2.4-m Automated Planet Finder Prospectus

Overview

The APF (Automated Planet Finder) is a 2.4-m f/15 telescope in its final commissioning phases atop Mt. Hamilton. APF was specifically optimized and intended for exoplanet discovery and characterization. However, a significant fraction of observing time may be available to the UC community for other types of projects involving Target of Opportunity observations of bright GRB's and supernovae, stellar abundance measurements, queue-scheduled observations, etc.

The telescope has an Alt-Az mount and two Nasmyth foci. At one of these foci sits the Levy Spectrometer, a high-resolution prism cross-dispersed echelle optimized for high precision radial velocity research. The other focus is currently vacant but offers a well-corrected 2 arc-minute diameter FOV. The diameter of M2 is kept small to minimize central obstruction losses, and mirrors M2 and M3 are coated with enhanced silver for higher efficiency in the visible. M3 is also on a motorized rotation stage that provides rapid (30-second) switchover between the two Nasmyth foci. The telescope is housed in an Ice-Storm dome that is slaved to the telescope and co-rotates with it. The dome has dual "up and over" shutters that can be used either in a split-shutter mode for best wind protection, or with both shutters over the top for faster all-sky access. Both telescope azimuth and dome can slew at up to 4 °/sec. The telescope elevation axis slews at only 2 °/sec. The telescope can point all the way down to the horizon, can work down to about 15 degrees elevation without vignetting, and up to within about 2° of the zenith. There are no other limitations on sky coverage. There are several different modes for dome shutter operation. To avoid vignetting when observing objects at elevation angles ≥ 81°, "split-shutter" mode must be used. For objects at elevation angles ≤ 41°, the "up-and-over" mode must be used. The dome includes AC units to keep the internal temperature close to the expected nightly average and large vent doors to allow rapid temperature equalization.

Considerations for target acquisition

Targets are acquired using a Princeton Instruments PhotonMax camera. This CCDTV camera uses a thermo-electrically cooled frame-transfer electron-multiplying CCD with 16-micron pixels in a 512x512 format (8.2mm x 8.2mm). The image scale is 0.108 arc-sec/pixel, yielding a 55"x55" FOV. All-sky pointing of the telescope is excellent at RMS=1.8 arc-secs RMS down to 15° elevation, with worst-case pointing errors <= 7 arc-secs. So targets always end up in the guider FOV. A trombone-style atmospheric dispersion compensator (ADC) provides excellent atmospheric dispersion compensation down to 15° elevation. There is no image rotator. The guider is fed by a beam-splitter that directs 4% of the incident light to the guider camera. Guiding is thus done directly on a small fraction of the image, rather than on light spilled off of slit jaws. The entrance slit is not viewable during guiding. Instead, a guide box is superimposed on the CCDTV image that marks the location of the slit. An exposure meter function keeps track of photons falling within the slit box, and can be set to terminate the exposure at some desired exposure value. More importantly, the exposure meter also calculates the photon-weighted time centroid of each observation that is required for computing accurate barycentric corrections.

- Magnitude limits of guider: V~ 4-15 (in safe mode); to 18.5 with charge multiplication mode (this will require further software effort to provide safeguards for the camera)
- Guider FOV: 55" x 55" at 0.108 arc-sec/pixel
- Telescope pointing accuracy (absolute)- < 1.8 arc-secs RMS (for elevations 15-88°)

Robotic Operation

At present, the facility is still in its commissioning phase, and is operated manually from the APF dome and/or from the remote ops facility at UCSC. Once fully operational, the facility will be available only from approved remote ops sites, or run in queue-scheduled mode from UCSC.

Levy Spectrometer characteristics

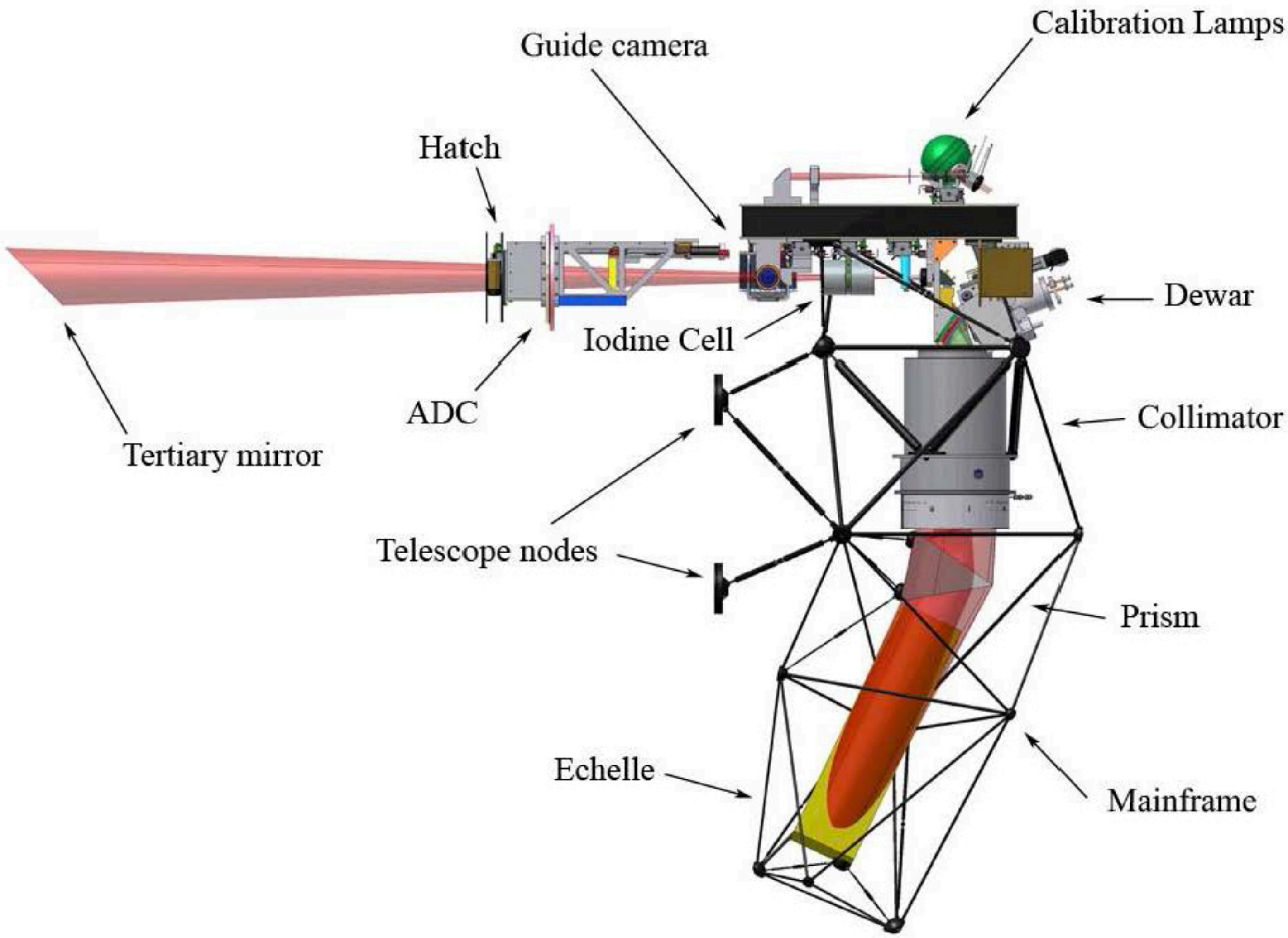
The Levy spectrometer is a prism cross-dispersed echelle. It features a 200mm diameter collimated beam and achieves a "throughput" (resolution x slit width product) of about 110,000 arc-seconds. The optical train is supported within a determinate structure Invar "space-frame" that has been optimized to provide a high degree of passive athermalization to hold constant focus and image scale. An all-dioptric f/3.17 lens group, used in double-pass, serves as both the collimator and camera. Cross-dispersion is done by a prism, also used in double pass.

- Collimator/camera- EFL 483.4 mm; f/3.17
- Grating- 41 gr/mm R-4 Echelle (214x840mm)
- Detector- E2V CCD42-90 (2048x4608)
- Pixel size- 13.5 microns
- Dispersion- 1.46 A/mm or 0.0197 A/pixel at 5500A
- Spectral coverage- 3743A-9800A with small gaps above 7500A
- Order separation- 8 arc-sec minimum at 7800A, increasing to 13 arc-sec at 3700A
- Max spectral resolution- ~119,000 at 5500A (150,000 peak when fine-focused for specific regions of the format)
- Throughput (spectral resolving power times slit width): 109,000 arc-secs
- Overall system efficiency- at least 17% at 550 nm (preliminary)
- Thermal control- passive athermalization with insulated housing and temp control
- Slit lengths and widths- 2x7.5, 1x3, 0.75x3, 0.5x3, 2x3, 1x2, 2x2, 1x4, 2x4 arc-secs (additional longer slits for better sky subtraction are presently being added)
- Maximum slit length- 7.5 arcsecs (without order overlap)
- Filters- none
- CCD readout time- ~30s
- CCD readout noise- 3-4 electrons
- Arc lamps/wavelength calibrations- Thorium-Argon, 50W incandescent, Iodine absorption cell
- Doppler accuracy goal- 1 m/s
- Some fringing visible redward of ~7300A; pronounced above 8000A

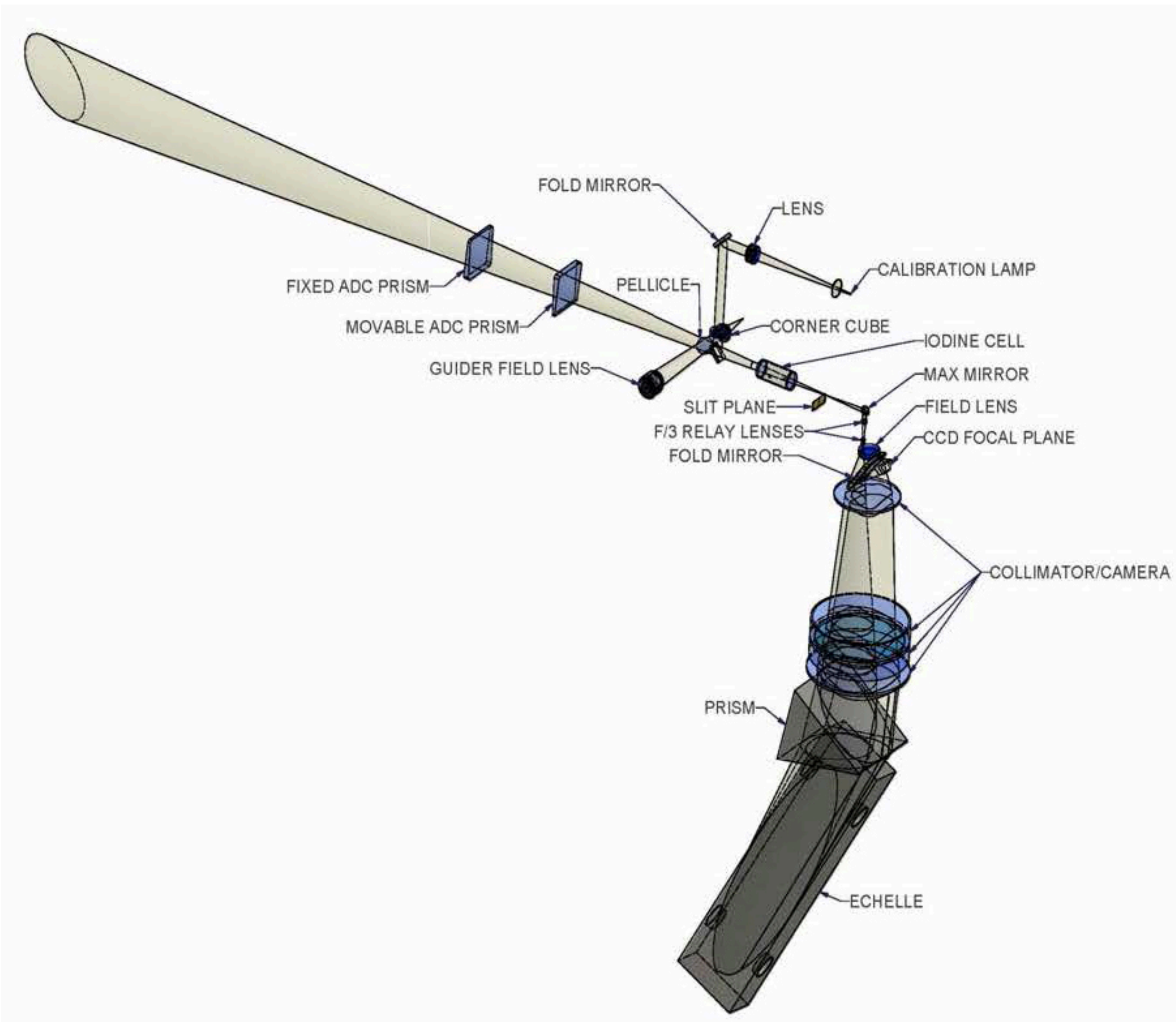
Echelle format table

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Paul Butler's idl order#	Echelle Order	Blaze wave (A)	Free Spectral Range	A/mm	A/pixel	Features	Comments	FSR blue end	FSR red end	Order sep (")	Cross dispersion scale ("/mm)	Cross dispersion scale ("/pixel)
2	not extracted	41	11365.37	277.2	2.949850	0.03982		Top edge of CCD	11227	11504	9.1	29.74	0.40149
3	not extracted	42	11094.77	264.2				heavily vignetted	10963	11227			
4	not extracted	43	10836.75	252.0				heavily vignetted	10711	10963			
5	not extracted	44	10590.46	240.7				heavily vignetted	10470	10711			
6	not extracted	45	10355.12	230.1				heavily vignetted	10240	10470			
7	not extracted	46	10130.01	220.2				heavily vignetted	10020	10240			
8	not extracted	47	9914.47	210.9				vignetted?	9809	10020	7.944	30.67	0.414045
9	not extracted	48	9707.92	202.2				Red rascal	9607	9809	7.95	30.81	0.415935
10	not extracted	49	9509.80	194.1			Huge H2O band	Red rascal	9413	9607			
11	not extracted	50	9319.61	186.4	2.421300	0.03269	Huge H2O band	Red rascal	9226	9413			
12	not extracted	51	9136.87	179.2				Red rascal	9047	9226			
13	not extracted	52	8961.16	172.3				Red rascal	8875	9047			
14	not extracted	53	8792.08	165.9				Red rascal	8709	8875	8.14	31.67	0.427545
15	not extracted	54	8629.26	159.8			8542 8662 Ca II	Red rascal	8549	8709			
16	not extracted	55	8472.37	154.0			8498 Ca II	Red rascal	8395	8549			
17	not extracted	56	8321.08	148.6	2.173900	0.02935		Red rascal	8247	8395			
18	not extracted	57	8175.09	143.4				Red rascal	8103	8247			
19	not extracted	58	8034.14	138.5				Red rascal	7965	8103	7.67	32.11	0.433485
20	not extracted	59	7897.97	133.9				Red rascal	7831	7965			
21	not extracted	60	7766.34	129.4				Red rascal	7702	7831			
22	63	61	7639.02	125.2			A-Band O2	Red rascal	7576	7702			
23	62	62	7515.81	121.2	1.968500	0.02657		Red rascal	7455	7576			
24	61	63	7396.51	117.4				Red rascal	7338	7455			
25	60	64	7280.94	113.8			fringing redward of here	Red rascal	7224	7338			
26	59	65	7168.93	110.3				Red rascal	7114	7224			
27	58	66	7060.31	107.0				Red rascal	7007	7114	7.85	32.42	0.43767
28	57	67	6954.93	103.8	1.851850	0.025	B-Band 02	Red rascal	6903	7007			
29	56	68	6852.65	100.8			B-Band 02	Red rascal	6802	6903			
30	55	69	6753.34	97.9				Red rascal	6704	6802			
31	54	70	6656.86	95.1				Red rascal	6609	6704			
32	53	71	6563.10	92.4	1.730100	0.02336	H-Alpha	Red rascal	6517	6609			
33	52	72	6471.95	89.9	1.706500	0.02304		Red rascal	6427	6517			
34	51	73	6383.29	87.4				Red rascal	6340	6427			
35	50	74	6297.03	85.1			Atm band	Red rascal	6254	6340			
36	49	75	6213.07	82.8				Red rascal	6172	6254			
37	48	76	6131.32	80.7	1.637015	0.0221	I2	Red rascal	6091	6172			
38	47	77	6051.69	78.6	1.600000	0.0216	I2	Red rascal	6012	6091	8.74	32.26	0.43551
39	46	78	5974.11	76.6			I2	Red rascal	5936	6012			
40	45	79	5898.48	74.7			Na D lines	Red rascal	5861	5936			
41	44	80	5824.75	72.8	1.553600	0.02097	I2	Red rascal?	5788	5861			
42	43	81	5752.84	71.0			I2		5717	5788			
43	42	82	5682.69	69.3			I2		5648	5717			
44	41	83	5614.22	67.6			I2		5580	5648			
45	40	84	5547.38	66.0			I2		5514	5580			
46	39	85	5482.12	64.5	1.457700	0.01968	I2		5450	5514			
47	38	86	5418.38	63.0	1.446600	0.01953	I2		5387	5450			
48	37	87	5356.10	61.6			I2		5325	5387			
49	36	88	5295.23	60.2			I2		5265	5325			
50	35	89	5235.73	58.8			I2		5206	5265			
51	34	90	5177.56	57.5			I2	Mg B triplet?	5149	5206			
52	33	91	5120.66	56.3			I2		5093	5149			
53	32	92	5065.00	55.1	1.351400	0.01824	I2		5037	5093			
54	31	93	5010.54	53.9	1.356200	0.01831	I2		4984	5037	10.27	31.81	0.429435
55	30	94	4957.24	52.7	1.326300	0.01786	Mg triplet line?		4931	4984			
56	29	95	4905.06	51.6					4879	4931			
57	28	96	4853.96	50.6			H-Beta		4829	4879			
58	27	97	4803.92	49.5					4779	4829			
59	26	98	4754.90	48.5					4731	4779			
60	25	99	4706.87	47.5					4683	4731			
61	24	100	4659.80	46.6					4637	4683			
62	23	101	4613.67	45.7					4591	4637			
63	22	102	4568.43	44.8					4546	4591			
64	21	103	4524.08	43.9	1.203400	0.01625			4502	4546			
65	20	104	4480.58	43.1					4459	4502			
66	19	105	4437.91	42.3					4417	4459			
67	18	106	4396.04	41.5					4375	4417			
68	17	107	4354.96	40.7					4335	4375			
69	16	108	4314.63	40.0					4295	4335	11.82	31.52	0.42552
70	15	109	4275.05	39.2					4255	4295			
71	14	110	4236.18	38.5			Ca I 4226		4217	4255			
72	13	111	4198.02	37.8			Ca I 4226		4179	4217			
73	12	112	4160.54	37.1					4142	4179			
74	11	113	4123.72	36.5					4105	4142			
75	10	114	4087.55	35.9					4070	4105			
76	9	115	4052.00	35.2	1.096500	0.0148			4034	4070			
77	8	116	4017.07	34.6					4000	4034			
78	7	117	3982.74	34.0			Ca II H line 3968		3966	4000			
79	6	118	3948.99	33.5			Ca II K line 3933		3932	3966			
80	5	119	3915.80	32.9					3899	3932			
81	4	120	3883.17	32.4					3867	3899			
82	3	121	3851.08	31.8					3835	3867			
83	2	122	3819.51	31.3					3804	3835			
84	1	123	3788.46	30.8					3773	3804	13.17		
85	0	124	3757.91	30.3	1.021500	0.01379		Bluest full order	3743	3773		31.96	0.43146

Schematic view #1



Schematic view #2

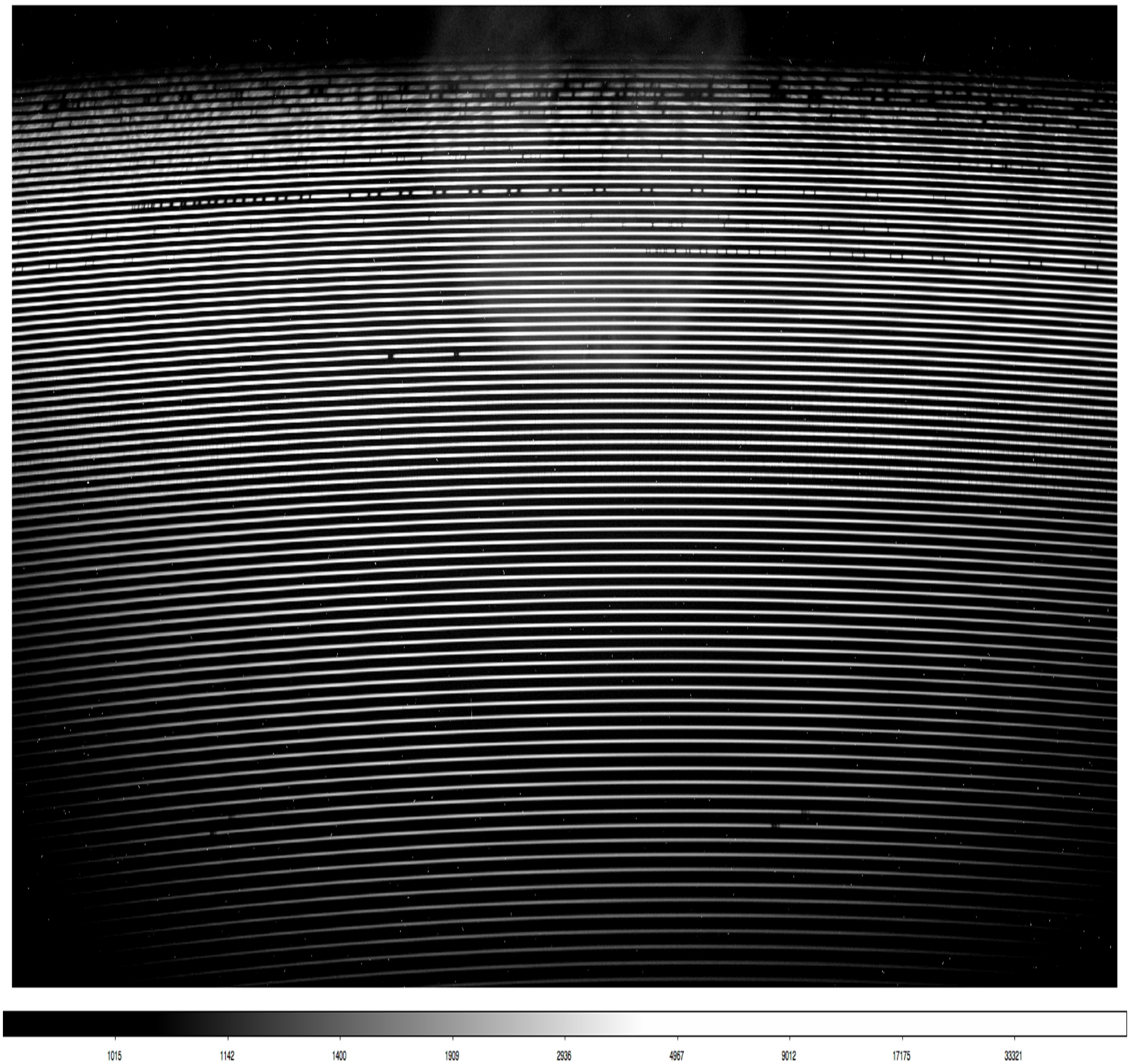


Commissioning process
A Readiness Review that covers the telescope, dome, and spectrograph testing occurred in November, 2012. Commissioning activities are still underway as of July, 2013. A link to the (password protected) Readiness Review Report is available at:

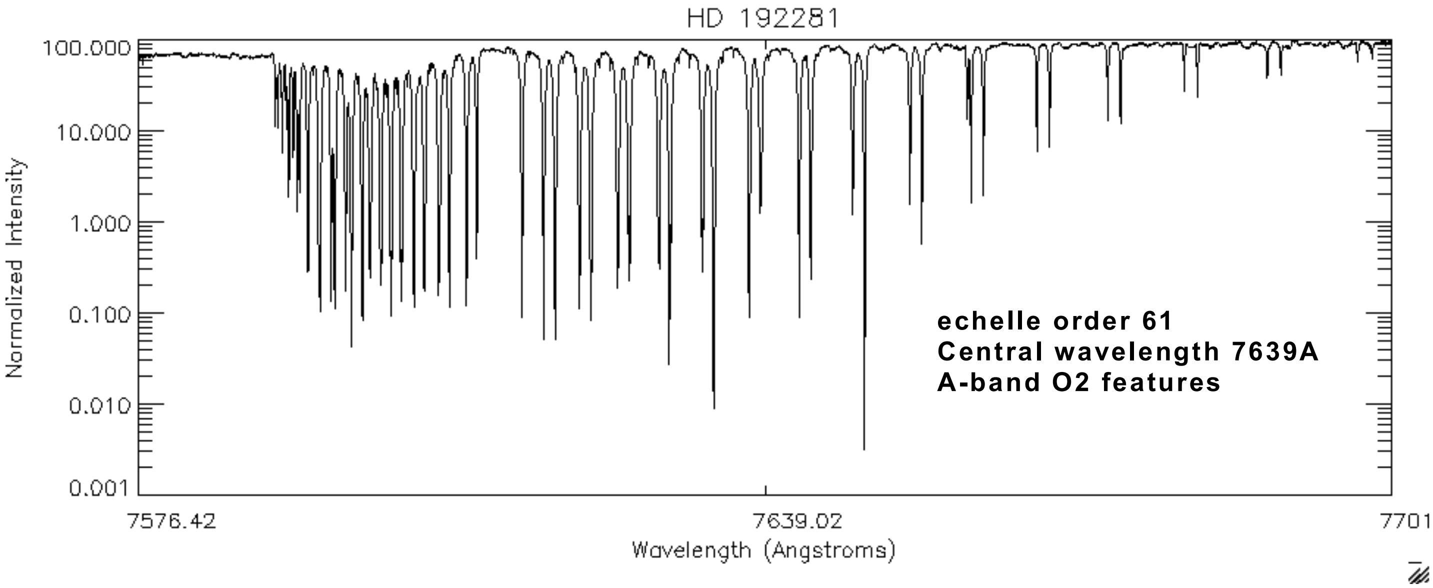
http://apf.ucolick.org/reports_docs/APF_Readiness_Review_Report_final.pdf

Sample Spectra

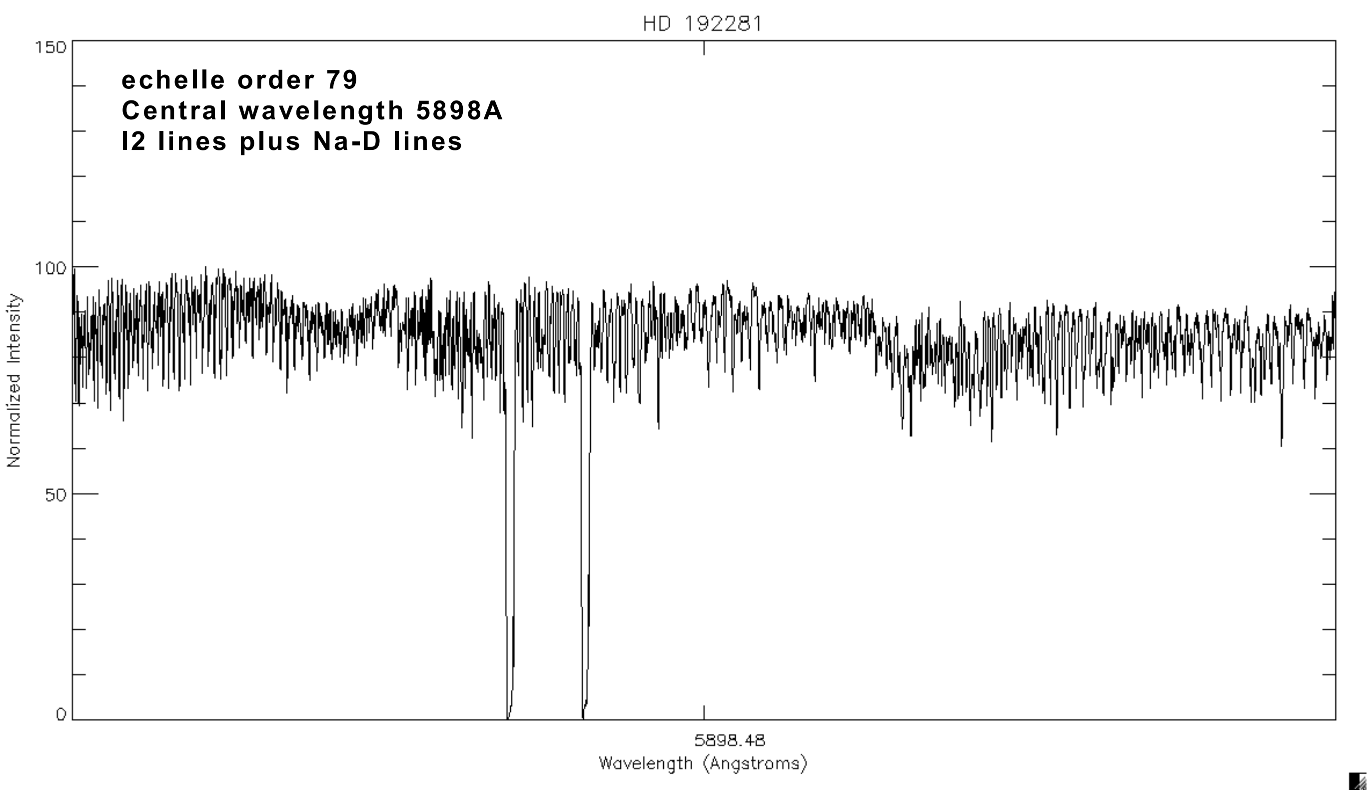
HD 192281 V=7.55 O5V



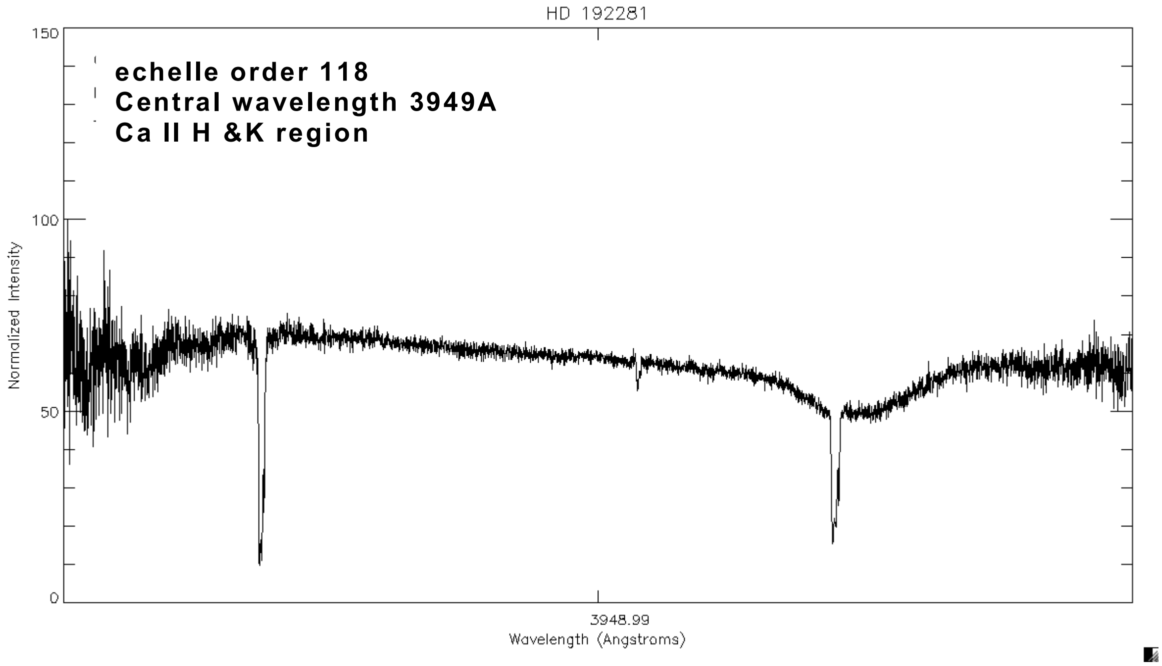
A-Band in HD 192281



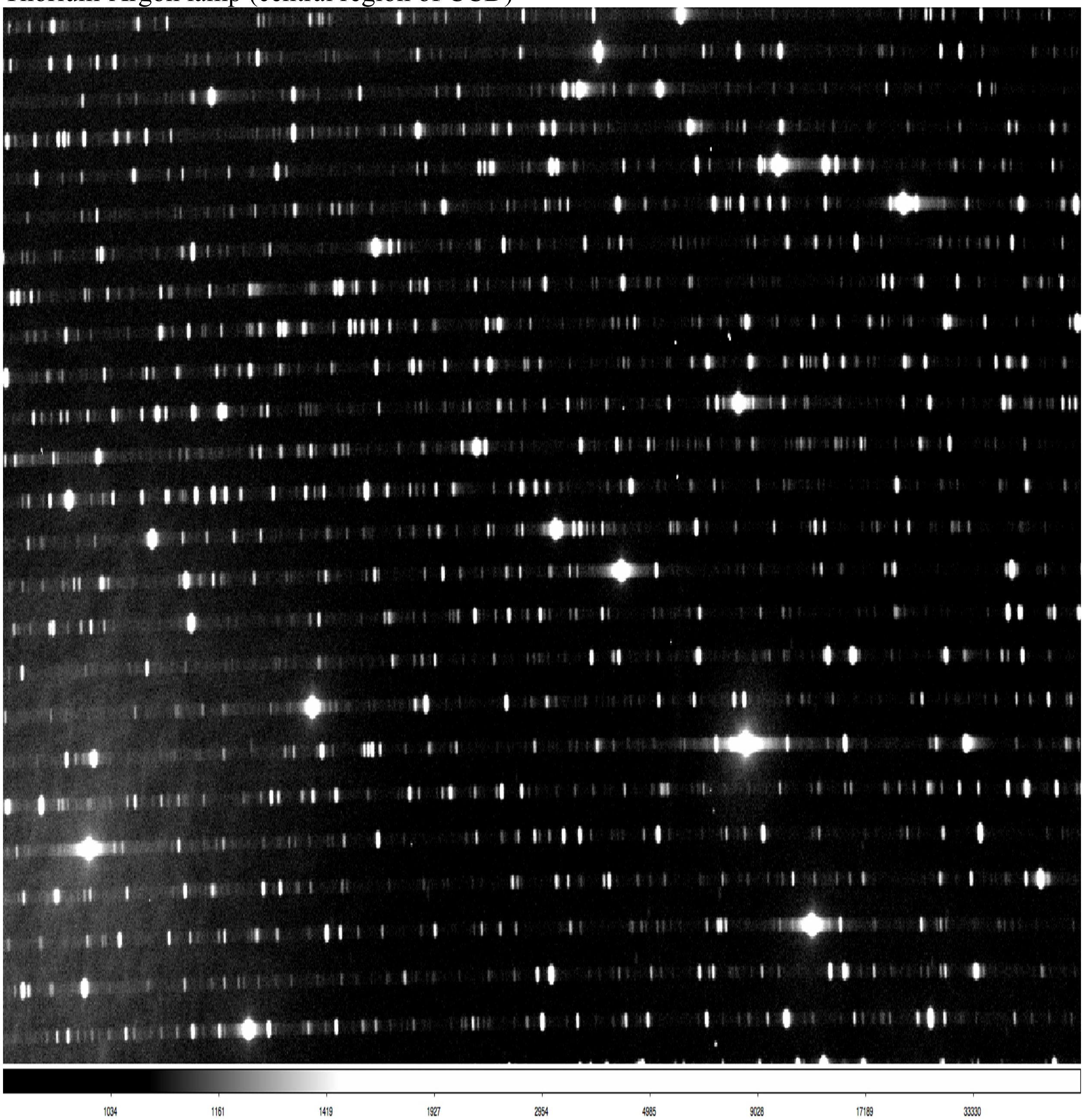
Na-D lines and I_2 in HD 192281



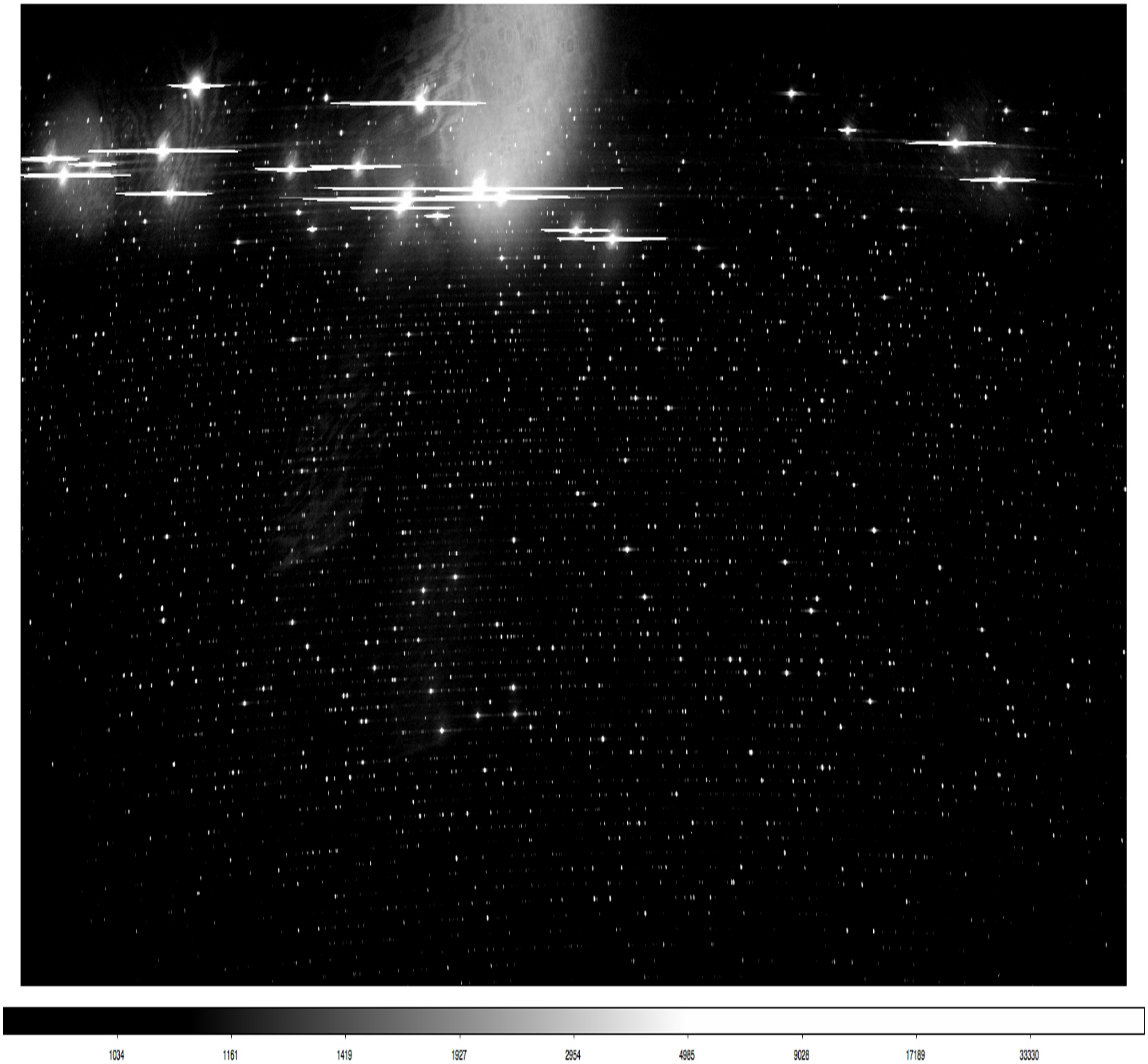
Interstellar CaII H and K in HD 192281



Thorium-Argon lamp (central region of CCD)

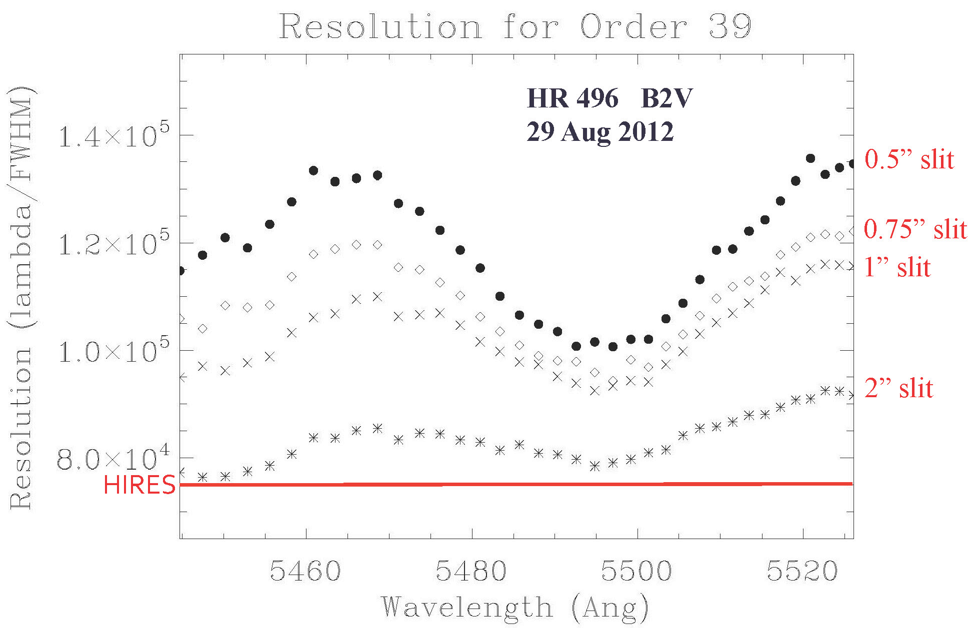


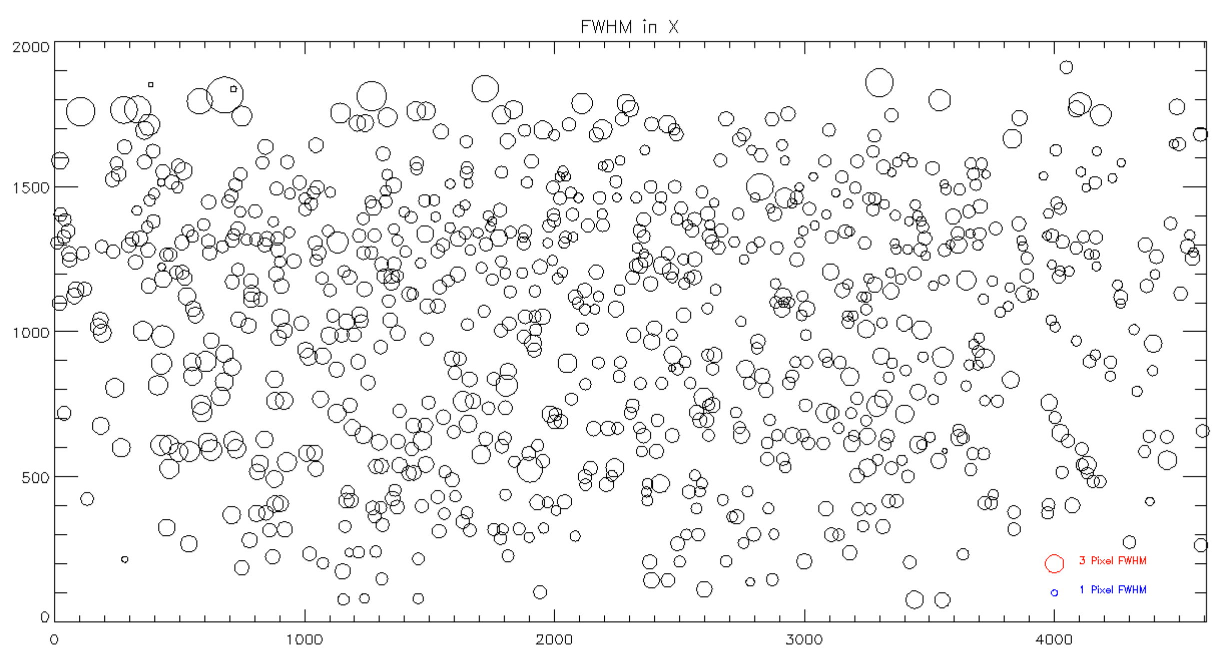
Thorium-Argon lamp (full field)



Resolution

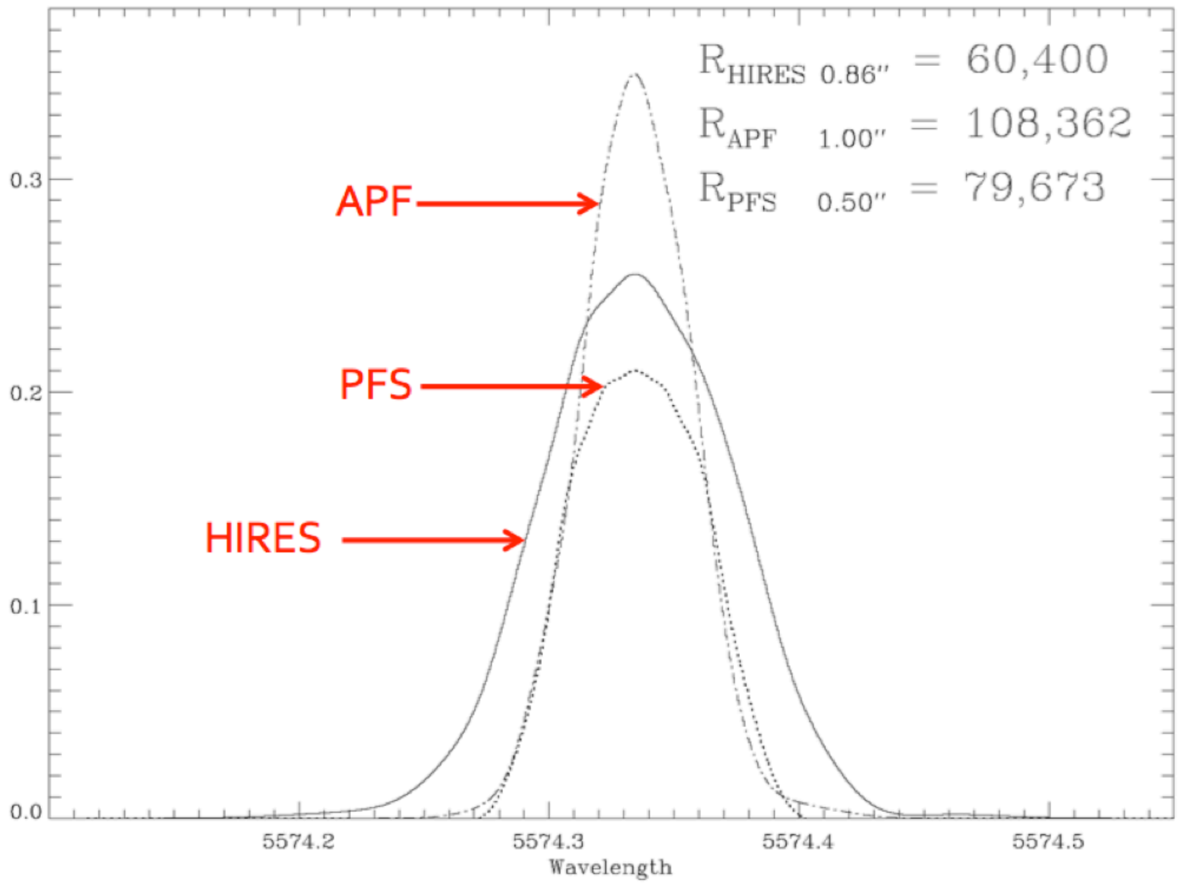
With the narrow (0.5”) slit, resolutions in excess of 100,000 are easily achieved across the entire Iodine region as illustrated in the next two plots. The values in these plots were all obtained at a single best-focus position. Further improvements in resolution can be obtained by slight focus adjustments for any particular region of the echelle format, in some cases reaching as high as 150,000.


Resolution for Order 39
HR 496 B2V
29 Aug 2012
0.5” slit
0.75” slit
1” slit
2” slit
HIRES
Resolution (lambda/FWHM)
Wavelength (Ang)


FWHM in X
3 Pixel FWHM
1 Pixel FWHM

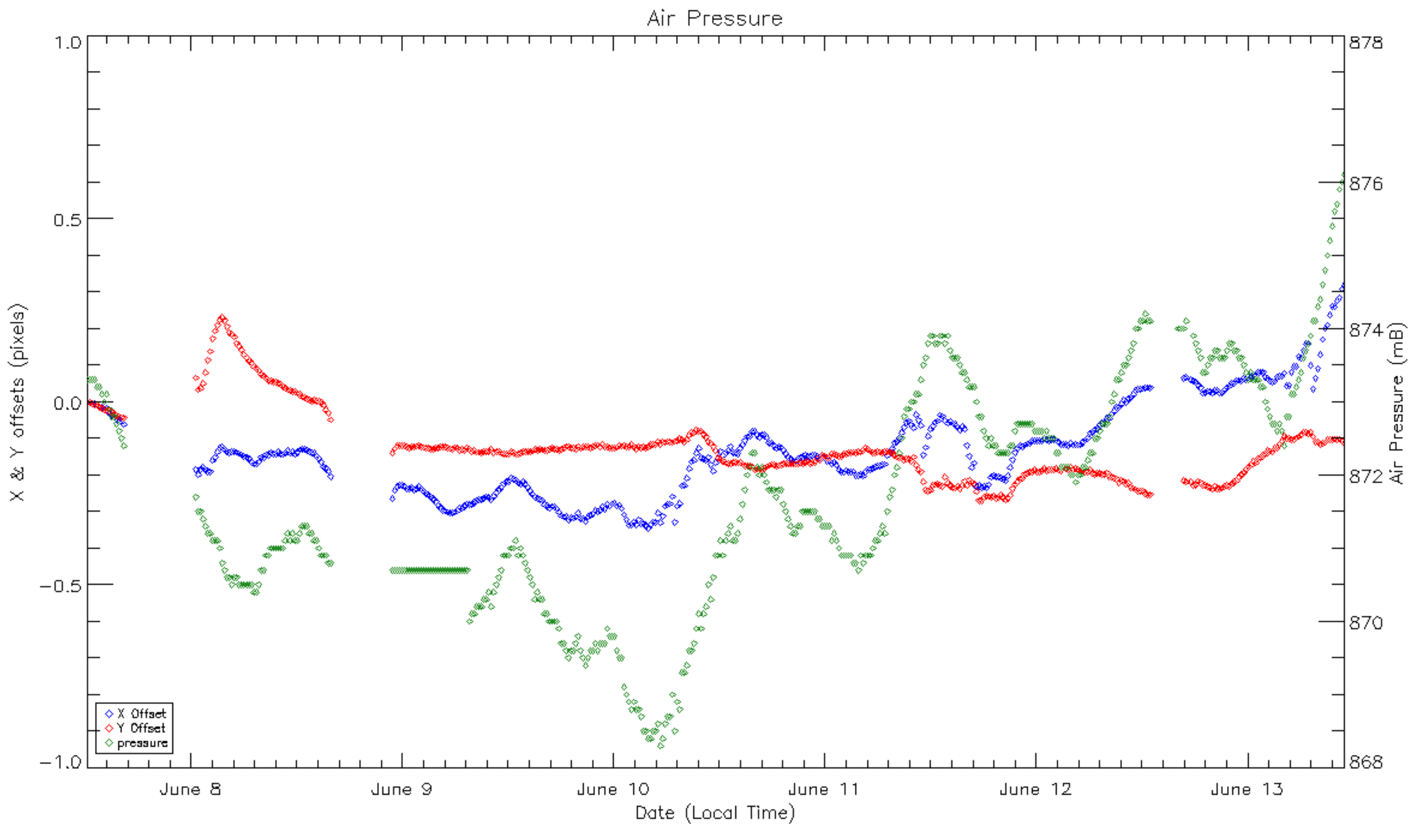
Point Spread Function

The next figure shows the instrumental point spread function (PSF) of APF/Levy as compared to that of the HIRES spectrometer on Keck, and the Planet Finding Spectrometer on Magellan.



Stability of the spectrum

We took many series of Th-Ar lamps through a pinhole slit to assess the positional stability of the spectrum on the CCD over time. Typically, these series run for days, with spectra taken about every 10 minutes. A representative sample of one such 6-day run is shown in the next figure.

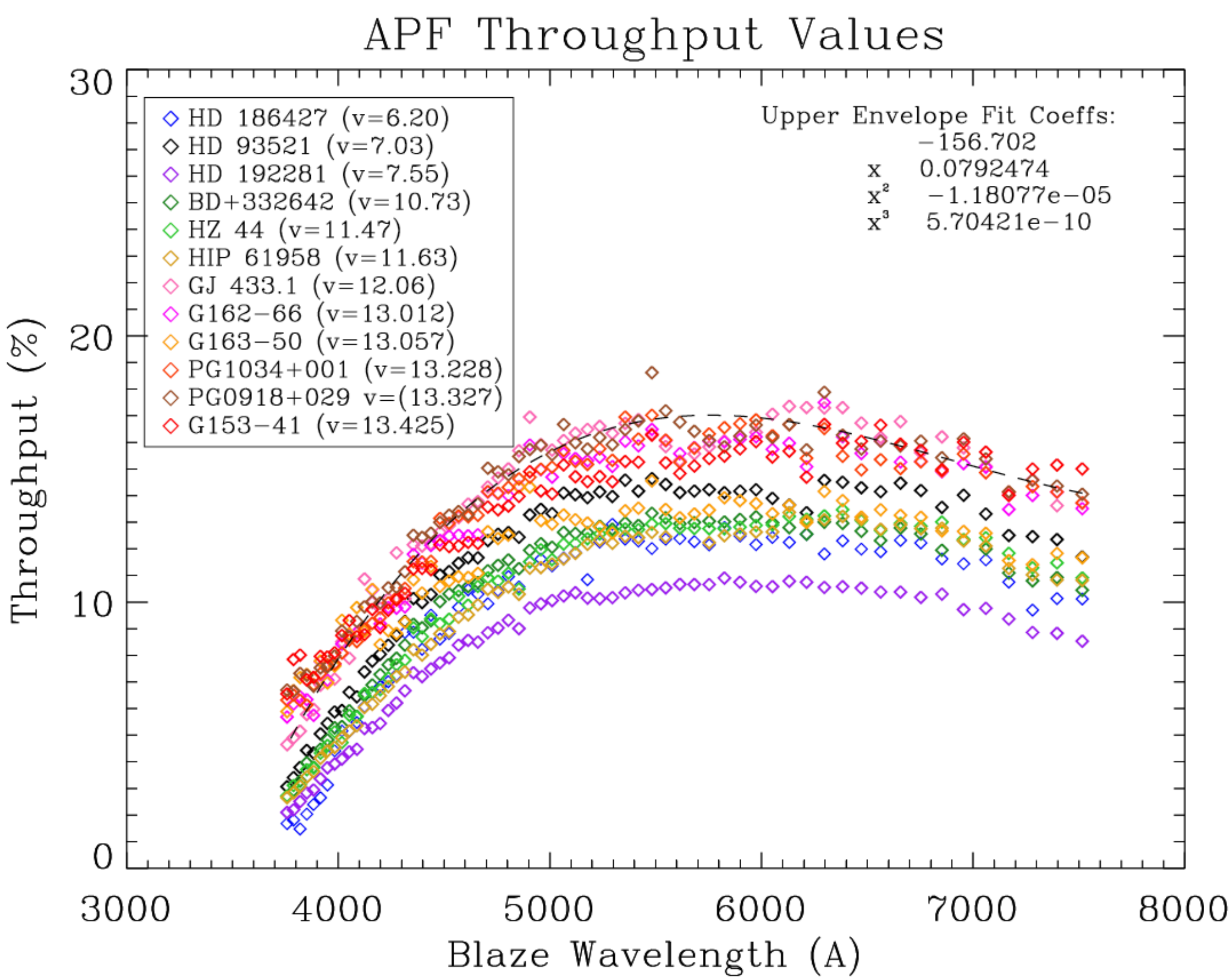


Here, blue represents the X-position (echelle dispersion direction) and red the Y-position (cross-dispersion direction) of the spectrum on the CCD. The green points represent the atmospheric pressure in milli-Bars. We looked at such plots for a large number of variables, most notably the temperatures inside and outside the spectrometer, and of various mechanical components of the optical train. Early n in the commissioning phase, we fund quite significant correlations that we were subsequently able to reduce or eliminate altogether through engineering changes to the electrical inter-connect panel and mounting clamps of the surrounding insulated enclosure of the spectrometer. After months of tracking down and eliminating such correlations, we are left now with a very slight residual correlation of spectrum shift with atmospheric pressure, barely visible by eye in the above plot between X-position and pressure. This is small enough to now be negligible, and would require an expensive vacuum-enclosure to eliminate completely. Most importantly, there seems to be no significant residual correlation between spectral position and the temperatures of any of several dozens of thermal monitors distributed across the instrument.

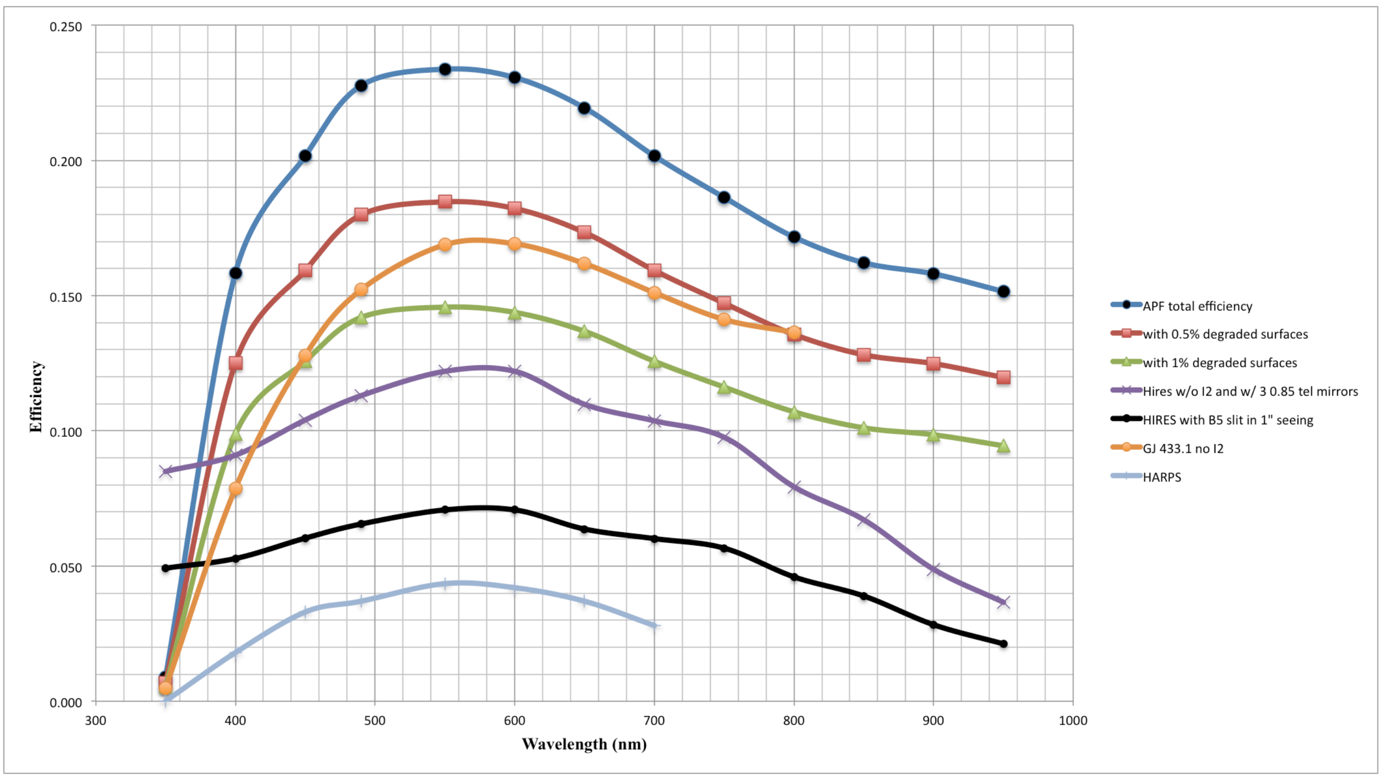
As the above plot shows, the spectrum is stable in position on the CCD to well within +/- 0.3 pixels P-P over the course of 6 days. This is vastly improved over that of HIRES at Keck, where shifts of 1-2 pixels are common from night-to-night. In any event, our I2 technique is quite effective at tracking these shifts and removing them to the level of sub m/s precision.

Overall system Efficiency (preliminary- still a work in progress)

The total overall system efficiency is shown in the next plot. This is a difficult quantity to measure as it depends on observing conditions (seeing, transparency, guiding, etc.) We have attempted here to arrive at a robust result by combining measurements taken on a wide set of photometric standard stars, the upper envelope of which defines the system efficiency under the most ideal observing conditions. In the plot, one may notice some correlation between star brightness and peak efficiency. Some of this may be real, perhaps because we are "over-guiding" on bright stars. But some of it is also an observing selection effect in that we tend to observe the fainter stars only during the best observing conditions.



The fit to the upper envelope was then compared with a detailed spreadsheet model of expected efficiency that was made up using as-measured efficiencies for each of the 47 surfaces encountered by each photon. The next plot shows this comparison. The blue curve shows the expected efficiency for all surfaces operating at their as-built values. Since most of these surfaces are already 5 years old by now, some drop in performance is expected due to coating degradation from humidity, and absorption/scattering from dirt/dust accumulation over the past 5 years. The red curve shows the expected efficiency if every one of the 47 surfaces were operating at 99.5% peak efficiency, while the green curves is for all surfaces operating at 99% peak efficiency. The orange curve is the actual measured system efficiency from the upper envelope of the previous plot. As can be seen, this orange curve is consistent with the as-built efficiency expected for all surfaces operating at 99-99.5% of their fresh peak values. For comparison, the black curve is the actual operating system efficiency of Keck + HIRES (peaking at about 7% when used in 1 arc-second seeing with decker B5). The light blue curve is the reported efficiency curve of HARPS and peaks at only 4.5%. So the APF facility, in terms of raw system efficiency, is about a factor of 4 faster than HARPS, and about a magnitude faster than Keck/HIRES.

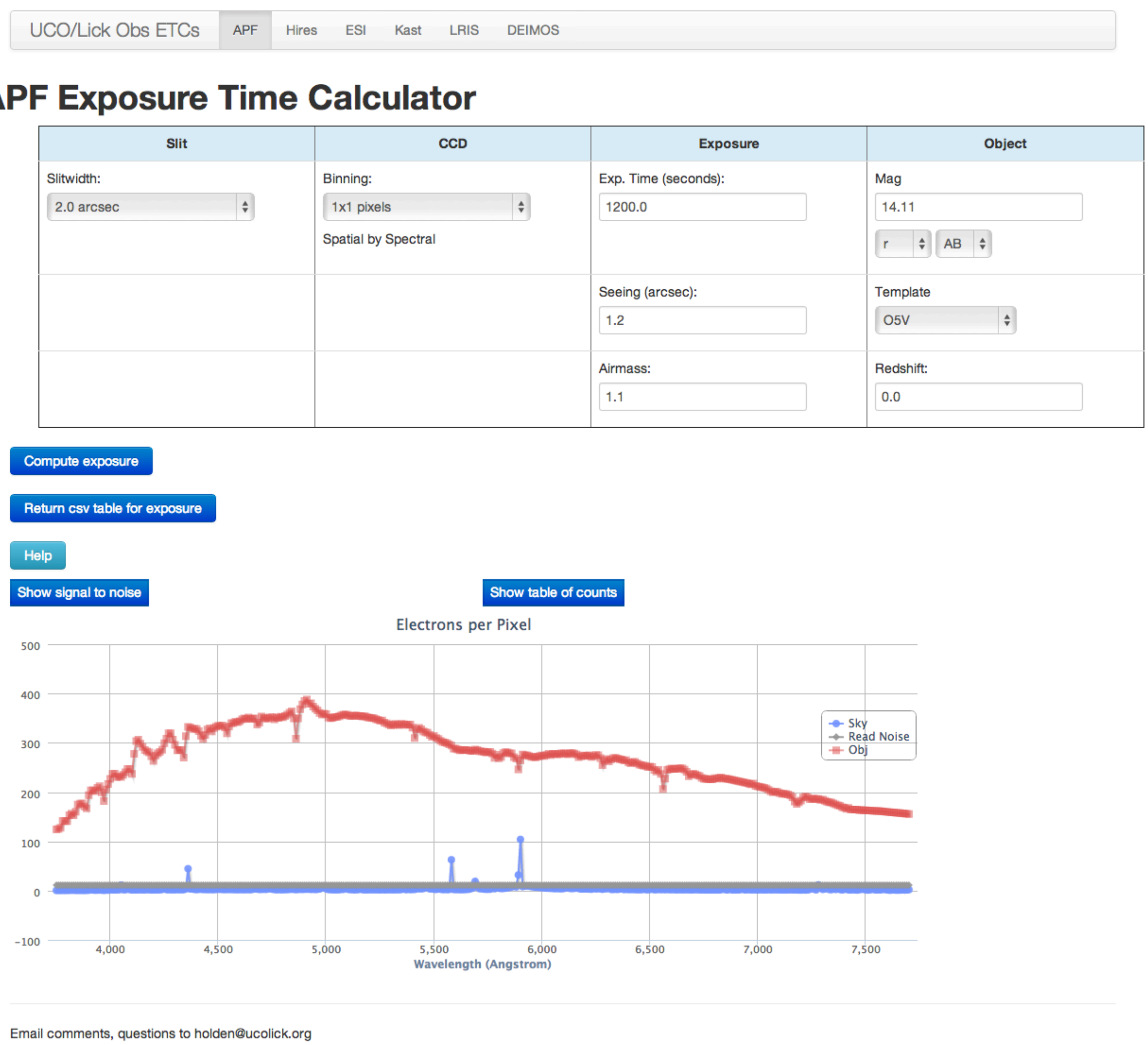


APF S/N simulator (untested and still under development)

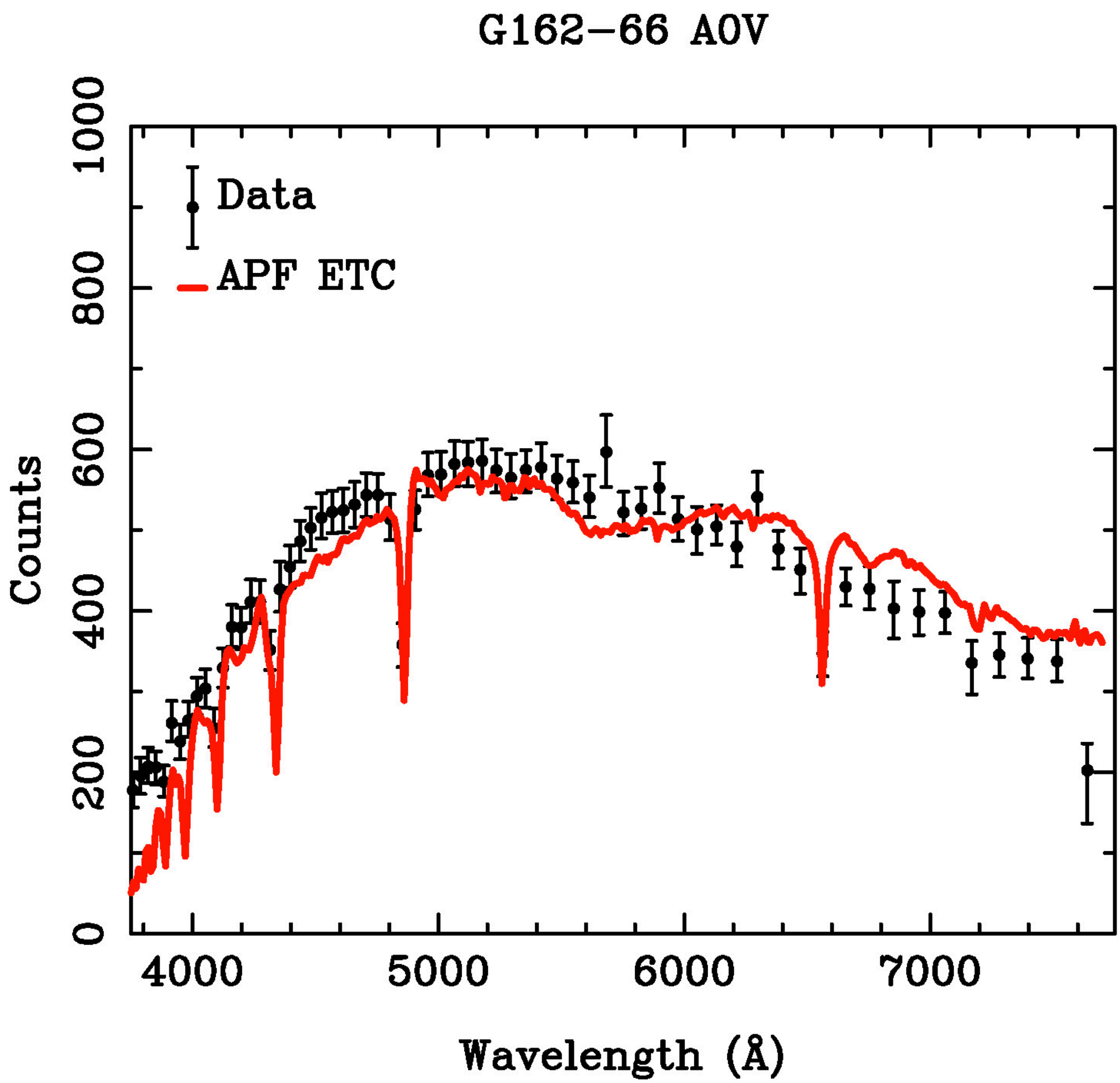
An exposure time calculator is under development by Brad Holden at:

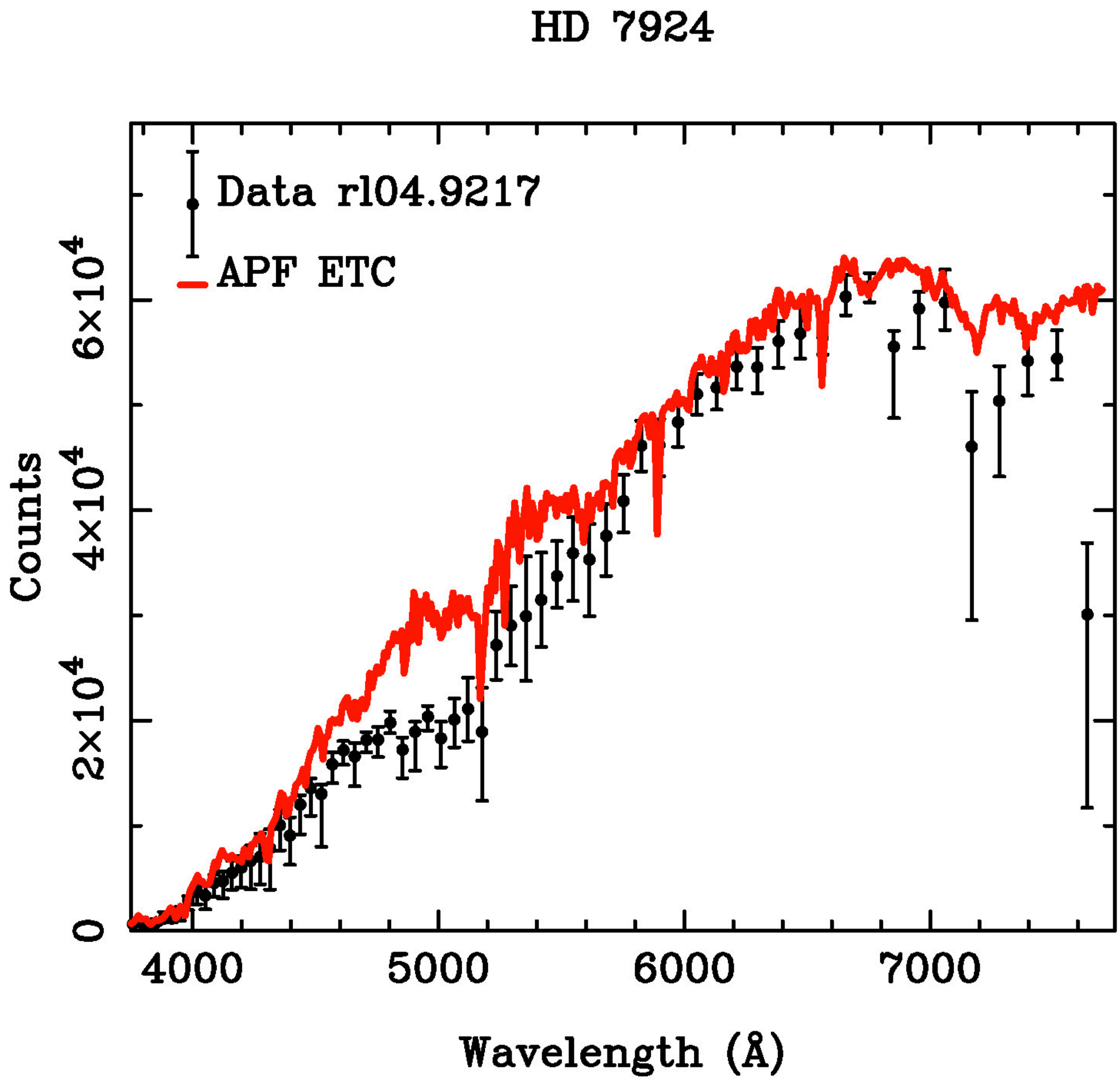
http://etc.ucolick.org/web_s2n/apf

Here is a sample screenshot simulating a 20 minute exposure on an R=14.11 magnitude O5 star. The plot can display either counts or S/N. At present, the simulator assumes perfect sky subtraction and perfect cosmic ray rejection.



The next two plots show comparisons of the simulator against actual APF observations of G162-66 (a dA2 white dwarf photometric standard with R=13.1) and HD 7924 (a V=7.2 K0V exoplanet host star). As can be seen, there may still be some slight color trends that are not accurately captured in the model and/or in the measured system efficiency. This is a work in progress.


G162-66 A0V
Data
APF ETC
Counts
0
200
400
600
800
1000
4000
5000
6000
7000
Wavelength (Å)



Rough speed comparison with Keck/HIRES (back-of-envelope calculation):
10m vs. 2.4m collecting area --> 17.4
Keck+HIRES+B5 decker in 1" seeing: peak efficiency ~ 7%
APF+Levy+1" slit in 1" seeing: peak efficiency ~17%
Expected speed ratio (Keck/APF) ~ 7
Measured speed ratio on HD 185144 = 6.3

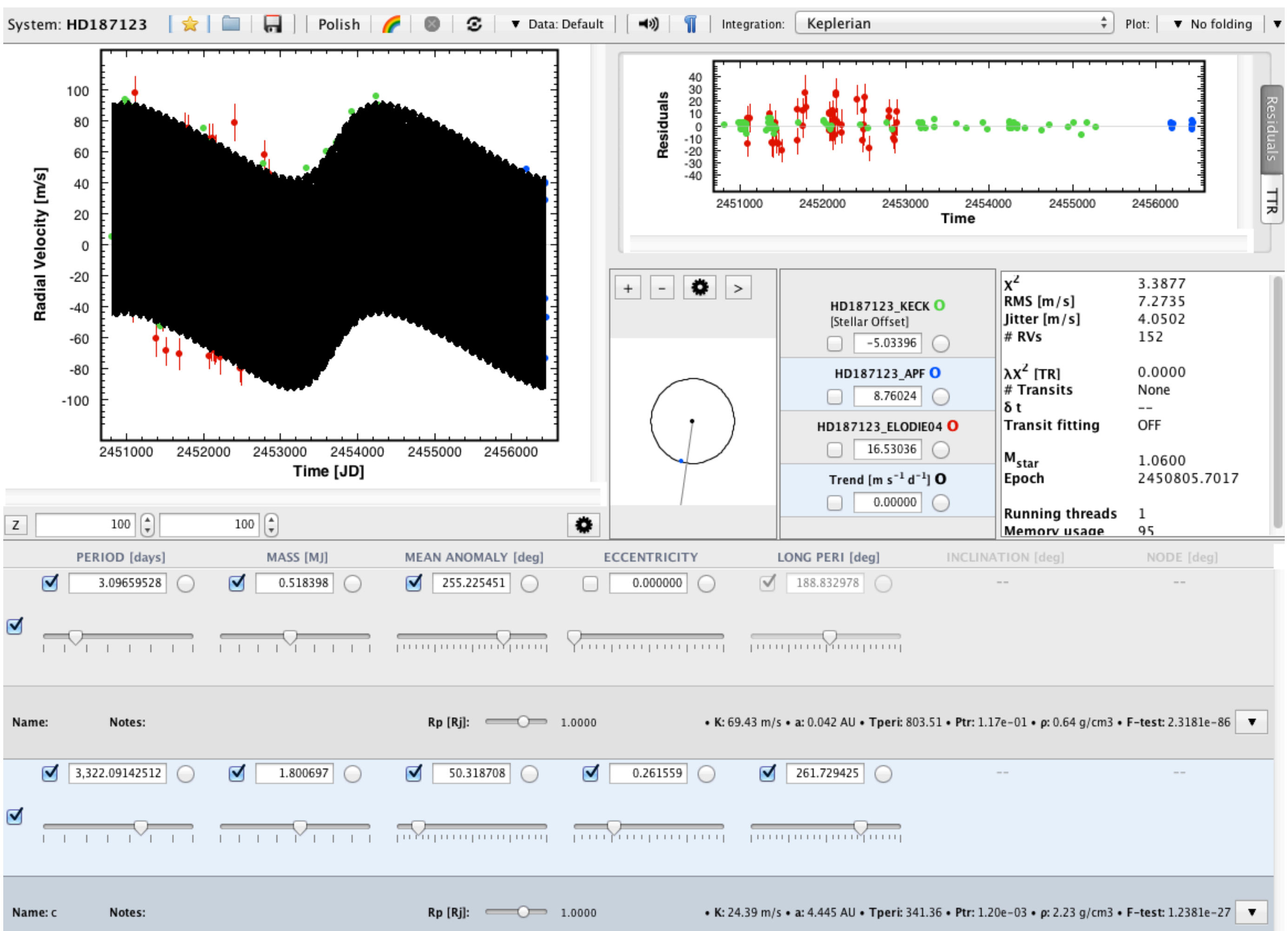
Keck -- j810229.fits, rj81.229 airmass = 1.58 seeing ~ 1"
IDL order 15: counts / A / sec = 340648
APF -- apf39212.fits, rl04.9212 airmass = 1.37 seeing ~ ?
IDL order 51: counts /A / sec = 54105

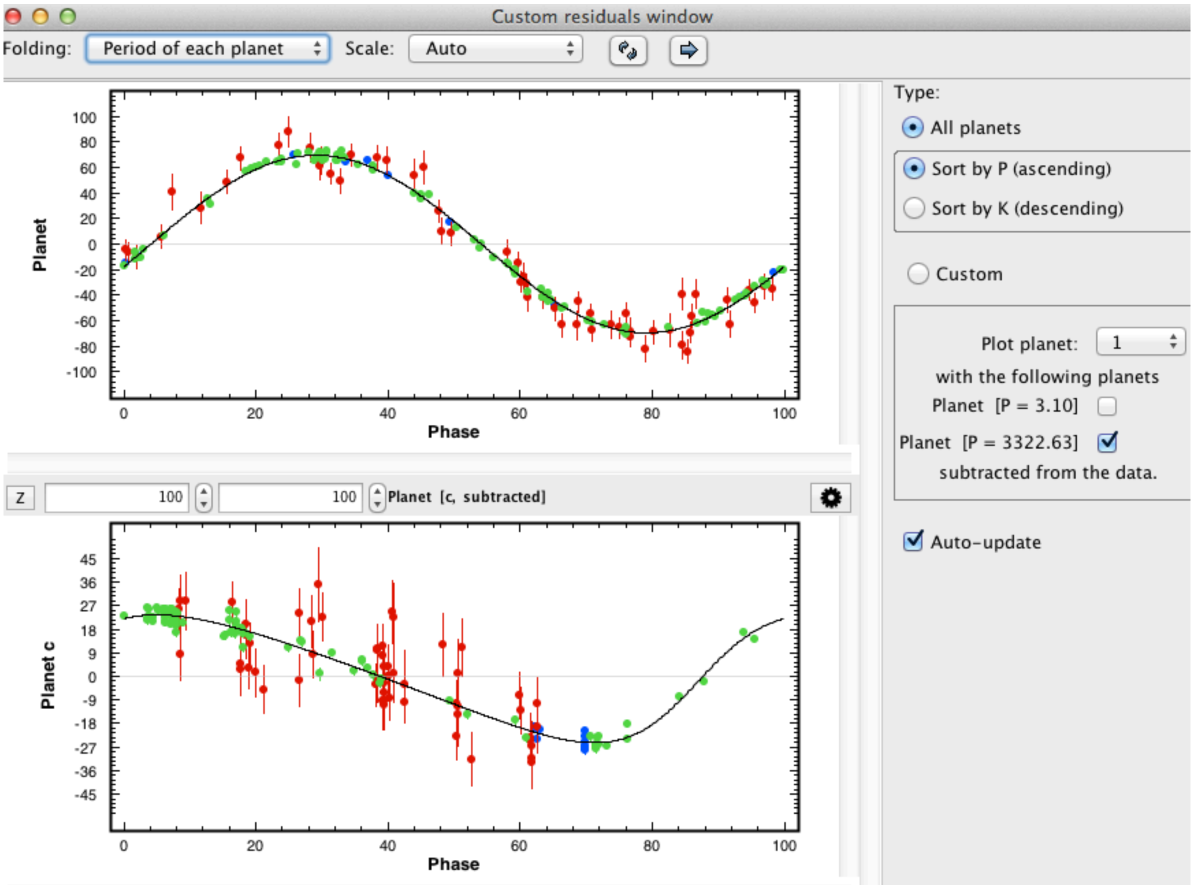
Preliminary assessment of radial velocity precision

Herewith is a brief update on the radial velocity performance of the APF as of June, 2013. In assessing RV precision, we combined data from two observing periods, Sept-Oct 2012, and from about a week in early June 2103. In one case, a few data points were obtained during January, 2013, but the instrument and telescope were in a severe state of instability during that time, due to lack of temperature stabilization, frequent insults to the spectrometer's interior, and telescope mis-tuning issues. For the most part, exposures were all obtained at an exposure meter setting that made the APF exposures ~5 times that of HIRES/Keck on overlap stars. The relative speed difference between APF and Keck is expected to be about 5-6, so this choice of 5x longer exposures for APF was done to create a more meaningful comparison of performance. That said, the APF delivers higher spectral resolving power and higher pixel sampling of the PSF, so might be expected to have an advantage for equal S/N spectra. That comparison involving the quantitative effects of resolution, sampling, and signal levels is beyond the scope of the present analysis, requiring much more data taken over a variety of conditions on carefully chosen stars.

HD 187123

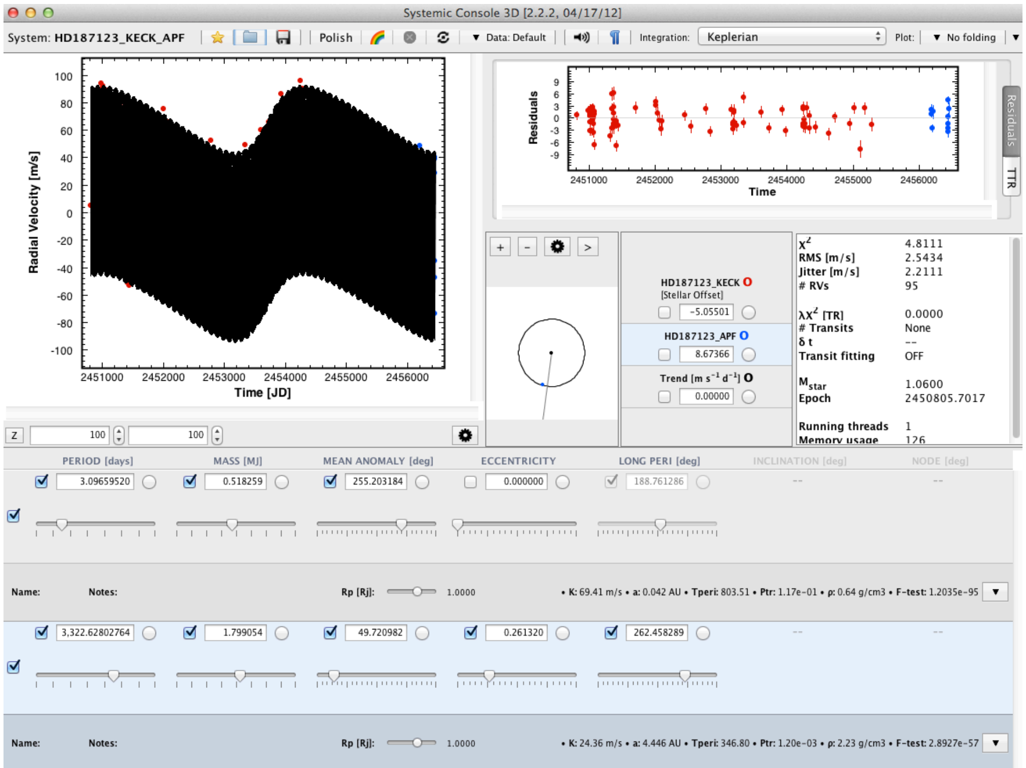
We first fit the system using all existing Keck (85) and Elodie (57) data, plus all APF (10) data. The fit easily reveals the well-known 3.1-d planet, plus now a clearly evident 2nd planet at ~3322d. This outer planet is highly significant and revealed unequivocally by the extensive Keck data set. The RMS of the fit here is strongly dominated by the Elodie data at 7.27 m/s.

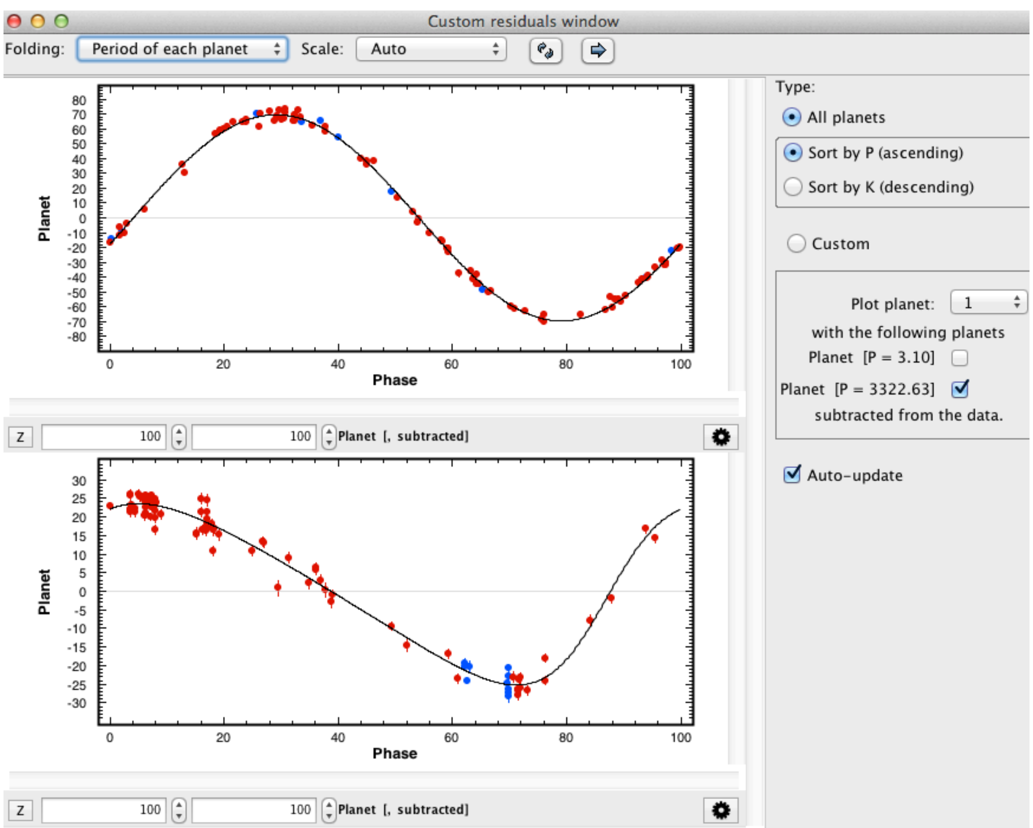




A seen above, the phase curve of the 3322d is well covered by the Keck data. This outer planet is now fully ready for publication.

Now, we remove the noisy Elodie data and look at the fit quality using only Keck and APF data and these same two planets.





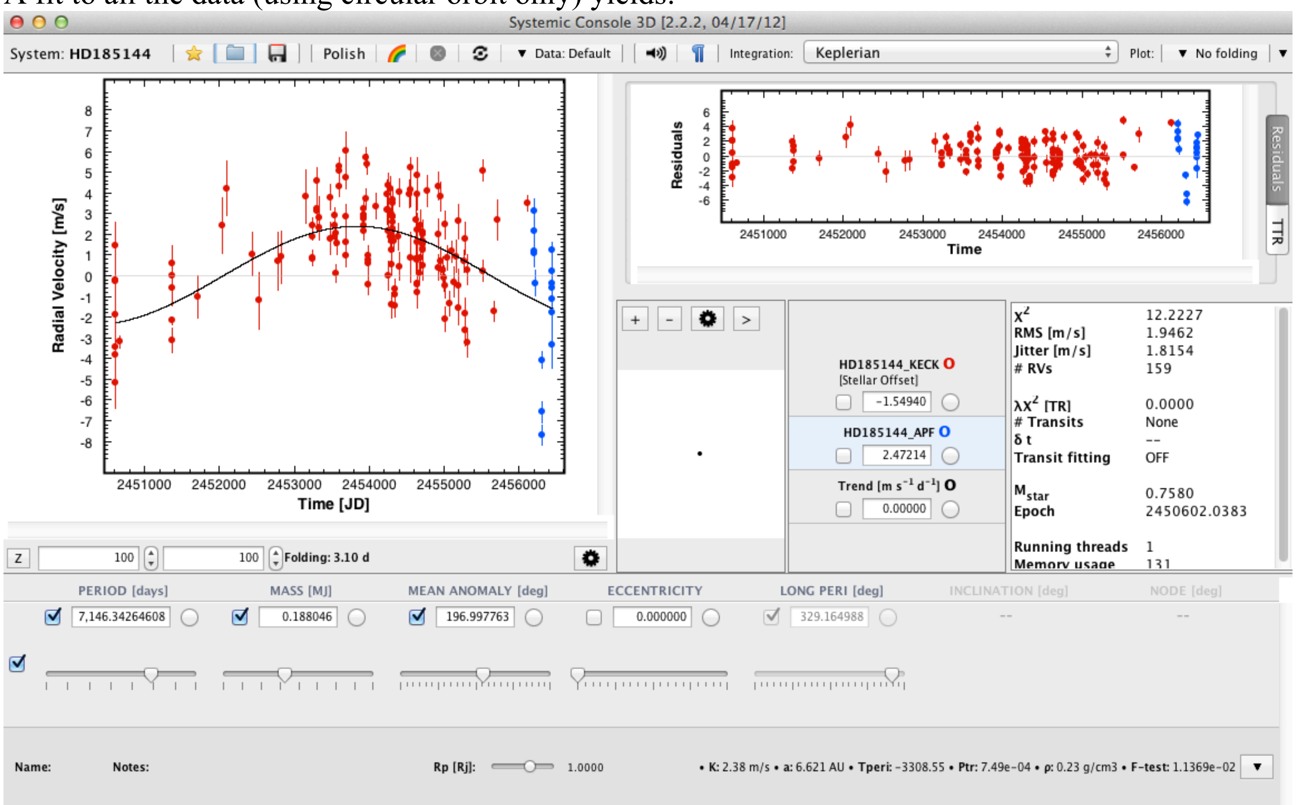
The RMS of the fit is now down to 2.54 m/s with jitter of 2.2. This means that the present fit would have a chi-squared fitting statistic of 1.0 if the stellar jitter were 2.2 m/s. The expected jitter for this star is 2.7 m/s, so we are fitting as well as can be expected given the uncertainty in the stellar jitter.

The same 2-planet fit for Keck data alone yields RMS=2.56 m/s. So APF data is *not* adding any additional scatter to the fit. It can be concluded that present limited set of APF velocities for HD 187123 are at least as precise as those from Keck.

HD 185144 (Sigma Dra)

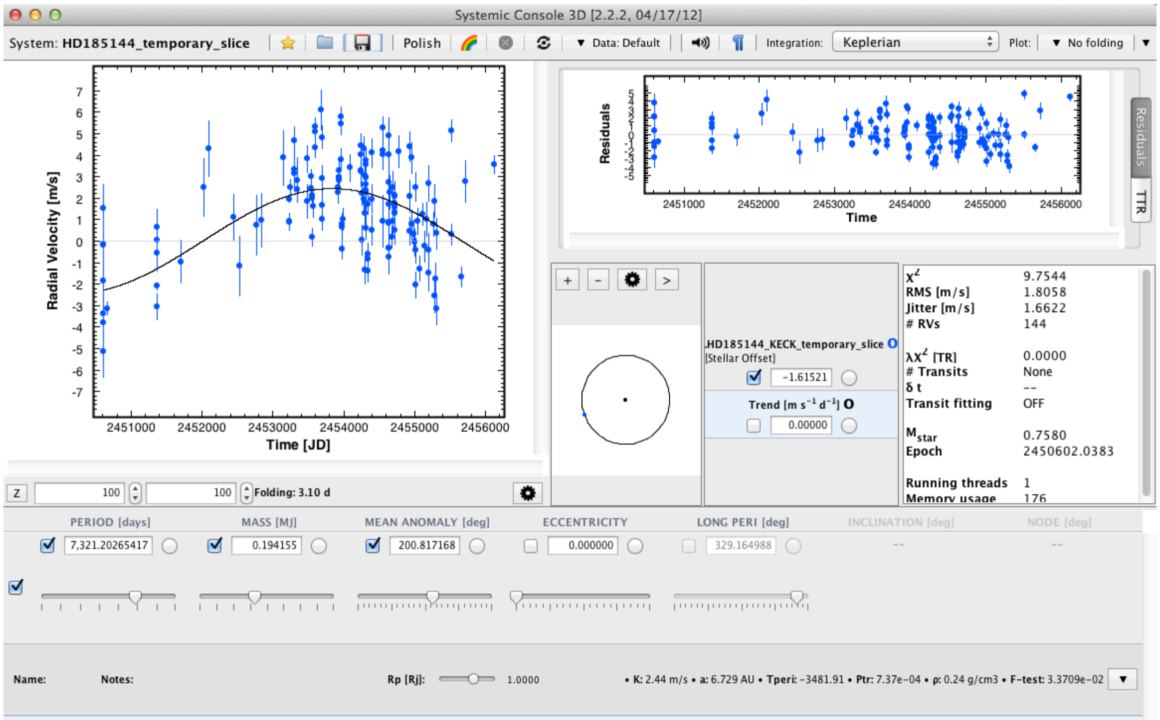
This is one of our traditional RV standard stars at Keck. However, over the 15 years it has been followed at Keck, a long-term 2nd companion now seems clear. APF velocities do not add much since there are so few of them, over a short time base, and the unknown APF velocity offset can be used to absorb a host of ills in the combined fit.

A fit to all the data (using circular orbit only) yields:

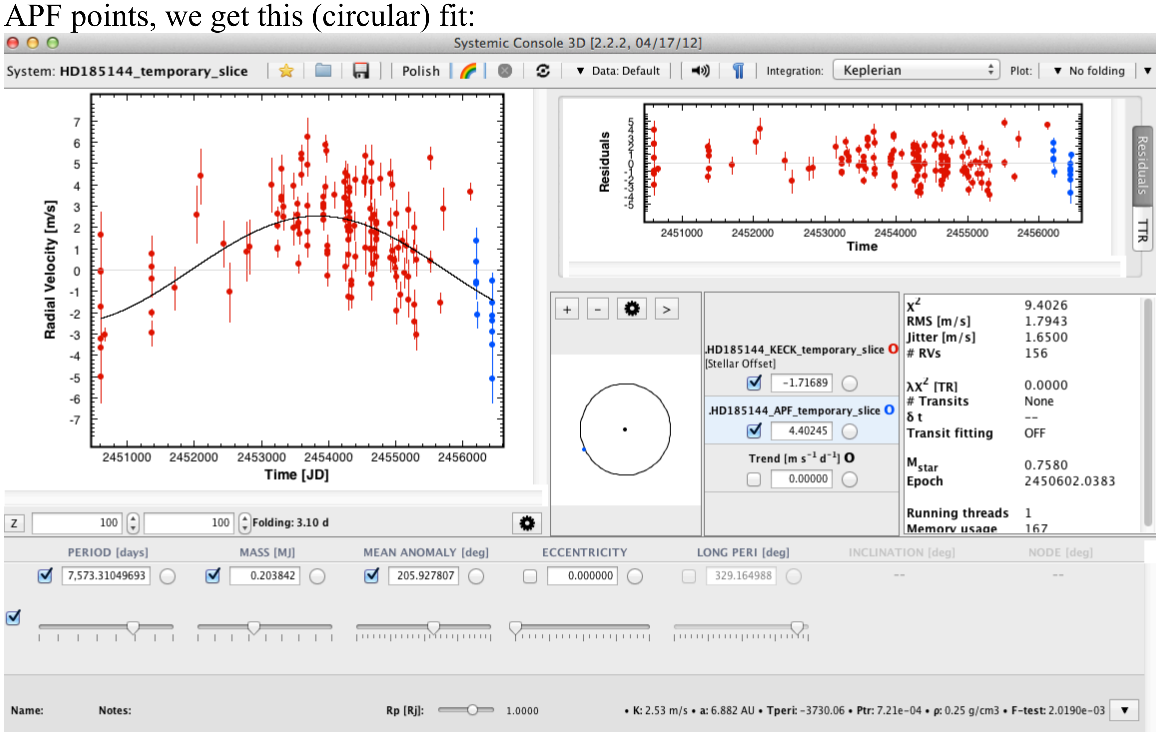


The RMS of this fit is 1.95 m/s.

A fit to Keck only data gives an RMS = 1.81 m/s as shown in the next figure.



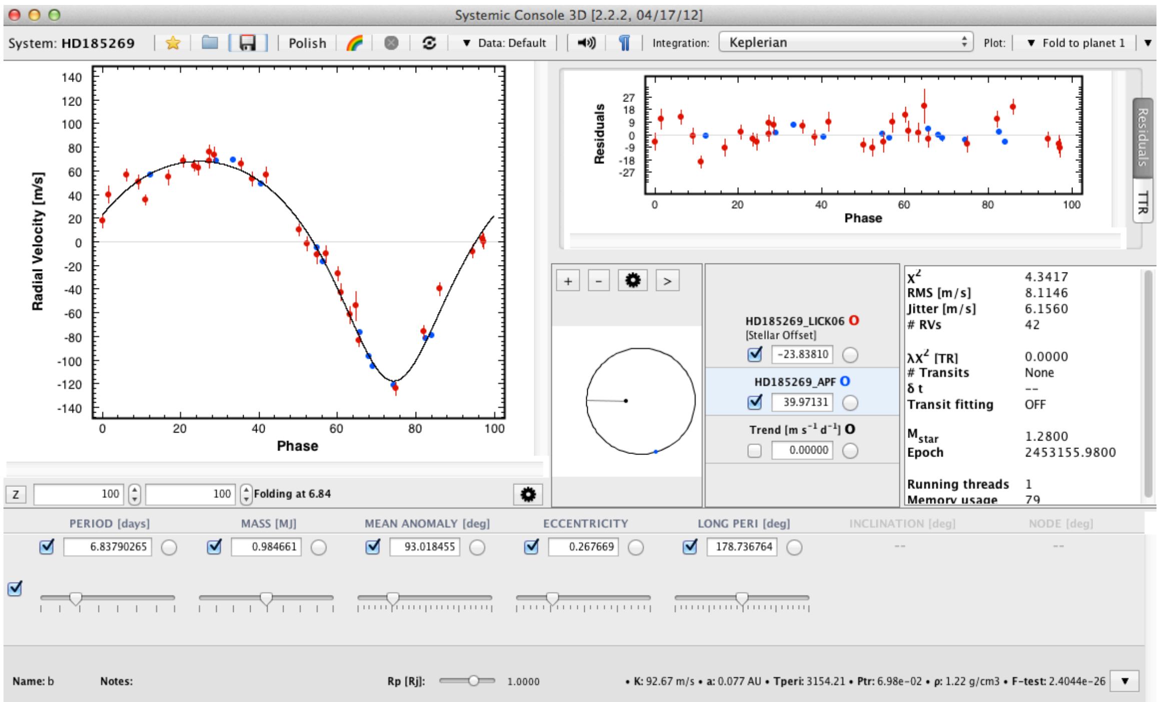
So, with this star, it is possible that APF is adding a bit of noise. The 3 data points taken in Jan 2013 are all low as a group with respect to the rest of the APF data. If we remove these Jan 2013 APF points, we get this (circular) fit:



The RMS drops to 1.79, in-line with what Keck gives. So it is possible that the Jan 2013 APF data is adding scatter to the fit for this star, but without it, the APF data looks every bit as good as Keck.

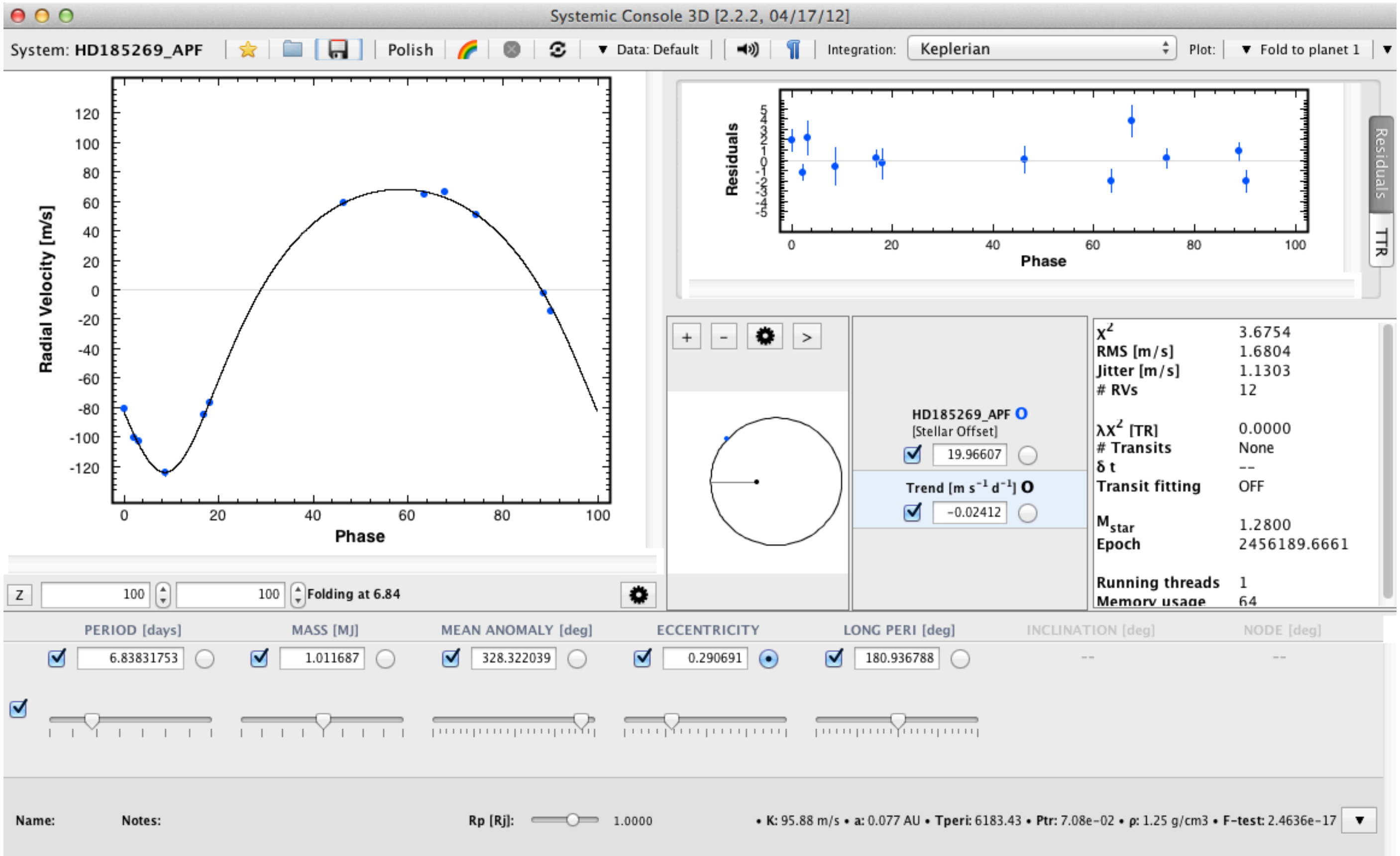
HD 185269

This star previously had Lick data only and hosts a well-known 6.8-day Hot Jupiter. We showed the six APF velocities from Sept-Oct 2012 at the Readiness Review, and now have 6 more from June, 2013. In both APF blocks, we were fortunate to cover essentially the entire phase diagram of this eccentric orbit. Here is the combined fit using all data.



The RMS= 8.1 m/s of the fit is dominated by the relatively poor Lick data. Fitting APF data only to this exact same orbit (varying only the velocity offset and T_0) drops the RMS to 3.2 m/s. Allowing the period, MA, eccentricity, and longitude of periastron to float yields RMS= 3.17, not significantly better. The derived jitter is 2.9 whereas the expected jitter for this star is 2.54 m/s. So the fit is basically perfect (chi-squared = 1.0) if the stellar jitter is as expected. It is also worth noting that, with an F-test = 6e-14, APF easily nailed this orbit after only 12 velocities.

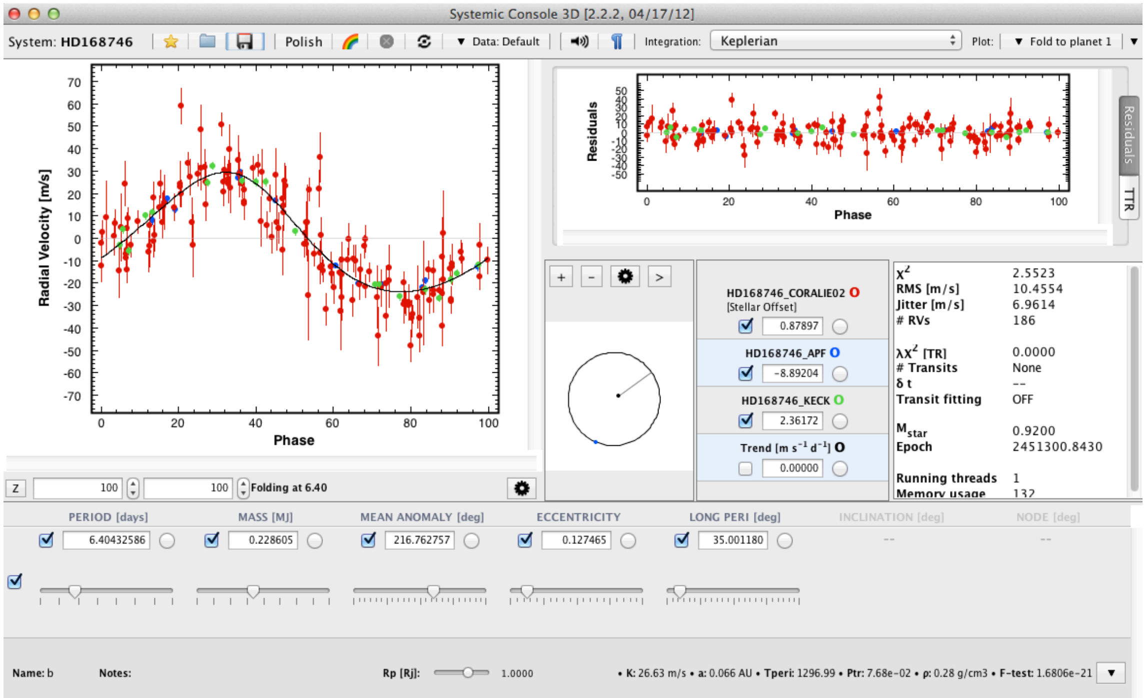
It is possible also that this system has a longer-term companion that might manifest as a small linear trend at this point. Indeed the chi-squared of the fit to the entire data set is definitely improved by allowing a very small (~-9 m/s/year) linear trend. Allowing that same trend to the APF data by itself improves the APF-alone-fit thusly:



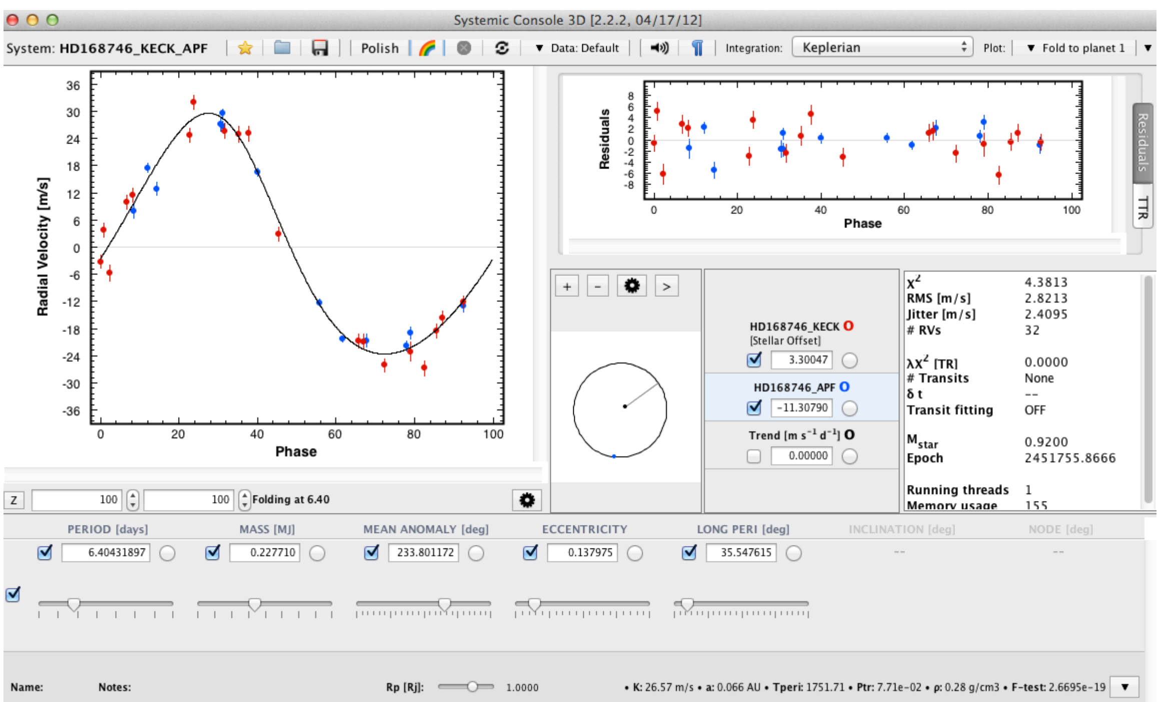
The fit is now at RMS=1.68 m/s with jitter of 1.1 m/s. Clearly, APF is doing very well indeed on this star, probably better than 2 m/s RMS. But it is difficult to know how much better due to the lack of high-precision data over a longer time base from other sources.

HD 168746

This star has a well-known 6.4-day Saturn-mass planet. We already had 154 CORALIE velocities, and 19 Keck velocities. We got 7 APF velocities in Sept-Oct of 2012, and added another 6 this past June, 2013. The fit to all the data yields an RMS=10.5 m/s, completely dominated by the relatively noisy CORALIE data.

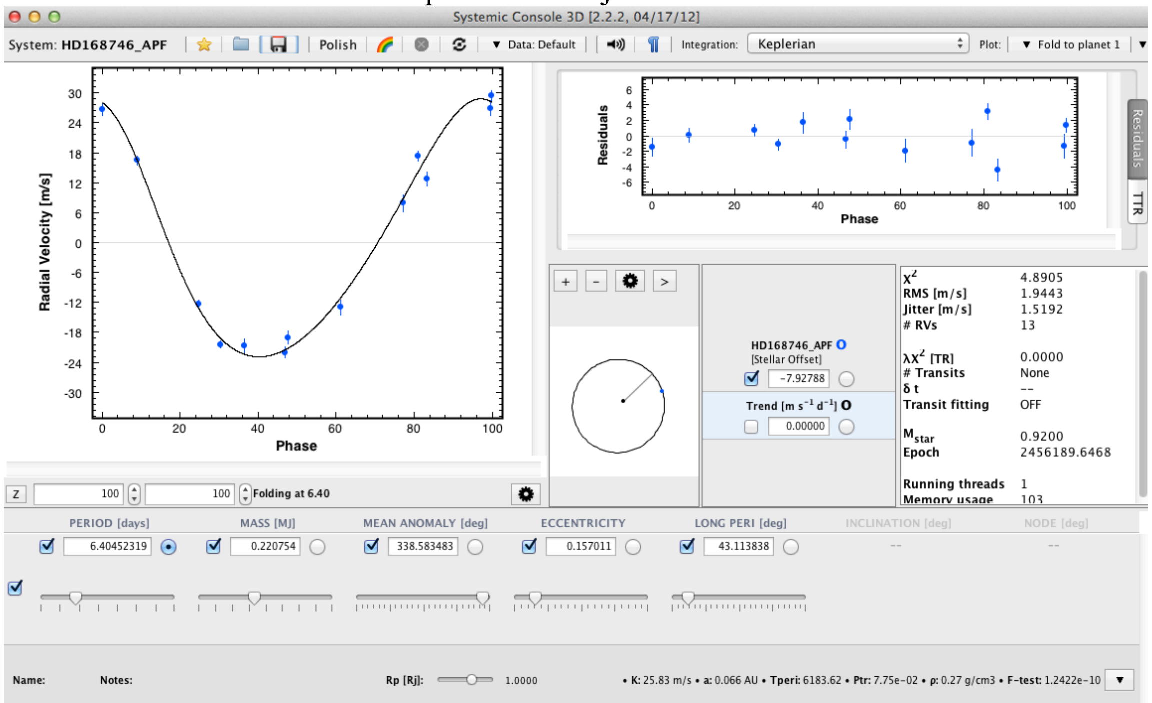


Removing the noisy CORALIE data yields a fit with RMS=2.8 m/s (using no adjustments other than the velocity offset between Keck and APF). Allowing the planet's orbital parameters to optimize yielded no further improvement in RMS.



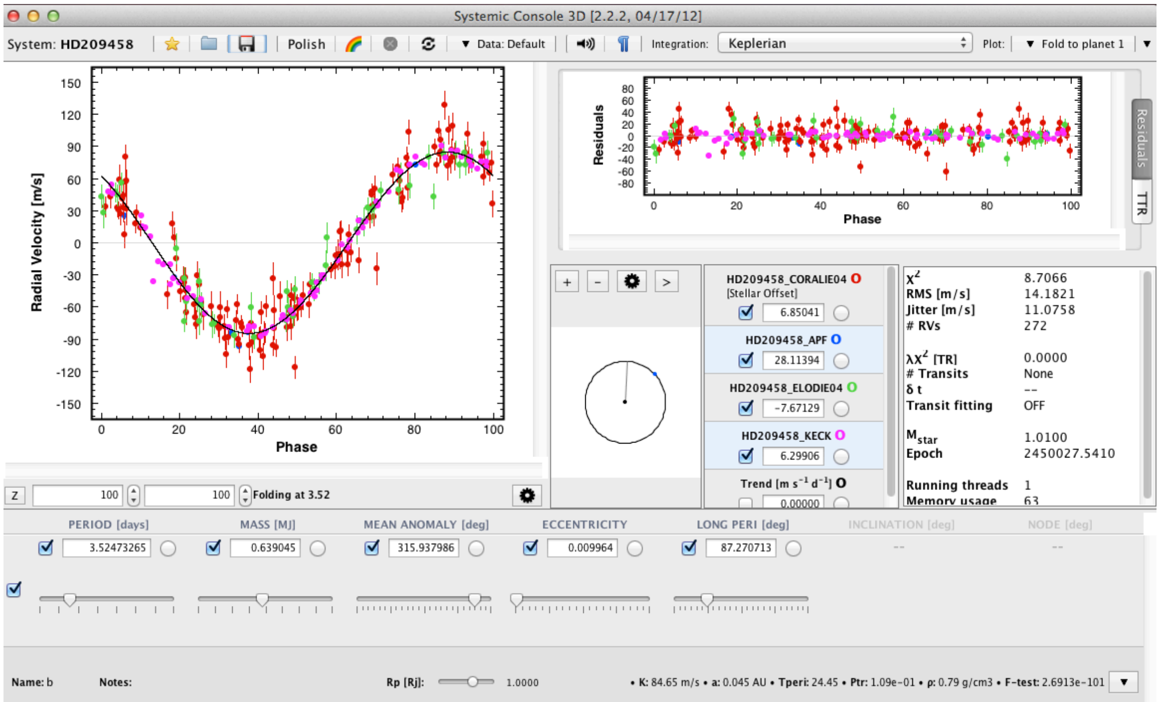
Using only the 13 APF points as fit to the identical orbit (with only velocity offset adjust) yields a fit with RMS=2.3 m/s. Allowing a slight tweak of orbital parameters produces a fit with RMS=

1.94 m/s. Again, with an F-test of 10e-10, the fit to the APF data alone easily nailed the orbit of this planet with only 13 velocities and provided a textbook-perfect chi-squared = 1.0 fit to well within the level of the 2.7 m/s expected stellar jitter.

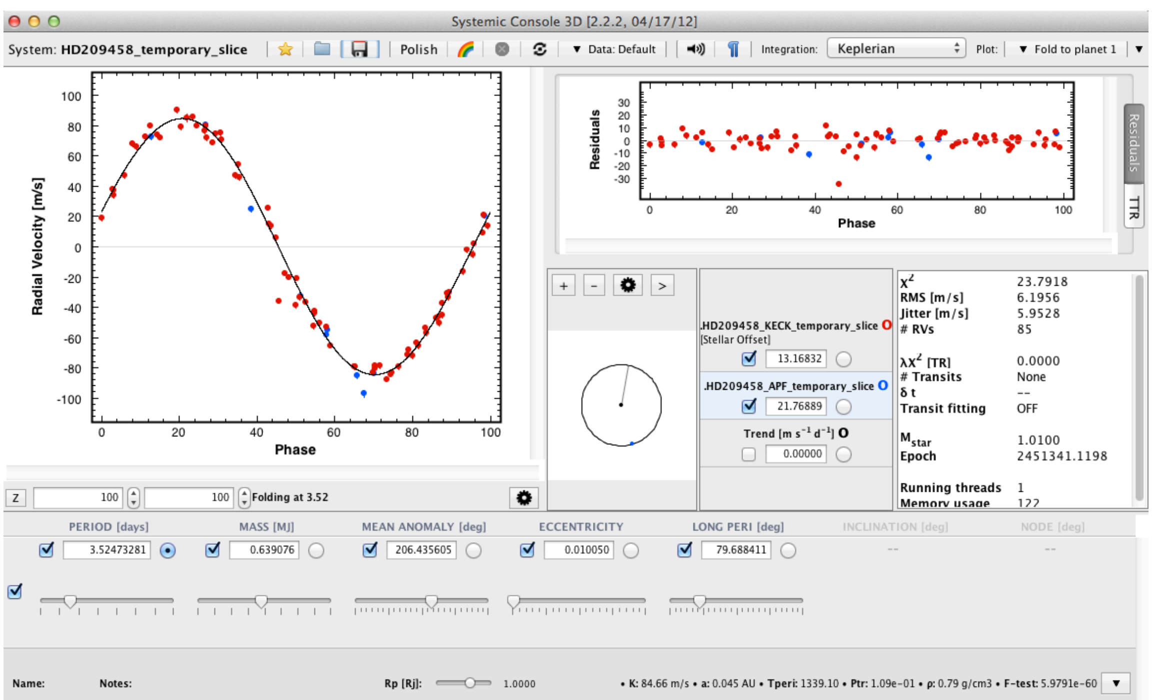


HD 209458

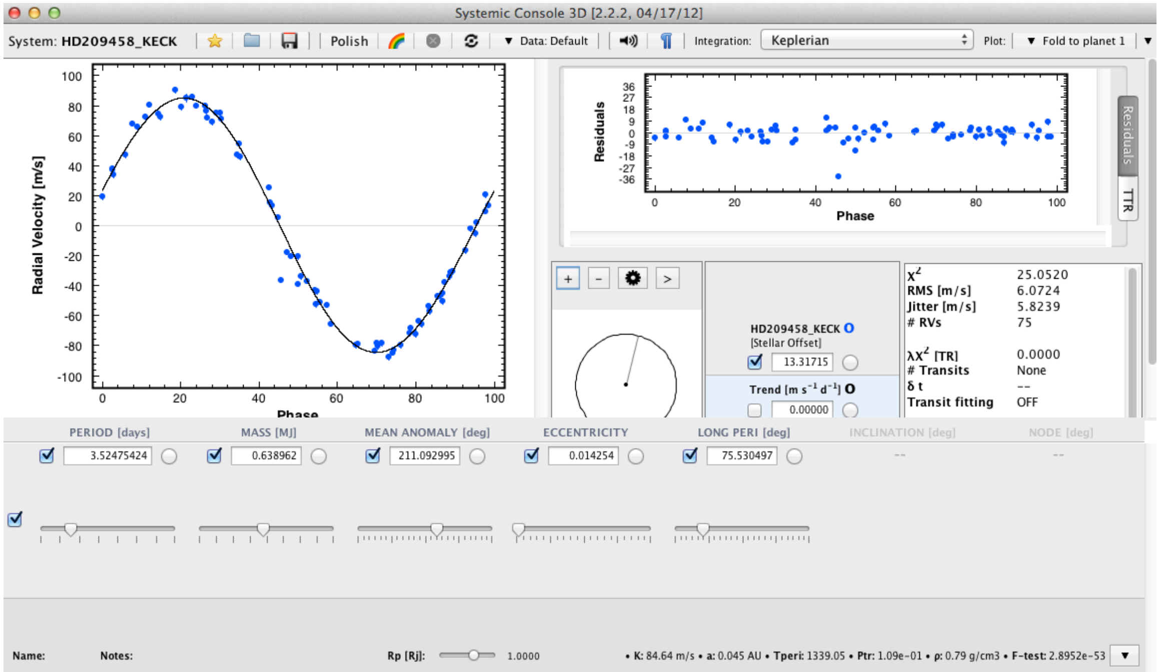
This star hosts the first known transiting Hot Jupiter. We already had 272 velocities from CORALIE, ELODIE, and Keck. Here, we ignore any points that might be contributing excess RMS due to the Rossiter-McLaughlin effect. A fit to the 3.5-day planet using all 272 velocities yields RMS=14.2 m/s, dominated again by CORALIE and ELODIE scatter.



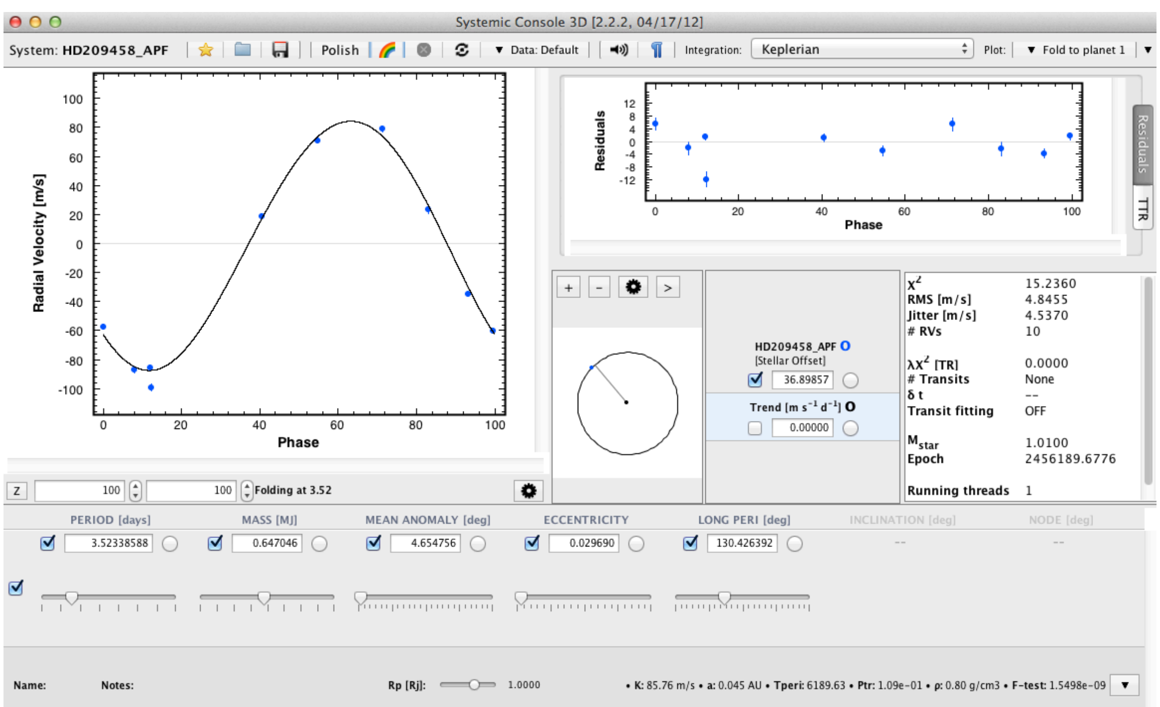
A fit using only Keck and APF data yields RMS=6.2 with jitter of 6.0 m/s. Expected jitter is 2.8 m/s. There are clearly still a few points that are showing Rossiter-McLaughlin, but the RMS is being mostly driven just by Keck scatter.



A fit to only Keck data yields RMS= 6.1 m/s as shown here. Clearly the APF points are *not* adding any excess scatter, and the existing scatter is being dominated by Keck data.



A fit using the same orbit to the APF data alone achieves the same RMS=6.1 m/s, while a fit allowing the orbital parameters to float produces RMS=4.85 m/s. While it is probably not fair to allow the orbital parameters to re-optimize when fitting this small number of APF data points alone, the APF data is apparently not contributing any excess noise over what Keck produces for this star.



Conclusions

We have attempted to estimate the radial velocity precision of the APF facility over the past 9 months as we work through the commissioning phase. The analysis herein rests on data that was taken over predominantly two observing periods: Sept-Oct 2012, and early June 2013. In all cases, the exposure times used were 5x that used at Keck on these same stars.

The present limited data set indicates that radial velocity precision with APF is at least as good as with Keck/HIRES, for exposures that are only 5x longer at APF than at Keck. In a few of the cases, the measured precision is clearly better than 2 m/s, but how much better is difficult to determine without better understanding of stellar jitter, and without having many more such test cases.

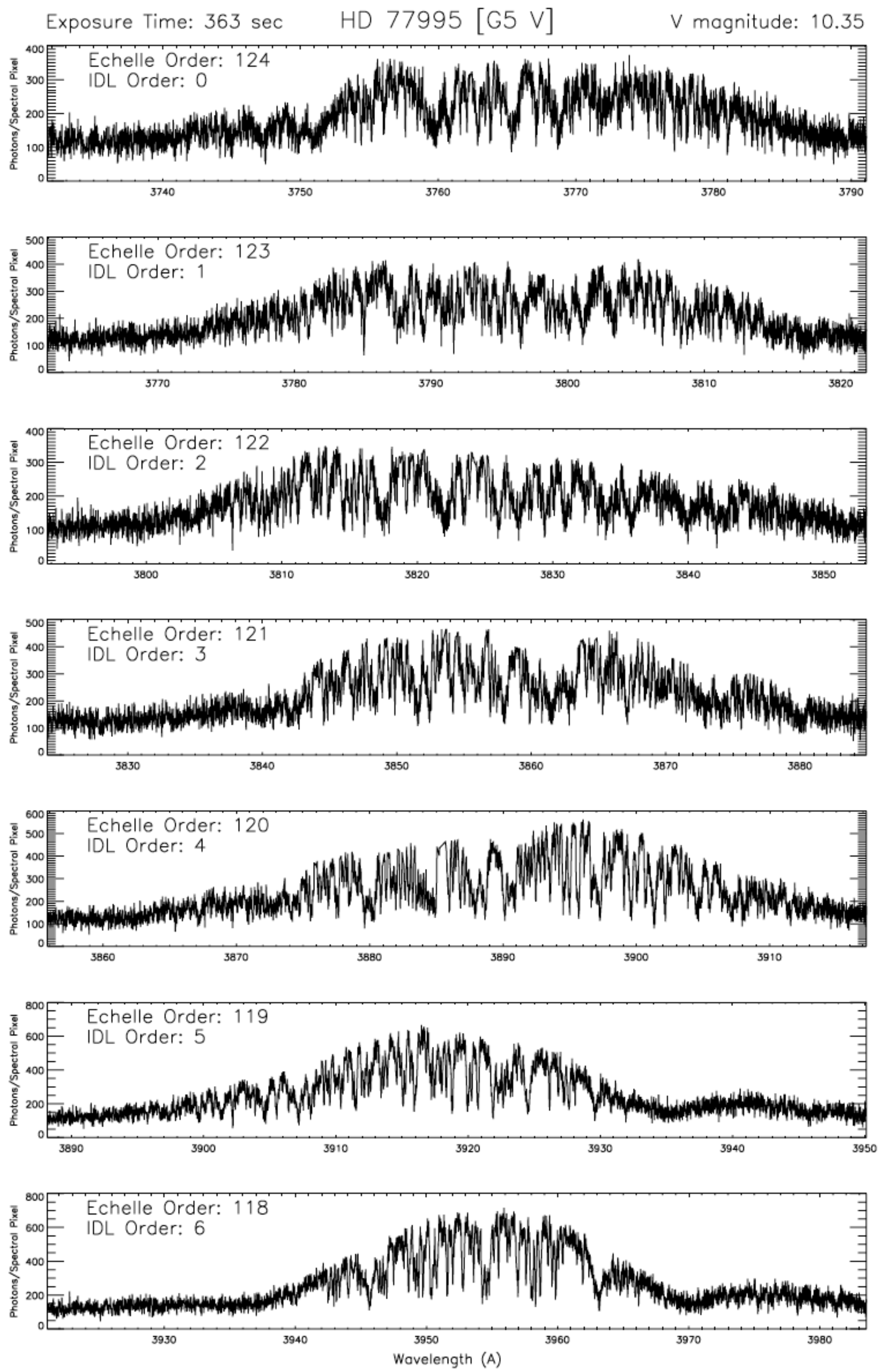
We will continue to acquire radial velocity test data on bright well-known test cases (either stars with well-known planetary systems, or true "null" stars with no observable radial velocity variations) as the commissioning phase continues.

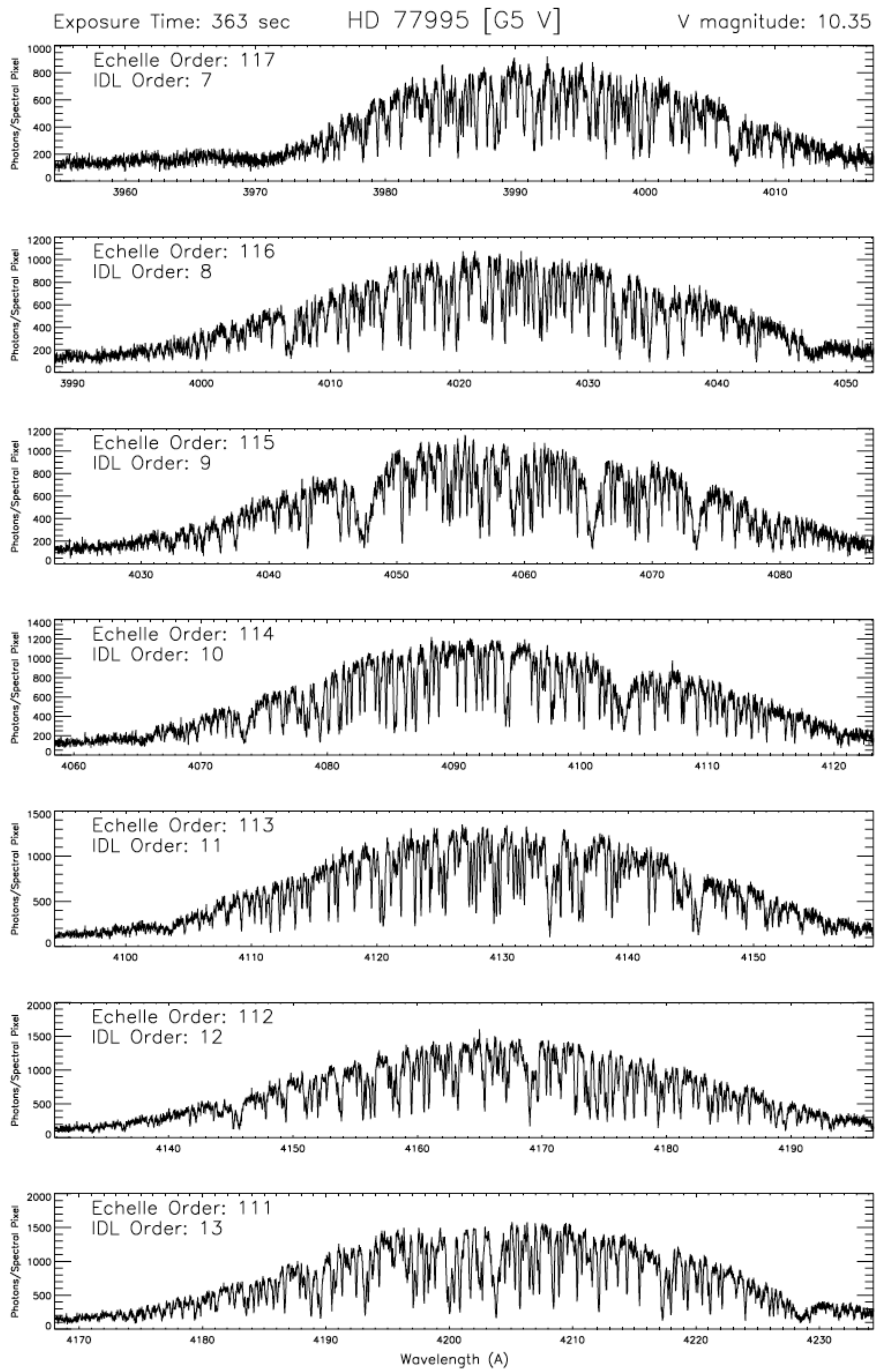
Sample Spectra at various magnitudes

We are in the process of putting together a representative sample of spectra to give prospective users an idea of what to expect in terms of counts, etc. at a given magnitude. We have observed a selection of both G stars (because everybody knows what a G-star looks like, and if you don't there is a solar atlas to compare with), and some almost featureless O,B stars. This 'sampler' catalog will be available on the web soon at TBD.

We do not yet have sample spectra fainter than V=14.11 for the reason that guiding fainter than V~15 requires using the CCD guider camera in a charge-multiplier mode, and this requires additional layers of protection that are not yet in place. We have been able to acquire a V~18 magnitude star with the camera, and the APF tracking is good enough that one could easily get a good exposure with the telescope in open-loop track mode only (not closed-loop guiding), but have yet to obtain such sample spectra.

Here is a representative cases of a 10-minute exposure on the G5V star HD 77995 and a 20-minute exposure on the sd:0 subdwarf PG 1544+253. As will be readily evident from the spectra of the latter, no attempt was made here to include sky subtraction in any of these spectra. So regions around bright night sky lines like Na-D are clearly affected. Also, the onset of fringing in the CCD can be seen for wavelengths redward of 7400A.


Exposure Time: 363 sec
HD 77995 [G5 V]
V magnitude: 10.35
Echelle Order: 124
IDL Order: 0
Echelle Order: 123
IDL Order: 1
Echelle Order: 122
IDL Order: 2
Echelle Order: 121
IDL Order: 3
Echelle Order: 120
IDL Order: 4
Echelle Order: 119
IDL Order: 5
Echelle Order: 118
IDL Order: 6
Photons/Spectral Pixel
Wavelength (A)



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HD 77995 [G5 V]
V magnitude: 10.35
Echelle Order: 117
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Echelle Order: 116
IDL Order: 8
Echelle Order: 115
IDL Order: 9
Echelle Order: 114
IDL Order: 10
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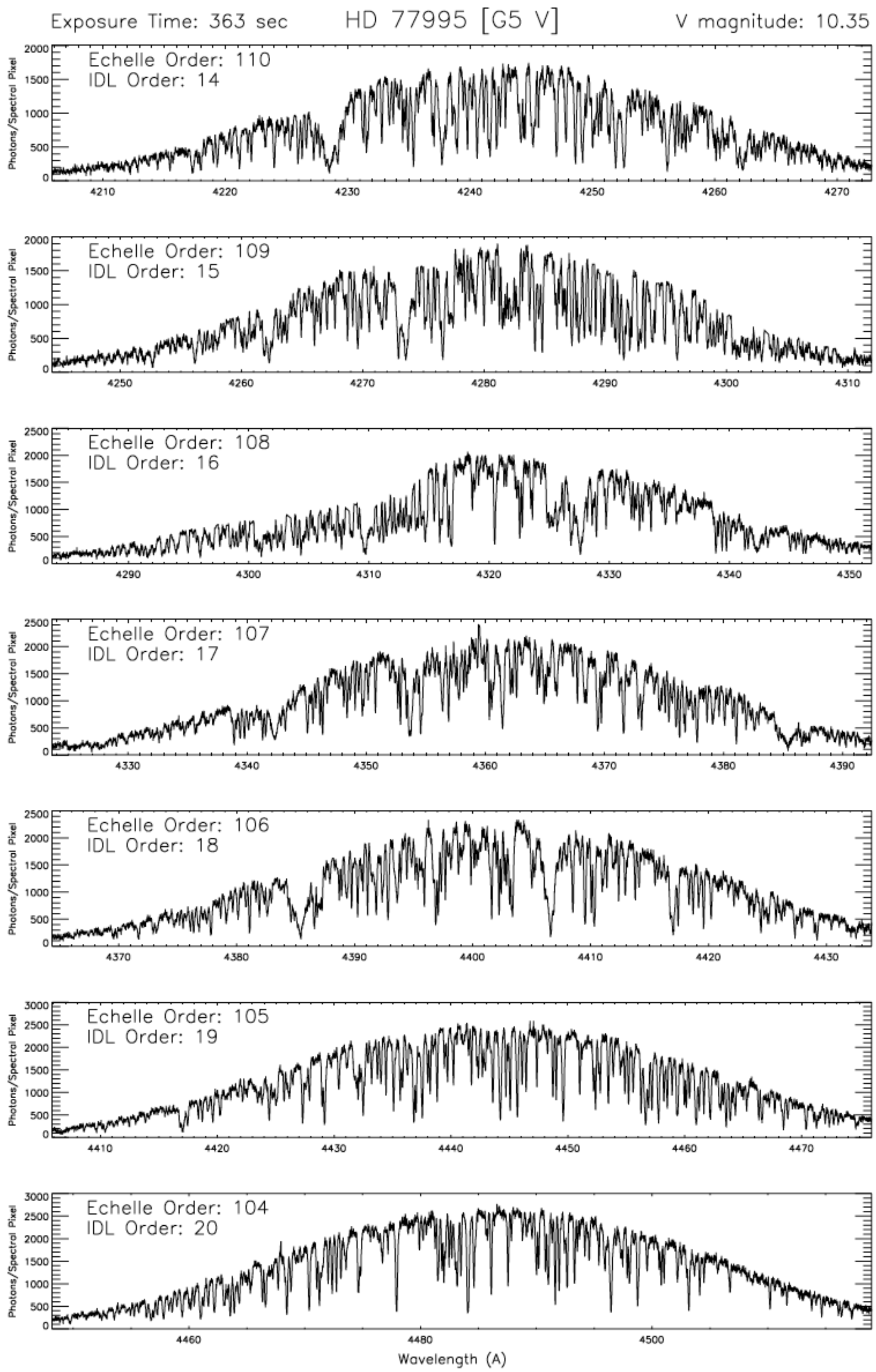
Echelle Order: 112
IDL Order: 12
Echelle Order: 111
IDL Order: 13
Photons/Spectral Pixel
Wavelength (A)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V magnitude: 10.35
Echelle Order: 110
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IDL Order: 16
Echelle Order: 107
IDL Order: 17
Echelle Order: 106
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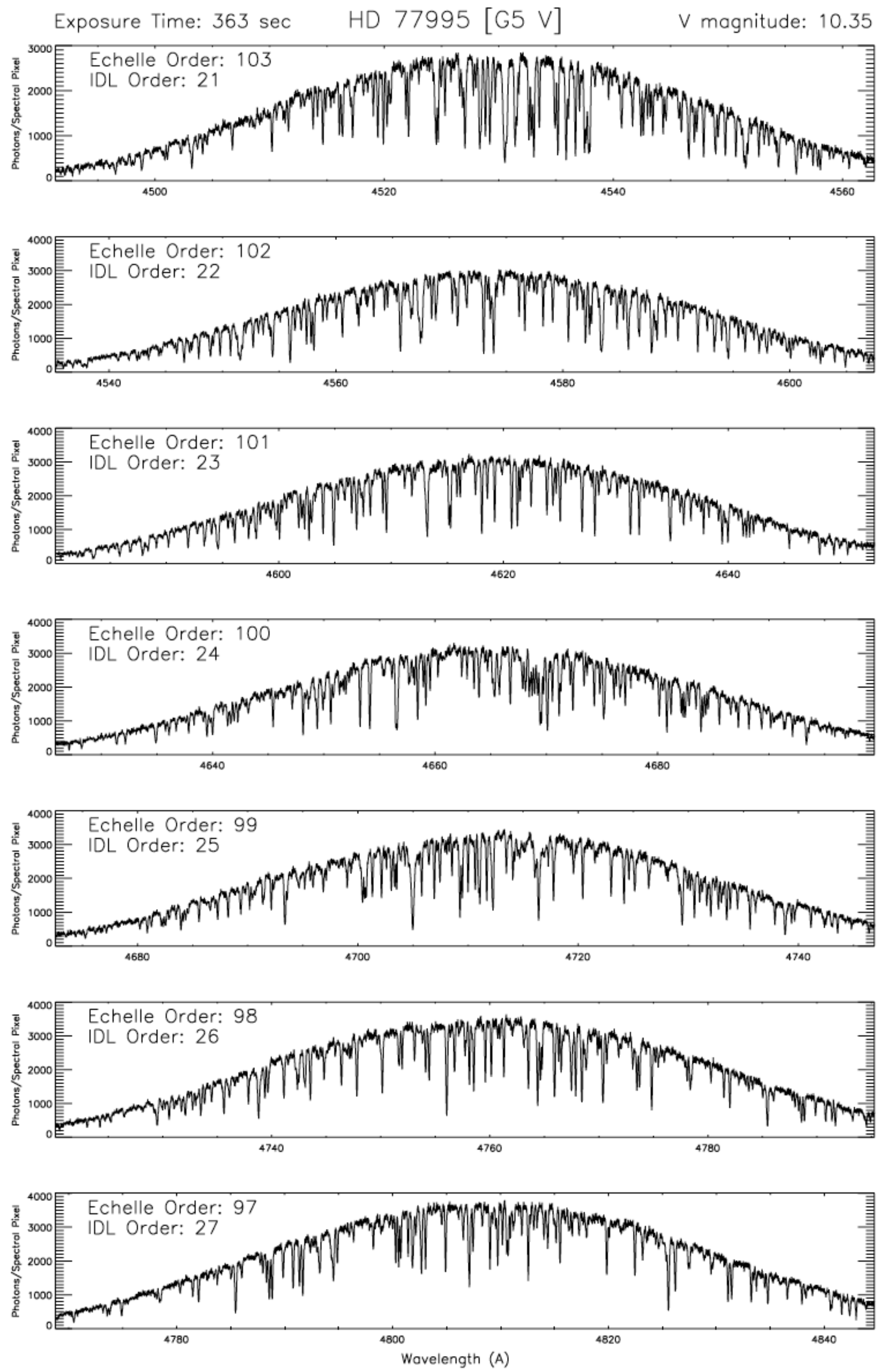
IDL Order: 20
Photons/Spectral Pixel
Wavelength (A)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HD 77995 [G5 V]
V magnitude: 10.35
Echelle Order: 103
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IDL Order: 22
Echelle Order: 101
IDL Order: 23
Echelle Order: 100
IDL Order: 24
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Echelle Order: 98
IDL Order: 26
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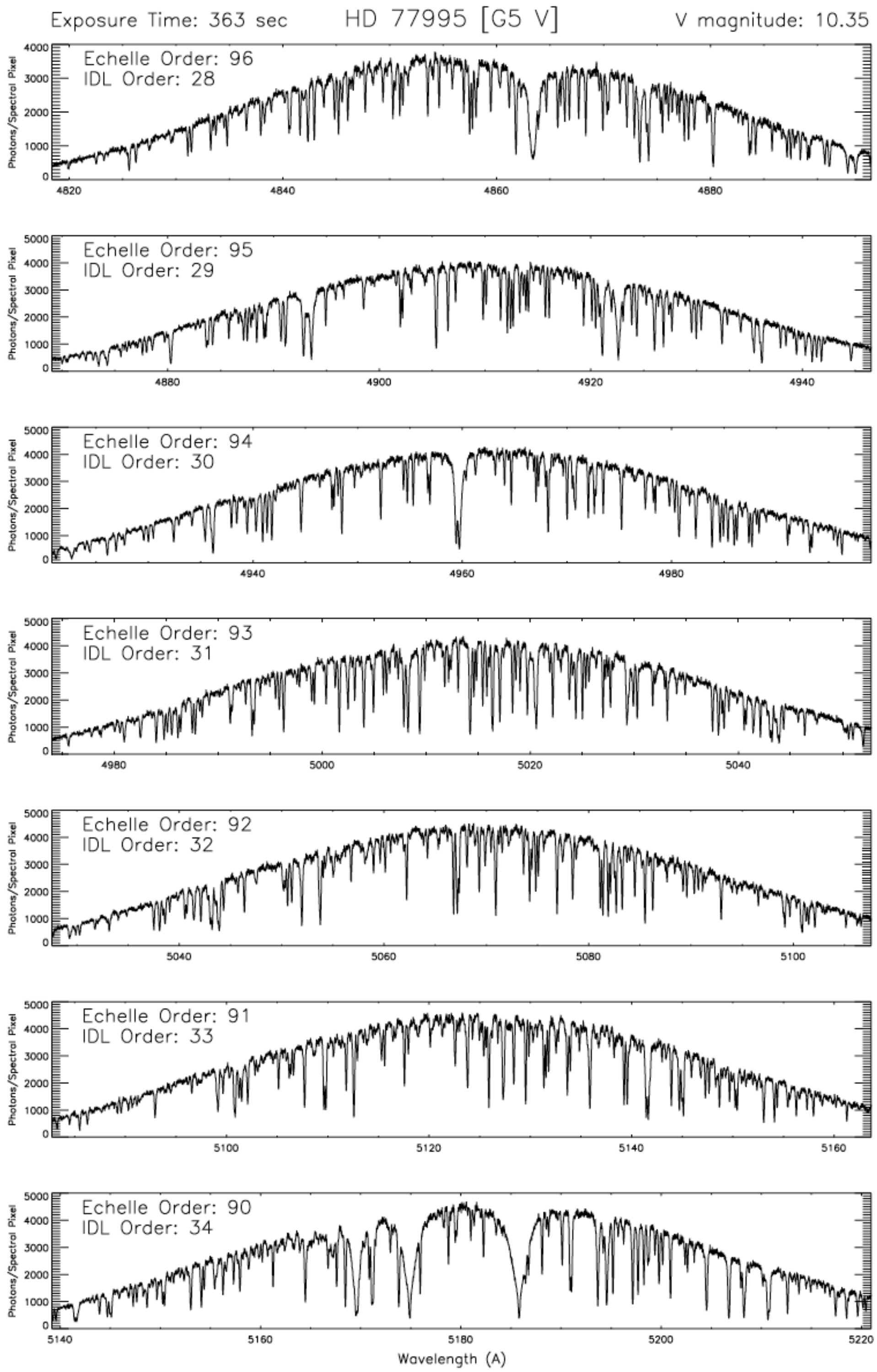
IDL Order: 27
Photons/Spectral Pixel
Wavelength (A)



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HD 77995 [G5 V]
V magnitude: 10.35
Echelle Order: 96
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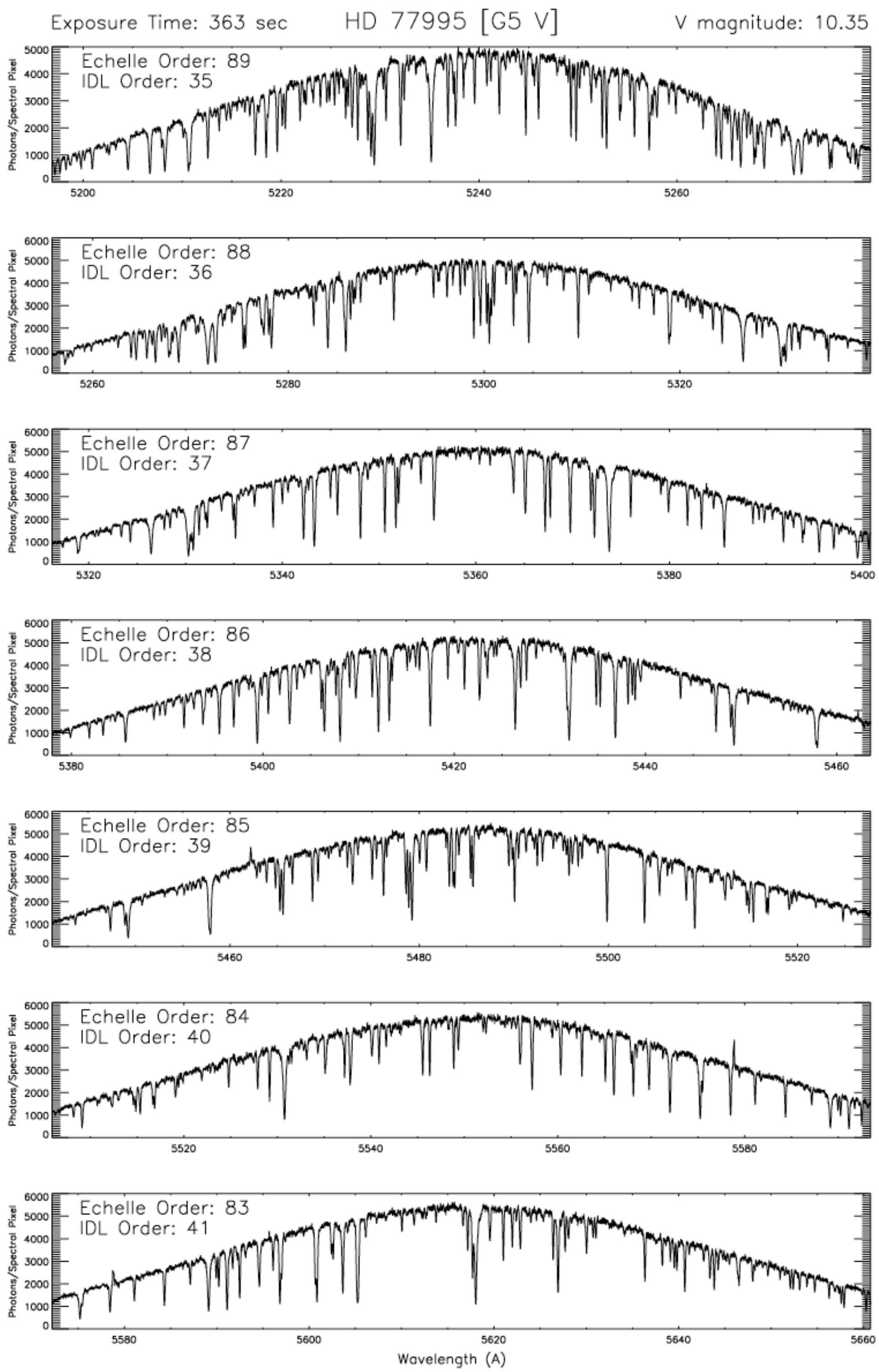
IDL Order: 30
Echelle Order: 93
IDL Order: 31
Echelle Order: 92
IDL Order: 32
Echelle Order: 91
IDL Order: 33
Echelle Order: 90
IDL Order: 34
Photons/Spectral Pixel
Wavelength (A)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IDL Order: 37
Echelle Order: 86
IDL Order: 38
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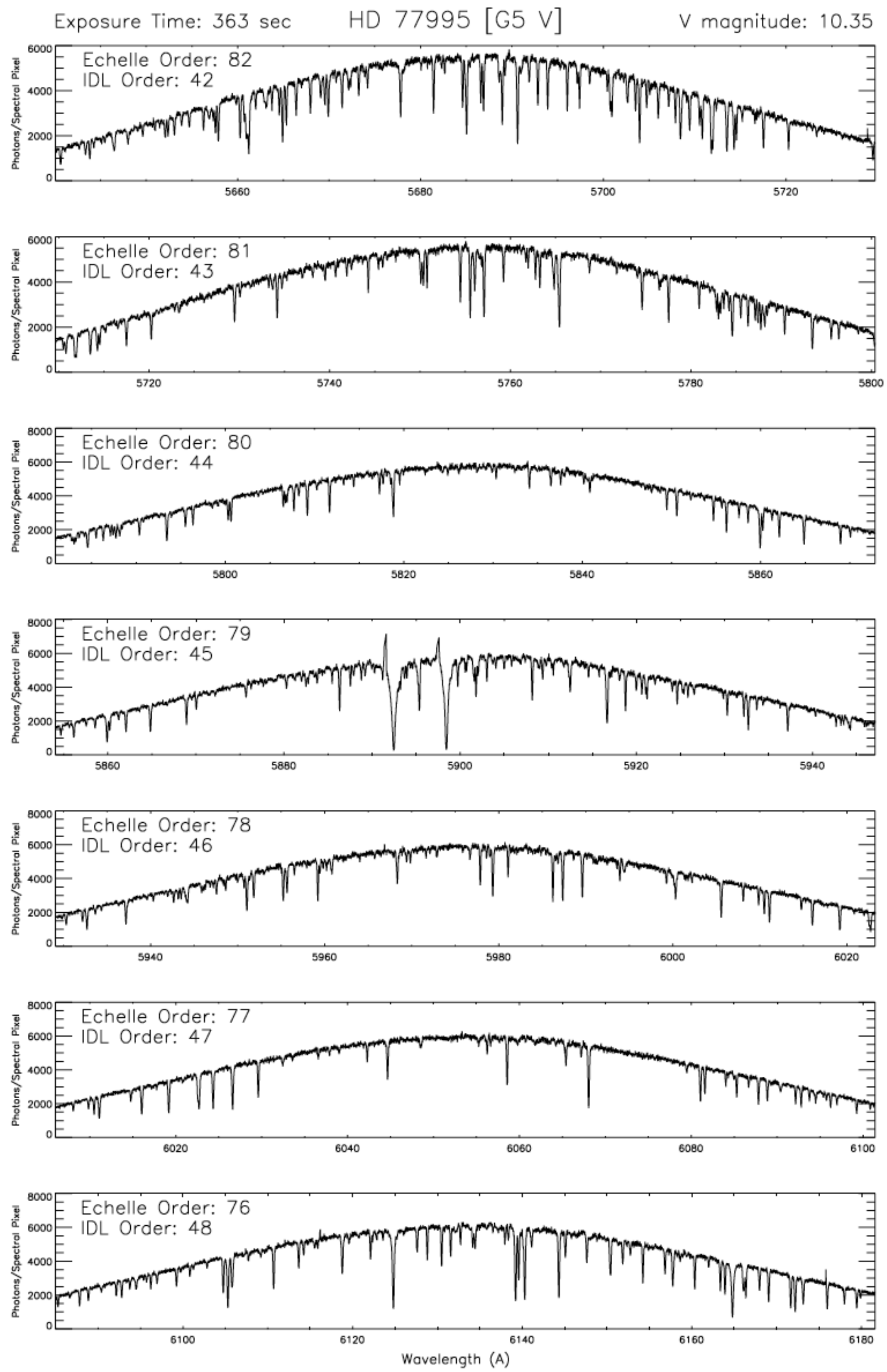
IDL Order: 41
Photons/Spectral Pixel
Wavelength (A)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IDL Order: 44
Echelle Order: 79
IDL Order: 45
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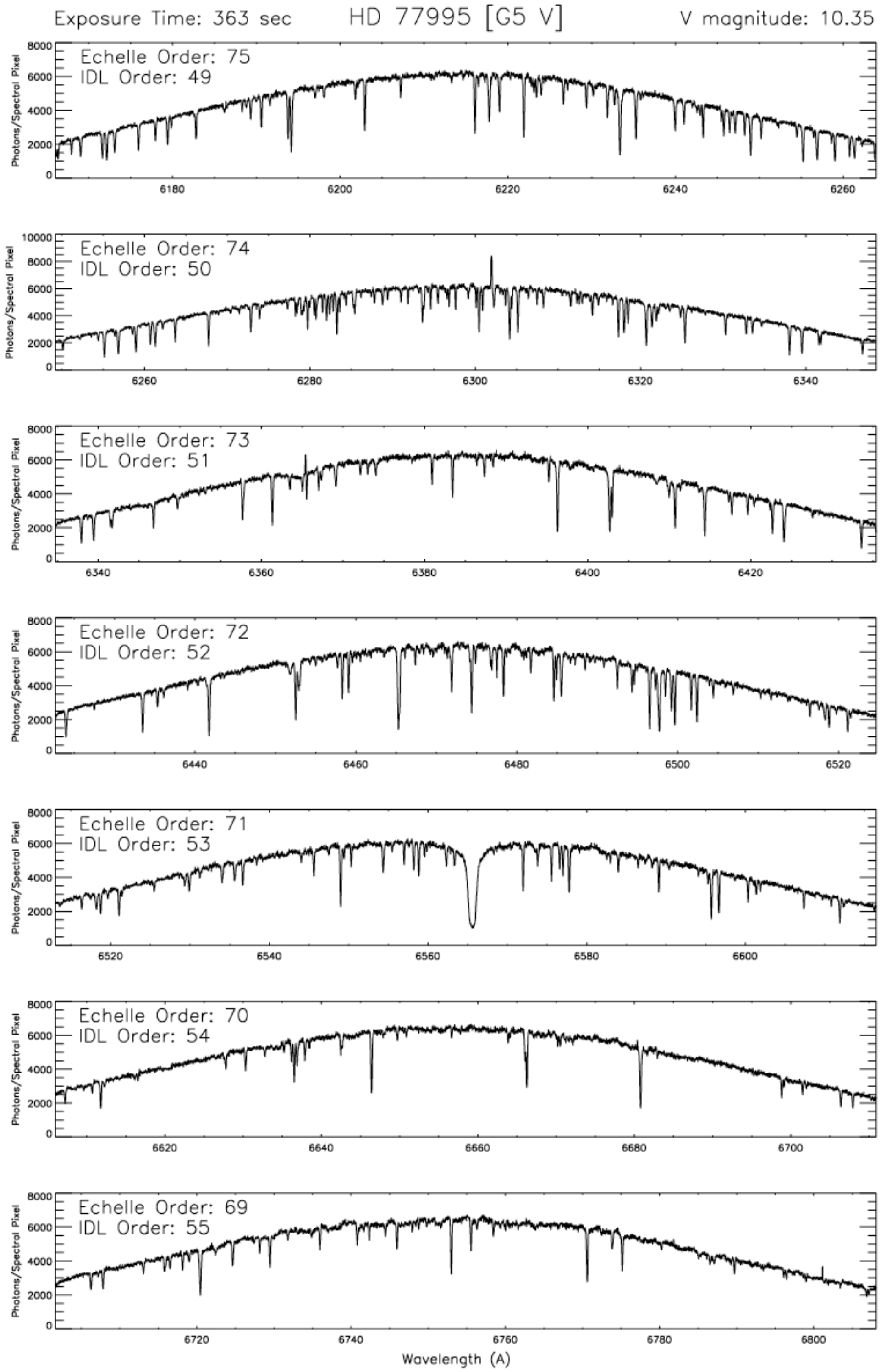
IDL Order: 48
Photons/Spectral Pixel
Wavelength (A)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Echelle Order: 72
IDL Order: 52
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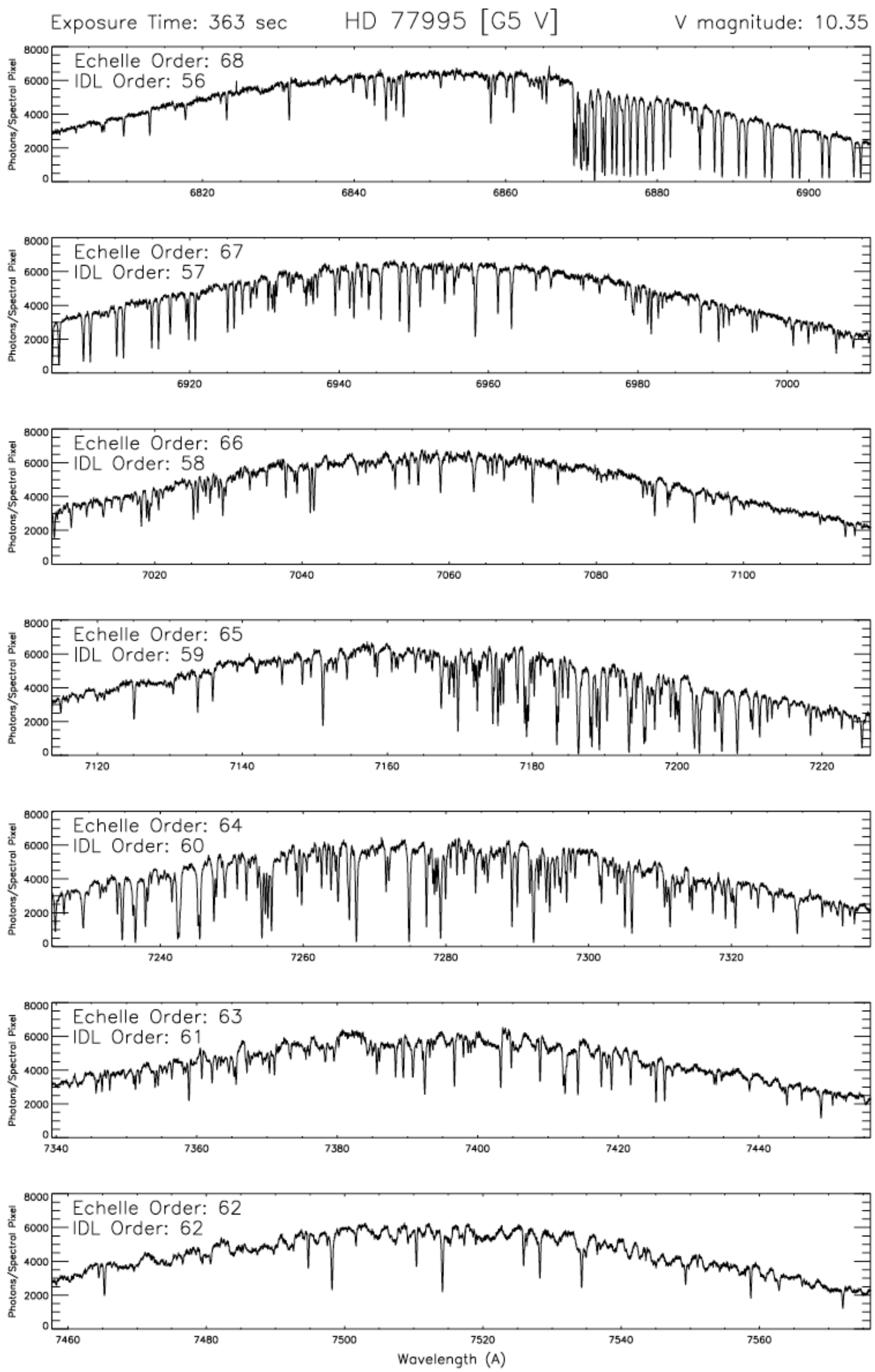
Photons/Spectral Pixel
Wavelength (A)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IDL Order: 58
Echelle Order: 65
IDL Order: 59
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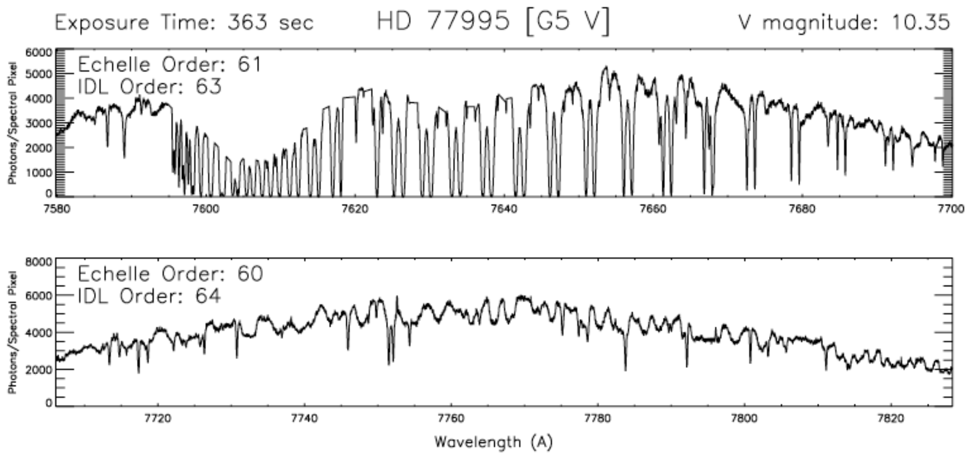
IDL Order: 62
Photons/Spectral Pixel
Wavelength (A)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Photons/Spectral Pixel
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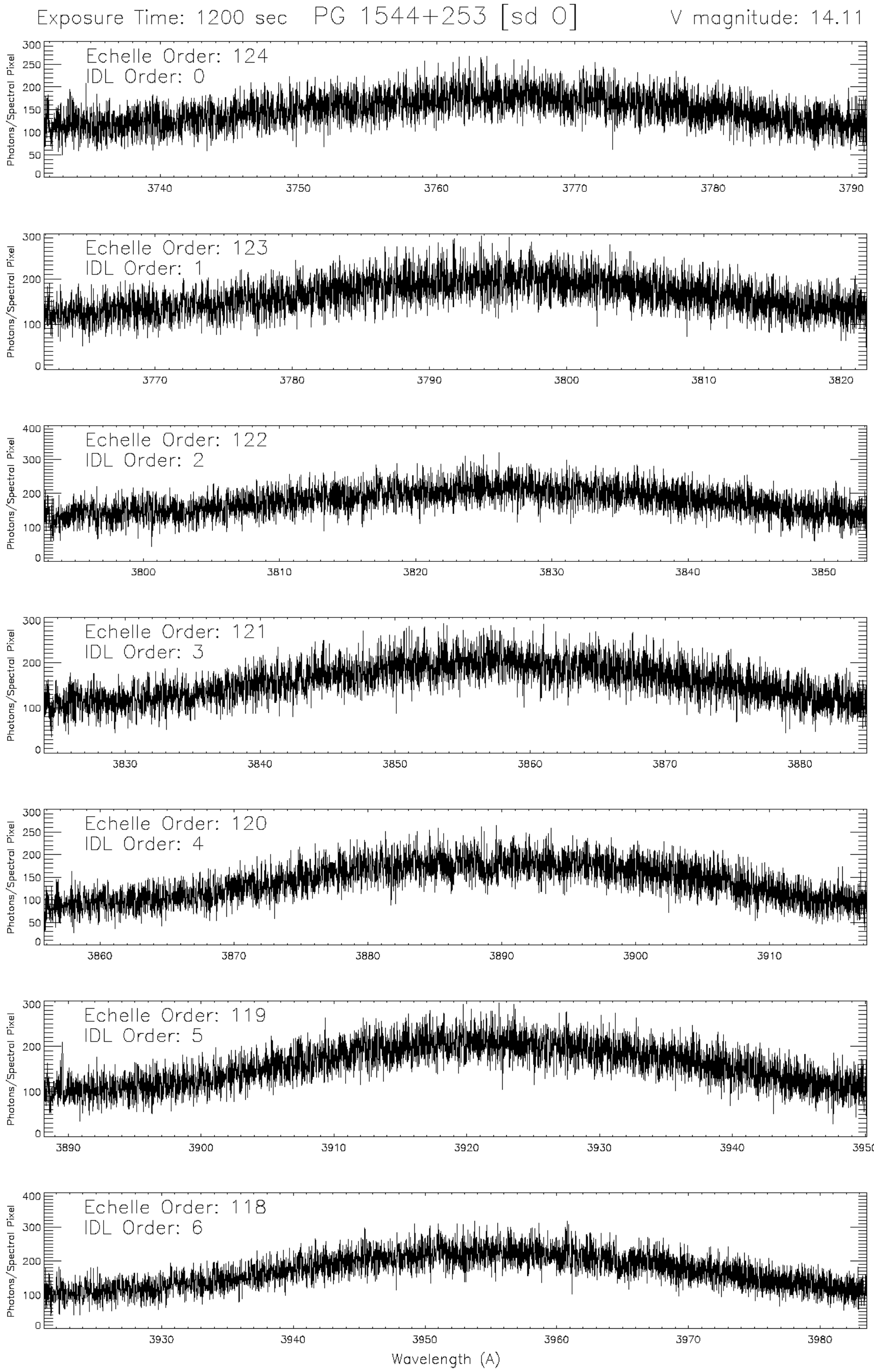
Photons/Spectral Pixel
Wavelength (A)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IDL Order: 1
Echelle Order: 122
IDL Order: 2
Echelle Order: 121
IDL Order: 3
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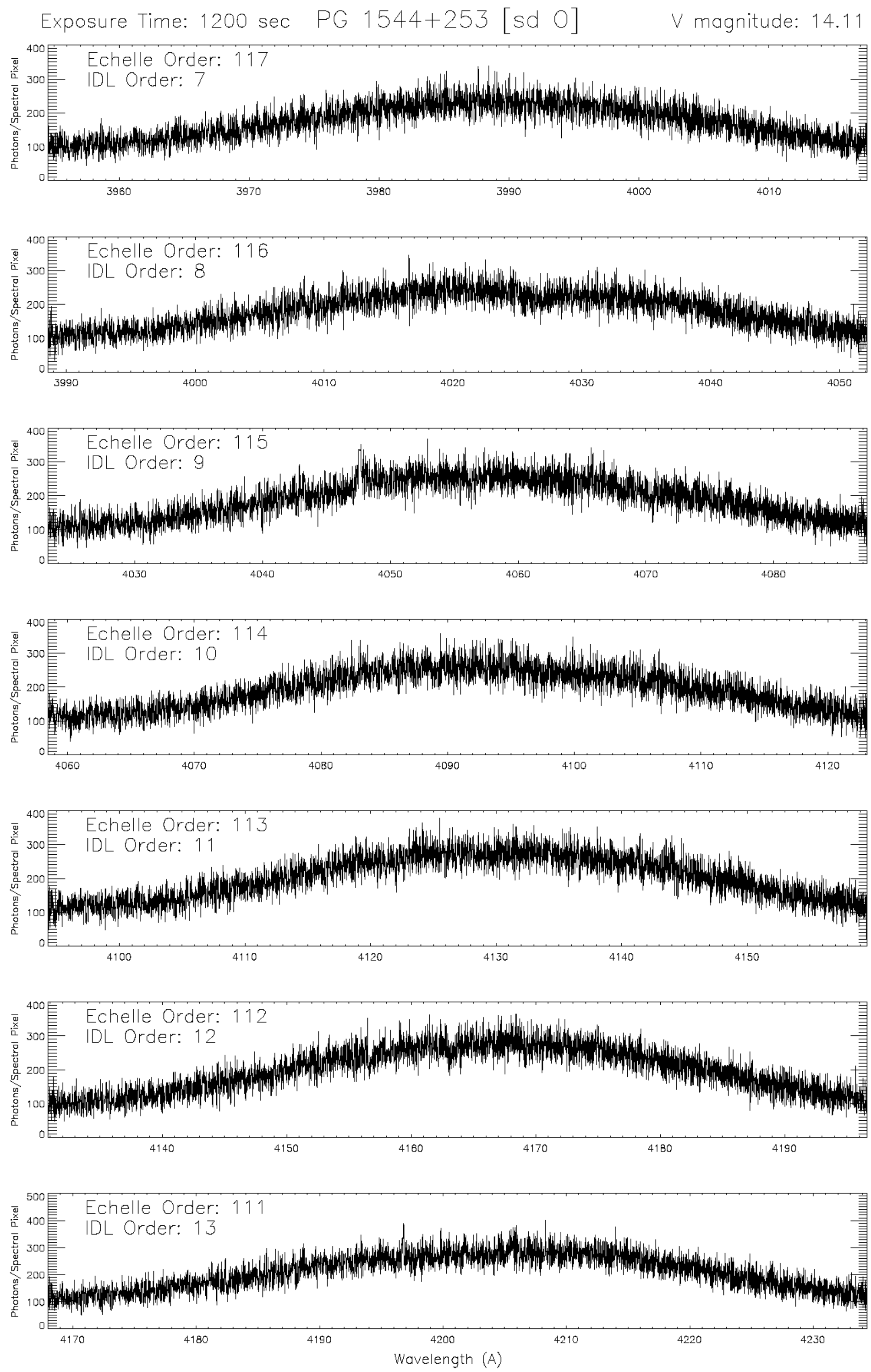
IDL Order: 6
Photons/Spectral Pixel
Wavelength (A)



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IDL Order: 8
Echelle Order: 115
IDL Order: 9
Echelle Order: 114
IDL Order: 10
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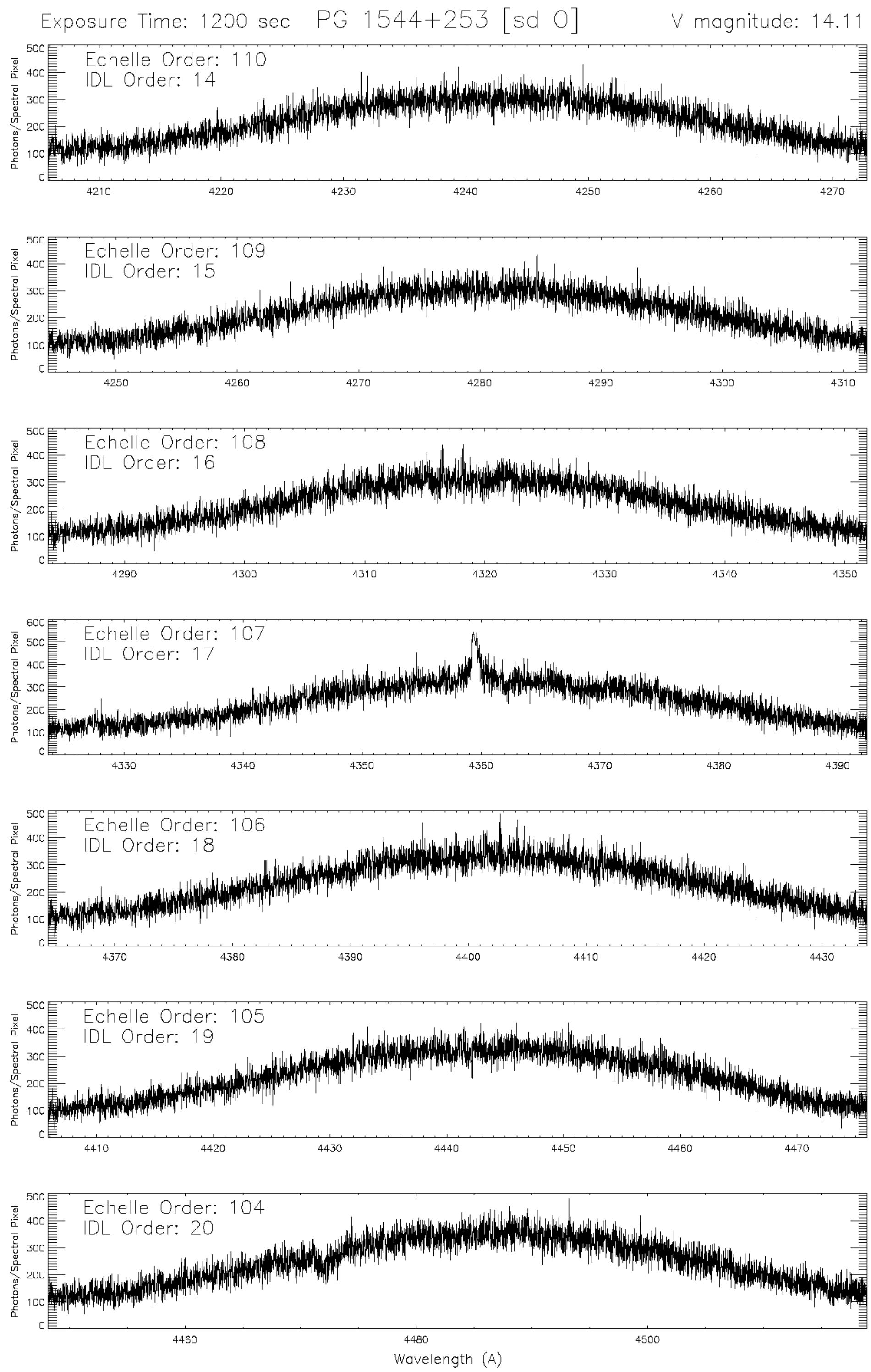
IDL Order: 13
Photons/Spectral Pixel
Wavelength (A)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IDL Order: 16
Echelle Order: 107
IDL Order: 17
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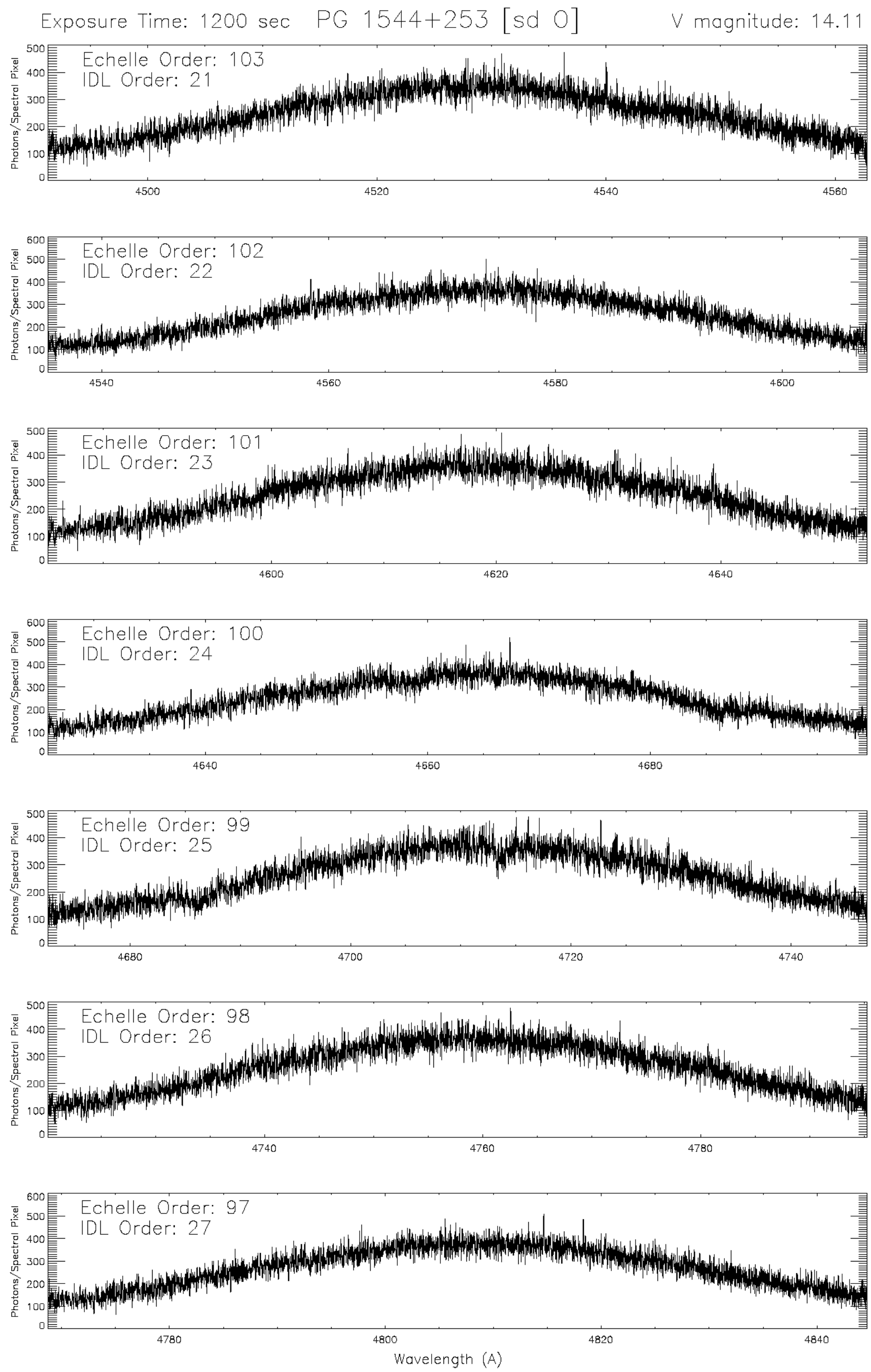
IDL Order: 20
Photons/Spectral Pixel
Wavelength (A)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IDL Order: 23
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IDL Order: 24
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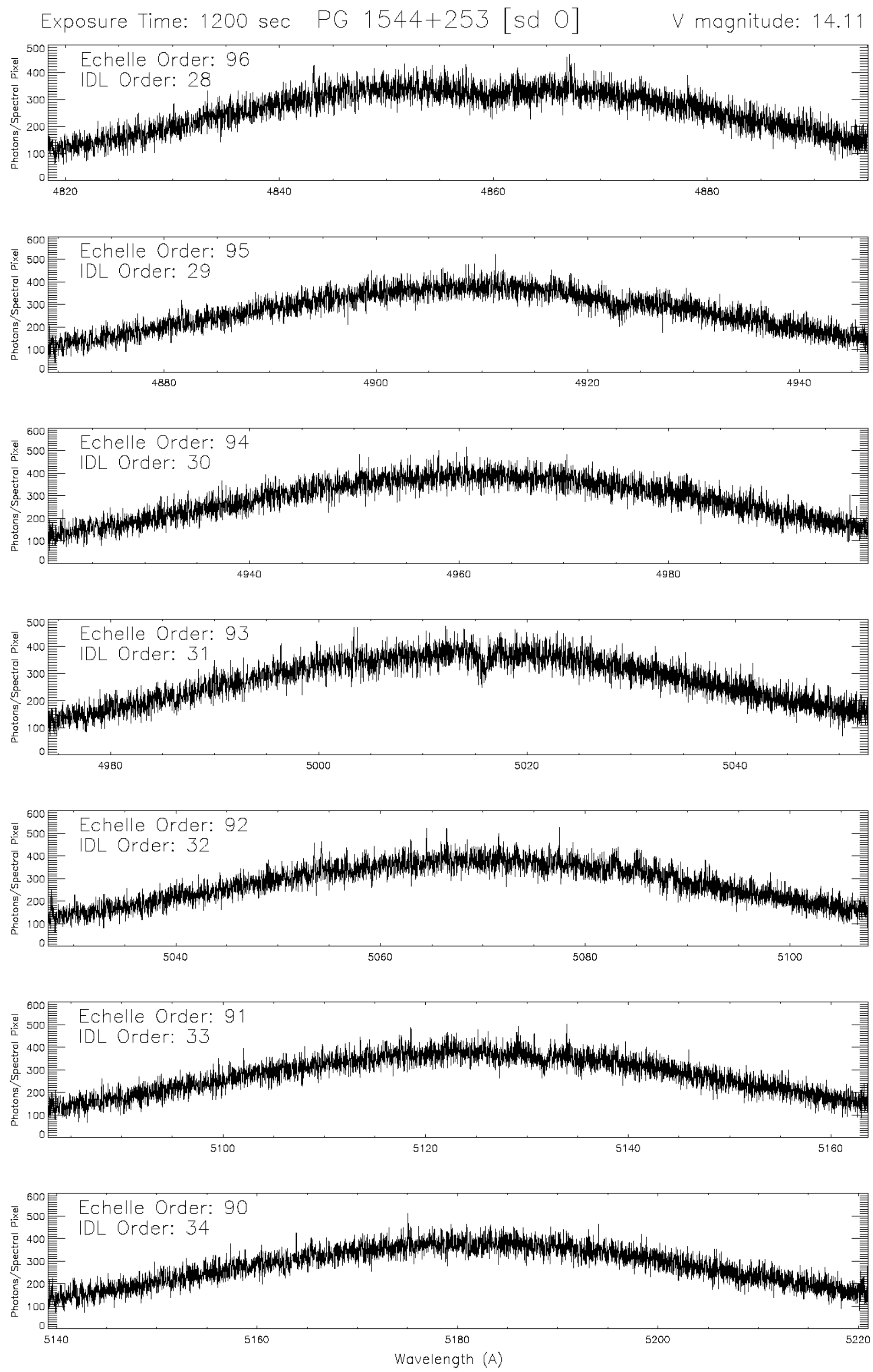
IDL Order: 27
Photons/Spectral Pixel
Wavelength (A)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V magnitude: 14.11
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IDL Order: 30
Echelle Order: 93
IDL Order: 31
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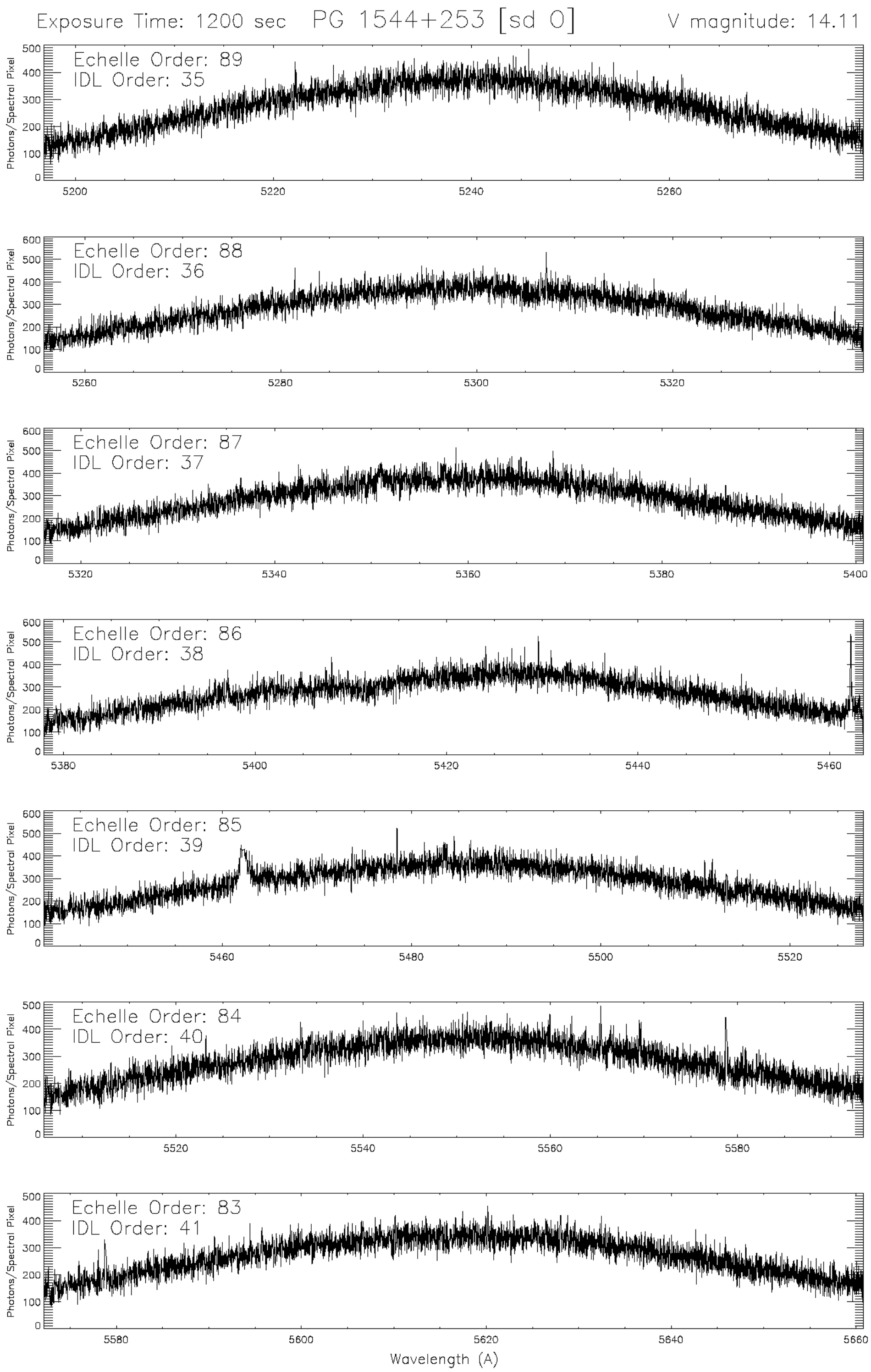
IDL Order: 34
Photons/Spectral Pixel
Wavelength (A)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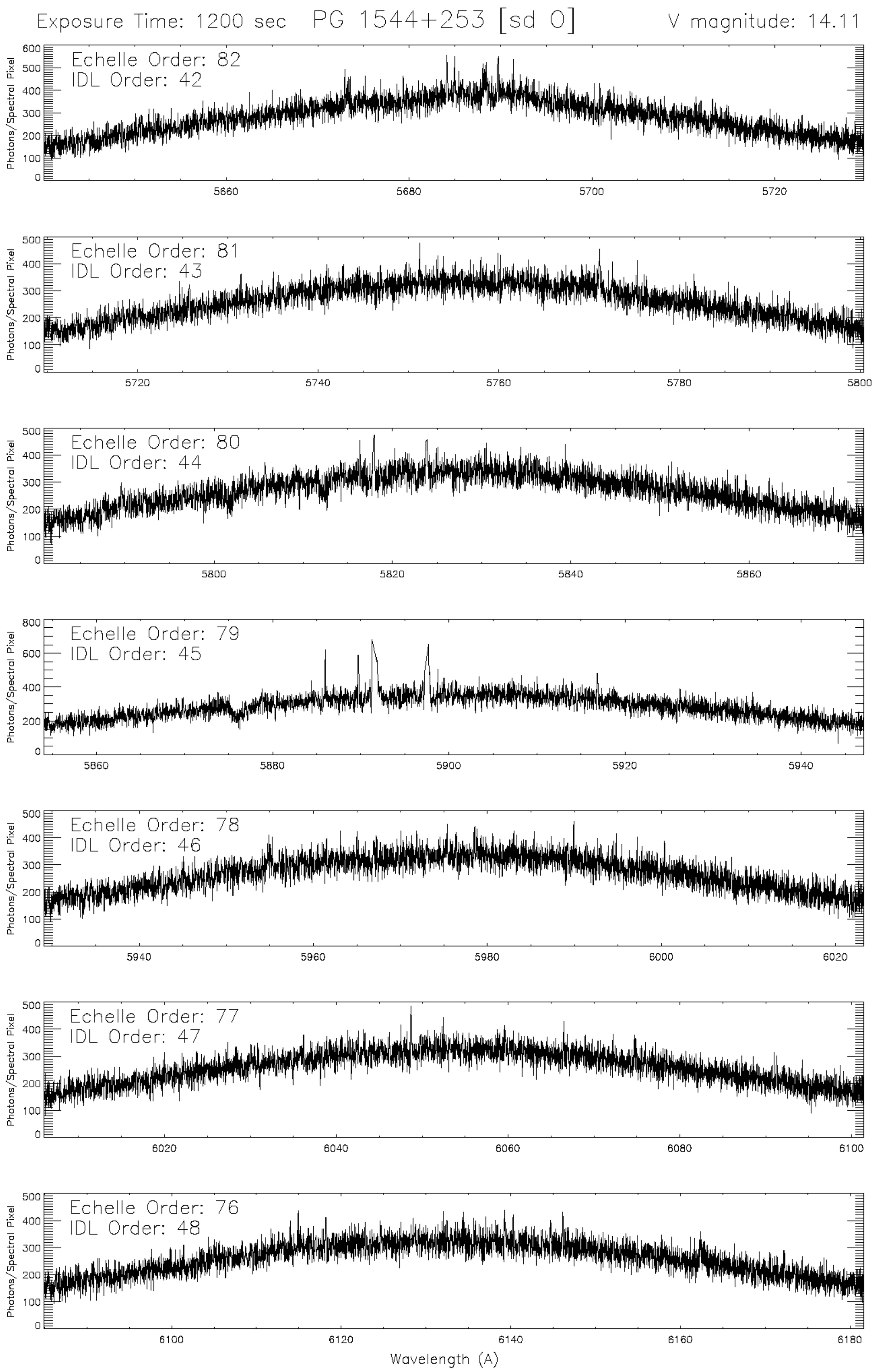
Photons/Spectral Pixel
Wavelength (A)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V magnitude: 14.11
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IDL Order: 42
Echelle Order: 81
IDL Order: 43
Echelle Order: 80
IDL Order: 44
Echelle Order: 79
IDL Order: 45
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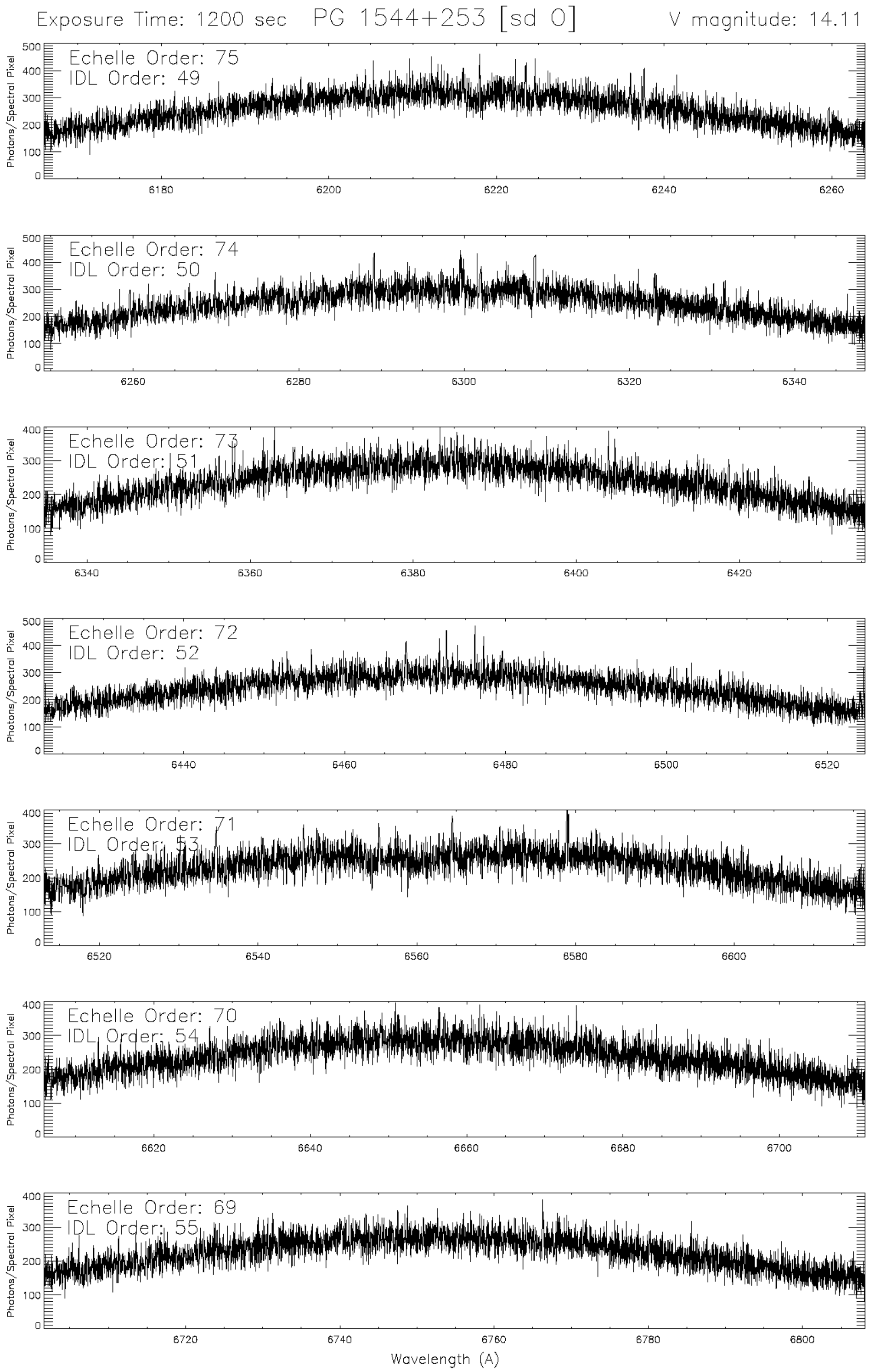
IDL Order: 47
Echelle Order: 76
IDL Order: 48
Photons/Spectral Pixel
Wavelength (A)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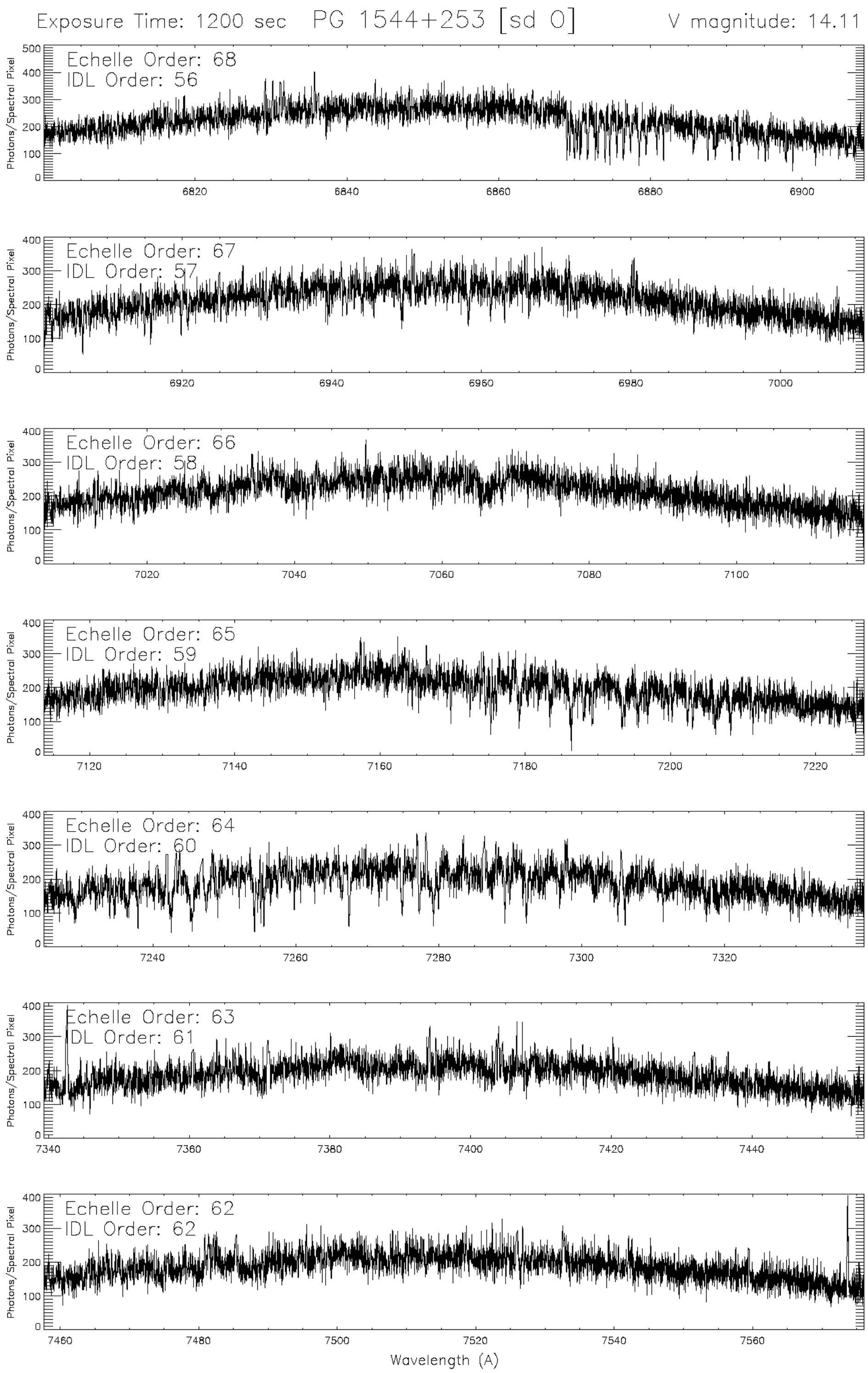
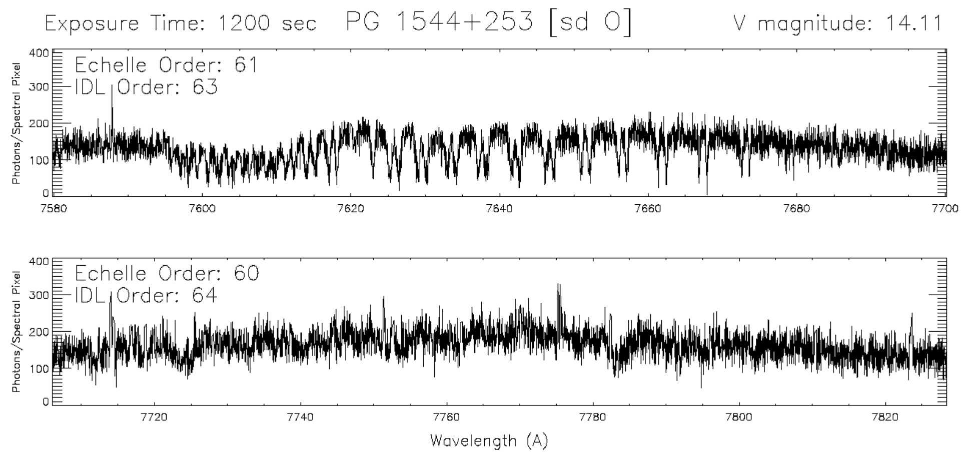
V magnitude: 14.11
Echelle Order: 75
IDL Order: 49
Echelle Order: 74
IDL Order: 50
Echelle Order: 73
IDL Order: 51
Echelle Order: 72
IDL Order: 52
Echelle Order: 71
IDL Order: 53
Echelle Order: 70
IDL Order: 54
Echelle Order: 69
IDL Order: 55
Photons/Spectral Pixel
Wavelength (A)


Exposure Time: 1200 sec
PG 1544+253 [sd O]
V magnitude: 14.11
Echelle Order: 68
IDL Order: 56
Echelle Order: 67
IDL Order: 57
Echelle Order: 66
IDL Order: 58
Echelle Order: 65
IDL Order: 59
Echelle Order: 64
IDL Order: 60
Echelle Order: 63
IDL Order: 61
Echelle Order: 62
IDL Order: 62
Photons/Spectral Pixel
Wavelength (A)


Exposure Time: 1200 sec
PG 1544+253 [sd O]
V magnitude: 14.11
Echelle Order: 61
IDL Order: 63
Photons/Spectral Pixel
Echelle Order: 60
IDL Order: 64
Photons/Spectral Pixel
Wavelength (A)