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Introduction

A well-tuned spectrograph is a powerful and versatile instrument. When used effectively, spectra can be taken from stars, nebulae, and even galaxies, and provide a range of data on parameters such as composition, temperature, and velocity. This project seeks to benchmark the abilities of the Wallace 16" telescope and its spectrograph. By taking extensive observations of several typical spectroscopic targets, we characterize the magnitude limits, resolution, and accuracy of the optical system, and document the workflow needed to ensure the best possible results from spectrographic data.

Observations

Over the course of the summer, a total of 2075 minutes of science data were collected, 67% of which were light frames. The majority of the useful data analyzed in this report were derived from observations of the spectral binary Sheliak (Beta Lyrae) and the Cat's Eye Nebula (NGC 6543). Observations were also made of the Ring Nebula (M57) and the spectral binary HD 174664, but low signal-to-noise thwarted attempts to generate accurate spectral profiles. The remain data sets should, however, be more than sufficient to accurately characterize the Wallace equipment.

Data were collected from Sheliak in two series, focusing on features near 5870 and 6550 Å respectively. For the high-wavelength series, data were collected in 10 minute exposures using the 300, 600, 1200, and 2400 g/mm gratings, while the low-wavelength series was composed of 5 minute exposures using the 300, 600, and 1200 g/mm gratings. The NGC 6543 data were collected in 20 minute exposures using the 300, 600, 1200, and 2400 g/mm gratings, and focused on a set of features near 6550 Å.

Reduction

The reduction of the data was done entirely in IRAF, and proved to be more subtle than we were initially aware, resulting in the need for several re-reductions of our entire dataset. This section will describe the reduction procedure in more detail than is usually necessary in the hopes of preventing future investigators from suffering a similar fate.

Raw CCD frames were dark- and bias-corrected using the standard `ccdproc` task. Flat-field correction was not attempted, due to the following complications: first, the ambient, diffuse light generally used to record flats is generally not featureless in the spectral domain, and second, flats would need to be taken for every wavelength setting used to account for the frequency response of the CCD. Future investigators are directed to the `calibrate` task in `onedspec`, which allows flux calibration via observations of a standard star, and should also accomplish flat correction as a side-effect.

Spectrum extraction was done according to the literature using the `apextract` package. An important issue here is the extraction of the Neon reference spectra, which provide the wavelength scale for the science images. This extraction must be done with an identical aperture to the science frames, which can be accomplished using the `references` parameter to `apsum`. “Tracing” of the aperture must also be disabled to ensure an exact match. Neon extraction can also become complex when the Neon spectral lines have a appreciable slope relative to the dispersion axis — as objects tend to drift vertically during long hand-guided exposures, it becomes necessary to extract and apply a separate Neon reference to each science frame.

Results

Plots of the reduced spectra are given in Figures 1-11. Spectral lines of interest are marked, along with their centerpoint and full width at half maximum given in Ångstroms, as determined by the `deblend` routine of `splot`. Table 1 summarizes count values for each observed object, after reduction.

Analysis

Photometry — The most important factors determining the strength of object’s signal are magnitude and angular size. M57, with a visible magnitude of 8.8, should in theory be around 2.5 times as bright as NGC 6543, but while the former has an angular diameter of around 230″, NGC 6543 has a bright core 20″ wide, making it vastly easier to find, guide, and image. Angular size comes into play again during aperture extraction, where larger spectra are prone to contamination by more noise than concentrated spectra of theoretically the same magnitude. All told, NGC 6543's 11.5 times smaller diameter gave it about a 17x increase in usable signal.

Choice of grating appears to be less important in signal strength than one might expect. Although there is a significant drop in signal when switching from the 300 to the 600 g/mm grating, subsequent switches to the 1200 and 2400 g/mm result in decreasing signal loss, especially when working in an already low-signal regime. In fact, at low counts the CCD appears less sensitive to increases in intensity as well — twice doubling the exposure time on M57 did not result in a corresponding linear increase in signal.

When faced with a dim object, increased exposure time is both the obvious and generally best strategy. The issue in this case is capturing dark frames. When using 20 minute exposures, taking a reasonable number of darks becomes a major hassle, and during the beginning of the summer we attempted to avoid taking a full set every night, hoping to scale our darks or re-use others with the same exposure and temperature. A significant part of the issue with the M57 data is that this strategy was not effective, and the spectral signal was completely drowned out by a large number of extremely hot pixels. To realize effective dark correction, we recommend that, even when taking a series across multiple nights, each night contain a full set of dark frames, taken immediately after the science images.

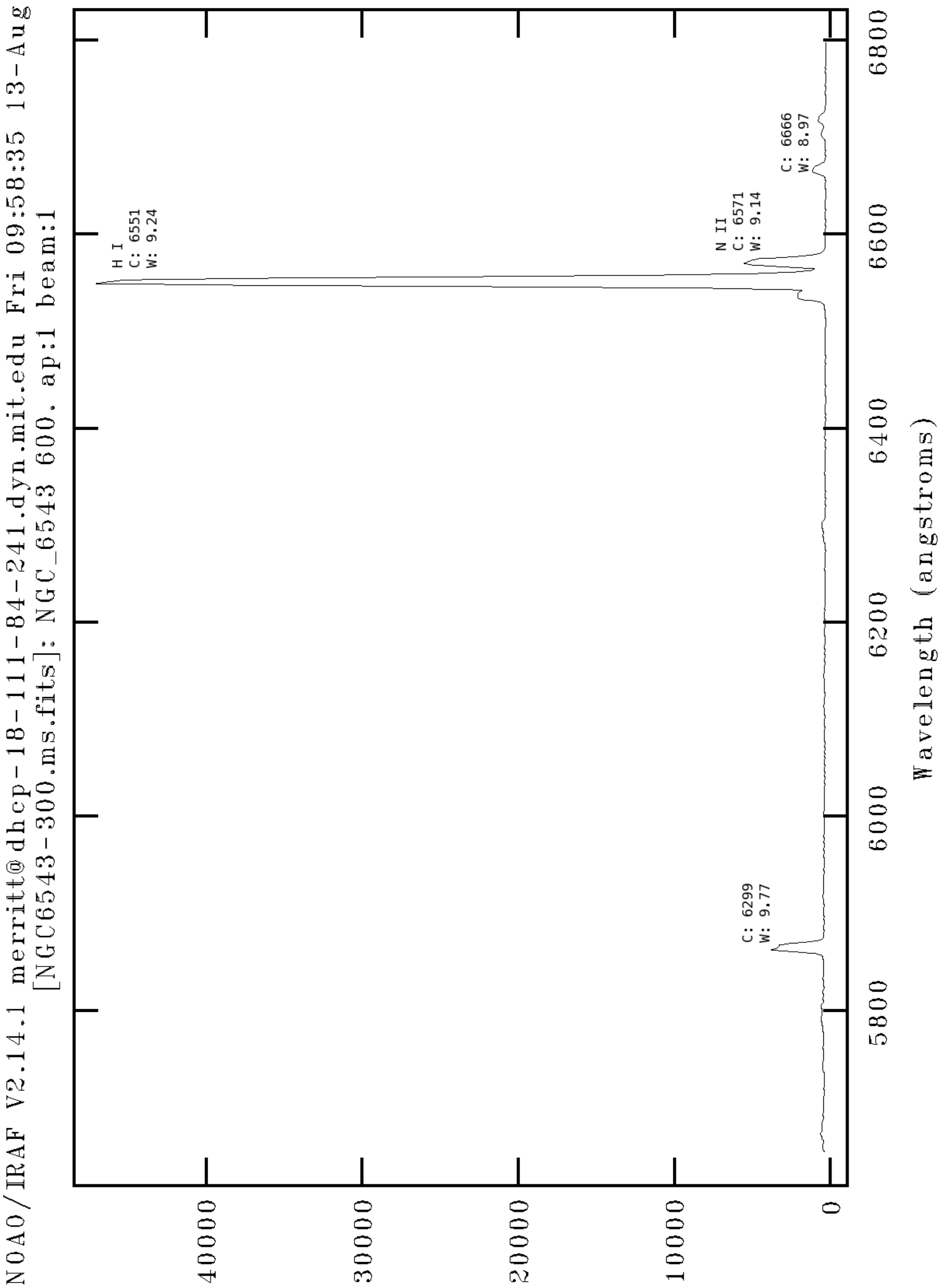
Spectral Resolution — At first glance, the data appear to show two very different pictures of the spectrograph's resolution. Most of the Sheliak data show spectral lines with full width at half maximum (FWHM) values ranging from ~4.5 Å on the 300 g/mm grating to 2-3 Å with the 1200 g/mm. The NGC6543 lines, however, have FWHM's of around 2 Å starting with the 600 grating (the 300 data are thicker due to lower signal to noise), and thinning to a little over 1 Å with the 2400. The cause of this discrepancy is not in the target, weather conditions, or focus, but rather the adjustment of the spectrograph's main mirror (documented in section 3.4 of the spectrograph's User Manual), which controls the centering of the spectral lines perpendicular to the dispersion axis. This has a surprisingly large effect on the resolution of the spectrograph, and the correct setting is non-obvious. Our initial strategy was to optimize the setting for brightness, and we attributed the apparently thinner regions of calibration lines to their being dim. However, this does not always yield the best possible resolution, which can be difficult to find as the focus shifts as well when adjusting the main mirror. The figures section include examples of neon spectrum from the high-resolution NGC6543 runs and the less-resolved Sheliak data.

Accuracy — The ~1 Å FWHM lines seen using the 2400 g/mm grating can be fairly easily fit to curves to find centerpoints with a good degree of precision. As an example, fitting a gaussian to the H-alpha line seen in the NGC 6543 data gives a center of 6561.15 Å, which can be used to calculate the radial velocity of the nebula to within 15.4% of the literature value given by SIMBAD. The data obtained using the 1200 g/mm grating yield a center only 0.32 Å away from the 2400 center, but the peaks from the 600 and 300 gratings are significantly lower, approximately 6 and 10 Å off respectively. Interestingly, this pattern is repeated in the Sheliak data — the 600 and 300 data show increasingly low peaks relative to the 2400 and 1200 data, although the intervals in the Sheliak data are larger. We can offer no adequate explanation of this trend.

Conclusion

The Wallace spectrograph system is capable of providing a wide range of useful data, subject to some constraints. Targets must generally be of small angular size, and to obtain strong signal-to-noise, magnitudes must generally be kept below 10. Calibration data must also be scrutinized at time of collection for optimal line focus and placement. Reduction, however, can easily become the most subtle part of the observational process, as the ultimate quality of the data is influenced by settings for extraction, alignment, combination, and especially wavelength calibration. With correct settings, final data, especially on the 1200 and 2400 g/mm gratings, is accurate enough for most general purpose spectrographic projects.

Figures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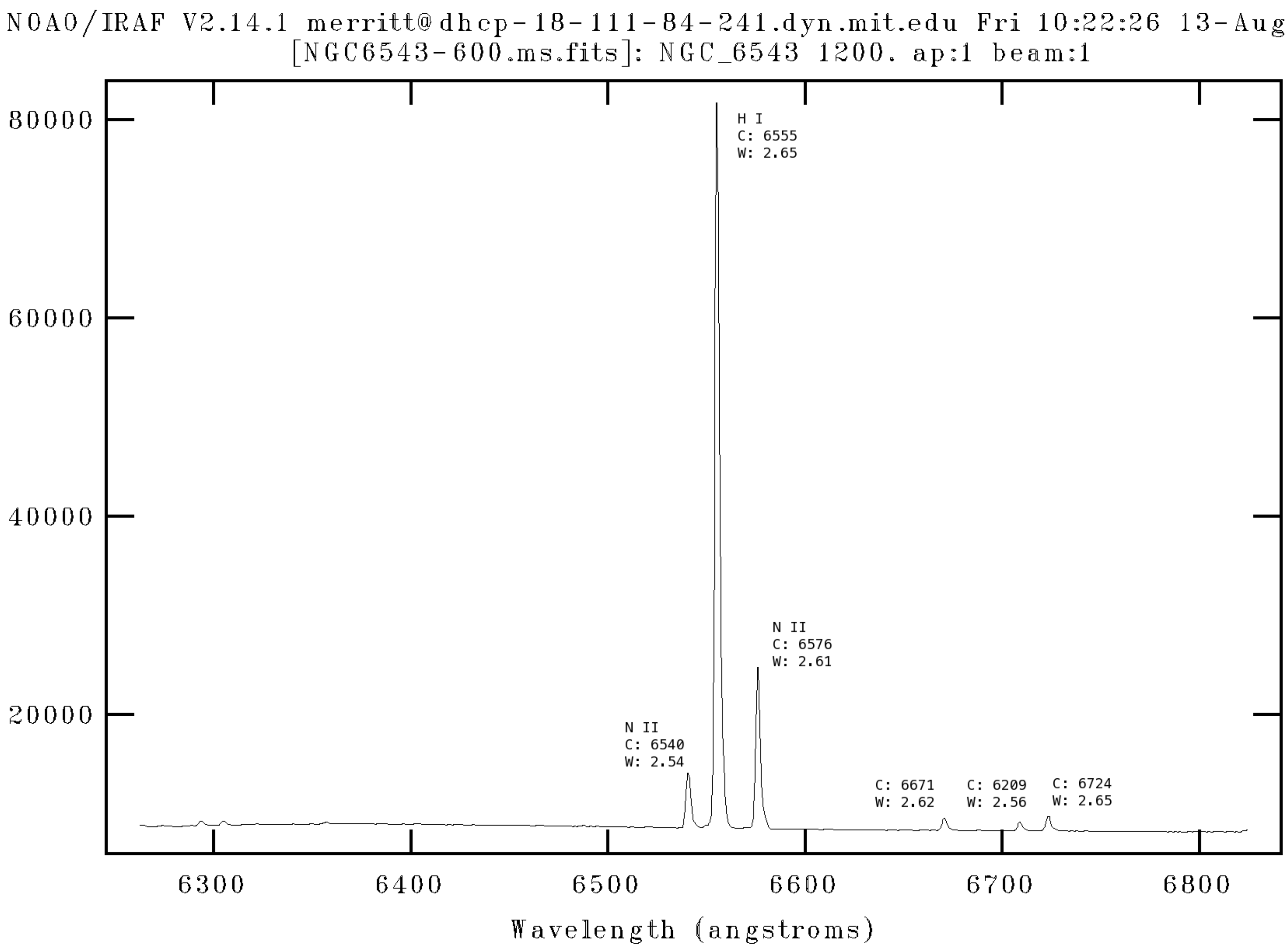
30000
40000
5800
6000
6200
6400
6600
6800
Wavelength (angstroms)



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C: 6540
W: 2.54
C: 6671
W: 2.62
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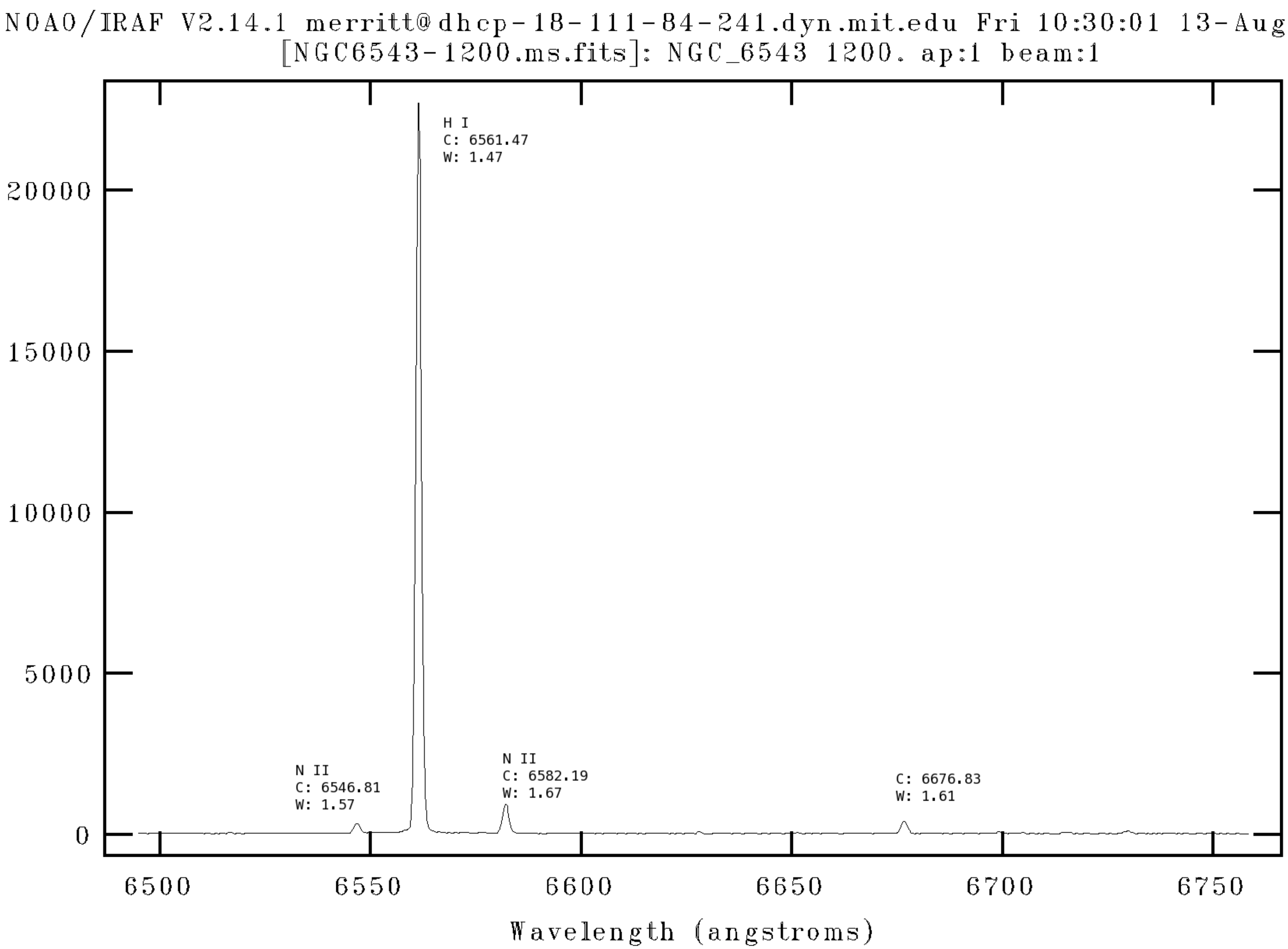
6500
6600
6700
6800
Wavelength (angstroms)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N II
C: 6582.19
W: 1.67
C: 6676.83
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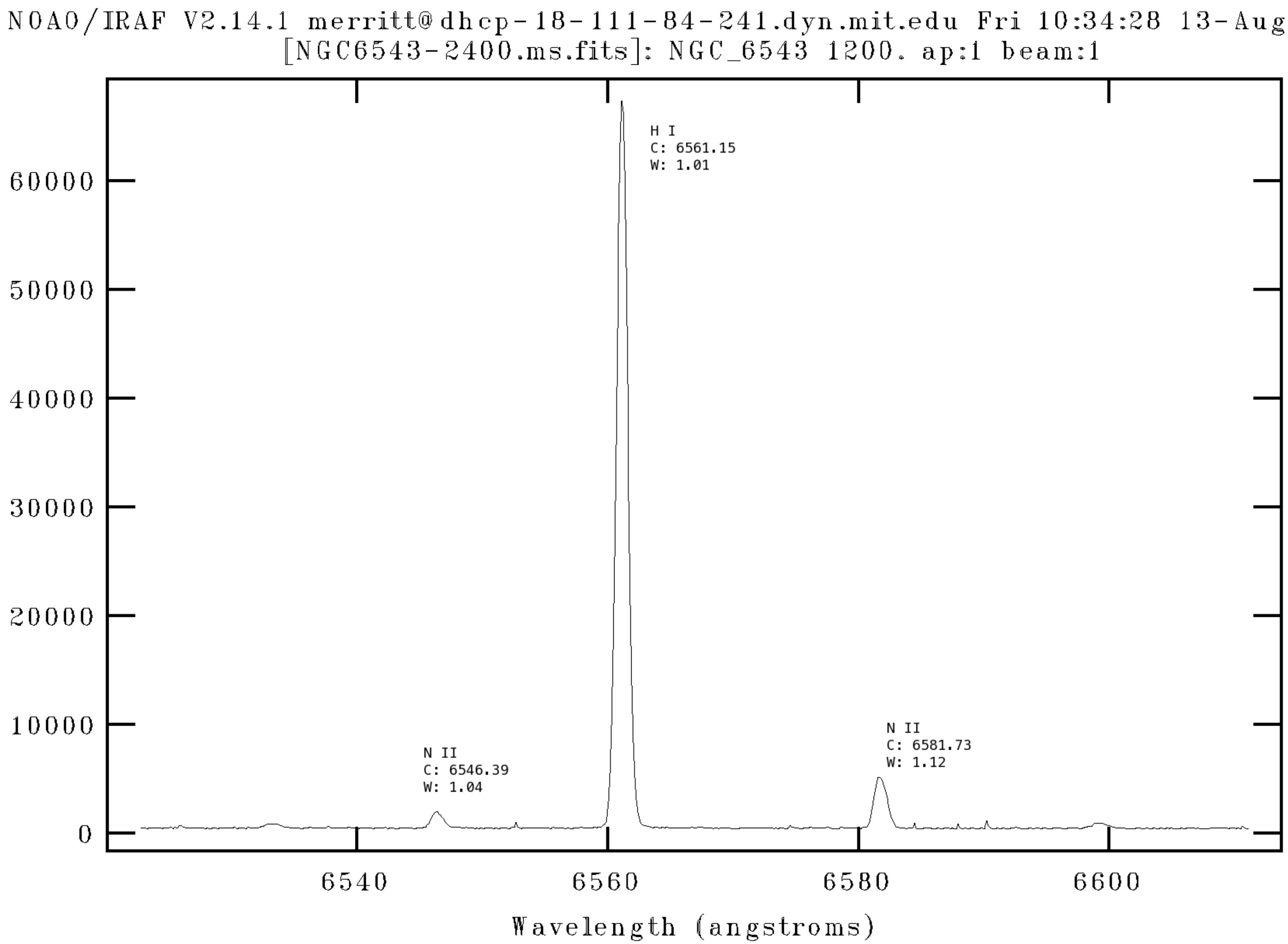
10000
5000
0
6500
6550
6600
6650
6700
6750
Wavelength (angstroms)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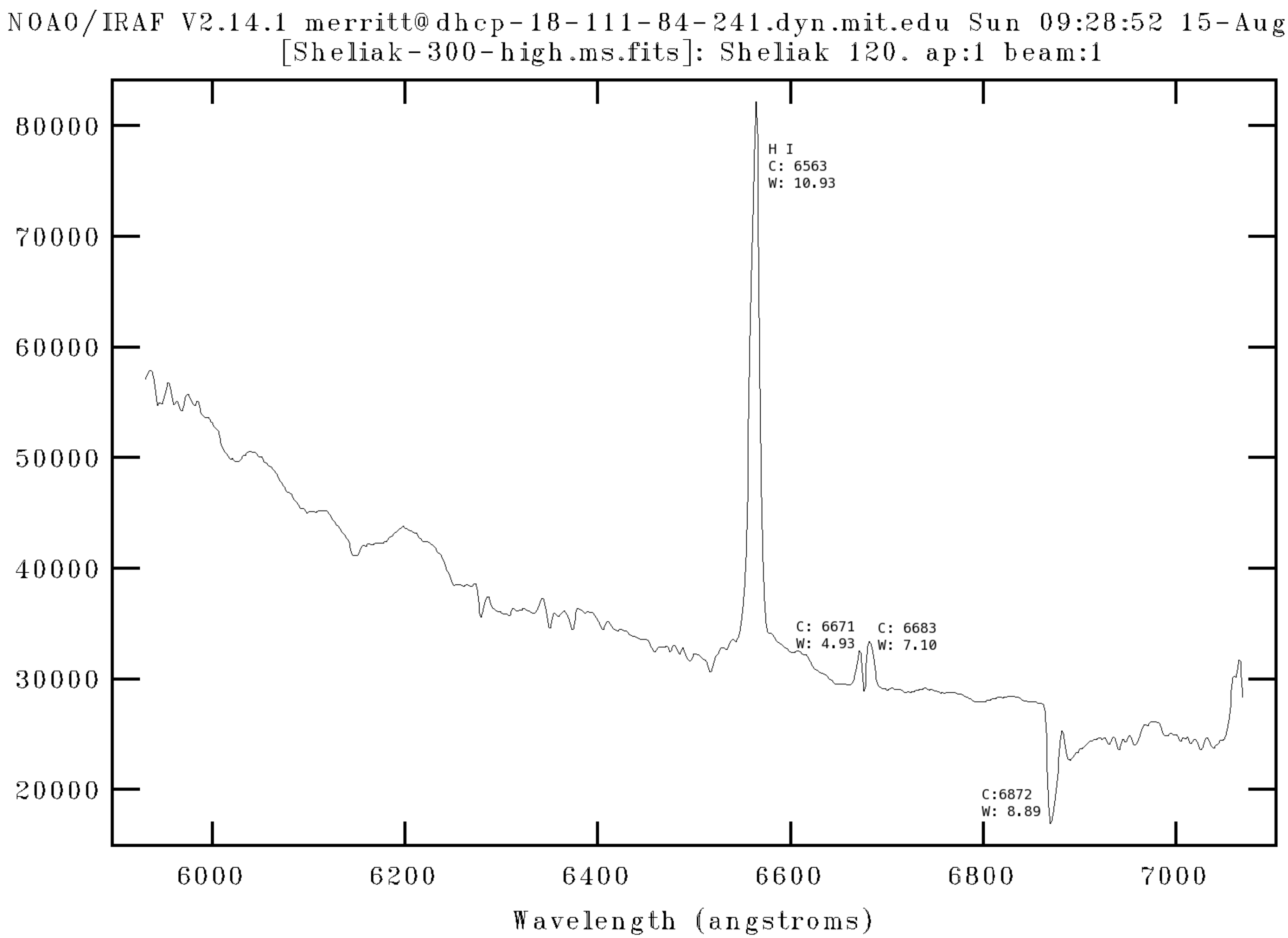
Wavelength (angstroms)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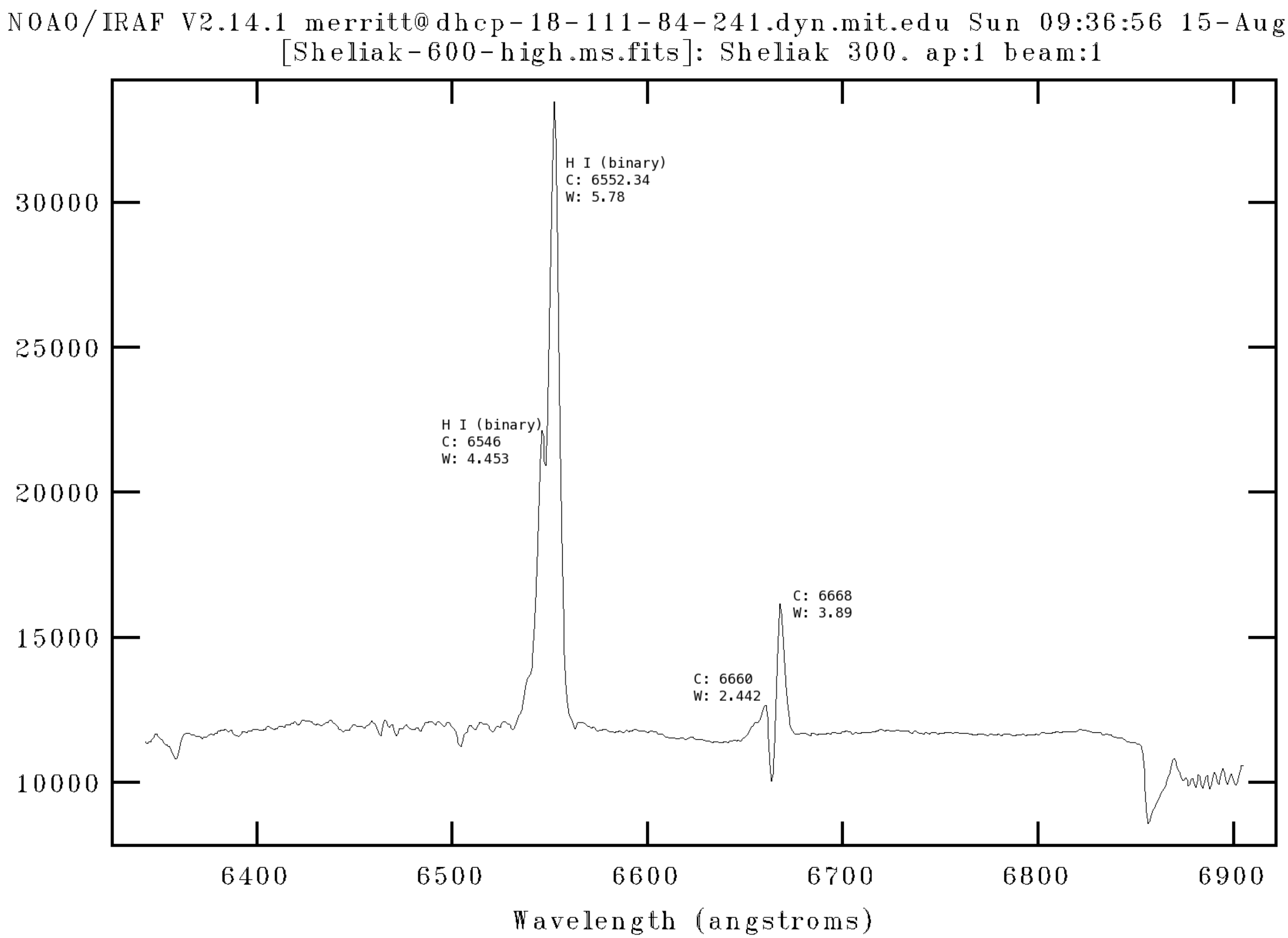
6800
7000
Wavelength (angstroms)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C: 6660
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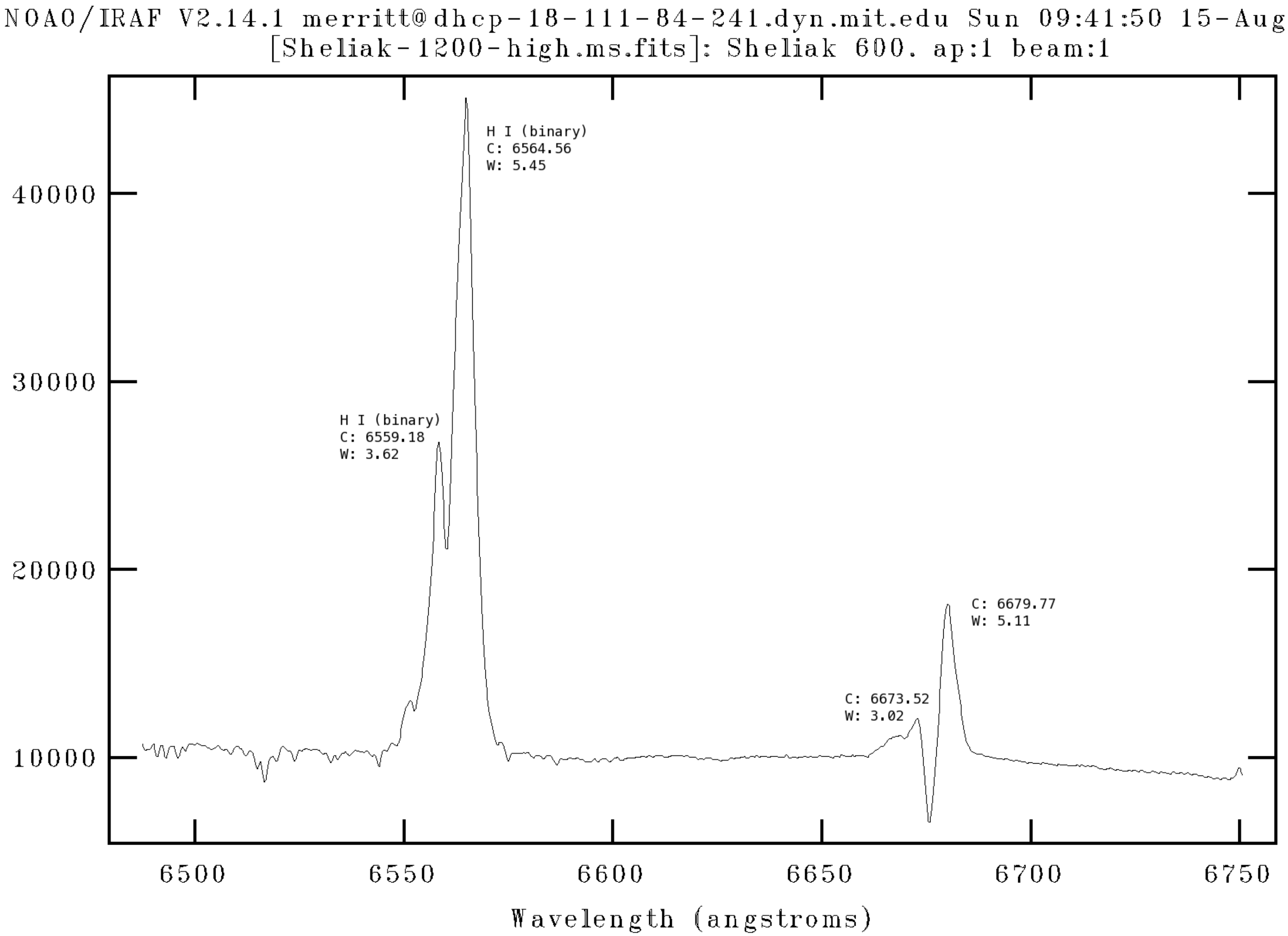
6800
6900
Wavelength (angstroms)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H I (binary)
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C: 6673.52
W: 3.02
C: 6679.77
W: 5.11
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30000
20000
10000
6500
6550
6600
6650
6700
6750
Wavelength (angstroms)

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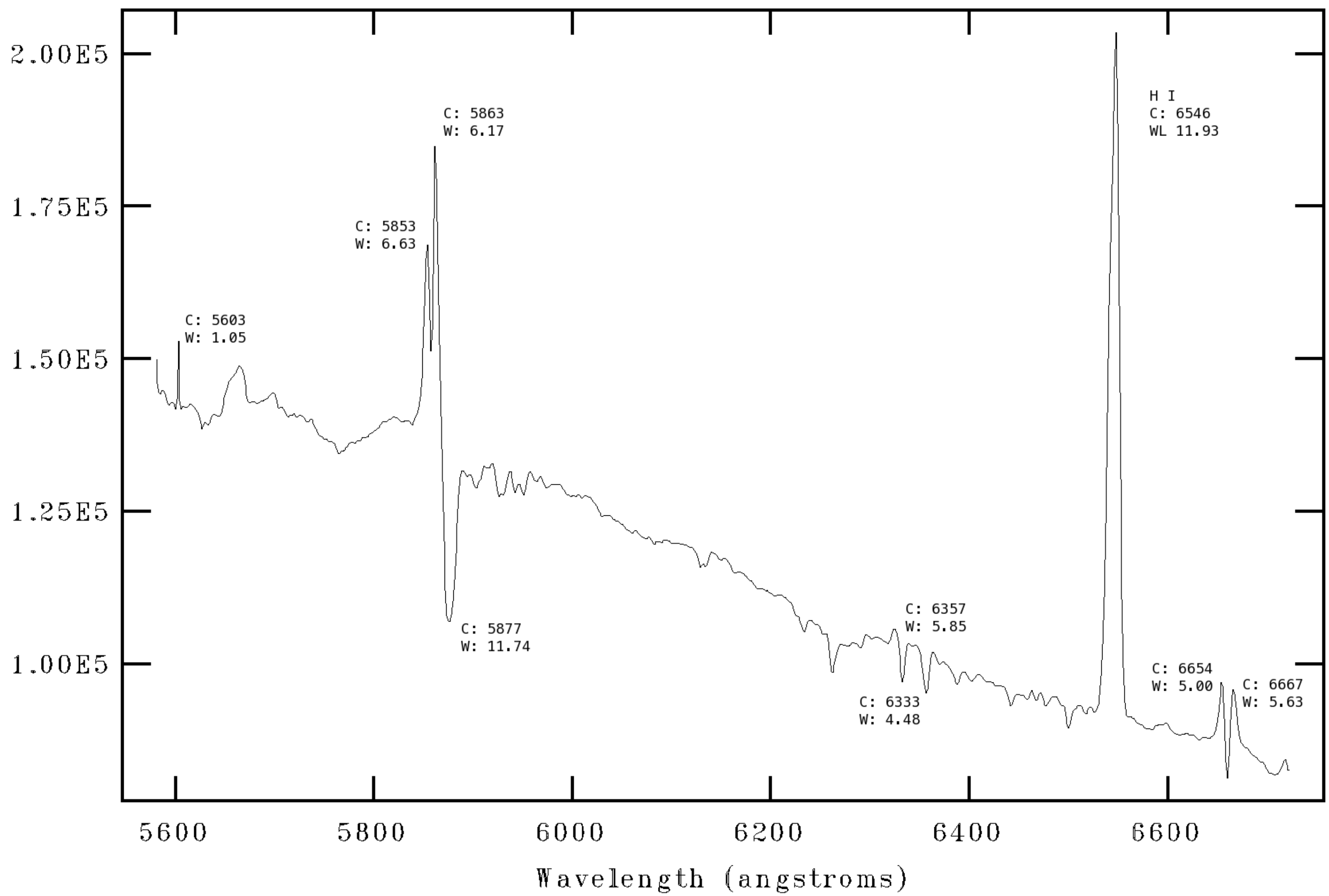

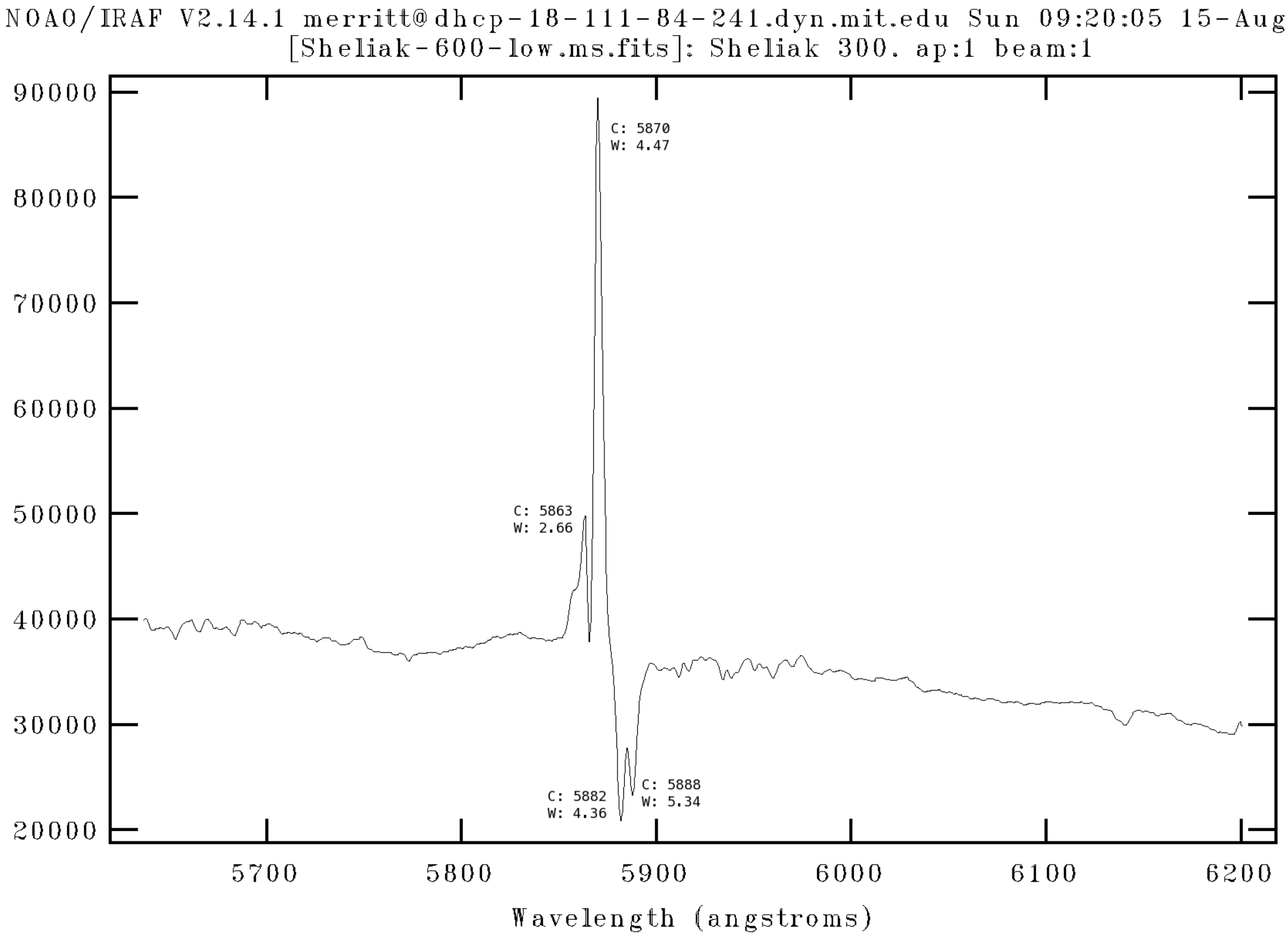

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C: 5863
W: 2.66
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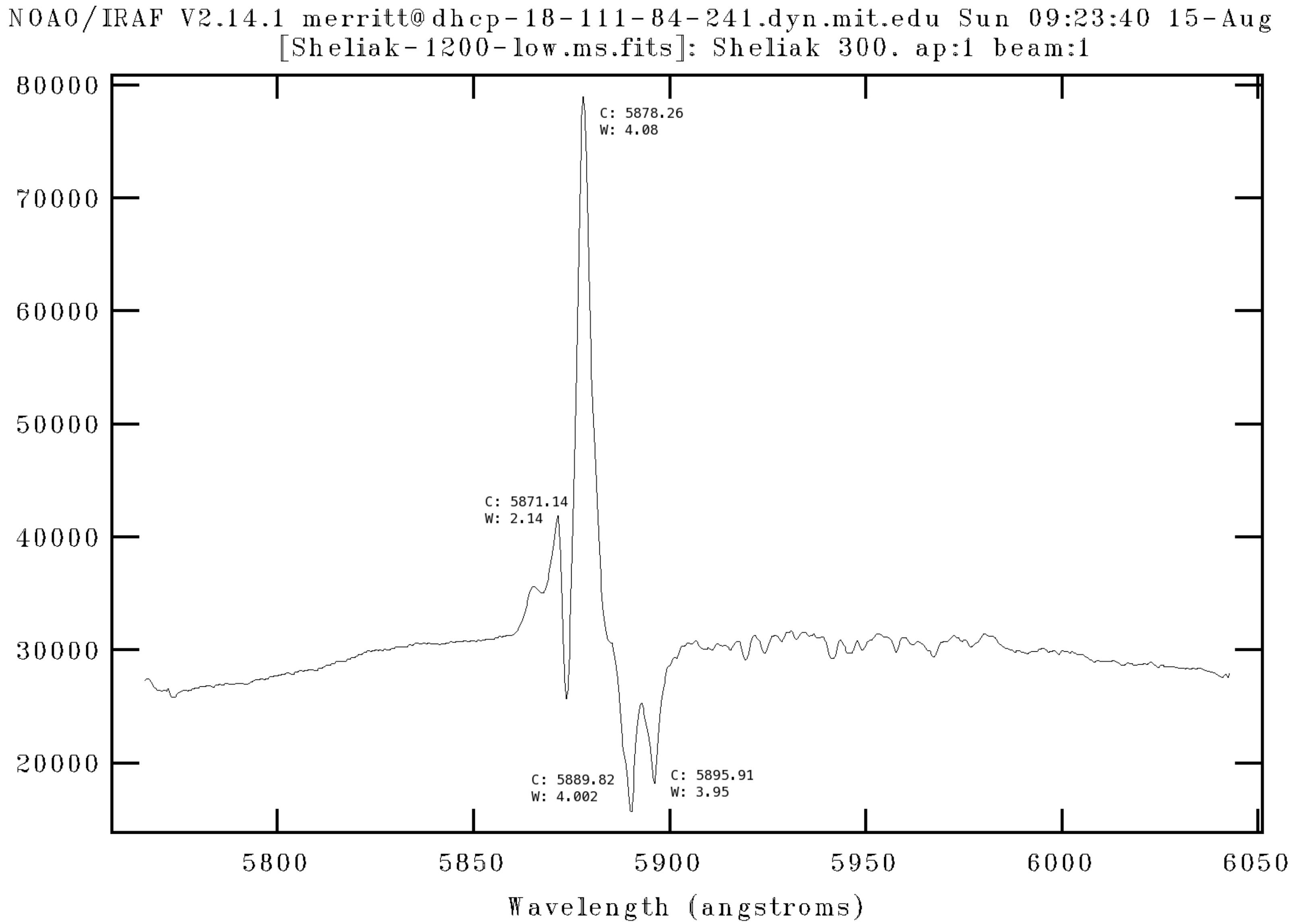
C: 5888
W: 5.34
5700
5800
5900
6000
6100
6200
Wavelength (angstroms)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30000
20000
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W: 4.08
C: 5871.14
W: 2.14
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5800
5850
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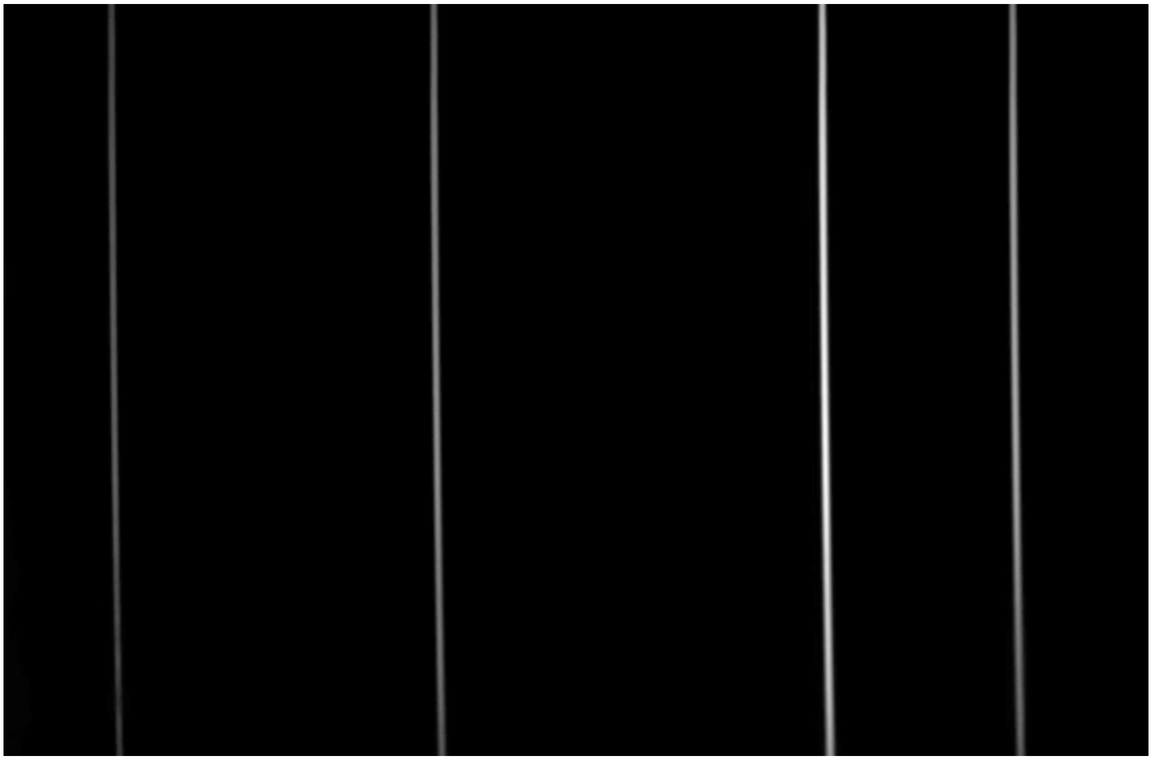
5950
6000
6050
Wavelength (angstroms)



Neon calibration from 1200 g/mm NGC6543 data set, showing high-resolution lines.

Neon calibration from 600 g/mm Sheliak (low wavelength) set, showing low-resolution lines.

Appendix

Table 1: Photometry

	Grating	Exposure Time	Apparent Magnitude (Visible)	Counts/min	Final Signal (Counts)
Sheliak	300	2m	3.5	2445	4890
	600	5m	3.5	120	600
	1200	10m	3.5	69	690
	2400	10m	3.5	63	630
NGC 6543	300	10m	9.8	180	1800
	600	20m	9.8	30	600
	1200	20m	9.8	15	300
	2400	20m	9.8	20	400
Vega	300	20s	0	424	8480
	600	20s	0	344	6880
	1200	20s	0	149	2980
	2400	20s	0	44	880
M57	300	5m	8.8	21	105
	300	10m	8.8	19	190
	300	20m	8.8	14.5	290
HD 174664	300	20m	7.2	34	680

Table 2: Data Inventory

5-24-2010	Test data, nothing particularly useful
5-25-2010	One 5 minute exposure, M57 Three 10 minute exposures, M57 Two 10 minute darks
5-29-2010	Two 20 minute exposures, M57
6-7-2010	One 10 minute exposure, M57 Five 20 minute exposures, M57 Two 20 minute darks Ten 2 minute exposures, Sheliak
6-8-2010	Two 20 minute exposures, M57 Two vega exposure brackets with darks Two 20 minute darks
6-29-2010	Two 10 minute exposures, M57
7-1-2010	Ten 10 minute exposures, NGC6543 (Cat's Eye Nebula) Five 10 minute darks
7-15-2010	Five 20 second exposures, Vega
7-17-2010	Five 20 second darks 600 Five 5 minute darks 600 Four 10 minute darks 1200 Ten 5 minute exposures, Sheliak 600 Eight 20 seconds exposures, Vega 600 Five 10 minute exposures, Sheliak 1200 Five 20 second exposures, Vega 1200
7-18-2010	Five 20 minute darks Five 20 minute exposures, Vega 2400 Five 10 minute exposures, Sheliak 2400
7-22-2010	Four 20 min minute darks Eleven 20 minute exposures, Cat's Eye 600 Two 10 second exposures, Vega 600
7-26-2010	Four 20 minute darks 1200 Three 20 minute darks 2400 Five 20 minute exposures, Cat's Eye 1200 Five 5 second exposures, Vega 1200 Five 20 minute exposures, Cat's Eye 2400 Five 20 second exposures Vega 2400
7-29-2010	Four 20 minute darks at 300 Five 20 minute exposures, Companion 300 Five 20 minute exposures, Sheliak 300
7-30-2010	Five 5 minute darks 600 Five 5 minute darks 1200 Six 5 minute exposures, Sheliak 600 Five 5 minute exposures, Sheliak 1200