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Spectral atlas of the symbiotic star MWC 560 for the region between H_β and H_α

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Abstract. An atlas of the spectrum of the unique symbiotic system MWC 560 = V694 Mon, which was taken in January 1995 with the CCD echelle spectrometer of the 6 m telescope is presented. The atlas covers a region from 4780 Å to 6580 Å, the spectral resolution limit is 0.3 Å, the signal–to–noise ratio is 80–100. About 400 emission lines of 27 species are identified.

Key words: binaries: symbiotic stars: individual (MWC 560) – emission line

1. Introduction

MWC 560 (V694 Mon) is a unique object that has been given both an extensive spectroscopic and photometric study for the last few years. The object has been ascertained to be a binary system from the symbiotic group: a red giant and a white dwarf in a common rarefied envelope. The spectral class of the giant is M4–6 III (Meier et al., 1996; Zhekov et al., 1996). The dwarf is surrounded by an accretion disk, both being in a dense envelope — a pseudo-photosphere, which corresponds in colour to a star of B5–A0 (Zhekov et al., 1996).

Matter outflows along the accretion disk axis, however, we see only one of the jets because the plane of the accretion disk and of the orbits are viewed face–on (Tomov and Kolev, 1997). The period of mutual revolution of the system's companions estimated from the regular light variations (since 1990 between $V \approx 9^{\rm m}.1$ and $10^{\rm m}.6$) is close to 2000 days (Doroshenko et al., 1993; Tomov et al., 1996). The radiation of MWC 560 is chiefly produced by the pseudo–photosphere (the continuum with blue-shifted absorption lines of the jet) and the envelope (emission lines). The contribution of the M giant is insignificant. It grows, naturally, with wavelength and becomes more pronounced in the years of low light of the system.

By the present time only one atlas of the MWC 560 spectrum has been available. It has been made from spectrograms of the coude spectrograph of the 2 m telescope of the Rozhen Observatory (Bulgaria) for the region 3600–4900 Å (Kolev and Tomov, 1993). The present paper may serve as its extension to the red region of the spectrum up to 6600 Å. It is based on CCD spectra obtained at the 6 m telescope.

2. Observational data and reduction

To make the atlas, two spectra were selected that were taken with the CCD echelle spectrometer "LYNX" placed at the Nasmyth focus of the 6 m telescope (Panchuk et al., 1993). The main spectrum was obtained on December 12, 1995 near the maximum light with a CCD of 1040 × 1160 pixels. It was complemented with one closest in time (taken on December 24, 1994 with a CCD of 520 × 580 pixels) from those we had available. The V magnitudes of the object which corresponded to those moments were $10^{\rm m}.1$ (from Doroshenko, 1996) and $10^{\rm m}.4$ (from Tomov et al., 1996). From 35 orders of the main spectrum 28 of the most informative were taken for the atlas, which represented a wavelength region of 4780 Å to 6580 Å without gaps. From the complementary spectrum 11 orders, 40–45 Å each, between 5660 and 6470 Å were entered in the atlas. The quality of the resultant spectrum was not uniform. The summation of the overlapping portions brought the signal–to–noise ratio in them to 80–100, however, in the portions represented by one spectrum, especially at the red boundary of the atlas, it is markedly lower. The spectral resolution limit is close to 0.3 Å.

Following the standard MIDAS procedures of taking account of the scattered light, removal of cosmic particle traces and extraction of the spectra from the images, the spectra were normalized to the continuum and reduced to the scale of laboratory wavelengths. The dispersion curves were plotted separately for each order immediately from emission lines of the object. In so doing lines were selected which yielded radial velocities close to the symbiotic velocity of MWC 560 (+35 km/s). The averaging of the overlapping spectrum orders was performed on the wavelength scale.

The visible spectrum of MWC 560 is poor in absorption lines especially near the brightness maximum. In our atlas are visible only the blue-shifted components of H_β, H_α, NaI and FeII(42), interstellar lines NaI, a few diffuse interstellar bands (DIB) and telluric lines of H_2O and O_2 and, at length, traces of the spectra of the M giant. To reveal these traces, the spectrum of β Peg M2.5 II–III obtained with the same resolution as the spectrum of MWC 560 and the list of absorption lines identified in it (Davis, 1947) were taken.

Principal attention was given to the identification of the emission spectrum. The following elements and ionization stages (species): HI, CI, NI, [NI], [OI], NaI, MgI, SiII, CaI, CaII, ScII, TiI, TiII, VII, CrI, CrII, MnII, FeI, FeII, [FeII], YII, ZrII, BaII, LaII, CeII, PrII, NdII have been revealed, which are mostly present in the blue part of the spectrum of MWC 560 (Kolev and Tomov, 1993) too.

The identification was performed in two steps. At first the whole set of lines within the boundaries of the atlas with the wavelengths and oscillator strength accessible to us was compared alternatively for each of the species listed. For instance, for FeI the table of Nave et al. (1994) was used, for FeII the data of Johansson (1978) and Boyarchuk and Savanov (1986), while for [FeII] the data of Quinet et al. (1996). The closeness of the tabulated and observed values not only for the wavelength but also for the relative intensity of a line was considered a condition for reliable identification. About one–third of all emission lines were used in measuring radial velocities and plotting dispersion curves. For these the departure of the measured wavelengths from the tabulated ones does not exceed ±0.04 Å. In the rest of the cases the wavelengths were estimated from the atlas, and discrepancies as large as $\pm 0.1 - 0.2$ Å were permissible. The relationships between the tabulated gf values and the observed residual intensities, r, were presented in a diagram form. As is seen in Fig. 1, where an example of r(lg gf) dependence for FeI is given, allowance for the excitation potential makes the relationships clear enough, which makes it possible to correctly refer a line to a given species. Subsequently our spectra were compared with the like and well described spectra of real objects to check that the identification was correct. As a whole, the spectrum of MWC 560 is close to the spectra of the symbiotic stars XX Oph (Merrill, 1951) and PU Vul (Belyakina et al., 1985; Iijima and Ortolani, 1984) as well as to the spectrum of the solar chromosphere (Pierce, 1968; Kastner, 1995). Its individual species are well represented in the spectra of T Tauri stars (Appenzeller et al., 1986) and η Car (Thackeray, 1967).

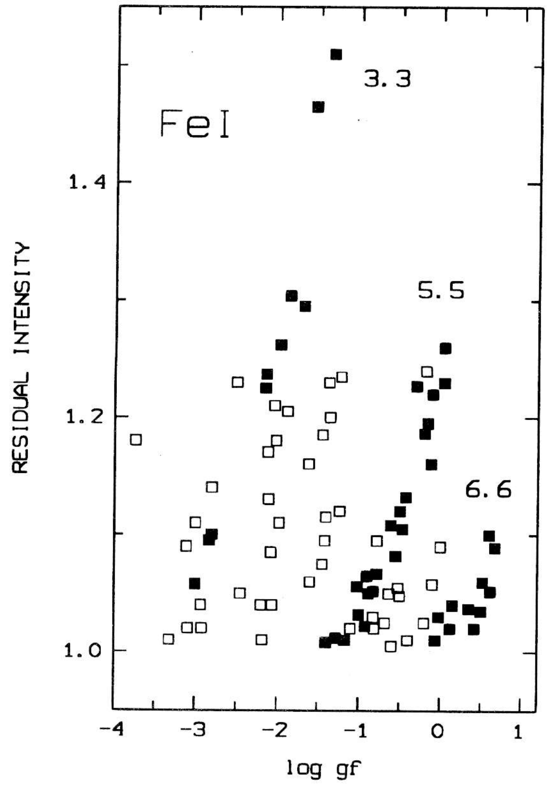

Figure 1: *Residual intensities of FeI emission in the spectrum of MWC 560 vrs oscillator strengths. Filled squares denote the lines with excitation potentials of the upper level 3.3, 5.5 and 6.6.*

3. Atlas and list of identified lines

The atlas is presented as a series of relationships between the residual intensity and the laboratory wavelength, which cover the spectrum of MWC 560 from 4780 Å to 6580 Å. A minor loss of information is due to the overestimation of the scattered light in the region of H_β and to the broad emission lines H_β and H_α. On the diagrams are shown the blue-shifted absorption lines and the interstellar diffusion bands. The telluric lines of H_2O and O_2 are marked with dots, while the heads of molecular bands and individual absorption lines of the M giant are labeled with angles and vertical bars, respectively.

In Table 1 are given only emission lines. Questionable features and the lines that fell within the gaps are not included in it, question-marks are for unreliable identification. The wavelengths are rounded-off to hundredths of an Å, in unidentified lines they are given with one decimal digit. The horizontal straight lines demarcate single lines or groups of close lines that merge into blends.

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List of identified emission lines in the spectrum of MWC 560 within 4779 – 6563 ÅÅ

TiII	(92)	4779.98
YII	(22)	4786.58
—		4789.5
—		4791.3
TiII	(48)	4792.39
NdII	(60)	4797.16
TiII	(17)	4798.53
LaII	(37)	4804.04
TiII	(92)	4805.09
TiII	(17)	4806.33
LaII	(37)	4809.00
NdII	(3)	4811.34
CrII	(30)	4812.34
[FeII]	(20F)	4814.55
ZrII	(66)?	4816.47
YII MnI	(22) (16)?	4823.31 4823.52
CrII	(30)	4824.14
NdII FeII	(3) (30)	4825.48 4825.72
CrII	(30)	4848.25
TiII	(29)	4849.18
YII	(22)	4854.86
CrII	(30)	4856.19
H_β		4861.33
TiII	(29)	4865.61
FeII FeI	(25) (318)	4871.27 4871.32
FeI	(318)	4872.14
TiII [FeII]	(114) (20F)	4874.01 4874.49
CrII CrII	(30) (30)	4876.40 4876.48
— FeI	 (318)	4877.8 4878.21
—		4882.4
YII	(22)	4883.68
CrII	(30)	4884.60
[FeII]	(4F)	4889.63
FeI	(318)	4890.75
FeI	(318)	4891.49
FeII	(36)	4893.81
—		4894.5
LaII YII	(7) (22)	4899.92 4900.12
FeI	(318)	4903.31
[FeII]	(20F)	4905.35
TiII	(114)	4911.19
NdII NI	(52) (9)	4914.38 4914.94
FeI	(318)	4919.00
FeI NdII LaII	(318) (2) (7)	4920.50 4920.69 4920.98
LaII	(7)	4921.80
FeII	(42)	4923.92
ZrII	(107)	4925.90
—		4927.5
BaII	(1)	4934.08
LaII NI	(72) (9)	4934.83 4935.12
—		4943.6
[FeII]	(20F)	4947.37
CrII		4952.79
FeI FeI	(318) (318)	4957.30 4957.60
Nd	(1)	4959.13
Nd	(22)	4961.40
—		4962.3
—		4963.1
FeI	(687)	4966.09
LaII	(37)	4970.39
—		4971.5
FeI	(984)	4973.11

TiII	(71)	4981.38
TiI	(38)	4981.73
YII	(20)	4982.13
FeI	(984)	4985.25
LaII	(22)	4986.82
—		4989.9
TiI	(38)	4991.07
FeII	(25)	4991.11
FeII	(36)	4993.35
FeI	(16)	4994.13
TiII		4996.39
—		4998.4
LaII	(37)	4999.46
TiI	(38)	4999.50
FeII	(25)	5000.73
CaII	(15)	5001.47
FeI	(965)	5001.86
TiII	(71)	5005.17
FeI	(984)	5005.72
FeI	(318)	5006.12
TiI	(38)	5007.21
TiII	(113)	5010.21
FeI	(16)	5012.07
TiII	(71)	5013.69
FeII	(42)	5018.44
CaII	(15)	5019.98
TiI	(38)	5020.03
CaII	(15)	5021.14
FeI	(965)	5022.24
—		5028.1
—		5028.6
ScII	(23)	5031.02
PrII	(37)	5034.41
FeII	(36)	5036.93
TiII	(71)	5037.81
SiII	(5)	5041.03
FeI	(16)	5041.07
FeI	(36)	5041.75
CeII	(16)	5044.01
—		5044.9

FeI	(114)	5049.82
—		5050.7
FeI	(16)	5051.63
CI	(12)?	5052.14
—		5052.9
SiII	(5)	5056.06
SiII	(5)	5056.35
—		5063.2
FeI	(383)	5068.77
TiII	(113)	5069.09
TiII	(113)	5072.29
CeII	(14)?	5075.30
FeI	(66)	5079.22
FeI	(16)	5079.74
FeI	(16)	5083.34
CdI	(2)?	5085.82
YII	(20)	5087.42
NdII	(48)	5092.80
CrII	(24)	5097.32
FeI	(66)	5098.70
FeII	(35)	5100.65
FeII	(185)	5100.86
—		5102.5
FeI	(16)	5107.45
FeI	(36)	5107.64
FeI	(1)	5110.41
PrII	(35)	5110.77
ZrII	(95)?	5112.28
LaII	(36)	5114.55
YII	(20)	5119.11
FeII	(35)	5120.34
LaII	(36)	5123.00
YII	(21)	5123.21
FeI	(16)	5123.72
ZrII	(87)	5124.98
FeI	(1090)	5125.12
—		5127.0
TiII	(86)	5129.16
NdII	(75)	5130.59
TiII	(86)?	5131.28

FeII	(35)	5132.66
FeI	(1092)?	5133.69
FeII	(35)	5136.79
FeI	(383)	5139.25
FeI	(383)	5139.46
FeI	(114)?	5141.74
FeII	(35)	5146.11
FeI	(16)	5150.84
CrII	(24)	5153.49
TiII	(70)	5154.07
FeII	(35)	5154.40
[FeII]	(18F)	5158.00
[FeII]	(19F)	5158.81
FeII	(167)?	5160.83
FeII	(35)	5161.18
LaII	(7)	5163.61
[FeII]	(35F)	5163.95
MgI	(2)	5167.33
FeI	(37)	5167.49
FeII	(42)	5169.03
FeI	(36)	5171.60
FeII	(35)	5171.62
MgI	(2)	5172.68
NdII?		5179.78
MgI	(2)	5183.61
TiII	(86)	5183.72
TiII	(86)	5185.90
CeII	(15)	5187.45
TiII	(70)	5188.68
FeI	(383)	5191.46
FeII	(52)	5191.58
ZrII	(95)	5191.60
FeI	(383)	5192.34
NdII	(75)	5192.60
TiI	(4)	5192.97
FeI	(36)	5194.94
YII	(28)	5196.43
FeII	(49)	5197.57
FeI	(66)	5198.71
[NI]	(1F)	5200.26
YII	(20)	5200.41
FeI	(66)	5202.34
—		5203.9
CrI	(7)	5204.52
YII	(20)	5205.72
CrI	(7)	5206.04
CrI	(7)	5208.43
FeI	(553)	5208.60
CrII	(24)	5210.84
TiII	(103)	5211.54
NdII	(44)	5212.36
FeI	(553)	5215.19
—		5215.7
FeI	(36)	5216.27
[FeII]	(19F)	5220.06
PrII	(35)	5220.11
TiII	(70)	5226.54
FeI	(383)	5226.87
FeI	(37)	5227.18
CrII	(43)	5232.53
FeI	(383)	5232.94
FeII	(49)	5234.62
CrII	(43)	5237.32
ScII	(26)	5239.82
CrII	(23)	5246.76
CrII	(23)	5249.43
NdII	(75)	5249.58
FeI	(66)	5250.65
TiII	(103)	5252.04
—		5252.7
FeII	(49)	5254.93
NdII	(43)	5255.51
FeII	(41)	5256.93
—		5258.3
LaII	(21)	5259.38
PrII	(35)	5259.73
[FeII]	(19F)	5261.61
TiII	(70)	5262.10
FeII	(48)	5264.80
FeI	(383)	5266.56
TiII	(103)	5268.63
[FeII]	(18F)	5268.87

FeI	(15)	5269.54
FeI	(37)	5270.36
FeII	(185)?	5272.39
FeI	(114)	5273.38
[FeII]	(18F)	5273.38
NdII	(75)	5273.43
CeII	(15)	5274.23
CrII	(43)	5274.99
FeII	(49)	5276.00
FeII	(184)?	5278.94
CrII	(43)	5279.88
CrII	(43)	5280.08
FeI	(383)	5281.79
FeII	(41)	5284.10
YII	(20)	5289.82
LaII	(6)	5290.83
NdII	(75)	5293.16
—		5294.1
[FeII]	(17F)	5295.70
LaII	(36)	5301.97
FeI	(553)?	5302.30
MnII	(11)	5302.32
VII	(54)	5303.23
LaII	(36)	5303.54
CrII	(24)	5305.85
CrII	(43)	5308.42
CrII	(43)	5310.69
NdII	(80)	5311.47
ZrII	(95)	5311.77
CrII	(43)	5313.58
FeII	(49)	5316.61
FeII	(48)	5316.78
ScII	(22)	5318.35
NdII	(75)	5319.82
PrII	(35)	5322.78
FeI	(553)	5324.18
FeII	(49)	5325.56
—		5327.3
FeI	(15)	5328.04
FeI	(37)	5328.53

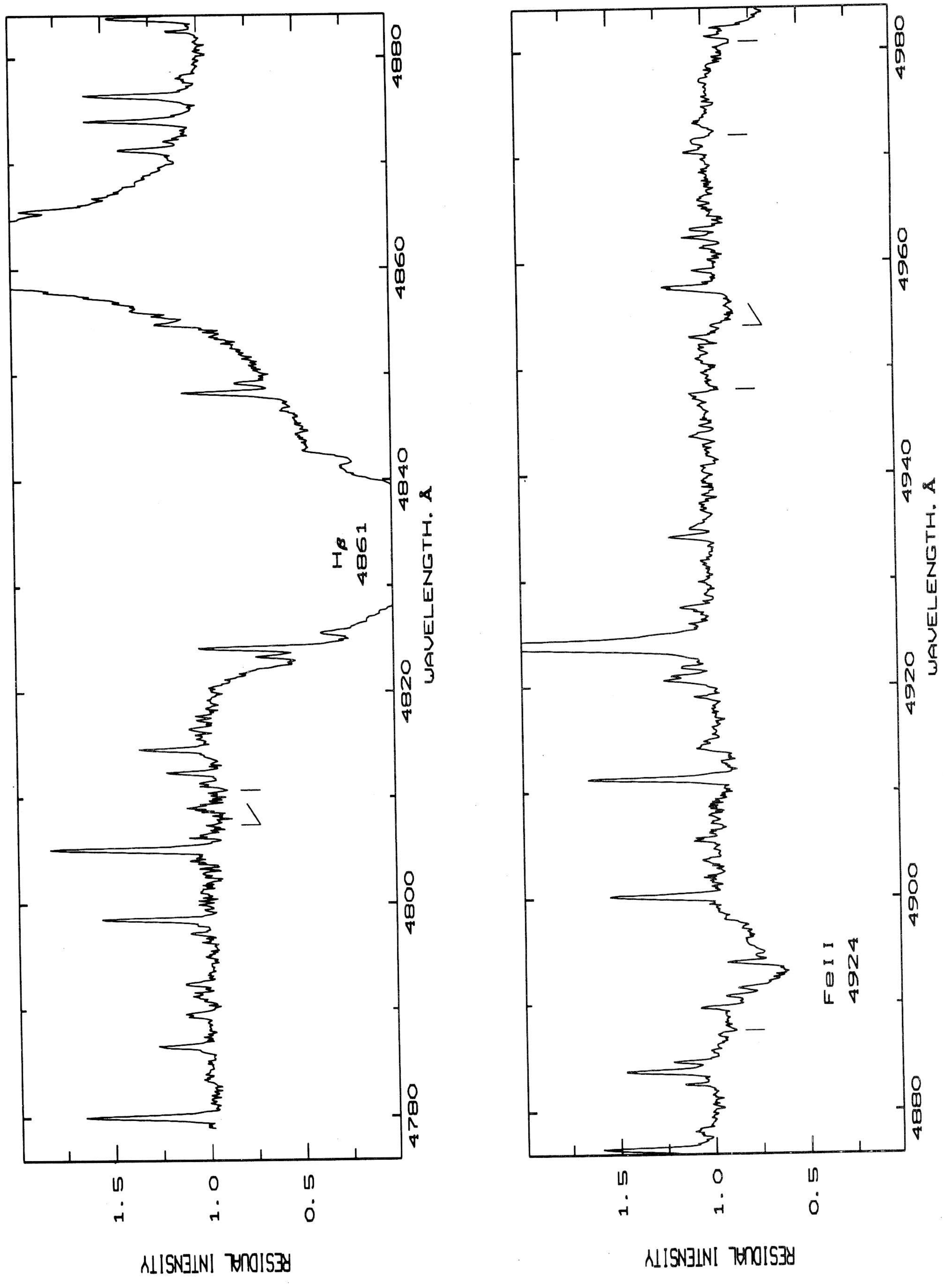
CeII	(13)	5330.56
[FeII]	(19F)	5333.65
CrII	(43)	5334.86
TiII	(69)	5336.79
FeII	(48)	5337.73
CrII	(43)	5337.79
—		5339.1
FeI	(553)	5339.93
FeI	(37)	5341.02
CrII	(24)	5346.10
CrII	(23)	5346.54
FeII	(49)	5346.56
ZrII	(115)?	5350.09
ZrII	(115)?	5350.35
CeII	(15)	5353.53
NdII	(80)	5356.98
ScII	(30)	5357.18
—		5358.1
NdII	(74)	5361.47
FeII	(48)	5362.86
FeI	(1146)	5364.87
FeI	(786)	5365.40
FeI	(1146)	5367.47
CrII	(29)	5369.30
FeI	(1146)	5369.96
FeI	(15)	5371.49
NdII	(79)	5371.91
[FeII]	(19F)	5376.47
CI	(11)?	5380.32
TiII	(69)	5381.02
FeI	(1146)	5383.37
FeI	(1145)?	5389.48
FeI	(553)	5393.17
CeII	(24)	5393.38
TiII	(80)	5396.30
FeI	(15)	5397.13
YII	(35)	5402.78
FeI	(1165)	5404.13
FeI	(15)	5405.78
—		5406.1

CrII	(23)	5407.61
CeII	(23)	5409.23
[FeII]	(17F)	5412.64
FeII	(48)	5414.07
FeI	(1165)	5415.20
TiII	(69)	5418.78
CrII	(23)	5420.92
FeI — FeII	(1146) (49)	5424.07 5424.7 5425.25
— FeII?		5427.5 5427.80
FeI	(15)	5429.70
NdII	(80)	5431.57
FeII	(55)	5432.98
FeI	(15)	5434.52
FeI	(15)	5446.91
TiII	(68)	5454.05
FeI CrII	(15) (50)	5455.61 5455.86
CeII?		5459.21
FeI —	(1163)?	5463.28 5463.6
CrII	(35)	5464.36
—		5468.3
CeII CrII	(24)? (50)	5472.29 5472.62
YII	(27)	5473.38
FeI TiII?	(1062)	5476.56 5476.84
CrII CrII	(50) (50)	5477.45 5478.36
YII	(27)	5480.75
TiII	(68)	5490.65
TiII	(68)	5492.85
YII FeI	(27) (15)	5497.37 5497.52
FeI CrII	(15) (50)	5501.46 5502.08
CrII	(50)	5503.20

FeI	(15)	5506.78
CrII	(50)	5508.62
YII	(19)	5509.90
CrII	(23)	5510.70
CeII	(24)	5512.04
YII	(27)	5521.56
FeII	(56)	5525.11
ScII [FeII]	(31) (17F)	5526.81 5527.33
MgI	(9)	5528.40
TiII	(68)	5529.94
FeII	(55)	5534.84
—		5538.3
YII	(27)	5544.61
YII	(27)	5546.01
FeII?		5567.83
FeI	(686)	5569.62
FeI	(686)	5572.84
FeI [OI]	(686) (3F)	5576.09 5577.34
FeI	(686)	5586.76
— CaI	 (21)	5588.0 5588.75
NdII CaI	(79) (21)	5594.42 5594.46
CaI FeI	(21)? (686)	5602.85 5602.94
FeI	(686)	5615.64
NdII	(86)	5620.61
FeI	(686)	5624.54
FeII	(57)	5627.49
ScII	(29)	5640.98
[FeII] FeI	(17F) (1107)?	5654.85 5655.49
ScII ScII	(29) (29)	5657.87 5658.33
YII	(38)	5662.94
ScII —	(29)	5667.15 5668.0

ScII	(29)	5669.03
ScII	(29)	5684.19
NaI NdII	(6)? (79)	5688.21 5688.52
FeI NdII	(209) (78)	5701.55 5702.24
NdII	(86)	5706.21
NdII	(79)	5708.28
FeI	(686)?	5709.39
YII	(34)	5728.90
[FeII] —	(34F)?	5746.96 5747.8
LaII	(70)	5769.06
YII	(34)	5781.69
NdII	(79)	5804.02
LaII	(4)	5805.76
FeII	(163)	5813.67
VII	(99)	5819.93
FeII	(164)	5823.17
NdII? FeII	 (182)?	5825.87 5826.12
FeII	(182)	5835.49
BaII	(2)	5853.68
NaI	(1)	5889.95
NaI VII	(1) (98)?	5895.92 5897.54
TiII		5910.06
FeI	(170)?	5916.25
VII	(98)	5928.86
FeII	(182)	5952.52
—		5987.2
FeII	(46)	5991.37
VII ZrII VII	(97) (136) (125)?	6028.26 6028.64 6028.96
—		6031.5
CrII	(105)	6053.48
FeI	(207)	6065.49
FeII	(46)	6084.10
ZrII —	(93)	6100.04 6100.2
FeII	(200)	6103.54
ZrII	(106)	6106.47
FeII	(46)	6113.32
ZrII	(93)	6114.78
CaI MnII	(3) (13)	6122.22 6122.43
FeII	(46)	6129.71
FeI	(169)	6136.61
FeI	(207)	6137.69
BaII	(2)	6141.72
—		6145.0
FeII	(74)	6147.74
FeII	(74)	6149.25
FeI	(1015)	6157.73
CaI	(3)	6162.17
CrII FeII	(187) (163)	6179.17 6179.38
FeI	(169)	6191.56
—		6195.5
FeI FeII TiII	(62) (34)	6219.28 6219.54 6220.01
—		6221.5
FeII	(34)	6229.34
FeI	(207)	6230.73
FeII	(74)	6238.39
FeII FeII	(34) (74)	6239.36 6239.95
ScII	(28)	6245.62
FeII	(74)	6274.55
FeI	(169)	6252.56
LaII	(33)	6262.30
FeI	(342)	6270.24
ScII	(28)	6279.74
—		6293.9
LaII	(47)	6296.08
[OI]	(1F)	6300.30

ScII	(28)	6309.89
LaII	(103)	6310.91
FeII		6317.99
LaII ScII	(19) (28)	6320.42 6320.84
—		6327.2
FeII	(199)	6331.96
SiII	(2)	6347.10
[OI]	(1F)	6363.78
FeII	(40)	6369.46
SiII	(2)	6371.36
FeII		6383.72
FeII		6385.45
FeI	(168)	6393.61
FeI	(816)	6411.65
FeII	(74)	6416.92
FeI	(62)	6430.85
FeII	(40)	6432.69
FeII	(74)	6456.38
FeII	(199)?	6482.19
TiII	(91)	6491.57
FeI	(168)	6494.98
FeII	(40)	6516.08
H_α		6562.81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Hβ
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4780
4800
4820
4840
4860
4880
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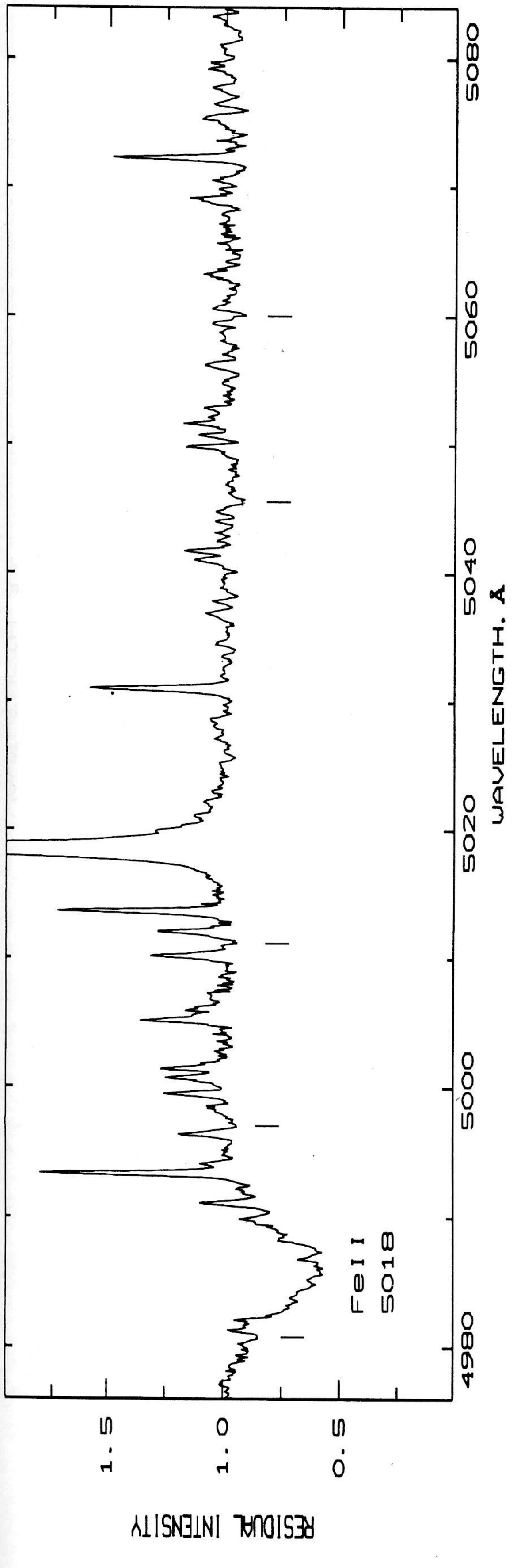
1.0
0.5
RESIDUAL INTENSITY
WAVELENGTH, Å
FeII
4924
4880
4900
4920
4940
4960
4980
1.5
1.0
0.5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WAVELENGTH, Å
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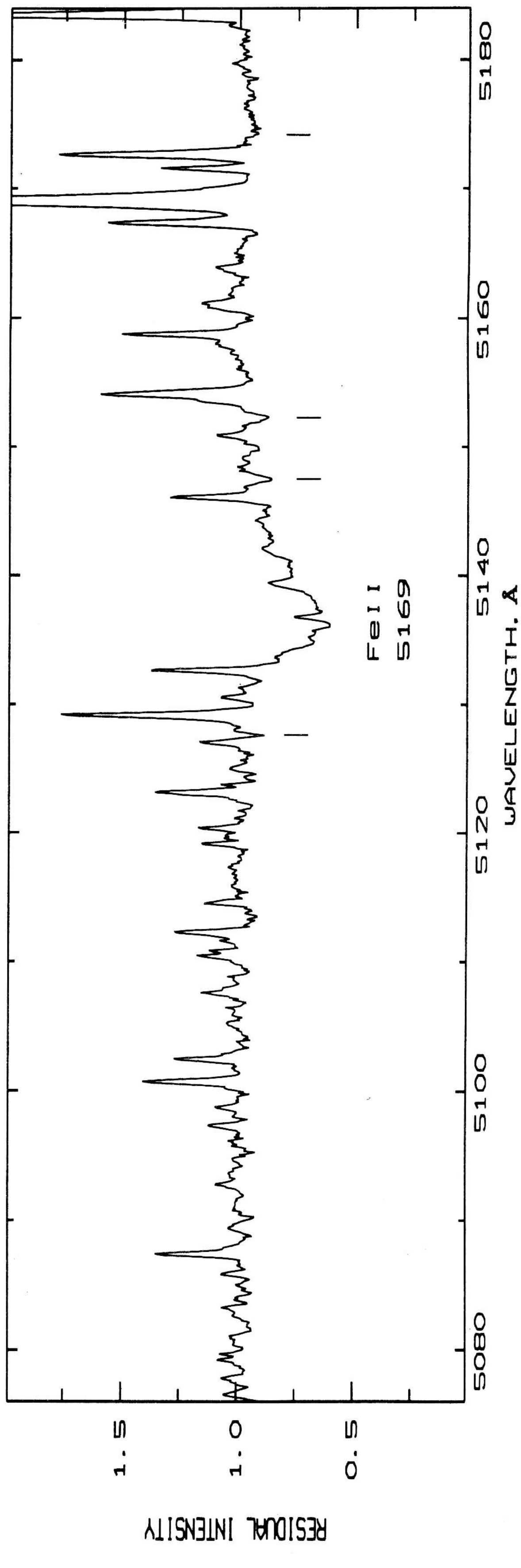
5020
5040
5060
5080
Fe II
5018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WAVELENGTH, Å
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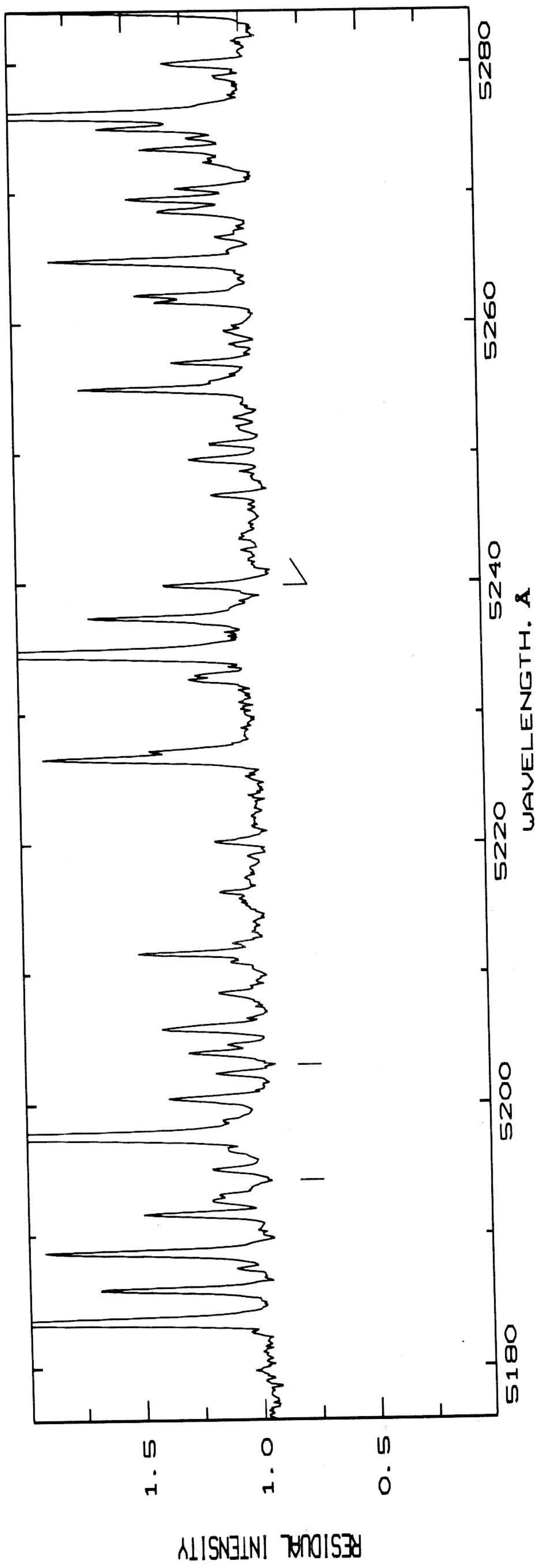
5140
5160
5180
Fe II
5169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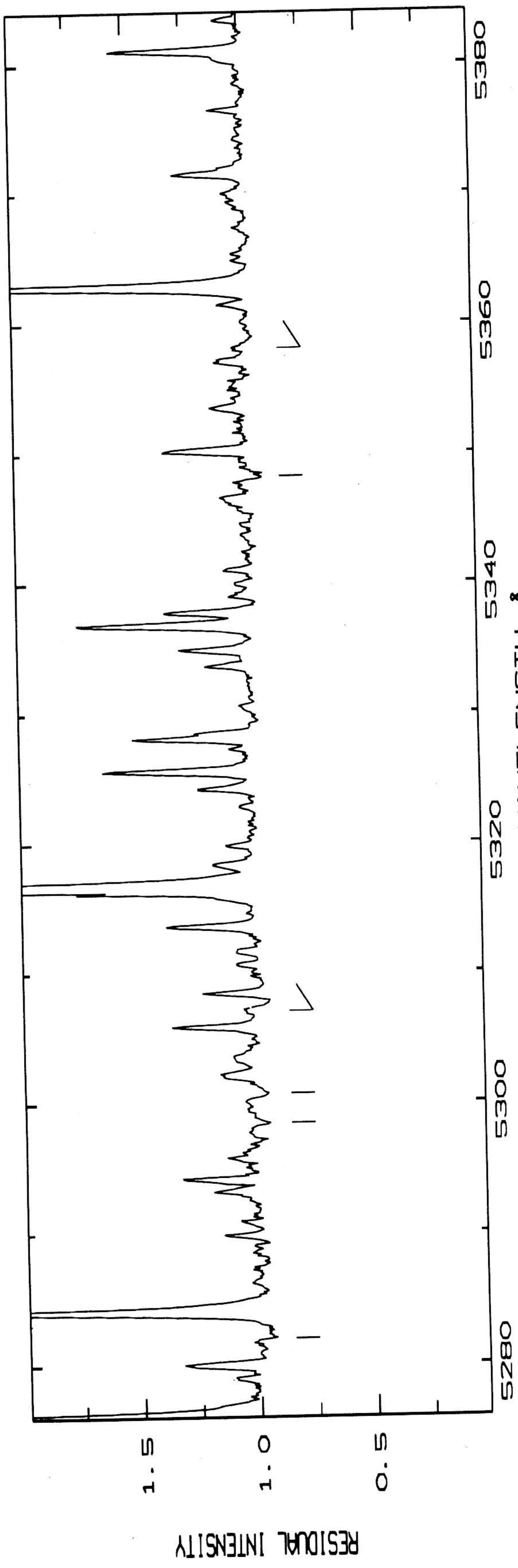
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5320
5340
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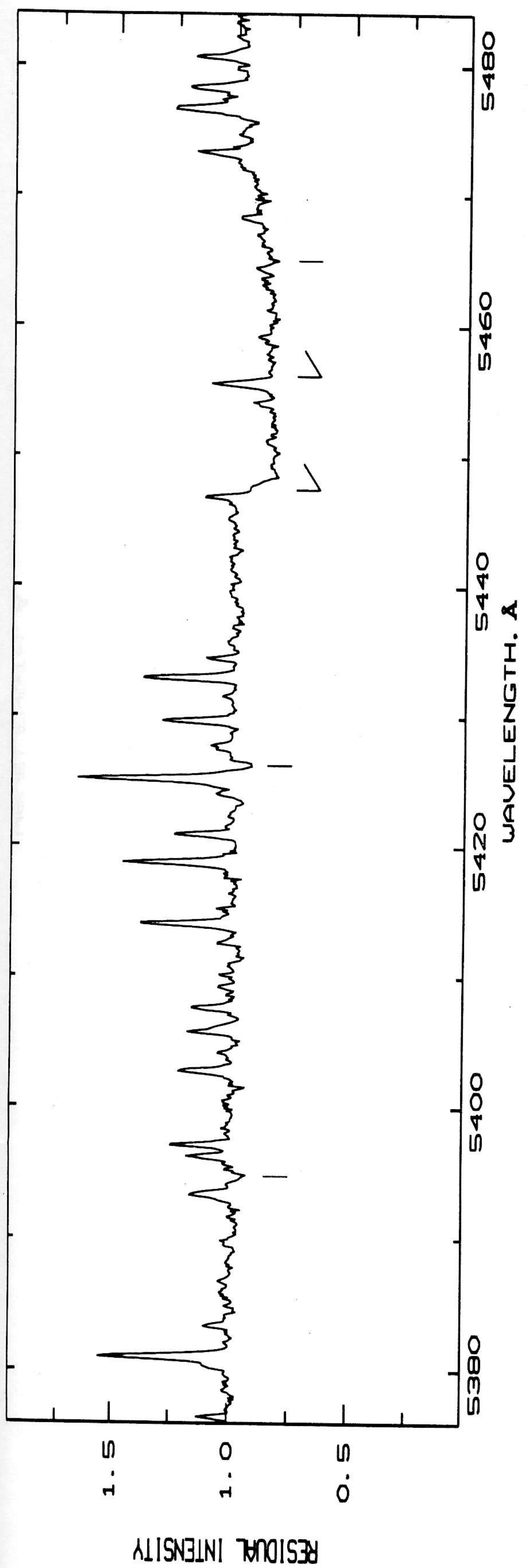
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5480
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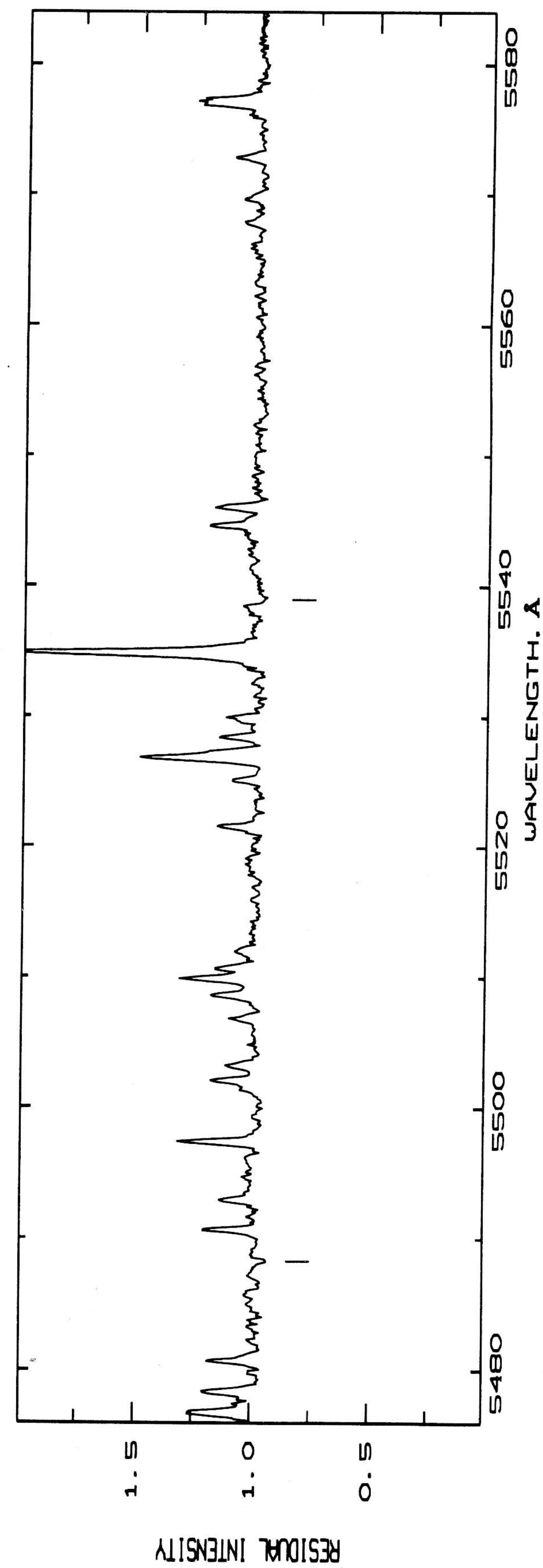
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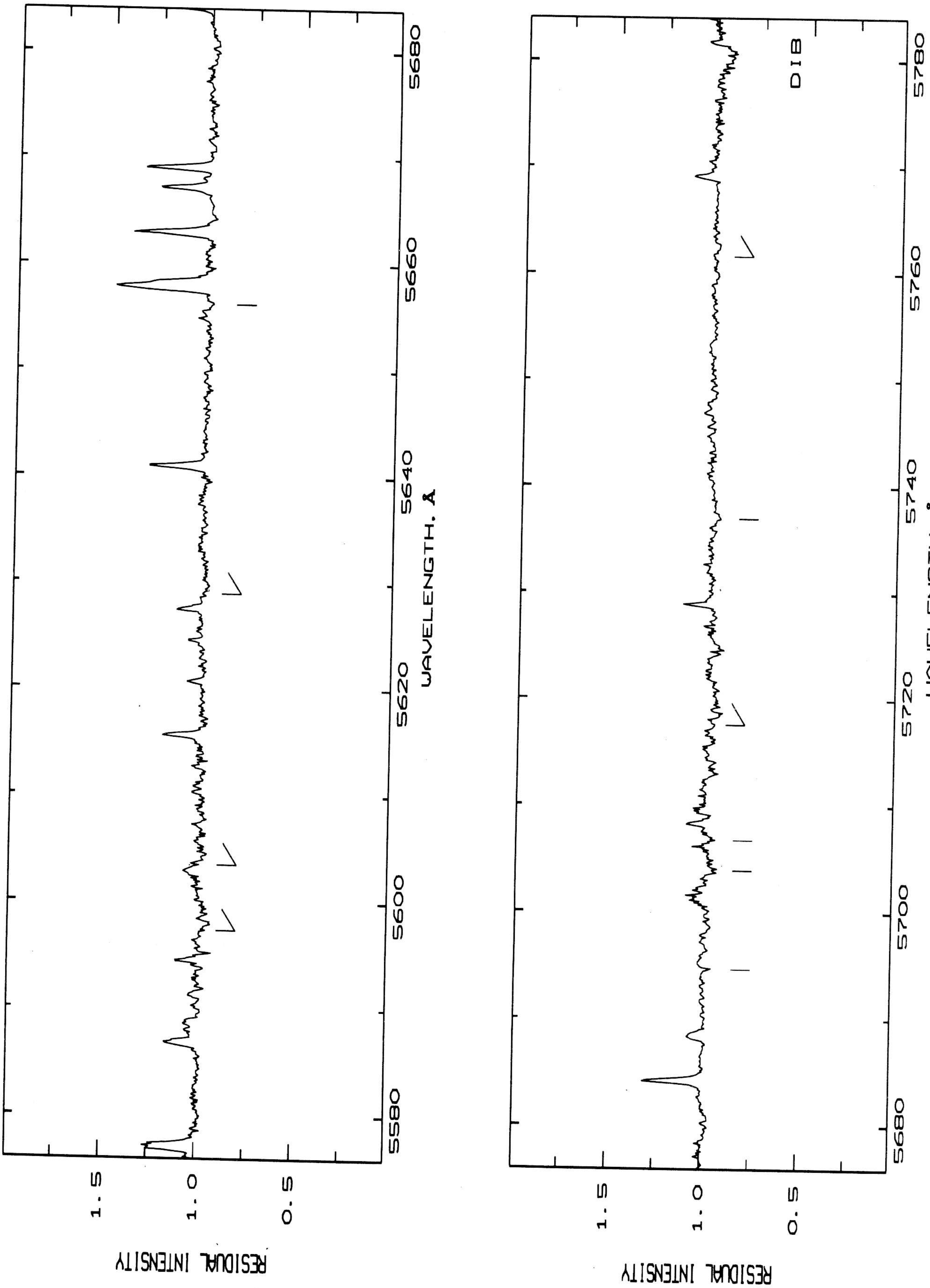
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5640
5660
5680
WAVELENGTH, Å
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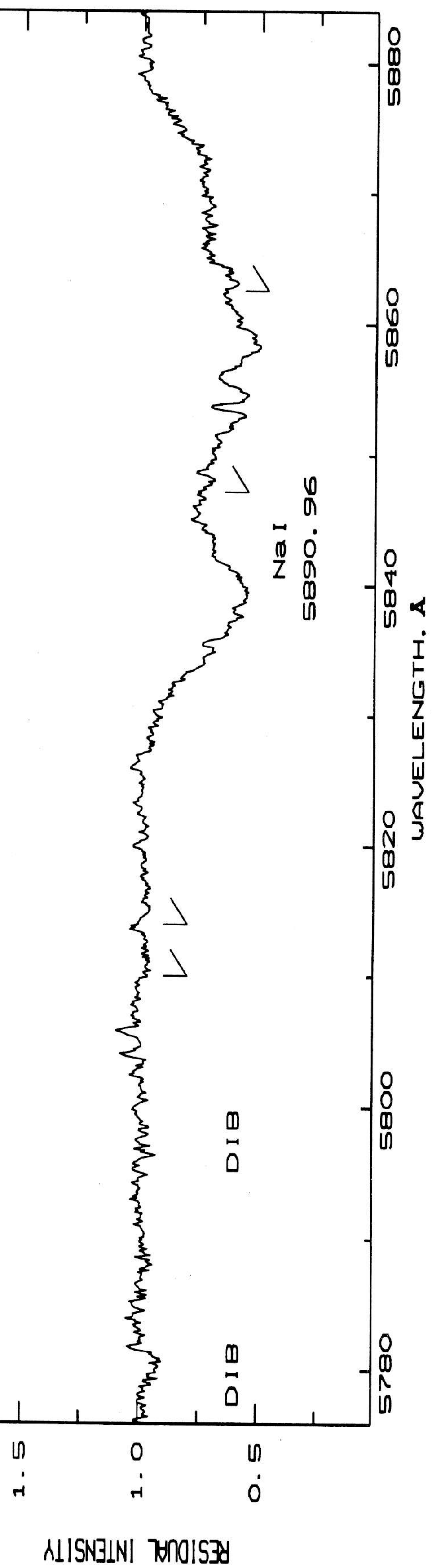
1.0
0.5
5680
5700
5720
5740
5760
5780
WAVELENGTH, Å
DIB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DIB
DIB
Na I
5890.96
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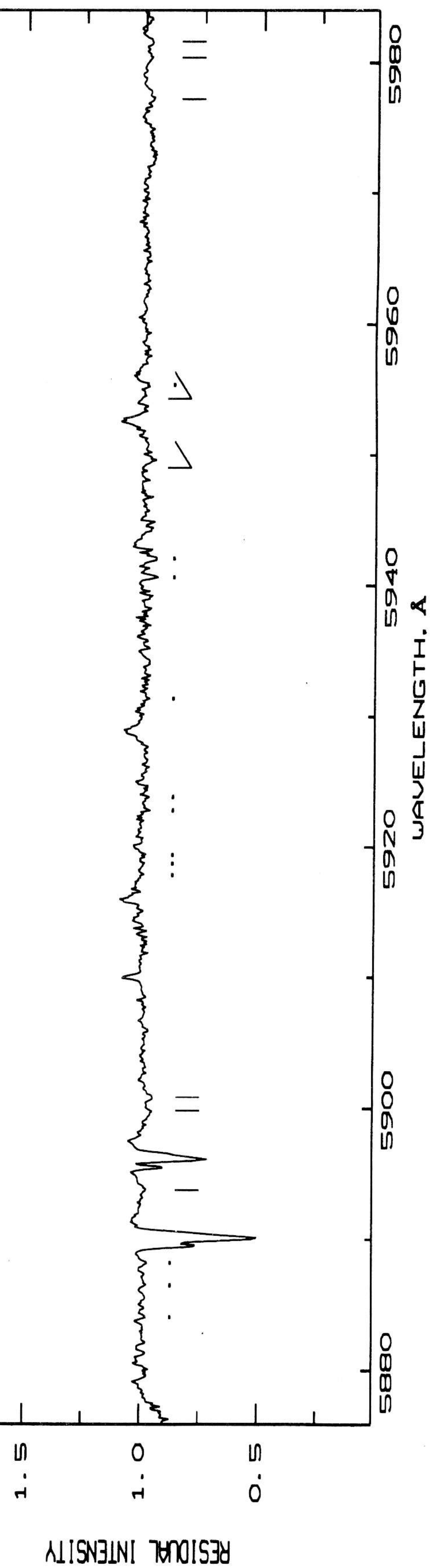
5820
5840
5860
5880
WAVELENGTH, Å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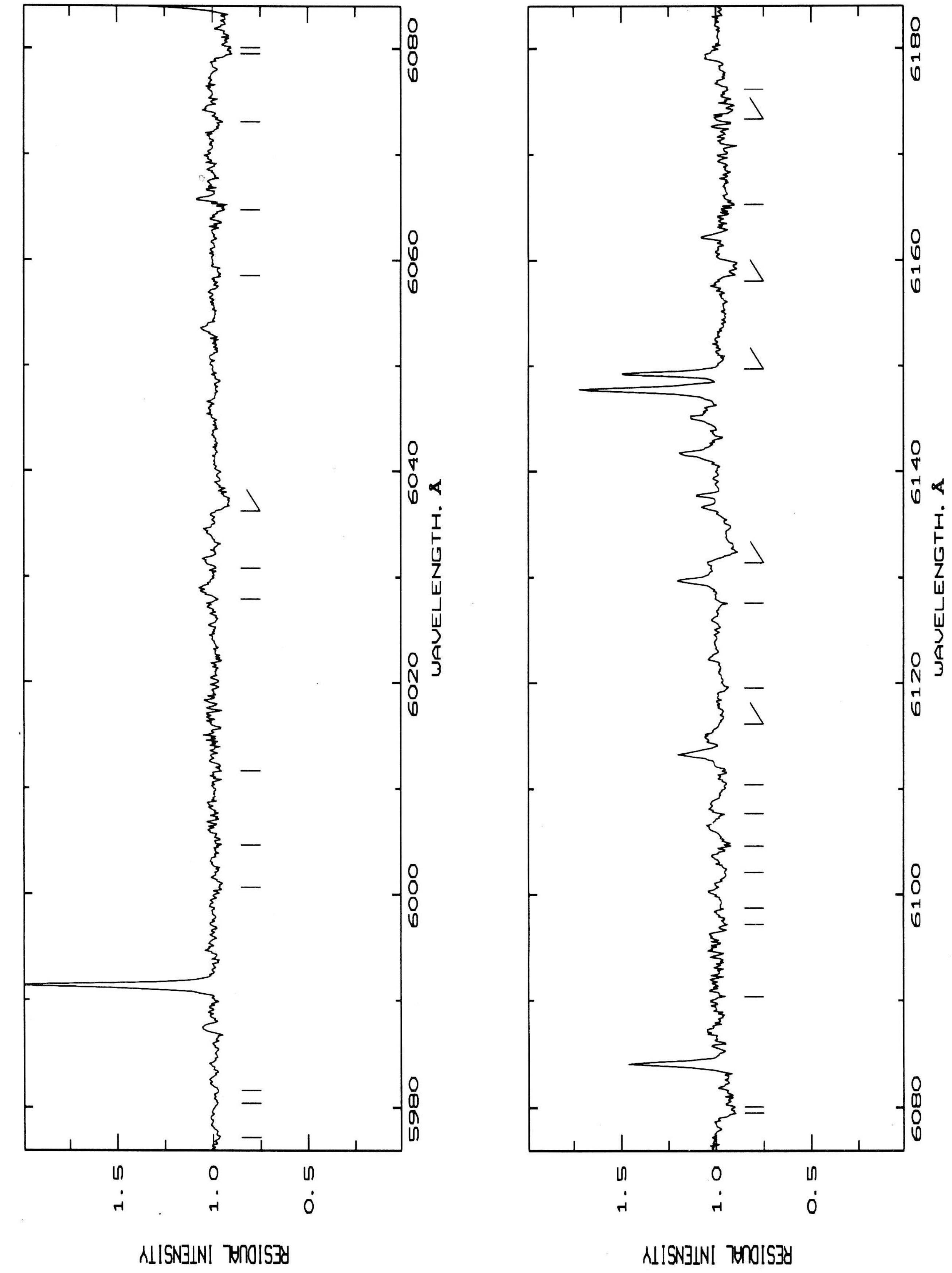
0.5
5880
5900
5920
5940
5960
5980
WAVELENGTH, Å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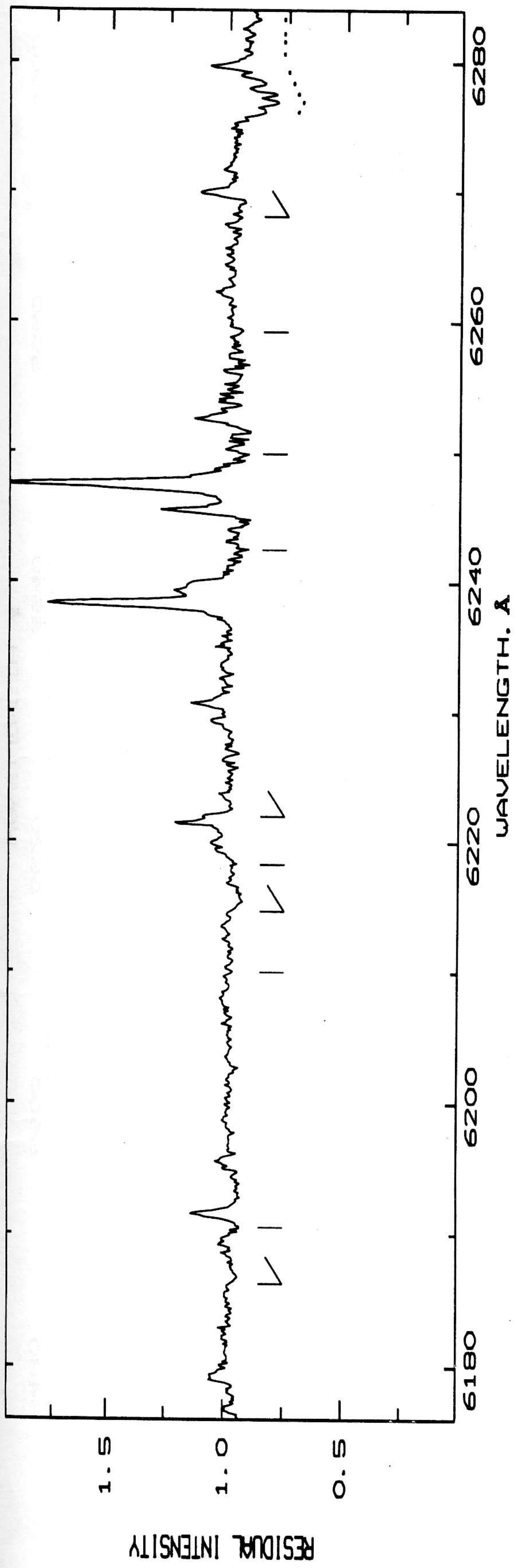
0.5
WAVELENGTH, Å
5980
6000
6020
6040
6060
6080
RESIDUAL INTENSITY
1.5
1.0
0.5
WAVELENGTH, Å
6080
6100
6120
6140
6160
6180


RESIDUAL INTENSITY
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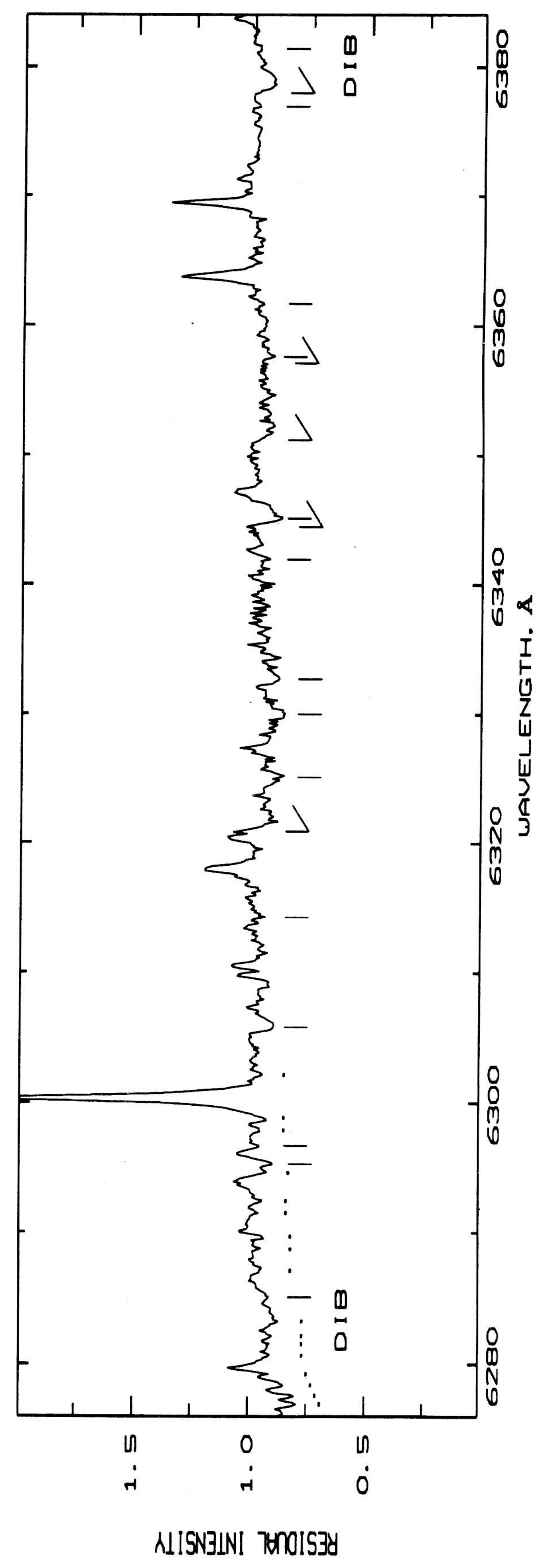
1.0
0.5
6180
6200
6220
6240
6260
6280
WAVELENGTH, Å


RESIDUAL INTENSITY
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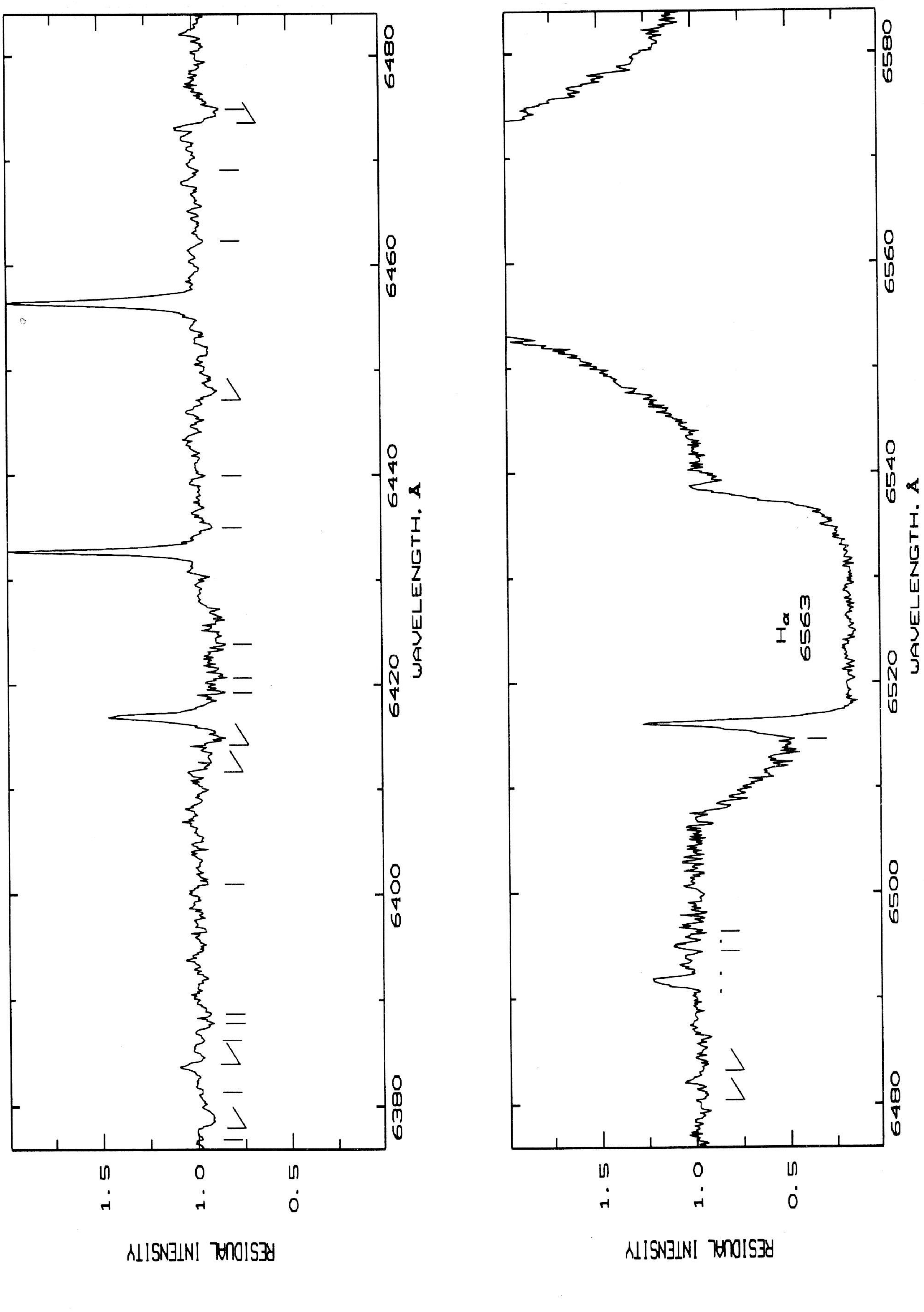
0.5
6280
6300
6320
6340
6360
6380
WAVELENGTH, Å
DIB
DIB


RESIDUAL INTENSITY
0.5
1.0
1.5
6380
6400
6420
6440
6460
6480
WAVELENGTH, Å
RESIDUAL INTENSITY
0.5
1.0
1.5
6480
6500
6520
6540
6560
6580
WAVELENGTH, Å
Hα
6563