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Metallic Line Profiles of the A0V Star Vega

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ABSTRACT

High dispersion (2.4 Å mm^{-1}) ultrahigh signal-to-noise Reticon spectra of Vega have been obtained with the coudé spectrograph of the 1.2-m telescope of the Dominion Astrophysical Observatory. A mean signal-to-noise ratio of 2500 over the spectral region λλ3825-5435 has been achieved. Examination of the line profiles confirmed the presence of two different types of profiles which were previously seen in IIIaJ and lower signal-to-noise Reticon spectra. The profiles of the strong lines are essentially classical rotational profiles with enhanced wings which are slightly stronger than expected while those of weak lines are clearly flat-bottomed resulting in a trapezoidal appearance. Vega is not unique in this respect as 10 Tri, ν Cap, β PsA, and possibly several other stars with spectral types near A0 have similar line profiles. A few possible theoretical explanations are presented. For example, these profiles might be the result of a fast rotating star seen nearly pole on.

Subject headings: stars: atmospheres-stars:early-type-stars:individual (α Lyr, 10 Tri, ν Cap, β PsA)

I. INTRODUCTION

Since Vega (α Lyr = HR 7001 = HD 172167), the primary photometric standard, is very bright and relatively sharp-lined, it has been studied extensively. Its photospheric abundances show it is metal week, but these chemical anomalies are sufficiently mildly so that only recently has it been possible to definitively demonstrate their extent (see Adelman and Gulliver 1990, Gigas 1986, and Sadakane, Nishimura and Hirata 1986). In 1971 one of us (JMF) attempted to monitor the radial velocity of Vega for periodic variations. To do this with the greatest precision available at that time the 9682M camera of the 1.2-m telescope coudé spectrograph of the Dominion Astrophysical Observatory with a reciprocal dispersion of 2.4 Å mm^{-1} and IIIaJ photographic emulsions were used. While measuring these plates on a scanning oscilloscope-display measuring machine some of the weakest lines appeared to have flat bottoms. The first spectrogram which showed such line profiles was plate 7108, dated 1 September 1971. Since the spectrograph and photographic plate combination did not have sufficient signal-to-noise to study radial velocity variability, further investigation was postponed.

A decade and a half later CRC observed Vega using a 1 x 1872 bare Reticon with 15μ pixels and the same telecope-camera combination (see Adelman and Gulliver 1990). The instrumental profile of the spectrograph plus Reticon has a FWHM of 0.074 Å (Gulliver and Hill 1990, Booth, Blackwell and Fletcher 1990). In the last two years, AFG and SJA have obtained still higher signal-to-noise (>2000) Reticon data. JMF asked the other coauthors whether they too had found flat bottomed lines and kept reminding them about how unusual they were.

We investigated various techniques to achieve as high a S/N as possible. These include the coadding of both multiple lamps and multiple spectra, the bracketing of spectra with lamp exposures, the use of different lamp illuminations including a broad-lined star, the varying of lamp exposure lengths, the use of high and low gain settings on the Reticon amplifiers and the assiduous cleaning of the Reticon window. The strategy that gives the best results includes: 1) a stop designed to reproduce the secondary mirror shadow is placed in the beam (this is especially important for lamp exposure), 2) the use of the low gain setting, 3) all exposures are integrated to about 10,000 ADC counts, 4) only a single lamp exposure just before the stellar exposure and of a comparable length is necessary, and finally, 5) either one or a pair of stellar exposures bracketed by comparison spectra are taken. A further important development is the modification of the RET72 and PLOTFITS routines (Hill and Fisher 1986) to allow immediate reduction and manipulation of the spectra at the telescope to ascertain their quality.

Initial reductions are performed using the program RET72 (Hill and Fisher 1986) which allows for division by the lamps, normalization of amplifier gains and FITS file output. This process revealed that consecutive exposures show virtually identical 'noise' which makes their coaddition pointless. The program REDUCE (Hill and Fisher 1986) is used to measure the comparison spectra and to linearize the stellar spectra in wavelength steps of 0.02 Å. The rectification step allows for the determination of a mean S/N from the continuum points themselves. The mean S/N for all 29 sections covering $\lambda\lambda$3825-5435 region is about 2500:1.

II. THE LINE PROFILES

Figure 1 a,b,c,d shows a sample spectrum of Vega centered at λ4520. This section has a mean S/N of some 2800:1. Also shown in Figure 1 are the line centres determined by measuring the spectrum using the program VLINE (Hill and Fisher 1986) and labeled with reference to Table 1.

During this process, a continuum is placed at 1.0 and one of two digitized stellar profiles is fitted to all discernible lines. The two profiles are produced using a modified version of VLINESUM (Hill and Fisher 1986) which coadds individual line profiles to give a composite, digitized version for use as a standard profile. One such profile is necessary for the weak lines and another for the strong lines because of their disparate shapes. For the weakest lines (typically those with line depths below 0.5 % of the continuum) and for severe blends, the FWHM of the standard profile is held fixed to a value of 20.2 km s^{-1}, the value found from slightly stronger lines. The necessity of using standard profiles has been established by tests with rotational, Gaussian and Lorentzian profiles convolved with the instrumental profile, all of which have proven to be inadequate.

Of the two profiles, that of the strong lines is essentially a classical rotational profile with enhanced wings which are slightly stronger than expected given the instrumental profile. But, that of the weak lines is highly unusual. It departs from the classical rotational (disc shaped) profile and it is clearly flat-bottomed resulting in a trapezoidal appearance. This unusual appearance is illustrated in Figure 2 which shows the features at $\lambda\lambda$4528-29 due to Fe I and Ti II. The prevalence of this type of profile throughout the spectrum of Vega means line blending cannot account for the flat-bottomed lines. Synthesis of sections of the spectrum using the program SYNTHE (Kurucz 1990) has confirmed that line blending is not the origin of the anomalous weak line profiles. Binarity is also an implausible explanation as

Reticon spectra taken at different times all show the same line widths (in km s^{-1}) for unblended lines of a given strength. The flat-bottomed profile must reflect some atmospheric phenomenon.

The success achieved using the two standard profiles can be judged from Figure 3 which is an enlarged view of the profiles fitted to 11 features from λ4539 to λ4549. With the exception of the bottom of Fe II (38) λ4541, the fit to the observed spectrum is excellent. The data for each line including its measured wavelength, equivalent width, central depth, FWHM and v sin i are shown in Table 1. The tentative identifications include results from the routines LINEID and IDPROC (Gulliver and Stadel 1990). To produce consistent line identifications, all available Reticon and photographic line data have also been considered by these routines.

III. OTHER STARS

That the flat-bottomed profiles of Vega had been found on IIIaJ spectrograms, but not on IIaO spectrograms suggested that a signal-to-noise ratio of at least order 100 would be required to see the phenomenon in question in other stars. SJA examined 2.4 Å mm^{-1} DAO Reticon spectra with signal-to-noise ratios typically 200 of 42 sharp and moderately sharp-lined (v sin i ≤ 40 km s^{-1}) stars with spectral types between B2 and F7. The spectra of both 10 Tri and ν Cap definitely show the weak flat-bottomed lines seen in Vega (Figure 4 a,b).

Holweger, Gigas, and Steffen (1986) and Holweger, Steffen, and Gigas (1986) presented sections of high resolution Reticon spectra of sharp-lined B9.5 to A2 V stars. The first paper shows that ν Cap (HR 7773) and β PsA (HR 8576) have flat bottomed weak lines although no comments are made to this effect. The confirmation of the nature of the weak line profiles of ν Cap with a different high resolution spectrograph indicates that a non-instrumental origin.

As in the examination of DAO Reticon spectra, a few other stars have weak lines which upon examination at higher signal-to-noise might exhibit line profiles intermediate between the flat bottomed and classical rotational types. Further not all early A stars with moderate values of v sin i show Vega type line profiles. But the four that do have moderate values of v sin i, 25 ± 10 km s^{-1} and a spectral type A1± 1.5

IV. POSSIBLE INTERPRETATIONS

At this time we have not examined the spectra of a sufficient number of stars to know the observational limits to this phenomenon except that the sharpest lined B, A, and F stars apparently do not show weak flat bottomed lines. The known class members simply reflect the programs of the various investigators. To define the shapes of profiles for weak lines in stars which are rotating much faster than about 40 km s^{-1} will require data with signal-to-noise ratios greater than 200.

Classical rotational profiles can be formally fitted to the flat-bottomed lines if the limb darkening coefficient is changed from its usual value of 0.6 to -0.6, i.e. limb brightening. This does not mean that limb brightening is a solution, rather this is a formal way of obtaining a fit. Perhaps the profiles might reflect some type of turbulence in the stellar atmospheres. Alternatively the profiles result from a temperature gradient over the star due to its rotation. If Vega is nearly pole on, then the equatorial regions would have a simulated lower gravity and some atomic lines would be stronger. This might give the same effect as limb brightening, but would depend on the kind of line observed. As so far we have concentrated on lines of iron peak elements, study of lines of other atomic species is important. That no very sharp-lined star has shown Vega-like weak profiles supports a rotational rather than a turbulence explanation. These possibilities need to be investigated as these small, but definite differences from classical line profiles may well contain very important astrophysical information.

Acknowledgments

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Table 1
Spectral Line Data

N	λ (Å)	EW (mÅ)	Depth s	FWHM (Å)	Vsini (km s^{-1})	Identification	
1	4488.330	14.1	0.025	0.57	19.0	Ti 2 (115)	4488.319
2	4489.176	27.1	0.051	0.55	18.2	Fe 2 (37)	4489.185
3	4491.398	34.3	0.065	0.54	17.9	Fe 2 (37)	4491.401
4	4493.550	2.9	0.005	0.60	20.1	Ti 2 (18)	4493.530
5	4494.553	6.5	0.010	0.62	20.6	Fe 1 (68)	4494.568
6	4495.628	0.5	0.001	0.61	20.2f	Fe 2 (147)	4495.520
						Fe 1 (827)	4495.566
7	4497.005	1.7	0.003	0.61	20.2f	Zr 2 (40)	4496.960
8	4497.771	0.6	0.001	0.61	20.2f	(Ti 1 (184)	4497.709)
9	4498.918	0.8	0.001	0.61	20.2f	Mn 1 (22)	4498.897
10	4499.702	1.2	0.002	0.61	20.2f	Unidentified line	
11	4500.607	0.5	0.001	0.61	20.2f	Unidentified line	
12	4501.269	61.0	0.114	0.55	18.2	Ti 2 (31)	4501.270
13	4502.232	0.8	0.001	0.61	20.2f	Mn 1 (22)	4502.220
14	4504.345	0.6	0.001	0.61	20.2f	Fe 1 (988)	4504.230
15	4505.045	0.4	0.001	0.61	20.2f	Ca 1 (24)	4505.000
16	4507.033	1.3	0.002	0.61	20.2f	Unidentified line	
17	4508.281	55.2	0.106	0.53	17.6	Fe 2 (38)	4508.283
18	4509.510	0.7	0.001	0.61	20.2f	Ca 1 (24)	4509.446
19	4511.854	1.2	0.002	0.61	20.2f	Cr 2 (191)	4511.820
20	4512.580	0.6	0.001	0.61	20.2f	(Al 3 (3)	4512.535)
21	4513.412	0.3	0.000	0.61	20.2f	Unidentified line	
22	4514.446	0.8	0.001	0.61	20.2f	Cr 1 (287)	4514.373
23	4515.340	47.4	0.090	0.54	17.9	Fe 2 (37)	4515.337
24	4516.508	0.7	0.001	0.61	20.2f	Cr 2 (191)	4516.560
25	4517.507	1.2	0.002	0.61	20.2f	Fe 1 (472)	4517.530
26	4518.340	2.8	0.005	0.61	20.2f	Ti 2 (18)	4518.300
27	4518.741	1.1	0.002	0.61	20.2f	Ti 1 (112)	4518.700
28	4519.897	1.5	0.002	0.61	20.2f	(Ni 1 (51)	4519.986)
29	4520.223	43.1	0.082	0.54	17.8	Fe 2 (37)	4520.225
30	4521.094	1.0	0.002	0.61	20.2f	Cr 1 (287)	4521.141
31	4522.630	66.4	0.127	0.53	17.7	Fe 2 (38)	4522.634
32	4524.666	0.9	0.002	0.61	20.2f	(Ti 2 (60)	4524.732)

Table 1 (continued)

N	λ (Å)	EW (mÅ)	Depth	FWHM (Å)	Vsini (km s^{-1})	Identification	
33	4525.130	3.4	0.006	0.61	20.2f	Fe 1 (826)	4525.142
						Ti 2 (18)	4525.210
34	4526.499	1.5	0.003	0.61	20.2f	Cr 1 (33)	4526.466
35	4527.240	0.8	0.001	0.61	20.2f	Cr 1 (33)	4527.339
36	4528.609	14.2	0.023	0.62	20.4	Fe 1 (68)	4528.619
37	4529.488	10.2	0.017	0.61	20.3	Ti 2 (82)	4529.465
38	4530.939	1.9	0.003	0.61	20.2f	Unidentified line	
39	4531.518	1.0	0.002	0.61	20.2f	Unidentified line	
40	4533.213	2.1	0.003	0.61	20.2f	Ti 1 (42)	4533.238
41	4533.962	67.8	0.126	0.55	18.1	Ti 2 (50)	4533.966
42	4534.157	13.0	0.021	0.61	20.2f	Fe 2 (37)	4534.166
43	4534.833	0.9	0.002	0.61	20.2f	Ti 1 (42)	4534.782
44	4535.608	0.9	0.001	0.61	20.2f	Ti 1 (42)	4535.574
45	4536.073	0.9	0.001	0.61	20.2f	Ti 1 (42)	4536.051
46	4537.106	0.5	0.001	0.61	20.2f	Unidentified line	
47	4537.794	0.5	0.001	0.61	20.2f	(Fe 1 (594)	4537.677)
48	4538.855	0.5	0.001	0.61	20.2f	(Fe 1 (969)	4538.840)
49	4539.565	2.2	0.004	0.61	20.2f	Cr 2 (39)	4539.620
50	4541.067	0.6	0.001	0.61	20.2f	Cr 1 (33)	4541.071
51	4541.517	24.9	0.046	0.56	18.4	Fe 2 (38)	4541.523
52	4542.419	1.0	0.002	0.61	20.2f	Fe 1 (894)	4542.422
53	4542.838	0.7	0.001	0.61	20.2f	(Cr 2 (16)	4542.770)
54	4544.052	2.8	0.005	0.61	20.2f	Ti 2 (60)	4544.009
55	4544.759	1.4	0.002	0.61	20.2f	Cr 2 (16)	4544.700
56	4545.128	3.7	0.006	0.63	20.9	Ti 2 (30)	4545.144
57	4545.517	1.5	0.003	0.61	20.2f	Cr 2 (16)	4545.490
						Fe 1 (894)	4545.540
58	4547.120	1.7	0.003	0.61	20.2f	(Ni 1 (146)	4547.234)
59	4547.839	2.3	0.004	0.61	20.2f	Fe 1 (755)	4547.851
60	4549.421	63.4	0.116	0.56	18.3f	Fe 2 (38)	4549.467
61	4549.614	100.9	0.184	0.56	18.3f	Ti 2 (82)	4549.622
62	4550.705	2.2	0.004	0.61	20.2f	Unidentified line	
63	4552.297	1.5	0.002	0.61	20.2f	Ti 2 (30)	4552.250
64	4552.625	1.0	0.002	0.61	20.2f	(Si 3 (2)	4552.616)

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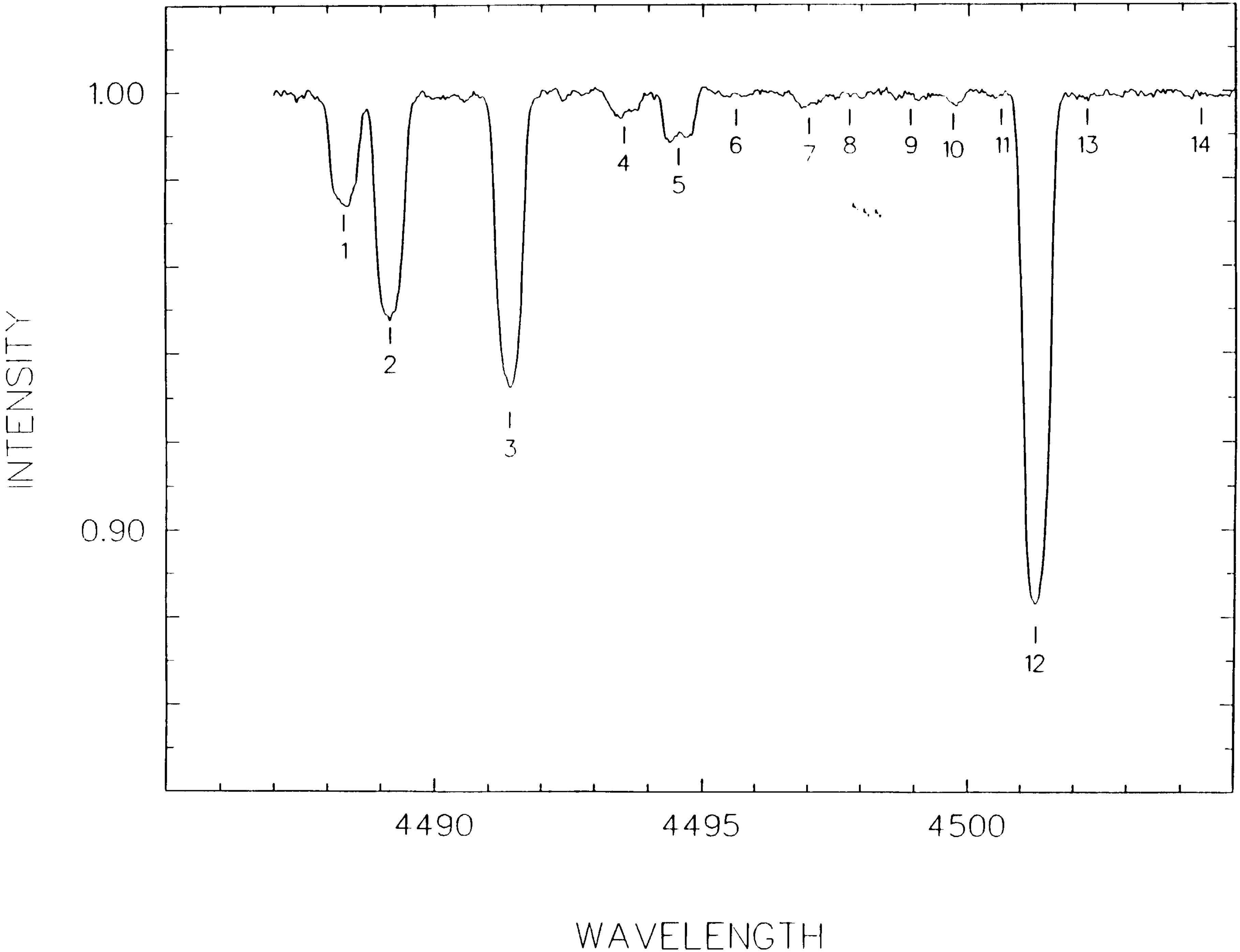
Figure Captions

Figure 1a. The spectrum of Vega with spectral line data referenced in Table 1.
Figure 1b, 1c, 1d. The same as Figure 1a.

Figure 2. The $\lambda\lambda$4528-29 features due to Fe I and Ti II. Also shown is the fit of a pure rotational profile with $\beta = 0.6$ (dotted line) and the standard stellar profile (dashed line).

Figure 3. The VLINE fit to the spectrum of Vega with spectral line data referenced in Table 1.

Figure 4. The spectra of 10 Tri ($\lambda\lambda$4518-4538)and ν Cap ($\lambda\lambda$4166-4186) showing flat-bottomed weak lines.



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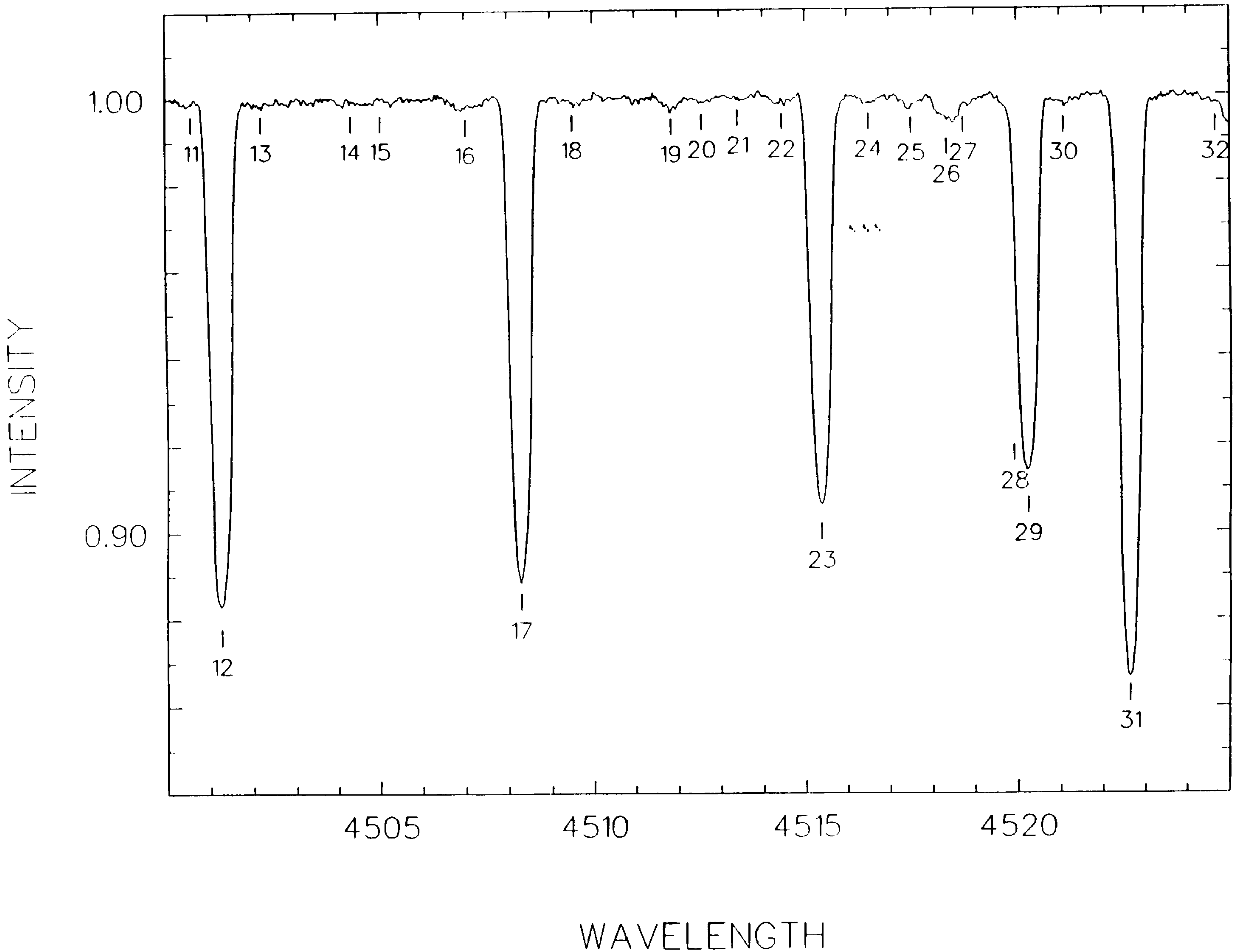
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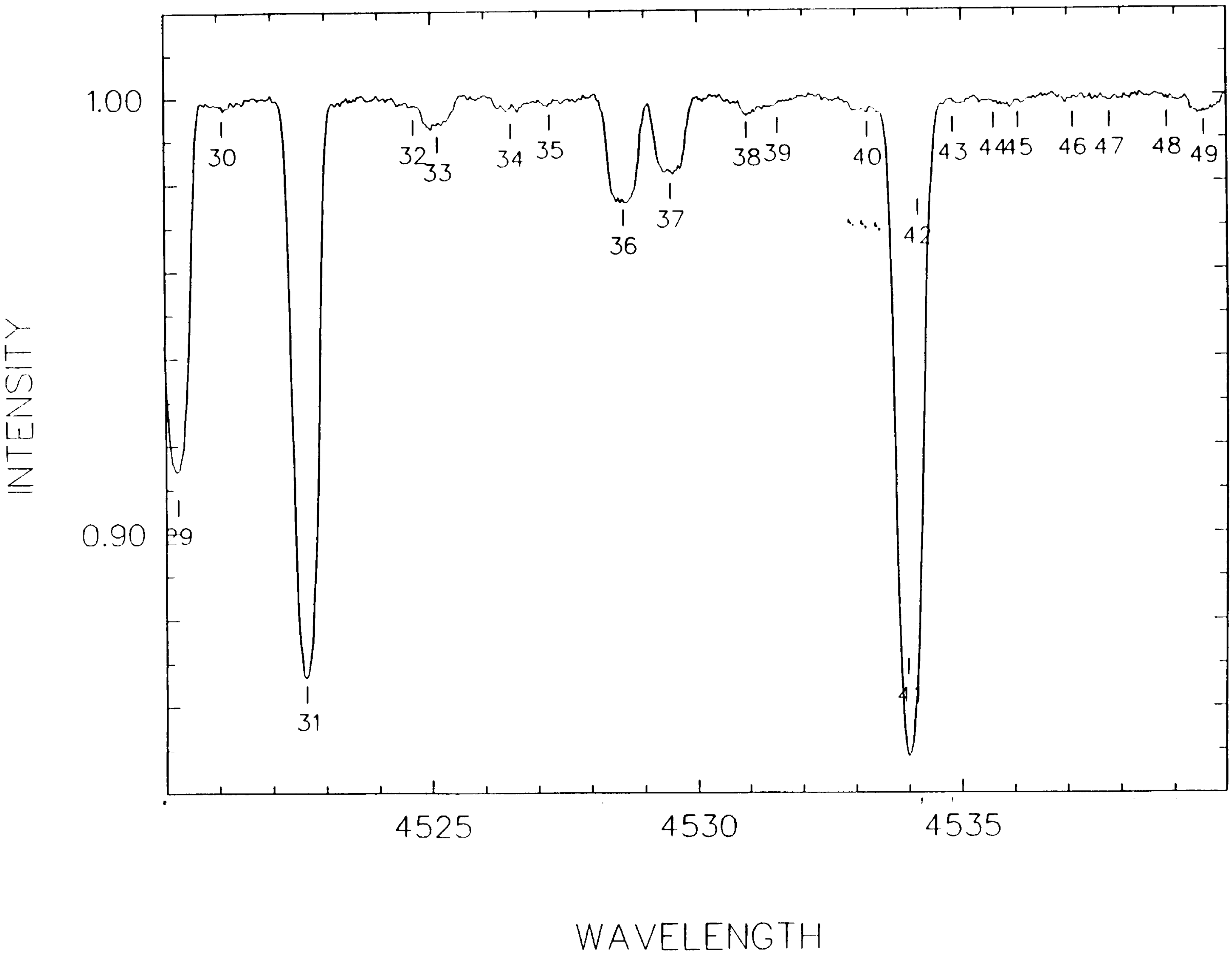

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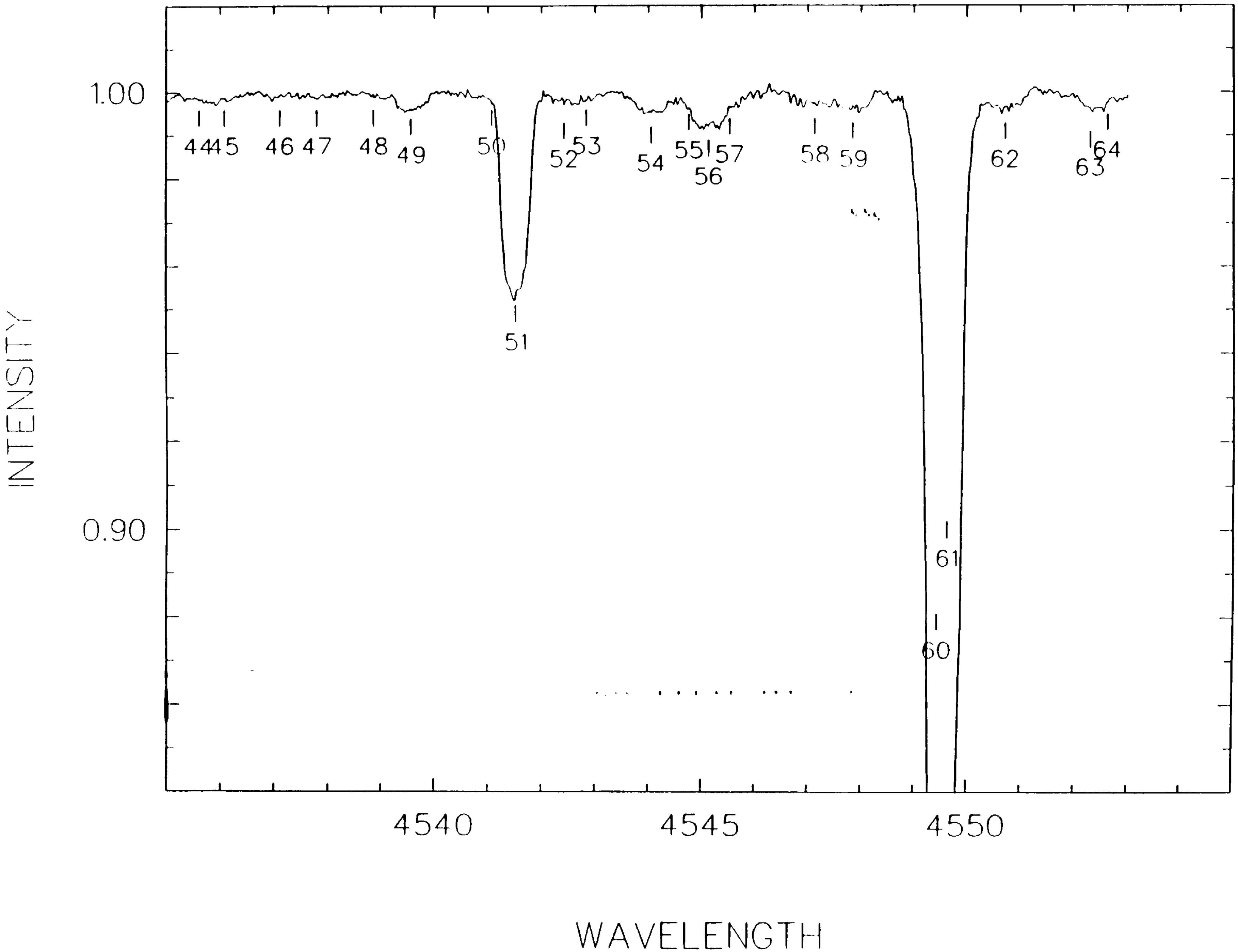

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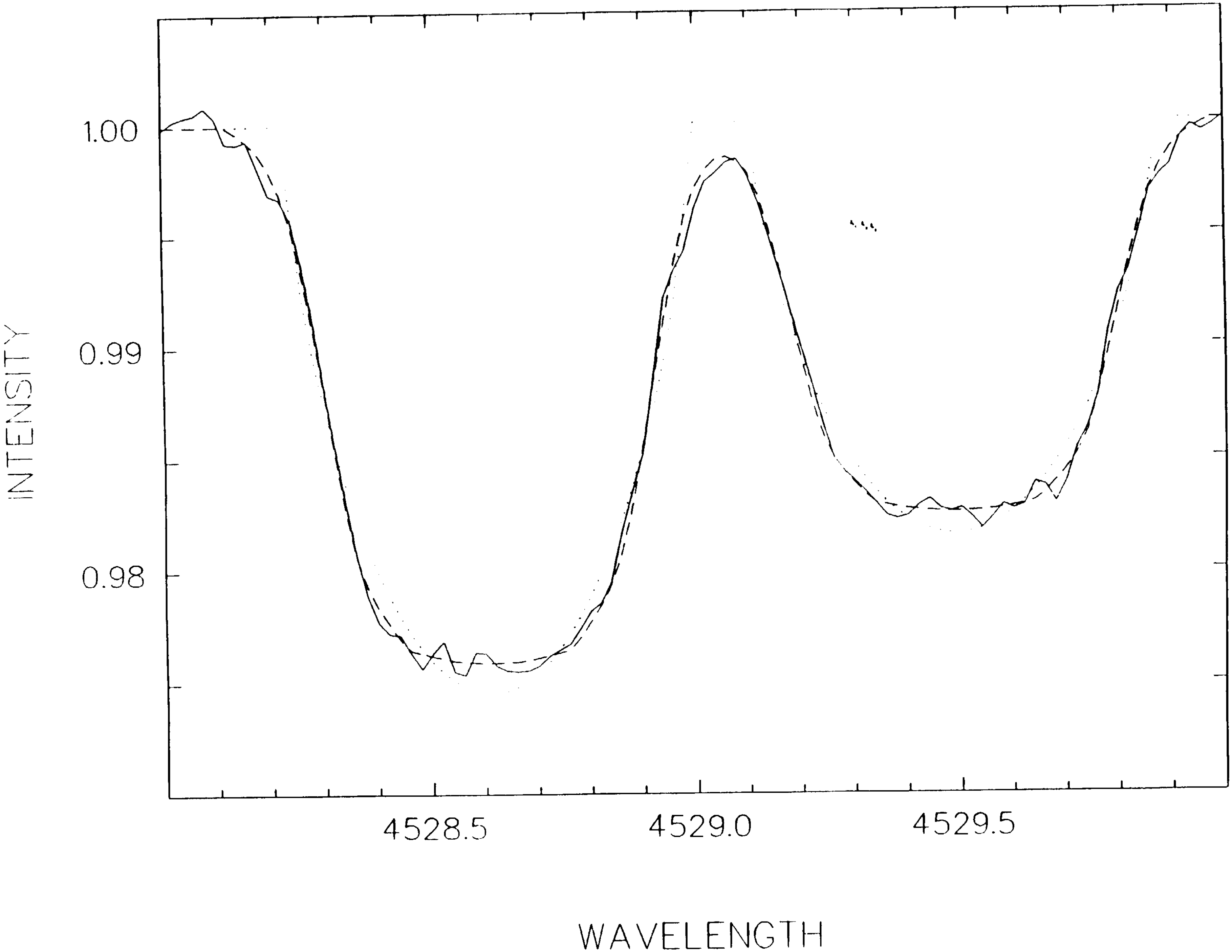
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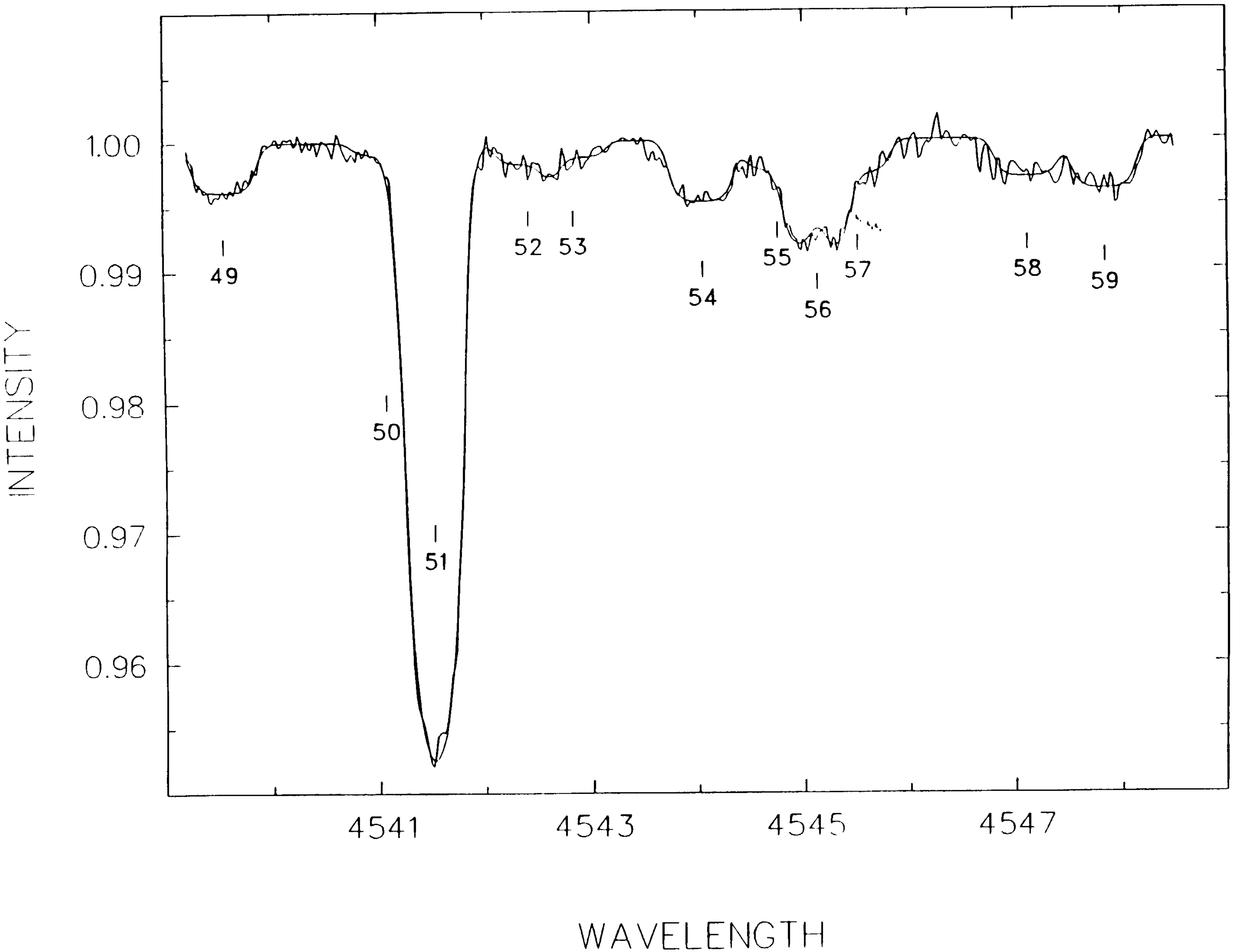

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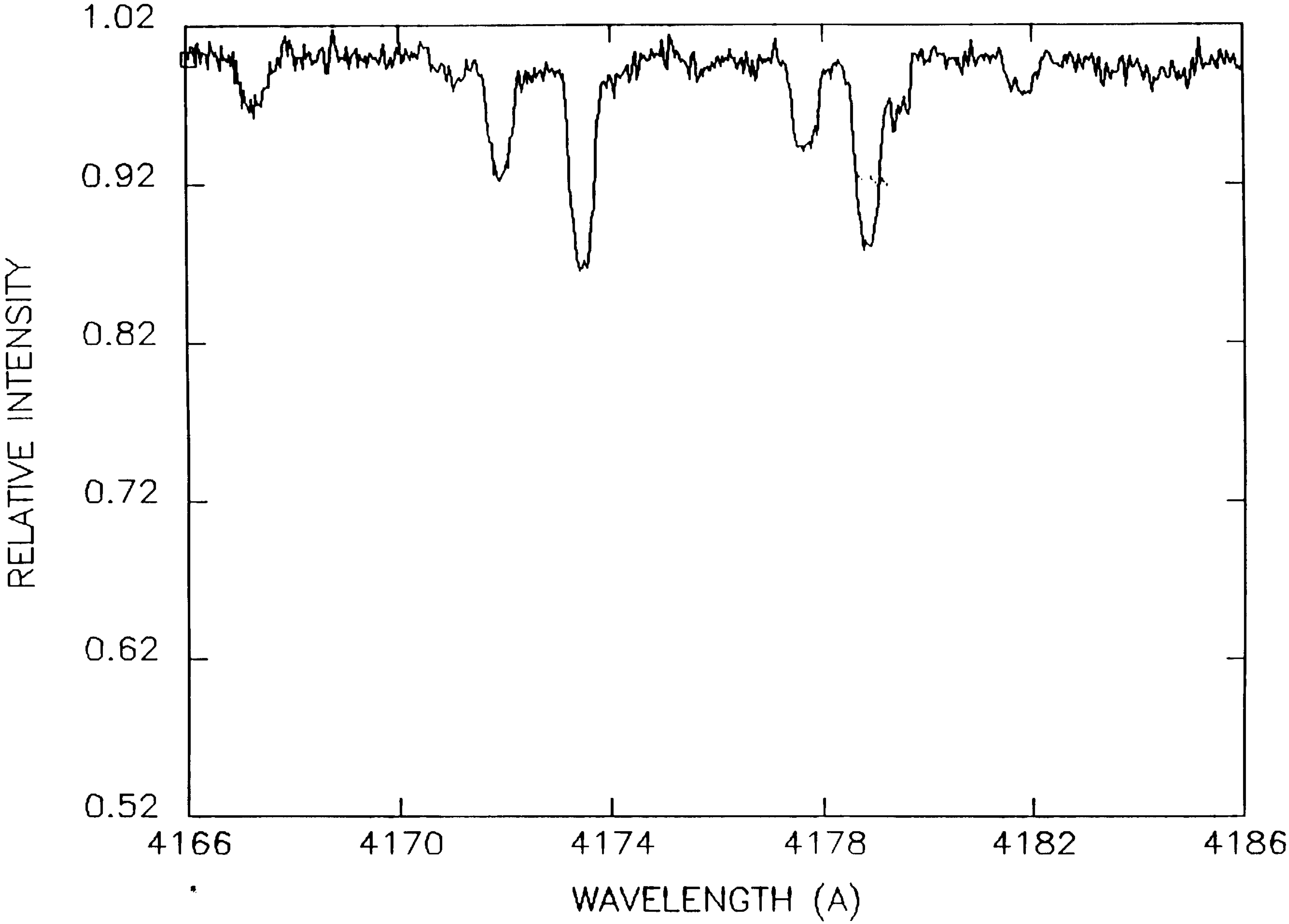
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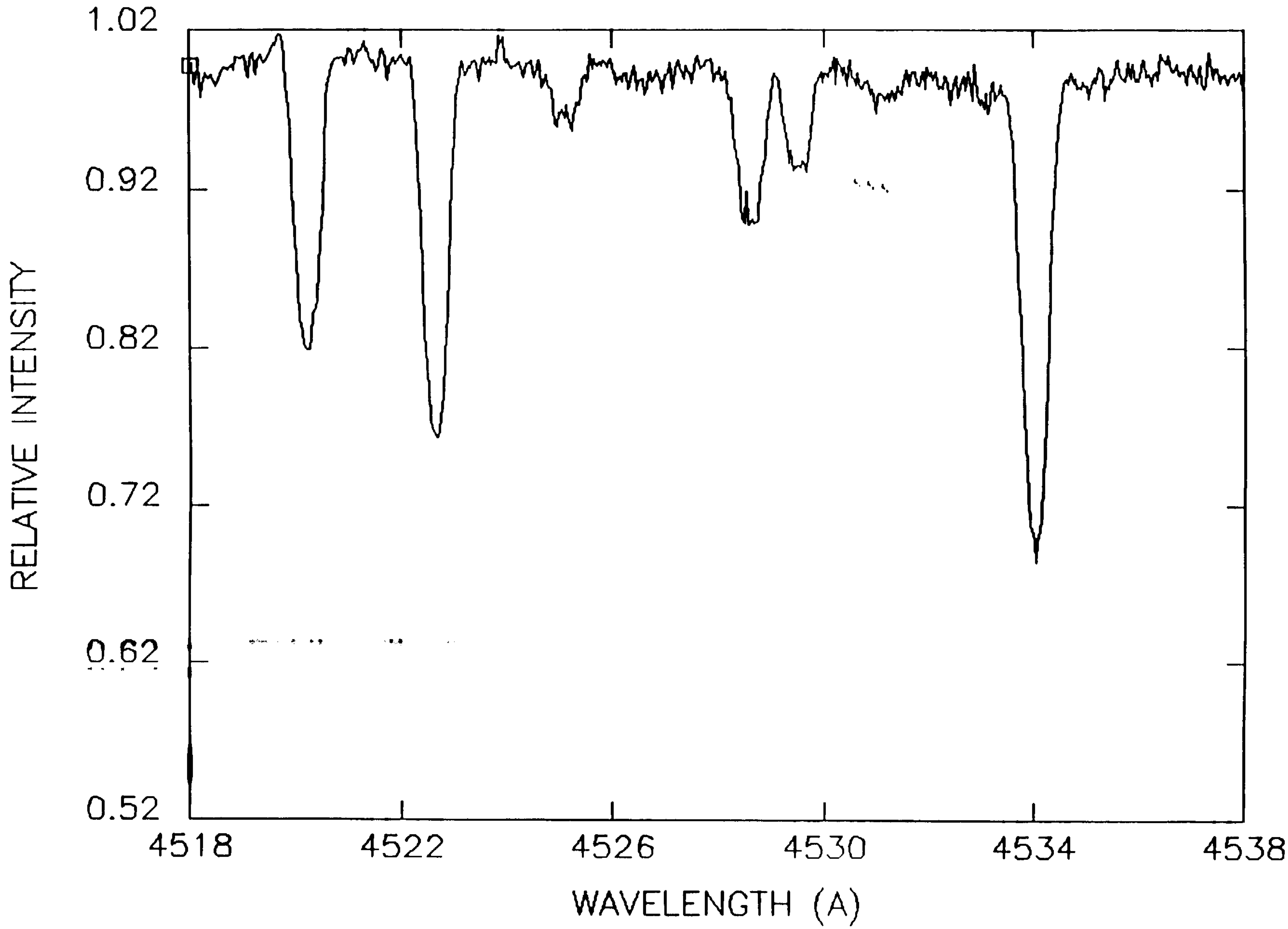
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4534
4538
WAVELENGTH (A)

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