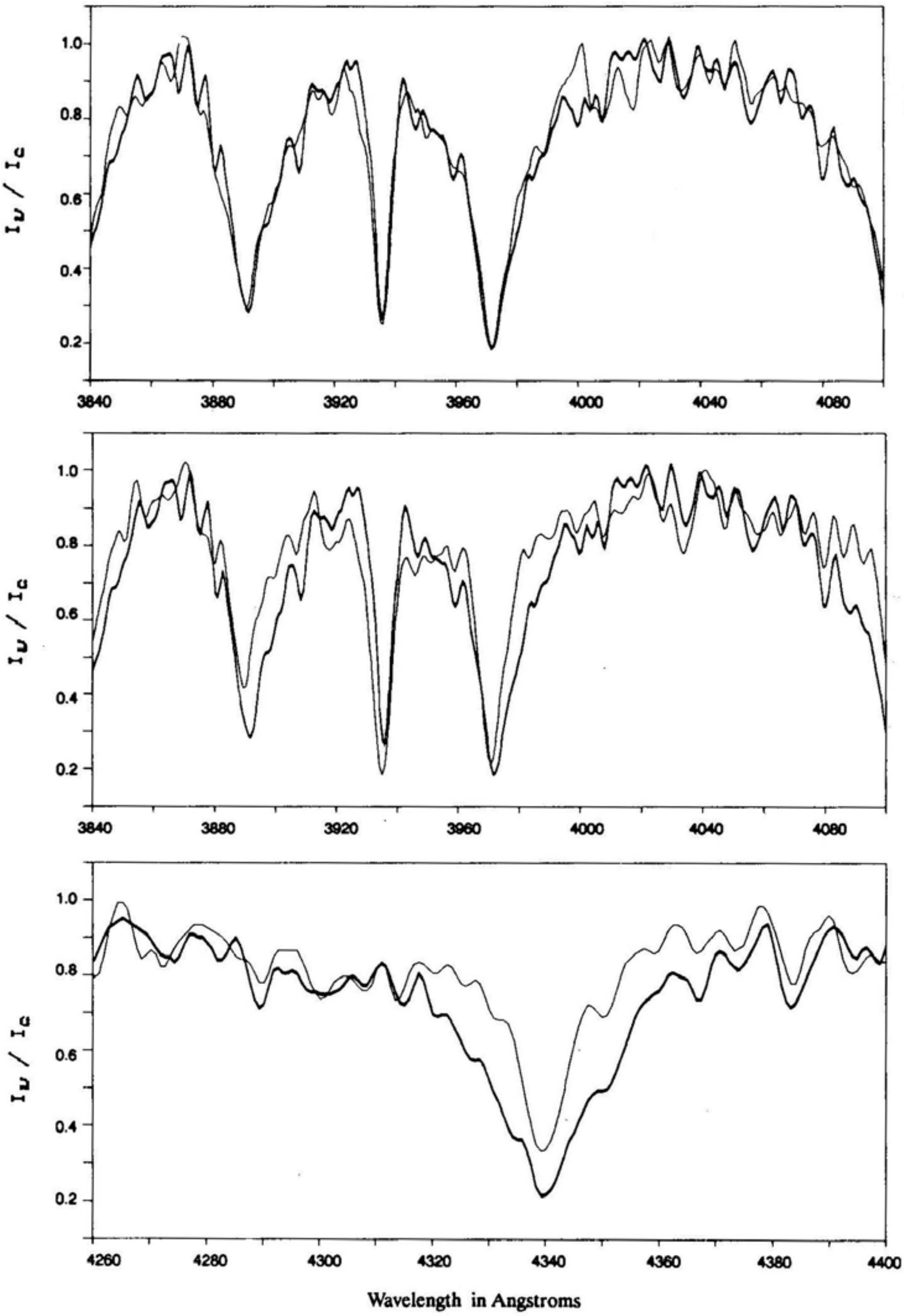

Figure 3. Same as Fig. 1 for HD 15385.

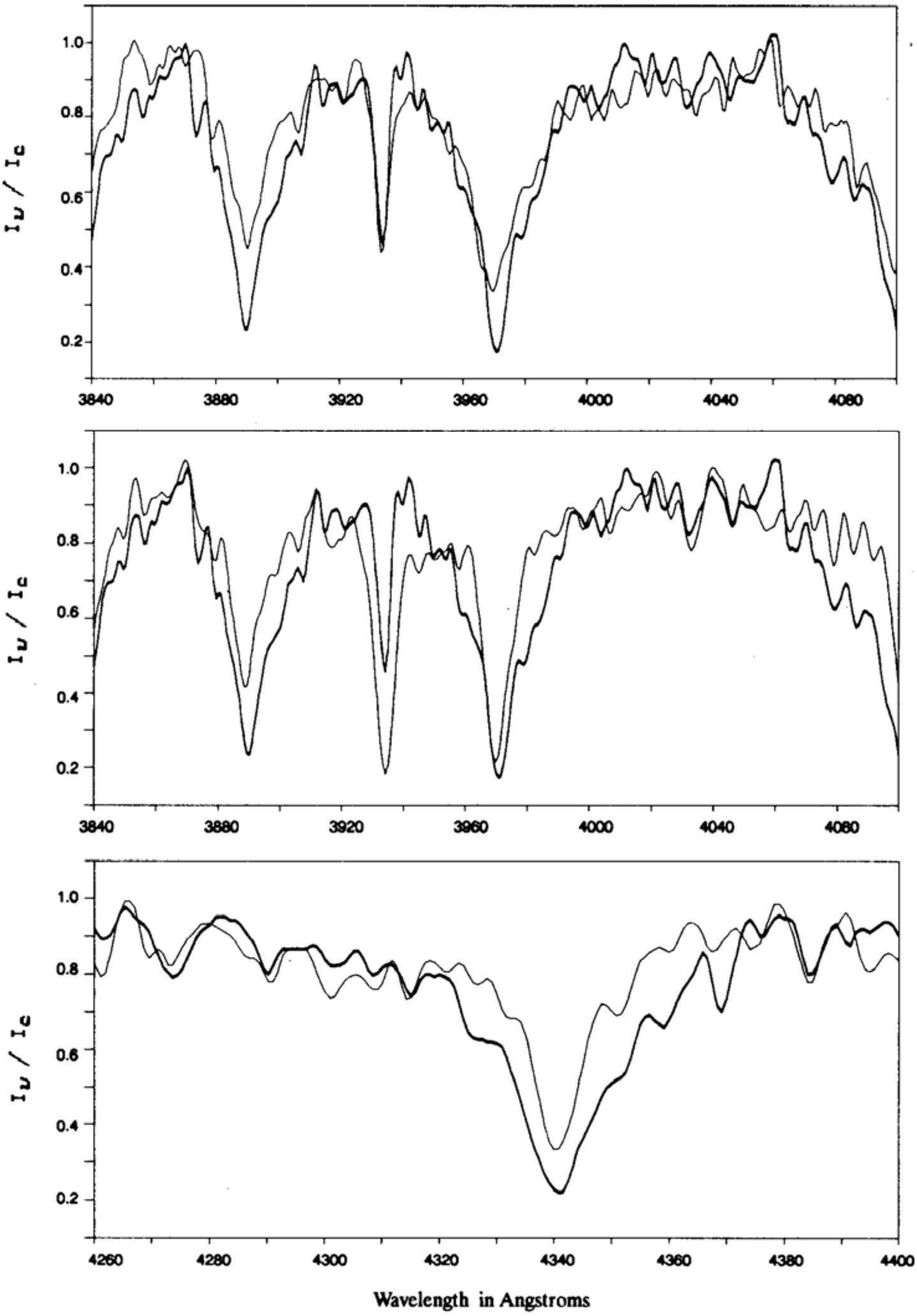

Figure 4. Same as Fig 1 for HD 18769.

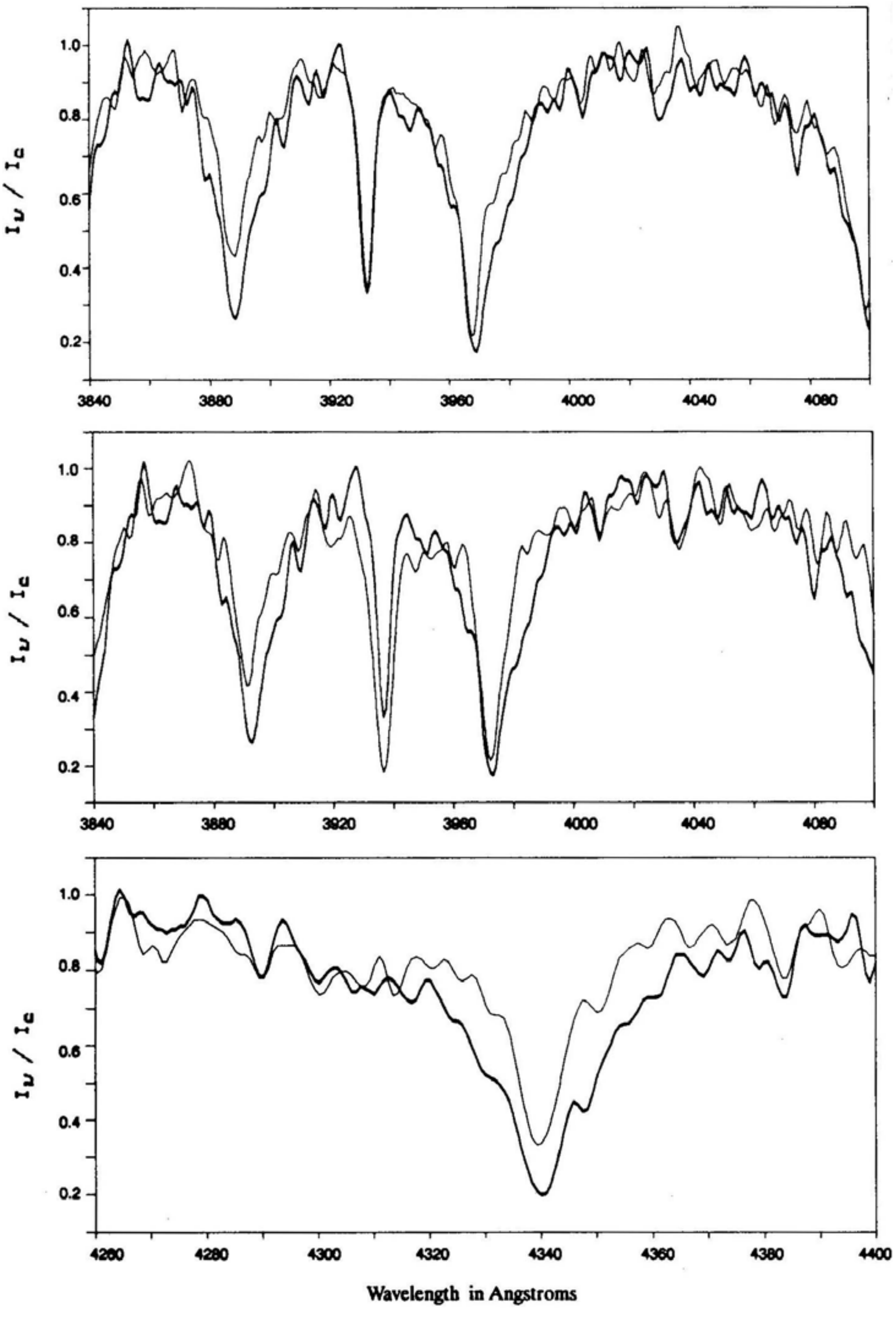

Figure 5. Same as Fig 1. for HD 20320.

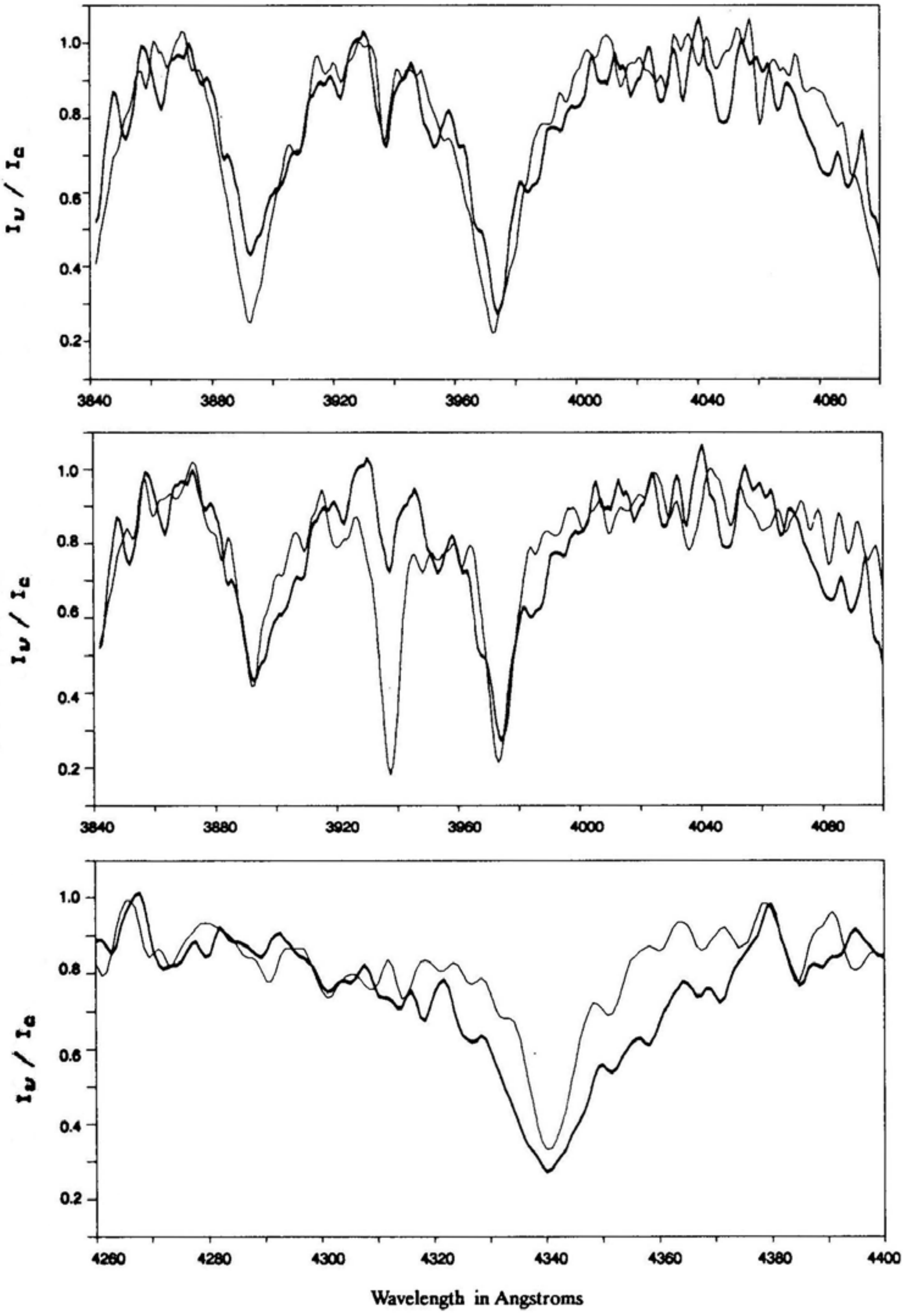

Figure 6. Same as Fig 1. for HD 26591.

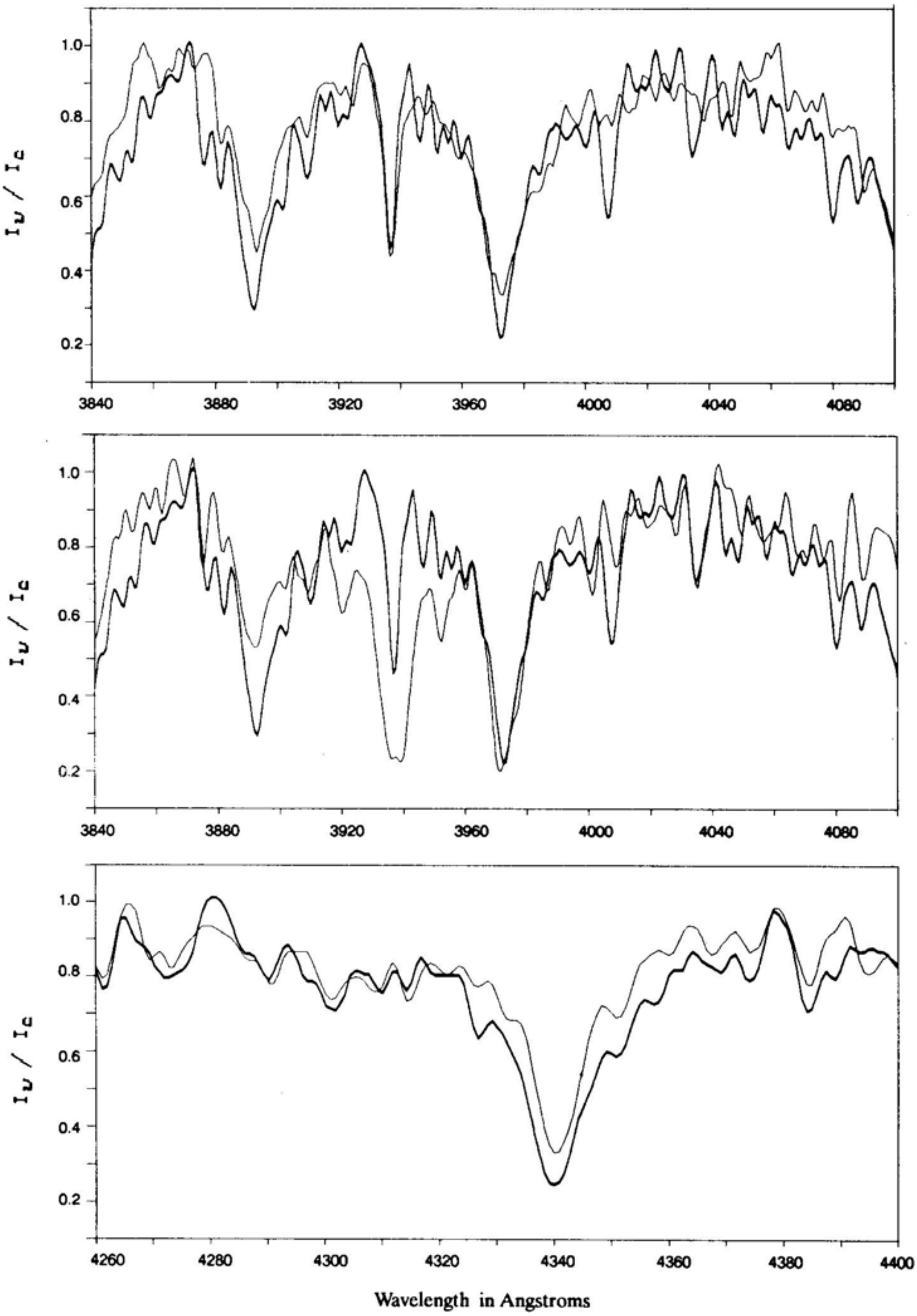

Figure 7. Same as Fig. 1 for HD 27749. Another spectrum of this star taken on the following night looks identical.

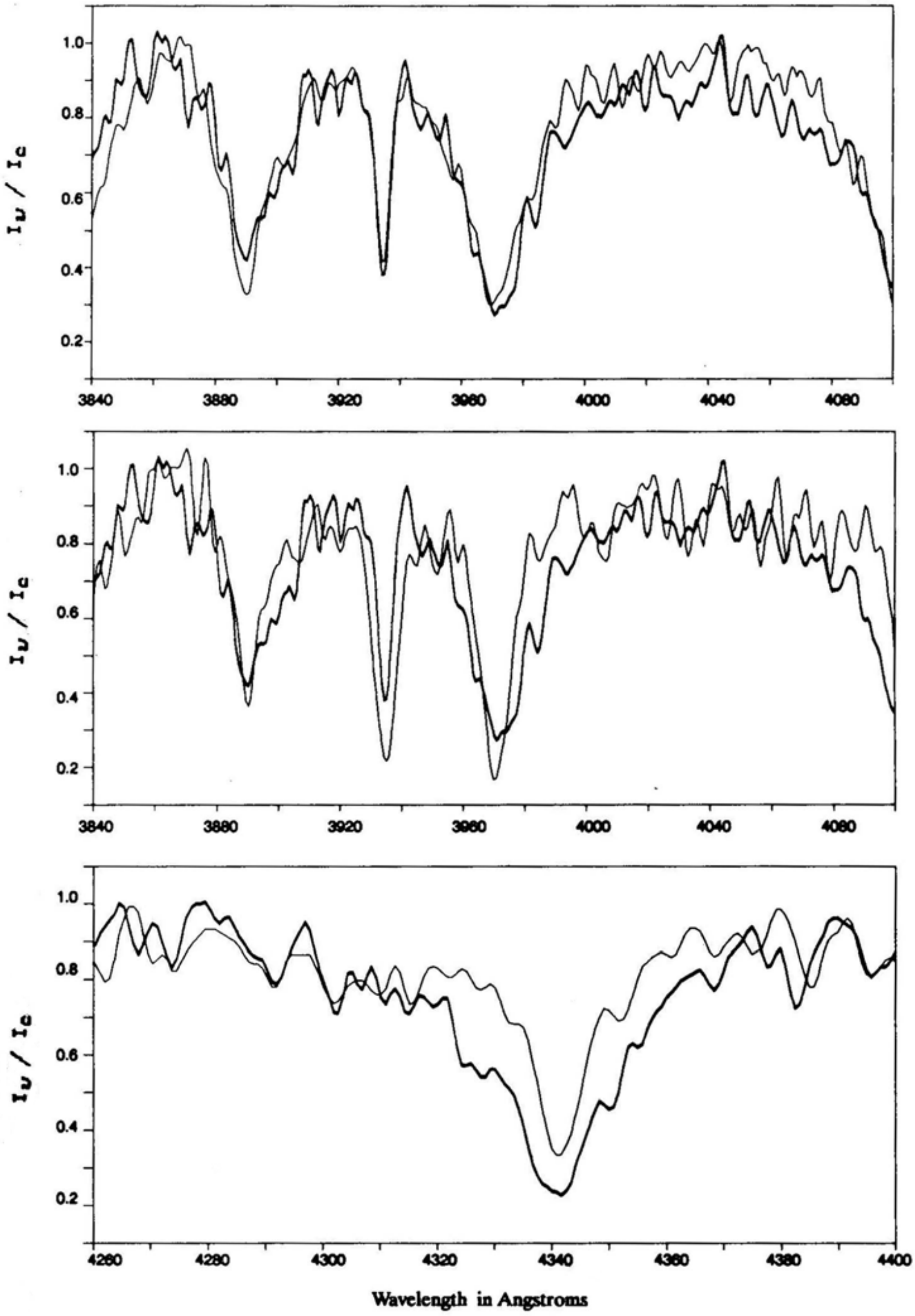

Figure 8. Same as Fig. 1 for HD 32667.

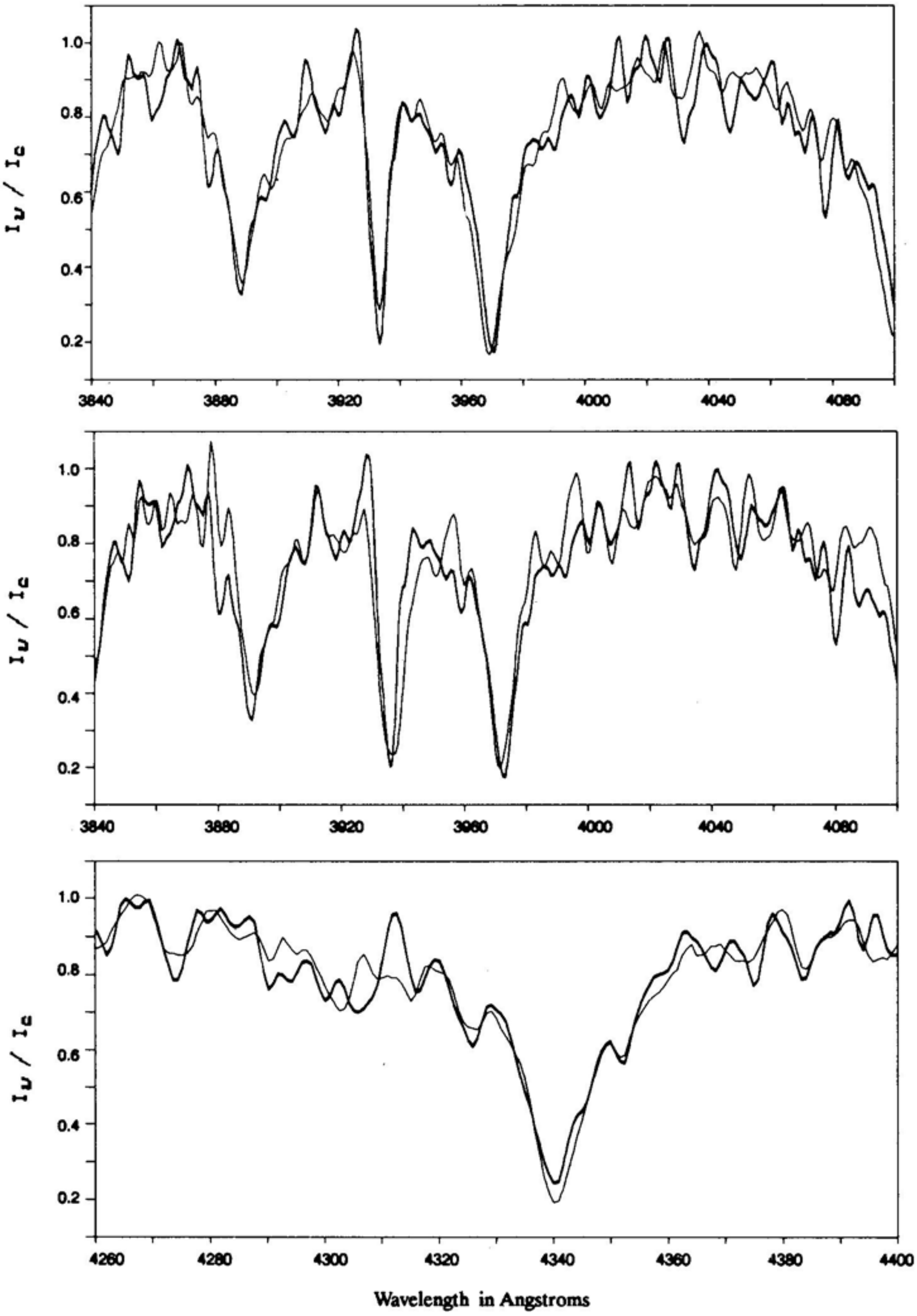

Figure 9. Same as Fig. 1 for HD 40372.

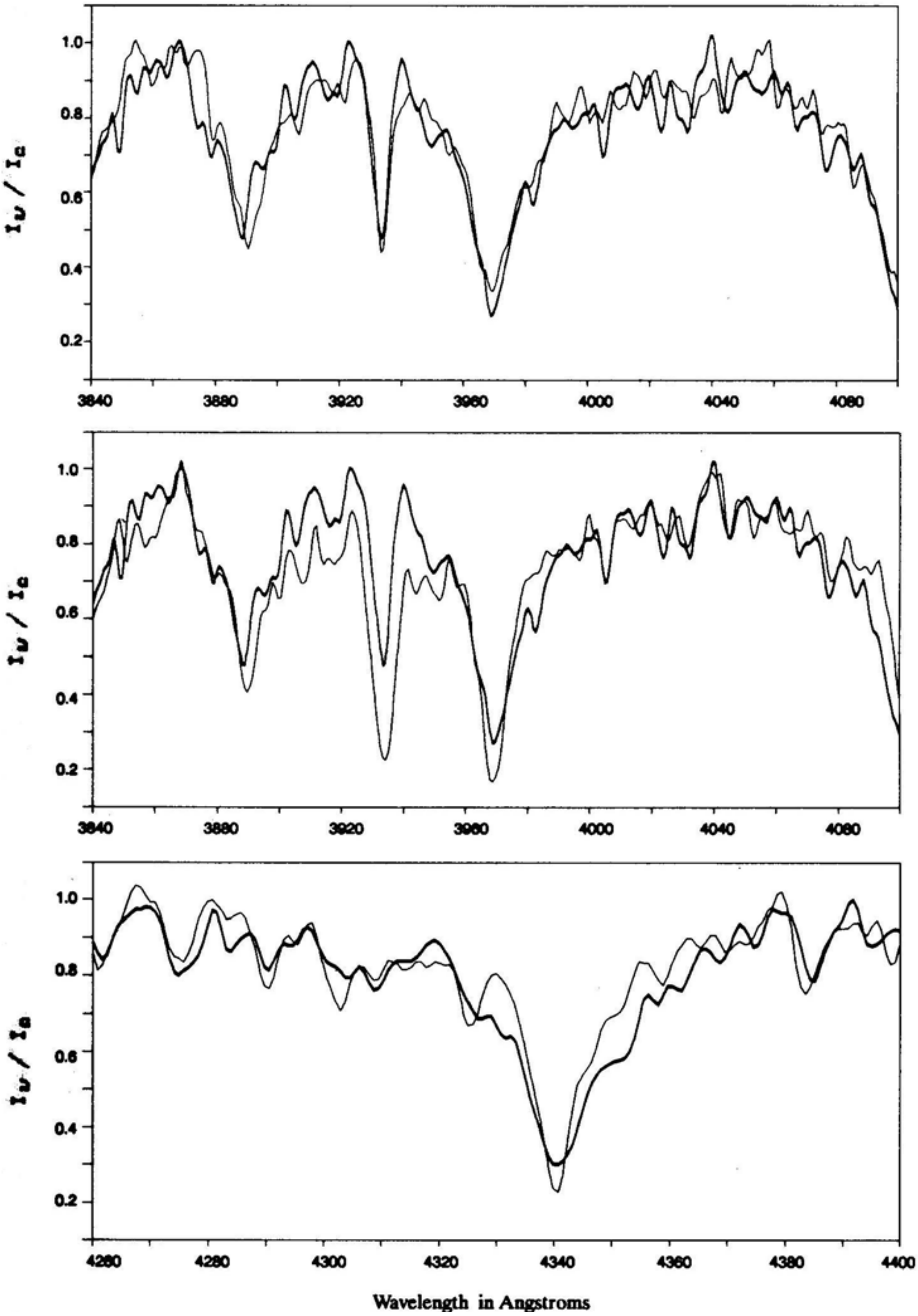

Figure 10. Same as Fig. 1 for HD 40536.

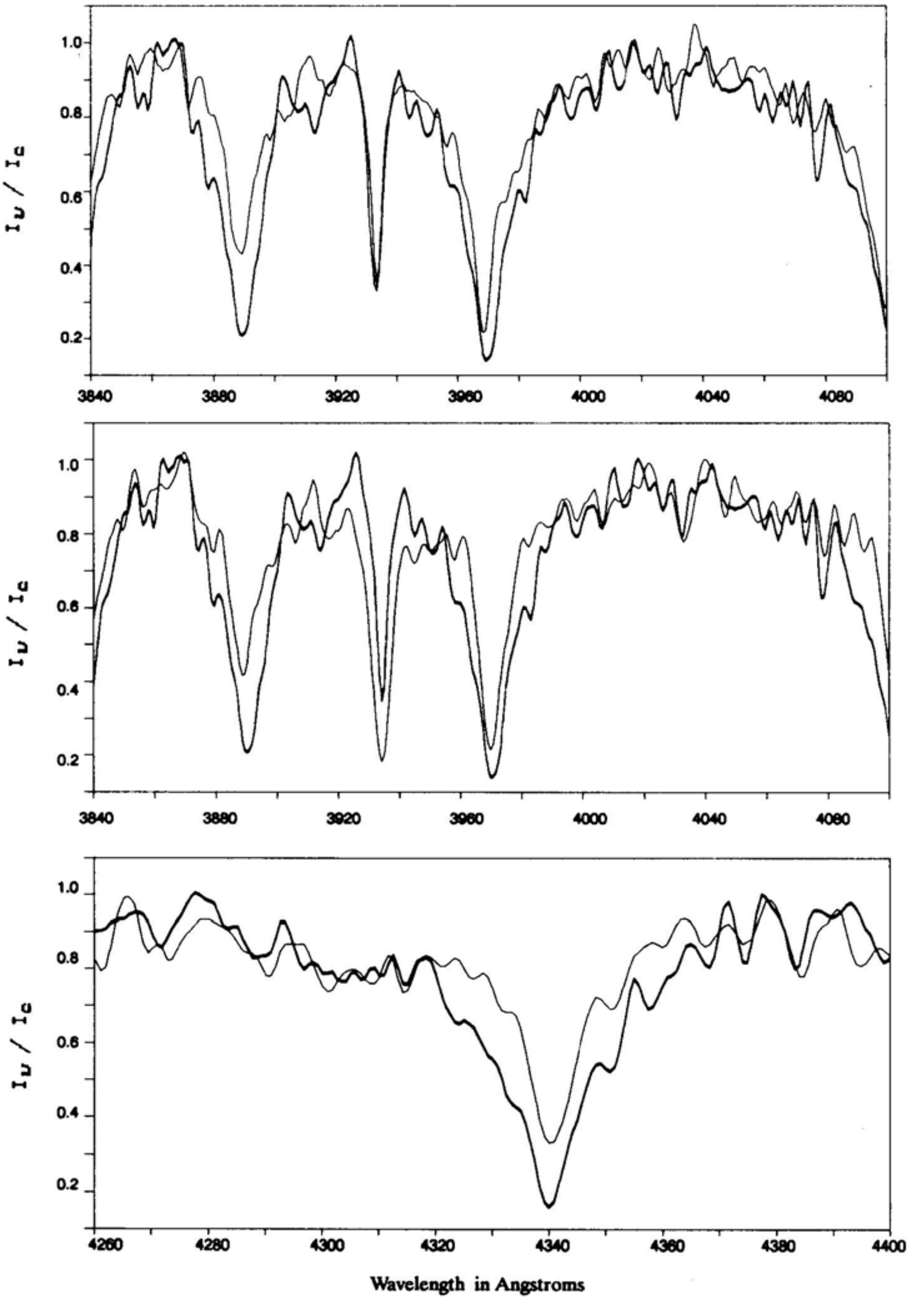

Figure 11. Same as Fig. 1 for HD 40932.

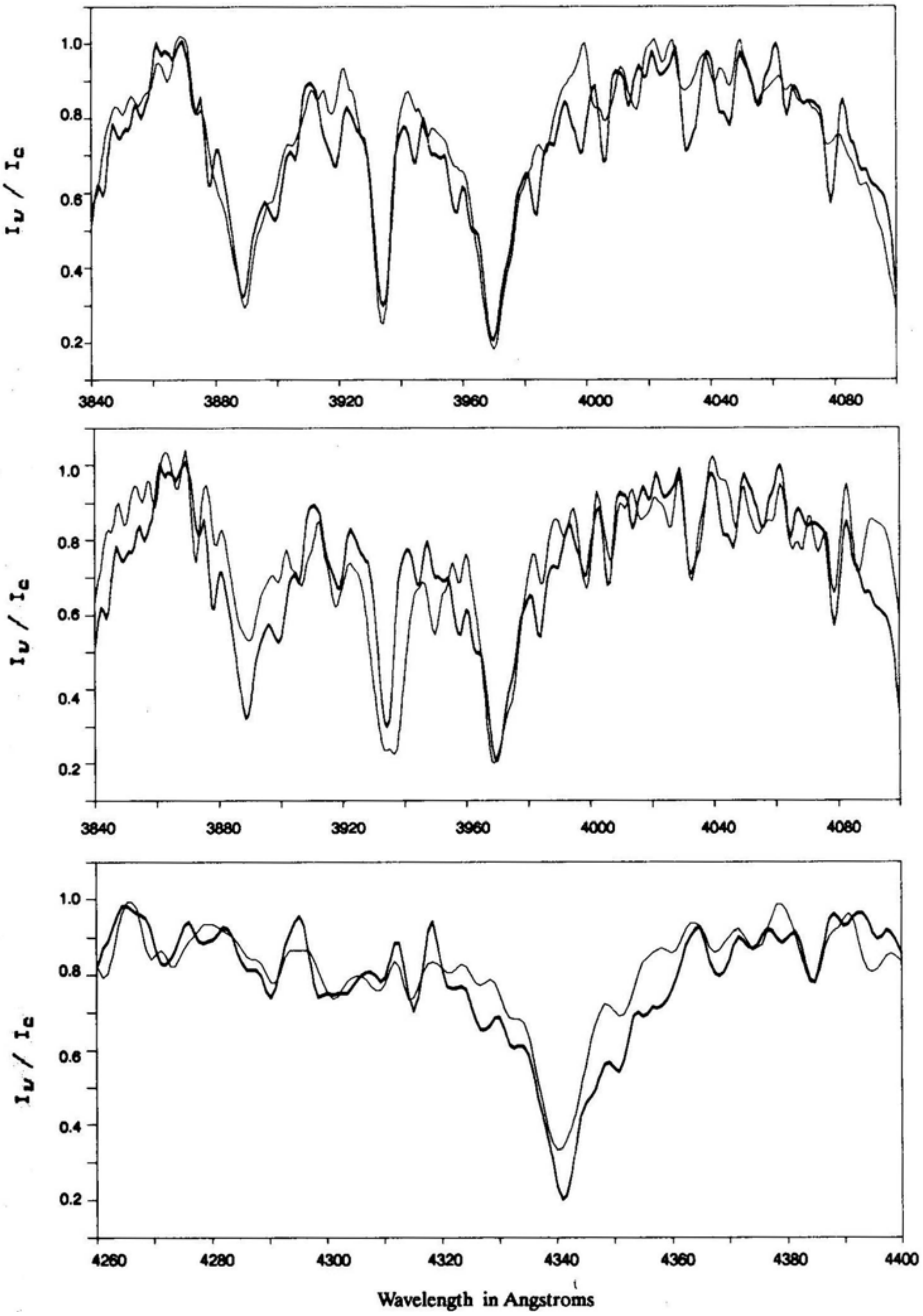

Figure 12. Same as Fig. 1 for HD 41357.

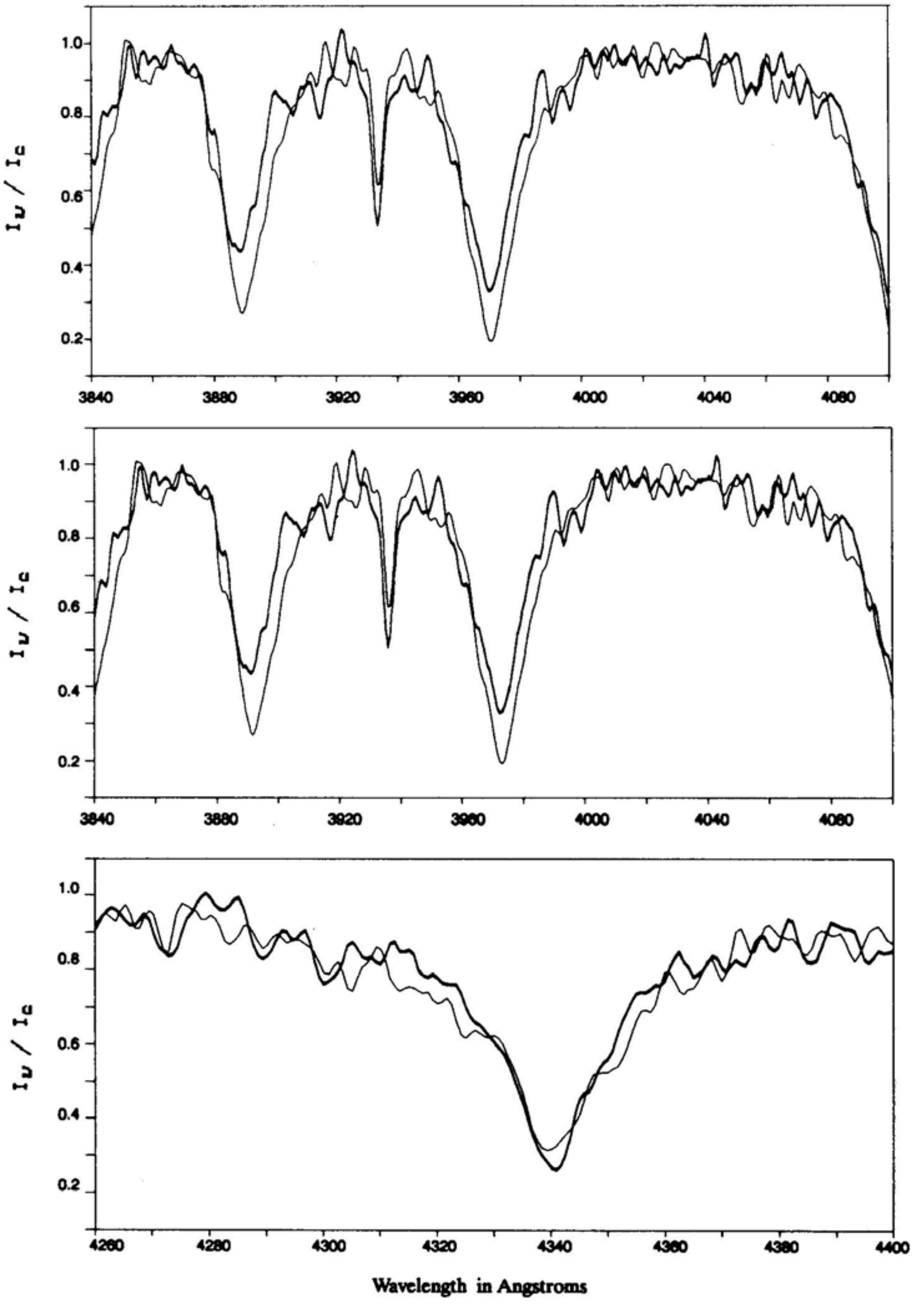

Figure 13. Same as Fig. 1 for HD 41841.

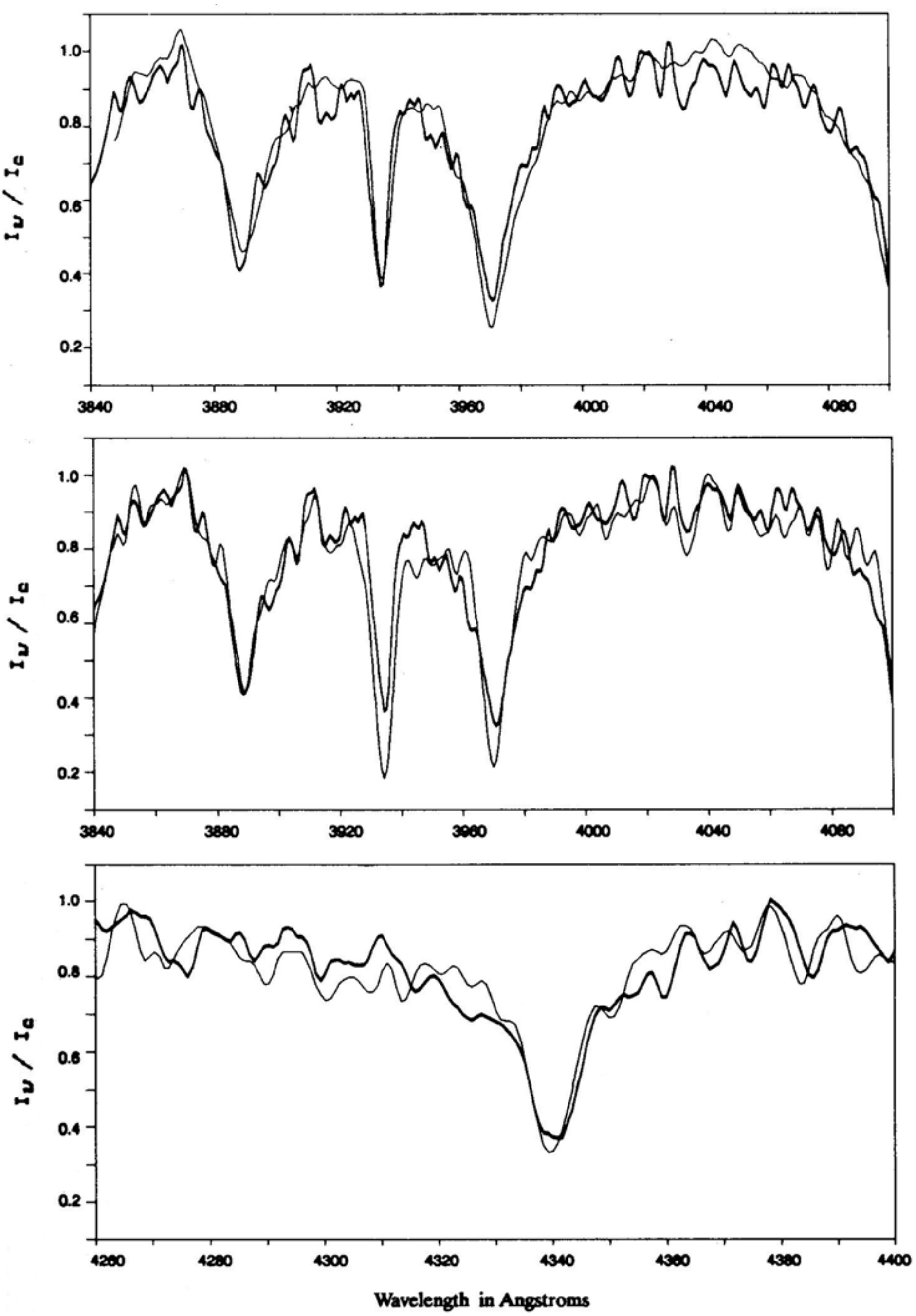

Figure 14. Same as Fig. 1 for HD 42954.

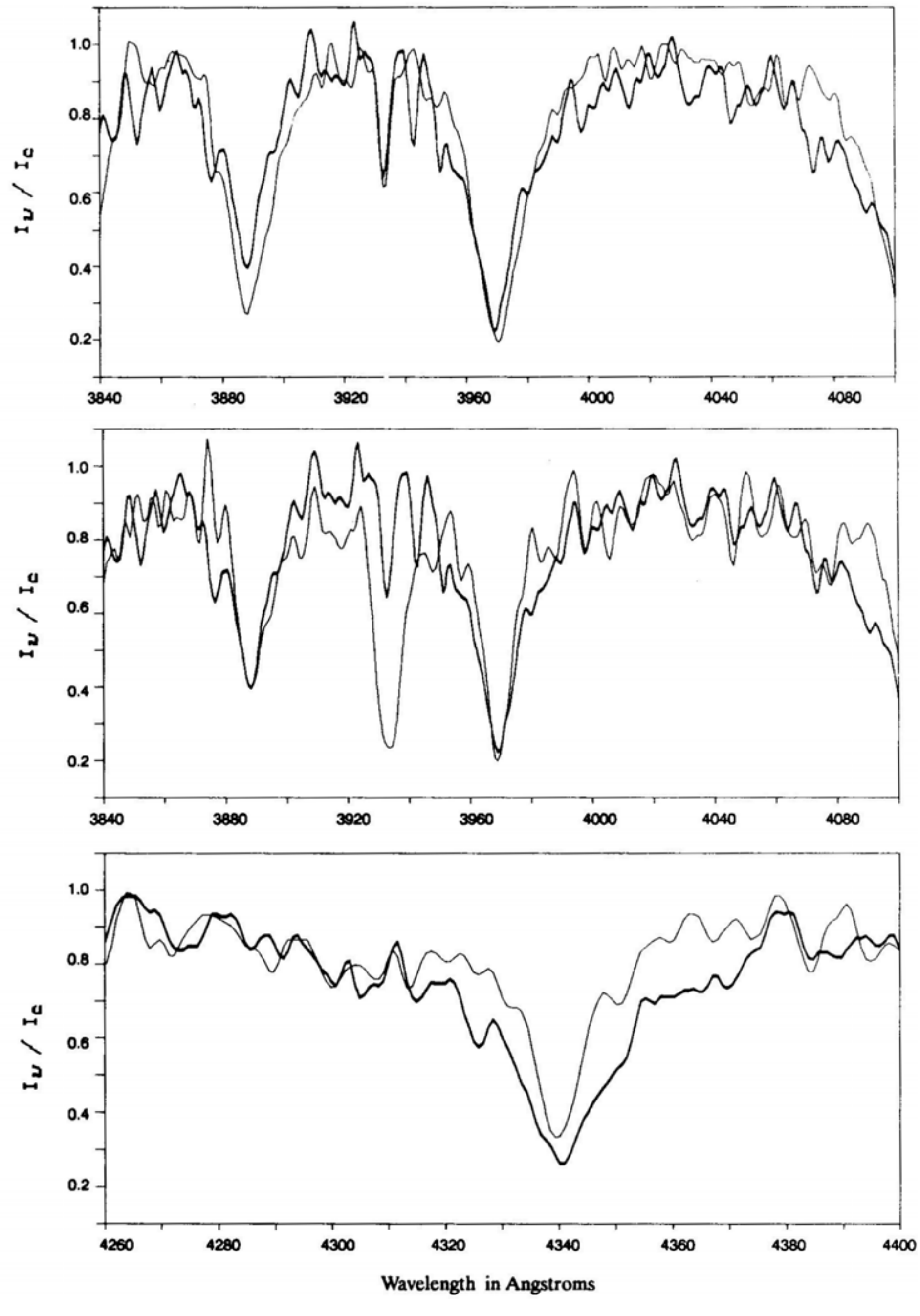

Figure 15(a). Same as Fig. 1 for HD 46052. (Orbital phase 0.097).

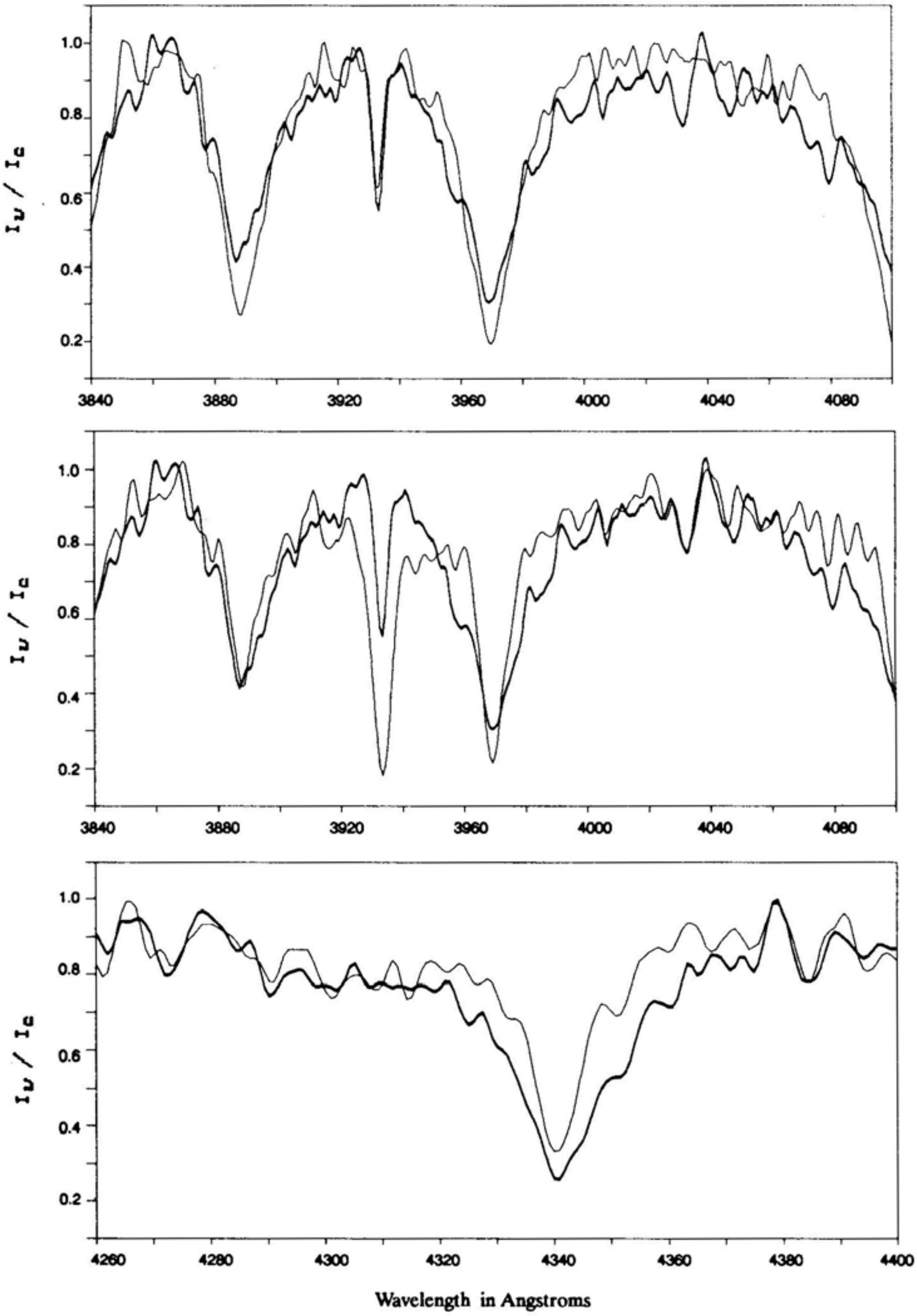

Figure 15(b). Same as Fig. 1 for HD 46052.(Orbital phase 0.988).

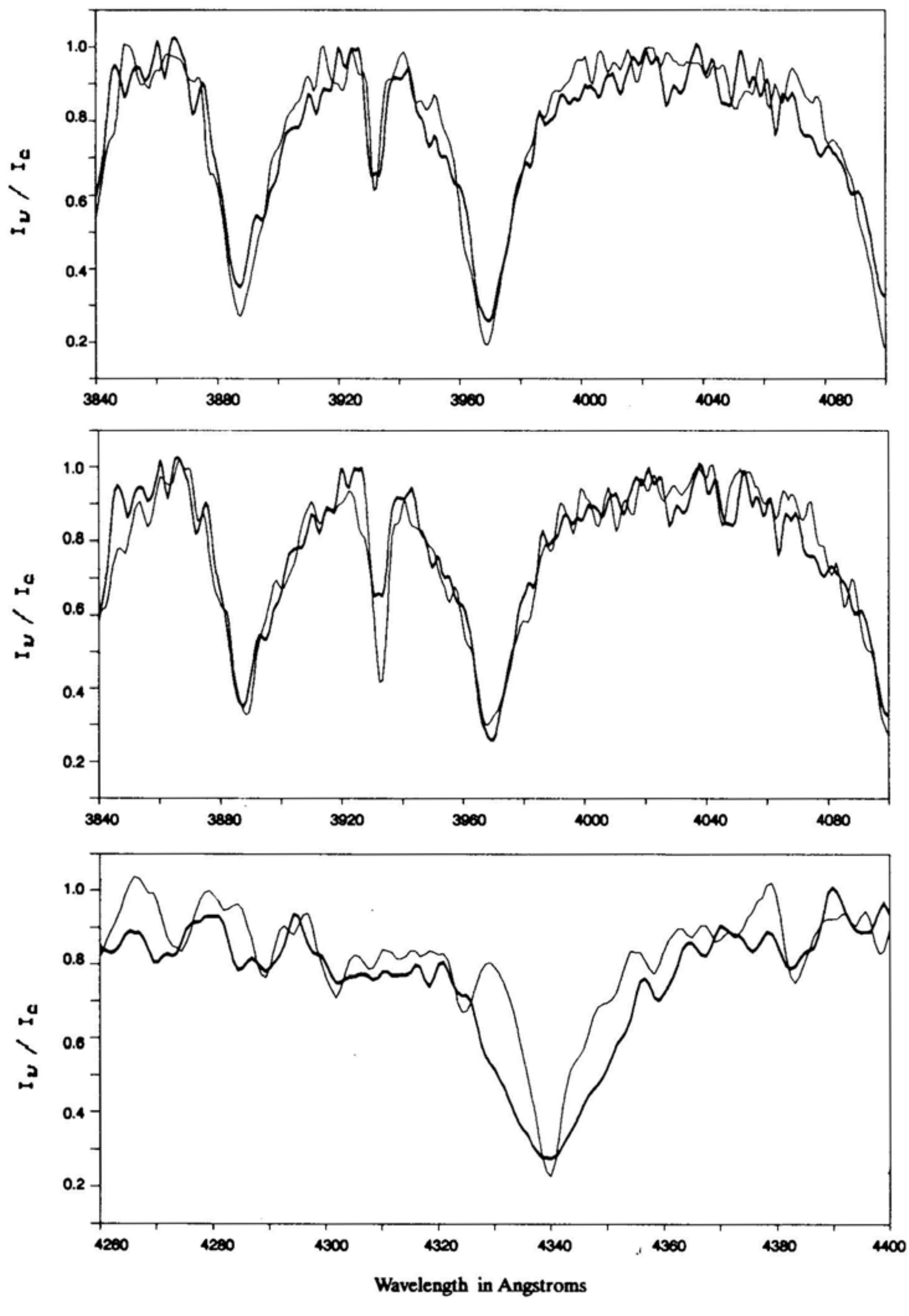

Figure 15(c). Same as Fig. 1 for HD 46052. (Orbital phase 0.824).

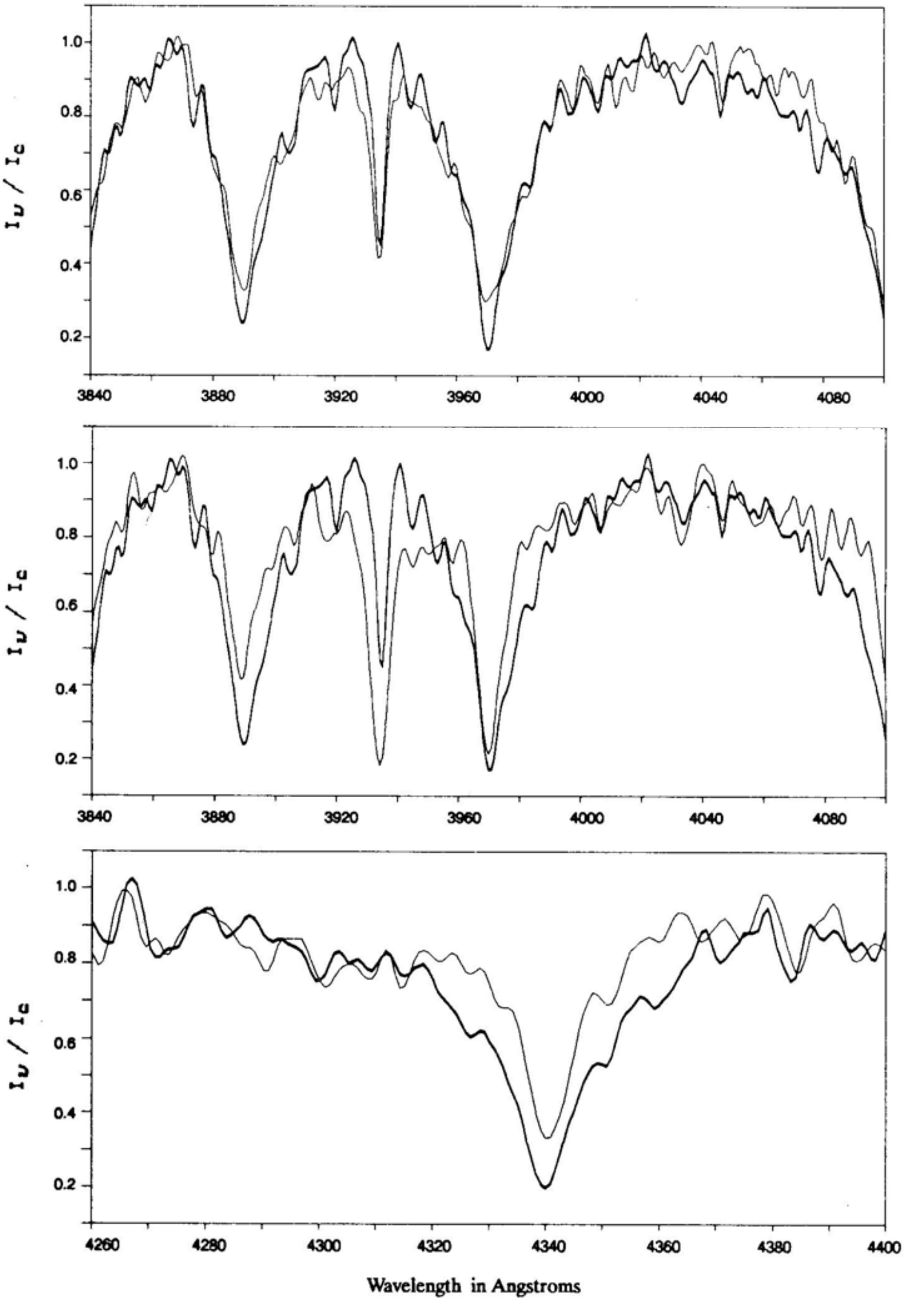

Figure 16. Same as Fig. 1 for HD 63589.

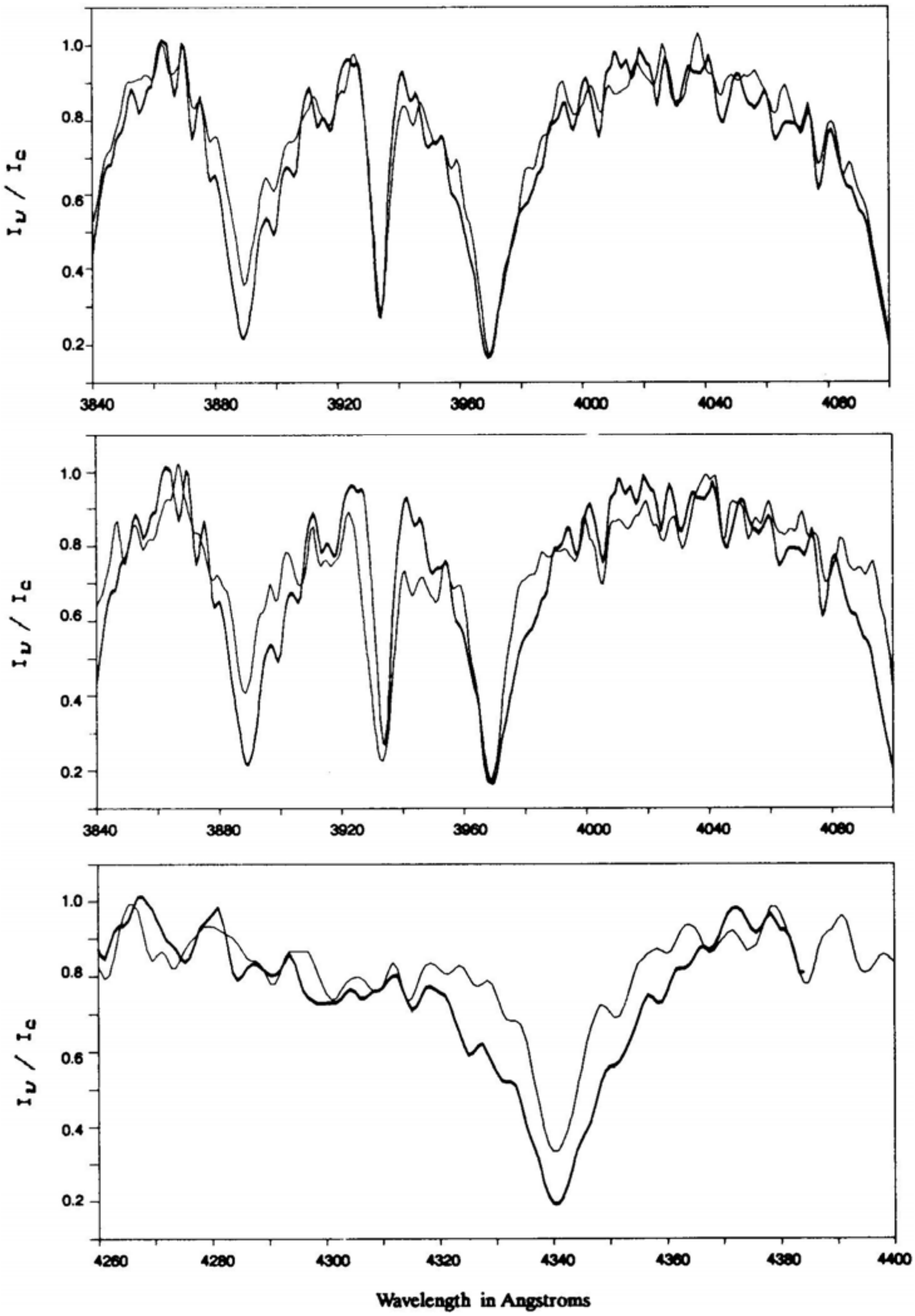

Figure 17. Same as Fig. 1 for HD 76756.

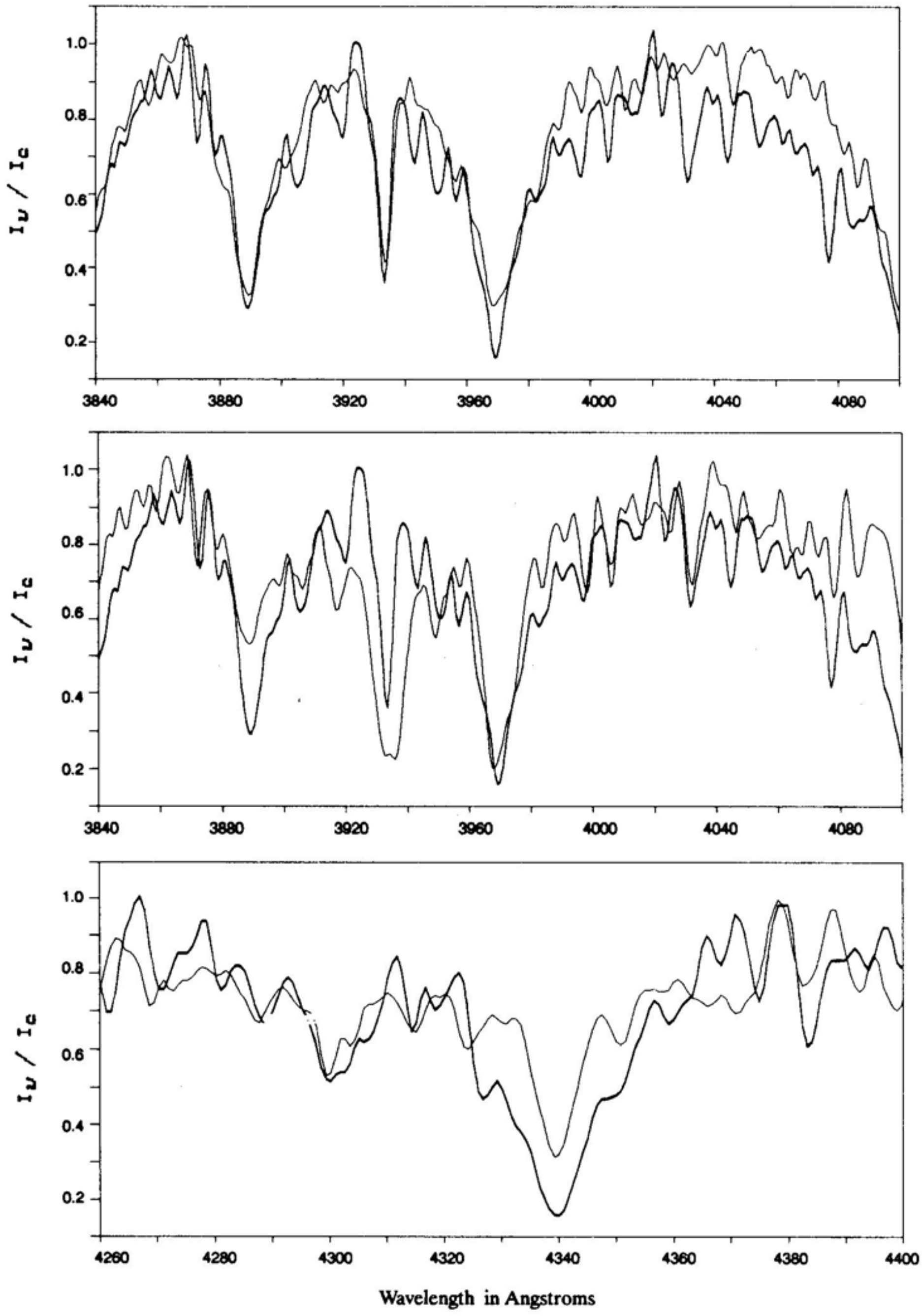

Figure 18. Same as Fig. 1 for HD 78209.

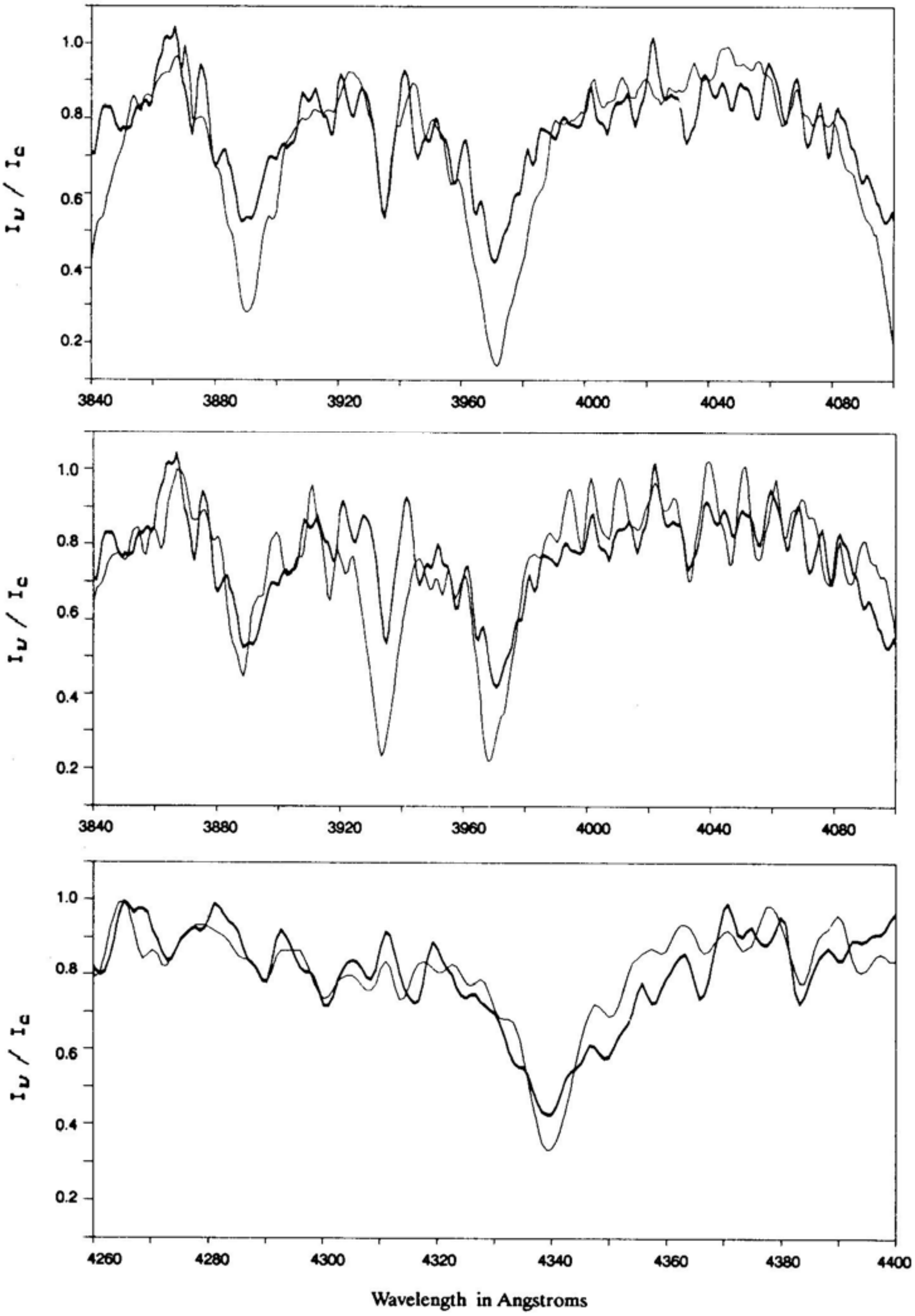

Figure 19. Same as Fig. 1 for HD 79193.

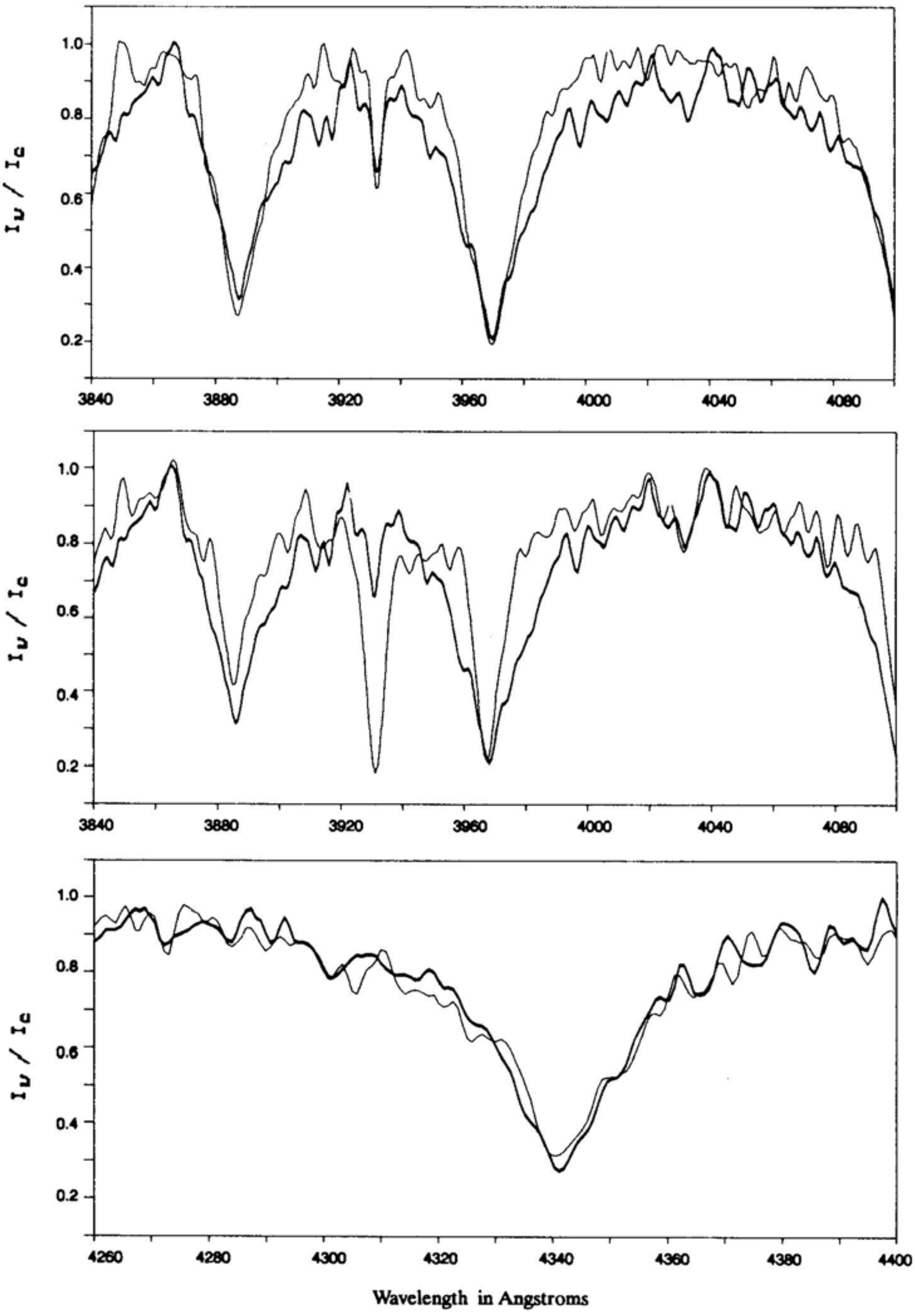

Figure 20. Same as Fig. 1 for HD 82191.

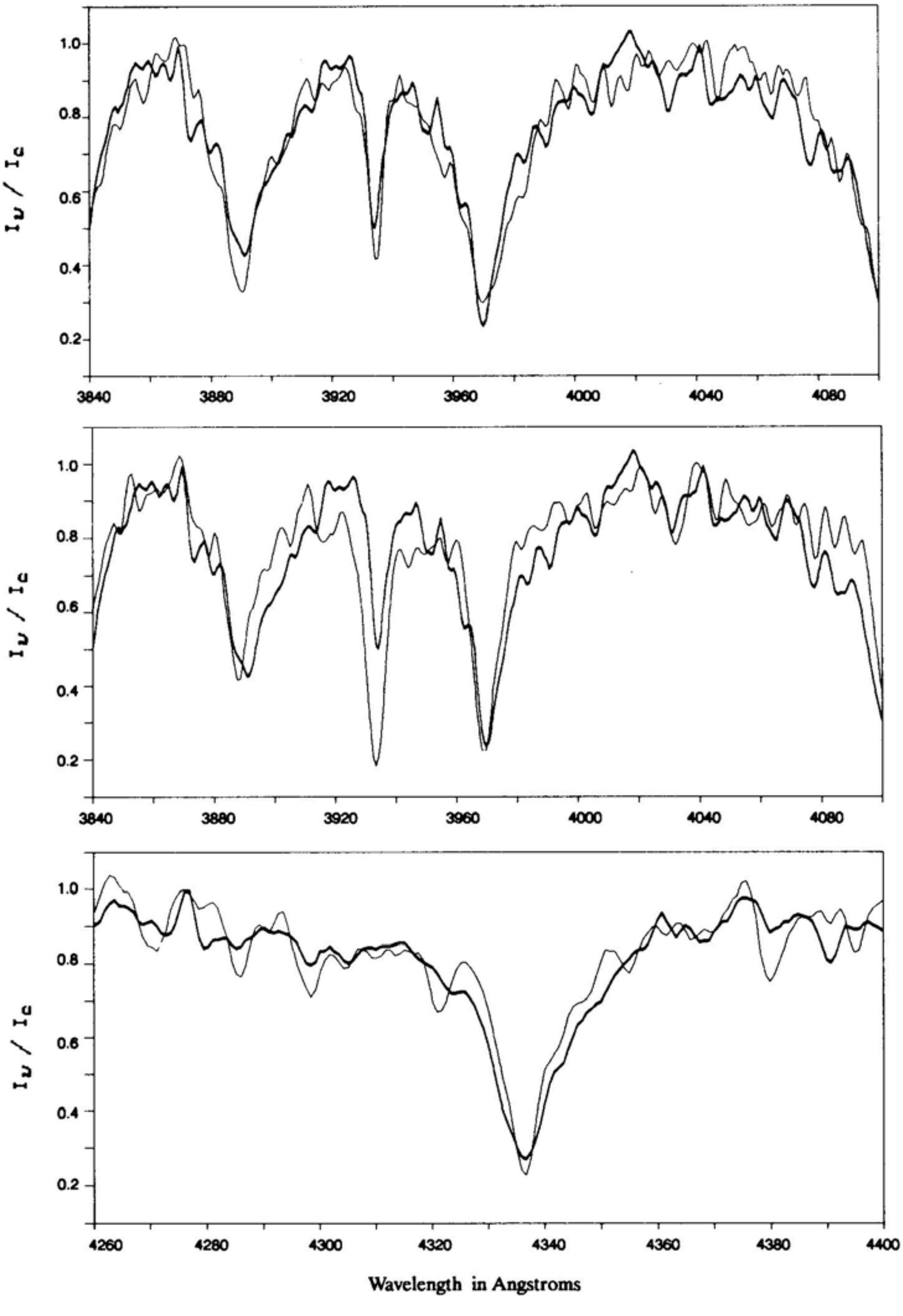

Figure 21(a). Same as Fig. 1 for HD 93903. (Orbital phase 0.540).

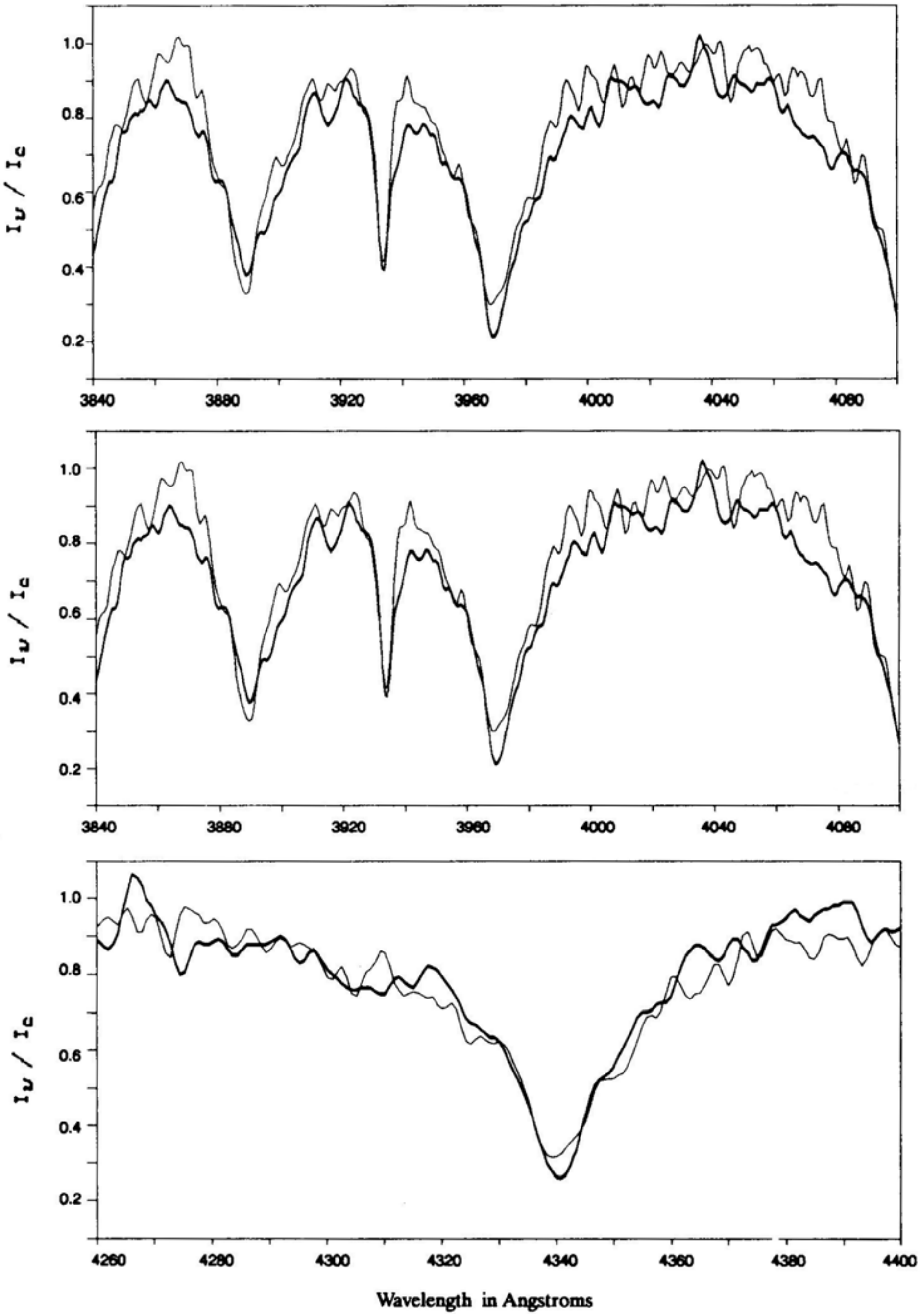

Figure 21(b). Same as Fig. 1 for HD 93903 (Orbital phase 0.370).

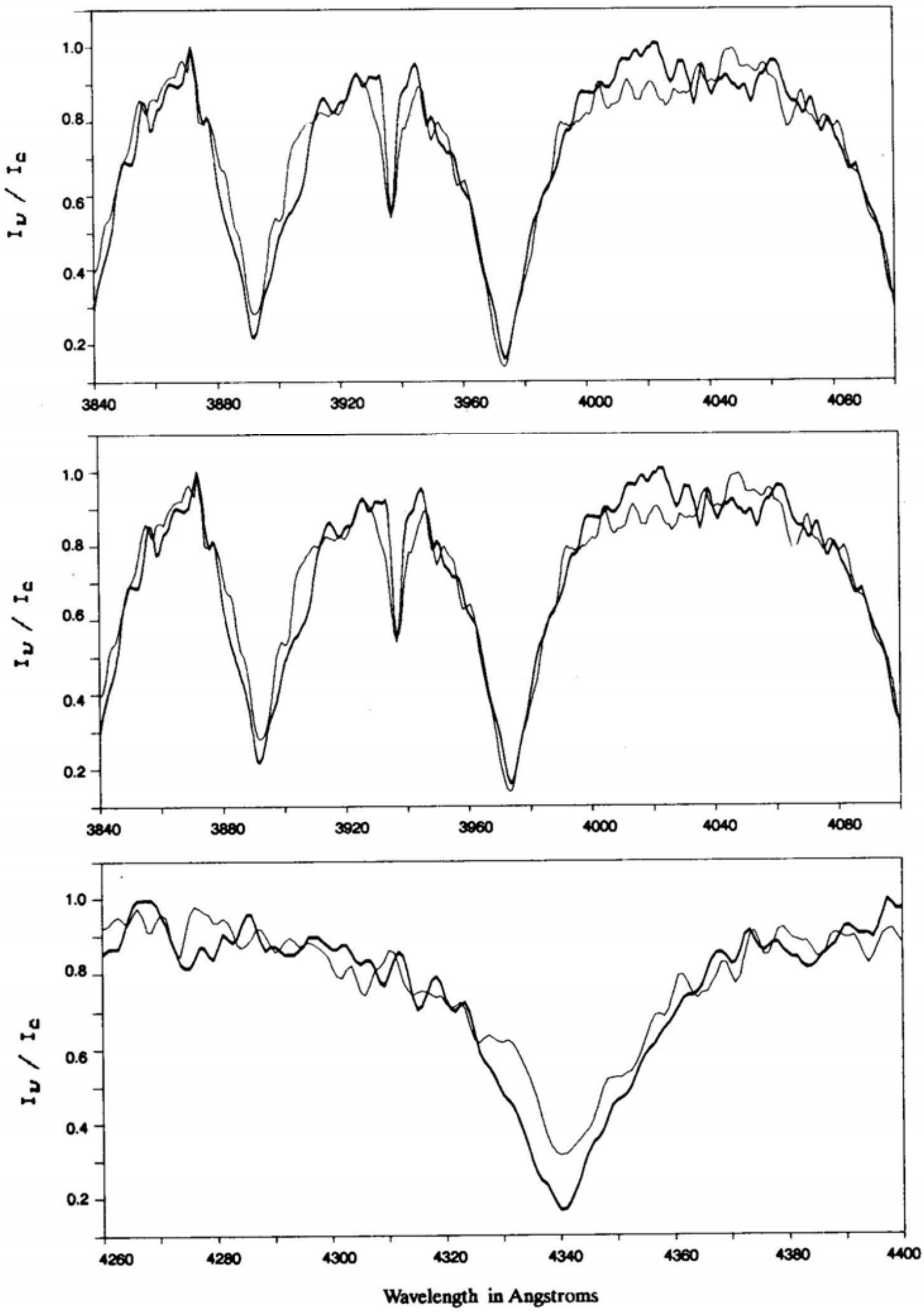

Figure 22. Same as Fig. 1 for HD 95608.

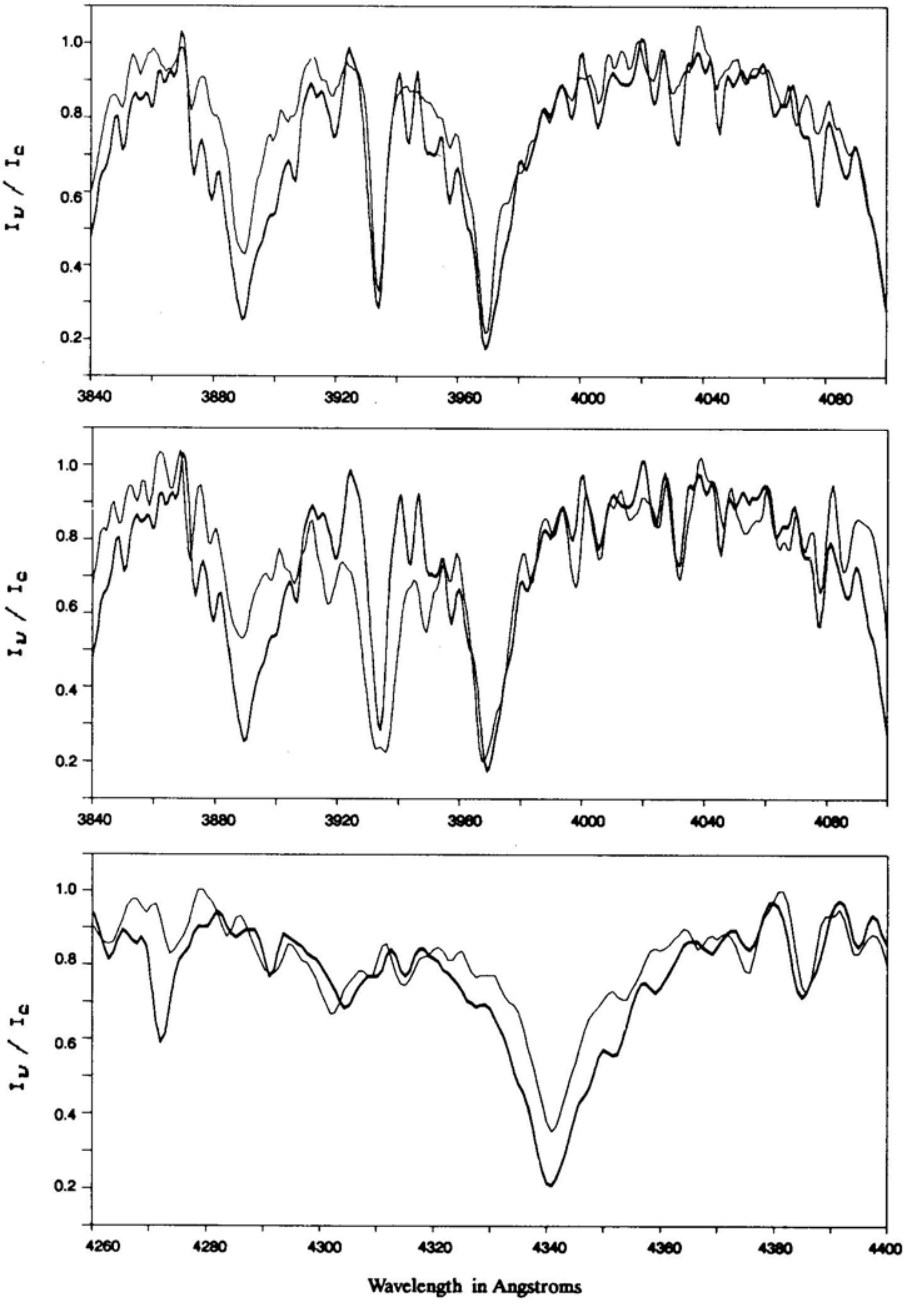

Figure 23. Same as Fig. 1 for HD 209625.

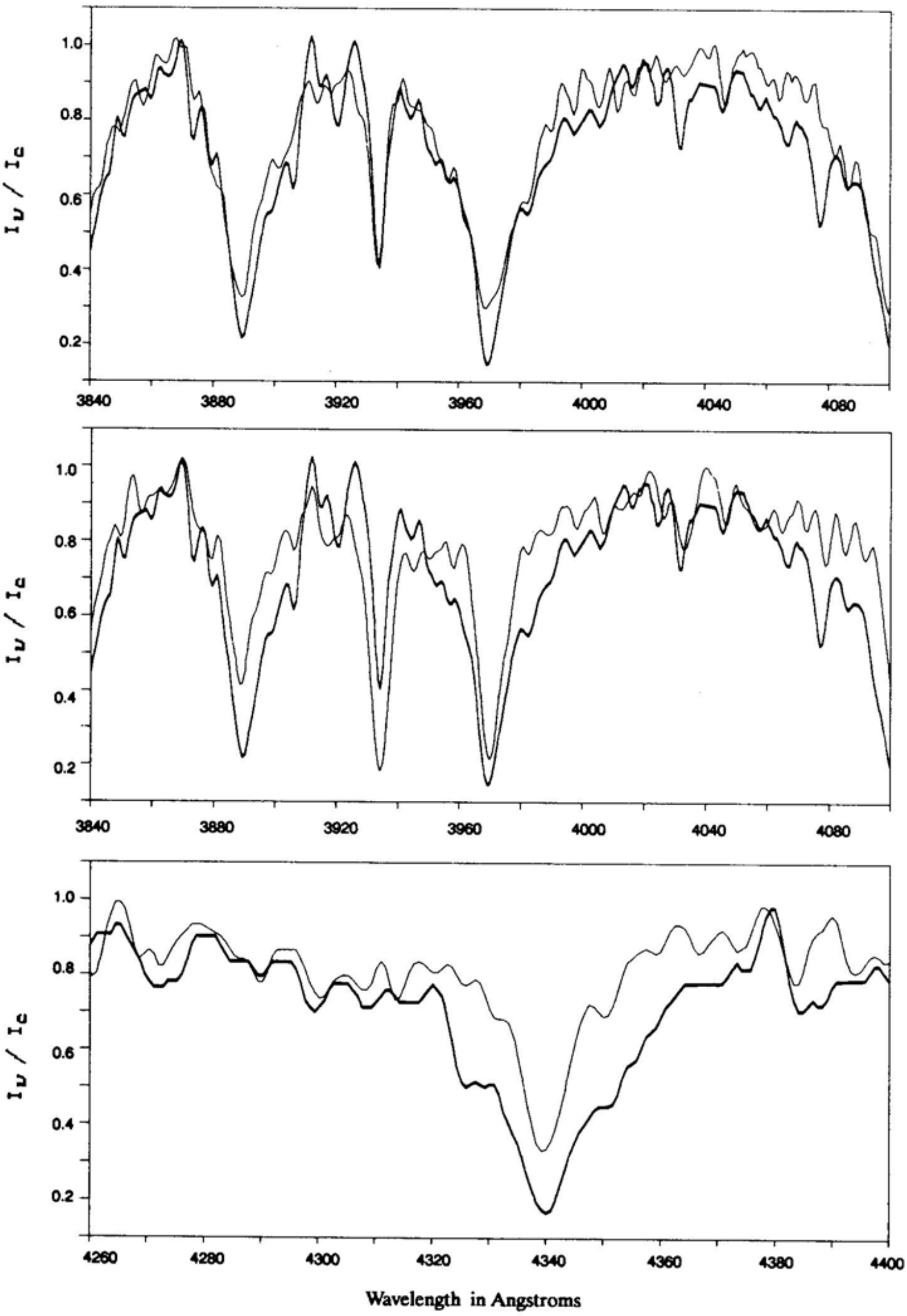

Figure 24. Same as Fig. 1 for HD 216608.

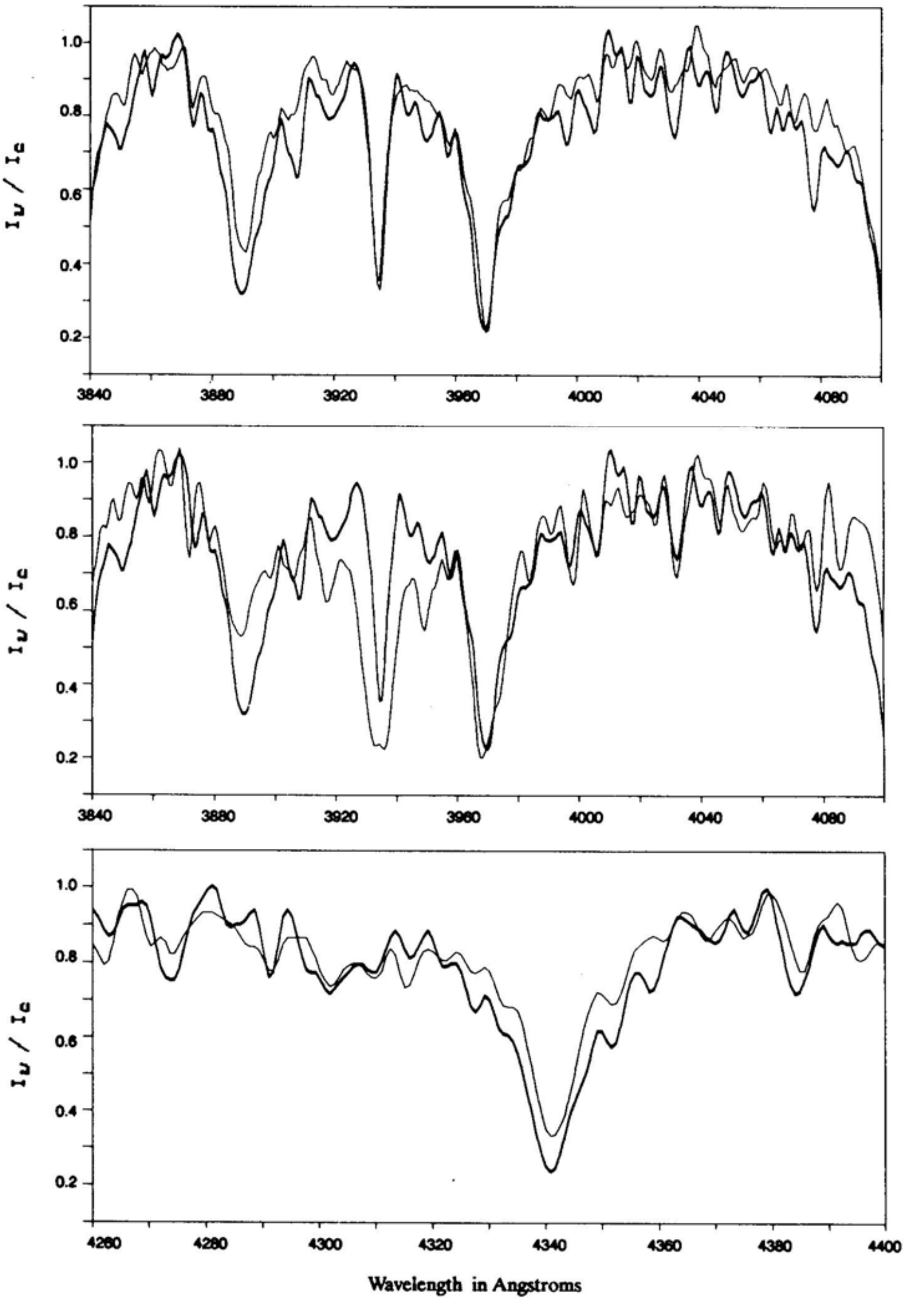

Figure 25. Same as Fig. 1 for HD 221675.

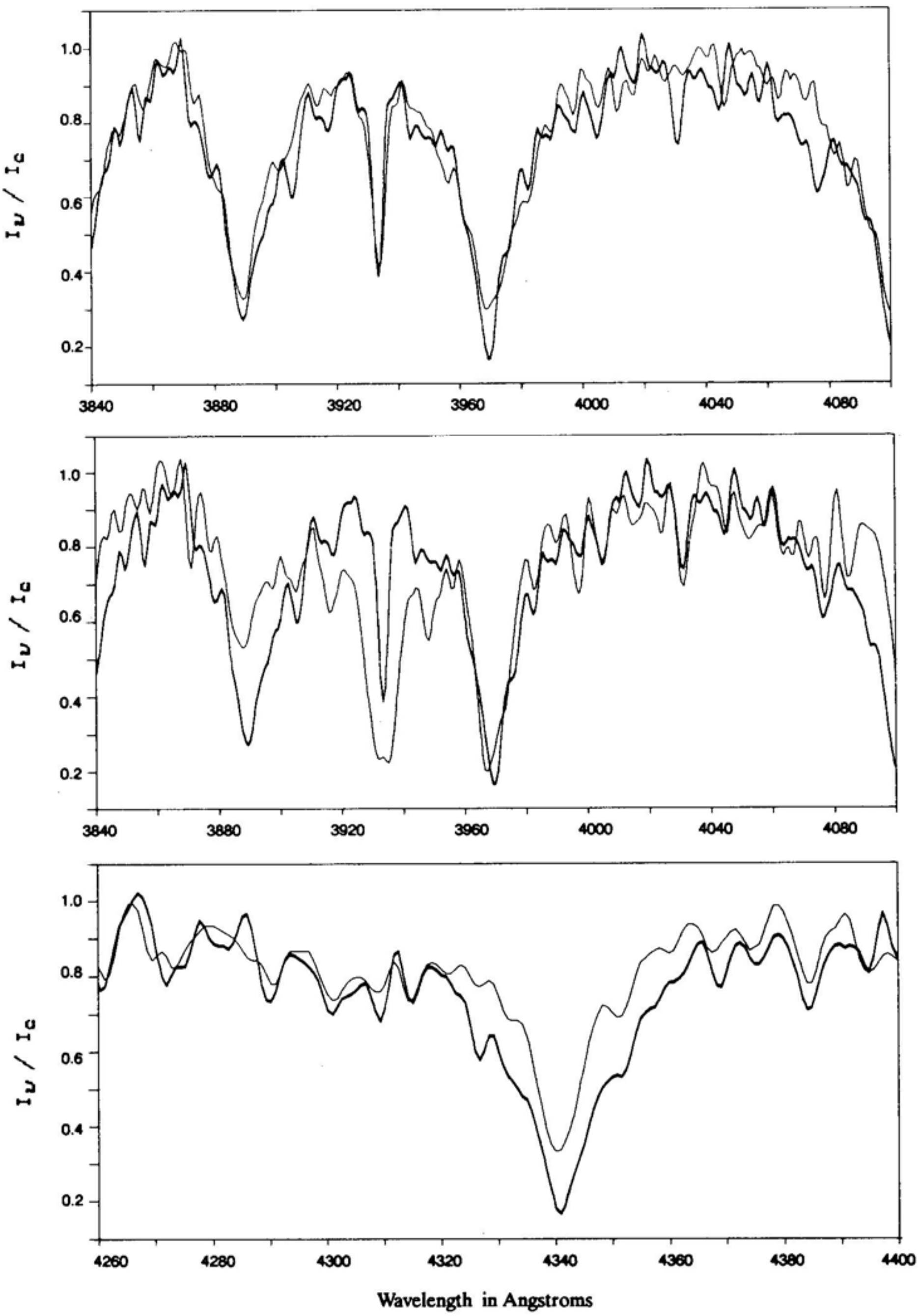

Figure 26. Same as Fig. 1 for HD 222377.

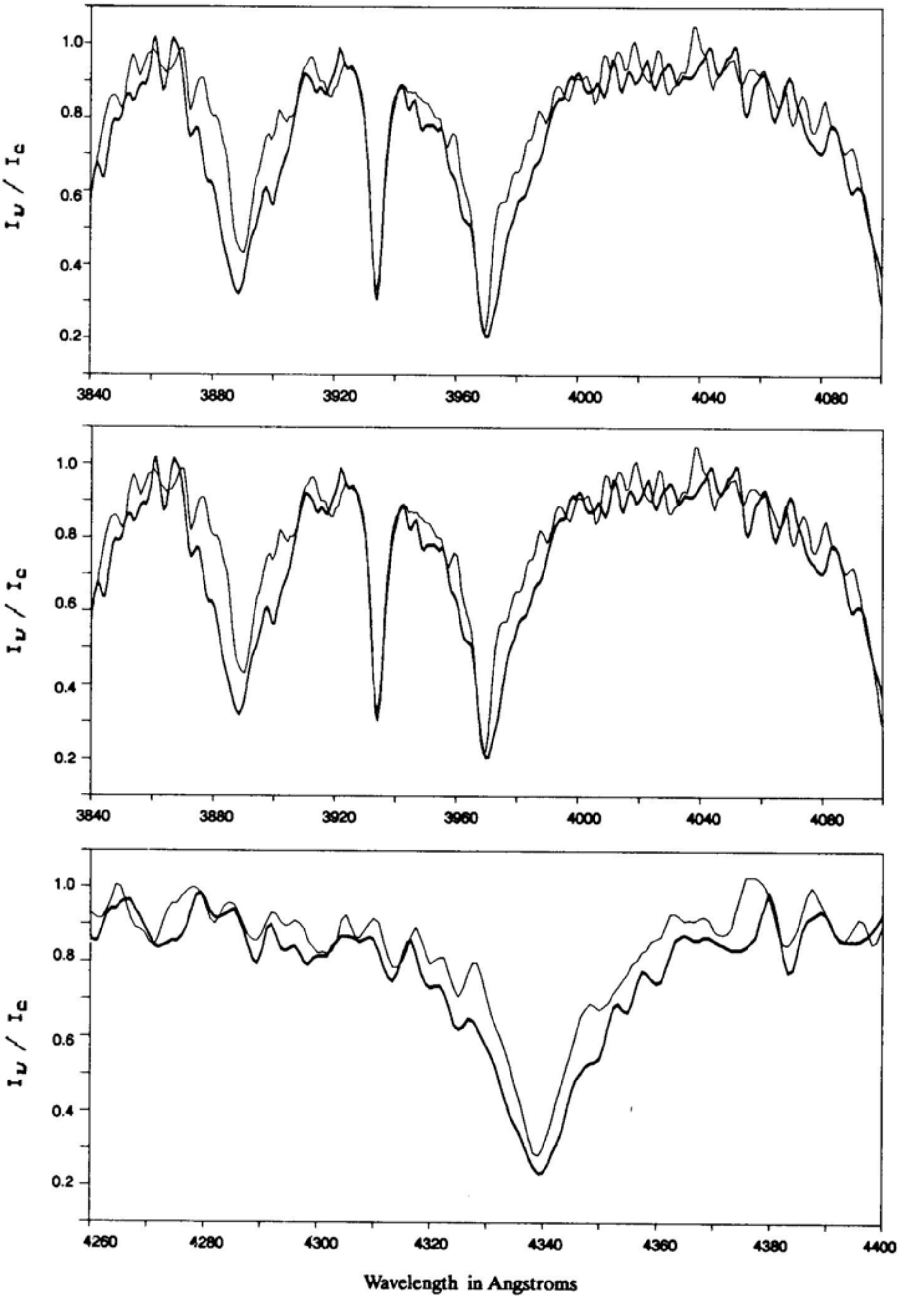

Figure 27. Same as Fig. 1 for HD 223438.

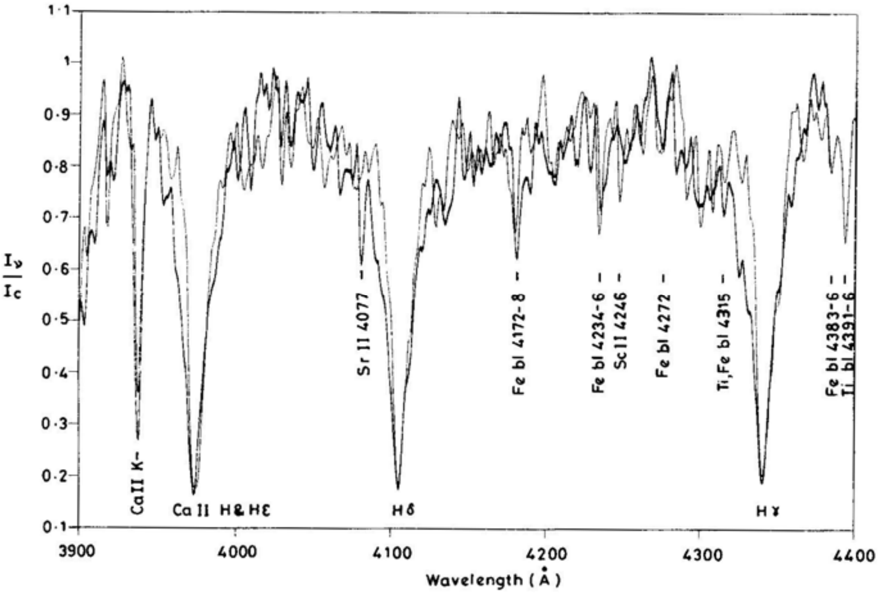

Figure 28. HD 76756 (A7 V m, thick line) compared with HD 41511 (A shell, thin line) taken on JD 244 7131.38.