Macchetto

SPACE TELESCOPE SCIENCE INSTITUTE

INSTRUMENT SCIENCE REPORT

CAL-FOS-004

TITLE: FOS Wavelength Calibration

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ABSTRACT

The dispersion relations for the eight FOS diffraction gratings are best approximated by 3rd degree polynomials. The RMS residual for the fits ranges from 0.02 pixel for grating H78 to 0.06 pixel for grating H19, substantially better than the spectral resolution of 1 pixel. When the 2.0 arcsec (C3) aperture is used instead of the 0.1 arcsec A4, line blending and over-exposure combine to increase the RMS residual to 1.2 pixel. The prism has a non-linear dispersion, varying from 3.8 Å px^{-1} at 1800 Å to 180 Å px^{-1} at 5500 Å. Wavelength as a function of pixel number for the prism can be approximated to an accuracy of 0.2 pixel by a fourth degree expansion in 1/x. Wavelength calibration data for the blue detector in vacuum was unintentionally omitted from the August, 1983 calibration. Here, we use data from the March 1983 ambient calibration to determine the blue dispersion constants.

DISTRIBUTION: Master file, library

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I. Introduction

The FOS contains six high resolution diffraction gratings (R=1200), two low resolution gratings (R=200) and one sapphire prism (R=40 to 400). In this report, we present dispersion relations for these dispersers on the red and blue digicon detectors. The gratings are labeled with their central wavelength and H or L indicating high or low resolution. An example: H27 refers to the high resolution grating centered on 2700Å.

II. Calibration Light Source

A Westinghouse hollow cathode emission line lamp with a 90% platinum, 10% chromium filament in neon gas and a MgF_2 window is used for the calibration source. This lamp provides spectral lines of suitable intensity throughout the FOS wavelength range of 1150-8000Å. Platinum emits lines in the ultraviolet (1150-3000Å), chromium and ionized neon lines dominate at 3000-5000Å and a series of strong NeI lines provides coverage between 5850Å and 7500Å.

III. Wavelength Identification

Our wavelength identifications follow those of Hartig in his August, 1982 report. He used the IUE line libraries of Turnrose and Bohlin (1981), supplemented by lines identified by Zaidel, et. al. (1970). Turnrose and Bohlin used the following heirarchy for judging the reliablity of wavelength references.

1. Shenstone (1939)
2. Fastie & Mount (1978)
3. Harrison (1969)
4. Kelly and Palumbo (1973)

The wavelengths, ionic species, and reference for each line used for the FOS wavelength calibration are listed in Table 1.

IV. Calibration Spectra

The calibration data for the blue detector in vacuum was not obtained in August, 1983. This should be remedied in the next thermal vacuum calibration. The blue side photometric calibration data, which could have been used for the wavelength calibration, is not available on tape, because the data tape was accidentally overwritten.

In the final version of this report we will use vacuum spectra on both the red and blue sides, taken with the 0.1 arcsec aperture (A4) and the internal lamp. At present, the red side vacuum spectra have been obtained. But, since blue side vacuum spectra are not available, we substitute air spectra, which are identical to the vacuum spectra, except for a small shift (<2 Å) in wavelength, and the air absorption below 1900 Å. The blue side H13 spectrum used for this report was obtained in the vacuum using the 1.0 arcsec aperture and the external Pt lamp. Because of the larger aperture, this spectrum has a resolution of 2.8 px compared with 1.0 px for the others. There may also be a small (<0.2 pixel) shift in the x-center between different apertures.

On the blue detector, wavelength increases as a function of pixel number in the grating spectra, but decreases as a function of pixel number on the red detector. On both sides, the prism wavelength scale is reversed relative to that of the gratings. In addition to being reversed, the blue grating spectra are shifted up to 15 pixels relative to the red spectra.

V. Data Reduction and Dispersion Relations

Approximately 30 "good" lines in each high resolution spectrum were selected for the FOS line library. "Bad" lines are excluded from the line library by the following criteria for the 0.1 arcsec (A4) spectra:

1. If the intensity minimum between two lines is greater than 30% of the more intense line, reject both lines.
2. If the intensity minimum between two lines is greater than 30% of the less intense line, reject the smaller line only.
3. A single line must not have asymmetric features that are greater than 30% of its peak intensity.

These criteria exclude most lines separated by less than 2 pixels. The value of 30% is somewhat arbitrary, but it strikes a balance between rejecting too many lines, and allowing multiple lines to affect the line centroiding calculation. The vacuum and air wavelength and line center of each line in the dispersion relation is shown in Table 1.

Polynomials of first through fourth degree were considered as candidates for the diffraction grating dispersion relations. The wavelength scale of all the gratings is linear to an accuracy of 0.3 pixels, but when plotted, the residuals show a systematic curvature, as shown for H19 on the red side in Fig. 1A. A third degree polynomial fit substantially decreases the residuals in comparison with a quadratic or linear fit. A fourth degree polynomial does not improve the fit, however. The RMS residuals of the various polynomial fits shown in Figures 1A through 1D for the grating H19 on the red side are typical of all gratings.

Grating H19

Polynomial	Standard Deviation
linear	.107
quadratic	.091
cubic	.064
quadric	.062

The residuals of the cubic dispersion relation are shown for each grating in Figures 2A-2K.

For the convenience of the reader, two sets of dispersion constants are given, one for wavelength as a function of pixel number in Table 2, and a second for pixel number as a function of wavelength in Table 3. Also for convenience, the linear approximation of the dispersion relation is included in Table 4 for both the red and blue detectors. It should be noted that the linear approximation is not the same as the first two coefficients of the cubic dispersion relation. The standard deviation of the curve fits varies from 0.02 to 0.06 pixel, depending on the grating. This is substantially better than the nominal resolution of 1.0 pixel.

VI. Wavelength Calibration for Large Apertures

Spectra taken with the larger apertures have a lower resolution (5.6 px for the 2.0 arcsec C3 aperture) than the 0.1 arcsec spectra. See figures 3I and 3J. In addition, the brighter spectral lines in the 2.0 arcsec spectra are saturated (>70,000 cts/s), making it hard to find lines that are unblended. However, dispersion relations can be computed from these large aperture spectra, resulting in a standard deviation of 1.2 px for H27, and 0.4 px for H57. The residuals are shown in Figs. 2 N and 2 O.

VII. Prism

The prism has a highly non-linear dispersion over its wavelength range of 1770-6000 Å (Figs. 4C and 4D). The dispersion is 180 Å px^{-1} at 5500 Å, but declines to 3.8 Å px^{-1} at 1800 Å. The dispersion relation can be approximated by a fourth degree expansion of 1/x (x = pixel number), to an accuracy better than 0.2 pixel. The equation is shown below.

$$\lambda = A1 + \frac{A2}{x-x_o} + \frac{A3}{(x-x_o)^2} + \frac{A4}{(x-x_o)^3} + \frac{A5}{(x-x_o)^4}$$

On the red detector, the equation was fitted to the positions and wavelengths of 17 lines, ranging from 1777 Å to 5209 Å with a RMS residual of 0.10 pixel. On the blue detector, fourteen lines are used, ranging from 1916 to 5852 Å resulting in a RMS residual of 0.12 pixel. To an accuracy of 2%, the dispersion relations for the red and blue sides are identical, except for a translation in X. The residuals for the curve fits are shown in Figures 2L and 2M, and the coefficients of equation 1 are listed in Tables 5A and 5B. Outside the wavelength range 1750-6000 Å, the approximation used here may not behave the same way as the true dispersion relation for a sapphire prism. As there are no resolved spectral lines outside the region, it is not possible to tell if this is the case.

Wavelength Identif ation References

F Fastie, W.G. and Mount, G.H. tudy of Ultraviolet Properties of Optical Components for he International UV Explorer and for Space Telescope", ohns Hopkins Univ., 1978.

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S Shenstone, A.G. Phil. Trans. y. Soc. 237, 453, 1939.

T Turnrose, B.E. and Bohlin, R.C., IUE Data Reduction XX. High Dispersion Line Libraries, NASA IUE Newsletter, 13, Jan.1981.

Z Zaidel, A.N., Profkof'ev, V.K. Raiskii, S.M., Slavnyi, V.A. and Shreider, E.Y. Tables of Spectral Lines, Plenum, N.Y. 1970.

TABLES

Table 1. FOS line libraries for all gratings on the red side, and for h13, h27, h40 and h57 on the blue side. The wavelength references are identified on p 6 .

Table 2. Wavelength as a function of pixel number: constants for third degree polynomial dispersion relations, for the red detector. The first column contains the wavelength at pixel zero and the second column contains the wavelength at the end of the spectrum In the case of L15 and L65, the spectrum does not cover the whole detector, therefore the cubic dispersion relation should not be extrapolated beyond the ends of the spectrum. Linear dispersion relations are given for the blue detector.

Table 3. Pixel number as a function of wavelength: constants for third degree polynomial dispersion relations, for the red detector except h13.

Table 4. Linear approximation of dispersion relations, red and blue detectors.

Tables 5A, 5B. Line libraries and dispersion constants for the prism. Fig 5A: Red detector, 5B: Blue detector.

FIGURES

All spectra are taken with the 0.1 arcsec A4 aperture, unless otherewise noted.

Figures 1A-1D. An example showing the improved residuals achieved with a third degree polynomial fit, grating h19, red detector. Fig 1A: Linear fit , 1B: Quadratic fit, 1C: Cubic fit, 1D: Fourth degree fit.

Figures 2A-2O. Residuals for third degree polynomial fits. Figs. 2A-2G: gratings h19, h27, h40, h57, h78, L15, L65, red side.
Figs 2H-2K: gratings h13, h27, h40, h57, blue side.
Figs 2L-2M: Residuals for prism, red and blue sides.
Figs 2N-2O: Cubic residuals for h27, h57 with 2 arcsec c3 apertur

Figures 3A-3J. Small scale plots, showing entire spectrum. Intensity Vs. air wavelength above 2000A, vacuum wavelength below 2000A. Fig 3A: h13 blue. Figs 3B-3H: gratings h19, h27, h40, h57, h78, L15, L65, red side. Figs 3I-3J: h27, h57 with 2 arcsec c3 aperture.

Figures 4A-4B: Red and blue prism spectra. Figs 4C-4D: Air wavelength Vs. pixel number.

Figure 5. Large scale plots with all FOS calibration lines labeled. The lower plot on each page is a 10x enlargement of the upper plot. Gratings h19, h27, h40, h57, h78, L65, red side.

Table 1

BLUE: GRATING H13

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	CUBIC RESIDUAL (PIXEL)	ION	REFERENCE
1	1198.781		109.01	0.032	PtII	S
2	1238.847		148.67	0.100	PtII	S
3	1248.600		158.06	-0.170	PtII	S
4	1403.896		312.55	0.073	PtII	S
5	1482.823		391.22	0.087	PtII	S
6	1494.724		403.01	0.013	PtII	S
7	1509.288		417.35	-0.165	PtII	S
8	1554.940		462.98	-0.057	PtII	S
9	1574.390		482.52	0.085	PtII	S
			STANDARD DEVIATION =	0.13450		

RED: GRATING H19

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	CUBIC RESIDUAL (PIXEL)	ION	REFERENCE
1	1621.658		475.79	0.055	PtII	S
2	1631.122		469.38	-0.011	PtII	F
3	1636.169		466.00	0.003	PtII	F
4	1668.987		443.82	-0.134	PtII	S
5	1681.683		435.55	0.122	NeII	K
6	1688.356		430.92	-0.020	NeII	K
7	1723.128		407.54	-0.013	PtII	S
8	1867.122		310.58	0.057	PtII	S
9	1870.404		308.15	-0.156	PtII	S
10	1883.051		299.81	0.029	PtII	S
11	1907.493		283.31	0.028	NeII	K
12	1911.702		280.43	-0.010	PtII	S
13	1916.083		277.52	0.038	NeII	K
14	1944.455		258.27	-0.064	PtII	S
15	2037.117	2036.463	195.82	0.058	PtII	H
16	2050.027	2049.370	187.03	-0.020	PtI	N
17	2116.239	2115.569	142.32	-0.024	PtII	S
18	2129.282	2128.610	133.56	0.025	PtI	Z
19	2144.920	2144.244	122.97	-0.011	PtII	S
20	2165.850	2165.170	108.84	-0.021	PtI	Z
21	2175.352	2174.670	102.45	0.003	PtI	Z
22	2191.000	2190.315	91.89	0.000	PtII	S
23	2235.610	2234.915	61.77	-0.043	PtI	H
24	2246.215	2245.518	54.64	-0.025	PtII	N
25	2263.363	2262.662	43.04	-0.068	PtII	S
26	2275.083	2274.380	35.15	-0.063	PtI	H
27	2293.085	2292.378	23.09	-0.004	PtI	F
28	2311.668	2310.957	10.65	0.070	PtII	S
29	2319.007	2318.294	5.71	0.066	PtI	F
			STANDARD DEVIATION =	6.42105E-02		

RED: GRATING H27

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	CUBIC RESIDUAL (PIXEL)	ION	REFERENCE
1	2235.610	2234.915	502.65	0.028	PtI	H
2	2246.217	2245.520	497.66	0.010	PtII	N
3	2263.363	2262.662	489.65	0.039	PtII	S
4	2275.083	2274.380	484.05	-0.053	PtI	H
5	2293.085	2292.378	475.72	0.062	PtI	F
6	2311.668	2310.957	466.94	0.014	PtII	S
7	2319.007	2318.294	463.49	0.012	PtI	F
8	2357.825	2357.104	445.22	-0.001	PtI	H
9	2378.002	2377.276	435.68	-0.040	PtII	S
10	2390.262	2389.533	429.93	-0.012	PtI	H
11	2425.608	2424.871	413.25	-0.036	PtII	S
12	2440.797	2440.057	406.07	-0.054	PtI	F

13	2487.919	2487.168	383.83	-0.052	PtI	H
14	2499.254	2498.500	378.49	-0.038	PtI	F
15	2539.963	2539.200	359.32	0.031	PtI	F
16	2628.815	2628.031	317.21	-0.043	PtI	F
17	2640.132	2639.345	311.92	0.020	PtI	F
18	2651.641	2650.852	306.42	-0.027	PtI	F
19	2660.243	2659.452	302.33	-0.044	PtI	N
20	2703.205	2702.403	281.99	-0.031	PtI	F
21	2734.770	2733.961	267.04	-0.026	PtI	F
22	2772.490	2771.672	249.25	0.063	PtI	F
23	2810.328	2809.500	231.25	-0.002	NeII	Z
24	2831.133	2830.300	221.43	0.039	PtI	N
25	2876.693	2875.849	199.83	0.046	PtII	S
26	2894.720	2893.872	191.33	0.090	PtI	F
27	2930.652	2929.795	174.23	0.021	PtI	F
28	2956.593	2955.730	161.92	0.007	NeII	H
29	2998.845	2997.971	141.94	0.049	PtI	F
30	3022.460	3021.580	130.78	0.073	CrI	Z
31	3199.544	3198.620	46.90	-0.025	NeII	Z
32	3219.139	3218.210	37.67	0.002	NeII	Z
33	3245.086	3244.150	25.42	-0.001	NeII	Z

STANDARD DEVIATION = 3.19872E-02

RED: GRATING H40

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	RESIDUAL (PIXEL)	ION	REFERENCE
1	3245.086	3244.150	506.75	-0.025	NeII	Z
2	3379.250	3378.280	463.82	0.029	NeII	Z
3	3409.107	3408.130	454.23	0.022	NeII	Z
4	3418.880	3417.900	451.08	0.011	PtI	Z
5	3448.688	3447.700	441.51	0.005	NeI	Z
6	3473.564	3472.570	433.52	0.014	NeI	Z
7	3521.476	3520.470	418.09	-0.023	NeI	Z
8	3579.701	3578.680	399.38	-0.004	PtII	Z
9	3594.505	3593.480	394.62	0.006	NeI	Z
10	3606.349	3605.320	390.80	-0.005	CrI	Z
11	3665.154	3664.110	371.87	-0.003	CrI	Z
12	3695.251	3694.200	362.14	-0.035	CrI	Z
13	3728.140	3727.080	351.59	0.013	NeII	Z
14	3767.360	3766.290	338.87	-0.055	NeII	Z
15	3778.232	3777.160	335.44	0.014	NeII	Z
16	3819.774	3818.690	322.01	-0.016	NeII	Z
17	3909.867	3908.760	292.96	0.013	NeII	Z
18	3920.270	3919.160	289.56	-0.028	PtI	Z
19	3942.616	3941.500	282.38	0.009	CrI	Z
20	3964.811	3963.690	275.20	-0.004	CrI	Z
21	3970.873	3969.750	273.27	0.015	CrI	Z
22	3977.795	3976.670	271.03	0.013	CrI	Z
23	3985.026	3983.900	268.71	0.031	CrI	Z
24	4255.528	4254.330	181.29	-0.008	CrI	Z
25	4276.013	4274.810	174.70	0.021	CrI	Z
26	4290.938	4289.730	169.87	0.008	CrI	Z
27	4352.993	4351.770	149.85	0.031	CrI	Z
28	4372.508	4371.280	143.51	-0.009	Cri	Z
29	4602.040	4600.750	69.44	-0.012	CrI	Z
30	4647.452	4646.150	54.76	-0.056	CrI	Z
31	4757.421	4756.090	19.37	-0.028	CrI	Z
32	4802.363	4801.020	5.00	0.059	CrI	Z

STANDARD DEVIATION = 0.026

Table 1

RED: GRATING H57

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	CUBIC RESIDUAL (PIXEL)	ION	REFERENCE
1	4581.334	4580.050	505.91	-0.083	CrI	Z
2	4602.040	4600.750	501.42	-0.019	CrI	Z
3	4923.655	4922.280	430.56	0.030	CrI	Z
4	5039.156	5037.750	405.00	-0.010	NeI	Z
5	5299.666	5298.190	347.39	0.051	NeI	Z
6	5332.264	5330.780	340.16	0.042	NeI	Z
7	5402.063	5400.560	324.64	-0.002	NeI	Z
8	5564.316	5562.770	288.69	0.032	NeI	Z
9	5691.400	5689.820	260.47	0.016	NeI	Z
10	5749.896	5748.300	247.45	-0.016	NeI	Z
11	5854.114	5852.490	224.31	-0.014	NeI	Z
12	5883.222	5881.590	217.76	-0.100	NeI	Z
13	5946.479	5944.830	203.82	0.004	NeI	Z
14	6031.672	6030.000	184.91	0.016	NeI	Z
15	6076.024	6074.340	175.03	-0.012	NeI	Z
16	6097.851	6096.160	170.19	-0.007	NeI	Z
17	6144.763	6143.060	159.79	0.005	NeI	Z
18	6165.298	6163.590	155.21	-0.012	NeI	Z
19	6219.003	6217.280	143.30	-0.006	NeI	Z
20	6268.226	6266.490	132.39	0.014	NeI	Z
21	6306.536	6304.790	123.88	0.004	NeI	Z
22	6336.184	6334.430	117.28	-0.015	NeI	Z
23	6384.757	6382.990	106.54	0.024	NeI	Z
24	6404.022	6402.250	102.19	-0.054	NeI	Z
25	6508.330	6506.530	79.09	-0.019	NeI	Z
26	6534.688	6532.880	73.25	-0.012	NeI	Z
27	6600.775	6598.950	58.64	0.028	NeI	Z
28	6680.127	6678.280	41.04	-0.002	NeI	Z
29	6718.897	6717.040	32.50	0.050	NeI	Z

Standard Deviation= .030

RED: GRATING H78

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	CUBIC RESIDUAL (PIXEL)	ION	REFERENCE
1	6268.226	6266.490	509.18	-0.031	NeI	Z
2	6306.536	6304.790	502.78	-0.012	NeI	Z
3	6336.184	6334.430	497.87	0.045	NeI	Z
4	6384.757	6382.990	489.71	0.030	NeI	Z
5	6404.022	6402.250	486.44	-0.014	NeI	Z
6	6508.330	6506.530	468.92	-0.003	NeI	Z
7	6534.688	6532.880	464.50	0.003	NeI	Z
8	6600.775	6598.950	453.37	-0.004	NeI	Z
9	6680.127	6678.280	439.98	-0.028	NeI	Z
10	6718.897	6717.040	433.47	-0.002	NeI	Z
11	6931.385	6929.470	397.64	0.023	NeI	Z
12	7034.353	7032.410	380.21	-0.007	NeI	Z
13	7175.920	7173.940	356.29	0.004	NeI	Z
14	7247.170	7245.170	344.23	-0.002	NeI	Z
15	7440.953	7438.900	311.46	-0.001	NeI	Z

STANDARD DEVIATION= .022

Table 1

RED: GRATING L15

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	CUBIC RESIDUAL (PIXEL)	ION	REFERENCE
1	1688.356	1688.356	114.39	0.020	NeII	K
2	1723.128	1723.128	109.48	0.011	PtII	S
3	1777.086	1777.086	101.80	-0.058	PtII	S
4	1883.051	1883.051	86.89	-0.008	PtII	S
5	1916.083	1916.083	82.27	0.040	NeII	K
6	2129.282	2128.610	52.08	-0.022	PtI	Z
7	2144.920	2144.244	49.92	0.023	PtII	S
8	2175.352	2174.670	45.65	0.039	PtI	Z
9	2246.215	2245.518	35.57	-0.060	PtII	Z
10	2440.797	2440.057	8.37	0.029	PtI	F
11	2487.919	2487.168	1.76	-0.014	PtI	H
		STANDARD DEVIATION =		4.26442E-02		

RED: GRATING L65

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	CUBIC RESIDUAL (PIXEL)	ION	REFERENCE
1	3920.270	3919.160	199.28	-0.084	CrI	Z
2	4352.993	4351.770	182.48	0.081	CrI	Z
3	4653.463	4652.160	170.69	0.102	CrI	Z
4	5209.872	5208.420	148.66	-0.039	CrI	Z
5	5854.114	5852.490	123.25	-0.080	NeI	Z
6	5946.479	5944.830	119.67	-0.021	NeI	Z
7	6144.763	6143.060	111.79	-0.089	NeI	Z
8	6268.226	6266.490	107.01	-0.011	NeI	Z
9	6336.184	6334.430	104.36	0.007	NeI	Z
10	6404.022	6402.250	101.73	0.049	NeI	Z
11	6508.330	6506.530	97.58	-0.005	NeI	Z
12	6680.127	6678.280	90.85	0.018	NeI	Z
13	6931.385	6929.470	80.99	0.026	neI	Z
14	7034.353	7032.410	76.98	0.051	NeI	Z
15	7247.170	7245.170	68.64	0.050	NeI	Z
16	7841.242	7839.080	45.34	-0.055	NeI	Z
		STANDARD DEVIATION =		6.59612E-02		

Table 1

BLUE: GRATING H27

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	RESIDUAL (PIXEL)
1	2235.610	2234.915	5.20	-0.015
2	2246.217	2245.520	10.26	0.006
3	2263.363	2262.662	18.44	0.055
4	2275.083	2274.380	24.03	0.009
5	2293.085	2292.378	32.62	-0.006
6	2311.668	2310.957	41.48	-0.010
7	2319.007	2318.294	44.97	-0.022
8	2357.825	2357.104	63.47	-0.018
9	2378.002	2377.276	73.08	0.065
10	2390.262	2389.533	78.92	-0.026
11	2425.608	2424.871	95.75	-0.021
12	2440.797	2440.057	102.98	-0.018
13	2487.919	2487.168	125.42	0.044
14	2499.254	2498.500	130.81	-0.041
15	2539.963	2539.200	150.19	-0.126
16	2628.815	2628.031	192.48	0.027
17	2640.132	2639.345	197.87	-0.024
18	2651.641	2650.852	203.35	0.028
19	2660.243	2659.452	207.45	0.039
20	2703.205	2702.403	227.91	0.034
21	2734.770	2733.961	242.95	0.037
22	2772.490	2771.672	260.93	-0.043
23	2810.328	2809.500	278.98	0.077
24	2831.133	2830.300	288.91	0.059
25	2876.693	2875.849	310.67	0.016
26	2894.720	2893.872	319.28	-0.050
27	2930.652	2929.795	336.46	0.006
28	2956.593	2955.730	348.87	0.011
29	2998.845	2997.971	369.11	-0.056
30	3022.460	3021.580	380.43	-0.071
31	3199.544	3198.620	465.59	0.018
32	3219.139	3218.210	475.05	-0.028
33	3245.086	3244.150	487.59	0.043

STANDARD DEVIATION = 4.57517E-02

BLUE GRATING H40

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	RESIDUAL (PIXEL)
1	3379.250	3378.280	44.81	-0.004
2	3409.107	3408.130	54.49	0.018
3	3418.880	3417.900	57.67	0.004
4	3448.688	3447.700	67.37	-0.013
5	3473.564	3472.570	75.45	-0.015
6	3521.476	3520.470	91.00	0.000
7	3579.701	3578.680	109.90	0.006
8	3594.505	3593.480	114.72	-0.006
9	3606.349	3605.320	118.56	0.001
10	3665.154	3664.110	137.66	0.008
11	3695.251	3694.200	147.43	0.008
12	3728.140	3727.080	158.12	0.013
13	3767.360	3766.290	170.95	-0.077
14	3778.232	3777.160	174.34	0.061
15	3819.774	3818.690	187.89	0.015
16	3909.867	3908.760	217.17	0.027
17	3920.270	3919.160	220.62	-0.041
18	3942.616	3941.500	227.87	-0.023

Table 1

19	3964.811	3963.690	235.06	0.011
20	4255.528	4254.330	329.76	-0.002
21	4276.013	4274.810	336.44	0.004
22	4290.938	4289.730	341.30	0.011
23	4352.993	4351.770	361.55	0.021
24	4372.508	4371.280	367.97	-0.027

STANDARD DEVIATION = 0.028

BLUE: GRATING H57

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	RESIDUAL (PIXEL)
1	4923.655	4922.280	70.53	-0.252
2	5039.156	5037.750	96.37	0.298
3	5299.666	5298.190	154.65	-0.288
4	5332.264	5330.780	161.94	-0.146
5	5402.063	5400.560	177.55	0.599
6	5564.316	5562.770	213.85	-0.078
7	5691.400	5689.820	242.28	-0.250
8	5749.896	5748.300	255.37	0.289
9	5854.114	5852.490	278.68	-0.379
10	5883.222	5881.590	285.20	0.207

STANDARD DEVIATION = 0.390

Table 2.

FOS WAVELENGTH CALIBRATION DISPERSION CONSTANTS: WAVELENGTH AS A FUNCTION OF PIXEL NUMBER. W= A + BX + CX**2 + DX**3

GRATING	A WAVELENGTH (PX 0)	WAVELENGTH (END)*	B	C	D
RED SIDE, VACUUM INTERNAL LAMP: **					
H19	2327.41	1562.0	-1.4868	2.8516E-5	-1.3428E-7
H27	3298.89	2207.7	-2.1187	4.4105E-5	-4.8014E-8
H40	4817.77	3216.8	-3.1117	8.0491E-5	-7.2848E-8
H57	6865.85	4536.7	-4.5278	1.2116E-4	-1.1881E-7
H78	9306.11	6229.2	-6.1273	6.4835E-4	-5.5300E-6
L15	2500.62	1600(px120) ++	-7.1837	1.4160E-4	-3.3808E-5
L65	9014.32	3550(px215) ++	-26.04	4.8561E-3	1.7110E-4
PRI	1780(px320)	6700(px485)			
BLUE SIDE, VACUUM EXTERNAL LAMP:					
H13	1087.98	1607.8	+1.021	-4.2133E-5	5.5420E-7
BLUE SIDE, AIR INTERNAL LAMP:					
H19	1537.7	2308.8	+1.486		
H27	2229.8	3305.6	+2.089		
H40	3243.9	4829.6	+3.077		
H57	4608.4	6913.8	+4.470		
L15, L65	not available				
PRI	5500(px25)	1900(px175)			

* Quarter stepping adds four extra pixels of information to the 512 pixel array. Because the x-substeps are numbered starting at zero, the end of the spectrum is at pixel 515.75.

**On the red side, wavelength decreases as a function of pixel number for all gratings. The wavelength scale for the prism is reversed (relative to the gratings) on both sides.

++The low resolution grating spectra cover a small section of the diode array. The pixel number at each end of the spectrum apears in brackets after the wavelenth range given by the linear approximation. The cubic fit for L65 blows up outside the range 45-200px. Similarly, the L15 relation becomes less accurate beyond px 115. It is best to use the linear approximation (Table 4) outside the quoted ranges.

Table 3

PIXEL NUMBER AS A FUNCTION OF WAVELENGTH

$$X = A + B\lambda + C\lambda^2 + D\lambda^3$$

COEFFICIENTS, H13
A -975.27
B 0.7761
C 1.45120E-04
D -2.40038E-06
SIGMA
0.1342 px

COEFFICIENTS, H19
1494.63
-0.5610
-5.66736E-05
-9.71137E-08
SIGMA
0.0616

COEFFICIENTS, H27
1474.70
-0.3818
-3.19823E-05
9.22722E-09
SIGMA
0.0319

COEFFICIENTS, H40
1456.50
-0.2512
-1.72490E-05
4.19338E-09
SIGMA
0.0739

COEFFICIENTS, H57
1429.67
-0.1739
-8.14800E-06
1.21320E-09
SIGMA
0.0296

COEFFICIENTS, H78
1365.73
-0.0854
-1.14319E-05
1.43616E-08
SIGMA
0.0224

COEFFICIENTS, L15
335.02
-0.1137
-1.41622E-05
-4.85117E-08
SIGMA
0.0426

COEFFICIENTS, L65
348.89
-0.0367
-4.81918E-07
8.57522E-10
SIGMA
0.0660

Table 4

LINEAR APPROXIMATION $\lambda = A + BX$

WAVELENGTH AS A FUNCTION OF PIXEL NUMBER

COEFFICIENTS, H13. BLUE
A 1089.42
B 1.0056
SIGMA
0.1904 px

COEFFICIENTS, H19 RED ↓
2327.34
-1.4828
SIGMA
0.1088

COEFFICIENTS, H27
3299.19
-2.1145
SIGMA
0.1687

COEFFICIENTS, H40
4817.85
-3.1008
SIGMA
0.1694

COEFFICIENTS, H57
6865.58
-4.5109
SIGMA
0.1629

COEFFICIENTS, H78
9288.88
-5.9303
SIGMA
0.0961

COEFFICIENTS, L15
2499.55
-7.0953
SIGMA
0.0846

COEFFICIENTS, L65
8991.76
-25.4390
SIGMA
0.0829

PRISM, RED SIDE

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	RESIDUAL (PIXEL)
1	1777.100		307.77	-0.221
2	1883.100		336.95	-0.145
3	1916.100		344.30	0.003
4	2129.272	2128.600	380.75	0.051
5	2144.876	2144.200	382.74	0.122
6	2175.382	2174.700	386.61	0.111
7	2245.897	2245.200	394.76	0.067
8	2440.840	2440.100	412.61	0.018
9	2487.951	2487.200	416.25	-0.099
10	2660.191	2659.400	427.02	0.111
11	2831.133	2830.300	435.86	-0.113
12	3232.933	3232.000	450.13	0.107
13	3324.756	3323.800	452.97	-0.218
14	3596.326	3595.300	458.93	0.081
15	3920.310	3919.200	464.64	0.078
16	4273.002	4271.800	469.49	-0.044
17	5209.852	5208.400	477.55	0.007

COEFFICIENTS

X0	507.66
A1	1124.9
A2	-1.37373E+05
A3	-1.55810E+06
A4	-3.73257E+07
A5	-1.04967E+08

$$\lambda = A1 + \frac{A2}{x - x_0} + \frac{A3}{(x-x_0)^2} + \frac{A4}{(x-x_0)^3} + \frac{A5}{(x-x_0)^4}$$

Table 5B

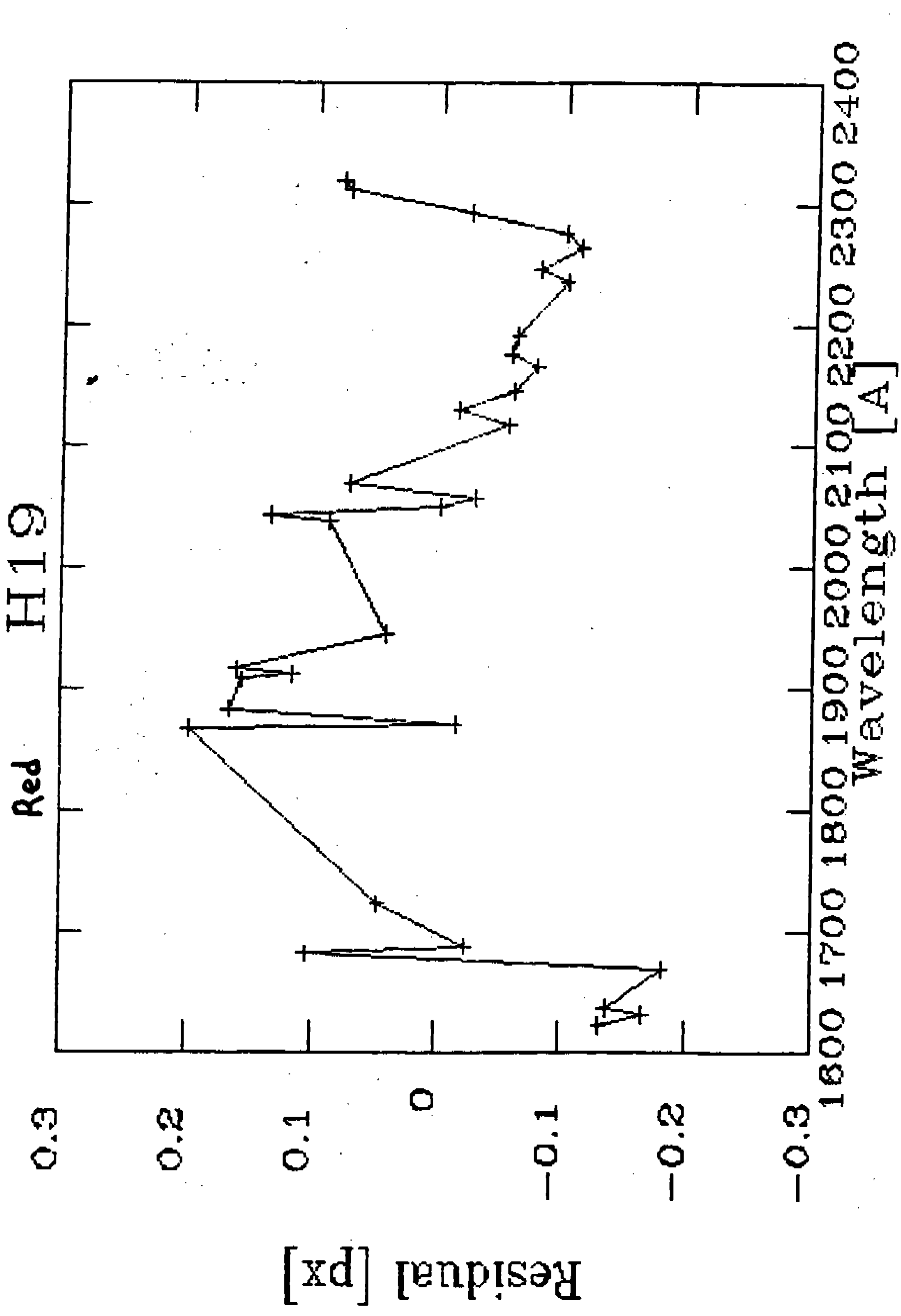
PRISM, BLUE SIDE

	WAVELENGTH VACUUM	WAVELENGTH AIR	LINE CENTER (PIXEL)	RESIDUAL (PIXEL)
1	1916.080		167.18	0.246
2	2144.916	2144.240	128.54	-0.038
3	2175.352	2174.670	124.66	-0.055
4	2245.917	2245.220	116.44	-0.034
5	2440.800	2440.060	98.58	-0.144
6	2487.921	2487.170	94.80	0.084
7	2660.241	2659.450	83.98	-0.162
8	2831.133	2830.300	75.04	0.097
9	3324.756	3323.800	57.80	0.243
10	3594.525	3593.500	51.94	-0.146
11	3920.310	3919.200	46.09	-0.078
12	4276.003	4274.800	41.18	0.050
13	5209.852	5208.400	33.06	0.000
14	5854.124	5852.500	29.53	-0.001

COEFFICIENTS

X_0 -1.1126
A_1 1134.1
A_2 1.36521E+05
A_3 -9.47290E+05
A_4 2.62715E+07
A_5 3.16059E+08

Fig 1A



Red
H19
Residual [px]
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
1600 1700 1800 1900 2000 2100 2200 2300 2400
Wavelength [A]

Fig 1B

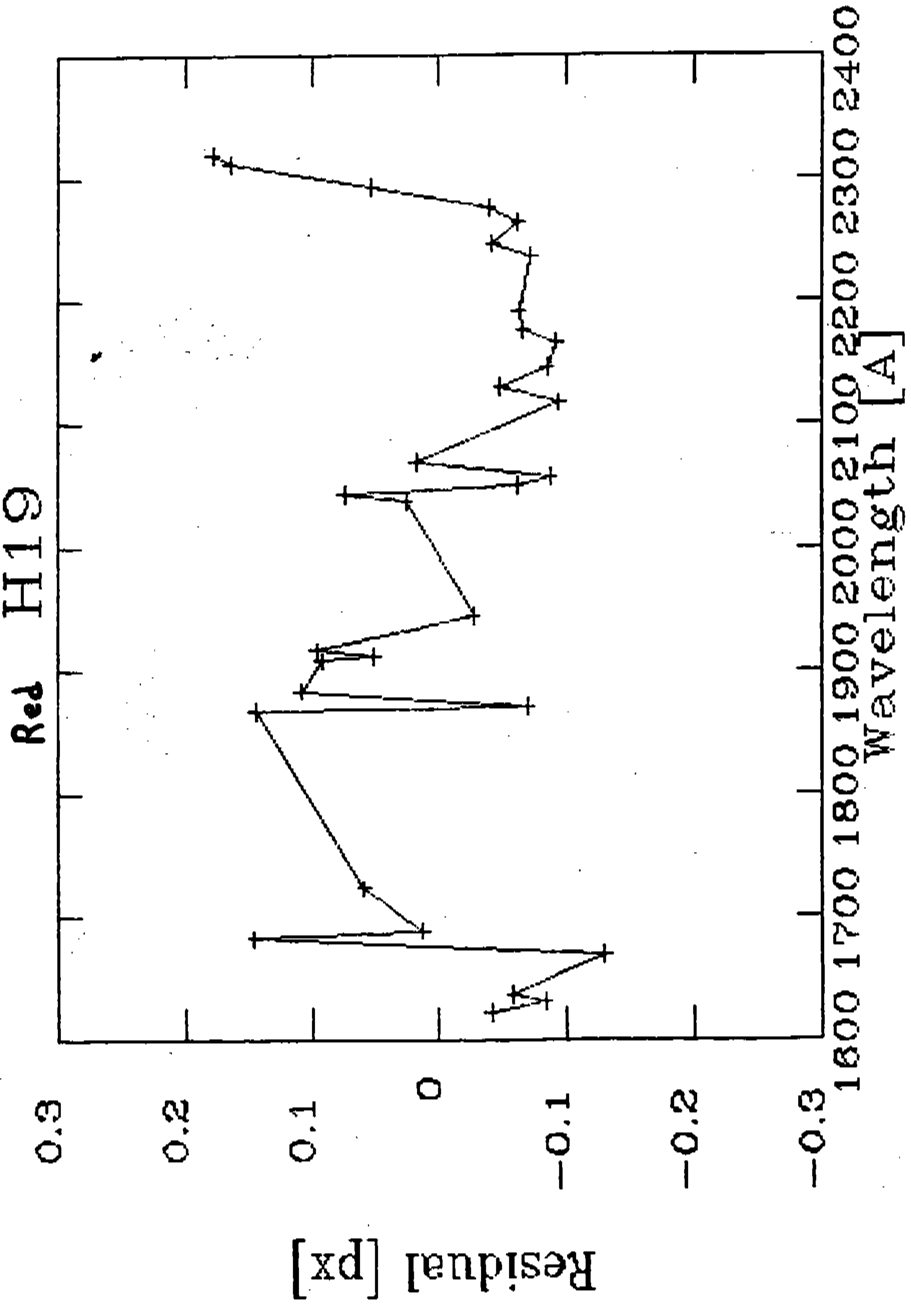
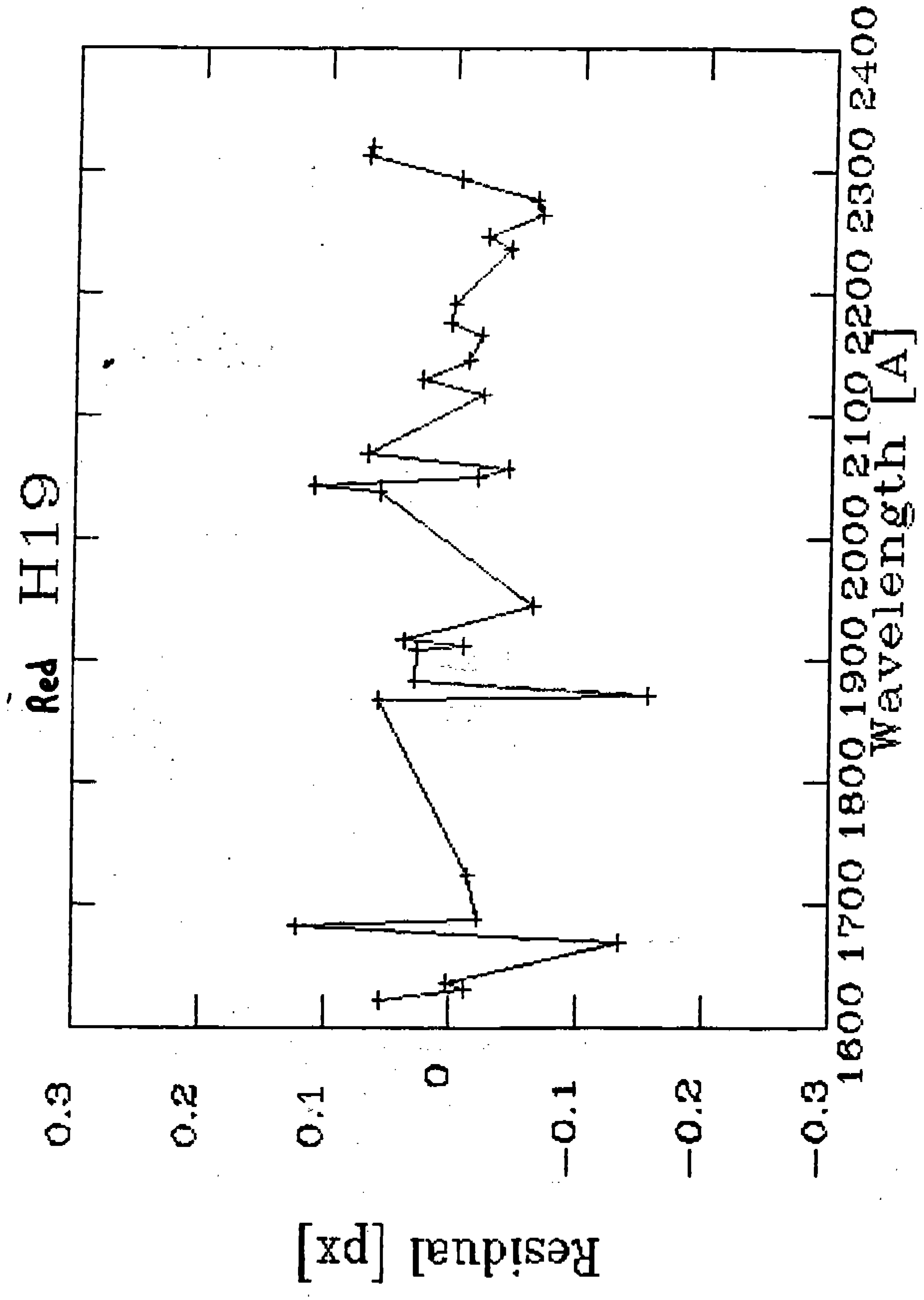

Red H19
Wavelength [A]
1600 1700 1800 1900 2000 2100 2200 2300 2400
Residual [px]
0.3 0.2 0.1 0 −0.1 −0.2 −0.3

Fig 1c



Red H19
Wavelength [A]
Residual [px]
1600
1700
1800
1900
2000
2100
2200
2300
2400
0.3
0.2
0.1
0
−0.1
−0.2
−0.3

Fig 1D

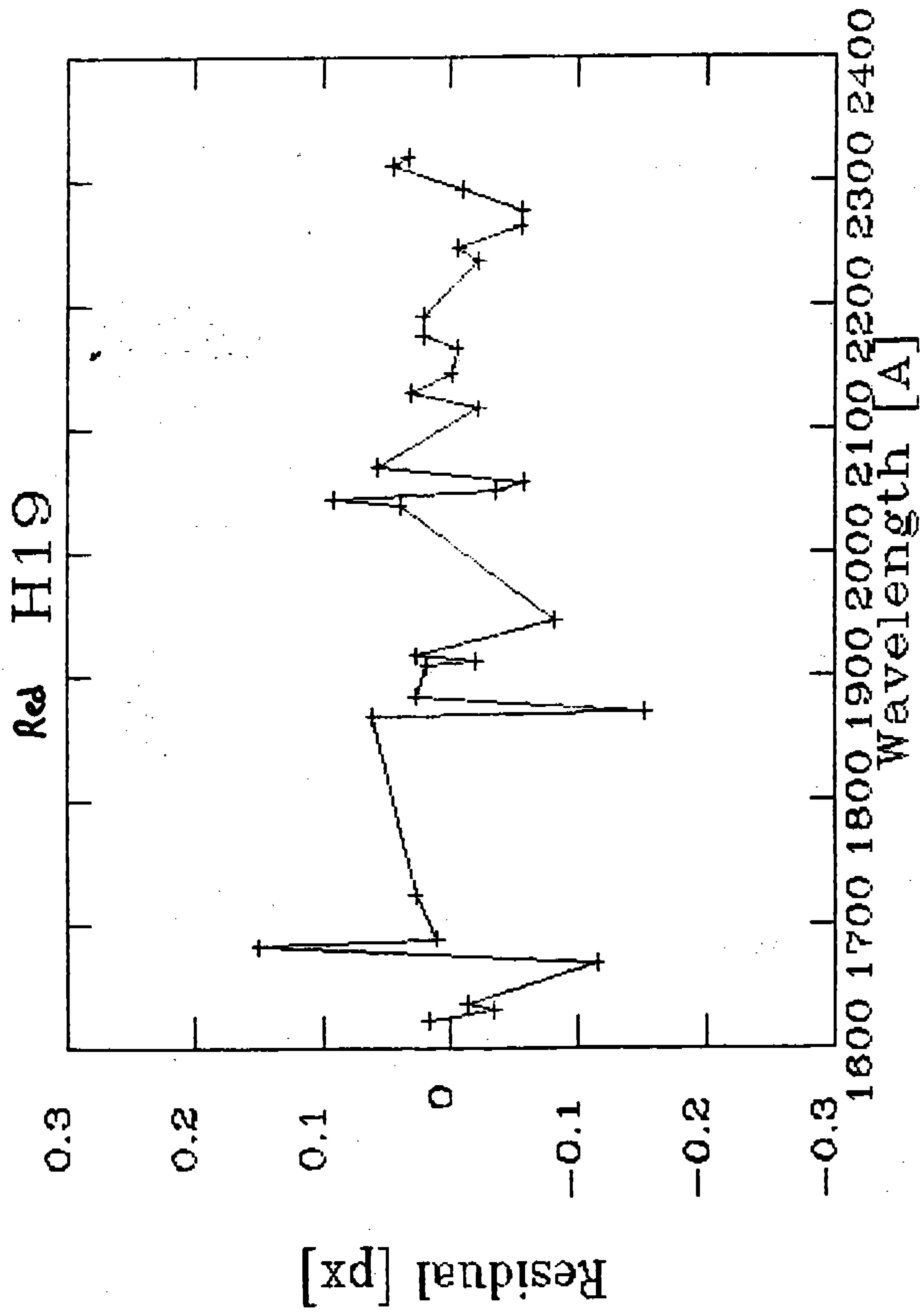
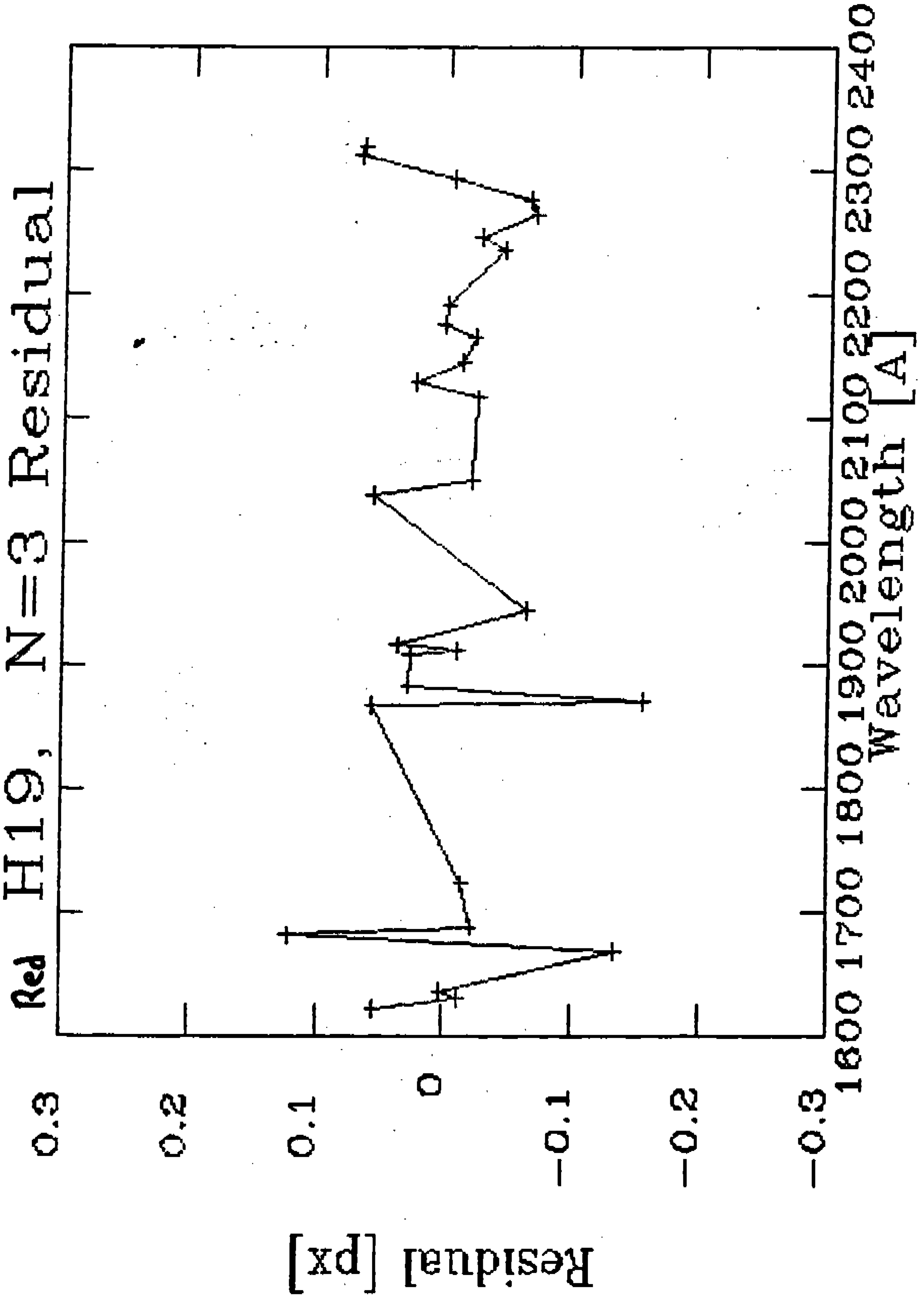
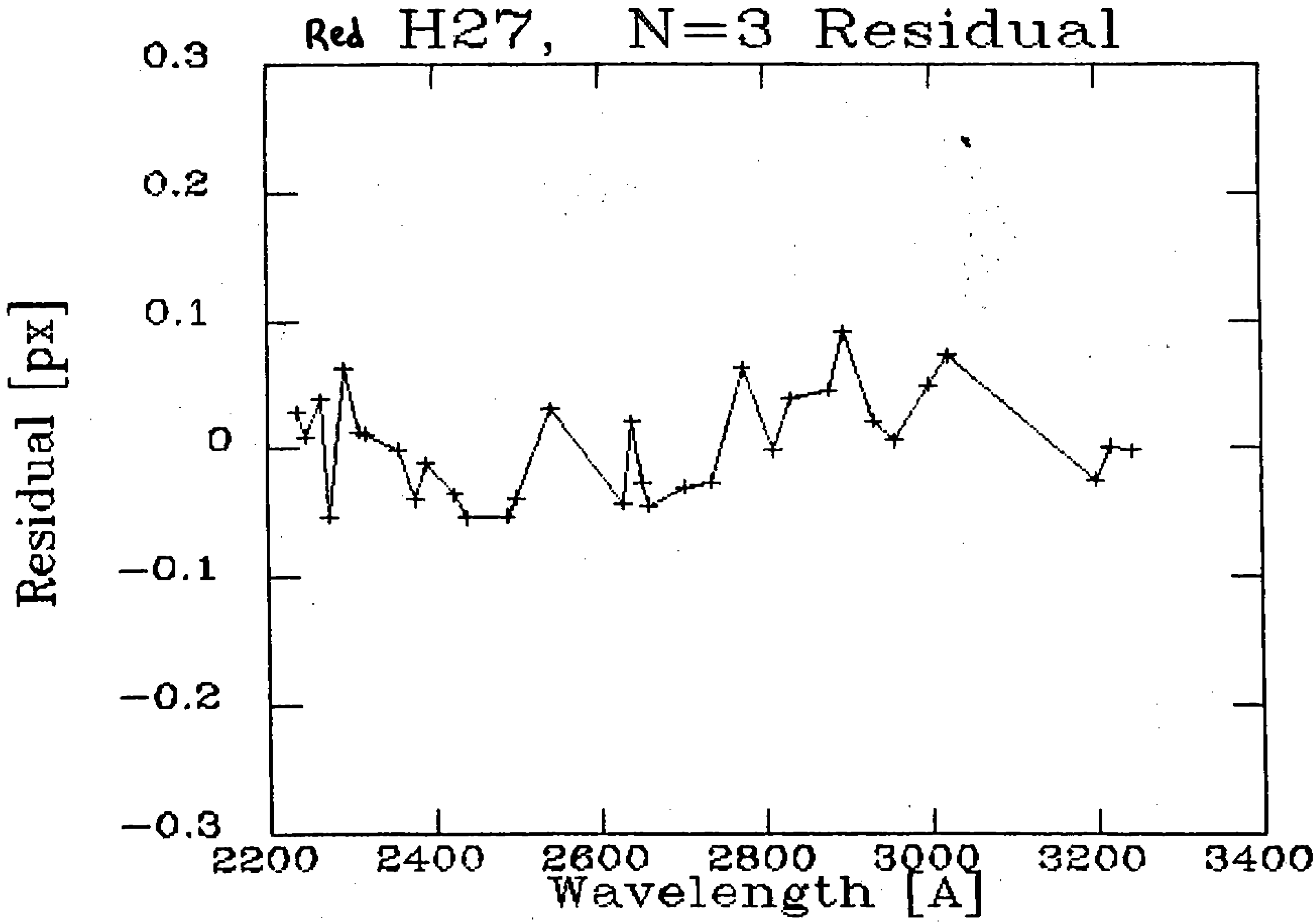

Red H19
Wavelength [A]
Residual [px]
1600
1700
1800
1900
2000
2100
2200
2300
2400
0.3
0.2
0.1
0
−0.1
−0.2
−0.3

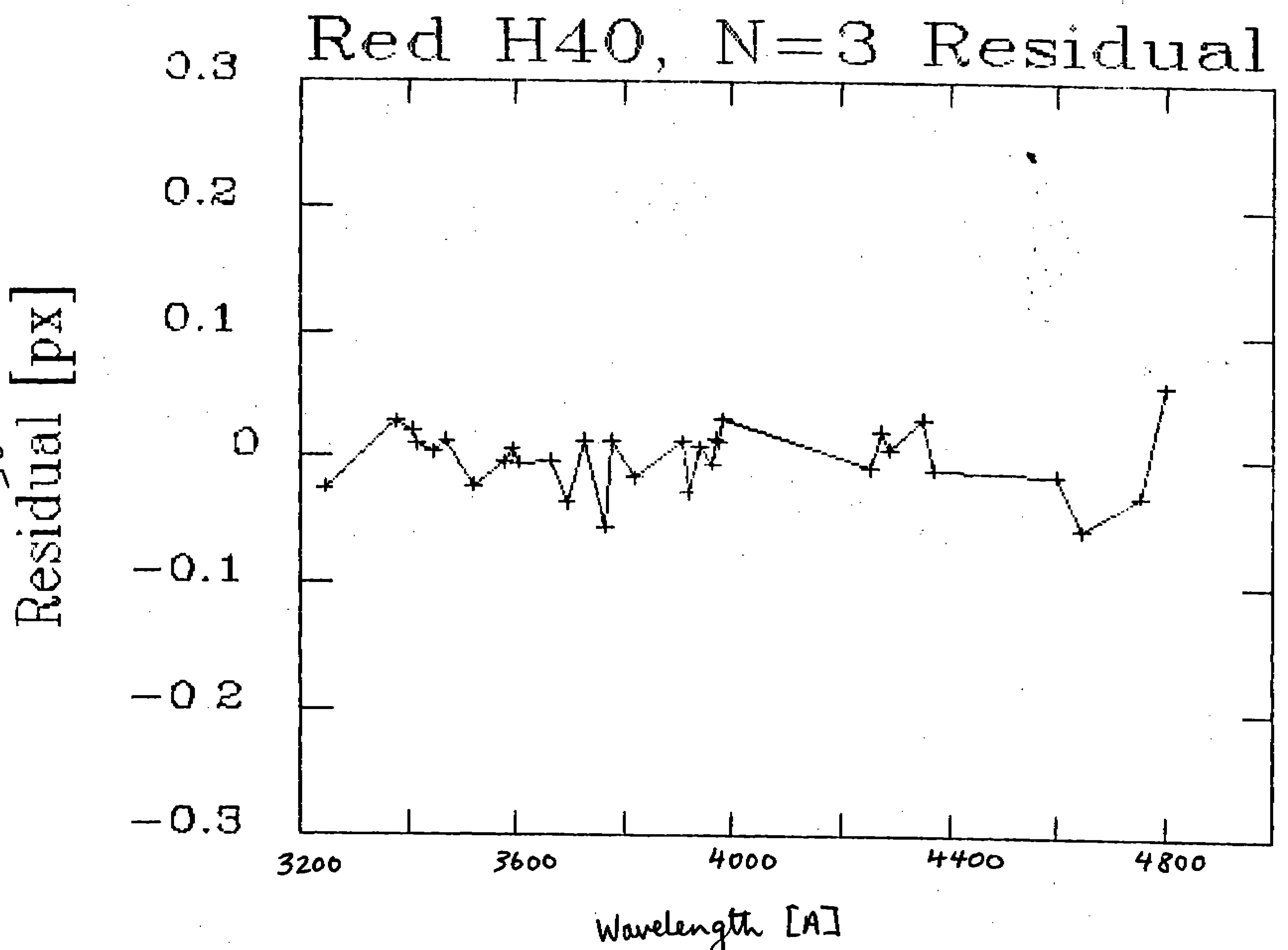
Fig 2A

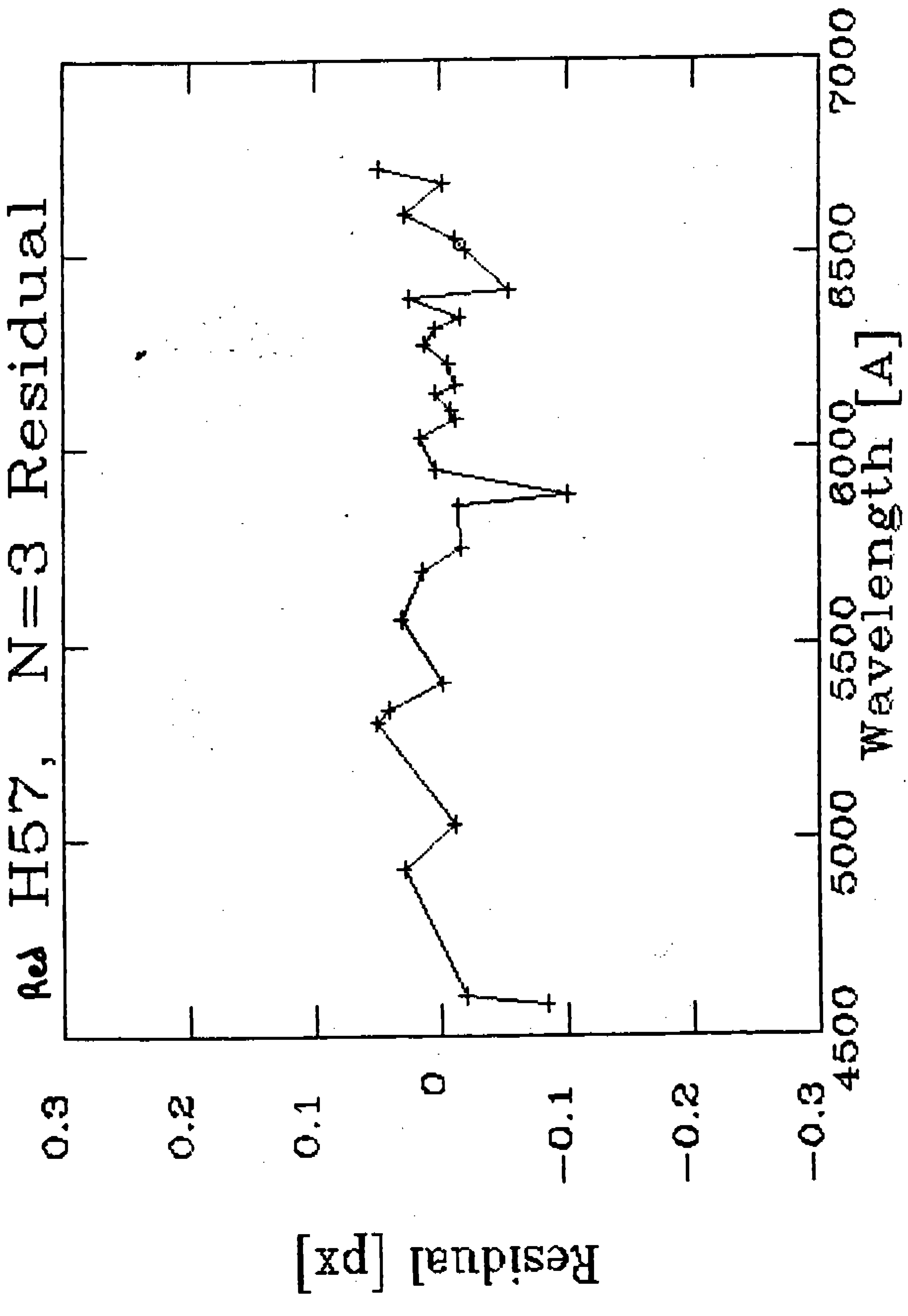


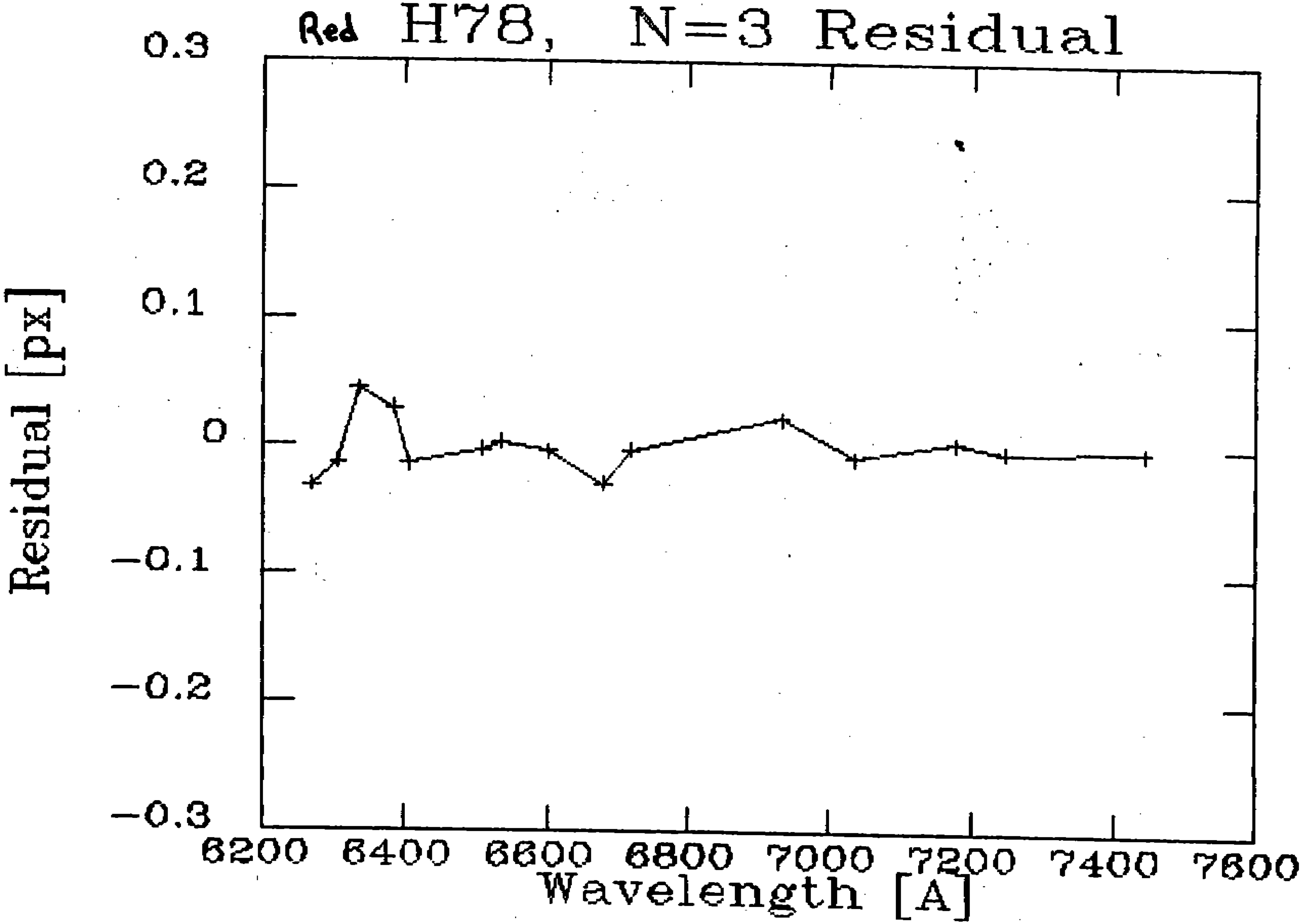
Red H19, N=3 Residual
Wavelength [A]
Residual [px]
1600 1700 1800 1900 2000 2100 2200 2300 2400
0.3 0.2 0.1 0 −0.1 −0.2 −0.3



Red H27, N=3 Residual
Residual [px]
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
2200
2400
2600
2800
3000
3200
3400
Wavelength [A]

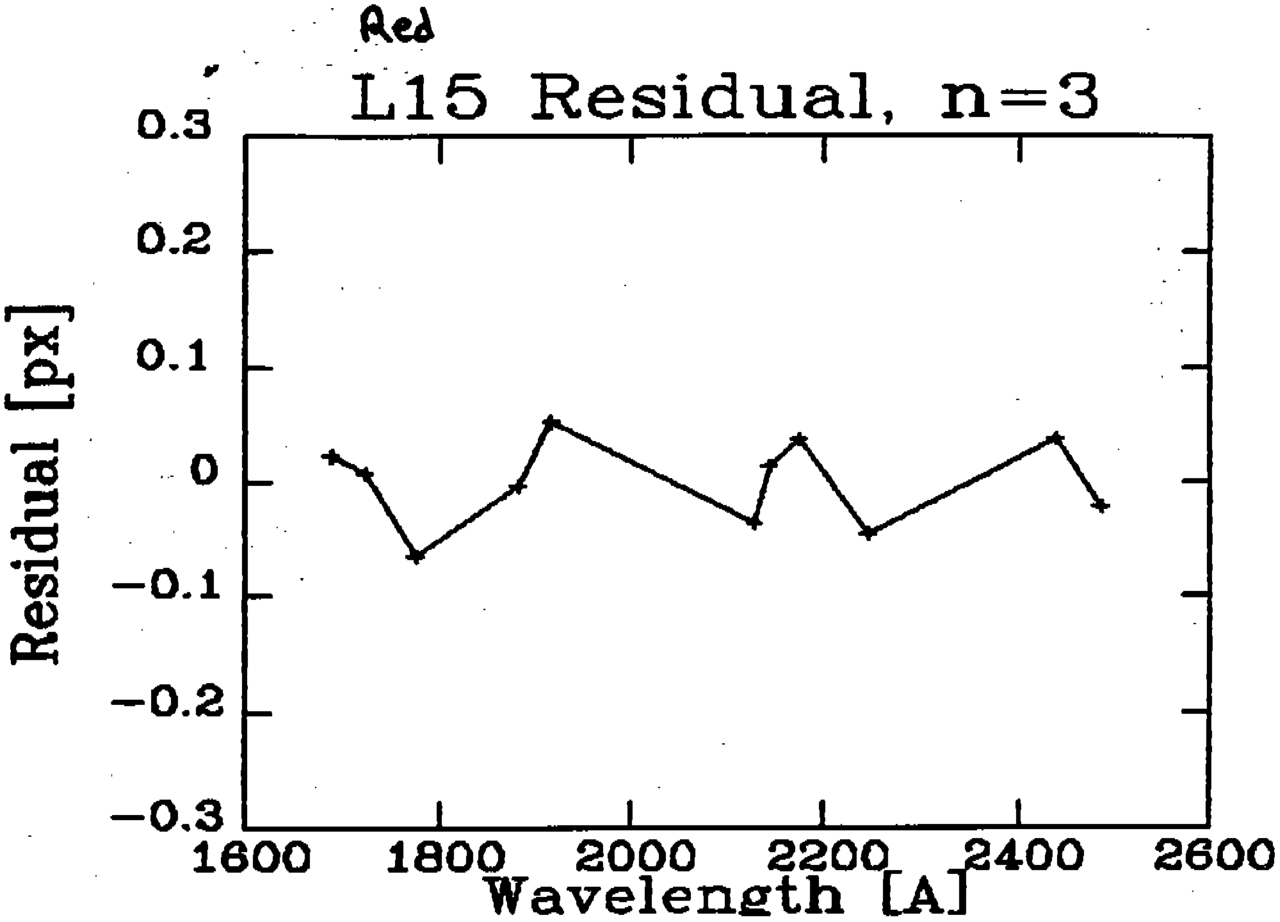

Red H40, N=3 Residual
Residual [px]
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
3200
3600
4000
4400
4800
Wavelength [A]

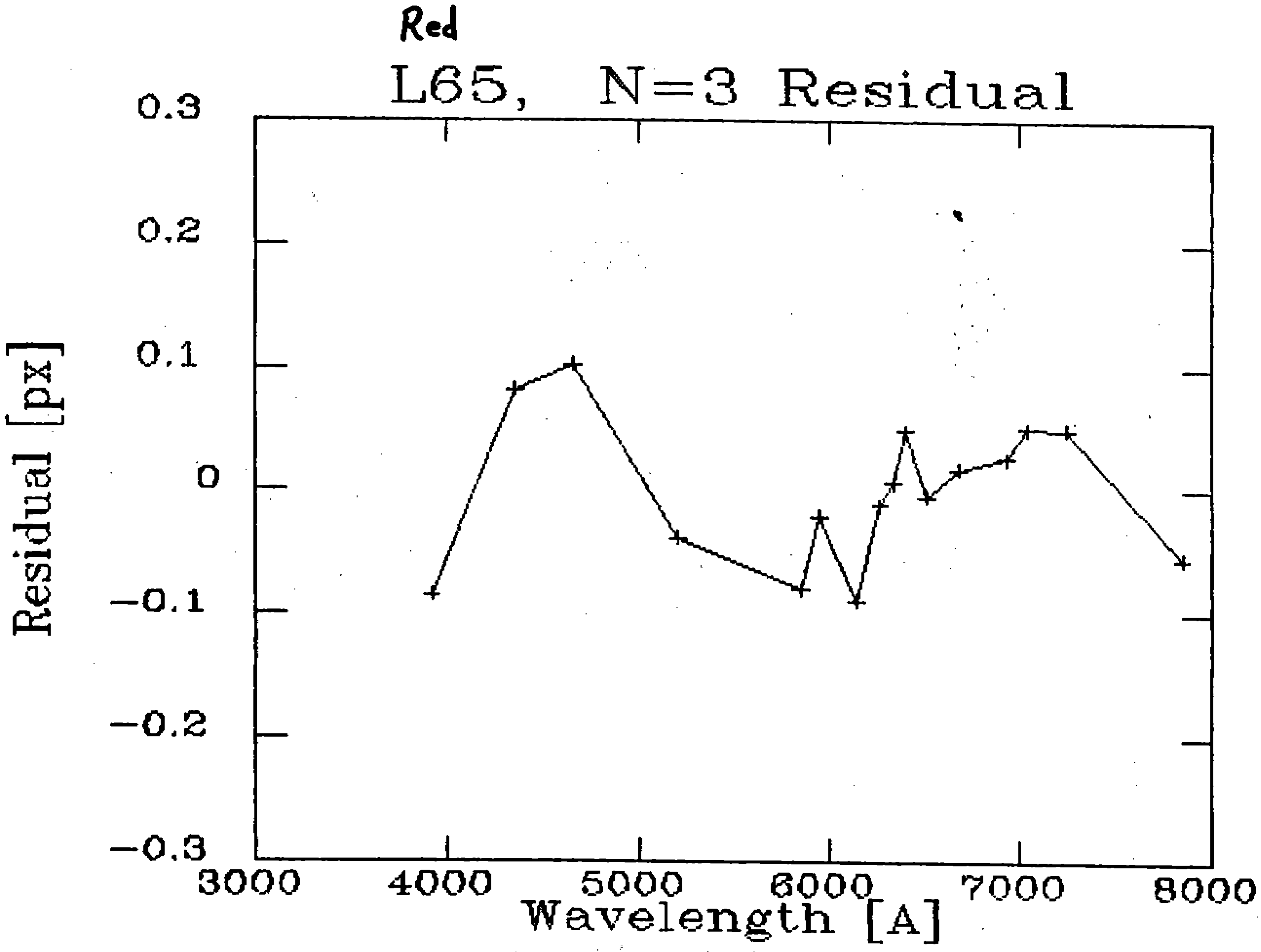

Red H57, N=3 Residual
Wavelength [A]
Residual [px]
4500
5000
5500
6000
6500
7000
0.3
0.2
0.1
0
−0.1
−0.2
−0.3



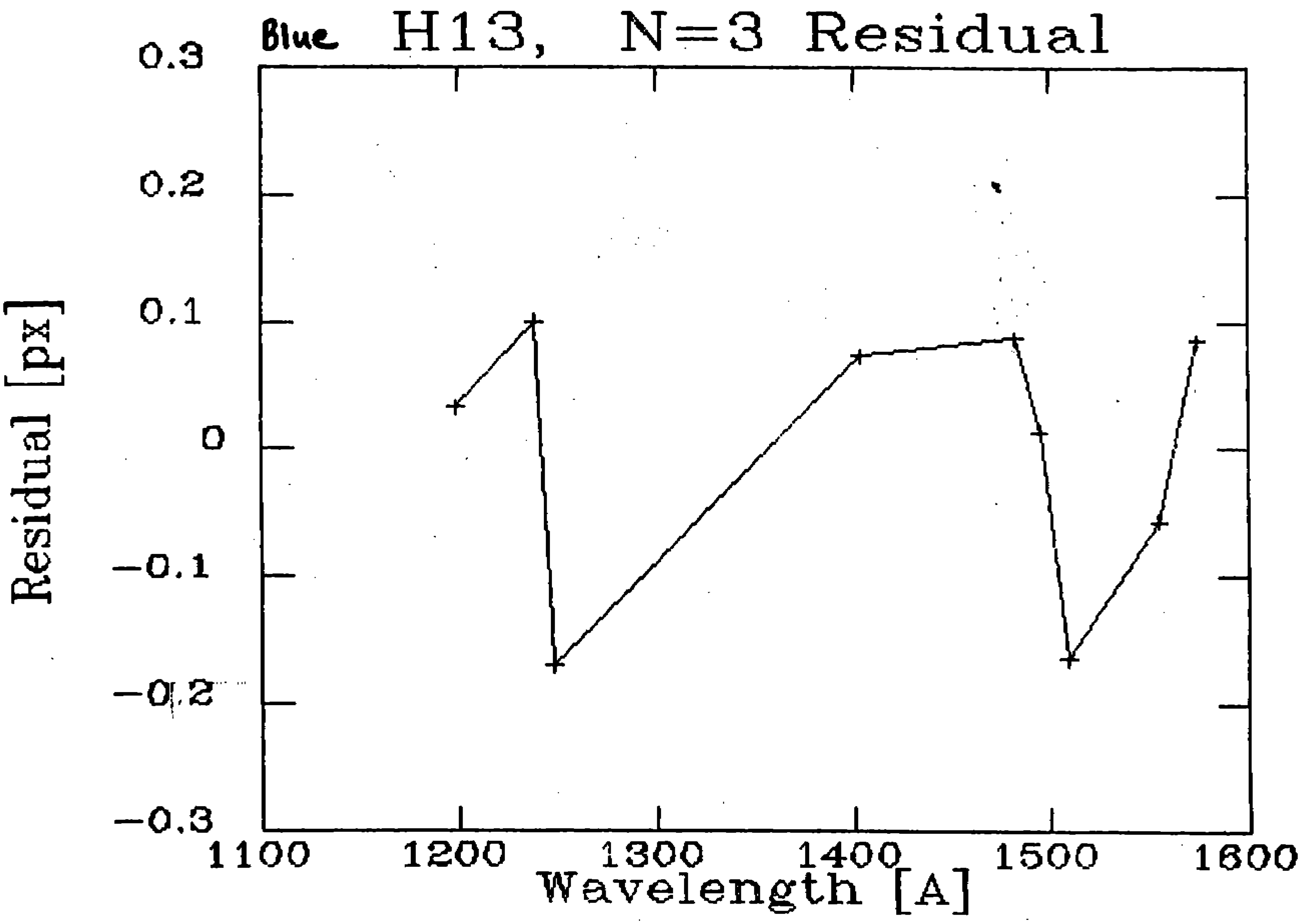
Red H78, N=3 Residual
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
Residual [px]
6200
6400
6600
6800
7000
7200
7400
7600
Wavelength [A]

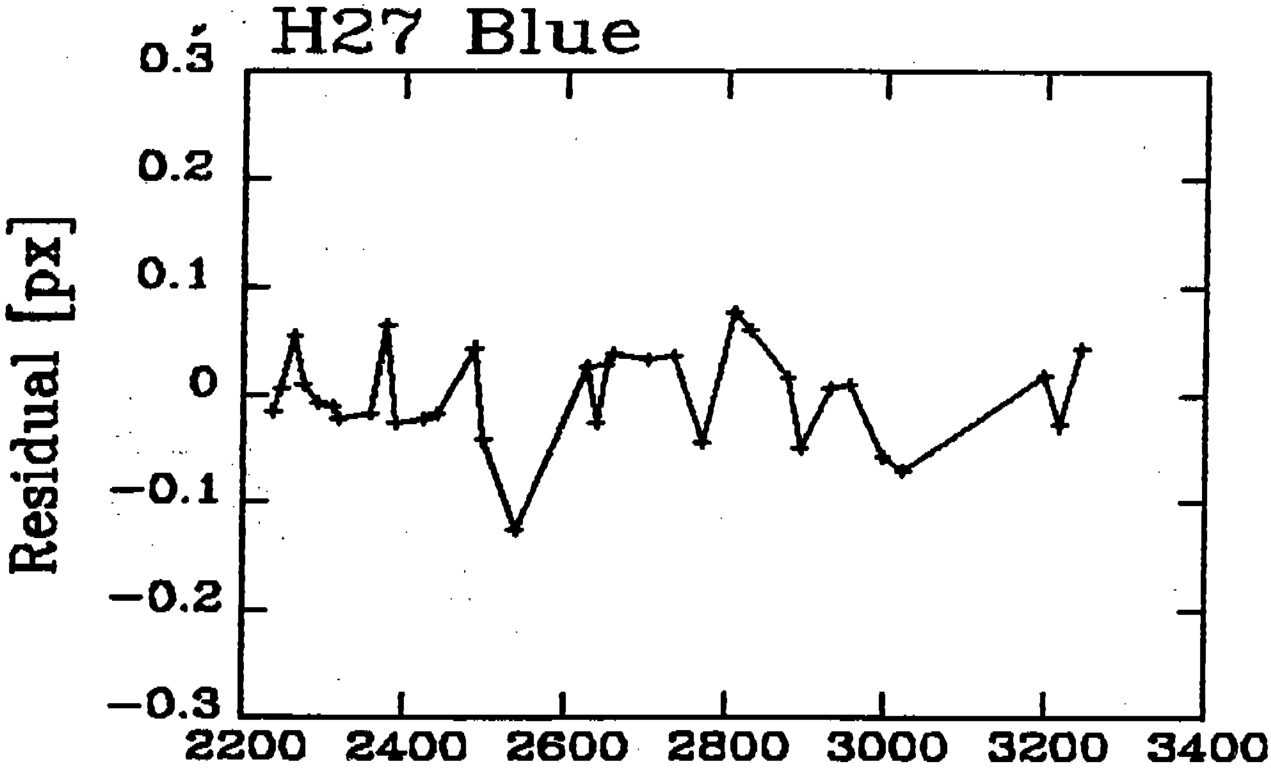
Fig 2F


Red
L15 Residual, n=3
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
Residual [px]
1600
1800
2000
2200
2400
2600
Wavelength [A]


Red
L65, N=3 Residual
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
Residual [px]
3000
4000
5000
6000
7000
8000
Wavelength [A]

(1.0 arcsec aperture)




H27 Blue
Residual [px]
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
2200
2400
2600
2800
3000
3200
3400

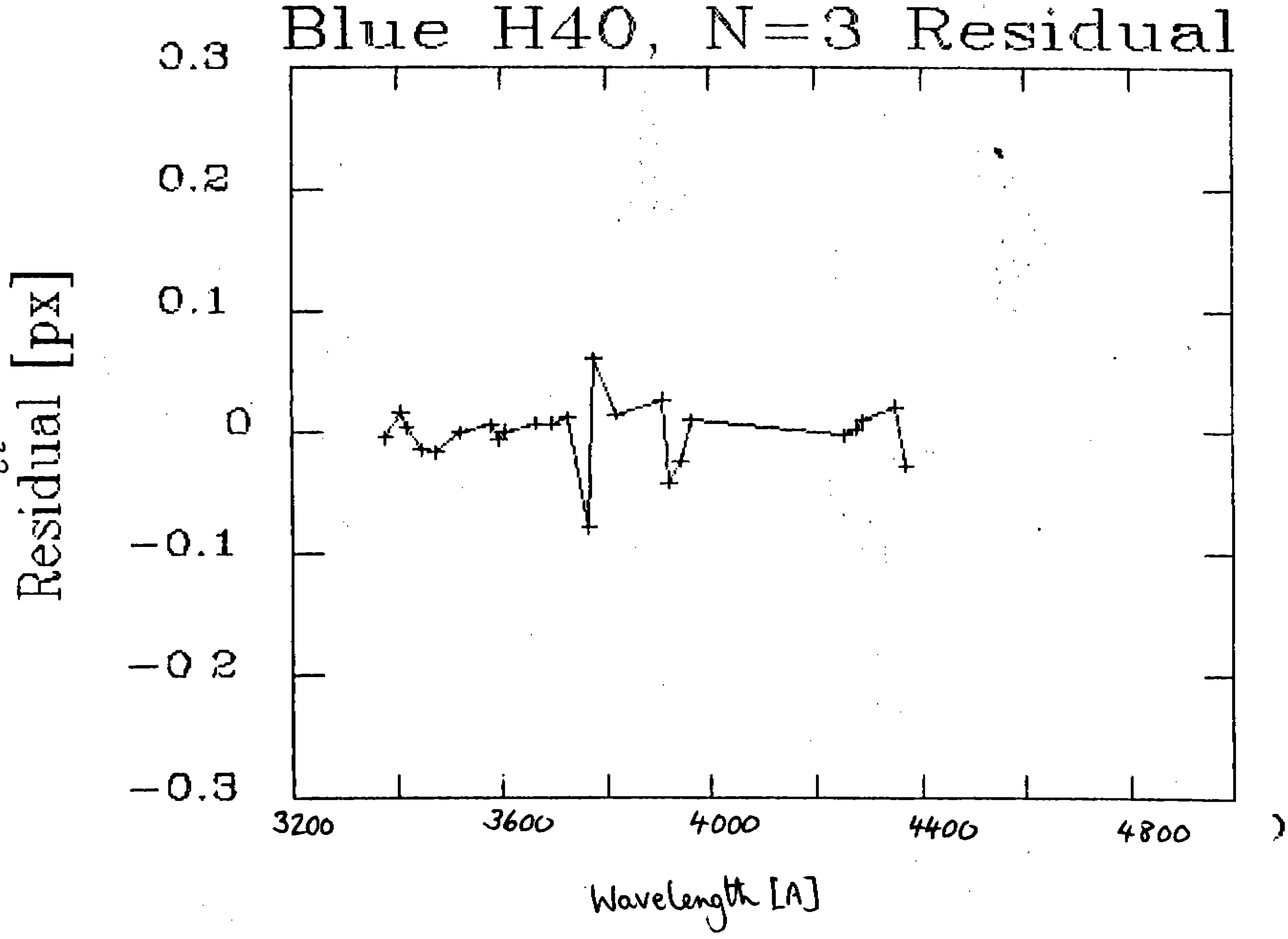

Blue H40, N=3 Residual
Residual [px]
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
3200
3600
4000
4400
4800
Wavelength [A]

Fig 2L

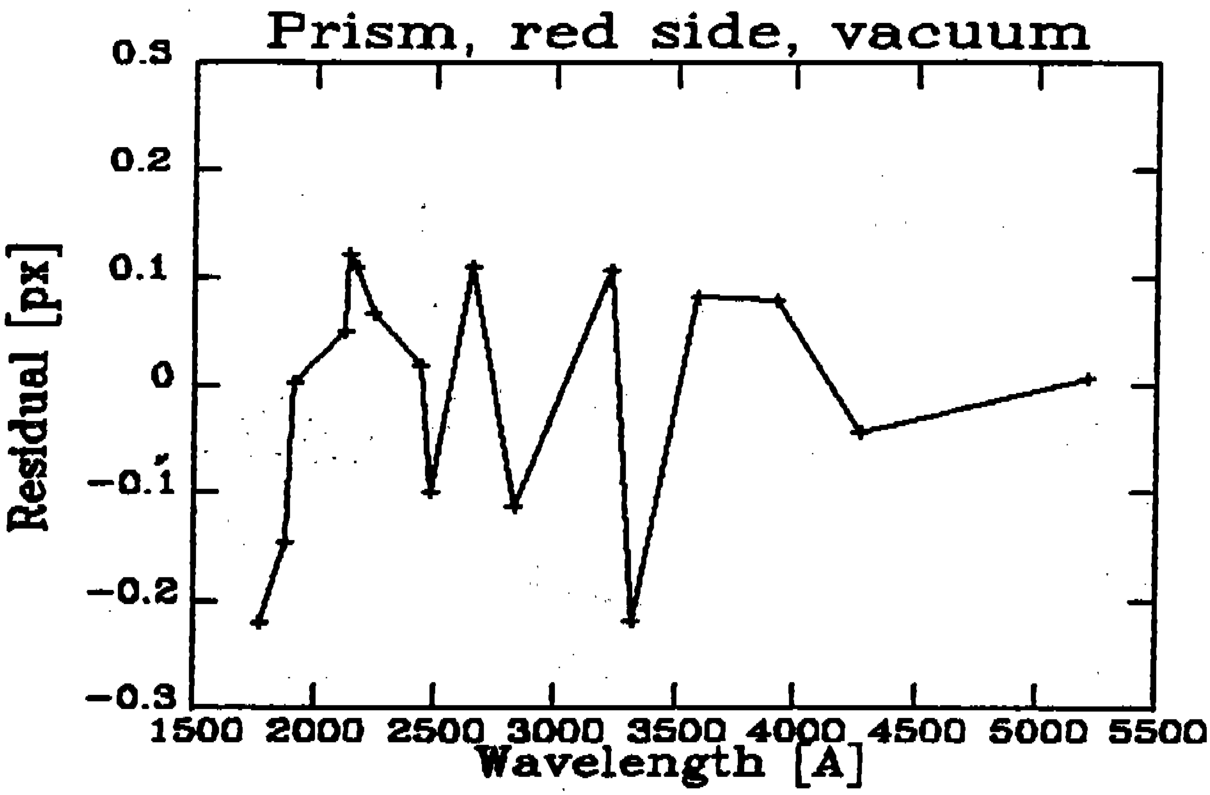
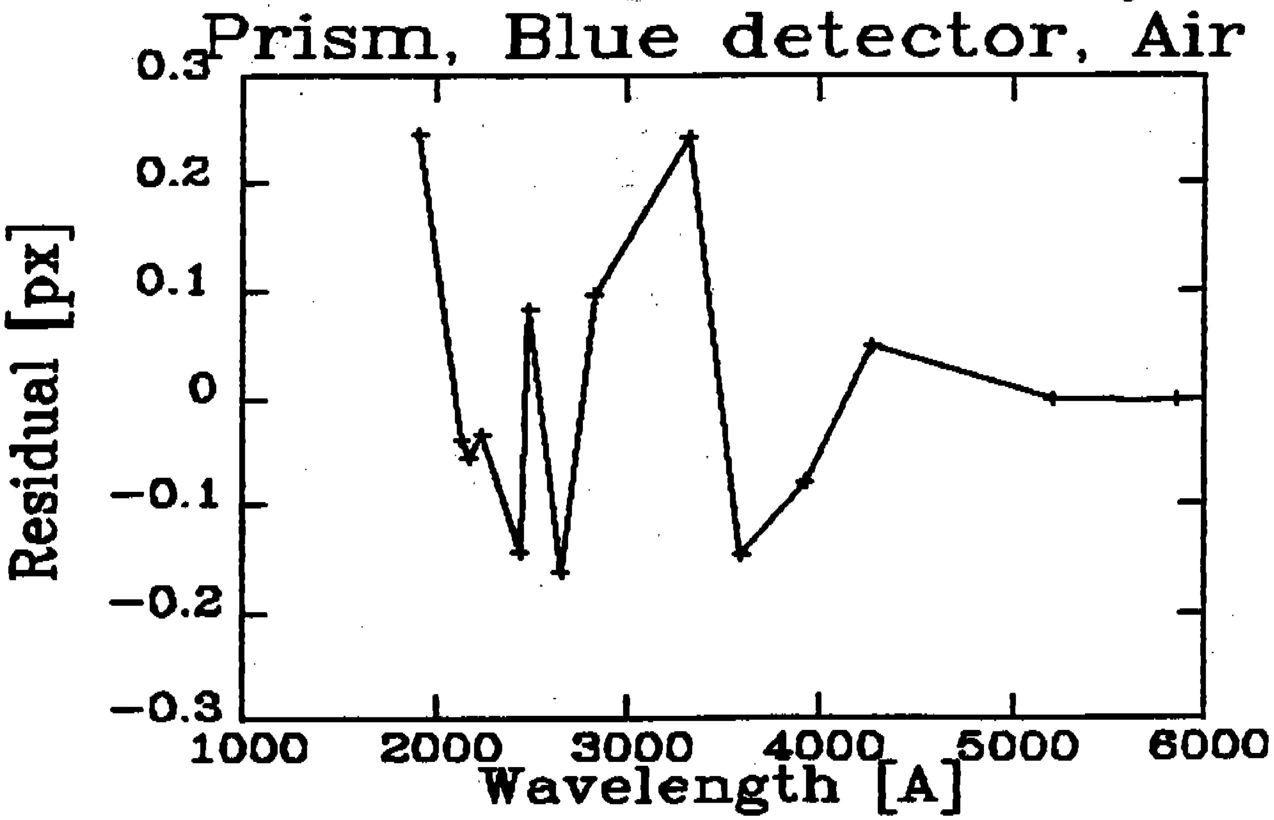
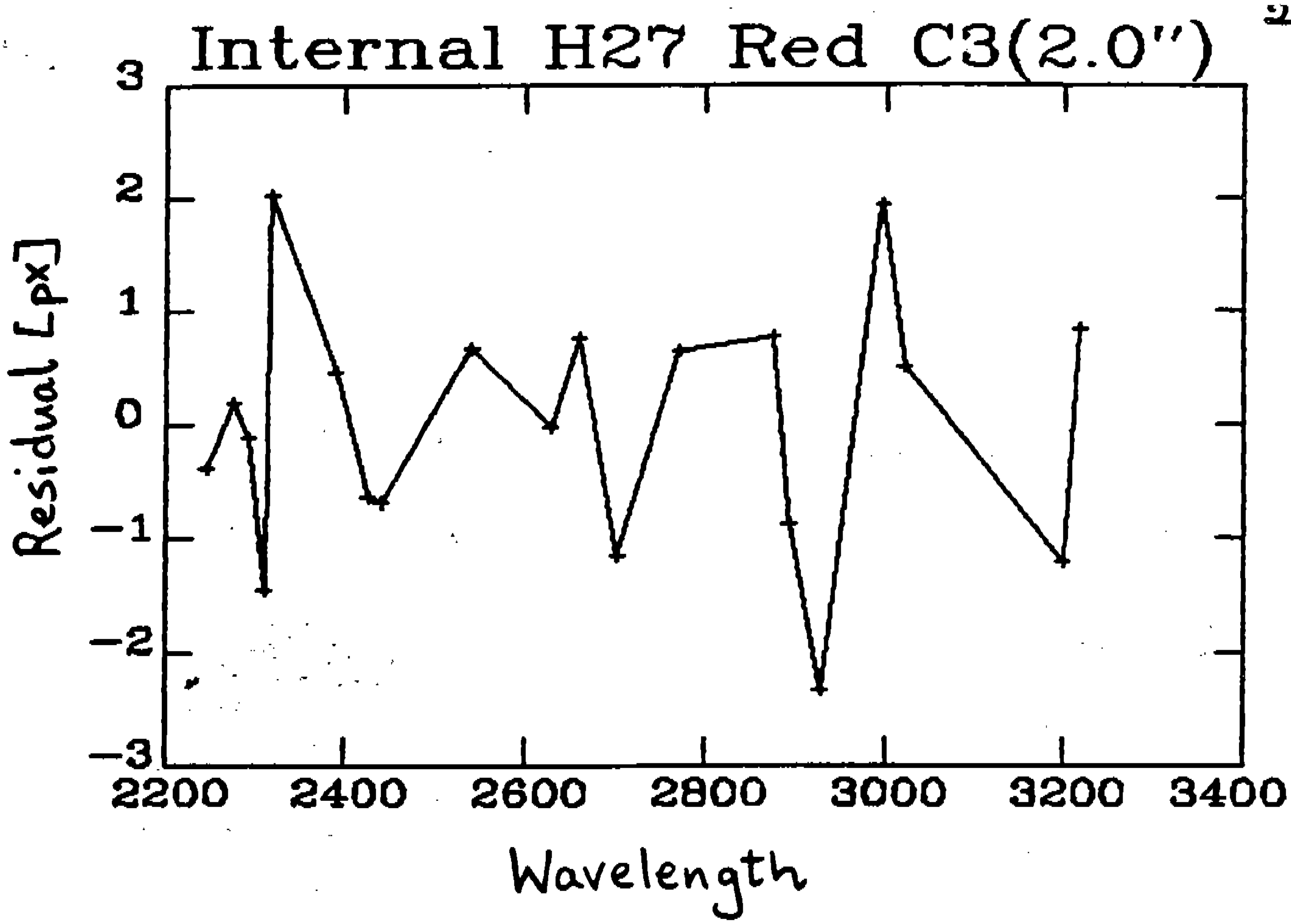
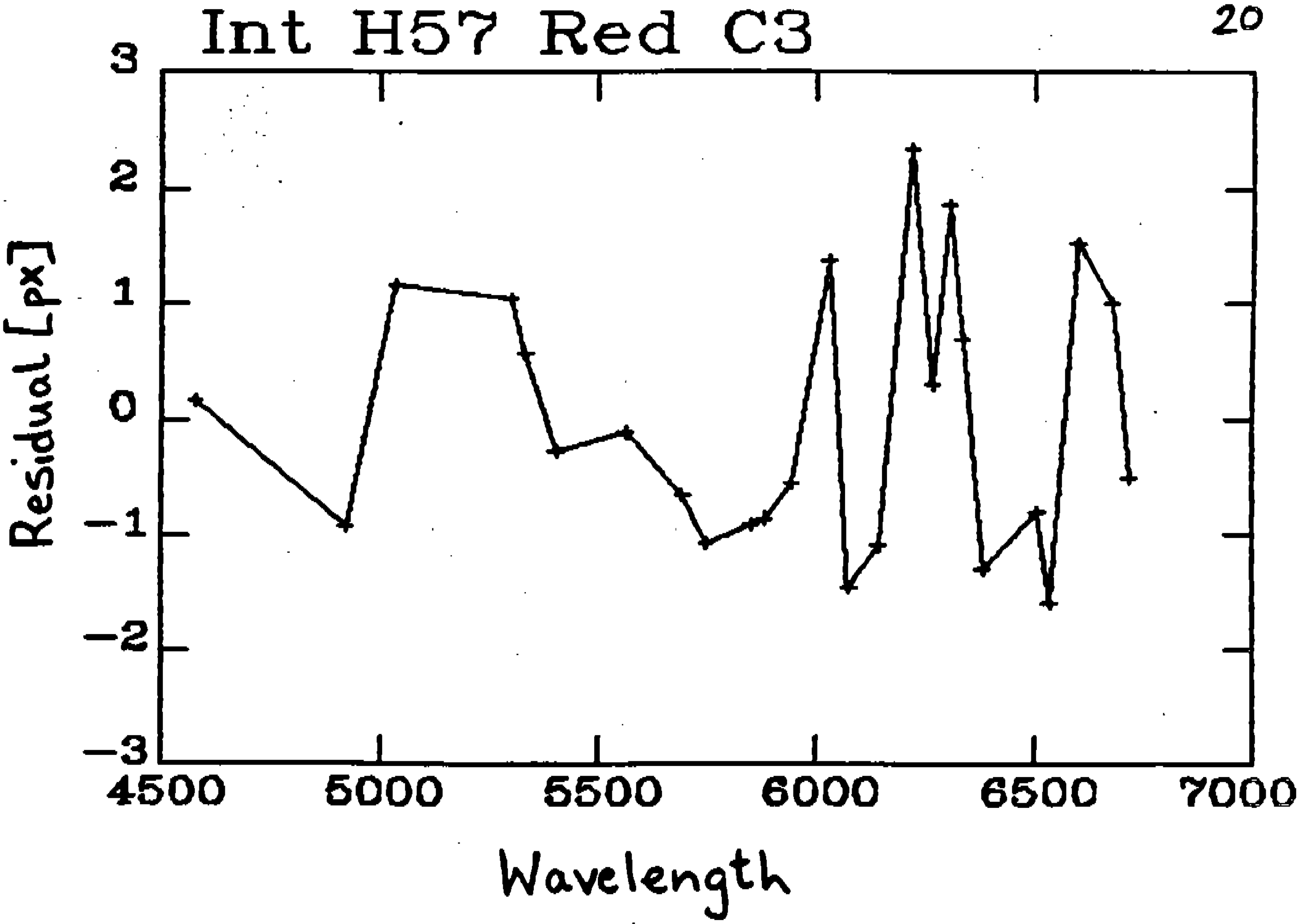

Prism, red side, vacuum
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Residual [px]
1500 2000 2500 3000 3500 4000 4500 5000 5500
Wavelength [A]

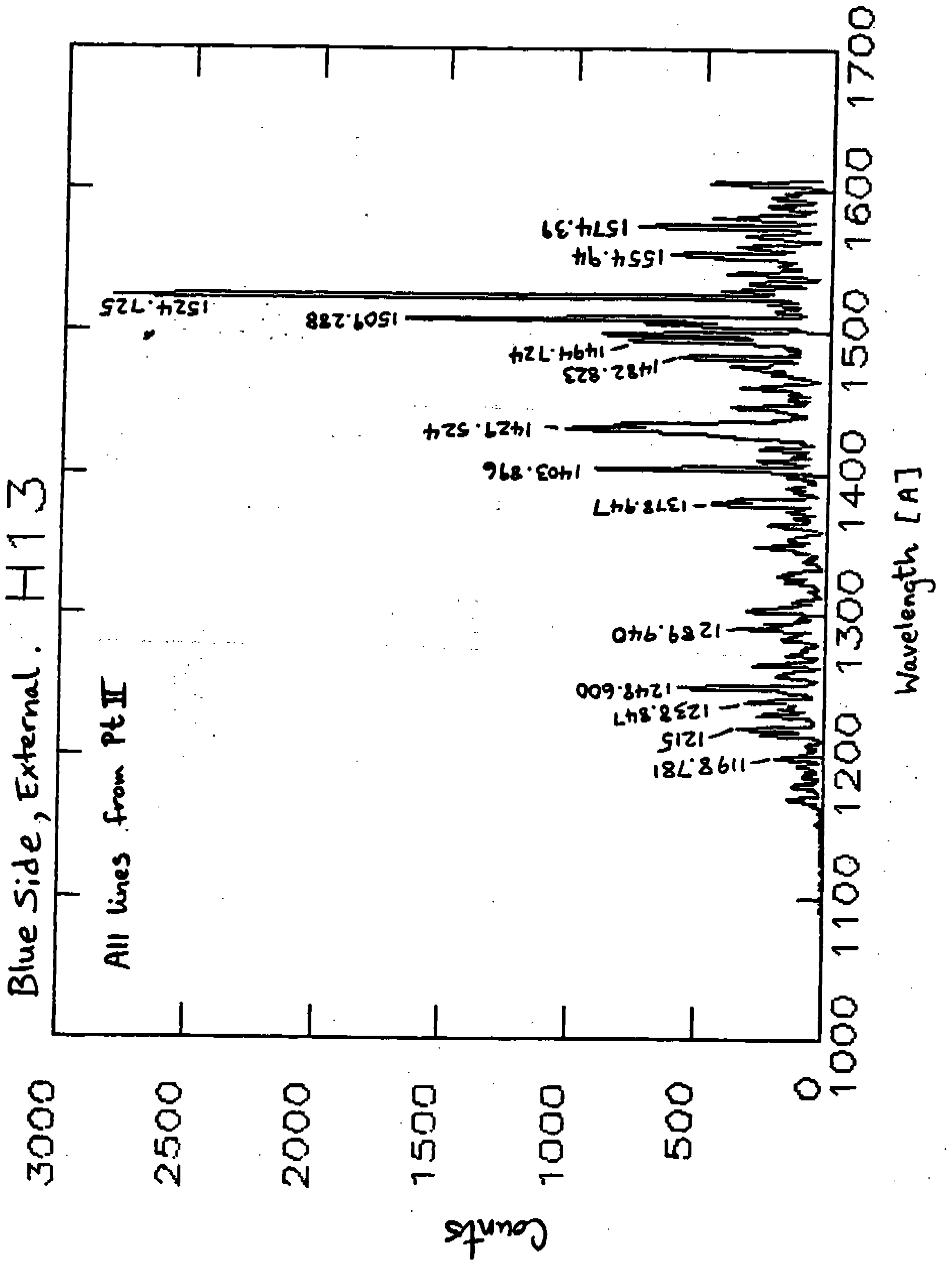
Fig 2M


Prism, Blue detector, Air
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Residual [px]
1000 2000 3000 4000 5000 6000
Wavelength [A]

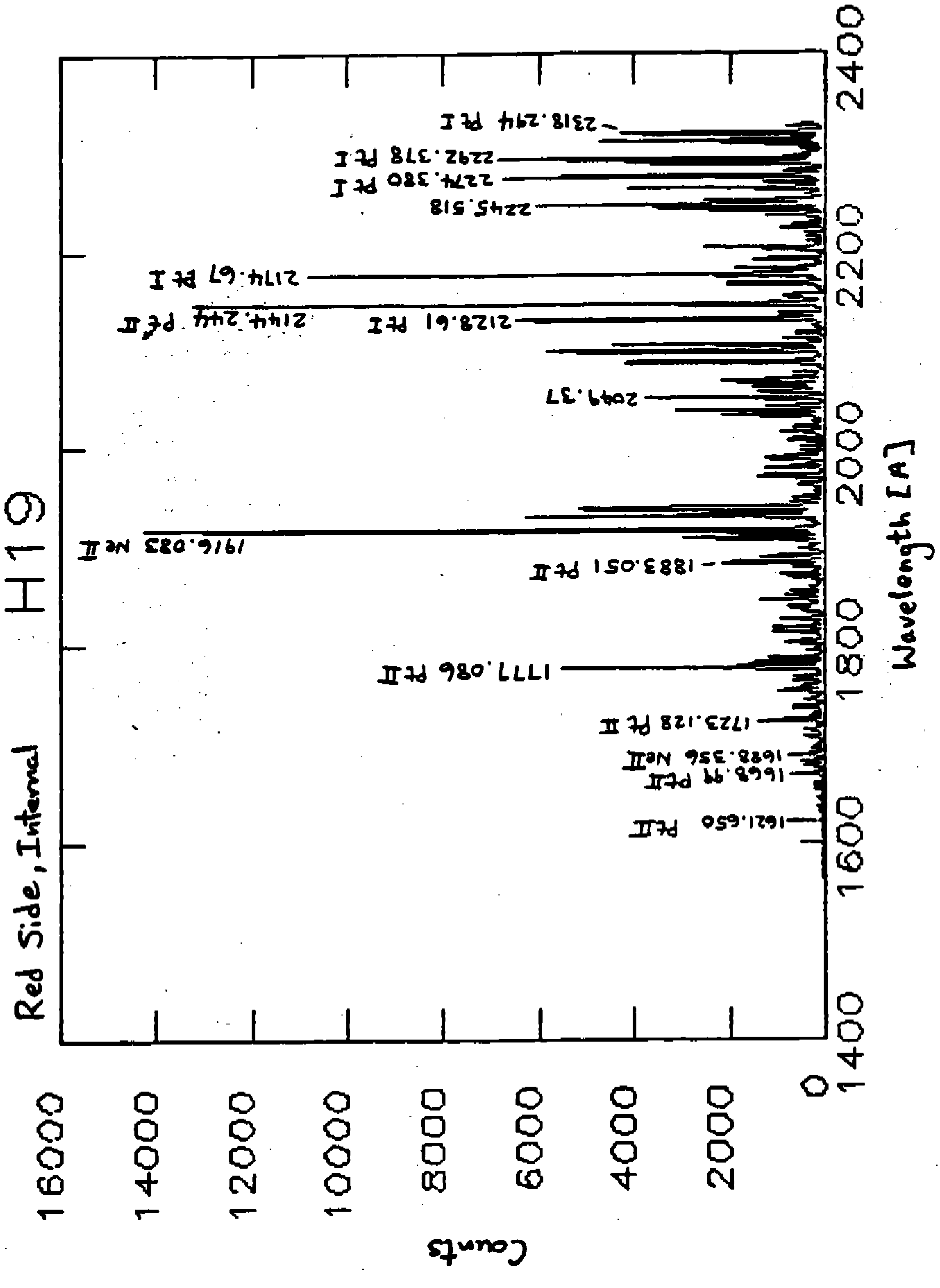

Internal H27 Red C3(2.0")
Residual [px]
Wavelength

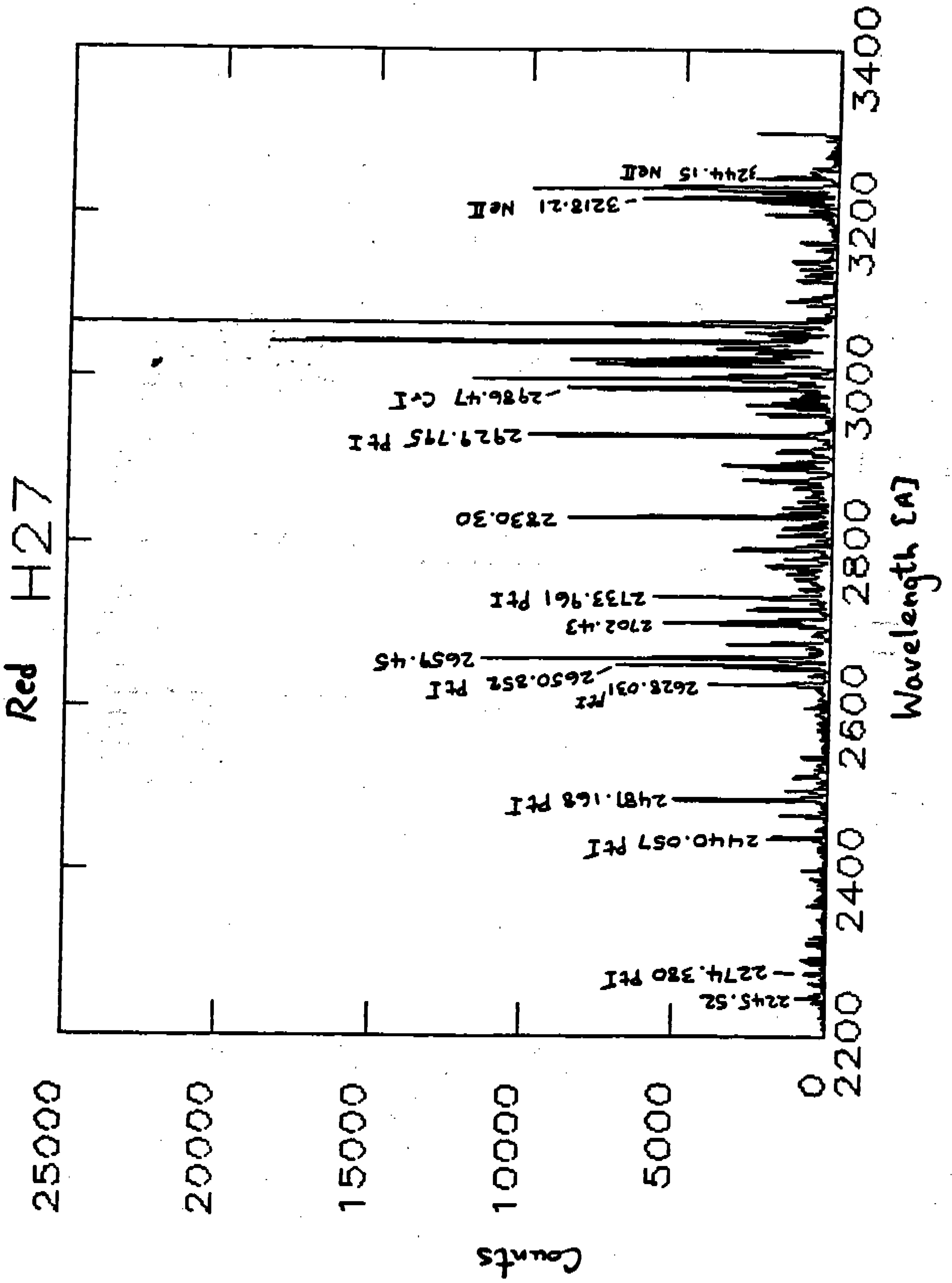

Int H57 Red C3
Residual [px]
Wavelength

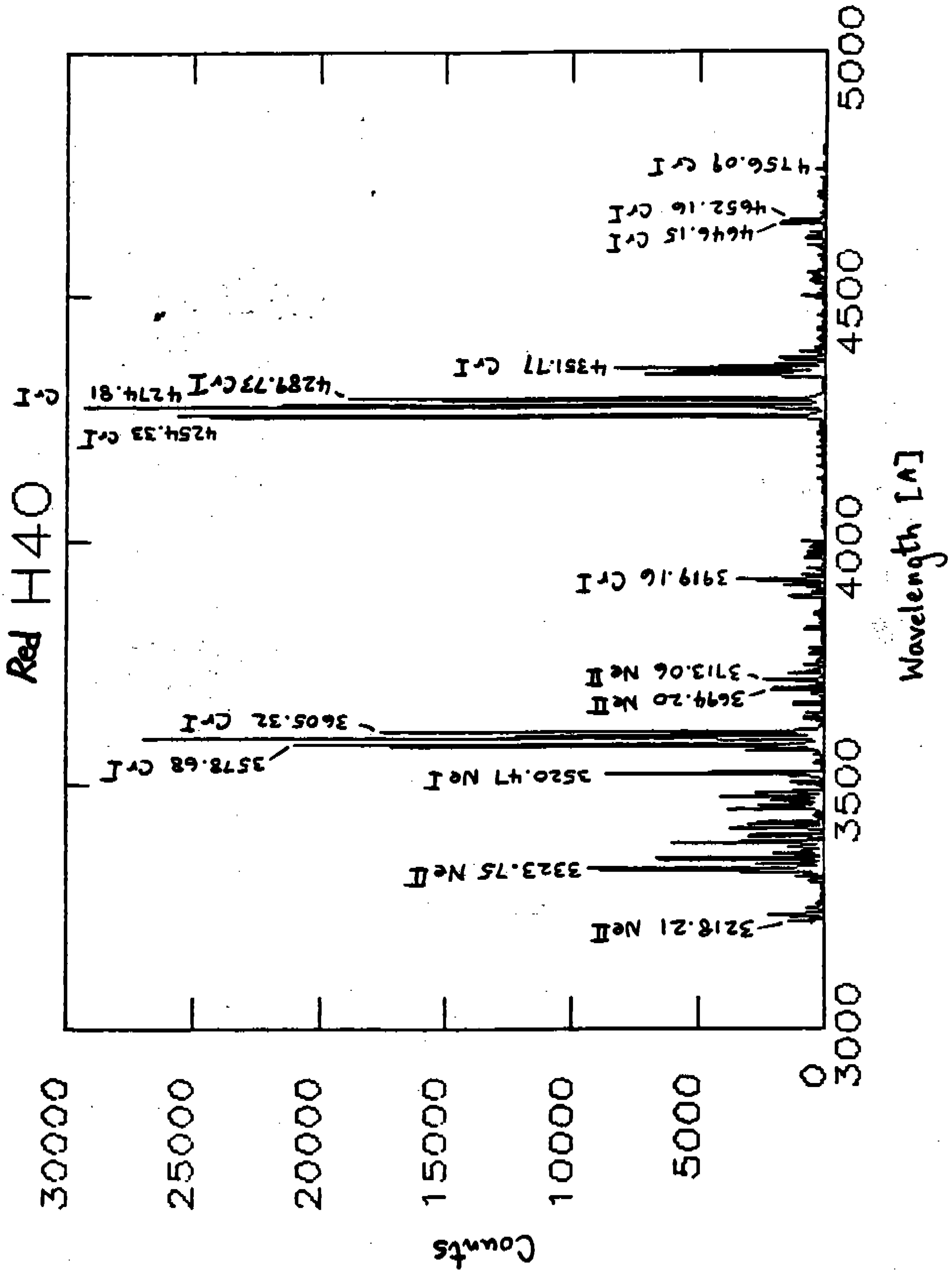
3A

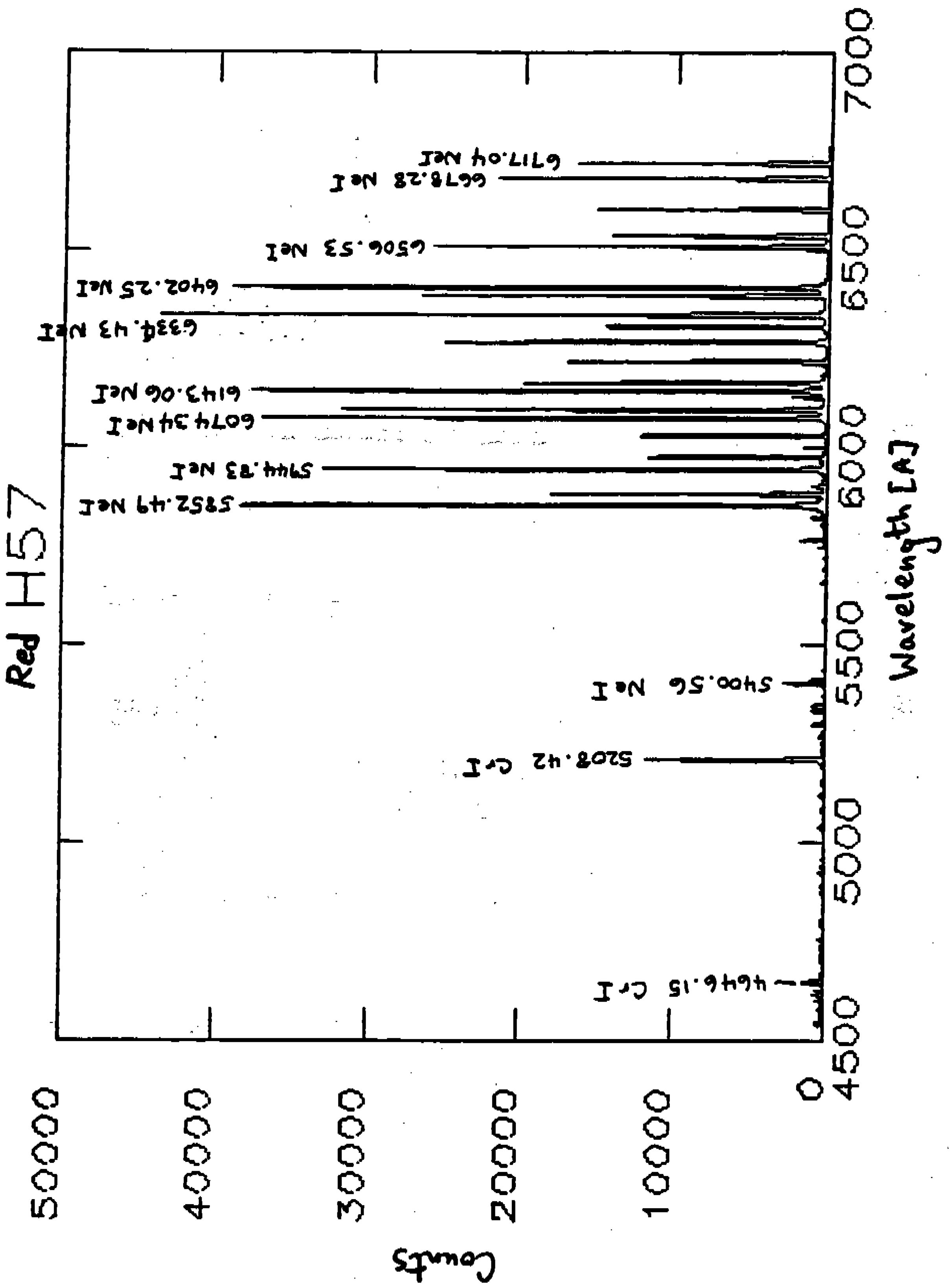


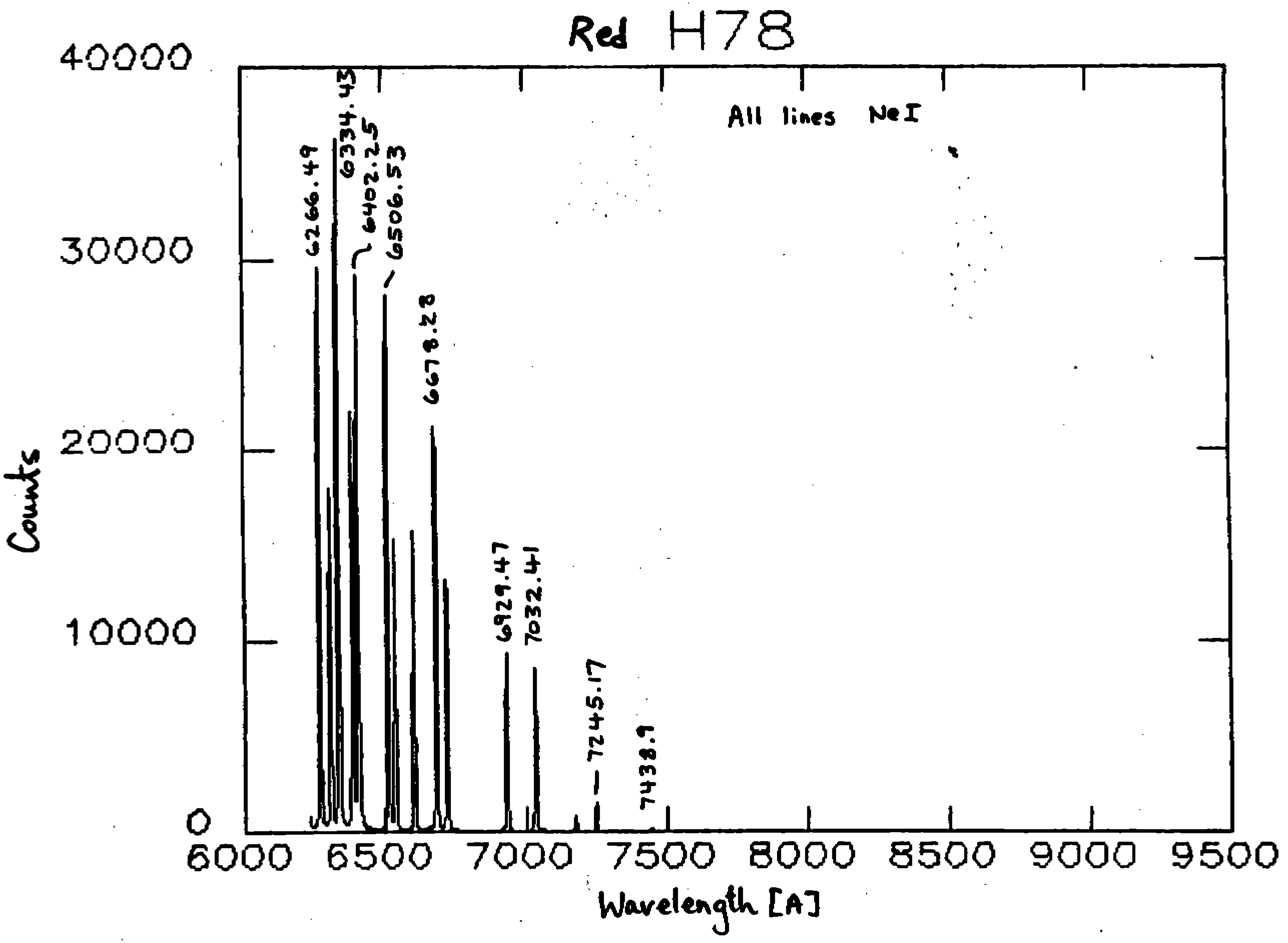
Blue Side, External. H13
All lines from Pt II
1524.725
1509.288
1574.39
1554.94
1494.724
1482.823
1427.524
1403.896
1378.947
1289.940
1248.600
1238.847
1215
1198.781
Counts
Wavelength [A]
0
500
1000
1500
2000
2500
3000
1000
1100
1200
1300
1400
1500
1600
1700


H19
Red Side, Internal
Counts
Wavelength [A]
0
2000
4000
6000
8000
10000
12000
14000
16000
1400
1600
1800
2000
2200
2400
2318.294 Pt I
2292.378 Pt I
2274.380 Pt I
2245.518
2174.67 Pt I
2144.244 Pt II
2128.61 Pt I
2049.37
1916.083 Ne II
1883.051 Pt II
1777.086 Pt II
1723.128 Pt II
1688.356 Ne II
1668.99 Pt II
1621.650 Pt II


Red H27
Counts
Wavelength [A]
25000
20000
15000
10000
5000
0
2200
2400
2600
2800
3000
3200
3400
2245.52
2274.380 PtI
2440.057 PtI
2481.168 PtI
2628.031 PtI
2650.852 PtI
2659.45
2702.43
2733.961 PtI
2830.30
2929.795 PtI
2986.47
3218.21 NeII
3244.15 NeII


Red H40
Counts
Wavelength [Å]
0
5000
10000
15000
20000
25000
30000
3000
3500
4000
4500
5000
3218.21 NeII
3323.75 NeII
3520.47 NeI
3578.68 CrI
3605.32 CrI
3694.20 NeII
3713.06 NeII
3919.16 CrI
4254.33 CrI
4274.81 CrI
4289.73 CrI
4351.77 CrI
4646.15 CrI
4652.16 CrI
4756.09 CrI

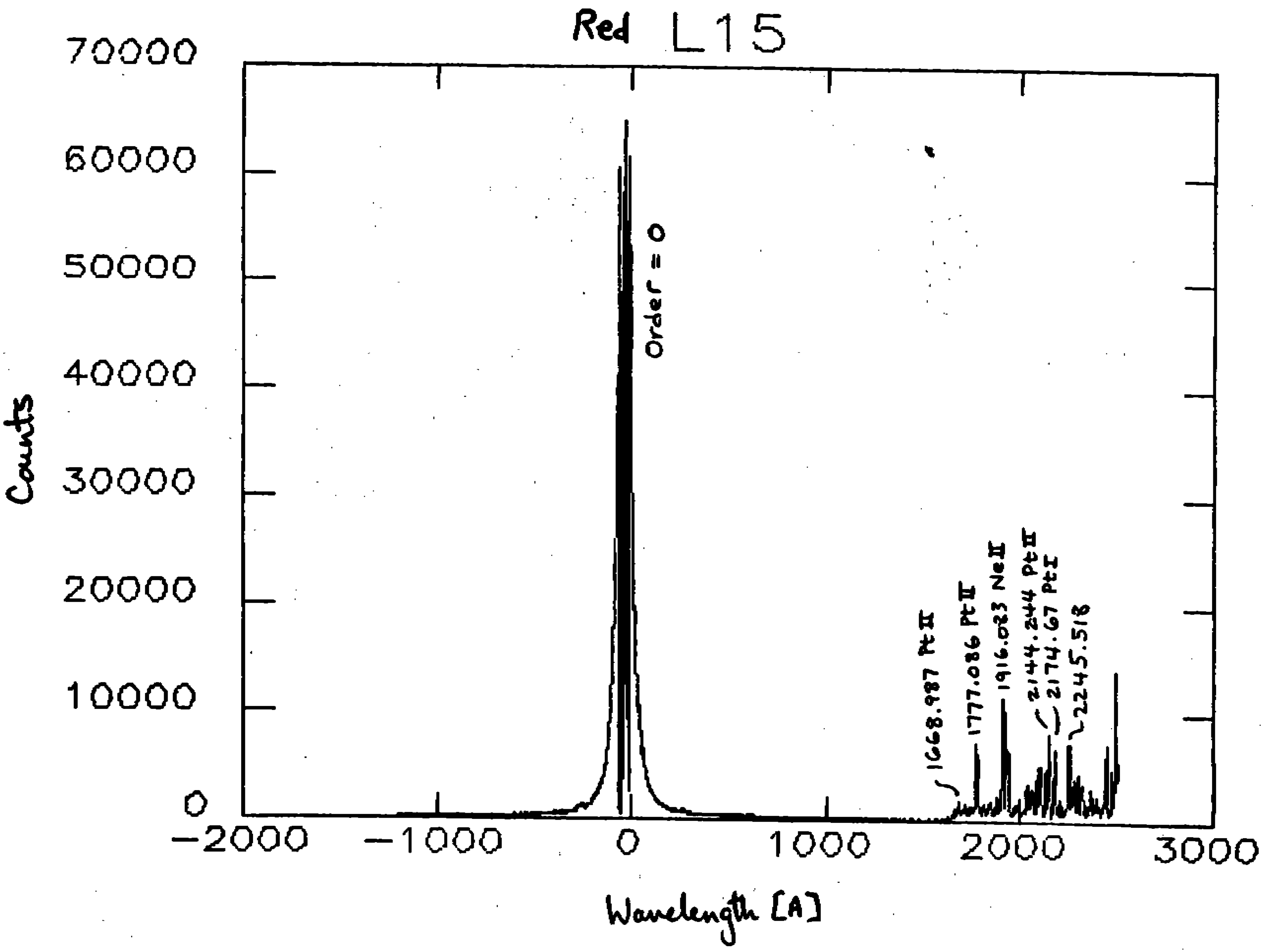

Red H57
Counts
Wavelength [A]
0
10000
20000
30000
40000
50000
4500
5000
5500
6000
6500
7000
4646.15 Cr I
5208.42 Cr I
5400.56 Ne I
5852.49 Ne I
5944.83 Ne I
6074.34 Ne I
6143.06 Ne I
6334.43 Ne I
6402.25 Ne I
6506.53 Ne I
6678.28 Ne I
6717.04 Ne I

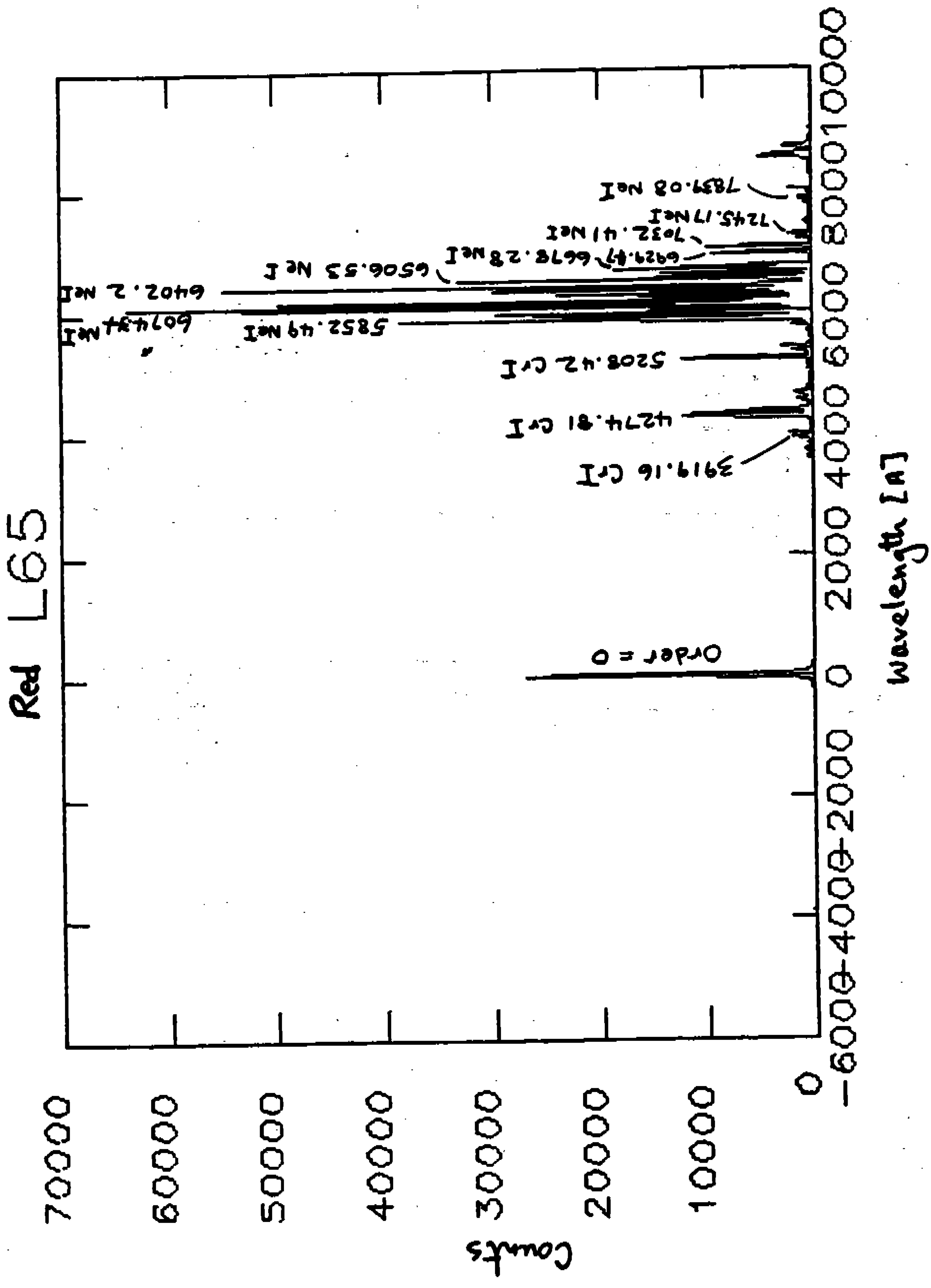


Red H78
All lines NeI
6266.49
6334.43
6402.25
6506.53
6678.28
6929.47
7032.41
7245.17
7438.9
Counts
0
10000
20000
30000
40000
Wavelength [A]
6000
6500
7000
7500
8000
8500
9000
9500

40

3F


Red L15
Counts
70000
60000
50000
40000
30000
20000
10000
0
−2000
−1000
0
1000
2000
3000
Wavelength [A]
Order = 0
1668.987 Pt II
1777.086 Pt II
1916.083 Ne II
2144.244 Pt II
2174.67 Pt I
2245.518



Red L65
Counts
Wavelength [A]
0
10000
20000
30000
40000
50000
60000
70000
-6000
-4000
-2000
0
2000
4000
6000
8000
10000
Order = 0
3919.16 CrI
4274.81 CrI
5208.42 CrI
5852.49 NeI
6074.34 NeI
6402.2 NeI
6506.53 Ne I
6929.47
6678.28 NeI
7032.41 NeI
7245.17 NeI
7839.08 NeI

Fig 3I

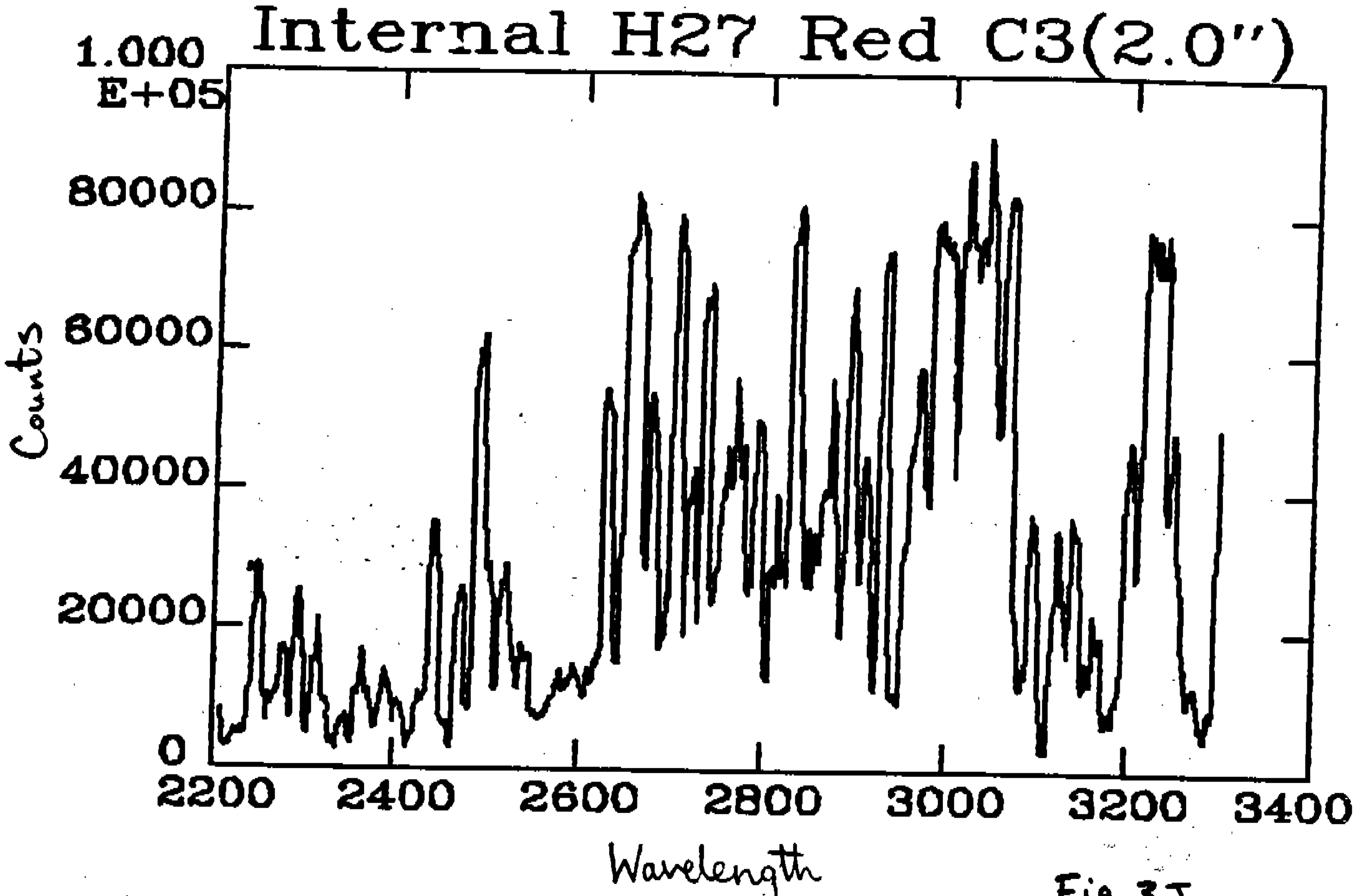

Internal H27 Red C3(2.0")
1.000 E+05
80000
60000
40000
20000
0
Counts
2200
2400
2600
2800
3000
3200
3400
Wavelength

Fig 3J

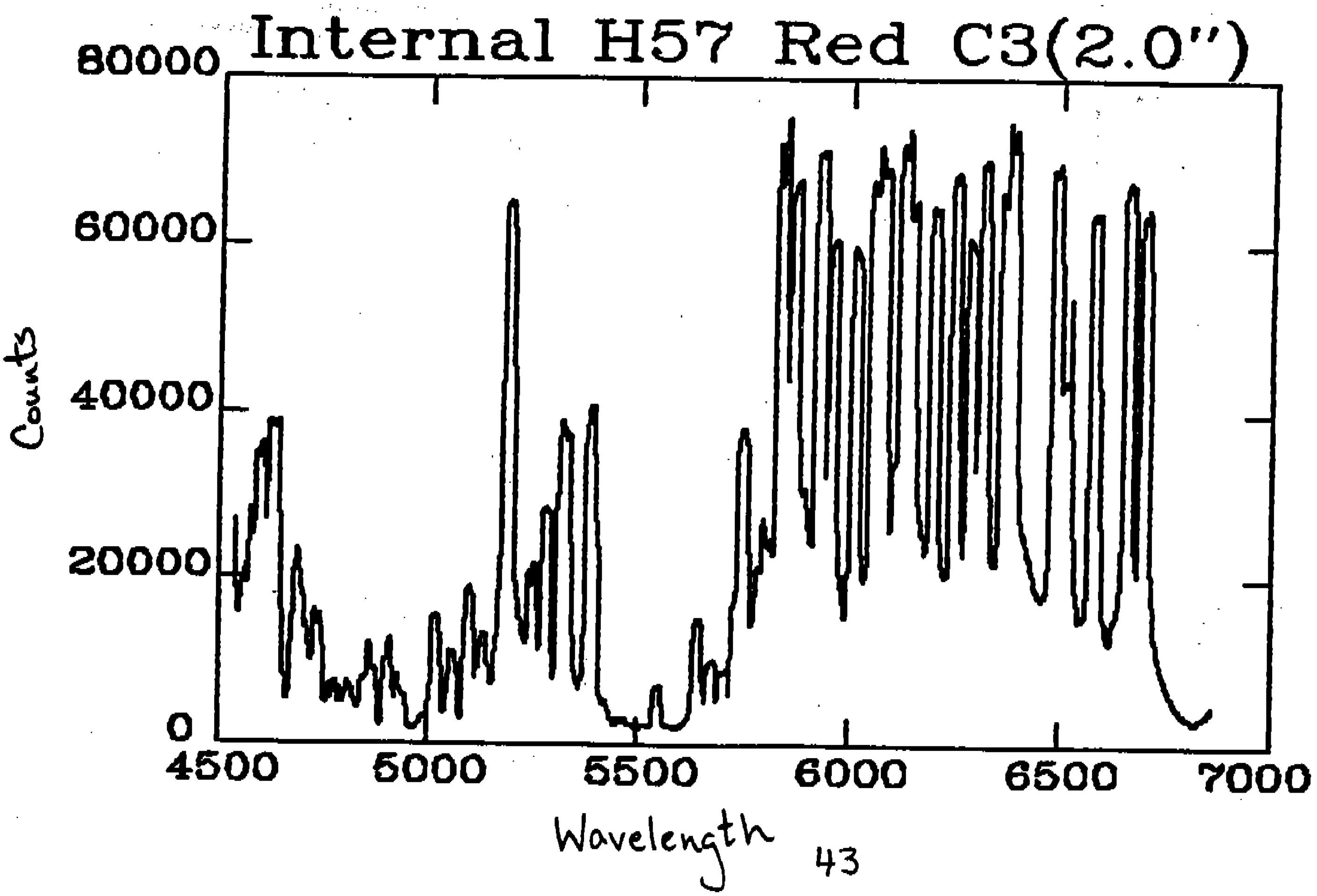

Internal H57 Red C3(2.0")
80000
60000
40000
20000
0
Counts
4500
5000
5500
6000
6500
7000
Wavelength

Fig. 4A

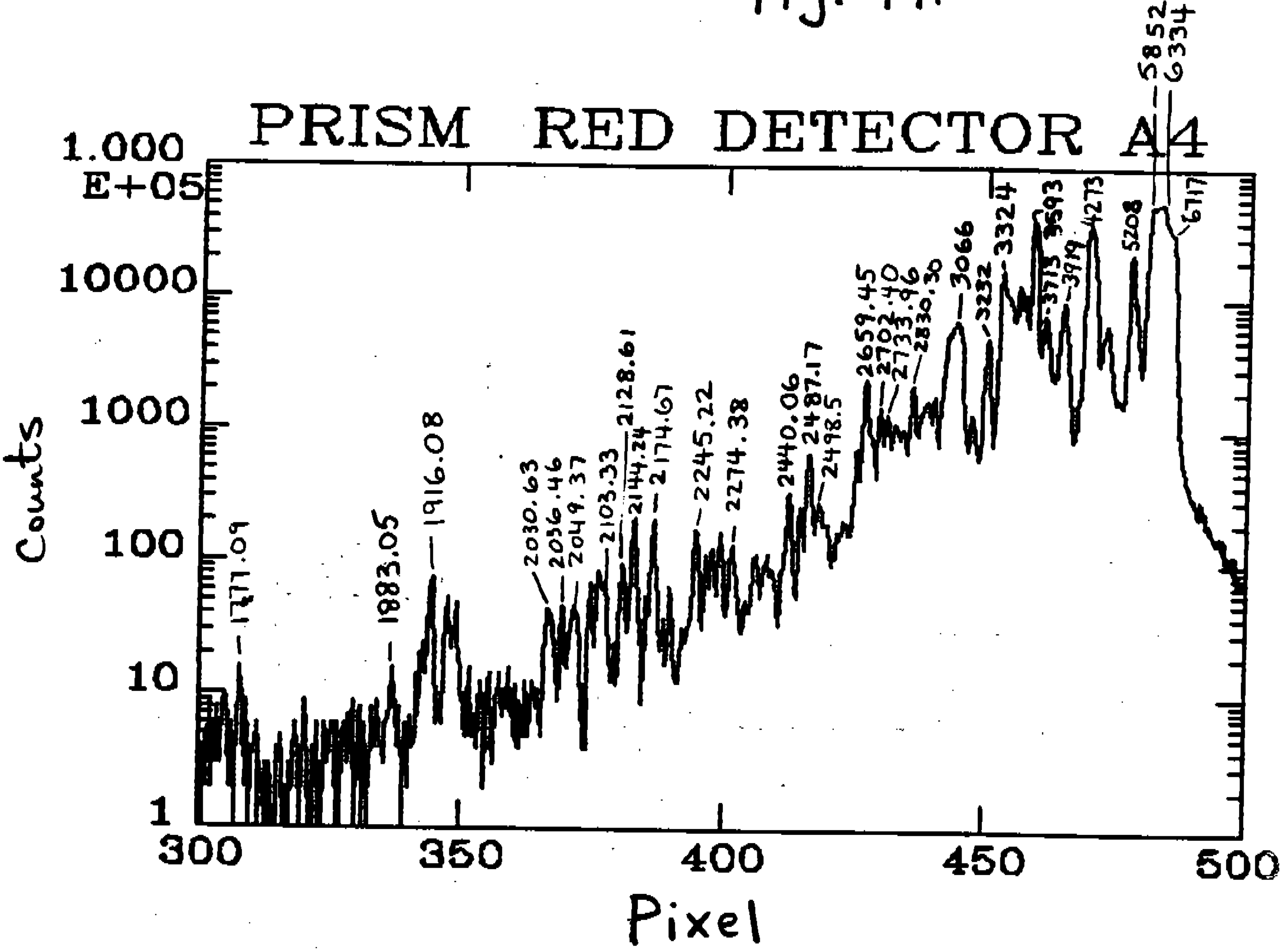

PRISM RED DETECTOR A4
Counts
Pixel
1.000 E+05
10000
1000
100
10
1
300
350
400
450
500
1777.09
1883.05
1916.08
2030.63
2036.46
2049.37
2103.33
2128.61
2144.24
2174.67
2245.22
2274.38
2440.06
2487.17
2498.5
2659.45
2702.40
2733.96
2830.30
3066
3232
3324
3715
3593
3919
4273
5208
5852
6334
6717

Fig. 4B

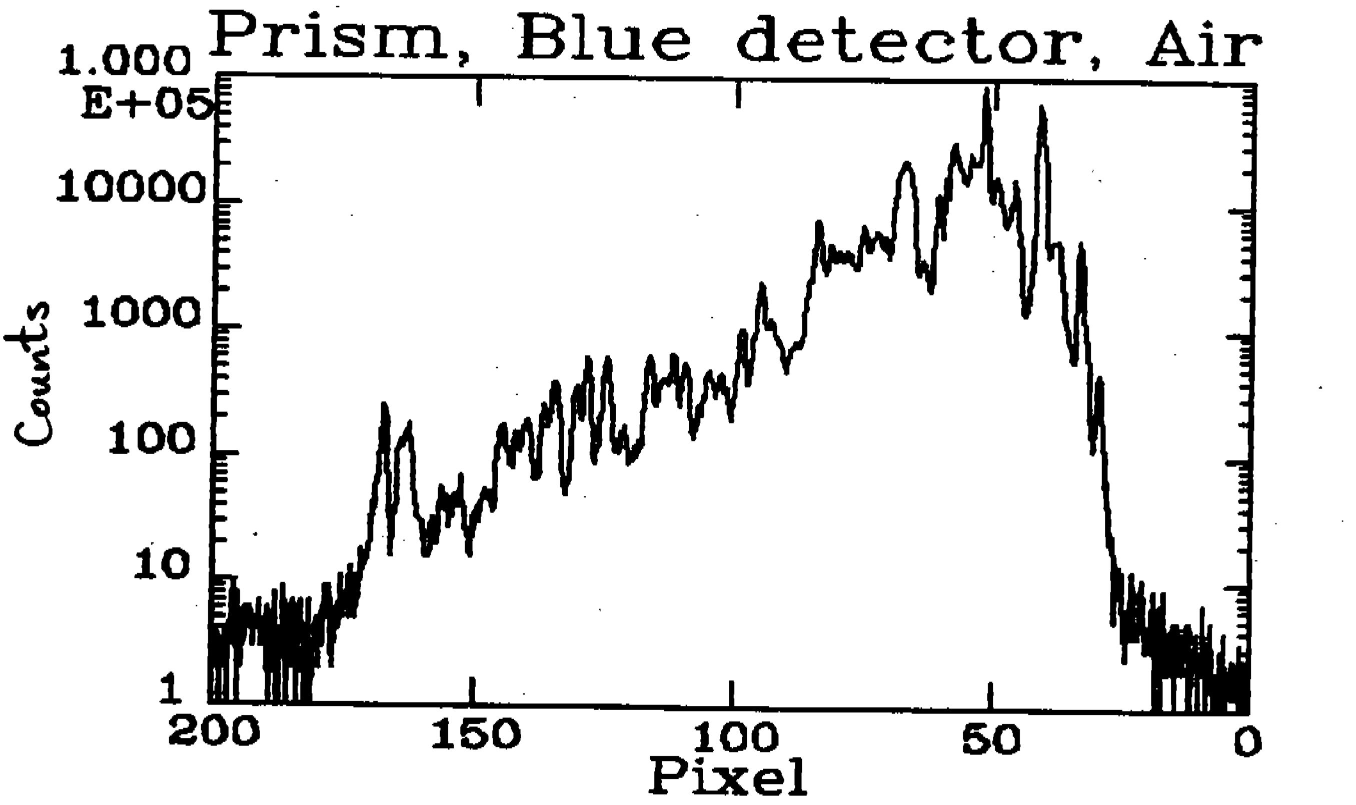
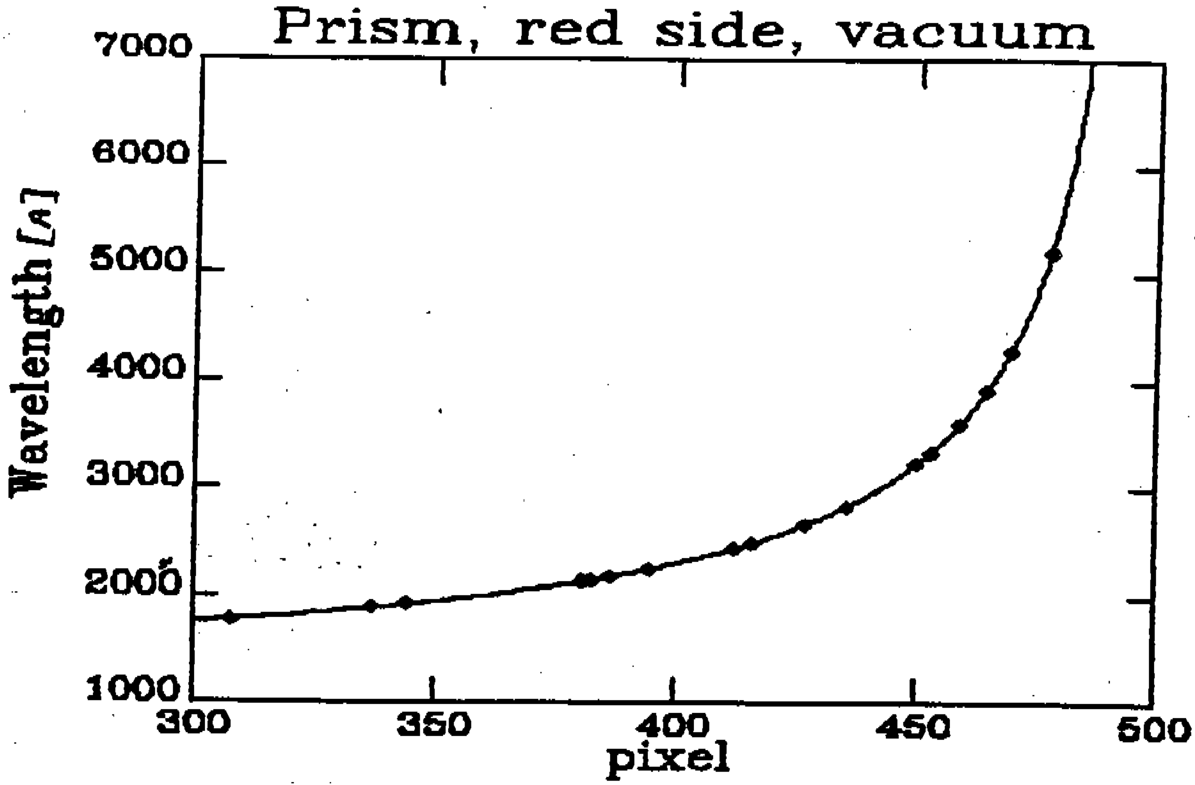

Prism, Blue detector, Air
Counts
Pixel
1.000 E+05
10000
1000
100
10
1
200
150
100
50
0

Fig 4C


Prism, red side, vacuum
7000
6000
5000
4000
3000
2000
1000
Wavelength [A]
300
350
400
450
500
pixel

4D

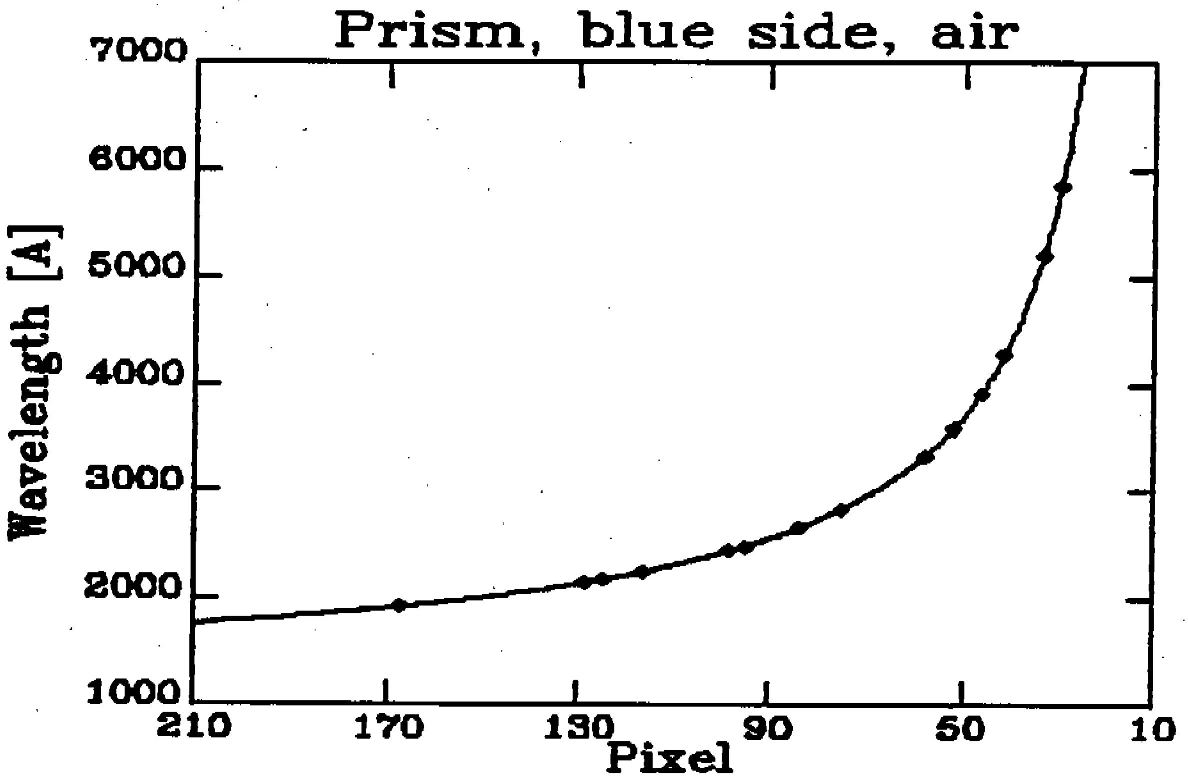
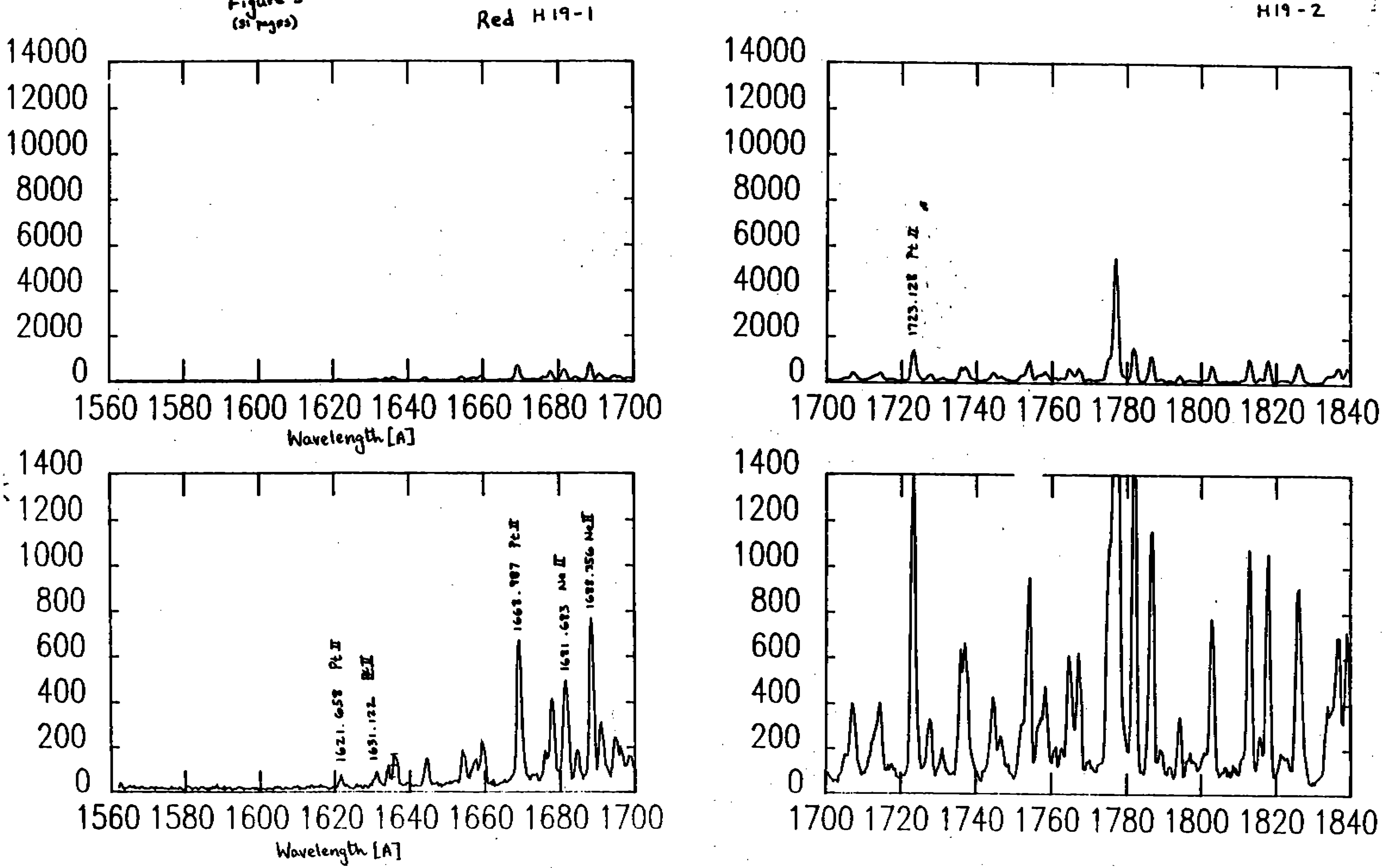
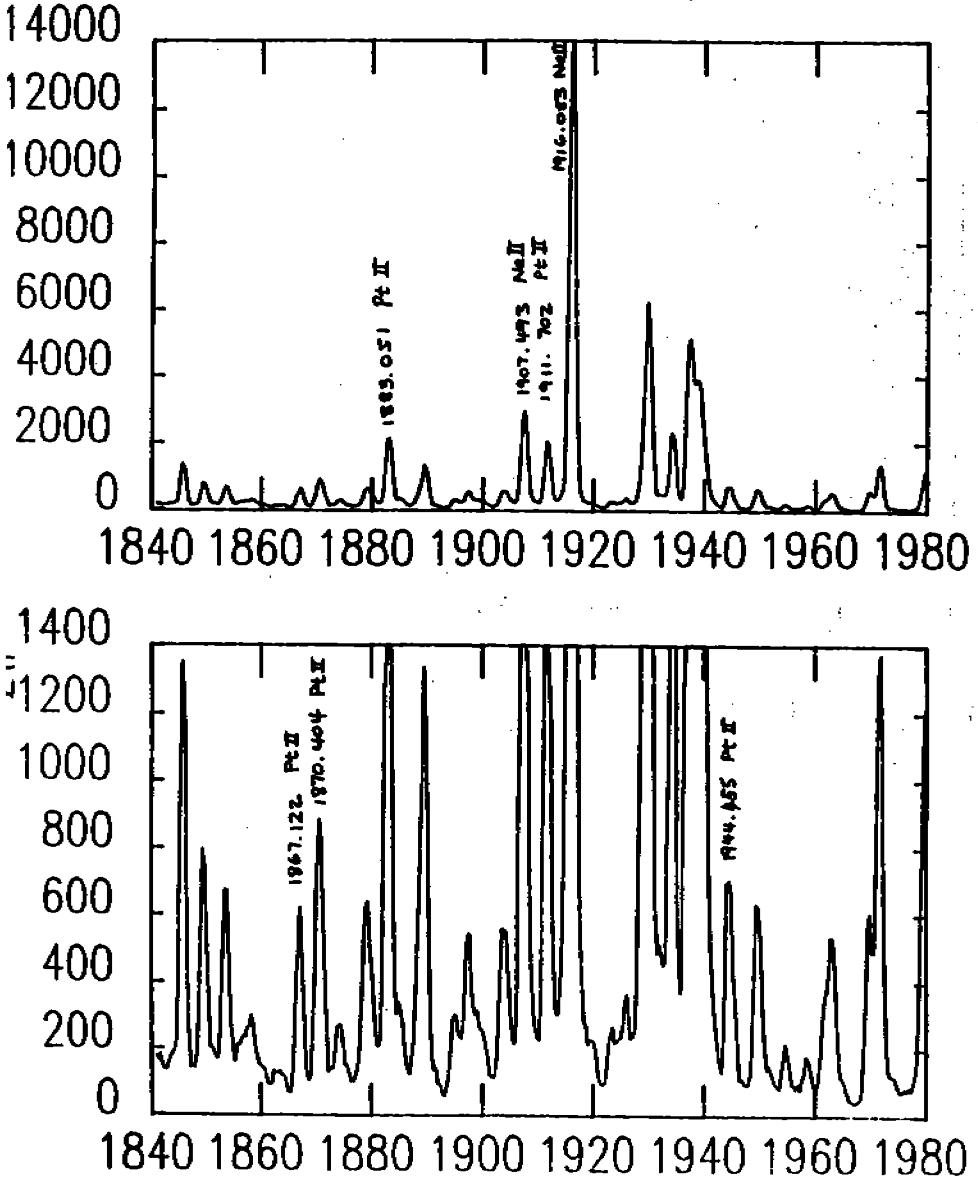

Prism, blue side, air
7000
6000
5000
4000
3000
2000
1000
Wavelength [A]
210
170
130
90
50
10
Pixel

Figure 5
(31 pages)

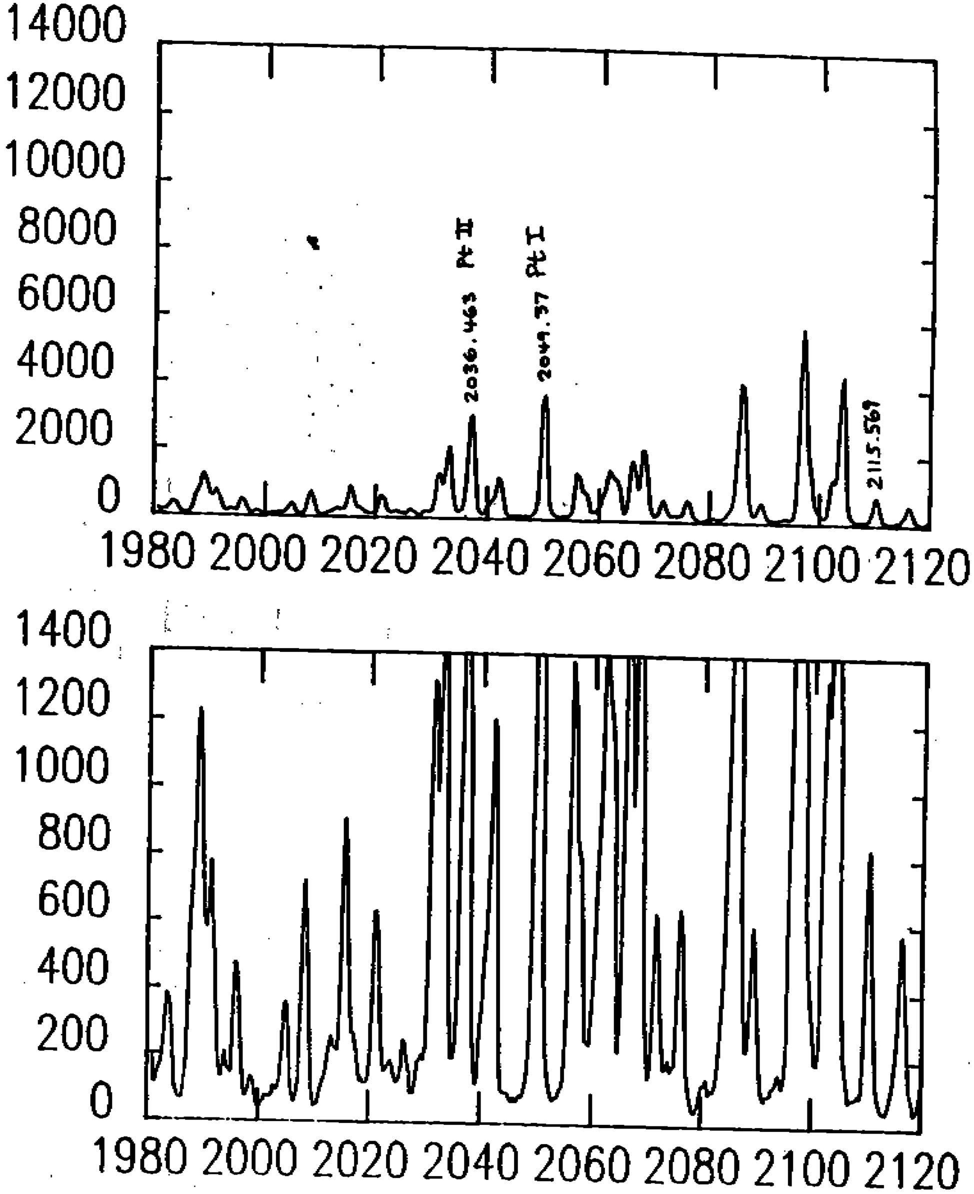


H19-3



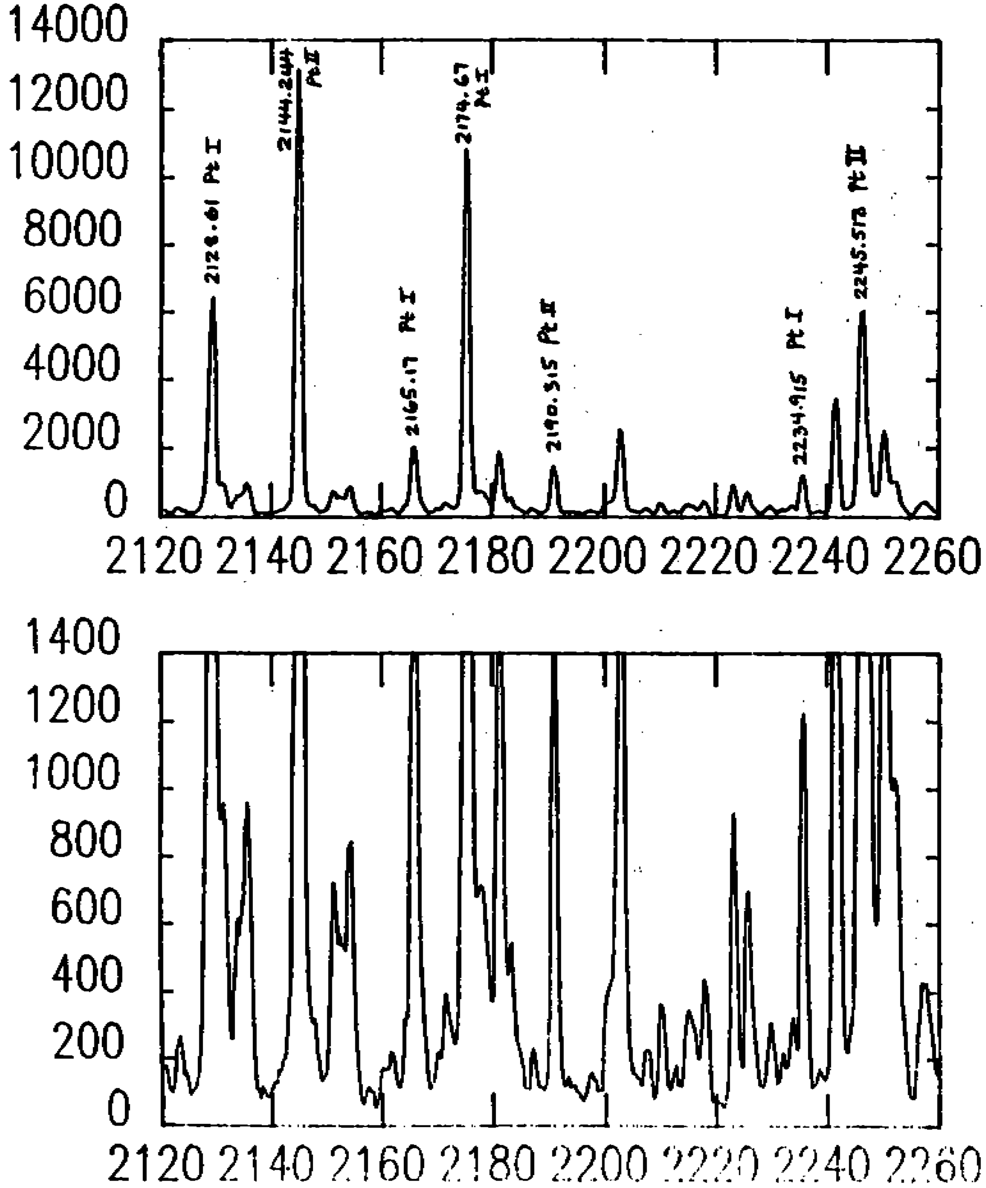
1883.051 Pt II
1907.493 Na II
1911.702 Pt II
1916.083 Na II
1867.122 Pt II
1870.404 Pt II
1944.185 Pt II

H19-4

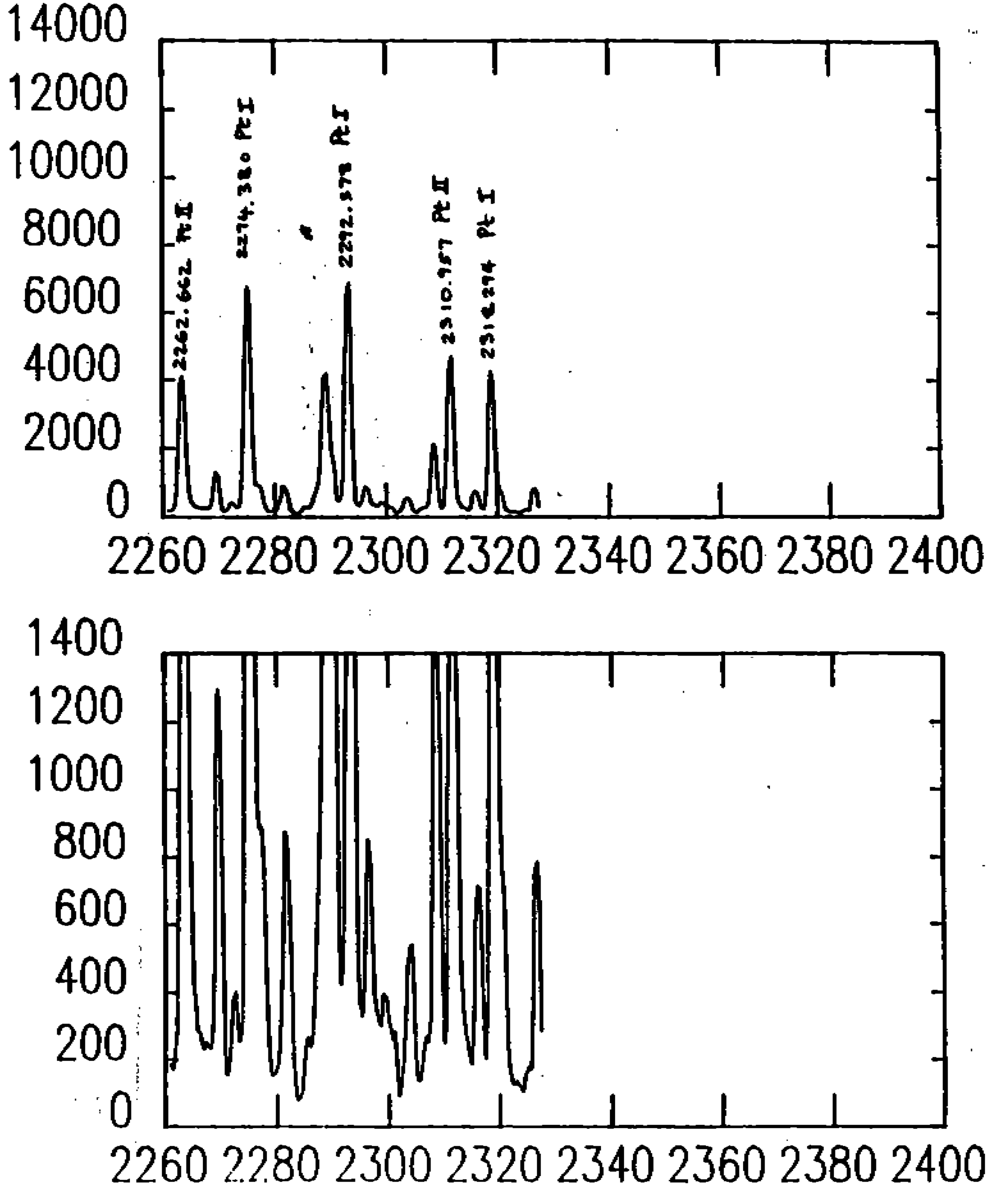


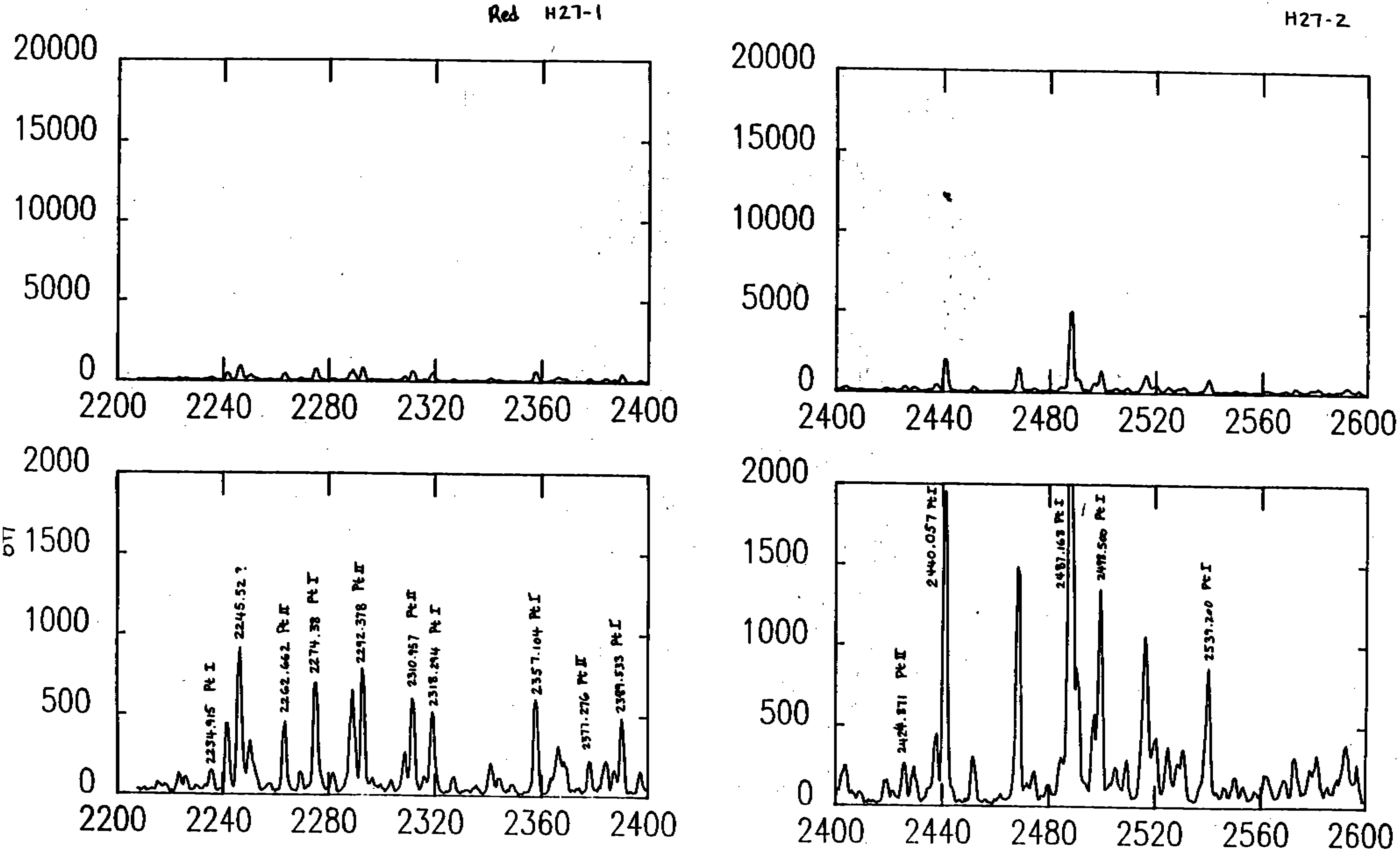
2036.463 Pt II
2049.37 Pt I
2115.569

H19-5

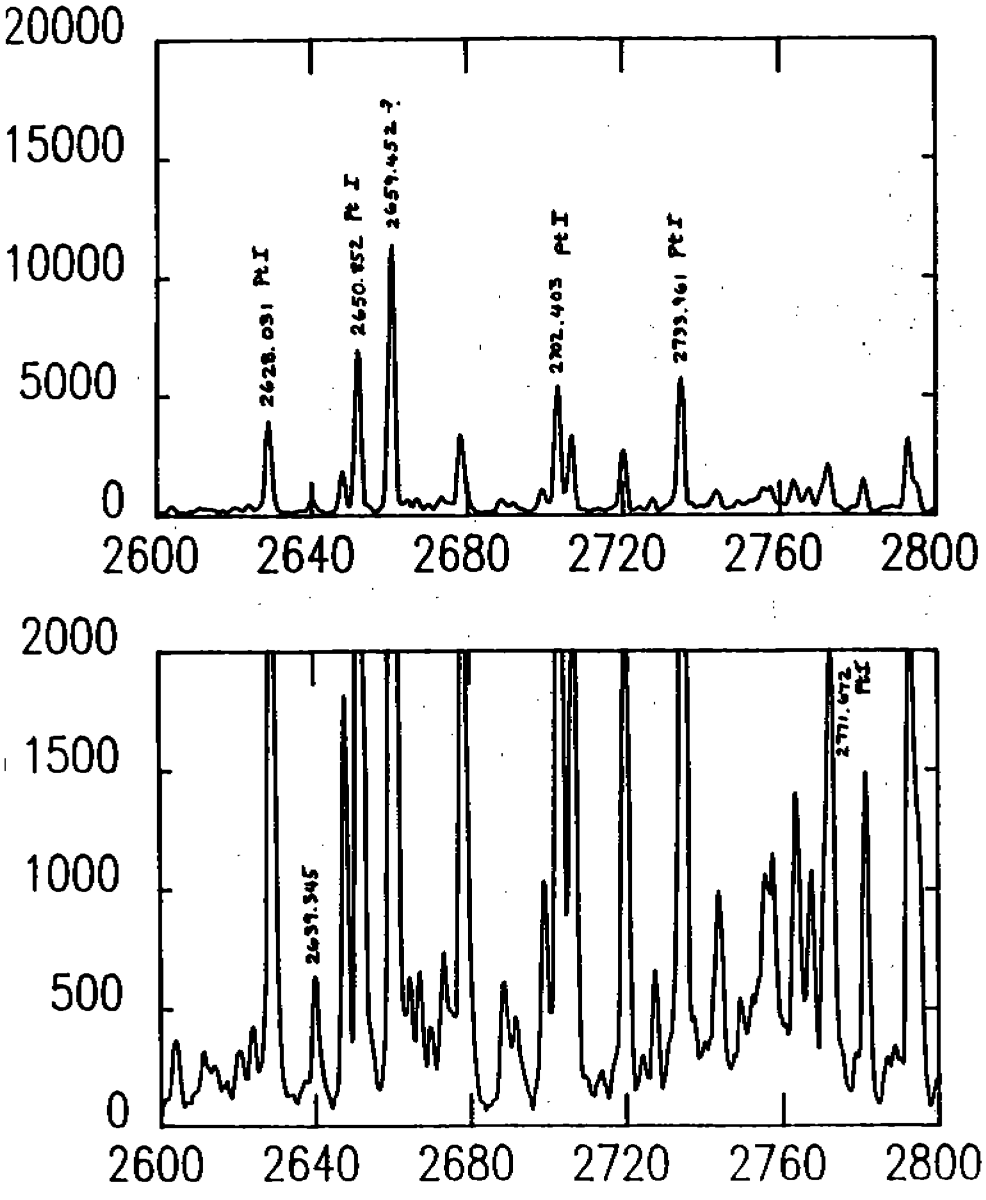

2128.61 Pt I
2144.244 Pt II
2165.17 Pt I
2174.67 Pt I
2190.515 Pt II
2234.915 Pt I
2245.578 Pt II
14000
12000
10000
8000
6000
4000
2000
0
1400
1200
1000
800
600
400
200
2120 2140 2160 2180 2200 2220 2240 2260

H19-6


2262.662 Pt II
2274.380 Pt I
2292.578 Pt I
2310.957 Pt II
2316.294 Pt I
14000
12000
10000
8000
6000
4000
2000
0
1400
1200
1000
800
600
400
200
2260 2280 2300 2320 2340 2360 2380 2400

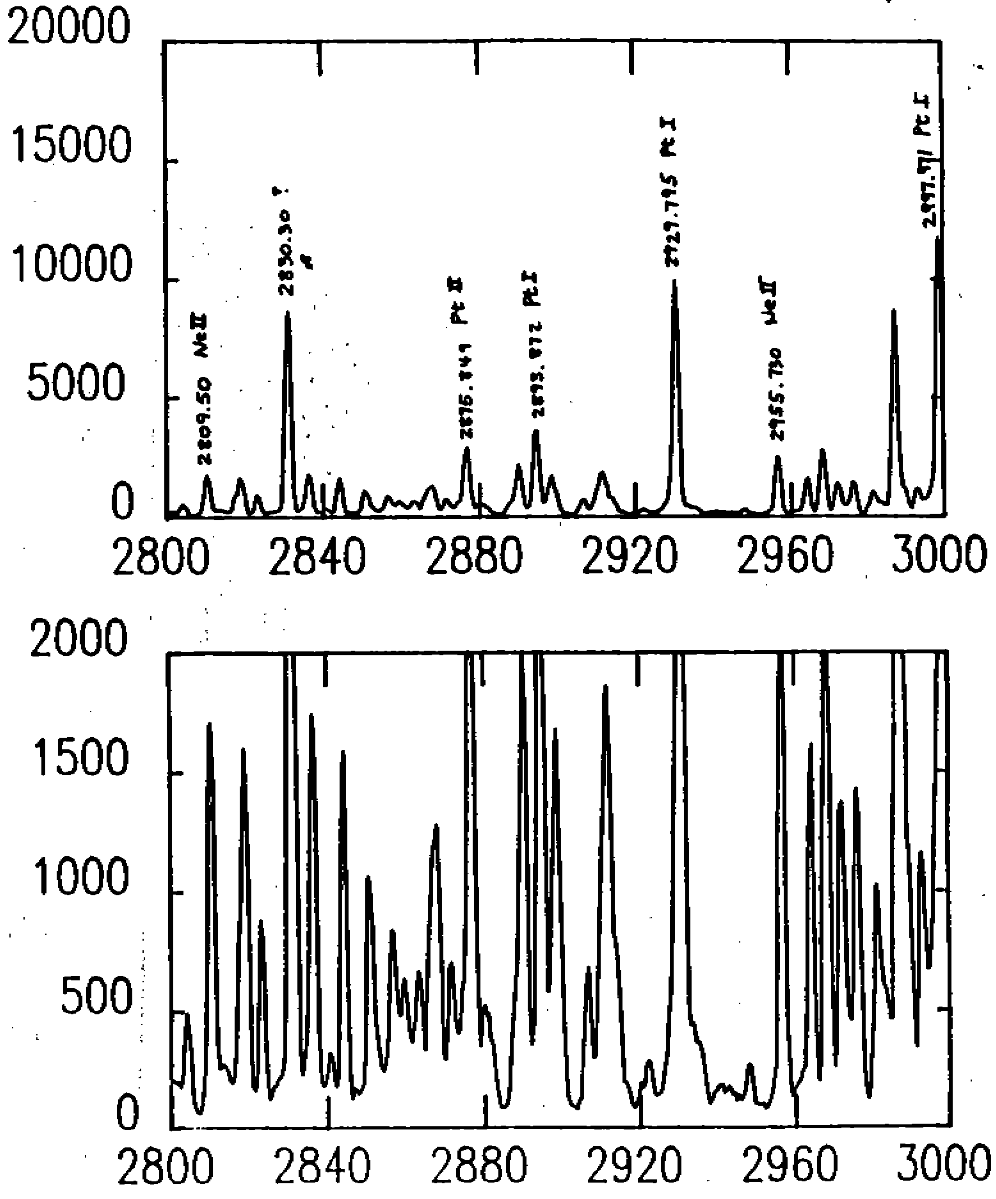

Red H27-1
H27-2
20000
15000
10000
5000
0
2000
1500
1000
500
2200
2240
2280
2320
2360
2400
2440
2480
2520
2560
2600
2234.915 Pt I
2245.52 ?
2262.662 Pt II
2274.38 Pt I
2292.378 Pt II
2310.957 Pt II
2318.294 Pt I
2357.104 Pt I
2377.276 Pt II
2389.533 Pt I
2424.871 Pt II
2440.057 Pt I
2487.163 Pt I
2498.500 Pt I
2539.200 Pt I

H27-3



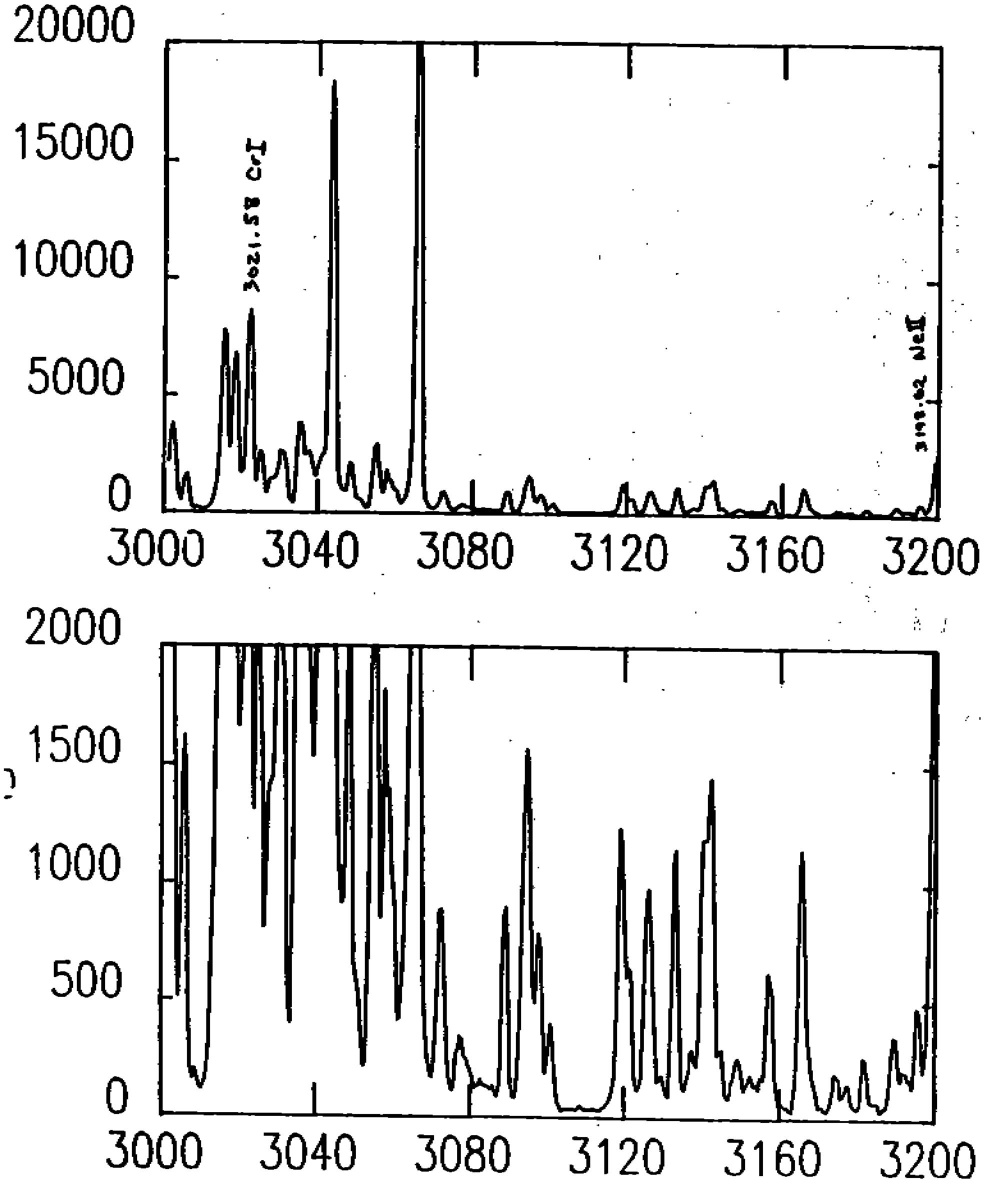
2628.031 Pt I
2650.852 Pt I
2659.452 ?
2702.403 Pt I
2733.961 Pt I
2639.545
2771.672 Pt I

H27-4



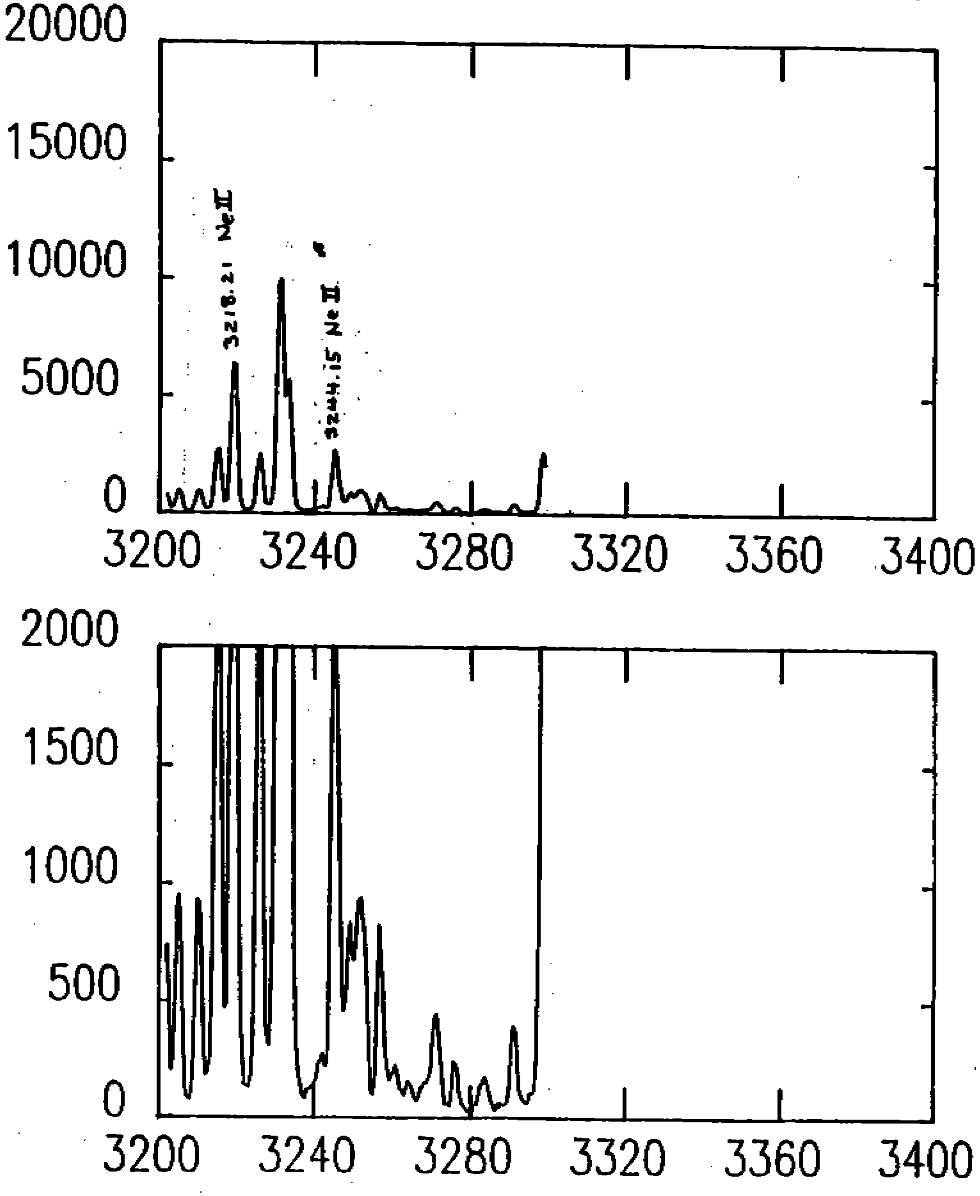
2809.50 Ne II
2830.30 ?
2875.849 Pt II
2893.872 Pt I
2929.795 Pt I
2955.730 Ne II
2997.971 Pt I

H27-5



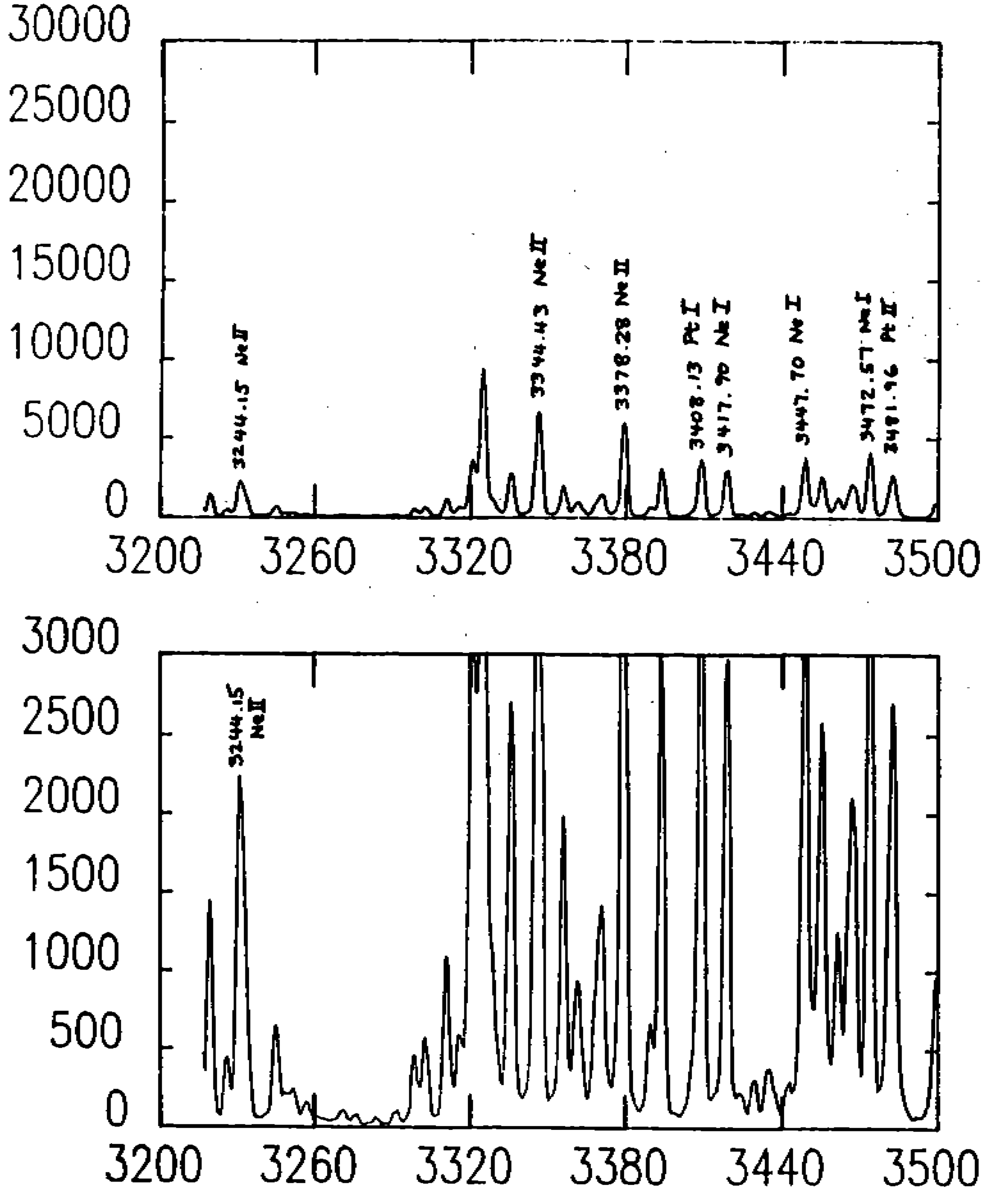
20000
15000
10000
5000
0
3000
3040
3080
3120
3160
3200
3021.58 CrI
3199.62 NeII
2000
1500
1000
500

H27-6

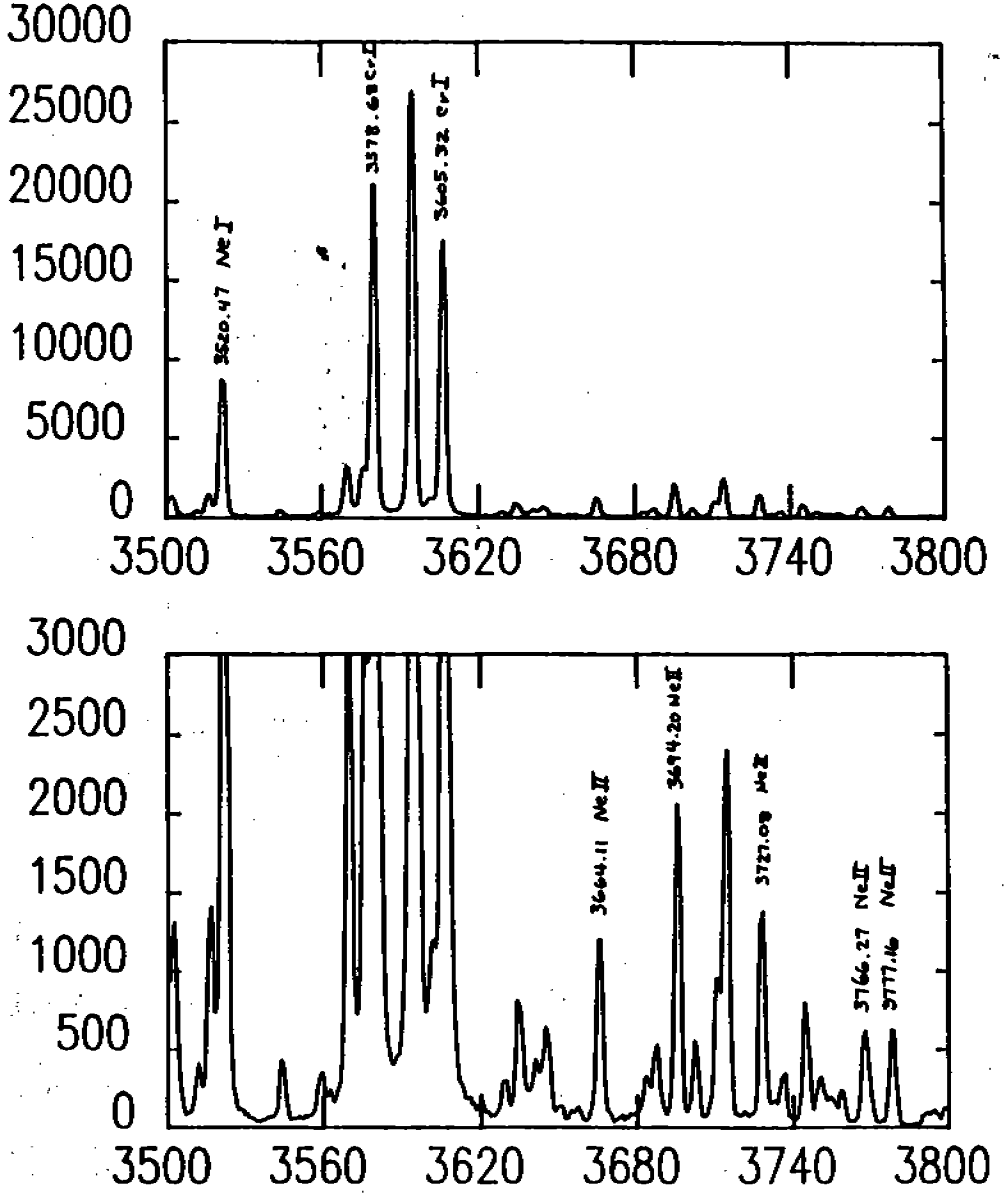


20000
15000
10000
5000
0
3200
3240
3280
3320
3360
3400
3218.21 NeII
3244.15 NeII
2000
1500
1000
500

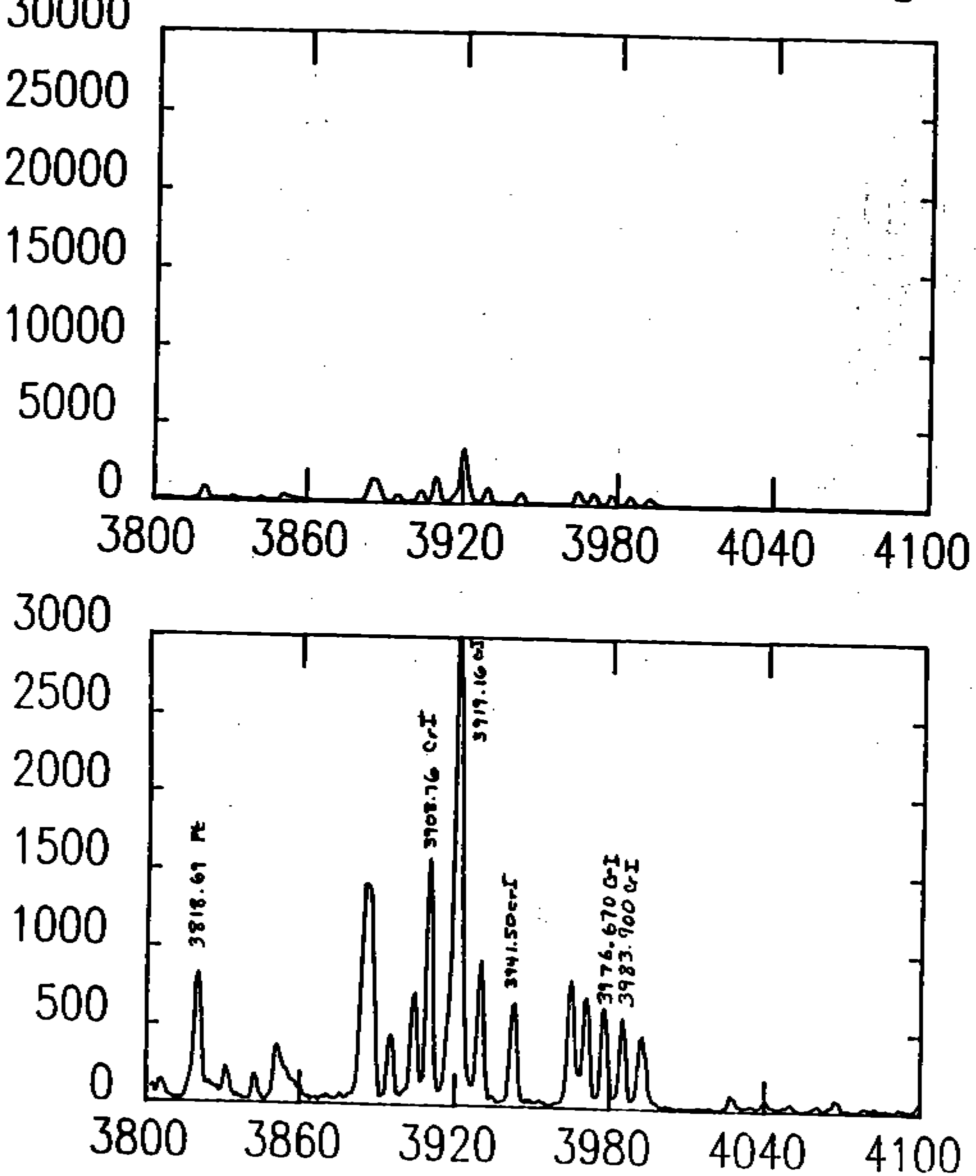
Red H40-1



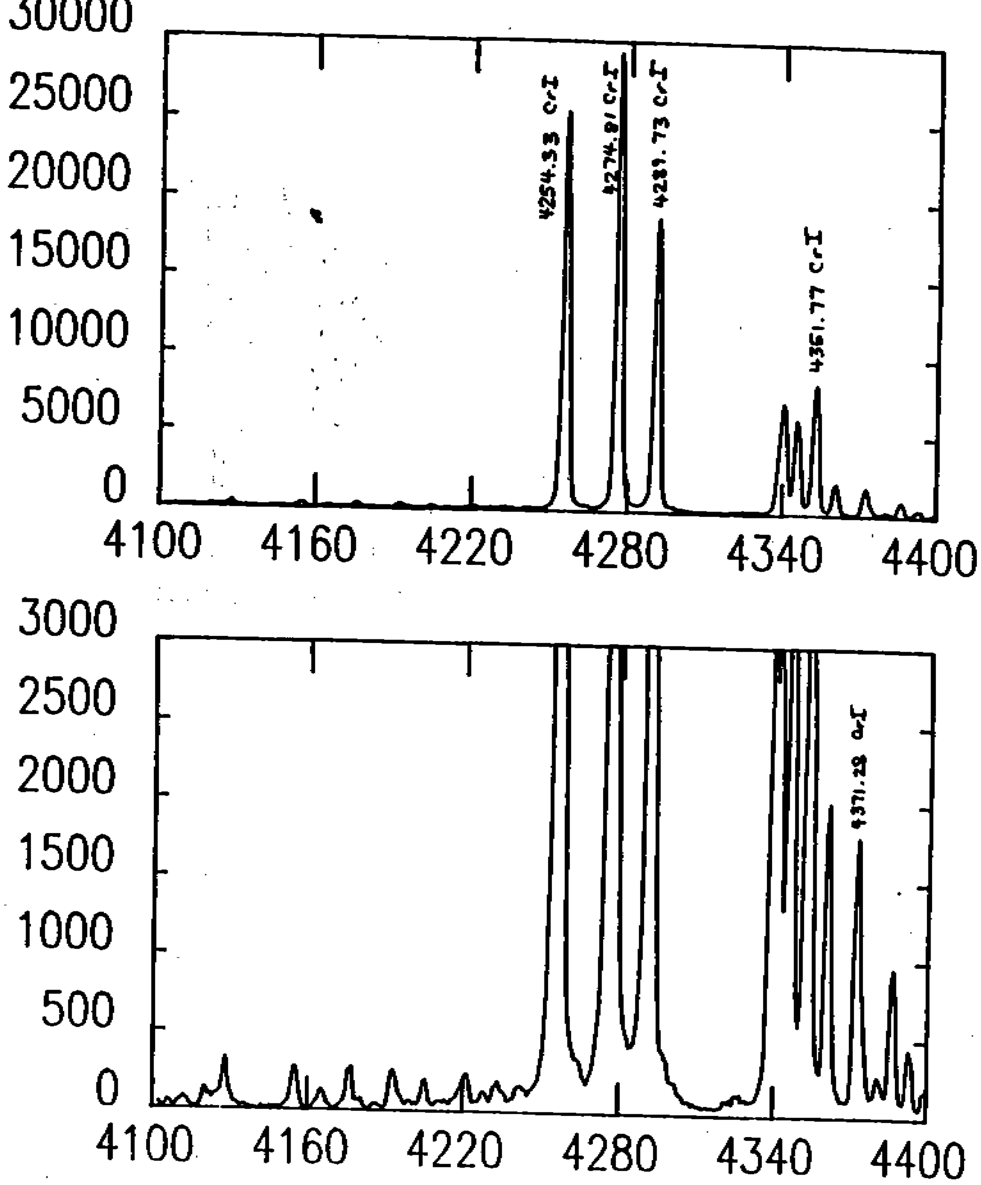
H40-2



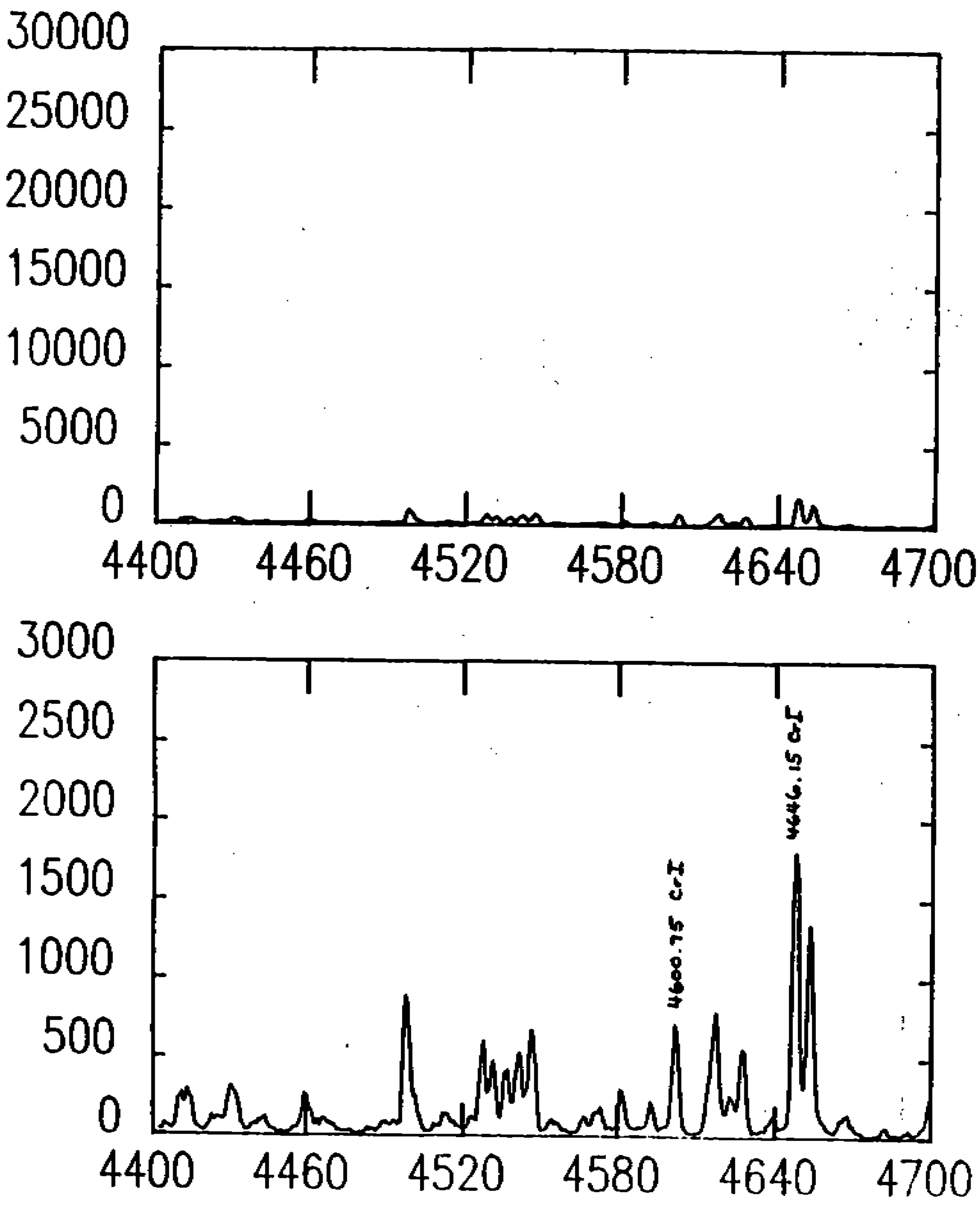
H40-3


30000
25000
20000
15000
10000
5000
0
3800
3860
3920
3980
4040
4100
3000
2500
2000
1500
1000
500
3818.61 Pt
3908.76 CrI
3919.16 CrI
3941.50 CrI
3976.670 CrI
3983.900 CrI

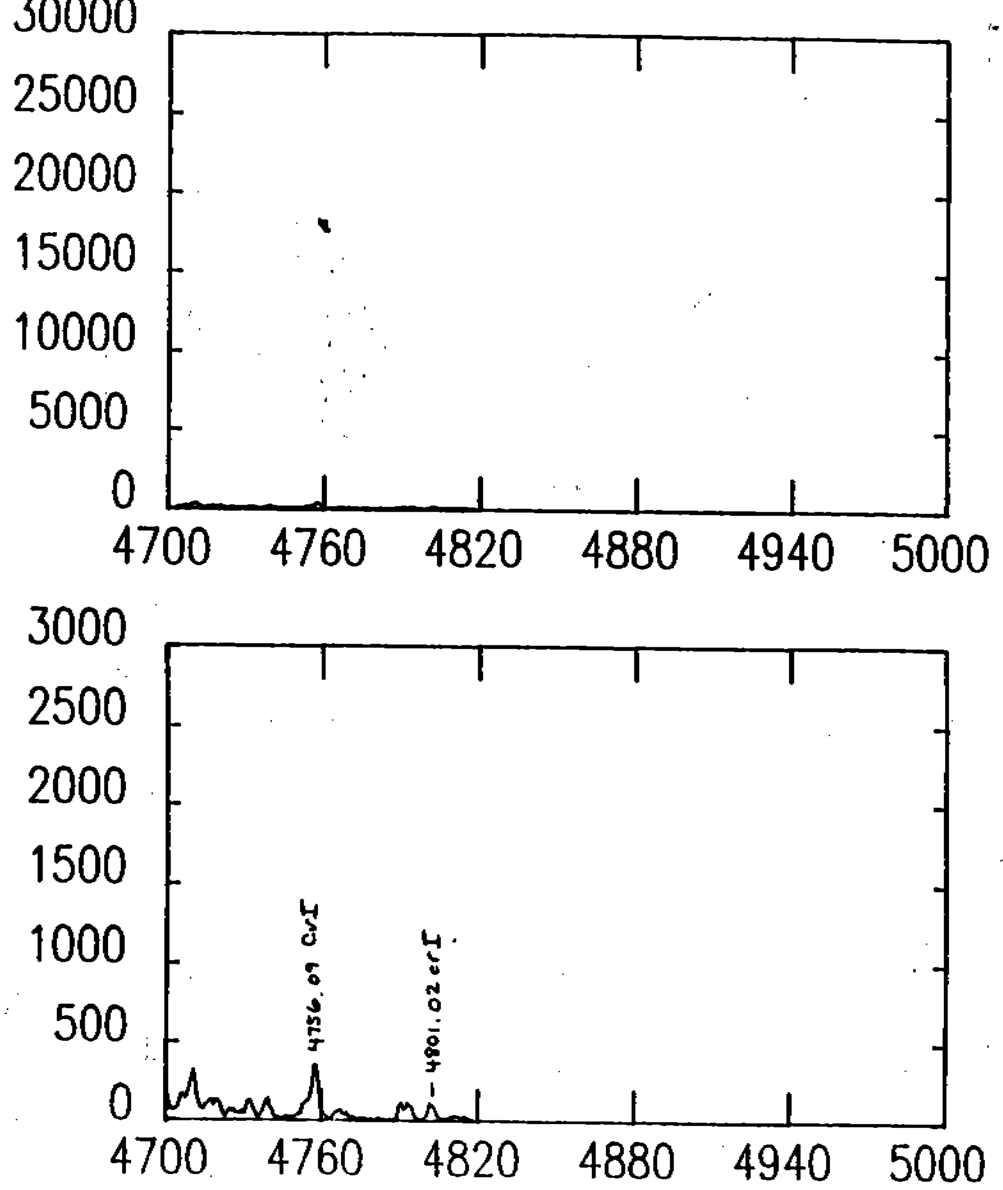
H40-4


30000
25000
20000
15000
10000
5000
0
4100
4160
4220
4280
4340
4400
4254.33 CrI
4274.81 CrI
4289.73 CrI
4351.77 CrI
3000
2500
2000
1500
1000
500
4371.28 CrI

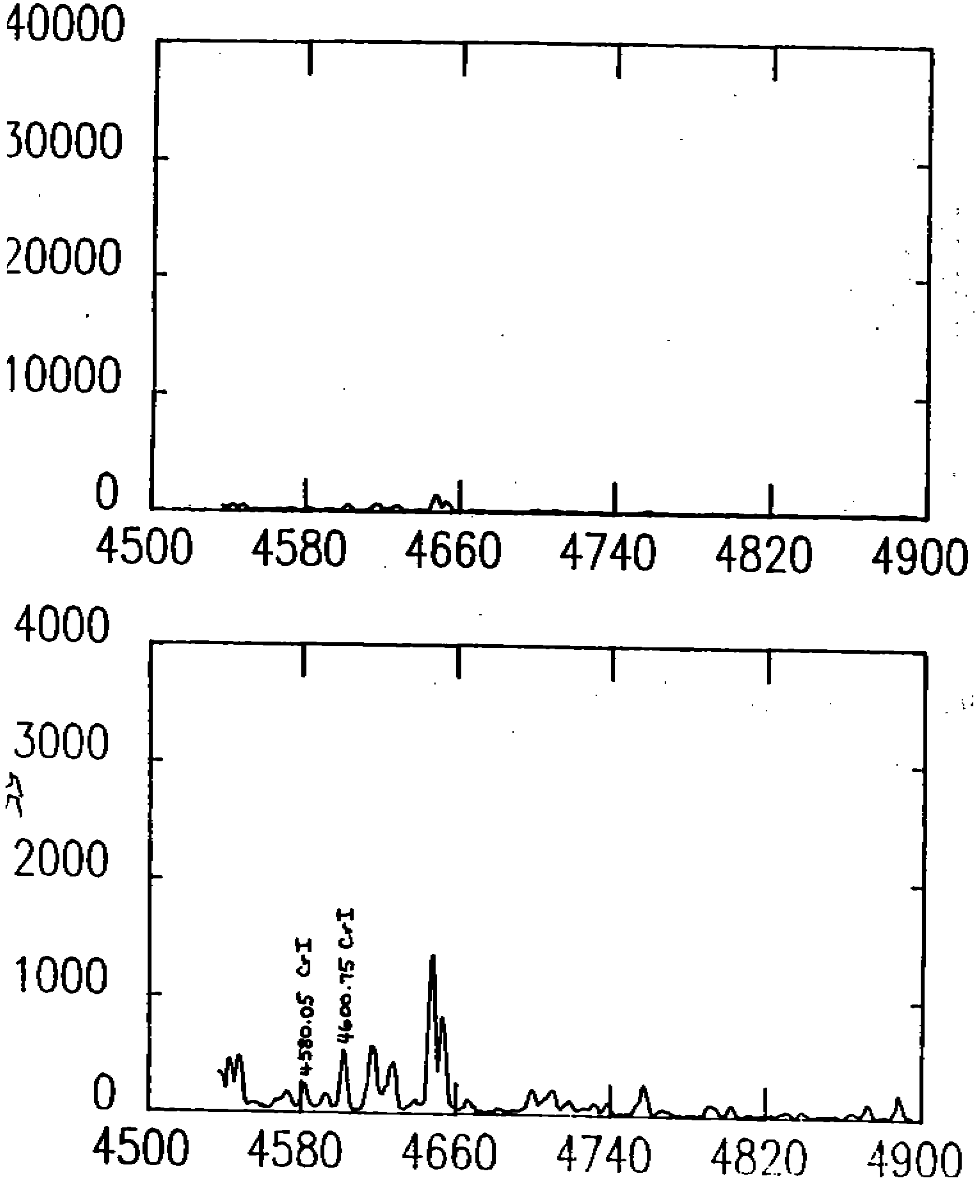
H40-5



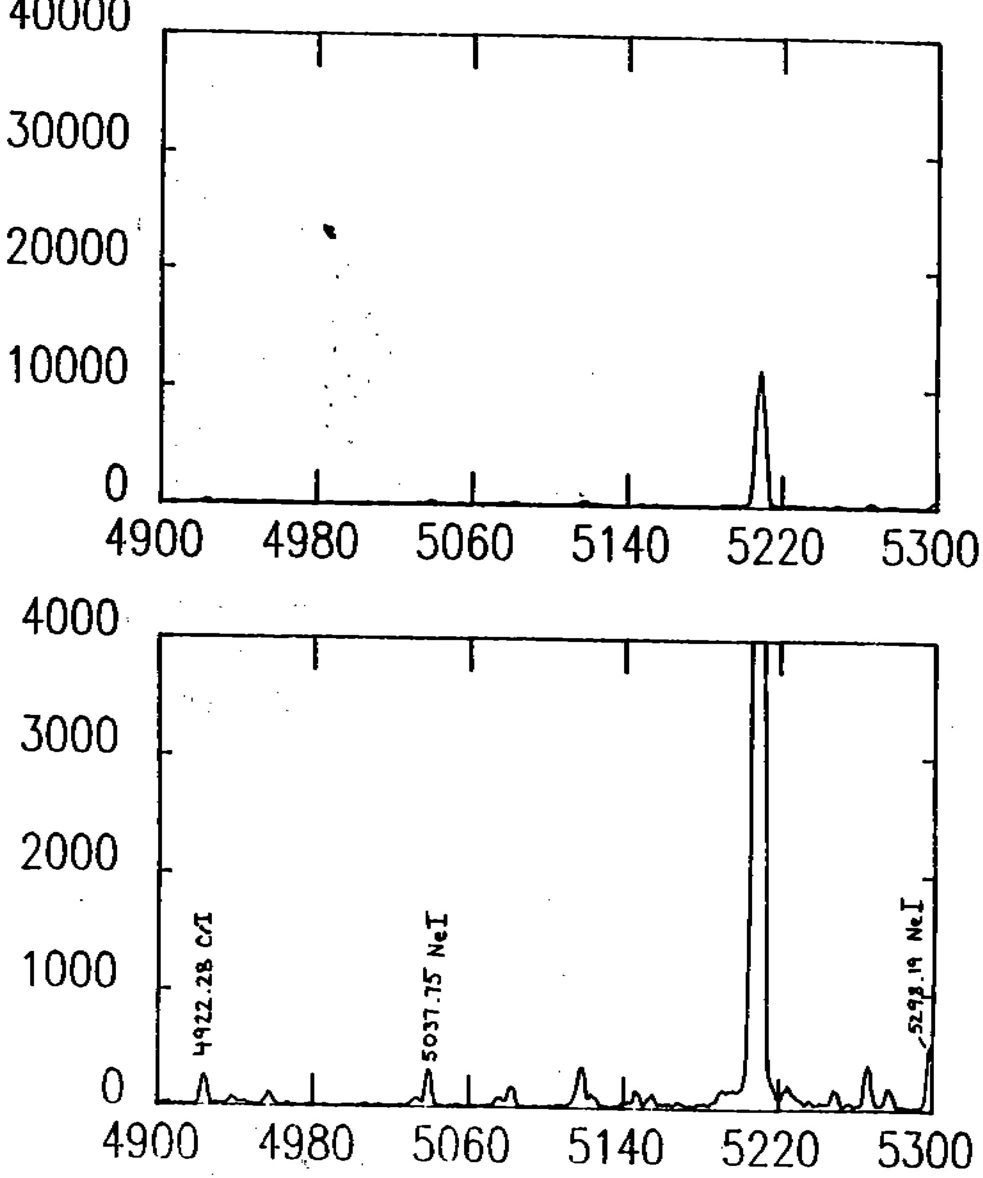
H40-6



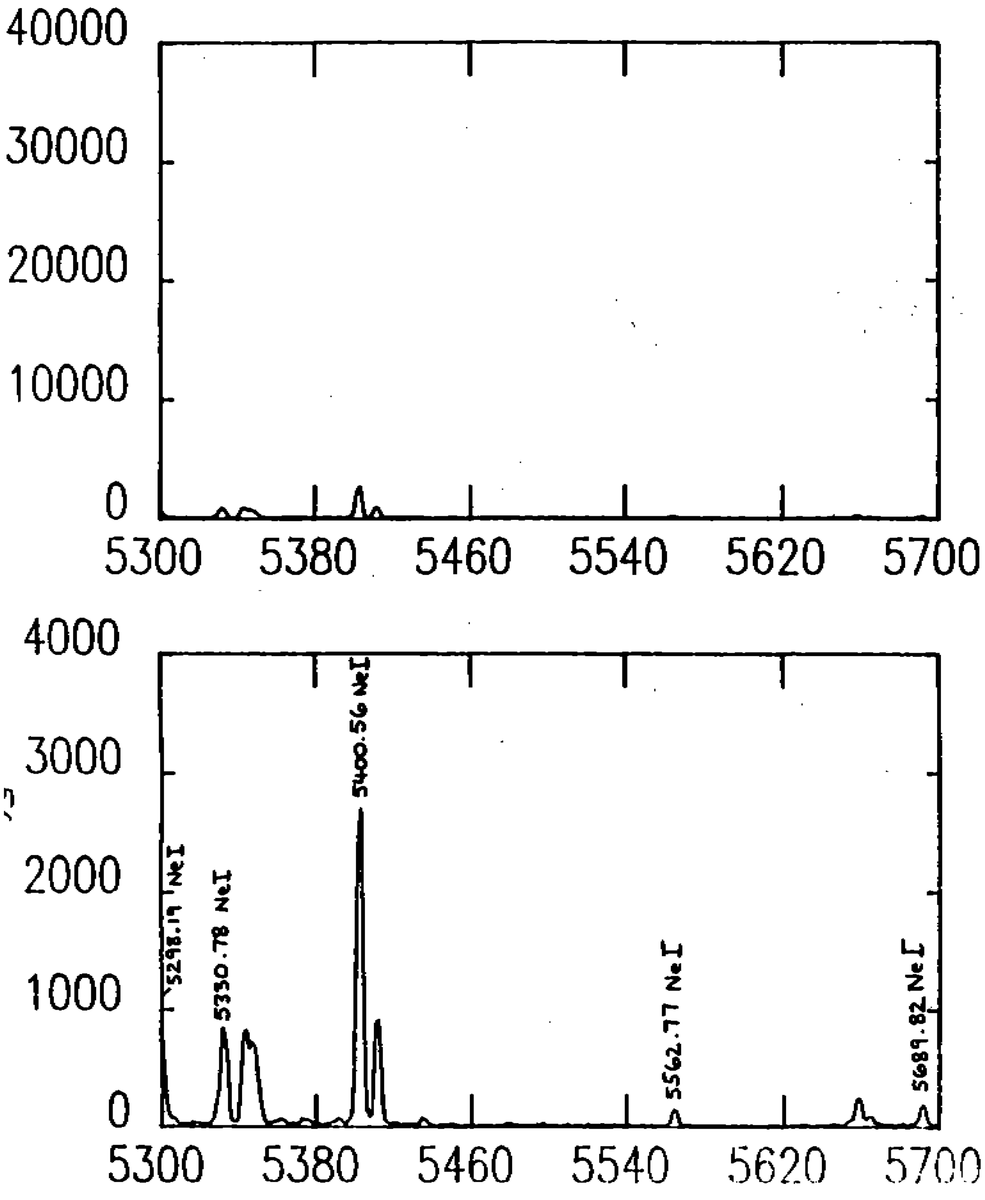
Red H57-1



H57-2

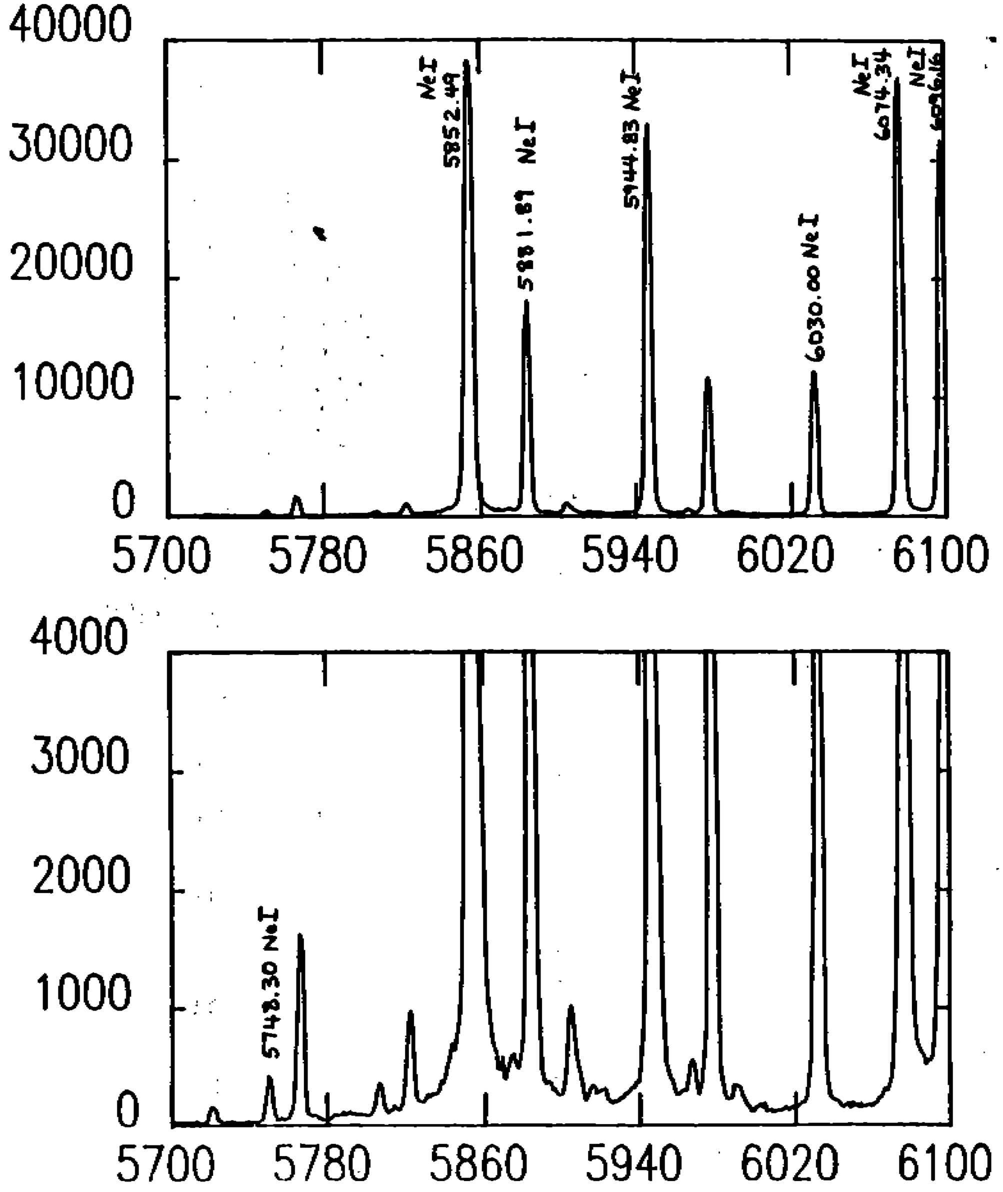


H57-3

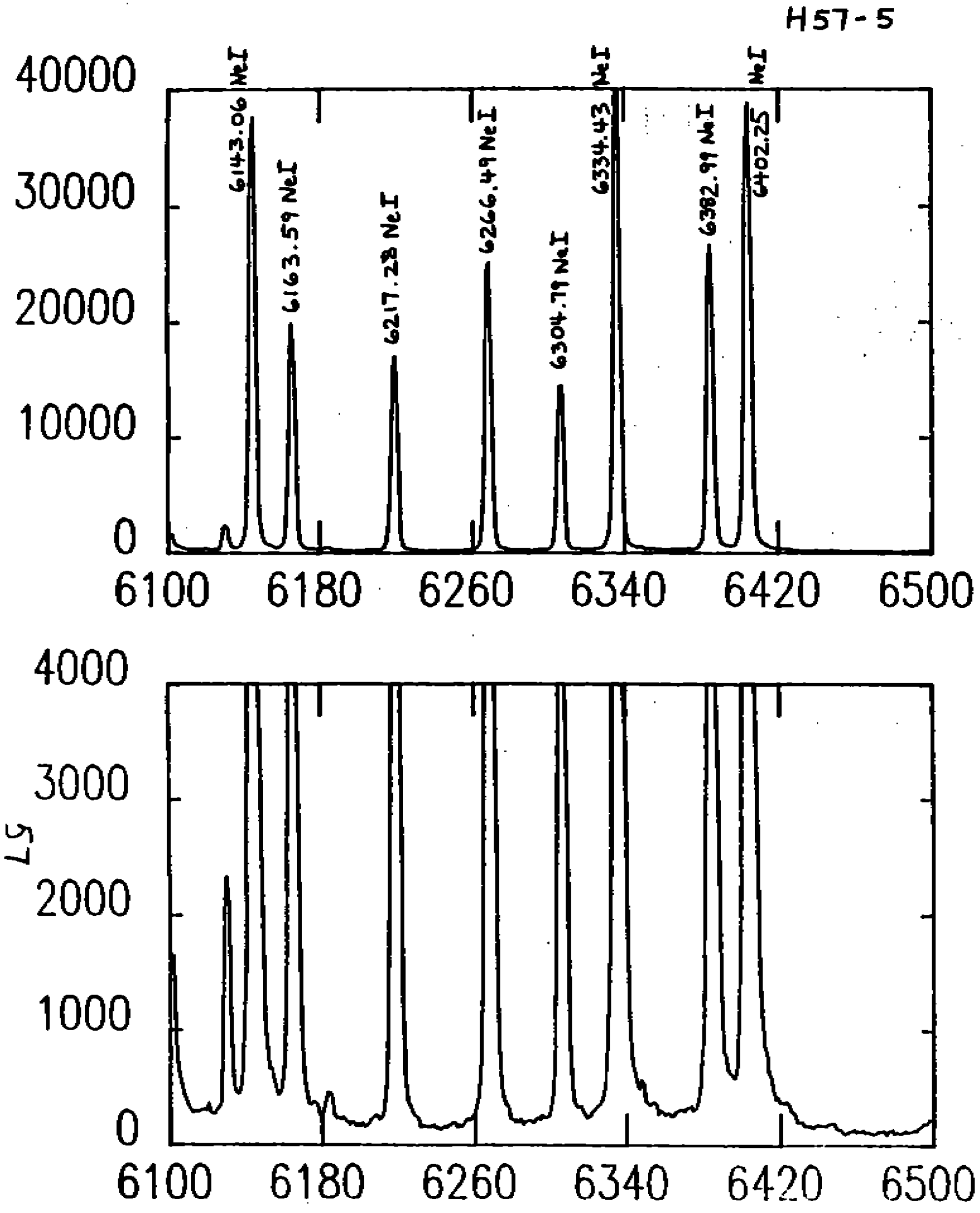


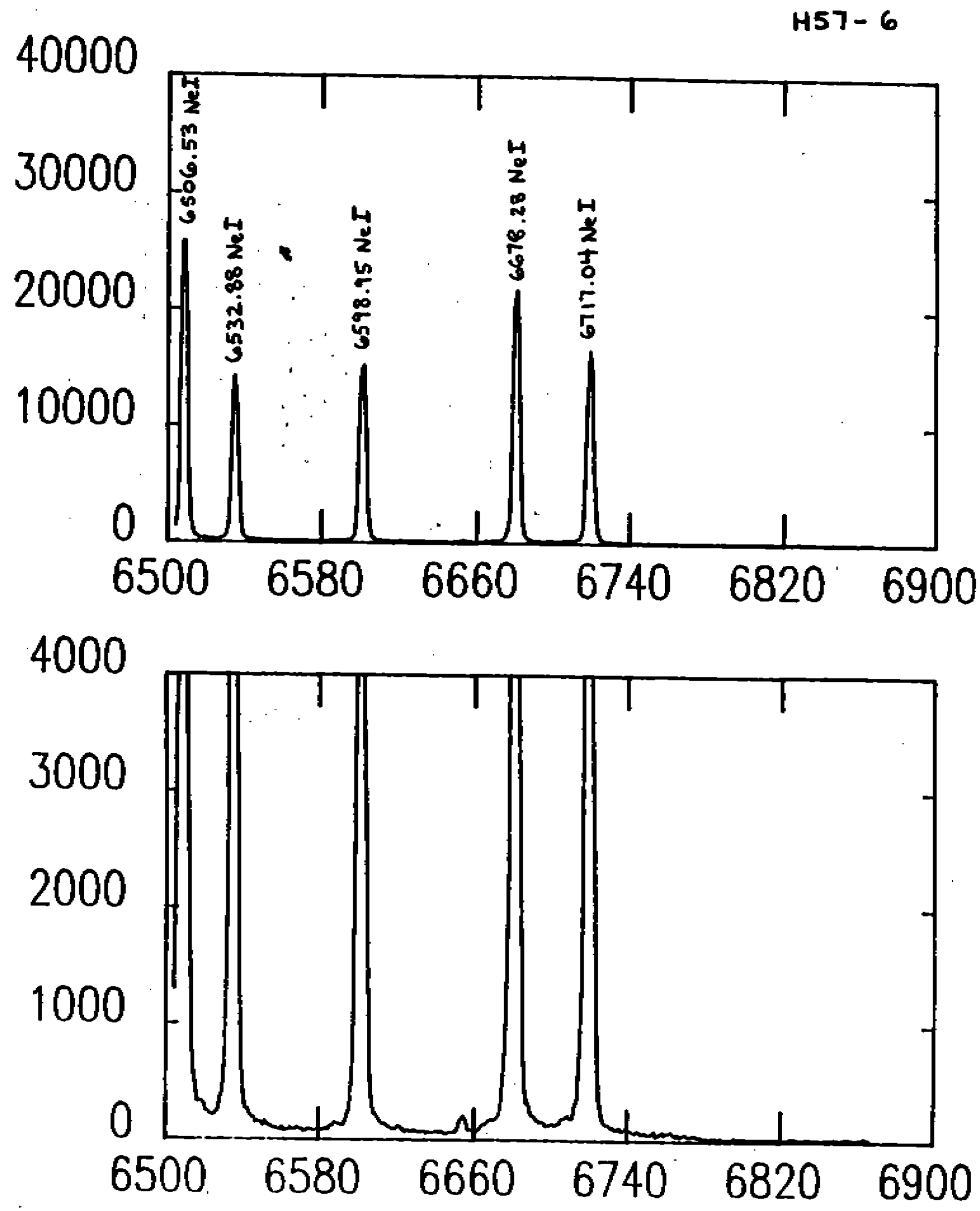
40000
30000
20000
10000
0
5300
5380
5460
5540
5620
5700
4000
3000
2000
1000
5298.19 NeI
5330.78 NeI
5400.56 NeI
5562.77 NeI
5689.82 NeI

H57-4

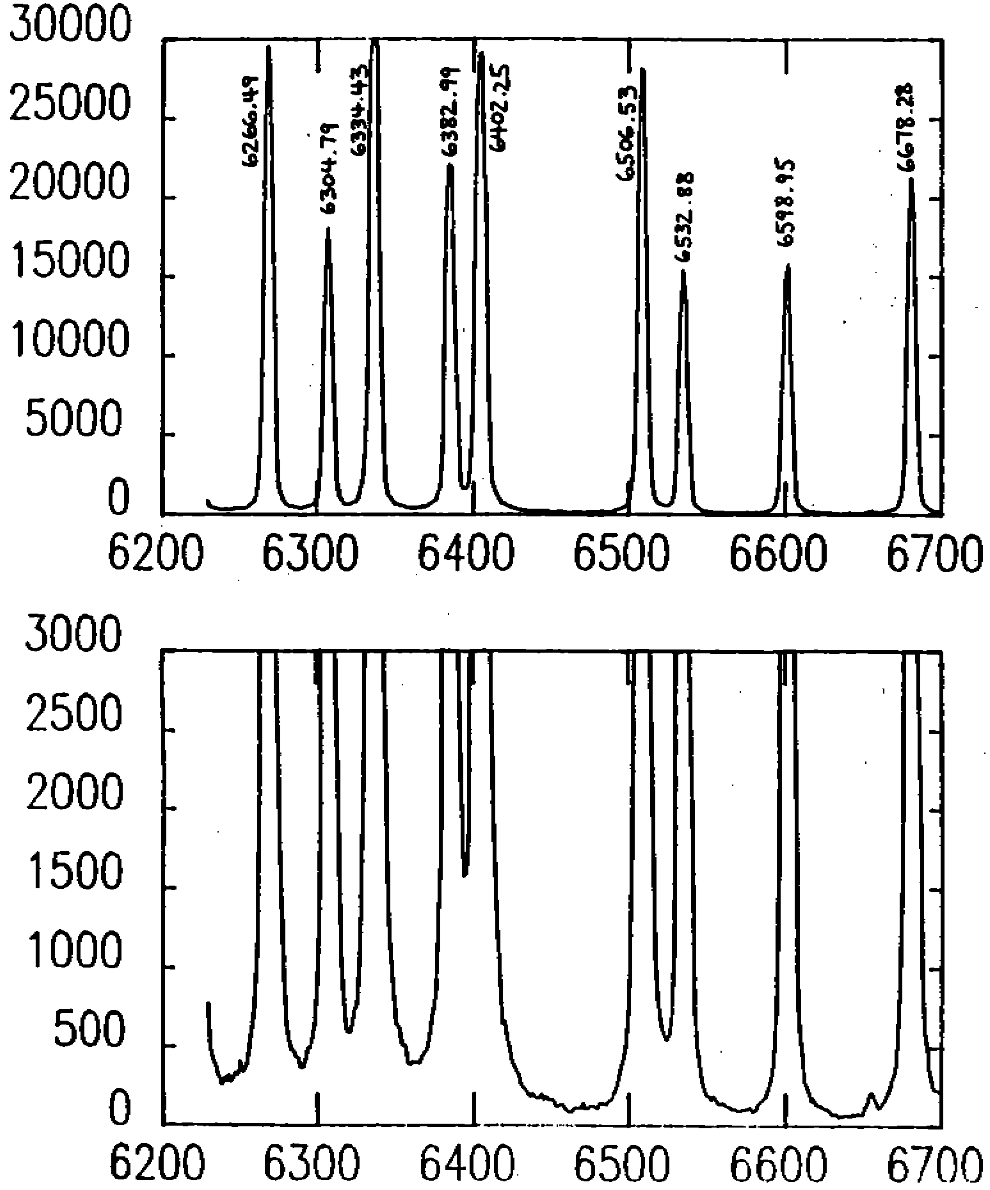


40000
30000
20000
10000
0
5700
5780
5860
5940
6020
6100
NeI 5852.49
5881.89 NeI
5944.83 NeI
6030.00 NeI
NeI 6074.34
NeI 6096.16
4000
3000
2000
1000
5748.30 NeI

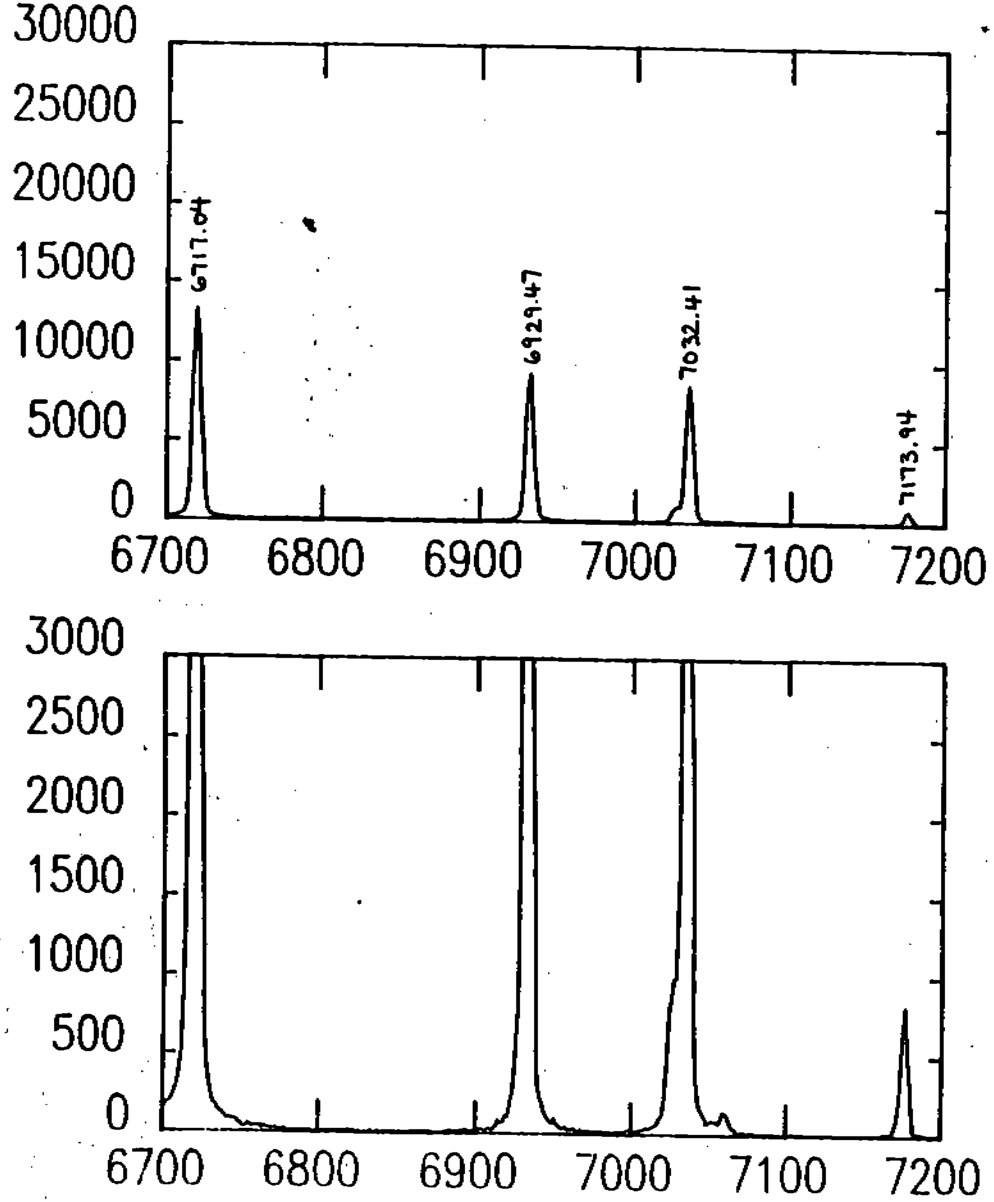

H57-5
6143.06 NeI
6163.59 NeI
6217.28 NeI
6266.49 NeI
6304.79 NeI
6334.43 NeI
6382.99 NeI
6402.25 NeI
40000
30000
20000
10000
0
4000
3000
2000
1000
6100
6180
6260
6340
6420
6500


H57-6
6506.53 NeI
6532.88 NeI
6598.95 NeI
6678.28 NeI
6717.04 NeI
40000
30000
20000
10000
0
4000
3000
2000
1000
6500
6580
6660
6740
6820
6900

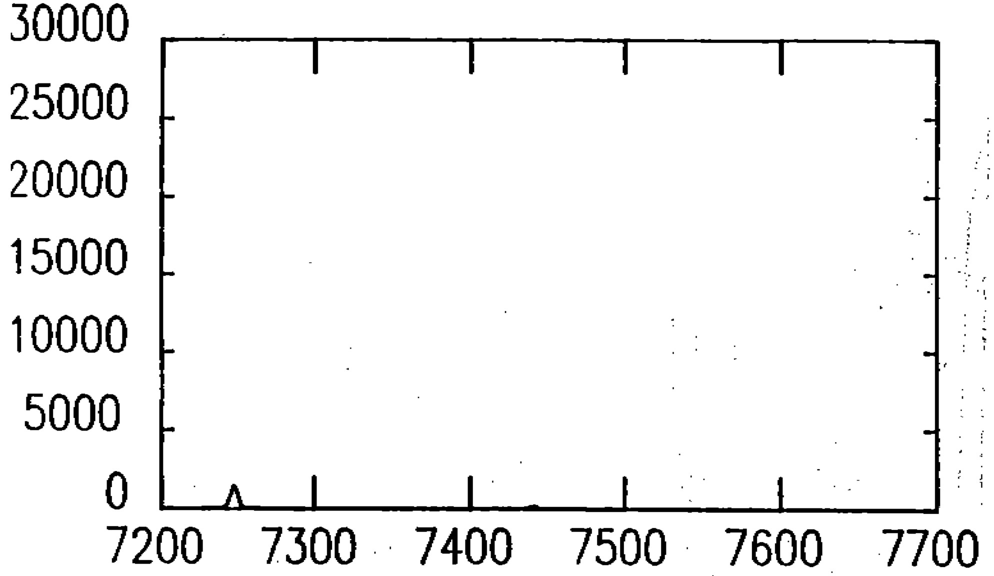
Red H78-1

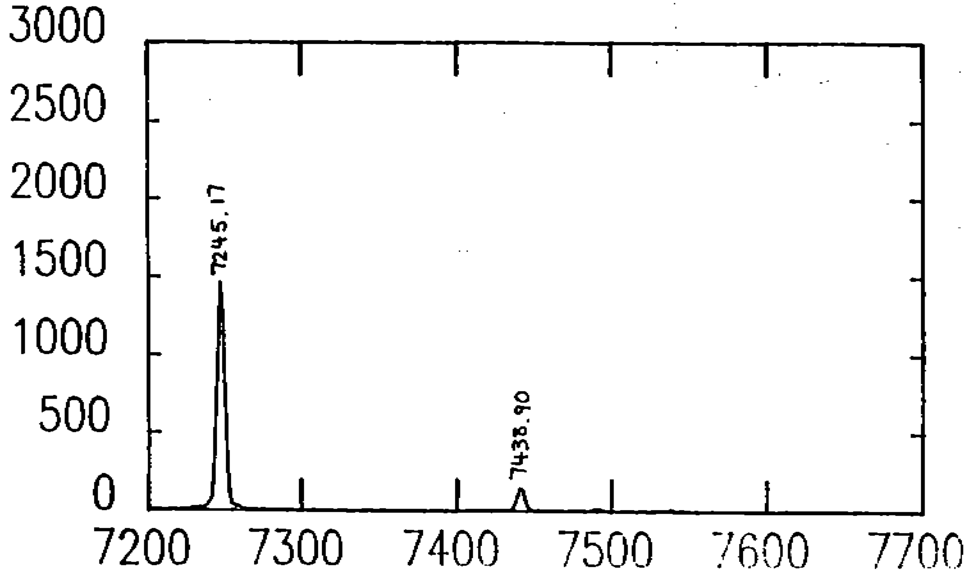


H78-2

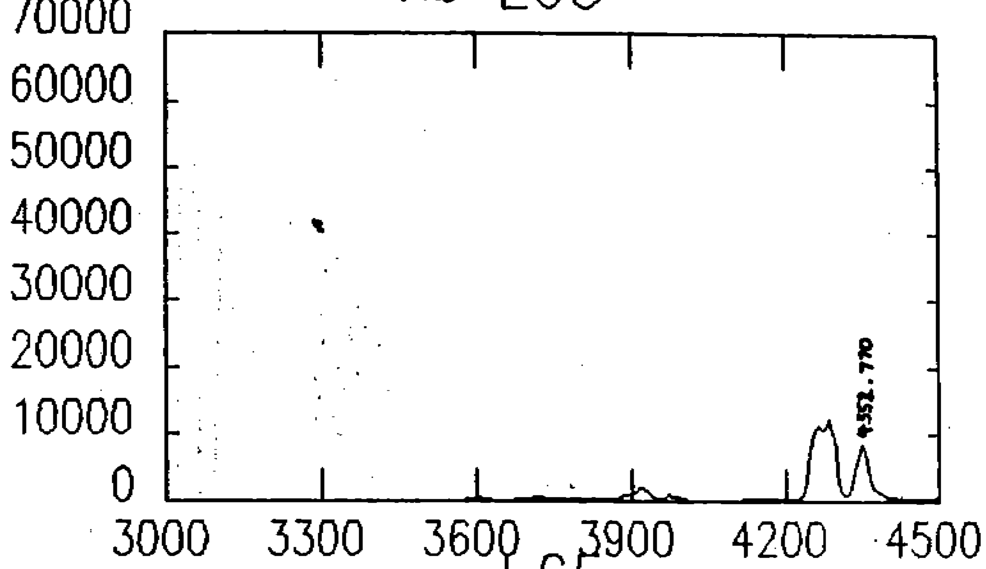


H78-3

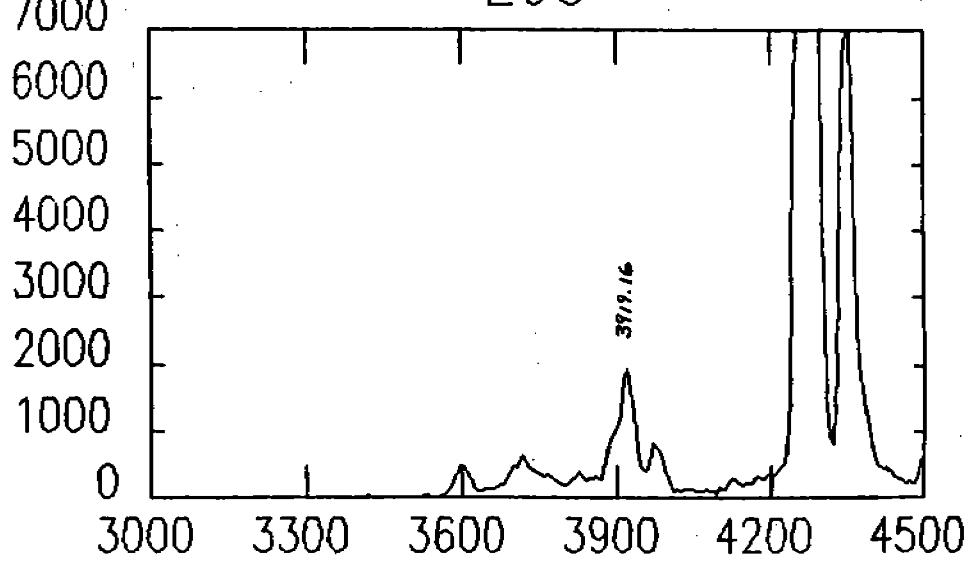


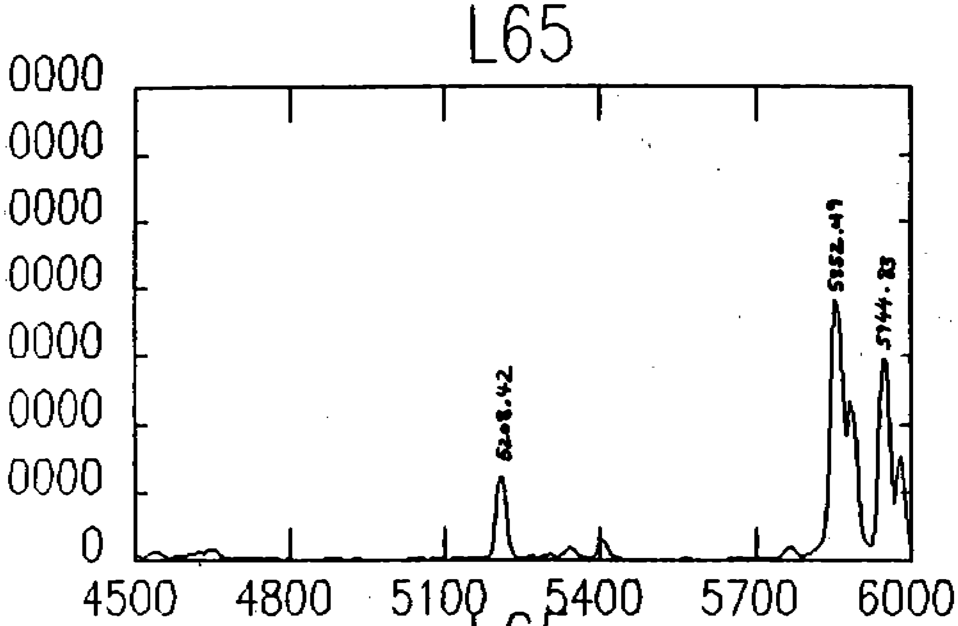


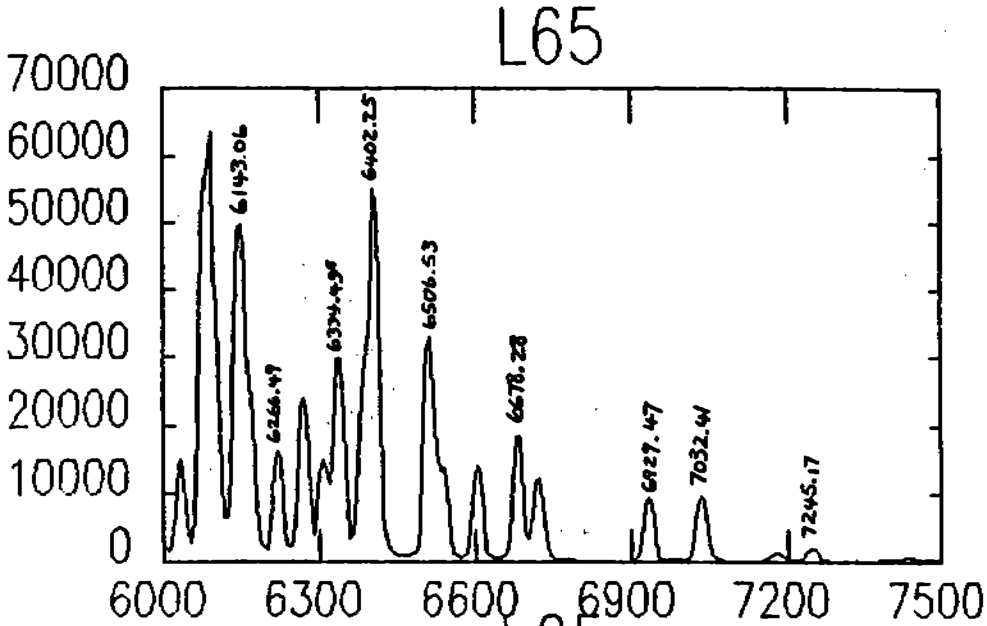
Red L65

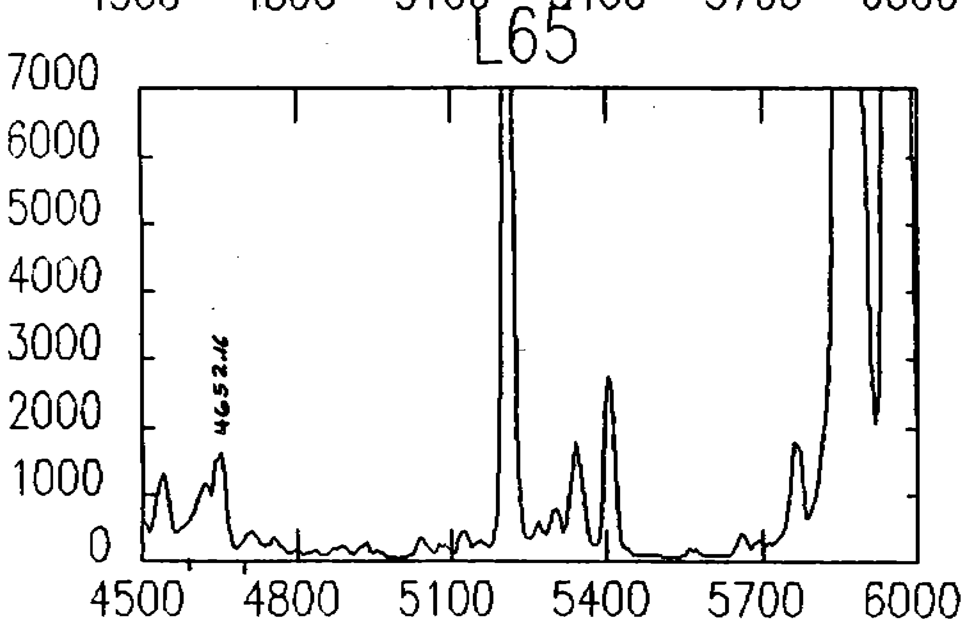


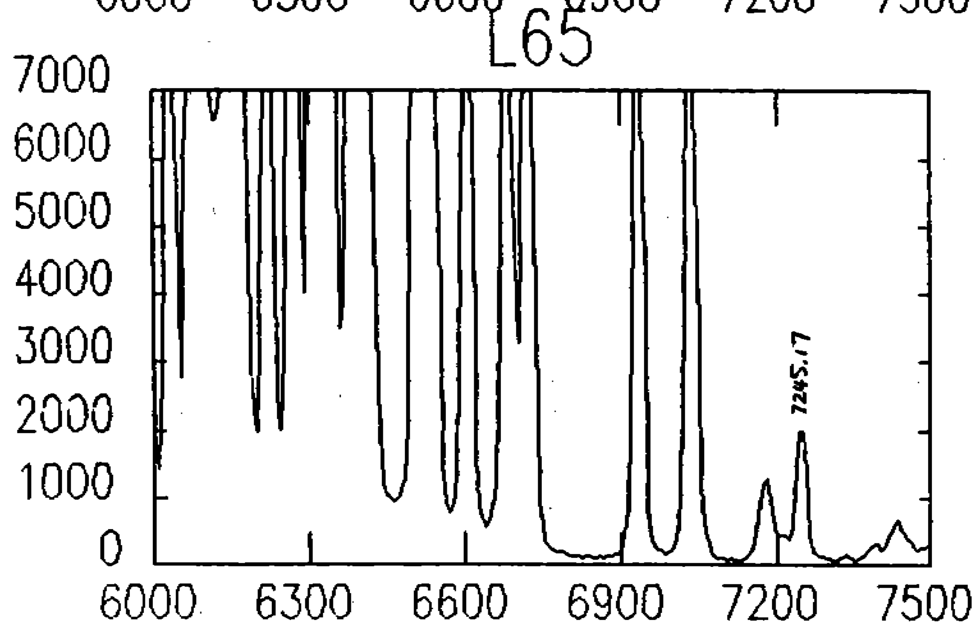
L65

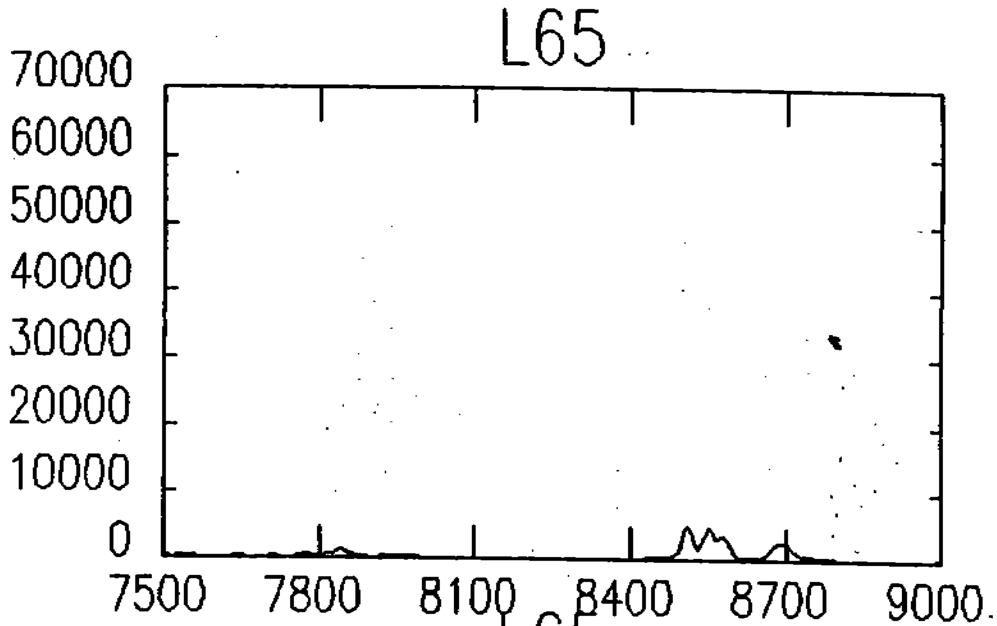


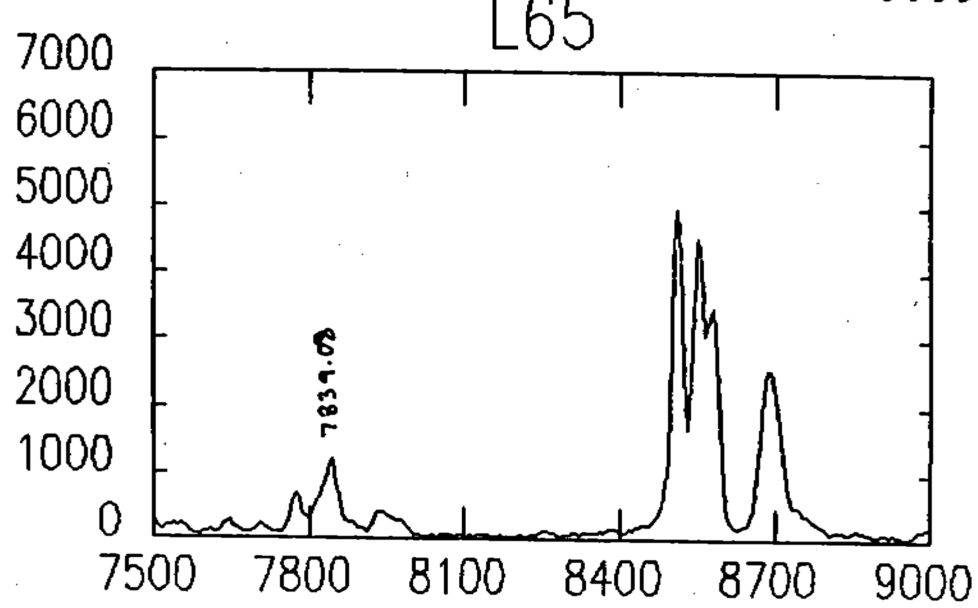

L65
5208.42
5852.49
5944.83
4500 4800 5100 5400 5700 6000


L65
6143.06
6266.49
6334.49
6402.25
6506.53
6678.28
6929.47
7032.41
7245.17
70000 60000 50000 40000 30000 20000 10000 0
6000 6300 6600 6900 7200 7500


L65
4652.16
7000 6000 5000 4000 3000 2000 1000 0
4500 4800 5100 5400 5700 6000


L65
7245.17
7000 6000 5000 4000 3000 2000 1000 0
6000 6300 6600 6900 7200 7500


L65
70000
60000
50000
40000
30000
20000
10000
0
7500
7800
8100
8400
8700
9000


L65
7000
6000
5000
4000
3000
2000
1000
0
7500
7800
8100
8400
8700
9000
7839.08