A High-Resolution Infrared Spectrum (2200-8800 cm^{-1}) of a Thorium-Argon-Neon Hollow-Cathode Lamp

A Th-Ar-Ne hollow cathode source was built into the Phoenix instrument-to-telescope interface unit for use in focusing and wavelength calibration. The hollow cathode is a commercial tube from Photron run at 10 milliamps. At the same time this hollow cathode was ordered a similar hollow cathode was purchased by the National Solar Observatory (NSO) for use at the McMath-Piece telescope. Mike Dulick (NSO), Dave Jaksha (NSO) and Peter Bernath (University of Waterloo) kindly observed the spectrum of this tube with the 1-m laboratory Fourier Transform Spectrometer. For this observation the tube was operated at 14 milliamps. The spectrum should be very similar to that of the Phoenix hollow cathode. This FTS spectrum (serial number 961113R0.002) provides a map of nearly the entire spectrum available with Phoenix, from 1.13 to almost 5 microns.

Plots (at the bottom of this page) were made by Lloyd Wallace, in collaboration with Ken Hinkle and Dick Joyce (all three KPNO). Brault's DECOMP, MONGO and various FORTRAN programs were used. The first plot is an introduction to the main set; it shows the complete spectrum at full resolution but compressed to a single page. The purpose is to show the prominent thermal continuum, the intervening absorption mostly by CO_2 around 2350 cm^{-1} and H_2 around 3755 cm^{-1}, the fringing on the thermal continuum which in this plot appears just to broaden the continuum, and the general increase in emission line strength and density from low frequency out to about 8000 cm^{-1}.

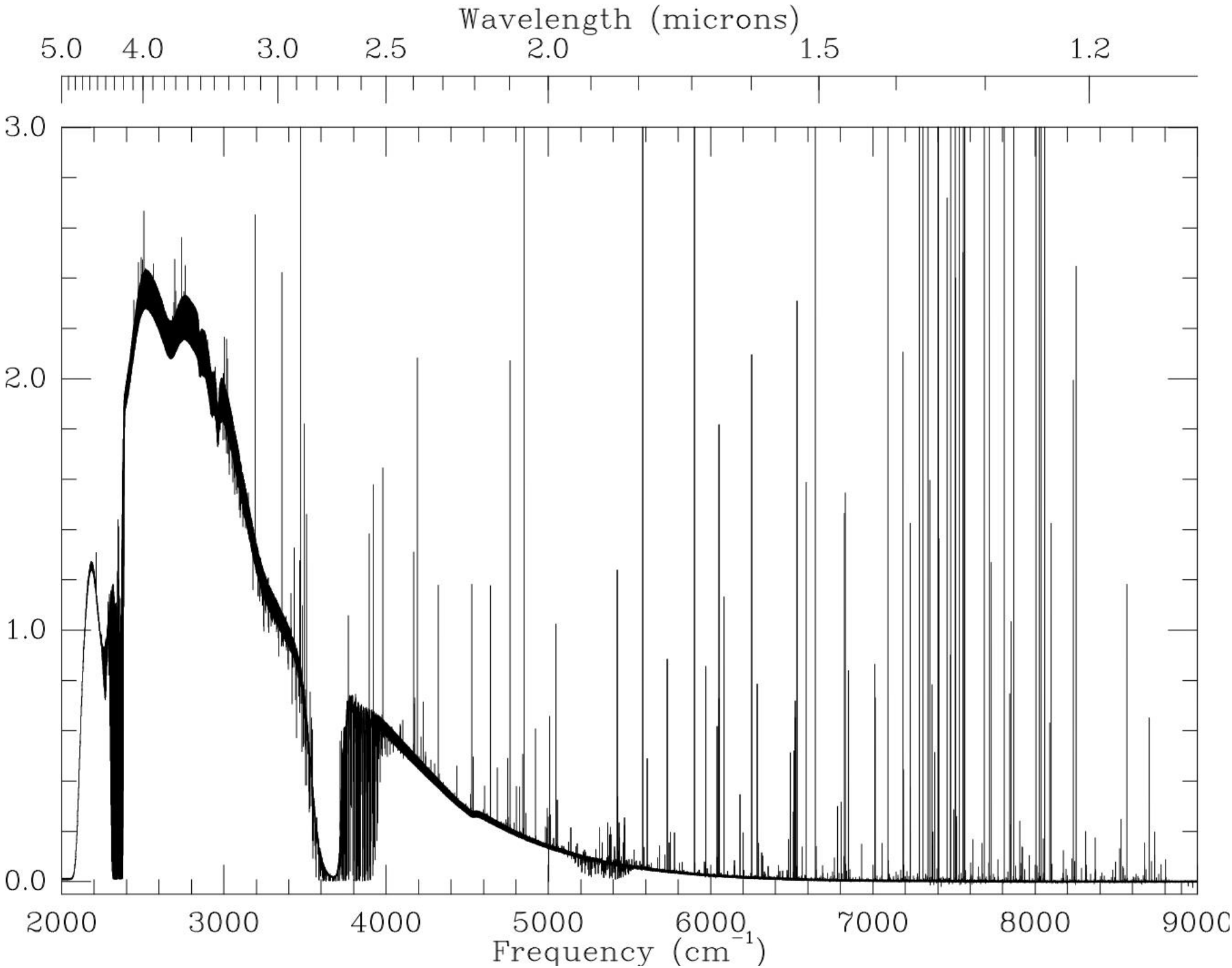
For the main body of the plots, we have apodized the spectrum and then determined the continuum level with its fringing and subtracted it off. The resolution of the apodized spectrum is 0.044 cm^{-1} (or λ / $\Delta\lambda$ ranging from 50000 at 2200 cm^{-1} to 200000 at 8800 cm^{-1}). The frequencies are from our measurements of this spectrum and the identifications are from the compilation of Outred (1978, J. Phys. Chem. Ref. Data, 7, 1) with updates for Ar I by Palmeri and Biemont (1995, Physica Scripta, 51, 76) and Ne I by Chang and Schoenfeld (1994, Physica Scripta, 49, 26). The sparse work an atomic spectra below ~ 2400 cm^{-1} is the reason for the many lines labeled "Unid".

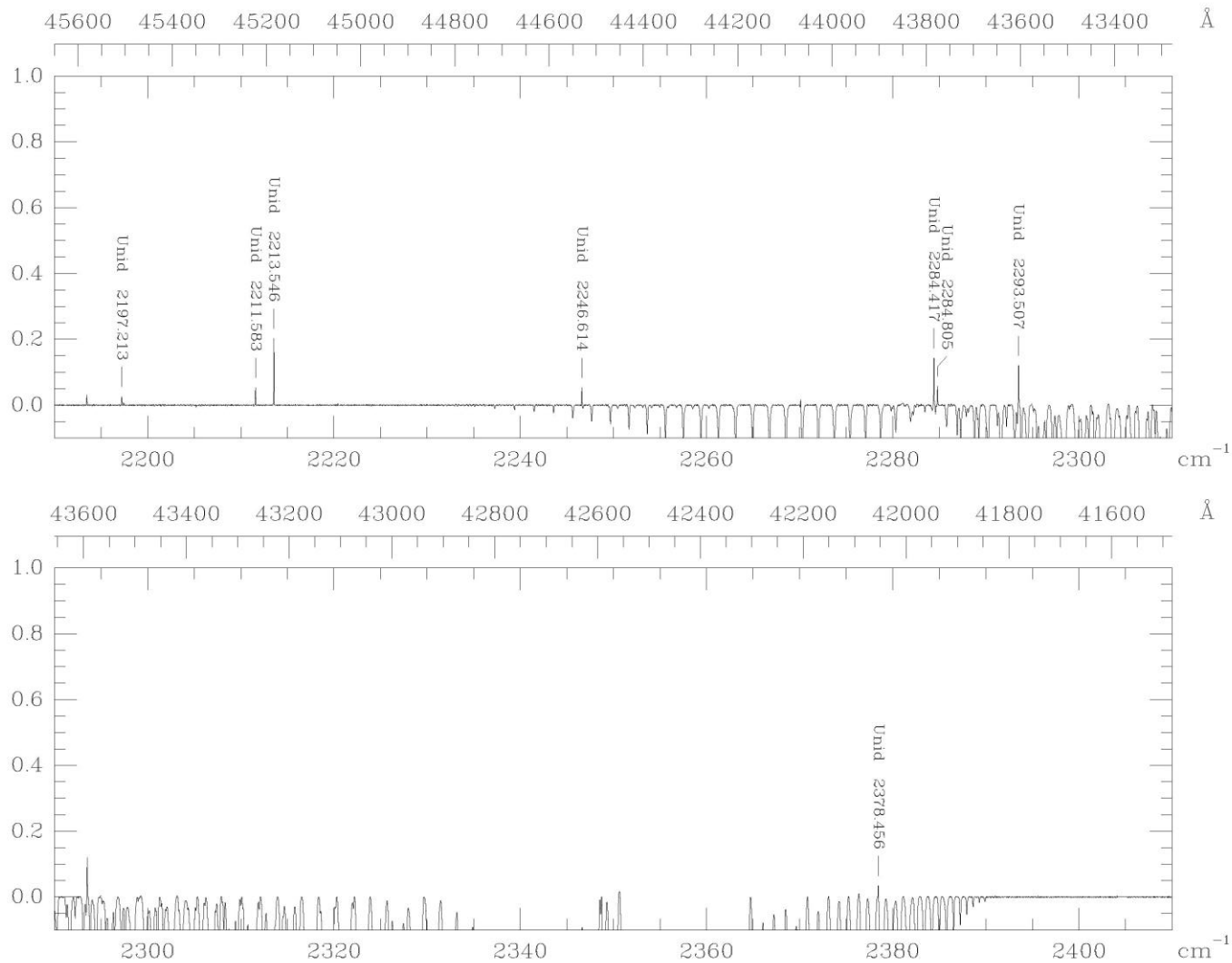
We have labeled the lines with emitter if known, the frequency, and if the line goes off scale, the line intensity on the scale of the plots in square brackets. Thus, the strongest line on the plots is "Ar I 7287.394 [44.1]". The intensity scale is "as observed" (and thus includes the transmission of the various optical elements in the FTS and the lamp window) divided by 3.e7. All of the plots are on the same scale so plots in adjacent bands are directly comparable.

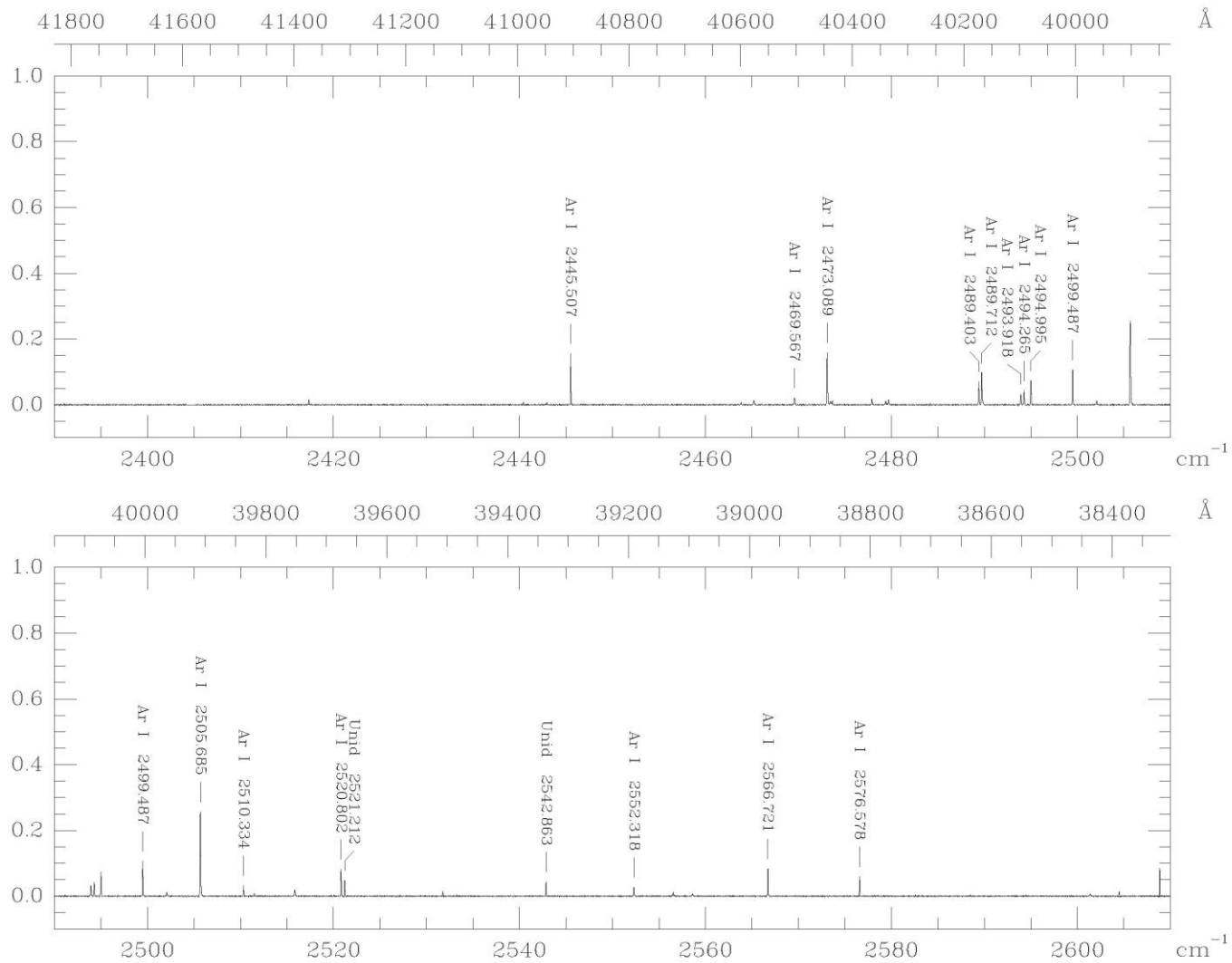
Lower resolution plots of a similar lamp have been made by Dick Joyce. The high resolution atlas by Palmer and Engleman (1983, Los Alamos National Laboratory # 9615) of a Thorium-Neon lamp covers the region from 7400 to around 36000 cm^{-1}. The spectrum presented here consists in large part of argon and neon lines. The thorium lines present are weak. A much more fully developed infrared thorium spectrum can be seen in a Th-Ar hollow cathode FTS spectrum taken by Engleman at a cathode destroying current of 320 milliamps (FTS # 820519R0.001).

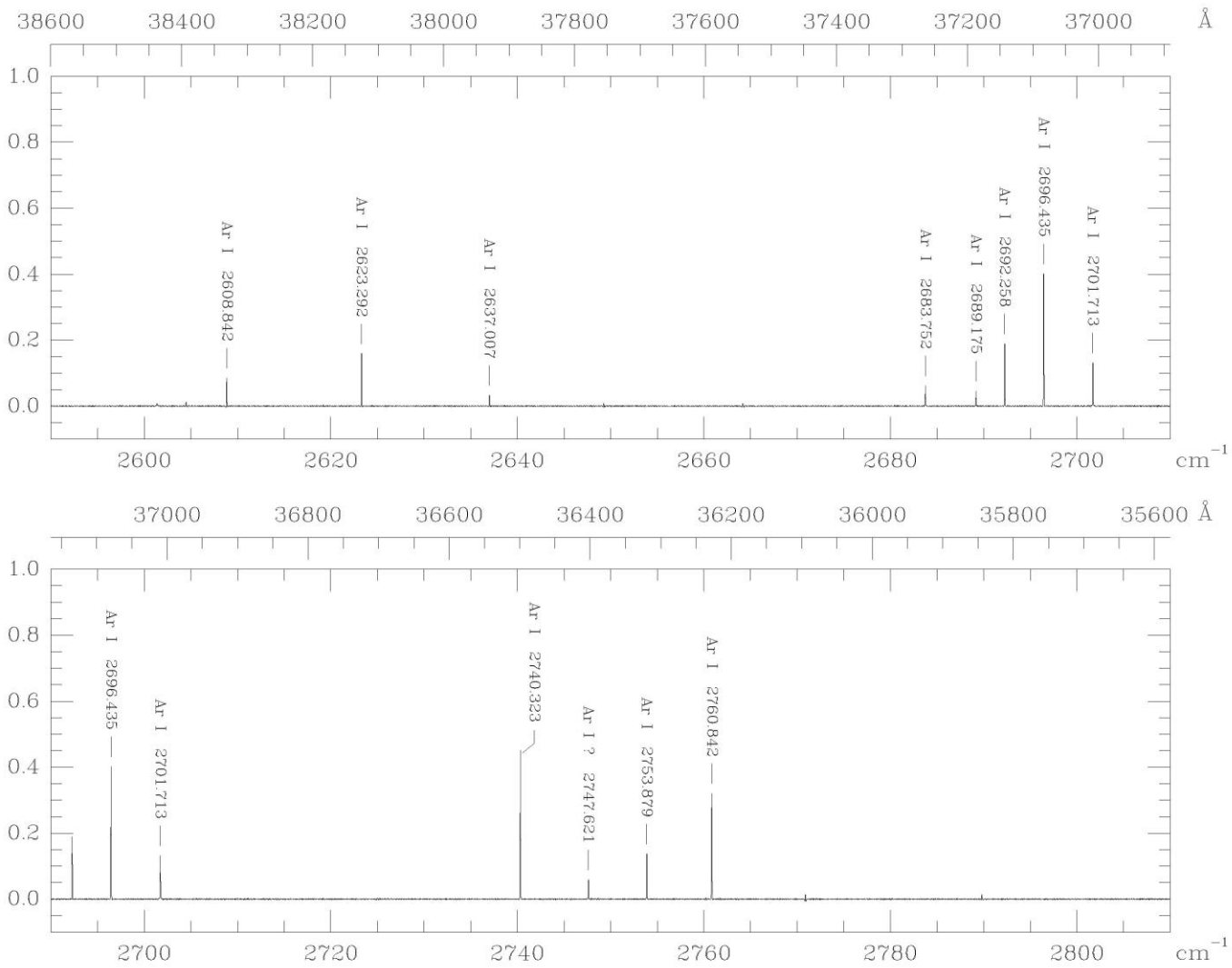
L.W. & K.H., December 1996

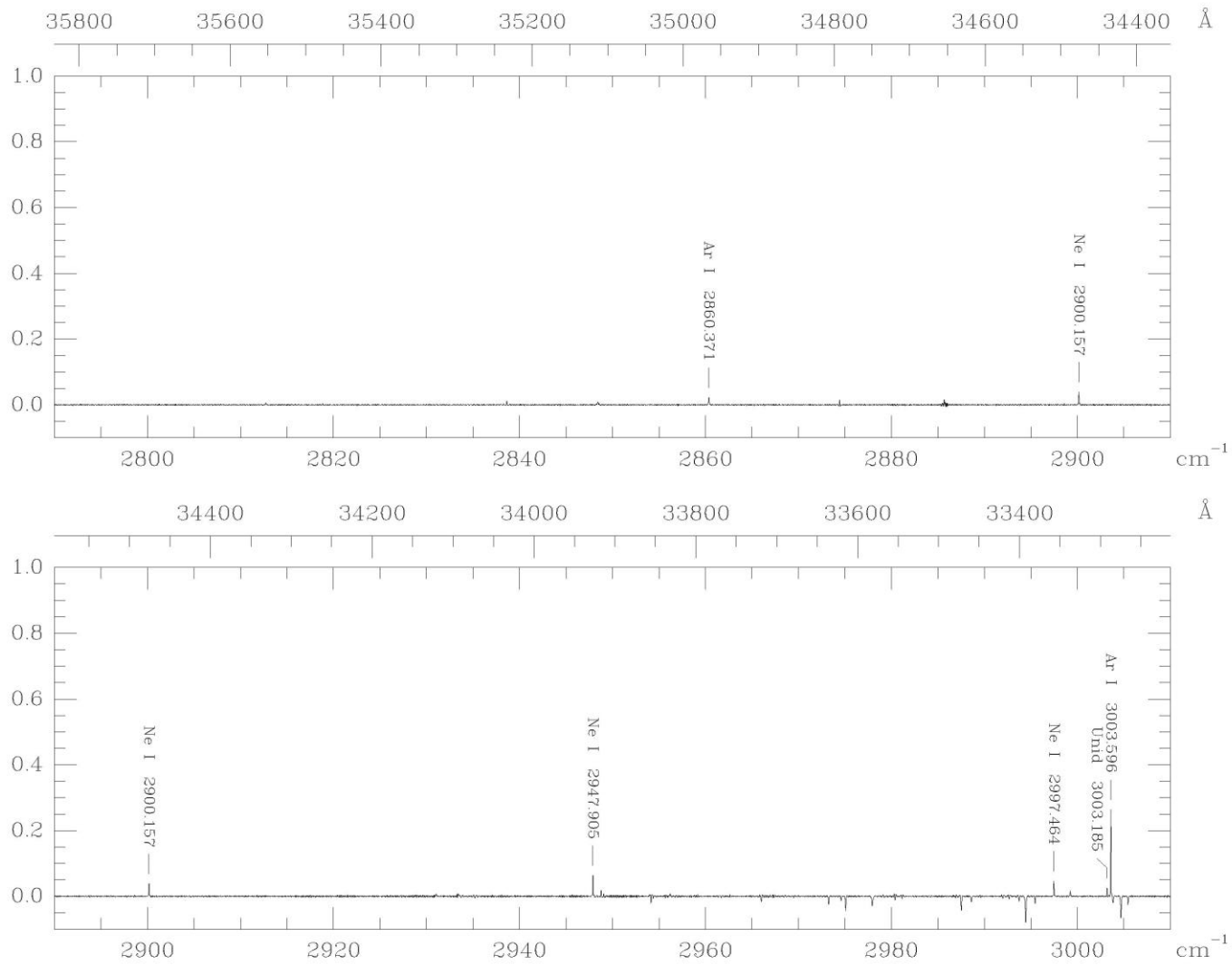
Low Disperion Overview			
2200-2400	2400-2600	2600-2800	2800-3000
3000-3200	3200-3400	3400-3600	3600-3800
3800-4000	4000-4200	4200-4400	4400-4600
4600-4800	4800-5000	5000-5200	5200-5400
5400-5600	5600-5800	5800-6000	6000-6200
6200-6400	6400-6600	6600-6800	6800-7000
7000-7200	7200-7400	7400-7600	7600-7800
7800-8000	8000-8200	8200-8400	8400-8600
8600-8800			

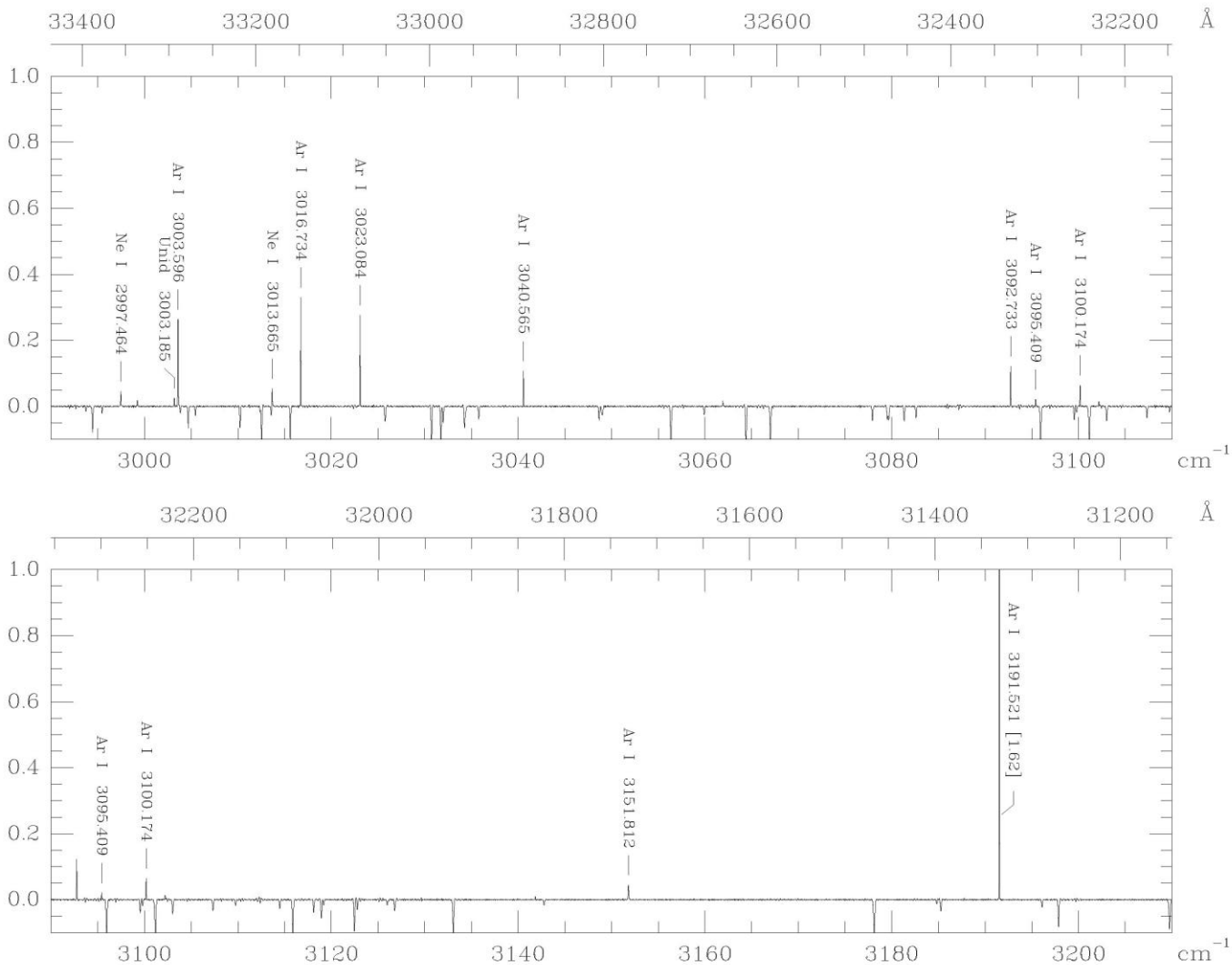

Wavelength (microns)
5.0
4.0
3.0
2.5
2.0
1.5
1.2
3.0
2.0
1.0
0.0
2000
3000
4000
5000
6000
7000
8000
9000
Frequency (cm^{-1})

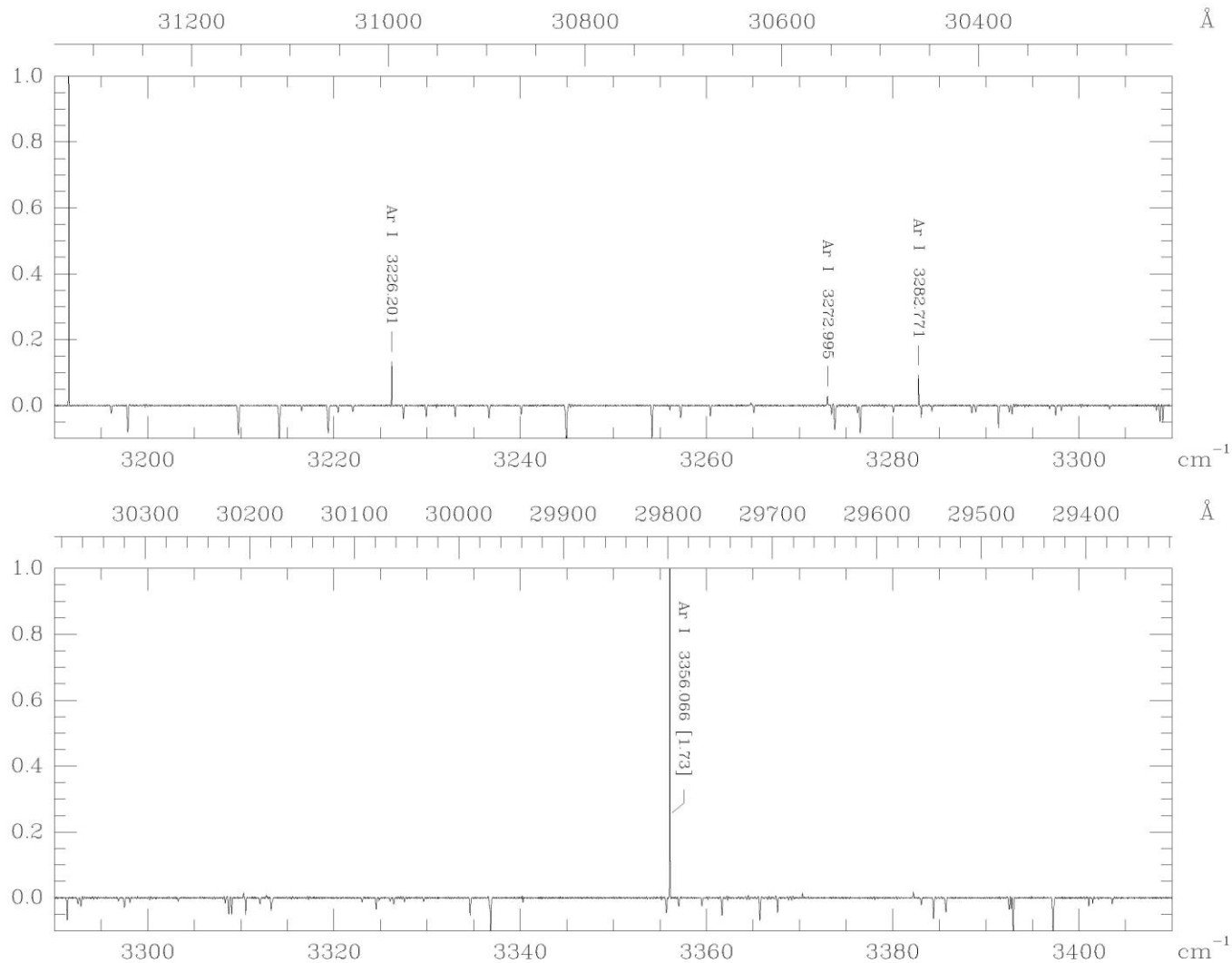

45600 45400 45200 45000 44800 44600 44400 44200 44000 43800 43600 43400 Å
1.0
0.8
0.6
0.4
0.2
0.0
Unid 2197.213
Unid 2211.583
Unid 2213.546
Unid 2246.614
Unid 2284.417
Unid 2284.805
Unid 2293.507
2200 2220 2240 2260 2280 2300 cm^{-1}
43600 43400 43200 43000 42800 42600 42400 42200 42000 41800 41600 Å
1.0
0.8
0.6
0.4
0.2
0.0
Unid 2378.456
2300 2320 2340 2360 2380 2400 cm^{-1}

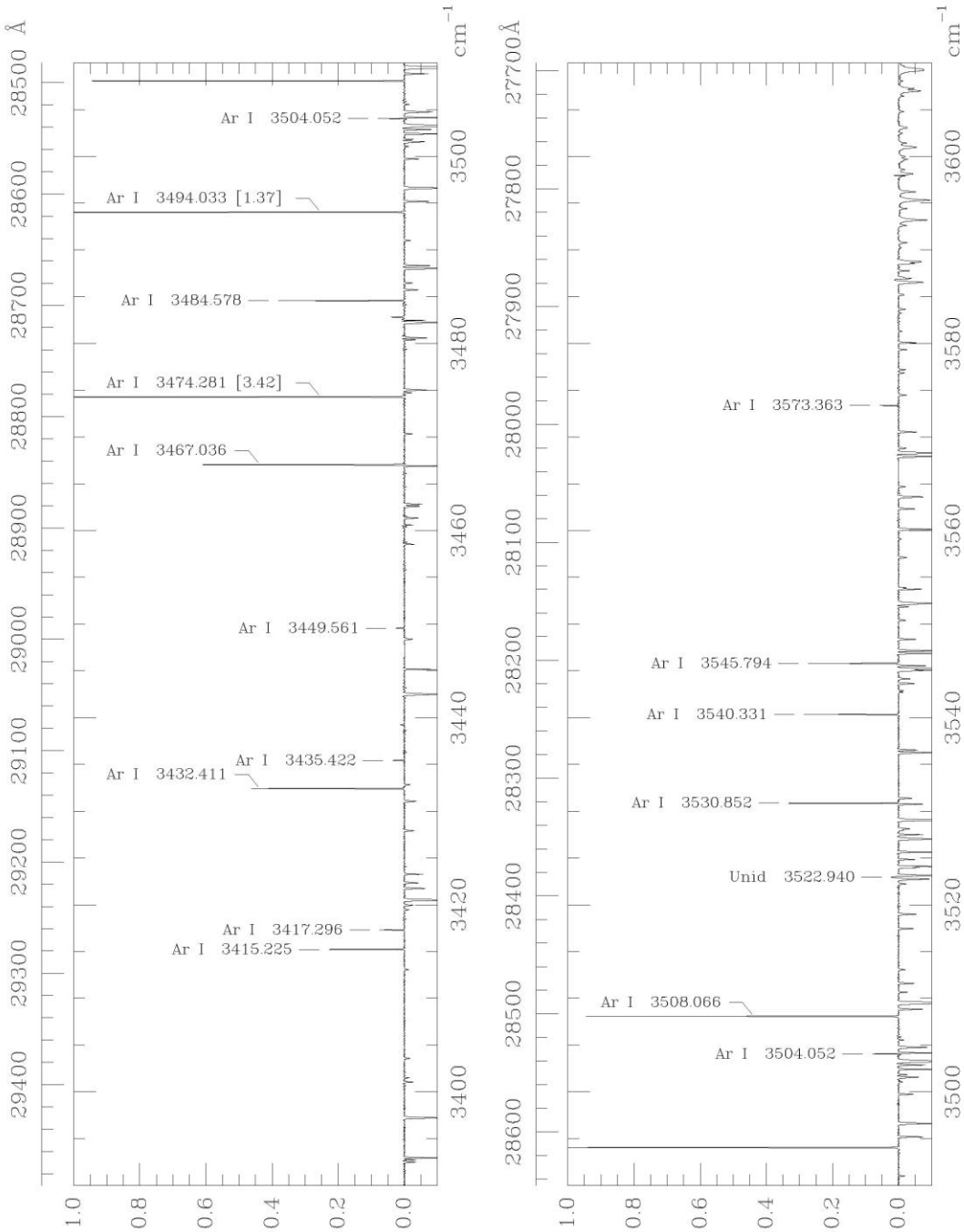

41800 41600 41400 41200 41000 40800 40600 40400 40200 40000 Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 2445.507
Ar I 2469.567
Ar I 2473.089
Ar I 2489.403
Ar I 2489.712
Ar I 2493.918
Ar I 2494.265
Ar I 2494.995
Ar I 2499.487
2400 2420 2440 2460 2480 2500 cm^{-1}
40000 39800 39600 39400 39200 39000 38800 38600 38400 Å
Ar I 2499.487
Ar I 2505.685
Ar I 2510.334
Unid 2521.212
Ar I 2520.802
Unid 2542.863
Ar I 2552.318
Ar I 2566.721
Ar I 2576.578
2500 2520 2540 2560 2580 2600 cm^{-1}

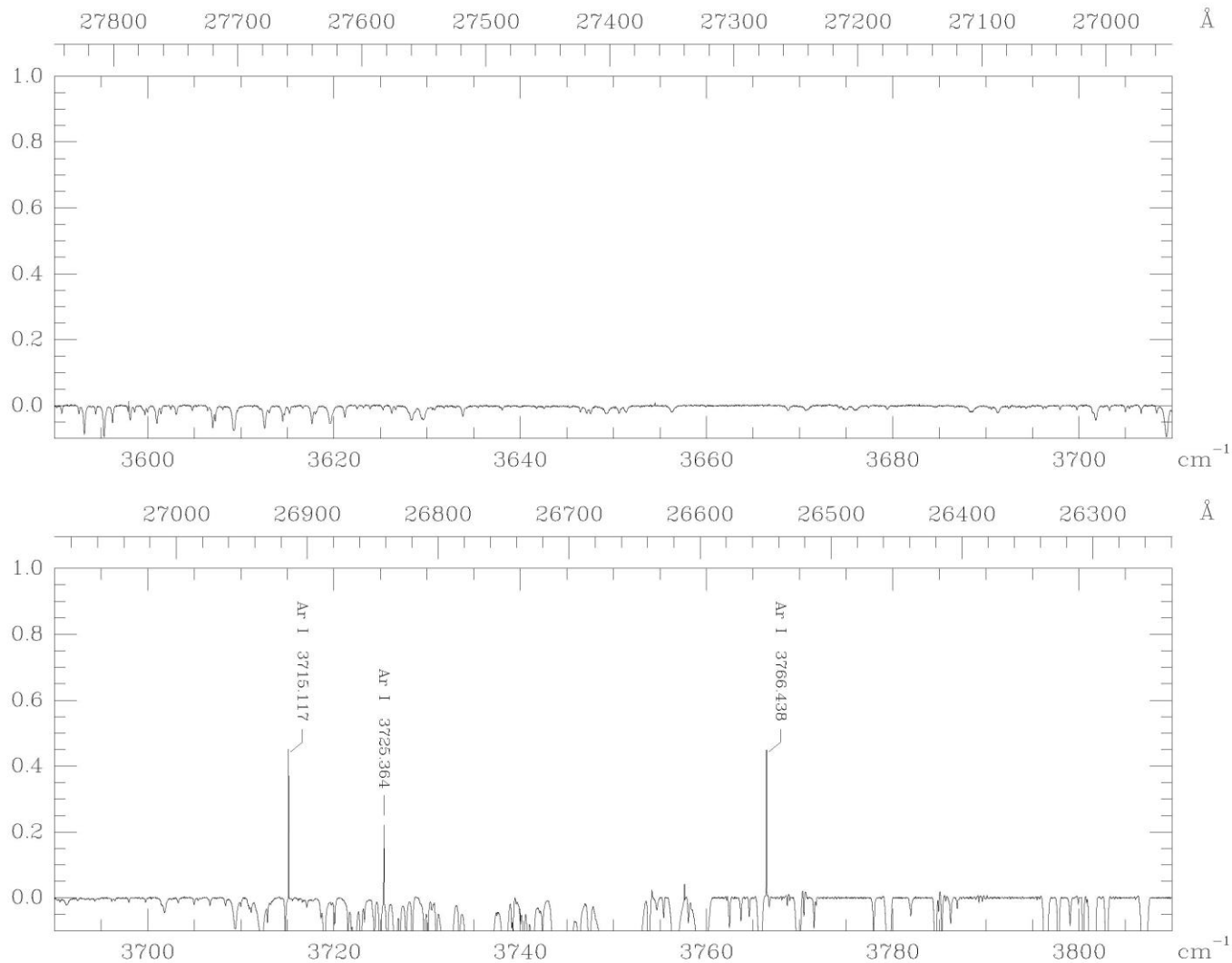

38600 38400 38200 38000 37800 37600 37400 37200 37000 Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 2608.842
Ar I 2623.292
Ar I 2637.007
Ar I 2683.752
Ar I 2689.175
Ar I 2692.258
Ar I 2696.435
Ar I 2701.713
2600 2620 2640 2660 2680 2700 cm^{-1}
37000 36800 36600 36400 36200 36000 35800 35600 Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 2696.435
Ar I 2701.713
Ar I 2740.323
Ar I ? 2747.621
Ar I 2753.879
Ar I 2760.842
2700 2720 2740 2760 2780 2800 cm^{-1}

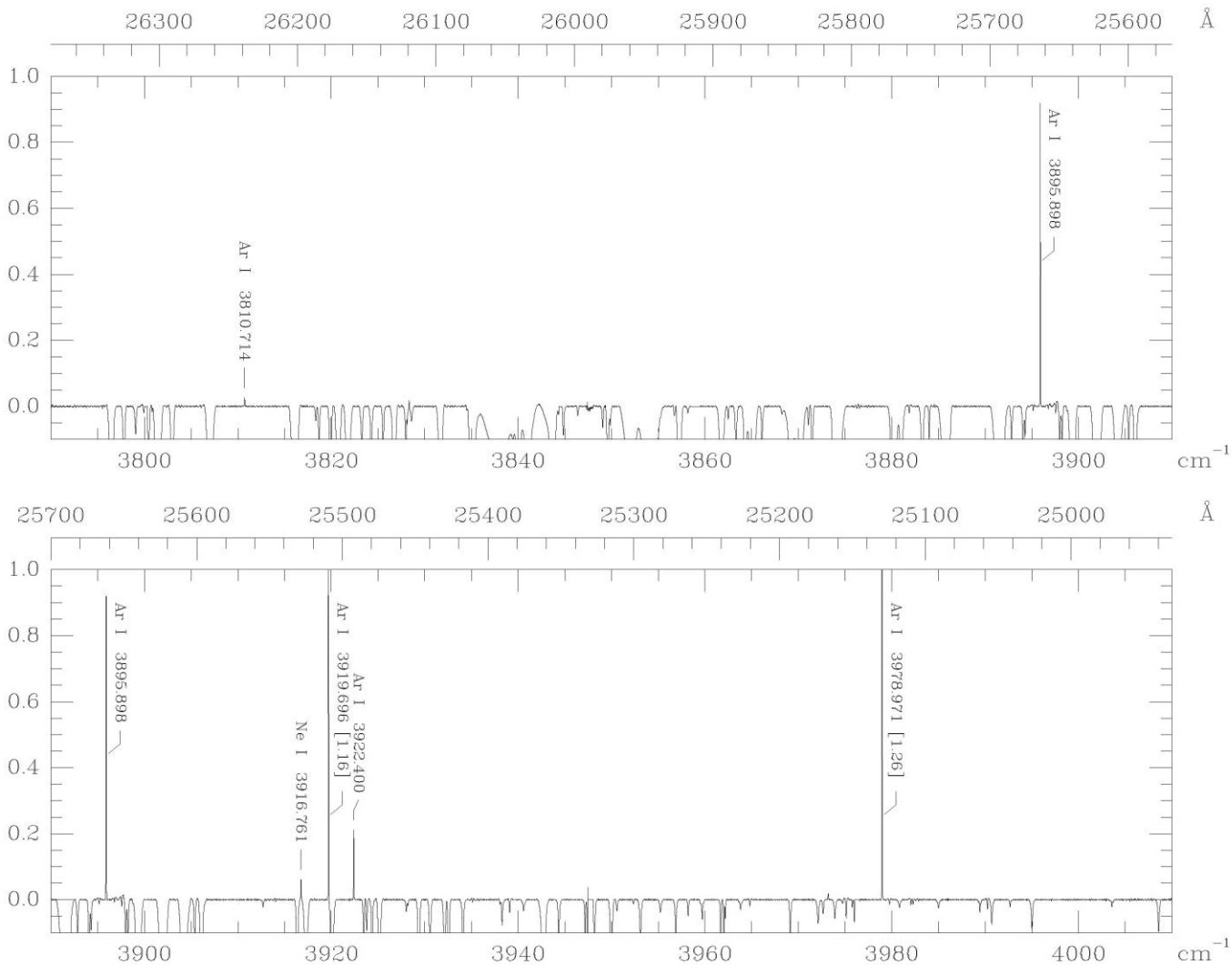

35800
35600
35400
35200
35000
34800
34600
34400
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 2860.371
Ne I 2900.157
2800
2820
2840
2860
2880
2900
cm^{-1}
34400
34200
34000
33800
33600
33400
Å
Ne I 2900.157
Ne I 2947.905
Ne I 2997.464
Ar I 3003.596
Unid 3003.185
2900
2920
2940
2960
2980
3000
cm^{-1}

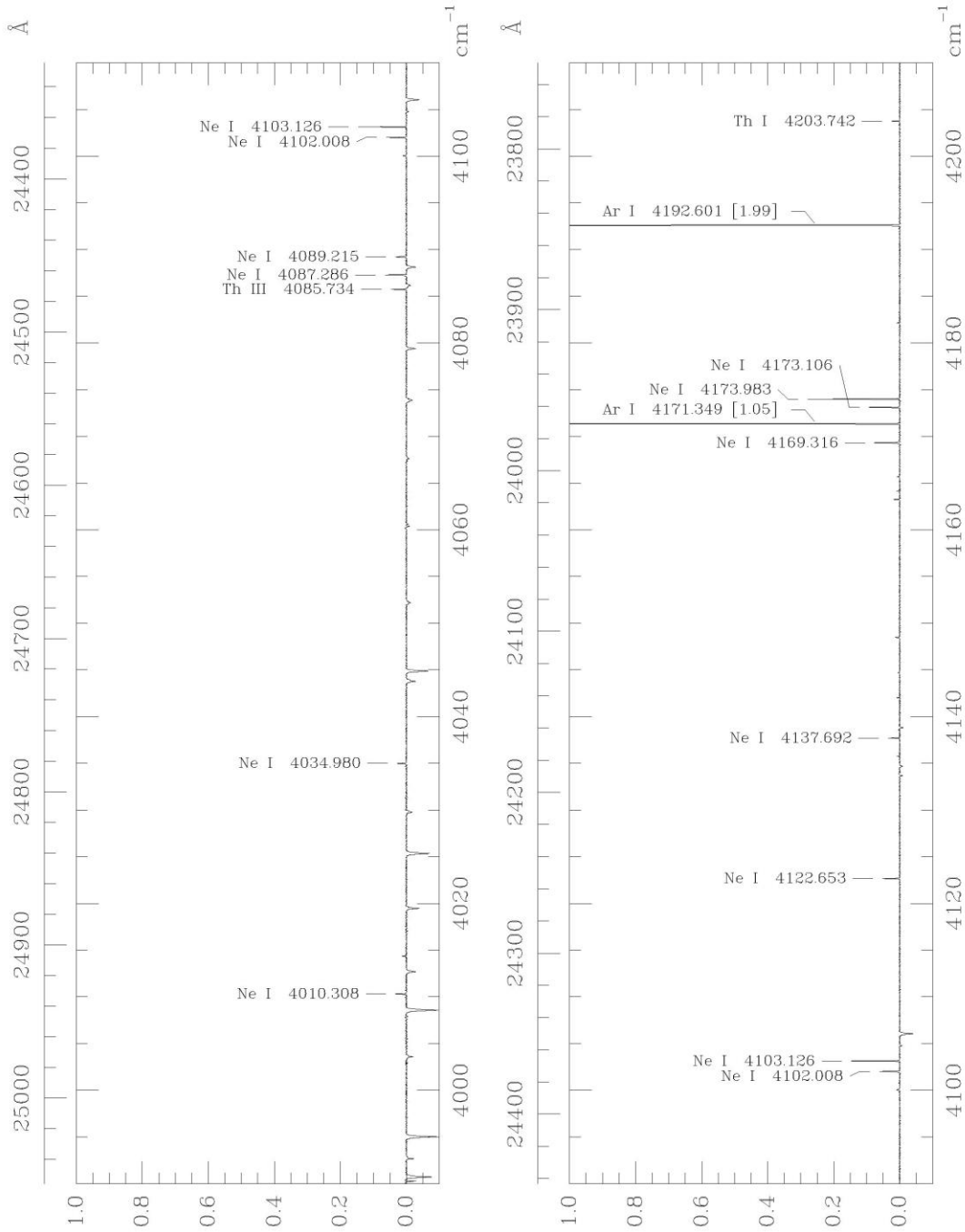

33400
33200
33000
32800
32600
32400
32200
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ne I 2997.464
Ar I 3003.596
Unid 3003.185
Ne I 3013.665
Ar I 3016.734
Ar I 3023.084
Ar I 3040.565
Ar I 3092.733
Ar I 3095.409
Ar I 3100.174
3000
3020
3040
3060
3080
3100
cm^{-1}
32200
32000
31800
31600
31400
31200
Å
Ar I 3095.409
Ar I 3100.174
Ar I 3151.812
Ar I 3191.521 [1.62]
3100
3120
3140
3160
3180
3200
cm^{-1}

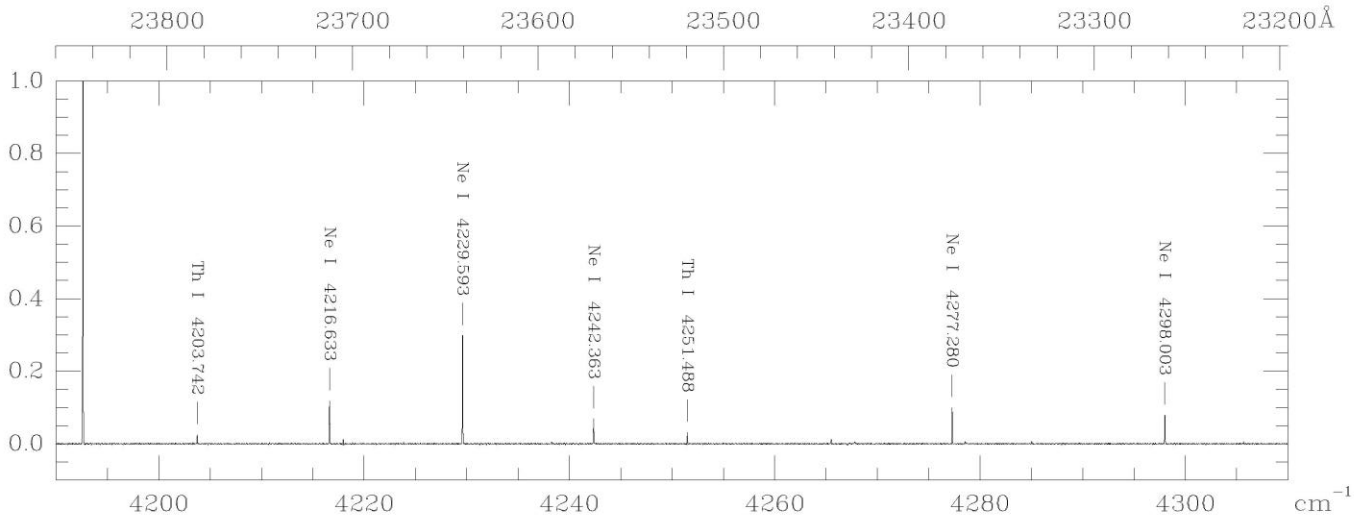

31200
31000
30800
30600
30400
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 3226.201
Ar I 3272.995
Ar I 3282.771
3200
3220
3240
3260
3280
3300
cm^{-1}
30300
30200
30100
30000
29900
29800
29700
29600
29500
29400
Å
Ar I 3356.066 [1.73]
3300
3320
3340
3360
3380
3400
cm^{-1}

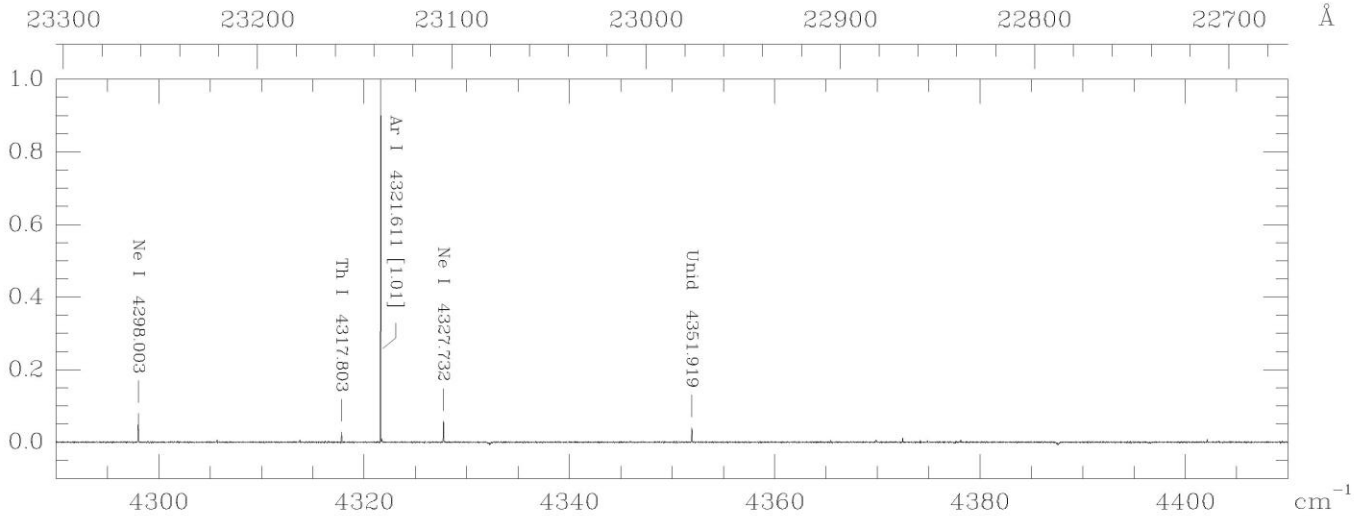

Å
cm^{-1}
Ar I 3504.052
Ar I 3494.033 [1.37]
Ar I 3484.578
Ar I 3474.281 [3.42]
Ar I 3467.036
Ar I 3449.561
Ar I 3435.422
Ar I 3432.411
Ar I 3417.296
Ar I 3415.225
Ar I 3573.363
Ar I 3545.794
Ar I 3540.331
Ar I 3530.852
Unid 3522.940
Ar I 3508.066
Ar I 3504.052

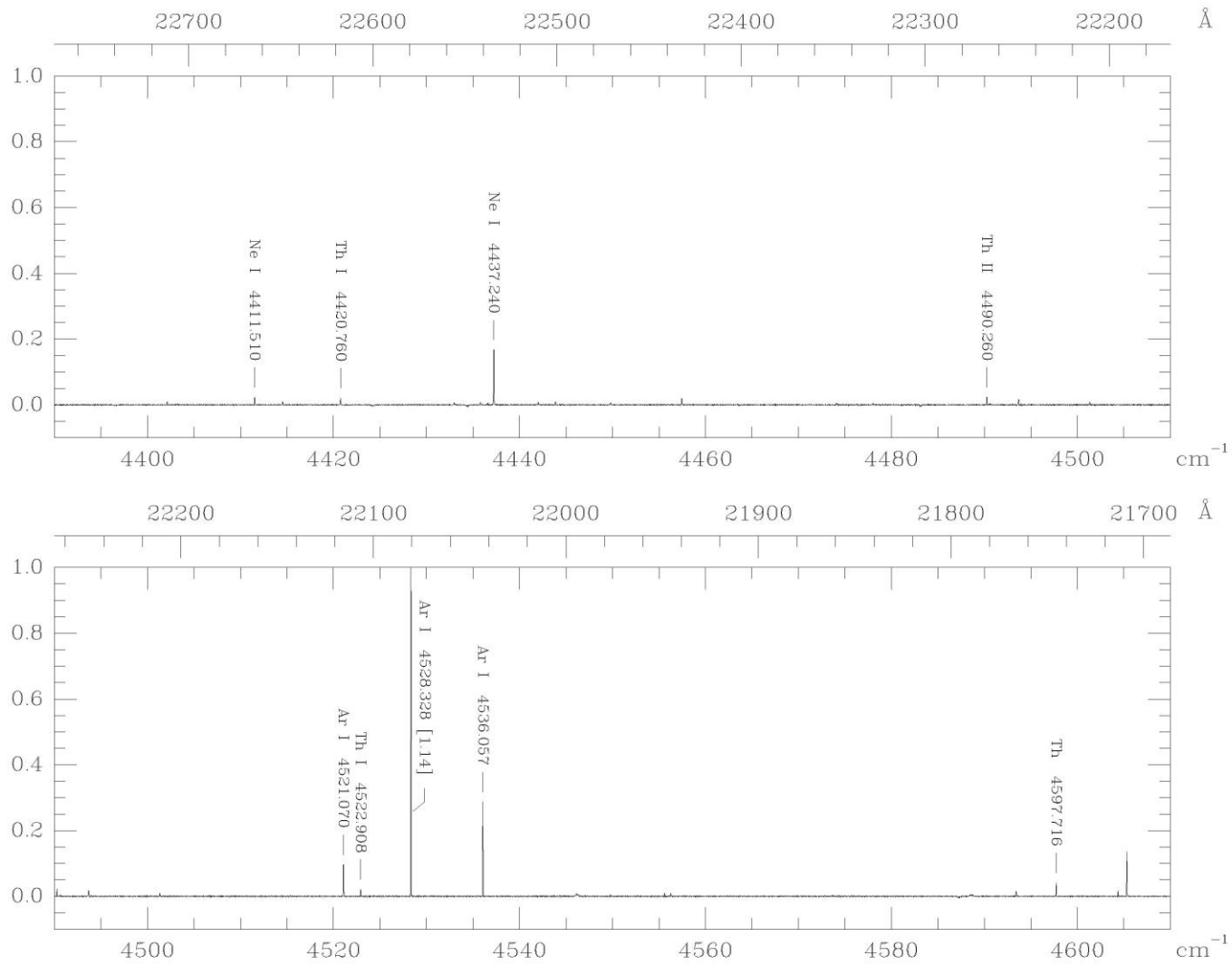

27800
27700
27600
27500
27400
27300
27200
27100
27000
Å
1.0
0.8
0.6
0.4
0.2
0.0
3600
3620
3640
3660
3680
3700
cm^{-1}
27000
26900
26800
26700
26600
26500
26400
26300
Å
Ar I 3715.117
Ar I 3725.364
Ar I 3766.438
3700
3720
3740
3760
3780
3800
cm^{-1}

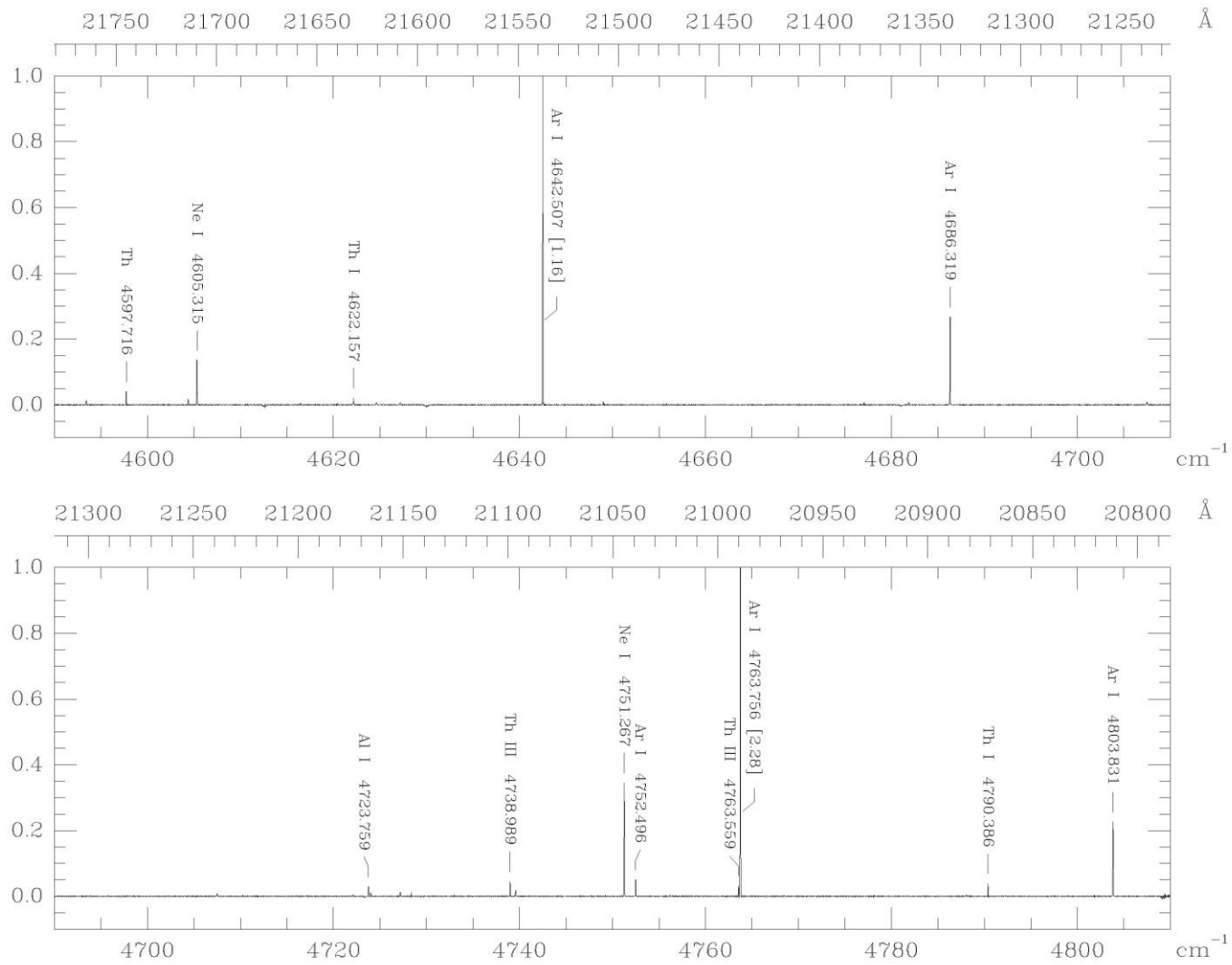

26300
26200
26100
26000
25900
25800
25700
25600
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 3810.714
Ar I 3895.898
3800
3820
3840
3860
3880
3900
cm^{-1}
25700
25600
25500
25400
25300
25200
25100
25000
Å
Ar I 3895.898
Ne I 3916.761
Ar I 3919.696 [1.16]
Ar I 3922.400
Ar I 3978.971 [1.26]
3900
3920
3940
3960
3980
4000
cm^{-1}

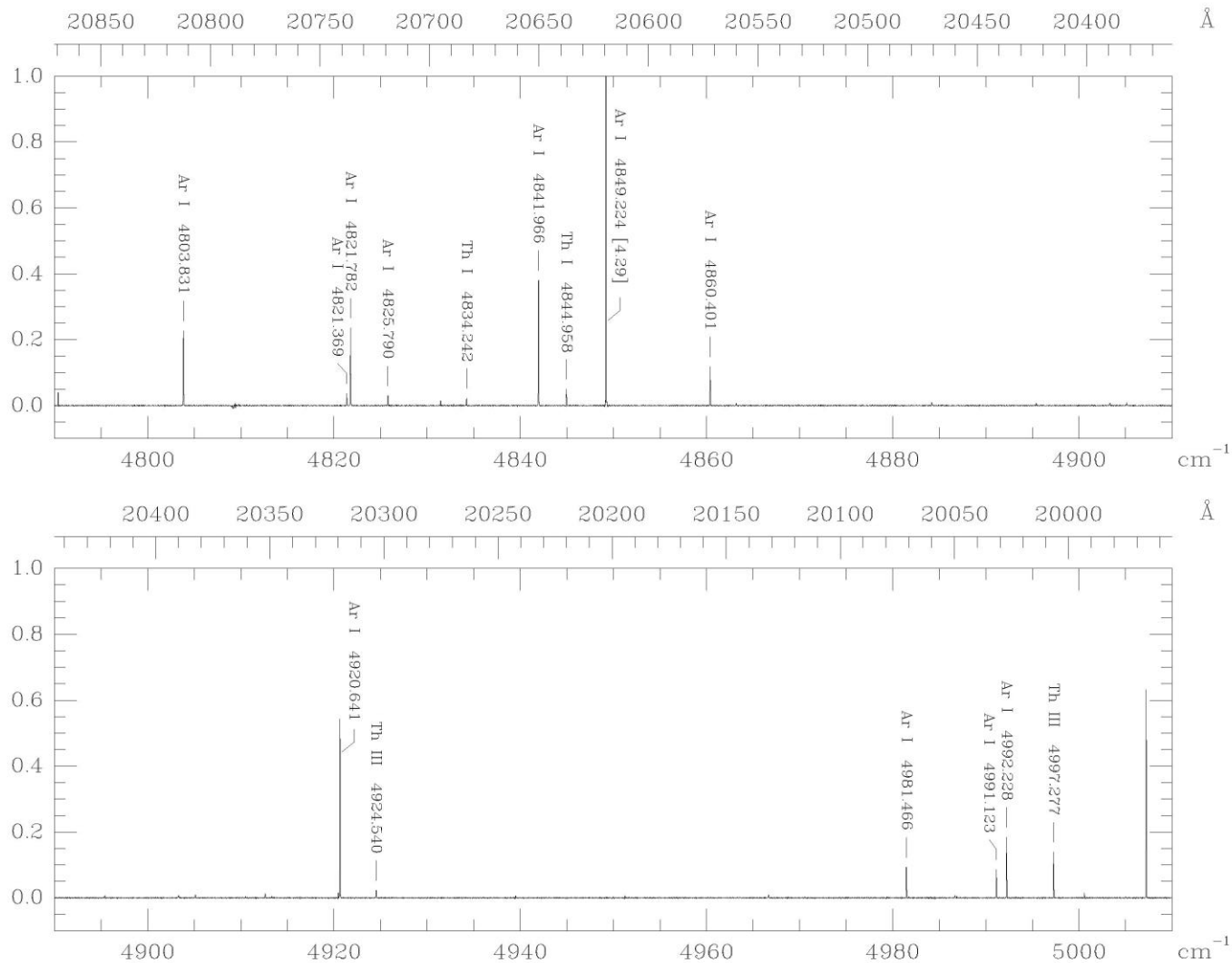

Å
cm^{-1}
Ne I 4103.126
Ne I 4102.008
Ne I 4089.215
Ne I 4087.286
Th III 4085.734
Ne I 4034.980
Ne I 4010.308
Th I 4203.742
Ar I 4192.601 [1.99]
Ne I 4173.106
Ne I 4173.983
Ar I 4171.349 [1.05]
Ne I 4169.316
Ne I 4137.692
Ne I 4122.653
Ne I 4103.126
Ne I 4102.008

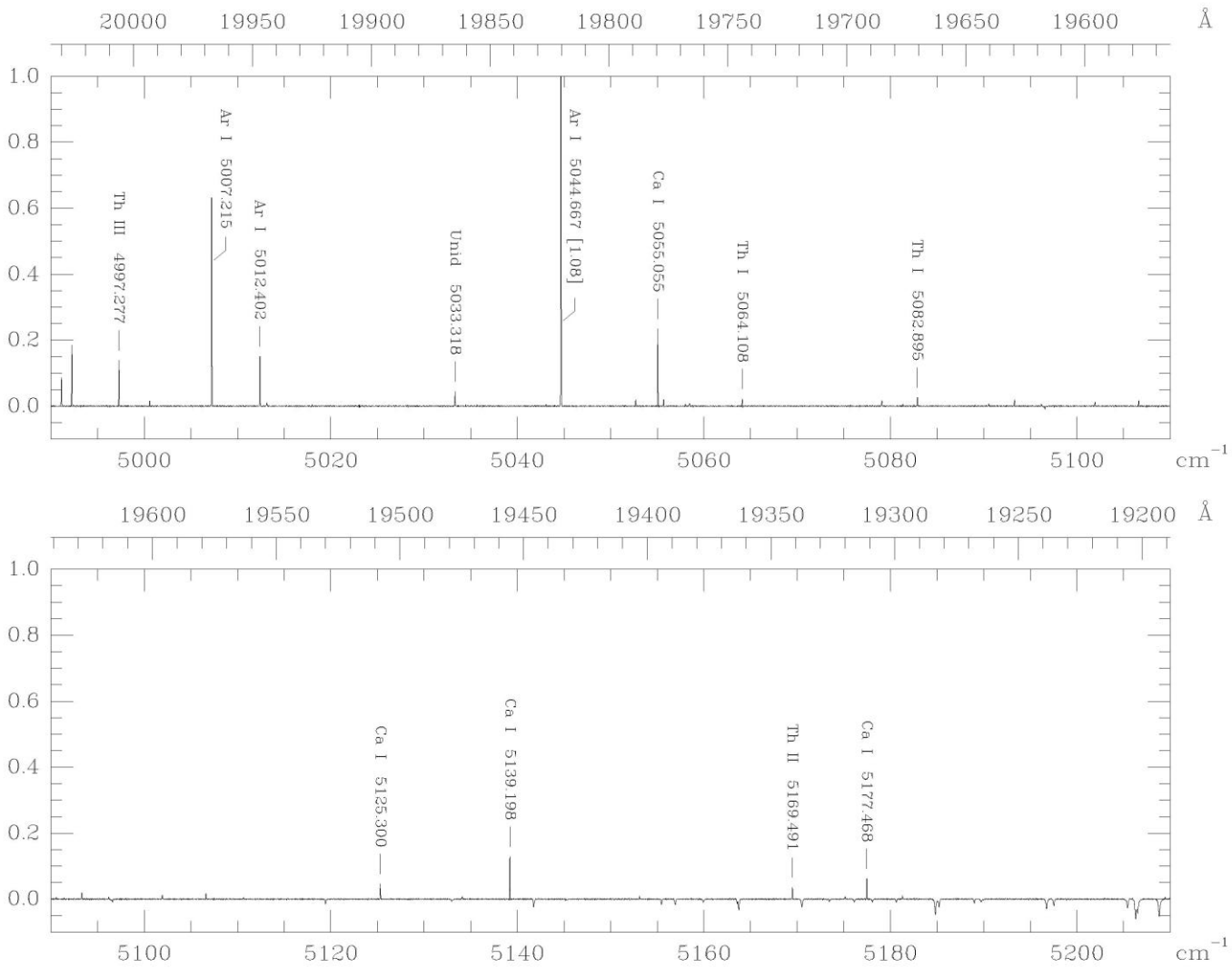

23800
23700
23600
23500
23400
23300
23200Å
1.0
0.8
0.6
0.4
0.2
0.0
Th I 4203.742
Ne I 4216.633
Ne I 4229.593
Ne I 4242.363
Th I 4251.488
Ne I 4277.280
Ne I 4298.003
4200
4220
4240
4260
4280
4300
cm^{-1}

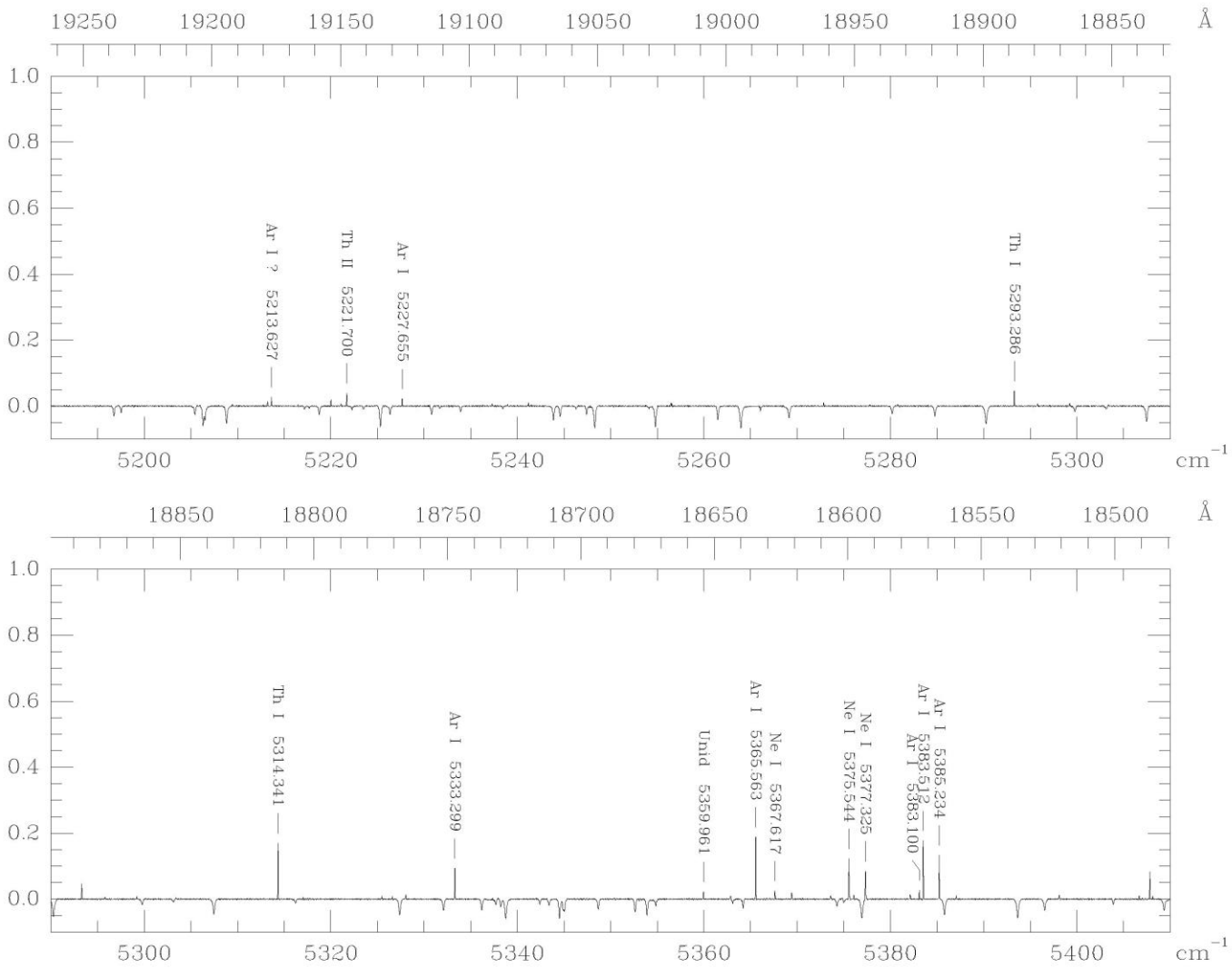

23300
23200
23100
23000
22900
22800
22700
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ne I 4298.003
Th I 4317.803
Ar I 4321.611 [1.01]
Ne I 4327.732
Unid 4351.919
4300
4320
4340
4360
4380
4400
cm^{-1}

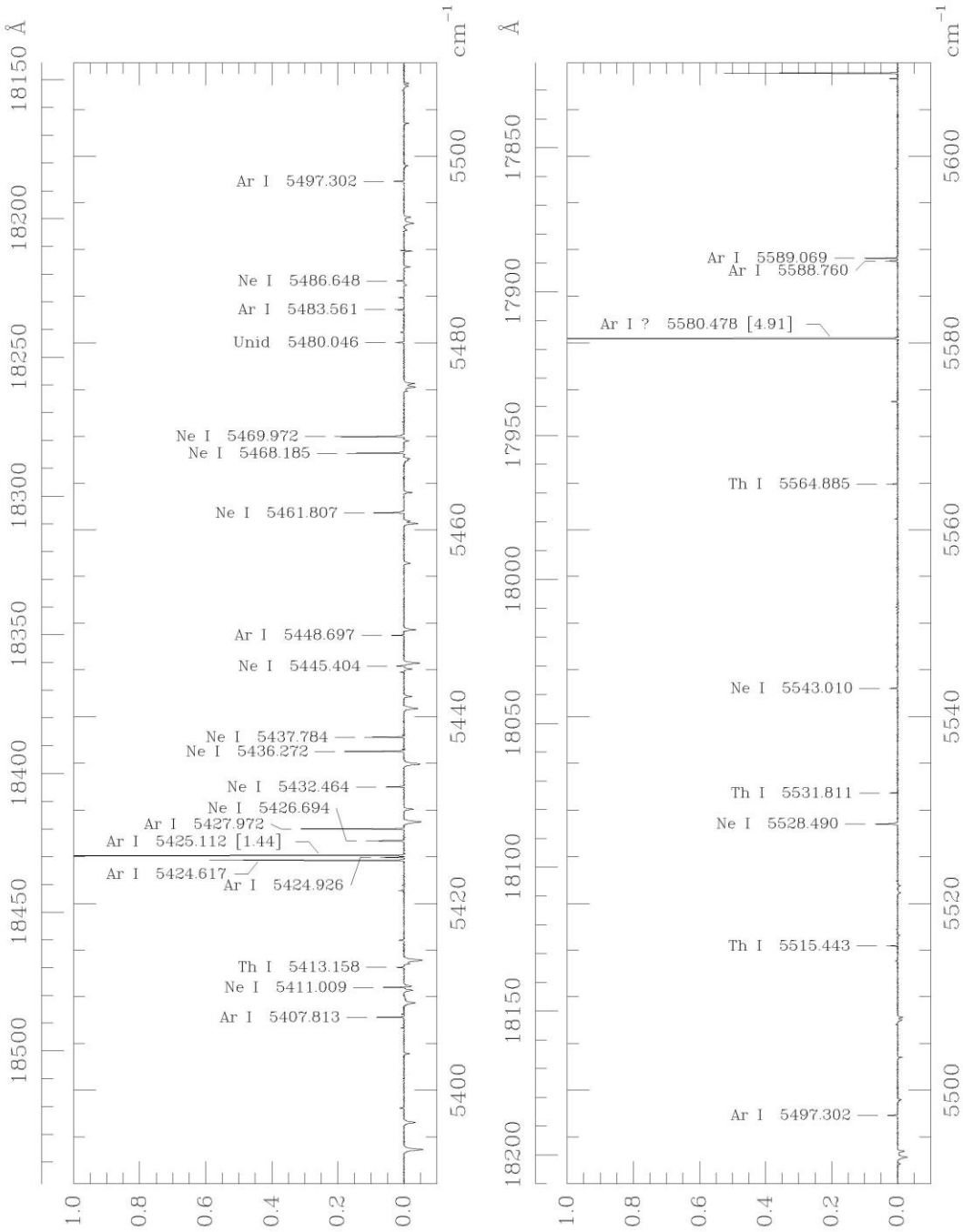

22700
22600
22500
22400
22300
22200
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ne I 4411.510
Th I 4420.760
Ne I 4437.240
Th II 4490.260
4400
4420
4440
4460
4480
4500
cm^{-1}
22200
22100
22000
21900
21800
21700
Å
Th I 4522.908
Ar I 4521.070
Ar I 4528.328 [1.14]
Ar I 4536.057
Th 4597.716
4500
4520
4540
4560
4580
4600
cm^{-1}

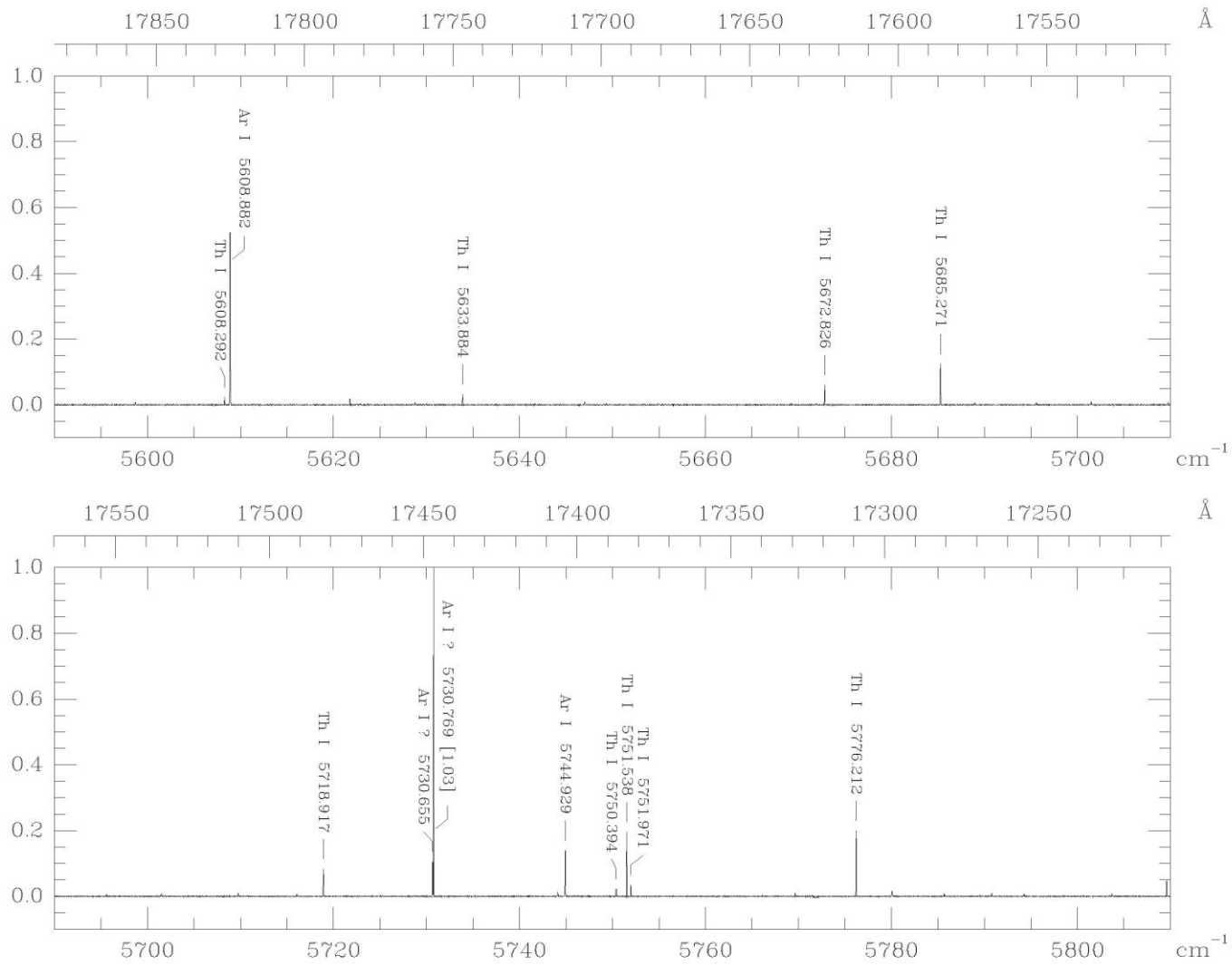

Å
cm^{-1}
Th 4597.716
Ne I 4605.315
Th I 4622.157
Ar I 4642.507 [1.16]
Ar I 4686.319
Al I 4723.759
Th III 4738.989
Ne I 4751.267
Ar I 4752.496
Th III 4763.559
Ar I 4763.756 [2.28]
Th I 4790.386
Ar I 4803.831

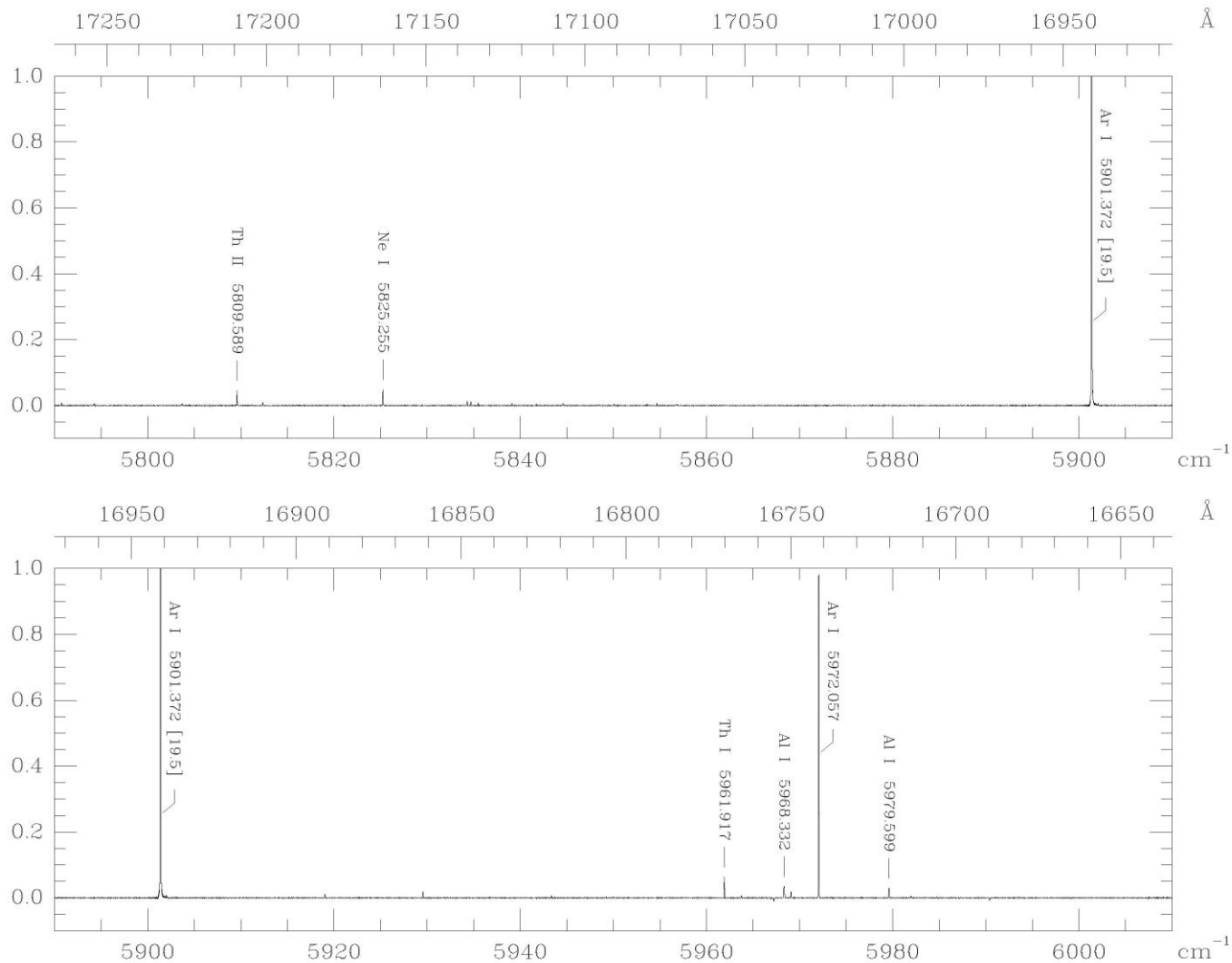

20850 20800 20750 20700 20650 20600 20550 20500 20450 20400 Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 4803.831
Ar I 4821.782
Ar I 4821.369
Ar I 4825.790
Th I 4834.242
Ar I 4841.966
Th I 4844.958
Ar I 4849.224 [4.29]
Ar I 4860.401
4800 4820 4840 4860 4880 4900 cm^{-1}
20400 20350 20300 20250 20200 20150 20100 20050 20000 Å
Ar I 4920.641
Th III 4924.540
Ar I 4981.466
Ar I 4991.123
Ar I 4992.228
Th III 4997.277
4900 4920 4940 4960 4980 5000 cm^{-1}

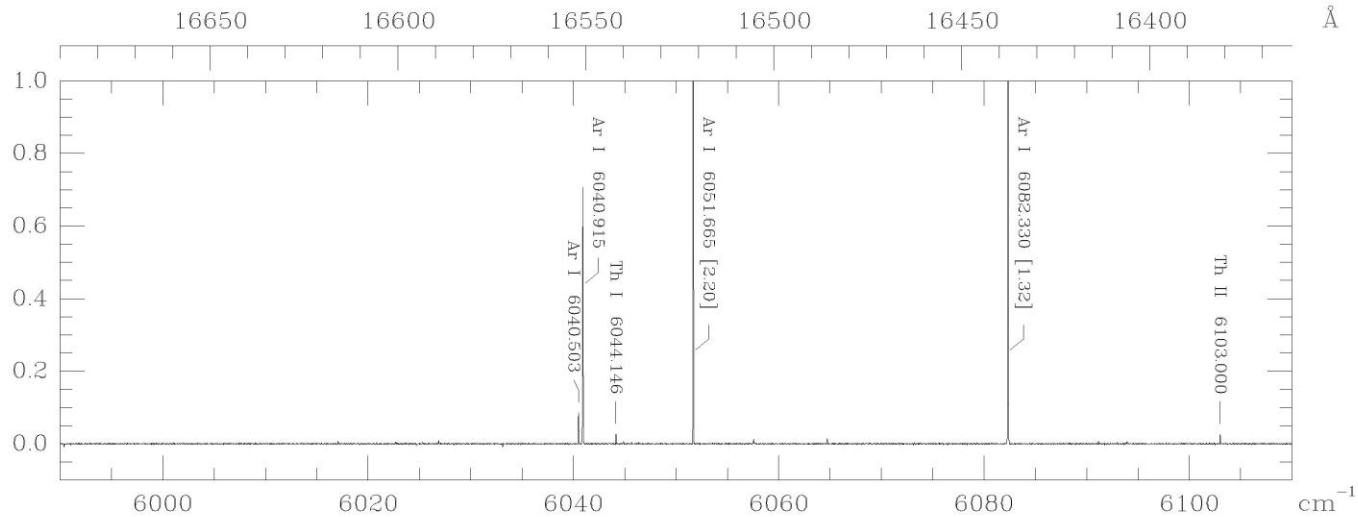

20000 19950 19900 19850 19800 19750 19700 19650 19600 Å
1.0
0.8
0.6
0.4
0.2
0.0
Th III 4997.277
Ar I 5007.215
Ar I 5012.402
Unid 5033.318
Ar I 5044.667 [1.08]
Ca I 5055.055
Th I 5064.108
Th I 5082.895
5000 5020 5040 5060 5080 5100 cm^{-1}
19600 19550 19500 19450 19400 19350 19300 19250 19200 Å
1.0
0.8
0.6
0.4
0.2
0.0
Ca I 5125.300
Ca I 5139.198
Th II 5169.491
Ca I 5177.468
5100 5120 5140 5160 5180 5200 cm^{-1}

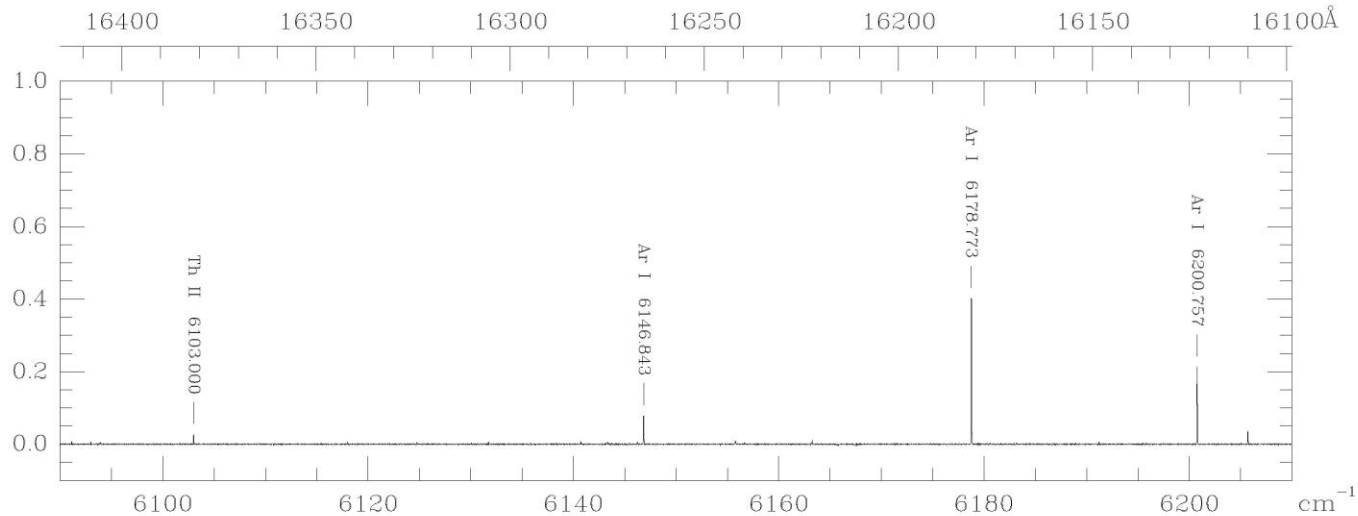

19250 19200 19150 19100 19050 19000 18950 18900 18850 Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I ? 5213.627
Th II 5221.700
Ar I 5227.655
Th I 5293.286
5200 5220 5240 5260 5280 5300 cm^{-1}
18850 18800 18750 18700 18650 18600 18550 18500 Å
Th I 5314.341
Ar I 5333.299
Unid 5359.961
Ar I 5365.563
Ne I 5367.617
Ne I 5375.544
Ne I 5377.325
Ar I 5383.512
Ar I 5383.100
Ar I 5385.234
5300 5320 5340 5360 5380 5400 cm^{-1}

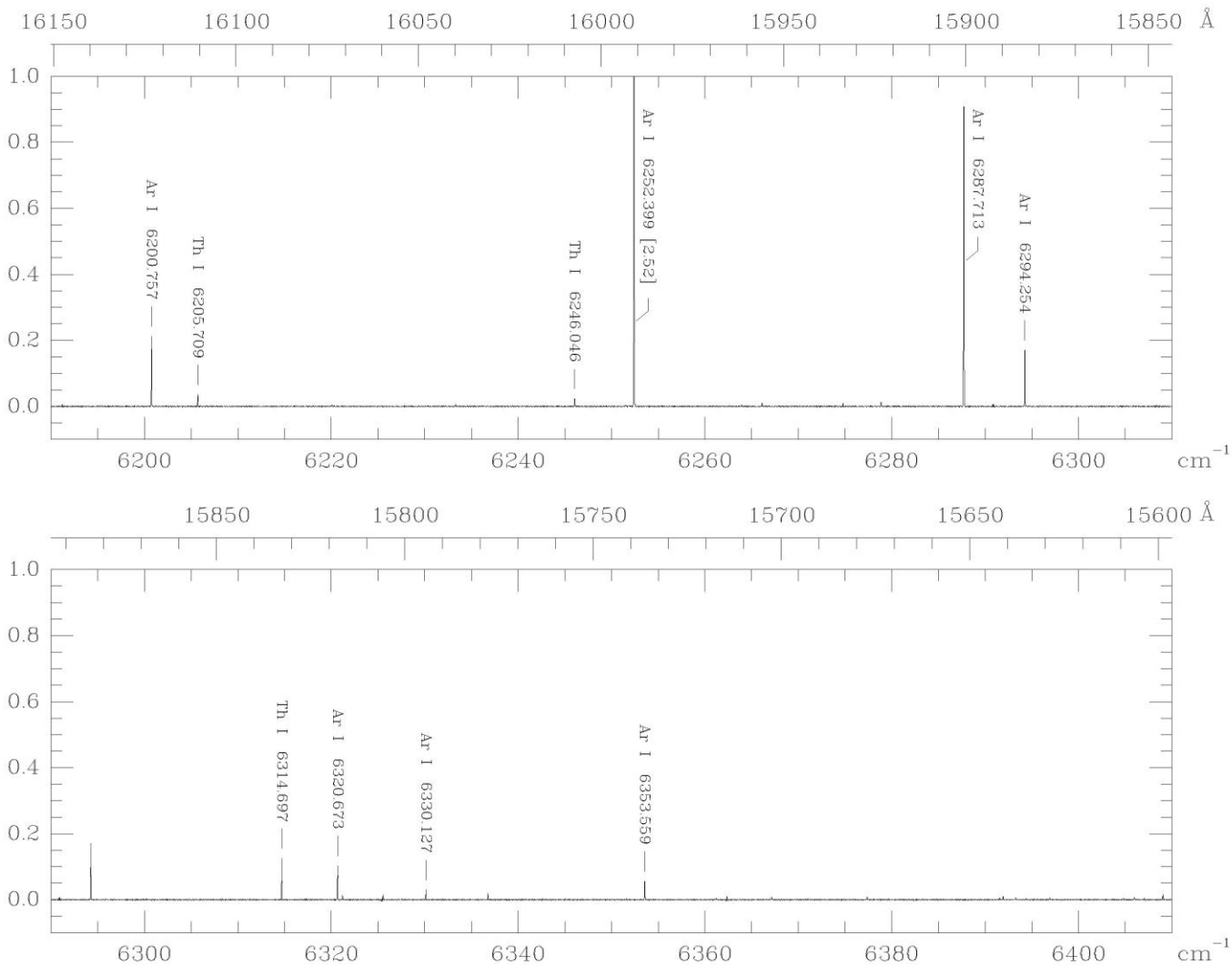

Å
cm^{-1}
Ar I 5497.302
Ne I 5486.648
Ar I 5483.561
Unid 5480.046
Ne I 5469.972
Ne I 5468.185
Ne I 5461.807
Ar I 5448.697
Ne I 5445.404
Ne I 5437.784
Ne I 5436.272
Ne I 5432.464
Ne I 5426.694
Ar I 5427.973
Ar I 5425.112 [1.44]
Ar I 5424.617
Ar I 5424.926
Th I 5413.158
Ne I 5411.009
Ar I 5407.813
Ar I 5589.069
Ar I 5588.760
Ar I ? 5580.478 [4.91]
Th I 5564.885
Ne I 5543.010
Th I 5531.811
Ne I 5528.490
Th I 5515.443
Ar I 5497.302

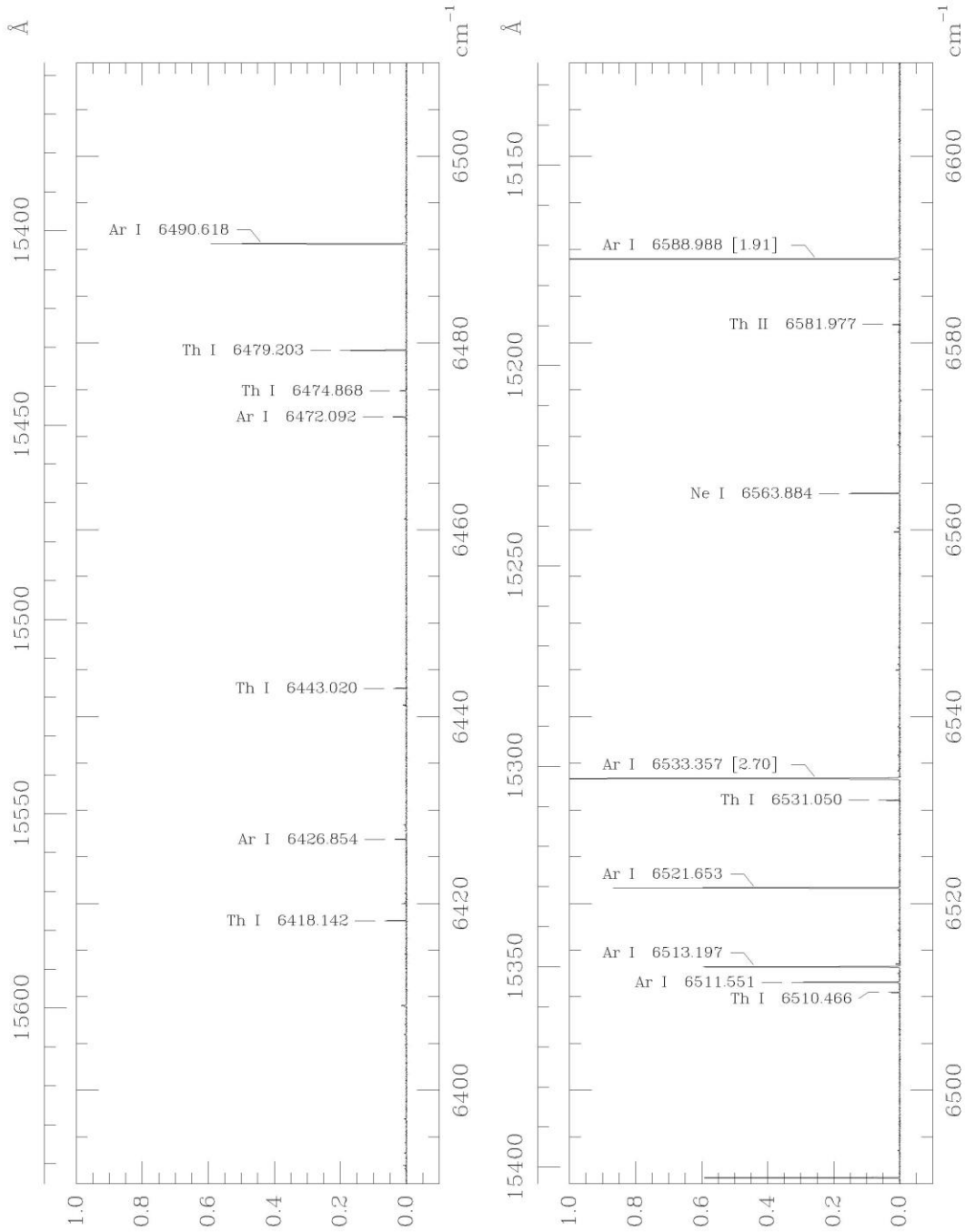

17850
17800
17750
17700
17650
17600
17550
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 5608.882
Th I 5608.292
Th I 5633.884
Th I 5672.826
Th I 5685.271
5600
5620
5640
5660
5680
5700
cm^{-1}
17550
17500
17450
17400
17350
17300
17250
Å
Th I 5718.917
Ar I ? 5730.655
Ar I ? 5730.769 [1.03]
Ar I 5744.929
Th I 5751.538
Th I 5750.394
Th I 5751.971
Th I 5776.212
5700
5720
5740
5760
5780
5800
cm^{-1}

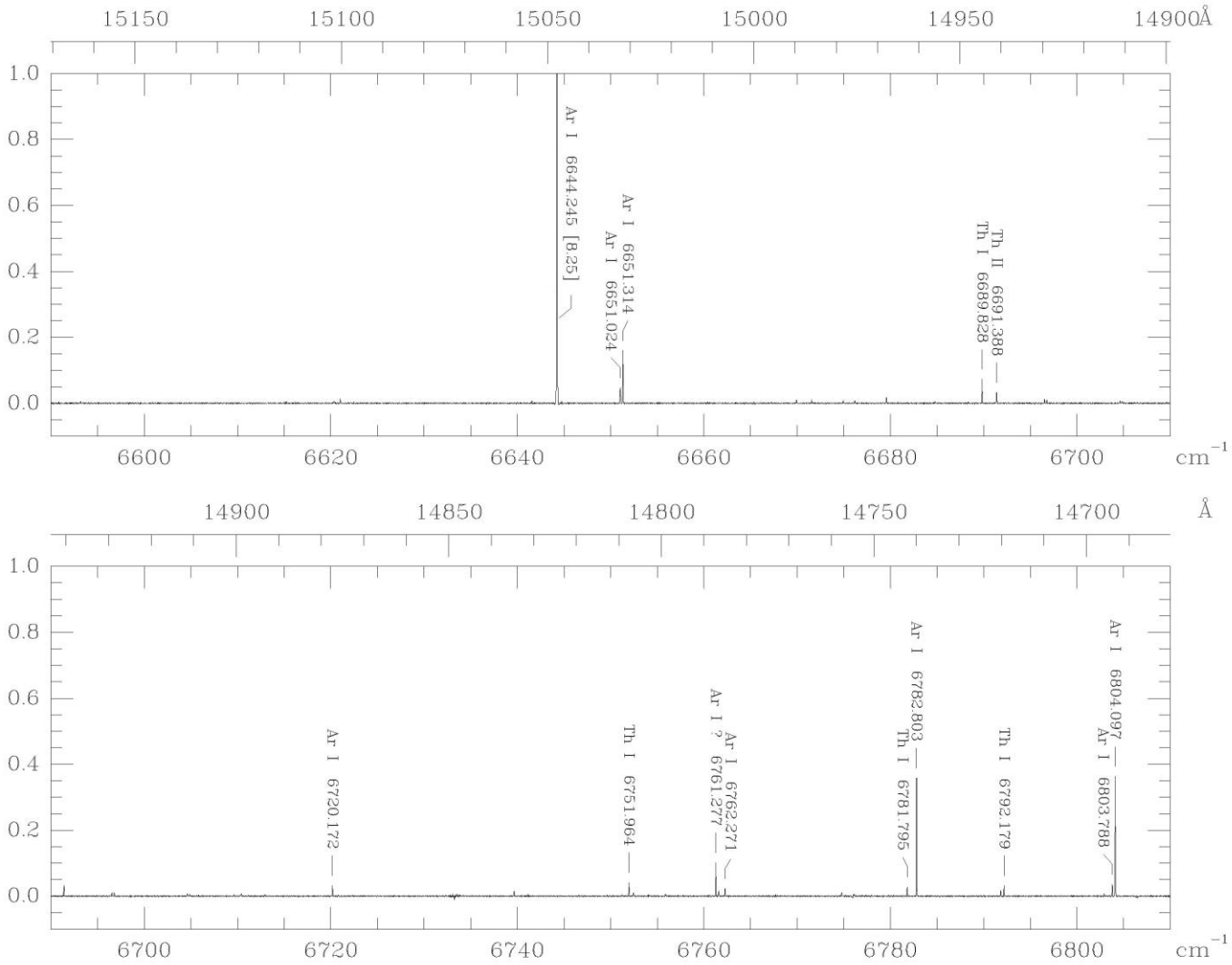

17250
17200
17150
17100
17050
17000
16950
Å
1.0
0.8
0.6
0.4
0.2
0.0
Th II 5809.589
Ne I 5825.255
Ar I 5901.372 [19.5]
5800
5820
5840
5860
5880
5900
cm^{-1}
16950
16900
16850
16800
16750
16700
16650
Å
Ar I 5901.372 [19.5]
Th I 5961.917
Al I 5968.332
Ar I 5972.057
Al I 5979.599
5900
5920
5940
5960
5980
6000
cm^{-1}

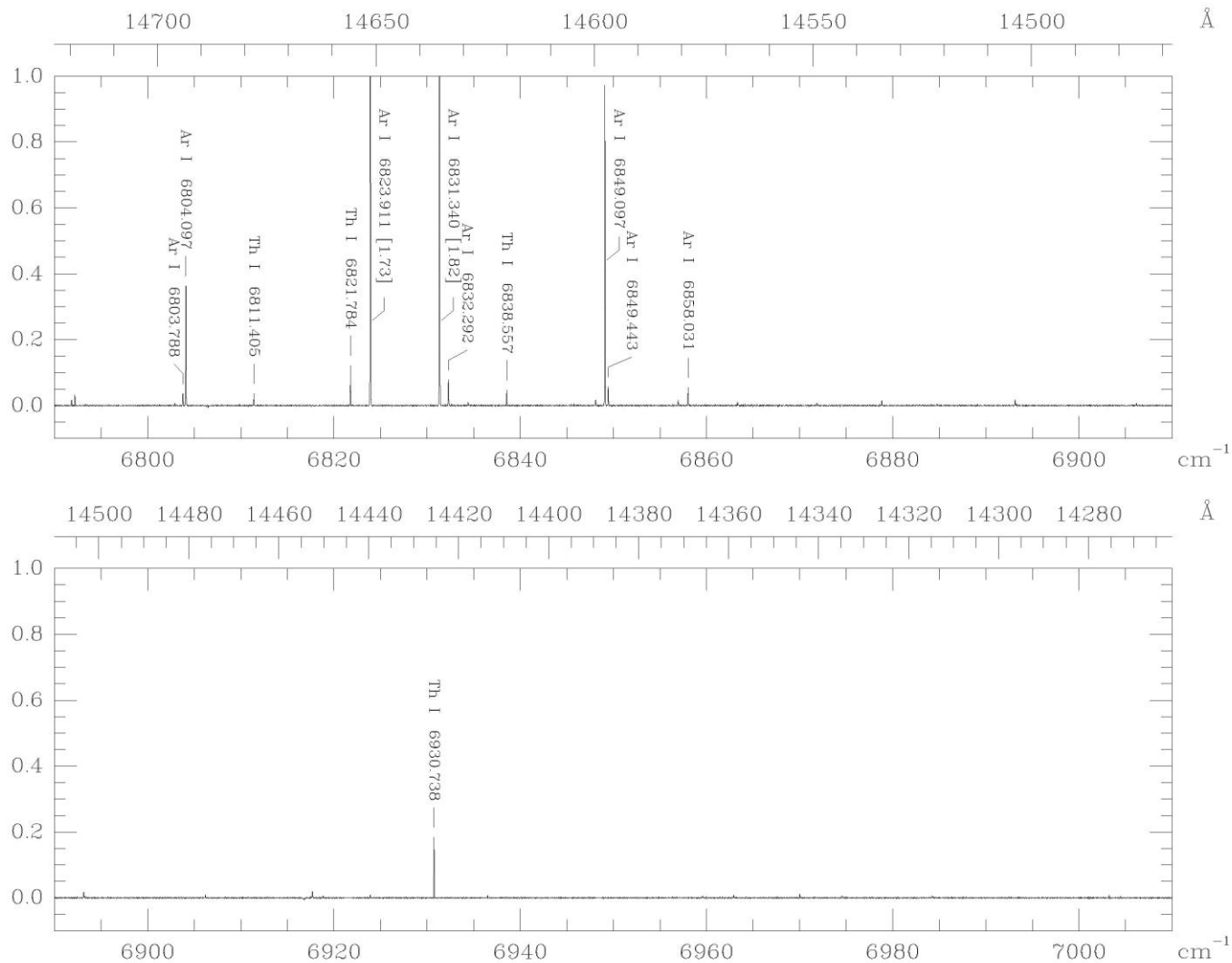

16650
16600
16550
16500
16450
16400
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 6040.915
Ar I 6040.503
Th I 6044.146
Ar I 6051.665 [2.20]
Ar I 6082.330 [1.32]
Th II 6103.000
6000
6020
6040
6060
6080
6100
cm^{-1}

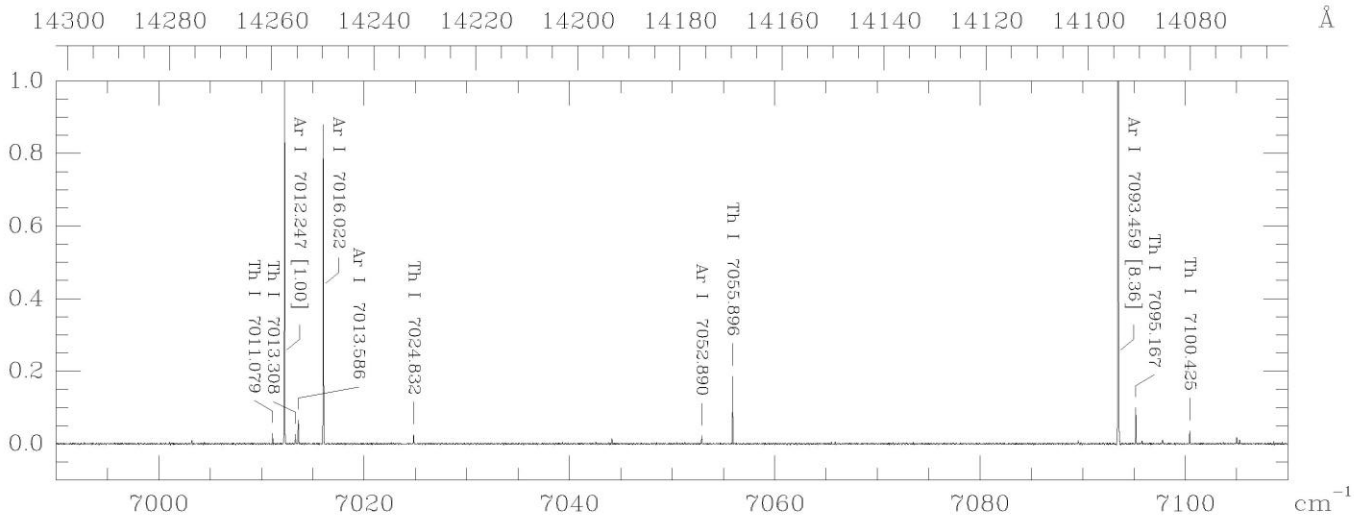

16400
16350
16300
16250
16200
16150
16100Å
1.0
0.8
0.6
0.4
0.2
0.0
Th II 6103.000
Ar I 6146.843
Ar I 6178.773
Ar I 6200.757
6100
6120
6140
6160
6180
6200
cm^{-1}

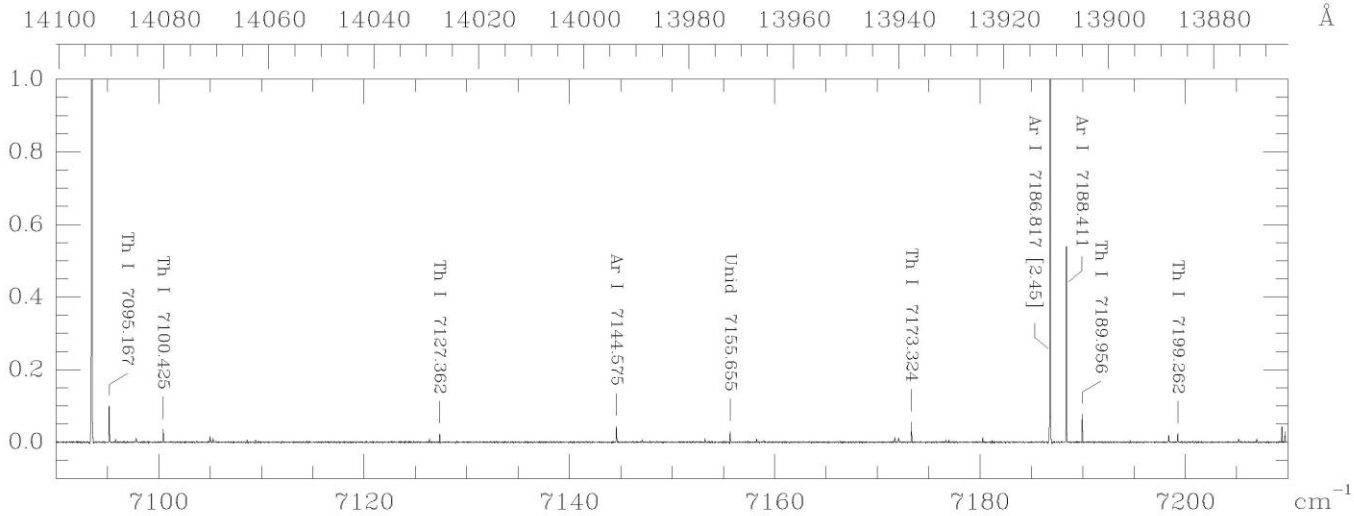

16150
16100
16050
16000
15950
15900
15850 Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 6200.757
Th I 6205.709
Th I 6246.046
Ar I 6252.399 [2.52]
Ar I 6287.713
Ar I 6294.254
6200
6220
6240
6260
6280
6300
cm^{-1}
15850
15800
15750
15700
15650
15600 Å
1.0
0.8
0.6
0.4
0.2
0.0
Th I 6314.697
Ar I 6320.673
Ar I 6330.127
Ar I 6353.559
6300
6320
6340
6360
6380
6400
cm^{-1}

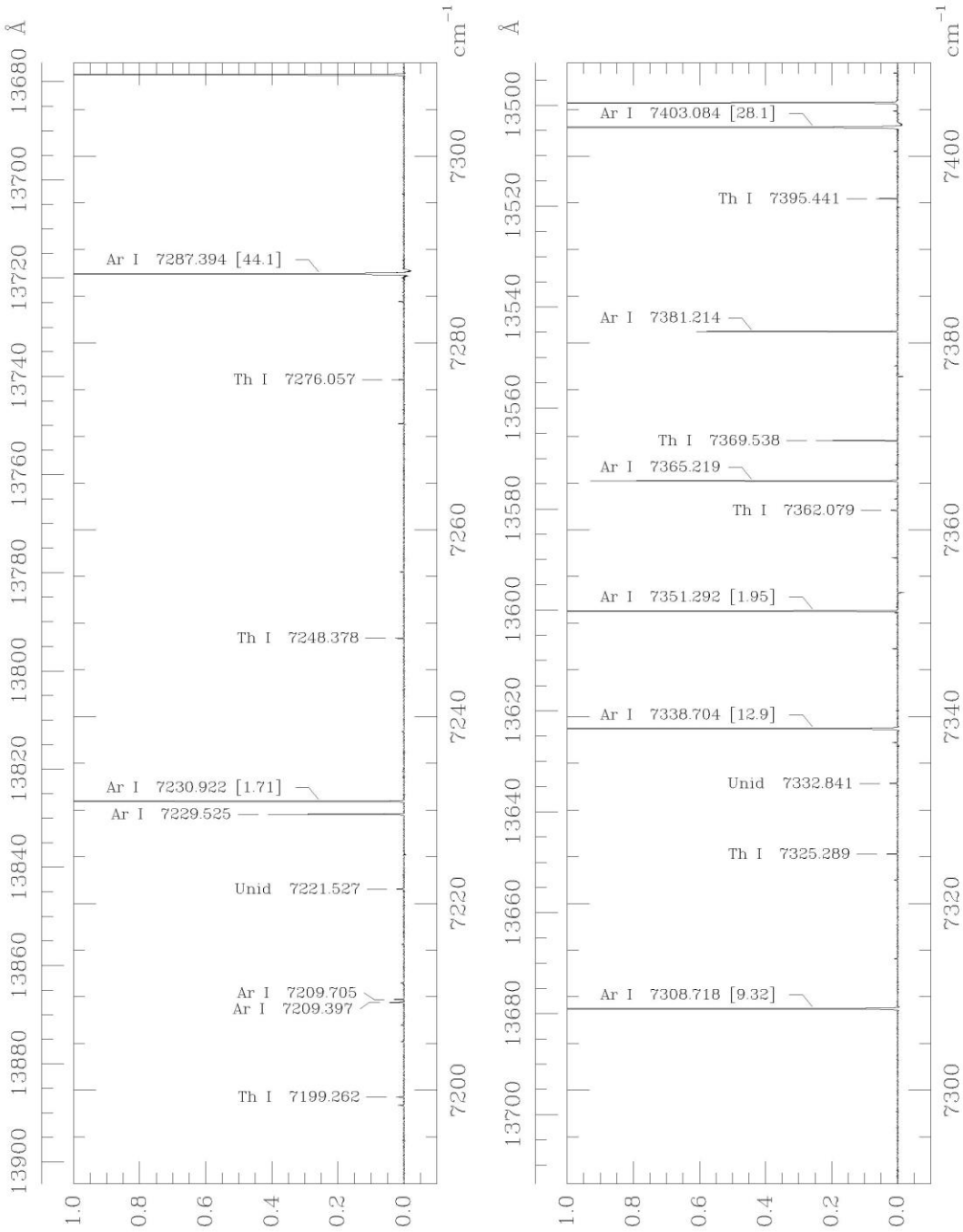

Å
cm^{-1}
Ar I 6490.618
Th I 6479.203
Th I 6474.868
Ar I 6472.092
Th I 6443.020
Ar I 6426.854
Th I 6418.142
Ar I 6588.988 [1.91]
Th II 6581.977
Ne I 6563.884
Ar I 6533.357 [2.70]
Th I 6531.050
Ar I 6521.653
Ar I 6513.197
Ar I 6511.551
Th I 6510.466

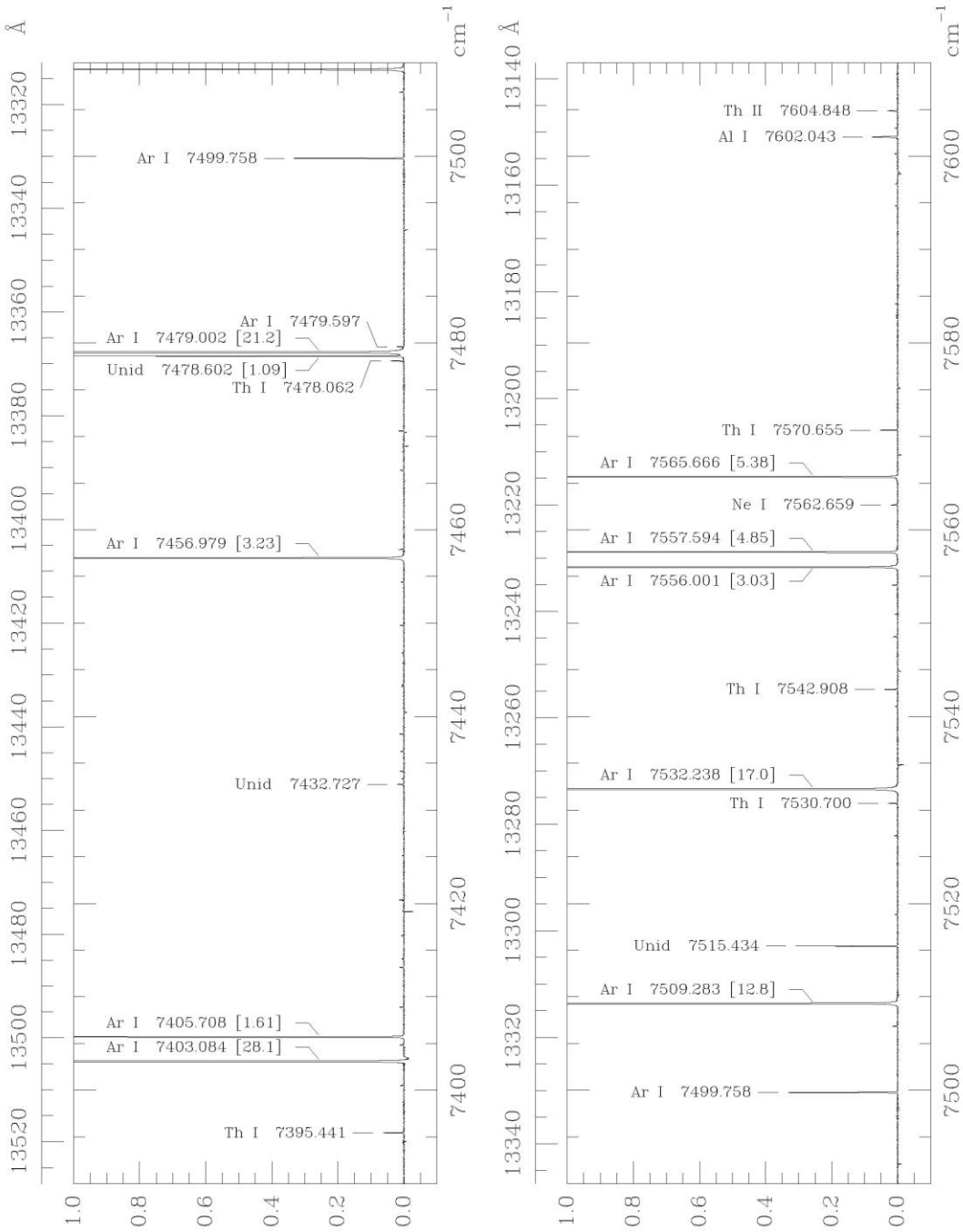

15150
15100
15050
15000
14950
14900Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 6644.245 [8.25]
Ar I 6651.314
Ar I 6651.024
Th II 6691.388
Th I 6689.828
6600
6620
6640
6660
6680
6700
cm^{-1}
14900
14850
14800
14750
14700
Å
Ar I 6720.172
Th I 6751.964
Ar I ? 6761.277
Ar I 6762.271
Ar I 6782.803
Th I 6781.795
Th I 6792.179
Ar I 6804.097
Ar I 6803.788
6700
6720
6740
6760
6780
6800
cm^{-1}

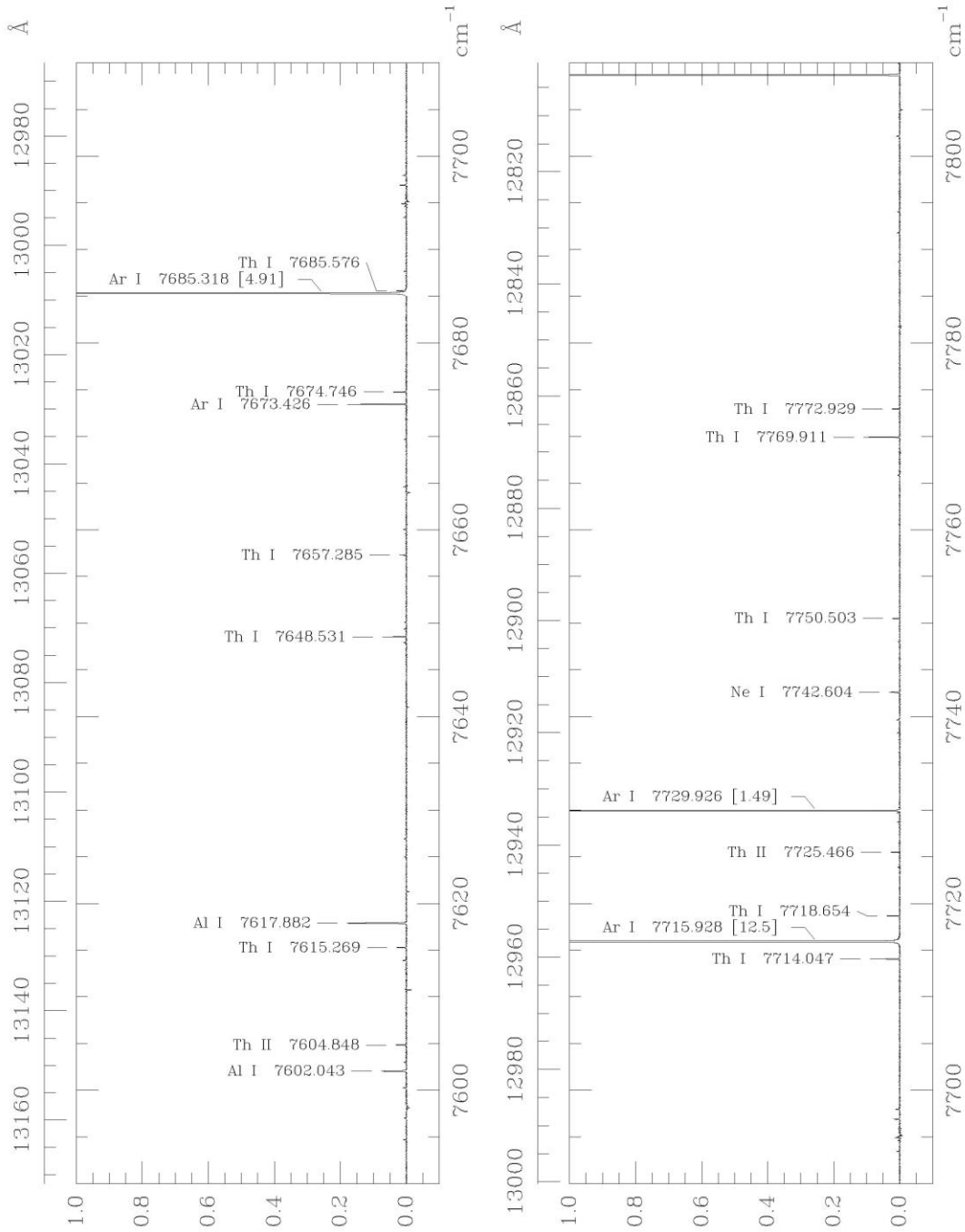

14700
14650
14600
14550
14500
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 6804.097
Ar I 6803.788
Th I 6811.405
Th I 6821.784
Ar I 6823.911 [1.73]
Ar I 6831.340 [1.82]
Ar I 6832.292
Th I 6838.557
Ar I 6849.097
Ar I 6849.443
Ar I 6858.031
6800
6820
6840
6860
6880
6900
cm^{-1}
14500
14480
14460
14440
14420
14400
14380
14360
14340
14320
14300
14280
Å
1.0
0.8
0.6
0.4
0.2
0.0
Th I 6930.738
6900
6920
6940
6960
6980
7000
cm^{-1}

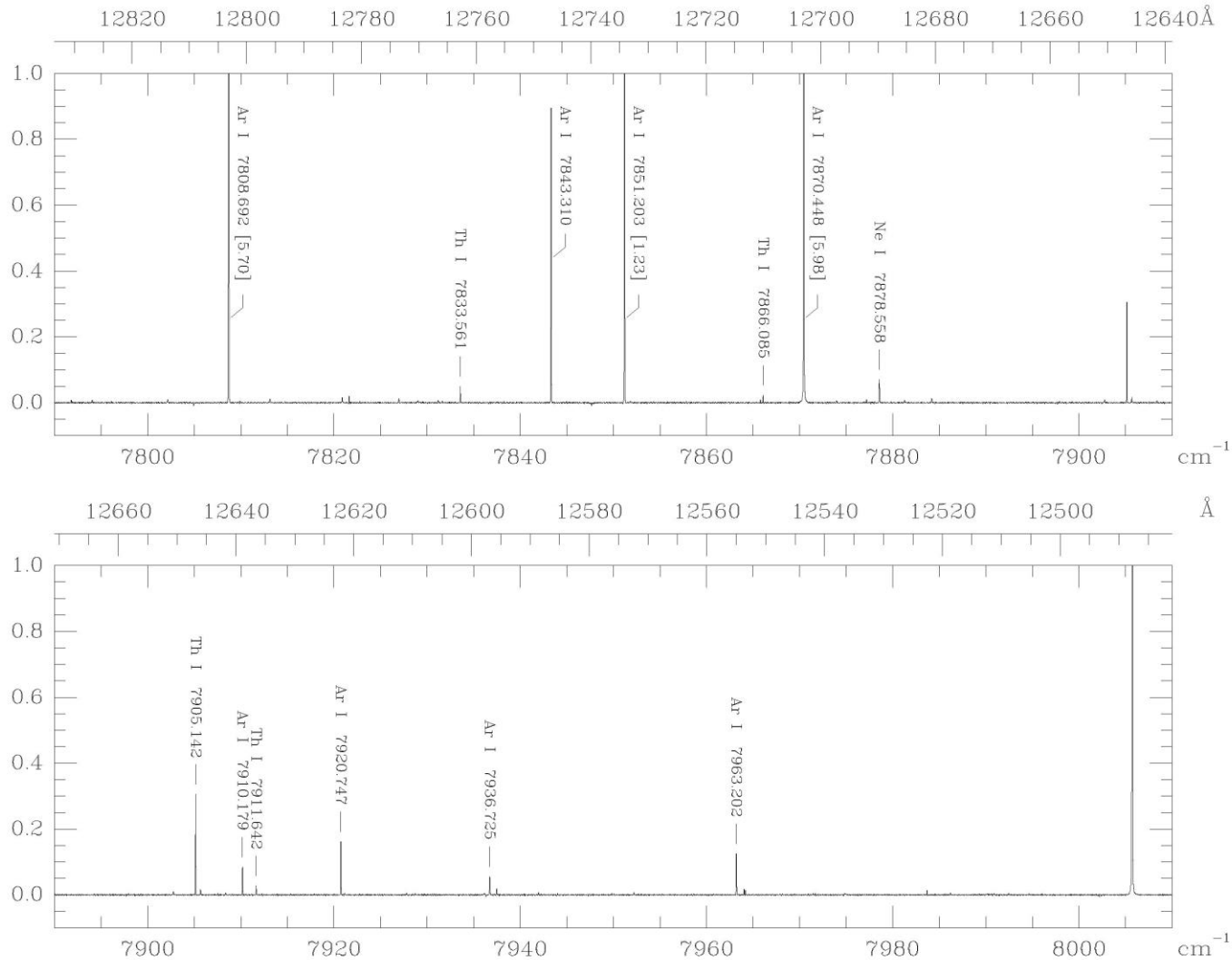

14300 14280 14260 14240 14220 14200 14180 14160 14140 14120 14100 14080 Å
1.0
0.8
0.6
0.4
0.2
0.0
Th I 7011.079
Th I 7013.308
Ar I 7012.247 [1.00]
Ar I 7016.022
Ar I 7013.586
Th I 7024.832
Ar I 7052.890
Th I 7055.896
Ar I 7093.459 [8.36]
Th I 7095.167
Th I 7100.425
7000 7020 7040 7060 7080 7100 cm^{-1}

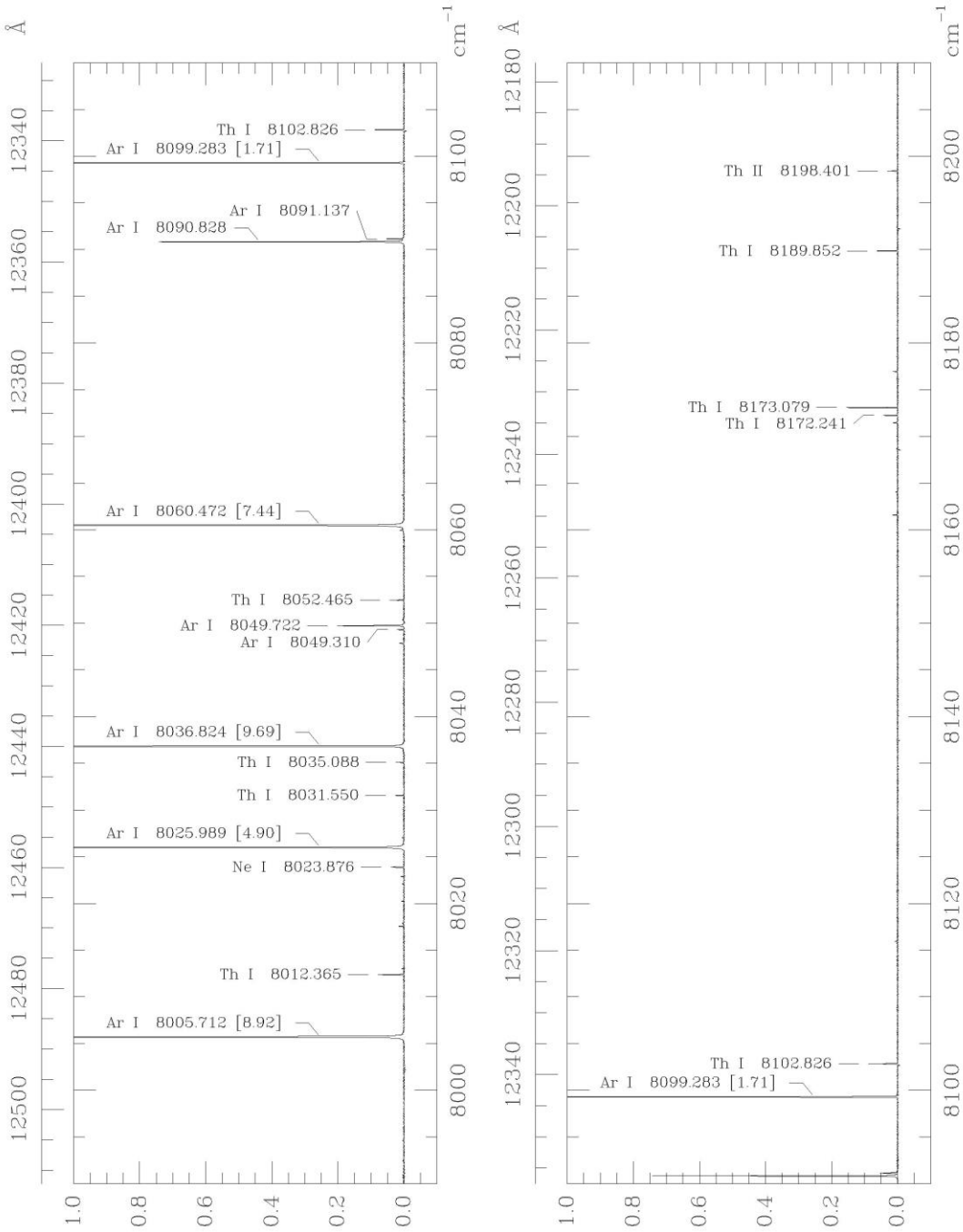

14100 14080 14060 14040 14020 14000 13980 13960 13940 13920 13900 13880 Å
1.0
0.8
0.6
0.4
0.2
0.0
Th I 7095.167
Th I 7100.425
Th I 7127.362
Ar I 7144.575
Unid 7155.655
Th I 7173.324
Ar I 7186.817 [2.45]
Ar I 7188.411
Th I 7189.956
Th I 7199.262
7100 7120 7140 7160 7180 7200 cm^{-1}

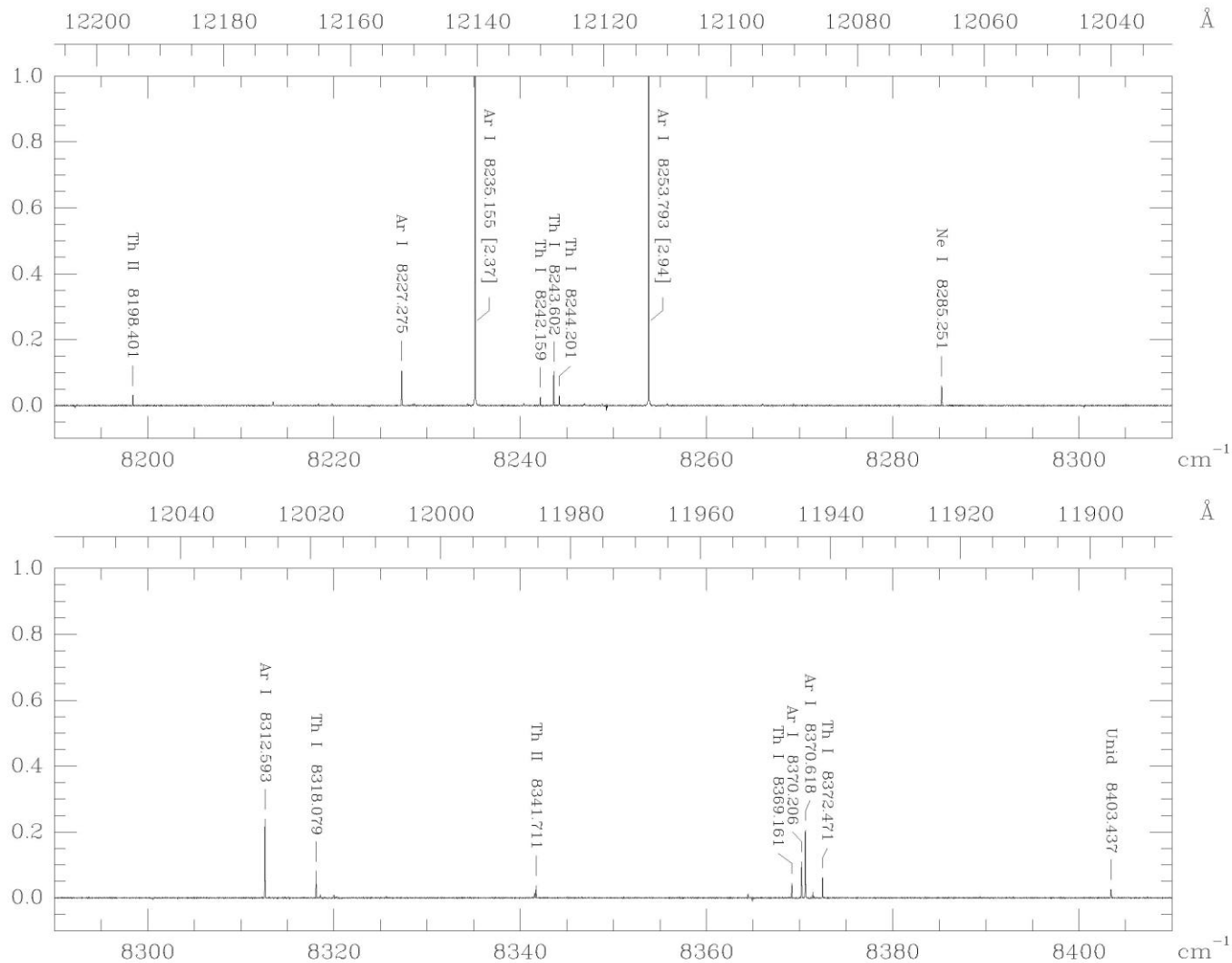

Å
cm^{-1}
Ar I 7287.394 [44.1]
Th I 7276.057
Th I 7248.378
Ar I 7230.922 [1.71]
Ar I 7229.525
Unid 7221.527
Ar I 7209.705
Ar I 7209.397
Th I 7199.262
Ar I 7403.084 [28.1]
Th I 7395.441
Ar I 7381.214
Th I 7369.538
Ar I 7365.219
Th I 7362.079
Ar I 7351.292 [1.95]
Ar I 7338.704 [12.9]
Unid 7332.841
Th I 7325.289
Ar I 7308.718 [9.32]

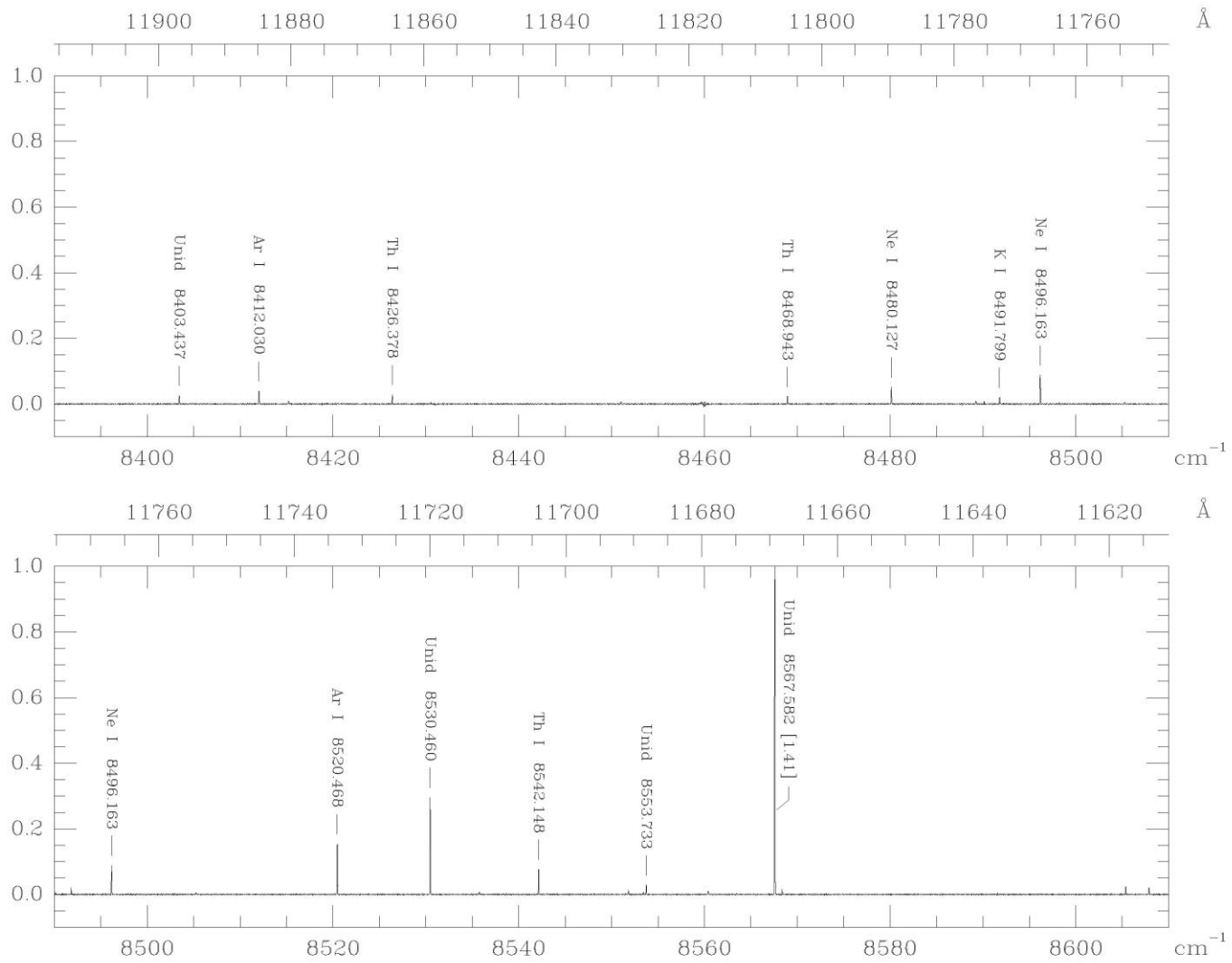

Å
cm^{-1}
Ar I 7499.758
Ar I 7479.597
Ar I 7479.002 [21.2]
Unid 7478.602 [1.09]
Th I 7478.062
Ar I 7456.979 [3.23]
Unid 7432.727
Ar I 7405.708 [1.61]
Ar I 7403.084 [28.1]
Th I 7395.441
Th II 7604.848
Al I 7602.043
Th I 7570.655
Ar I 7565.666 [5.38]
Ne I 7562.659
Ar I 7557.594 [4.85]
Ar I 7556.001 [3.03]
Th I 7542.908
Ar I 7532.238 [17.0]
Th I 7530.700
Unid 7515.434
Ar I 7509.283 [12.8]
Ar I 7499.758

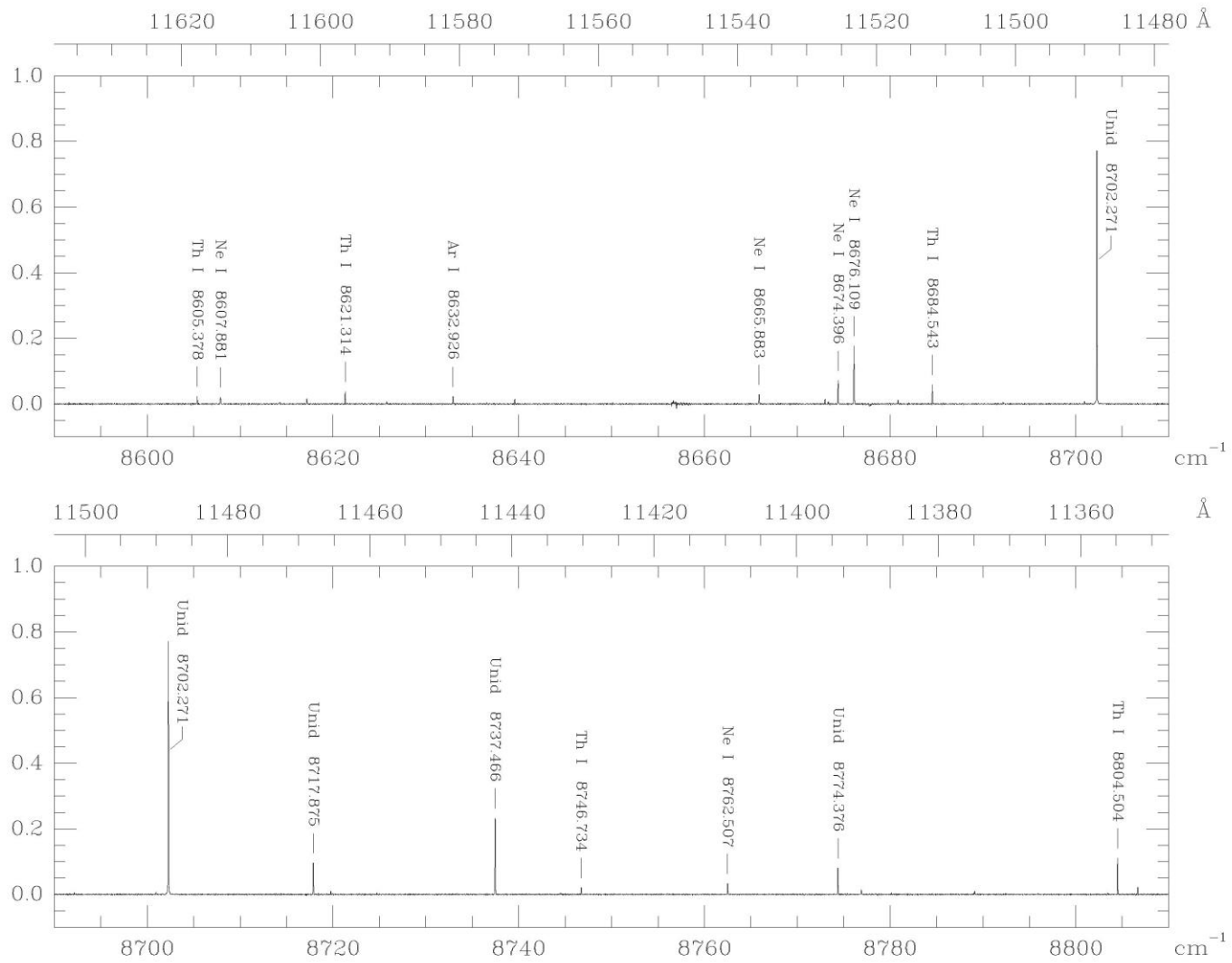

Å
cm^{-1}
Th I 7685.576
Ar I 7685.318 [4.91]
Th I 7674.746
Ar I 7673.426
Th I 7657.285
Th I 7648.531
Al I 7617.882
Th I 7615.269
Th II 7604.848
Al I 7602.043
Th I 7772.929
Th I 7769.911
Th I 7750.503
Ne I 7742.604
Ar I 7729.926 [1.49]
Th II 7725.466
Th I 7718.654
Ar I 7715.928 [12.5]
Th I 7714.047


12820 12800 12780 12760 12740 12720 12700 12680 12660 12640Å
1.0
0.8
0.6
0.4
0.2
0.0
Ar I 7808.692 [5.70]
Th I 7833.561
Ar I 7843.310
Ar I 7851.203 [1.23]
Th I 7866.085
Ar I 7870.448 [5.98]
Ne I 7878.558
7800 7820 7840 7860 7880 7900 cm^{-1}
12660 12640 12620 12600 12580 12560 12540 12520 12500 Å
1.0
0.8
0.6
0.4
0.2
0.0
Th I 7905.142
Th I 7911.642
Ar I 7910.179
Ar I 7920.747
Ar I 7936.725
Ar I 7963.202
7900 7920 7940 7960 7980 8000 cm^{-1}


Å
cm^{-1}
Th I 8102.826
Ar I 8099.283 [1.71]
Ar I 8091.137
Ar I 8090.828
Ar I 8060.472 [7.44]
Th I 8052.465
Ar I 8049.722
Ar I 8049.310
Ar I 8036.824 [9.69]
Th I 8035.088
Th I 8031.550
Ar I 8025.989 [4.90]
Ne I 8023.876
Th I 8012.365
Ar I 8005.712 [8.92]
Th II 8198.401
Th I 8189.852
Th I 8173.079
Th I 8172.241
Th I 8102.826
Ar I 8099.283 [1.71]


12200
12180
12160
12140
12120
12100
12080
12060
12040
Å
1.0
0.8
0.6
0.4
0.2
0.0
Th II 8198.401
Ar I 8227.275
Ar I 8235.155 [2.37]
Th I 8242.159
Th I 8243.602
Th I 8244.201
Ar I 8253.793 [2.94]
Ne I 8285.251
8200
8220
8240
8260
8280
8300
cm^{-1}
12040
12020
12000
11980
11960
11940
11920
11900
Å
Ar I 8312.593
Th I 8318.079
Th II 8341.711
Th I 8369.161
Ar I 8370.206
Ar I 8370.618
Th I 8372.471
Unid 8403.437
8300
8320
8340
8360
8380
8400
cm^{-1}


11900
11880
11860
11840
11820
11800
11780
11760
Å
1.0
0.8
0.6
0.4
0.2
0.0
Unid 8403.437
Ar I 8412.030
Th I 8426.378
Th I 8468.943
Ne I 8480.127
K I 8491.799
Ne I 8496.163
8400
8420
8440
8460
8480
8500
cm^{-1}
11760
11740
11720
11700
11680
11660
11640
11620
Å
1.0
0.8
0.6
0.4
0.2
0.0
Ne I 8496.163
Ar I 8520.468
Unid 8530.460
Th I 8542.148
Unid 8553.733
Unid 8567.582 [1.41]
8500
8520
8540
8560
8580
8600
cm^{-1}


11620
11600
11580
11560
11540
11520
11500
11480 Å
1.0
0.8
0.6
0.4
0.2
0.0
Th I 8605.378
Ne I 8607.881
Th I 8621.314
Ar I 8632.926
Ne I 8665.883
Ne I 8674.396
Ne I 8676.109
Th I 8684.543
Unid 8702.271
8600
8620
8640
8660
8680
8700
cm^{-1}
11500
11480
11460
11440
11420
11400
11380
11360
Å
Unid 8702.271
Unid 8717.875
Unid 8737.466
Th I 8746.734
Ne I 8762.507
Unid 8774.376
Th I 8804.504
8700
8720
8740
8760
8780
8800
cm^{-1}