BUILDING THE HST/WFC3 FLUX CALIBRATION LADDER

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In 2009, the Wide Field Camera 3 (WFC3) was installed in the Hubble Space Telescope during SM4. WFC3 is a panchromatic instrument, covering the wavelength range between 0.2 to 1.7 microns with a UVIS and an IR channel. Observing modes available are direct imaging and slitless spectroscopy, with options to 'stare' and 'scan' during exposures. We have established the photometric stability to be ~0.5%, and the relative photometry to approximately 1 –5% depending on wavelength. However, the absolute flux calibration has larger, unknown uncertainties. Thus, the goal of the Photometric Flux Calibration Ladder is to provide increased accuracy of the zeropoint measurements, improve characterization of photometric uncertainties, provide high accuracy color corrections as well as monitor sensitivity trends in both the UVIS and NIR channels. Our aim is to develop a calibration ladder from the brightest standard star(s), e.g Vega, to the faintest to improve the absolute photometric calibration and cross-calibration of the observing modes now available for grism spectroscopy and direct imaging. The source list consists of stars observed with STIS, ACS, NICMOS, SPITZER/IRAC, and some of the proposed JWST calibration standards. Brightness spans the range from V = 0 -17 mag, and J=0-15 mag. Stellar spectral types include white dwarfs, A, G, as well as K and M stars.

I will discuss our efforts to provide an absolute, above the atmosphere, calibration of Vega, including the challenges to achieving a 1% absolute calibration of the HST/WFC3.

Hubble Space Telescope

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- 200 miles above Earth
- 90 minute orbit
- 5 active instruments: COS, STIS, ACS, WFC3, FGS
- MAMAs, CCDs, HgCdTe.
- imaging, grism and long slit spectroscopy
- total wavelength coverage: 0.1 to 1.7 microns
- 8700+ research papers

Wide Field Camera 3

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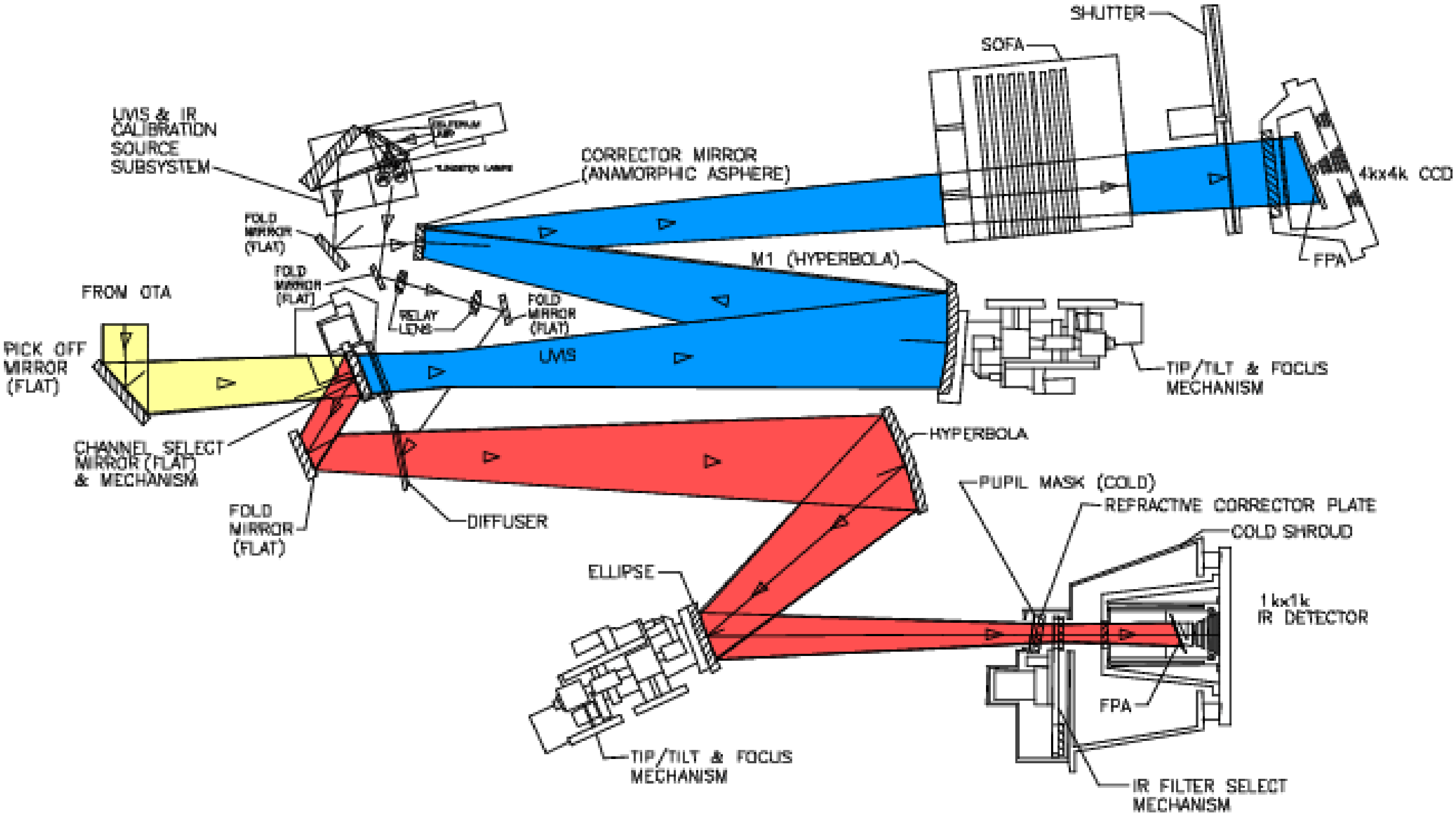


Science Cases

for relative photometry:

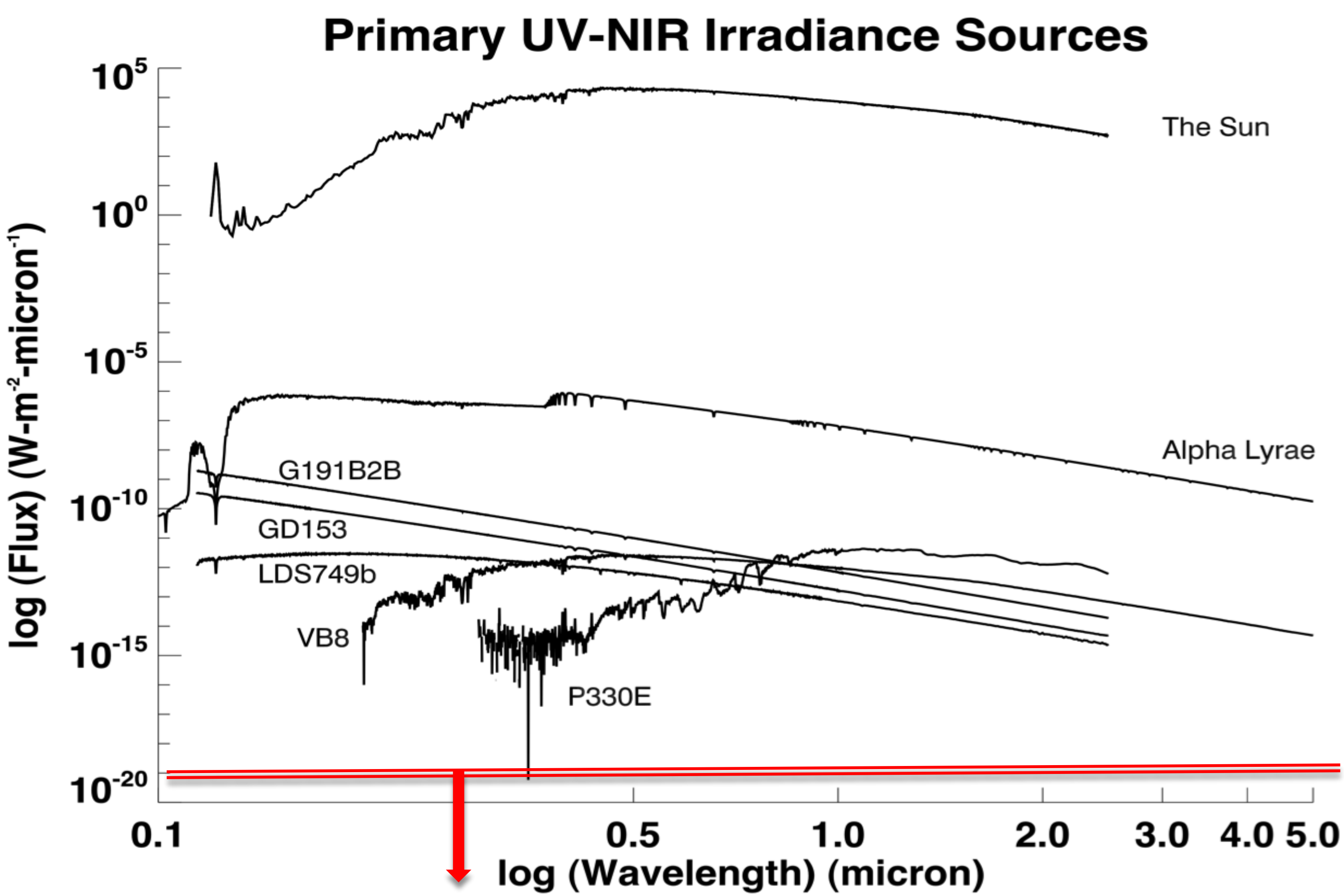
- detection of transiting planets
- stability of solar flux
- effective temperature of stars

for absolute flux:

- supernova cosmology
- fundamental stellar parameters – mass, distance, size
- cross-calibration of bandpasses, instruments

Challenge: dynamic range

Flux Dynamic Range



Challenge: managing uncertainties

from 'NIST' to Source

$$E(\lambda)_{celestial-source} = \frac{S(\lambda)_{celestial-source}}{S(\lambda)_{SI-source}} \times E(\lambda)_{SI-source}$$

$$\sigma^2_{celestial-source} = \sigma^2_{SI-source} + \sigma^2_{measurement}$$

But in reality we get this:

$$\sigma^2_{celestial-source} = \sigma^2_{nist} + \sigma^2_{primary} + \ldots\sigma^2_{etc}$$

Sources of Uncertainty

- flatfields
- persistence (IR)
- wavelength calibration
- color (spectral energy distribution)
- stability
- linearity

Vega and the WFC3 Flux Calibration Ladder

Objective

- **SI-traceable photometric calibration**
  - i.e. absolute flux in $W\text{-}m^{-2}$
- **Improve photometric uncertainties**
  - Absolute flux uncertainites < 5%
  - Relative flux uncertainties < 1%
- **Identify and characterize photometric uncertainties** Flat field effects
  - Position dependence of response functions

Flux Calibration Ladder

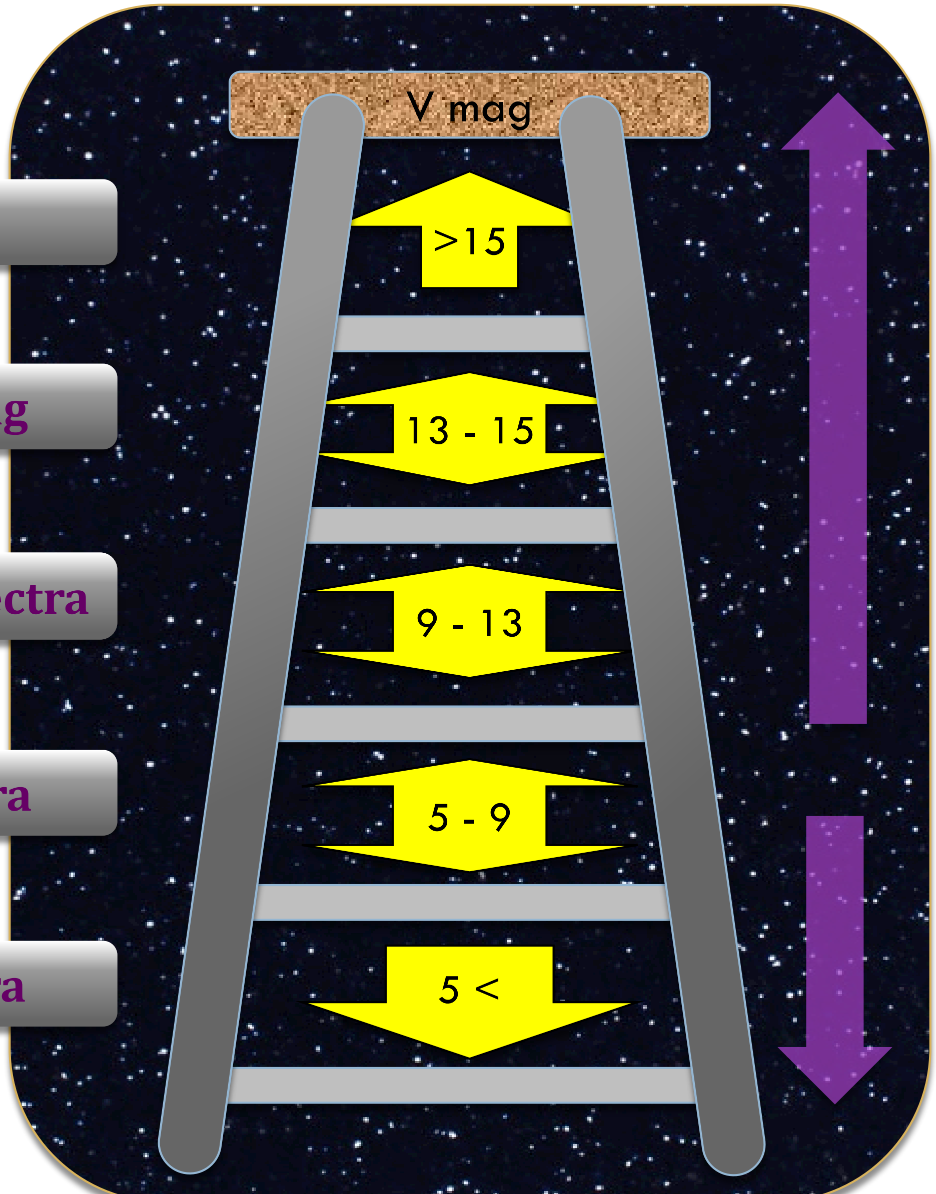
imaging

spectra & imaging

-1st & +1st order spectra

+1st order spectra

-1st order spectra



STARE MODE

SCAN MODE

Object	Calibration Method		Error	References
Mars planet	Direct	Blackbody		Sinton & Strong (1960) Rieke, Lebofsky & Low (1985)
	Direct	Transfer standard		Neugebauer et al. (1971) Wieland et al. (2011)
Sirius A1 V star	Direct	Blackbody, Emissive Spheres	<1%	Price et al. (2004)
	Indirect	Stellar Atmosphere Model		Cohen et al. (1992)
Sun G2 V star	Direct	Radiometers, Pyrometers, Lamps		Thuillier et al. (2003)
Vega A0 V star	Direct	Blackbodies, Lamps	~1% - 8%	Megessier (1995)
	Indirect	Infrared Flux Method		Leggett 1985
G191B2B DA WD	Indirect	Stellar Atmosphere Model	~1-2%	
GD 71 DA WD	Indirect	Stellar Atmosphere Model	~1-2%	Bohlin et al. (1995)
GD 153 DA WD	Indirect	Stellar Atmosphere Model	~1-2%	

Standard Stars

Name	Status	HST	SPITZER	OTHER
Vega (α Lyr)		STIS		MSX, ACCESS,NISTStars
HD18069			IRAC primary	JWST
G191B2B	primary	STIS & NICMOS	IRAC	JWST
HD37725			IRAC secondary	JWST, ACCESS
GD71	primary	STIS & NICMOS		JWST
HD 93521		STIS		ACCESS
GD153	primary	STIS & NICMOS		JWST
P177D (GSC 03493-00432)		STIS & NICMOS		
SNAP2 (2MASS J16194609+5534178)	secondary	STIS & NICMOS		2MASS, SDSS, JWST
P330E (GSC-02581-02323)	secondary	STIS & NICMOS	IRAC, MIPS	
VB8 (GJ 644 C)	secondary	STIS & NICMOS		
WD1657+343	secondary	STIS & NICMOS		SDSS
LTT 15209	secondary	STIS & NICMOS		
KF06T2 (2MASS J17583798+6646522)		NICMOS	IRAC primary	
180227 (2MASS J18022716+6043356)	secondary	NICMOS	IRAC, IRSB secondary	2MASS, JWST
HR 7018			IRS secondary	
LDS749B (EGGR 145)	secondary	STIS & NICMOS	IRAC	JWST
[HMT98] AS-36-4				ARNICA
2MASSJ23122061+1046340				2MASS

Standard Stars

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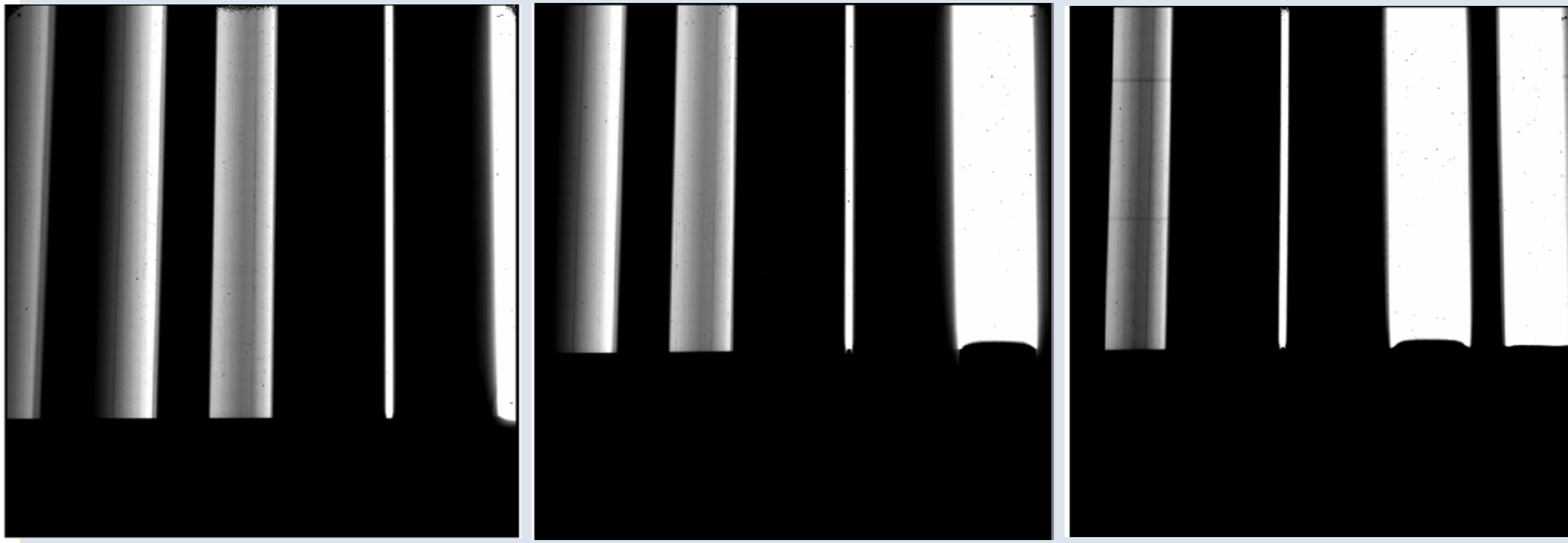
Name	Sp. Type	RA(J 2000) (+/-0.1")	DEC(J2000) (+/-0.1")	B	V	J[2]	H[2]	K[2]
Vega (α Lyr)	A0V	1:3:56.3364	38:47:1.28	0.03	0.03	-0.18	0.03	0.13
HD18069	A3 IV	02:53:46.9820	-16:03:22.90	10.21	9.89	9.602	9.539	9.534
G191B2B	DA	05:05:30.6128	+52:49:51.96	11.44	11.69	12.543	12.669	12.764
HD37725	A3	05:41:54.3707	+29:17:50.93	8.51	8.35	7.953	7.915	7.902
GD71	DAw	05:52:27.6100	+15:53:13.80	12.783	13.032	13.728	13.901	14.115
HD 93521	O9V	10:48:23.5114	+3:34:13.09	6.79	7.03	7.499	7.647	7.696
GD153	DA1.5	12:57:2.3370	+22:01:52.68	13.17	13.40	14.012	14.209	14.308
P177D (GSC 03493-00432)	G V	15:59:13.5700	+47:36:41.90	13.963	13.356	14.495	14.81	14.884
SNAP2 (2MASS J16194609+5534178)	G V	16:19:46.1110	+55:34:17.82	17.09	16.23	14.97	14.59	14.49
P330E (GSC-02581-02323)	G2 V	16:31:33.8200	+30:08:46.50	12.972	12.917	11.769	11.454	11.379
VB8 (GJ 644 C)	M7 V	16:55:35.2900	-08:23:40.10	18.7	16.70	9.776	9.201	8.816
WD1657+343	DA	16:58:51.1200	+34:18:53.30	16.12	16.15			
LTT 15209	G1V	17:32:0.9925	+3:16:16.13	7.21	6.56	5.342	5.076	4.998
KF06T2 (2MASS J17583798+6646522)	K1.5 III	17:58:37.9900	+66:46:52.20	15.1	14.2	11.899	11.273	11.149
180227 (2MASS J18022716+6043356)	A2V	18:02:27.1700	+60:43:35.70	12.0	11.985	11.872	11.850	11.832
HR 7018	A0V	18:37:33.5001	+6:31:35.72	5.690	5.740	5.725	5.773	5.753
LDS749B (EGGR 145)	DB	21:32:16.2400	+00:15:14.40	14.634	14.674	14.894	15.050	15.217
[HMT98] AS-36-4	UD	21:52:25.5000	+02:23:35.00			15.31	14.769	14.514
2MASSJ23122061+1046340	UD	23:12:20.6200	+10:46:34.00	19.5		15.084	14.463	14.225

Strategy

- Obtain spectra from UV to IR
  - STIS between 0.2 -1.0 microns
  - WFC3/IR between 0.8 -1.65 microns
  - Scan mode for brightest stars in WFC3/IR
- Photometry:
  - WFC3/UVIS and WFC3/IR
- Cross check photometry with spectroscopy
- Stars are observed in more than mode
- Select stars for
  - SI traceability– Vega
  - Cross-calibration with space and ground
  - Spectral type range: Improve color corrections
  - Brightness range: Minimize non-linearity effect

Spectral Scan Positions on the Detector



Grism orders from right to left are +2nd, +1st, 0th, -1st and -2nd. Left: 0th, -1st, -2$^{nd.}$ Slivers of the +1st on the right edge, and -3rd on the left edge are visible. Center: +1st, 0th, -1st and -2nd orders. Right: +2nd, +1st, 0th and -1st orders are visible. The 0th, +1st and +2nd orders are saturated

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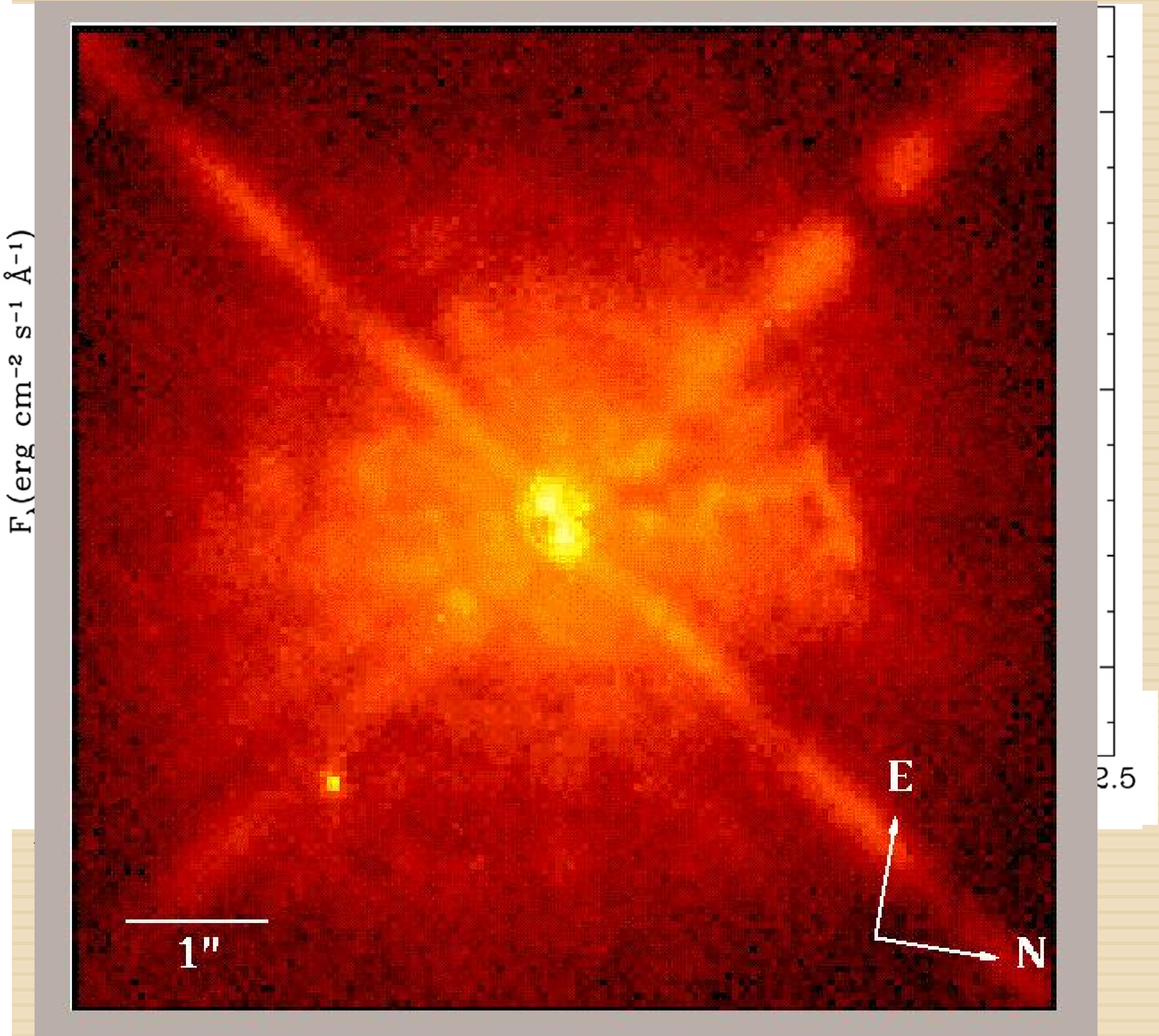
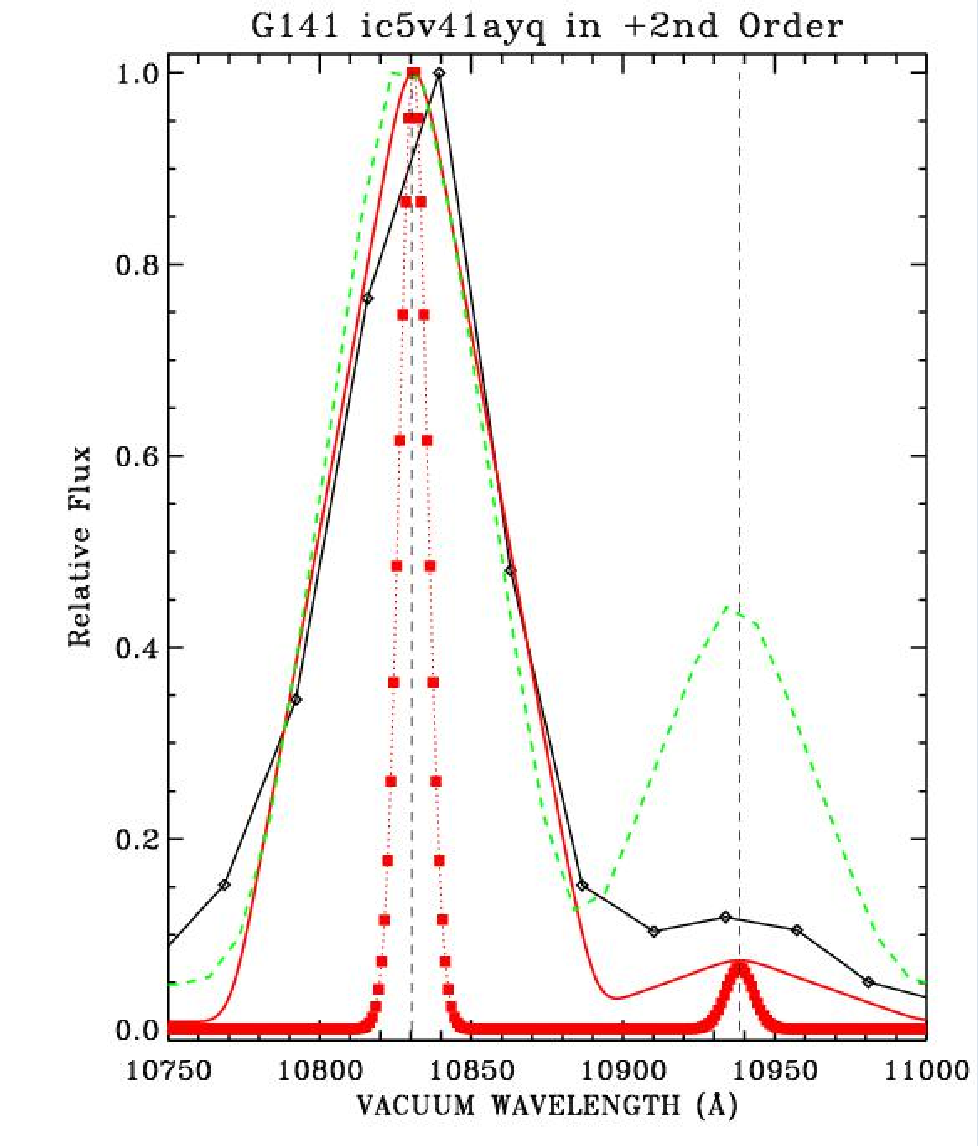
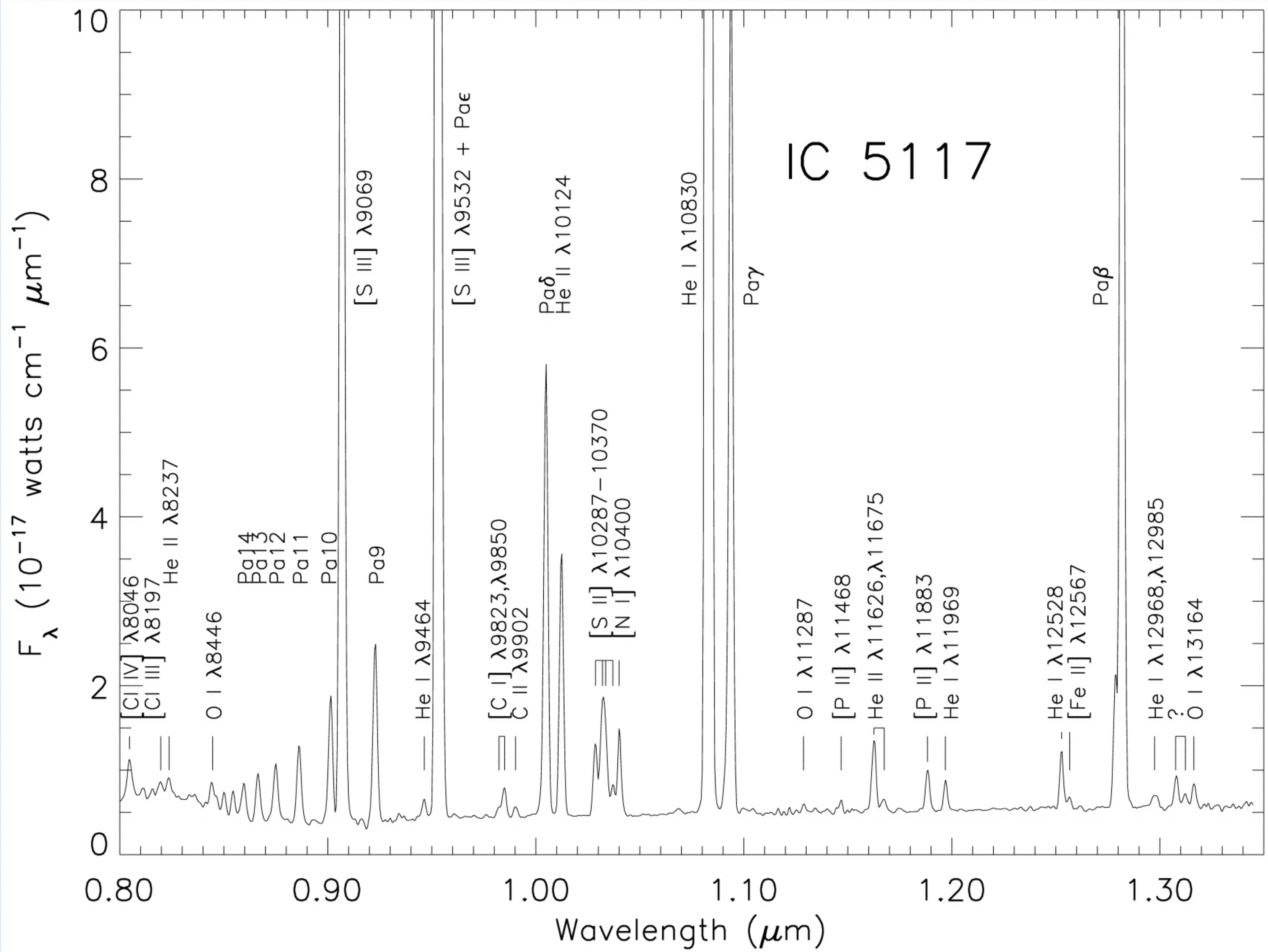
Wavelength Calibration

Planetary Nebula Vy 2-2




G141 ic5v41ayq in +2nd Order
Relative Flux
1.0
0.8
0.6
0.4
0.2
0.0
10750
10800
10850
10900
10950
11000
VACUUM WAVELENGTH (Å)

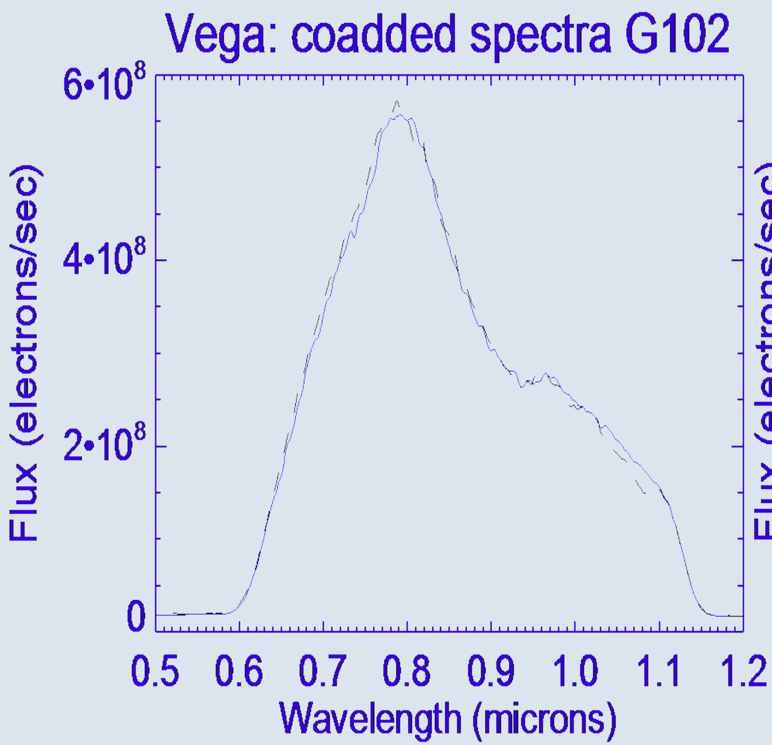
Planetary Nebula IC 5117

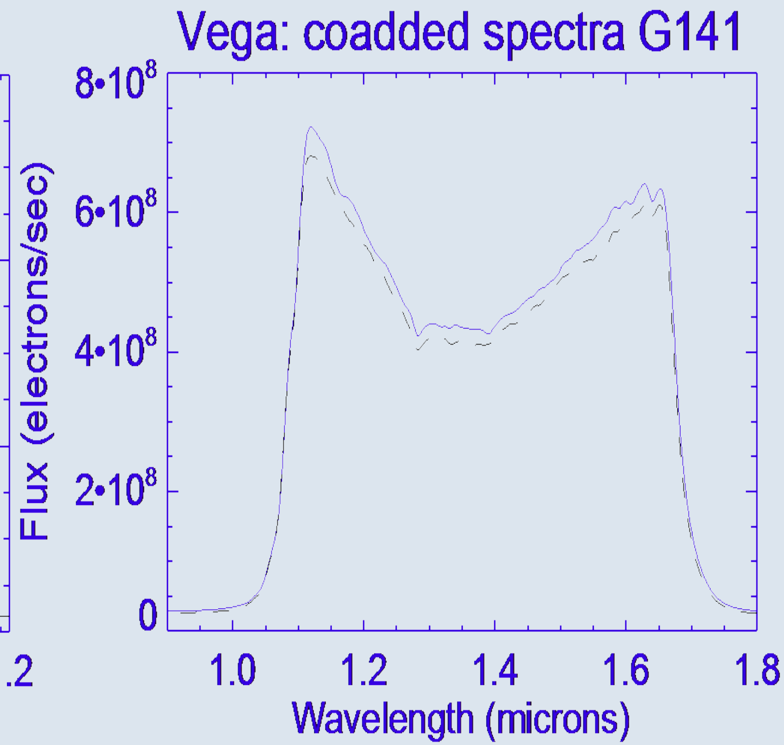


Adopted updated wavelength identification of IC 5117 by Rick Rudy (private communication).

Figure from Rudy et al, 2001, AJ 121, 362

Coadded unfluxed spectra of Vega





-1st orders of the G141 and G102 WFC3 IR grisms. G141: Paschen β is the dip at -1.28 microns, and the series of features between 1.6 and 1.7 microns are Br 13,12, 11. G102: Pa γ is just visible at 1.09 microns, and Pa δ at 1.05 microns.

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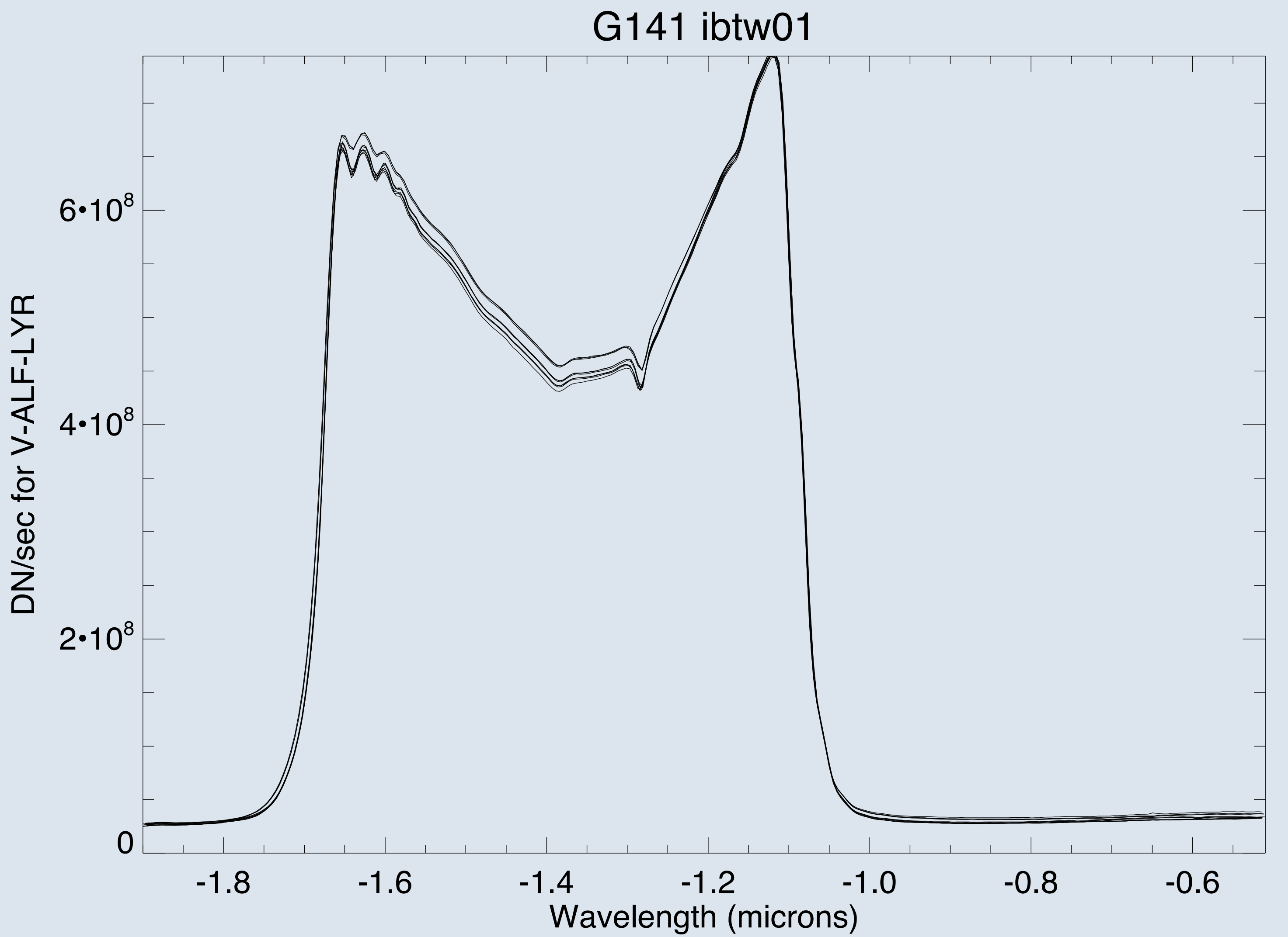
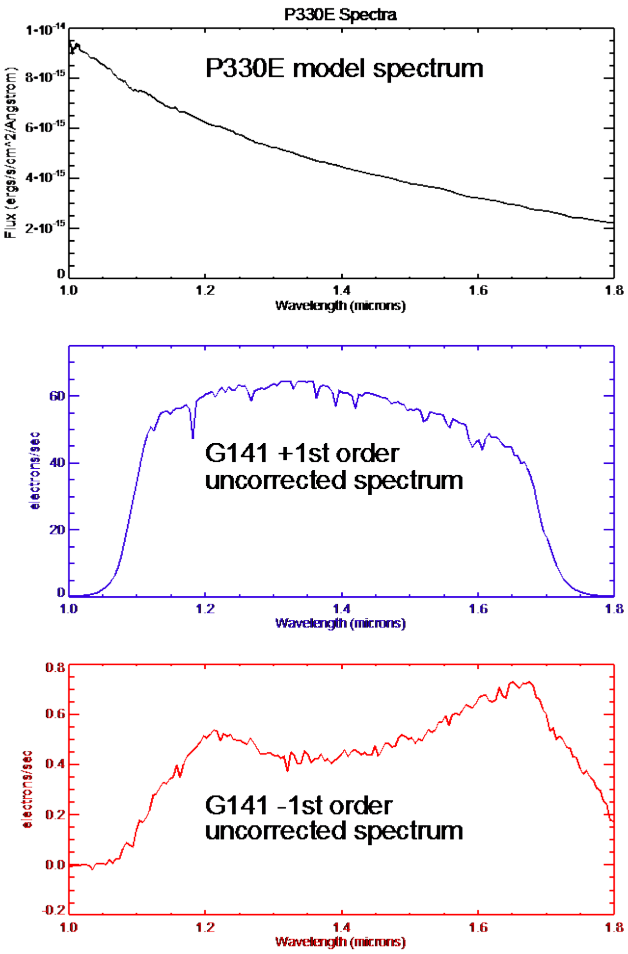
Comparison of scanned spectra: G141

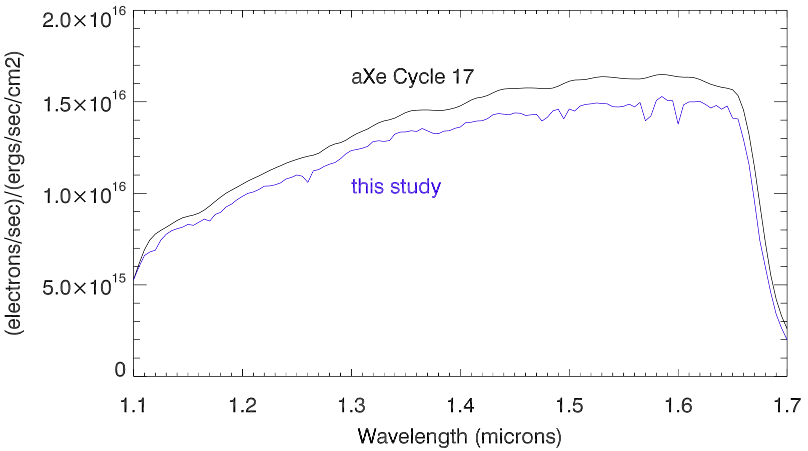


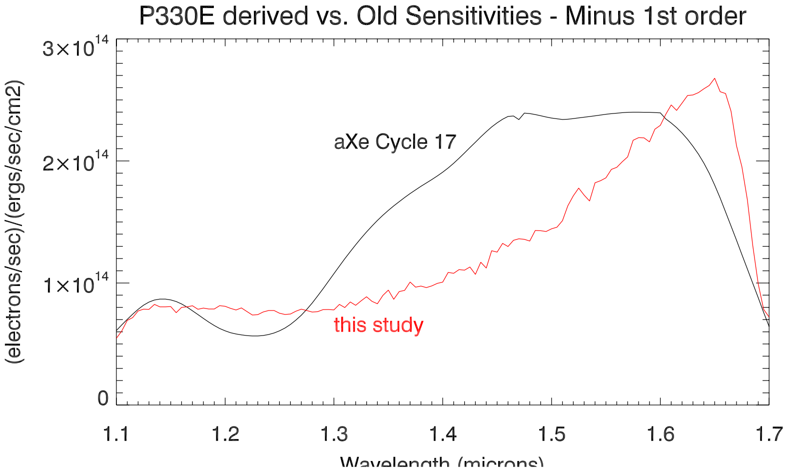
-1st order spectra in G141 coadded at each scan position, after dark subtraction, flatfielding, dispersion correction and rectification.

Response Functions

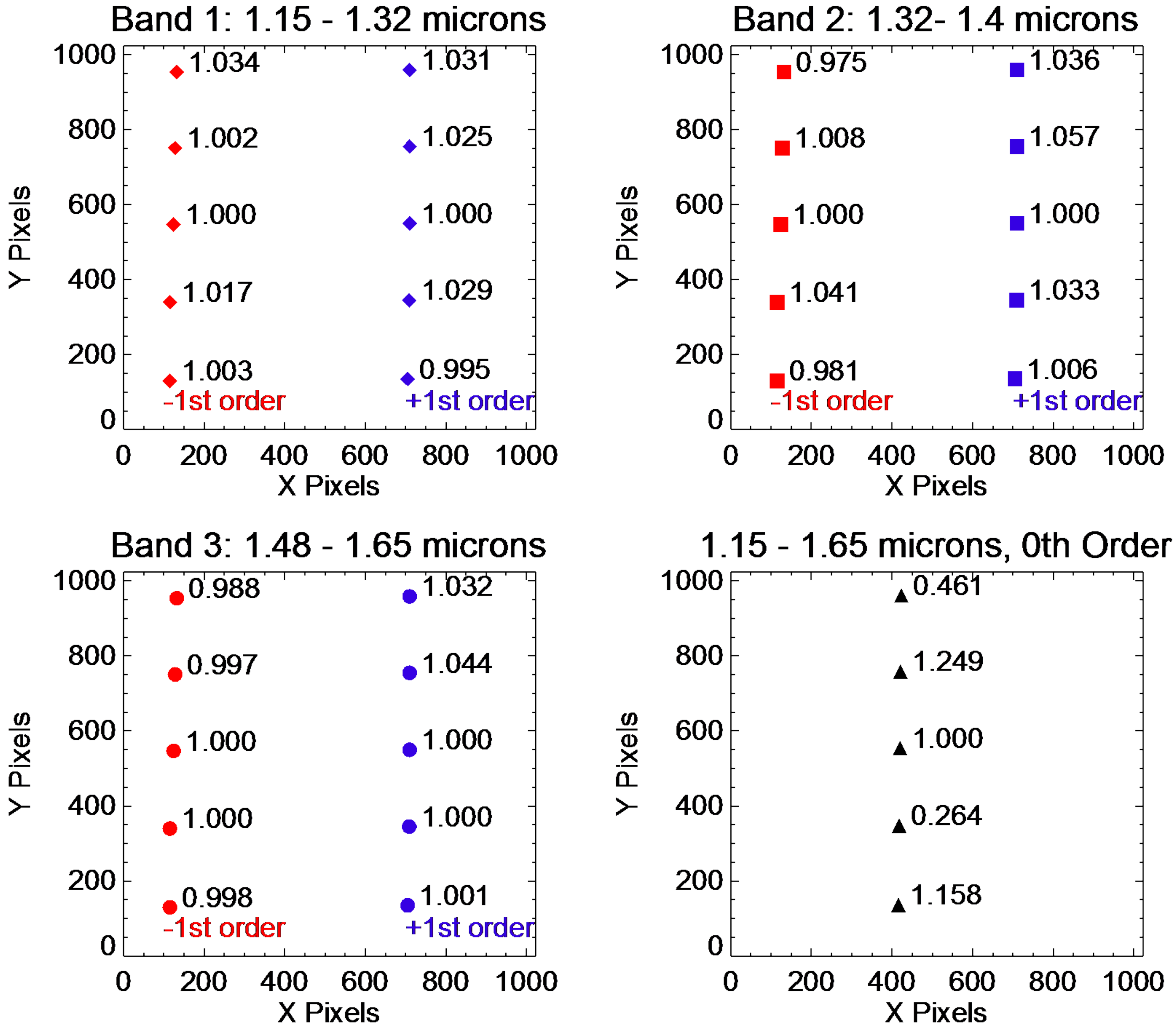
Sensitivity Function

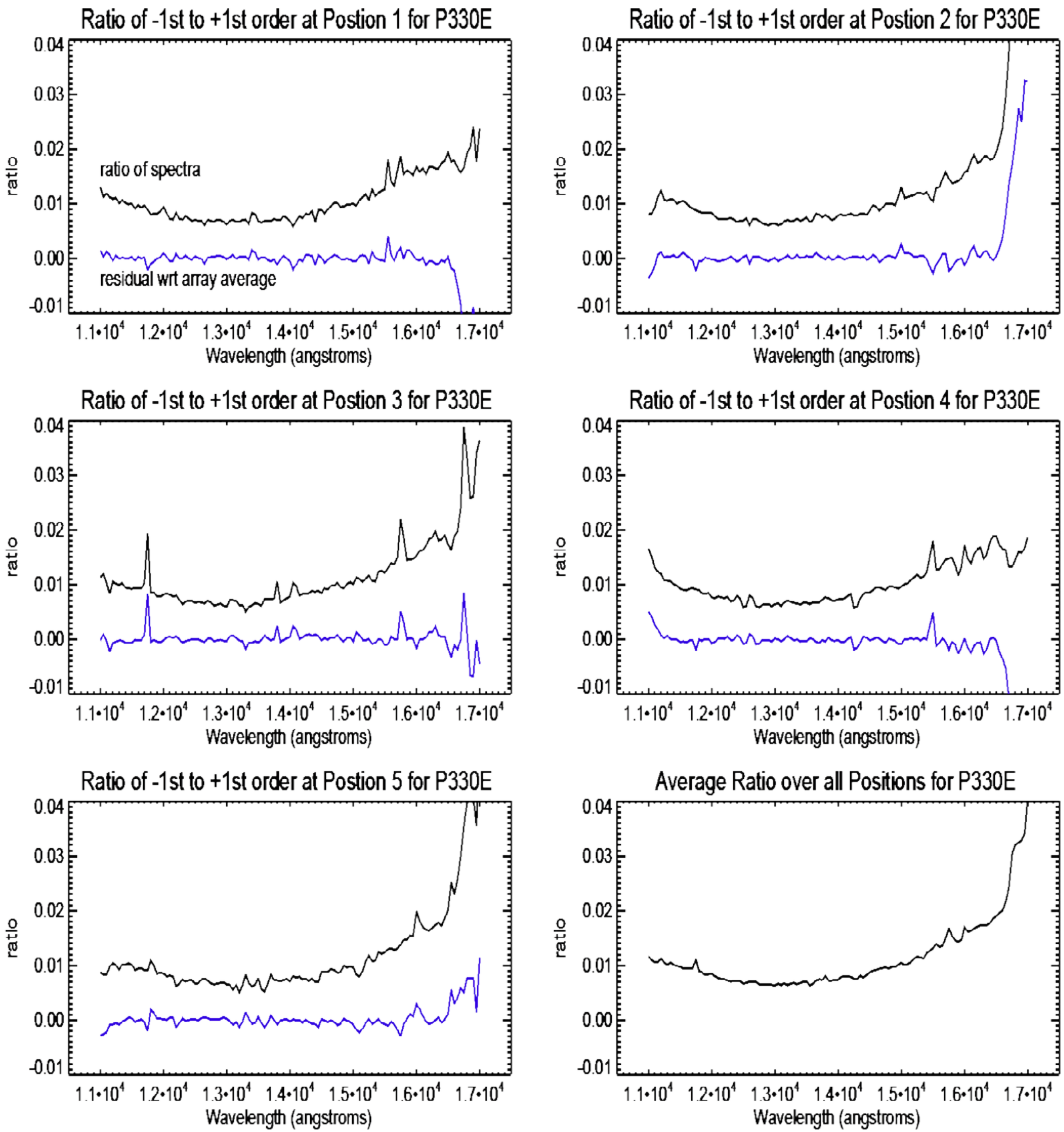






Spatial Variation in Response


Band 1: 1.15 - 1.32 microns
1.034
1.031
1.002
1.025
1.000
1.000
1.017
1.029
1.003
0.995
-1st order
+1st order
Y Pixels
X Pixels
Band 2: 1.32- 1.4 microns
0.975
1.036
1.008
1.057
1.000
1.000
1.041
1.033
0.981
1.006
-1st order
+1st order
Y Pixels
X Pixels
Band 3: 1.48 - 1.65 microns
0.988
1.032
0.997
1.044
1.000
1.000
1.000
1.000
0.998
1.001
-1st order
+1st order
Y Pixels
X Pixels
1.15 - 1.65 microns, 0th Order
0.461
1.249
1.000
0.264
1.158
Y Pixels
X Pixels


Ratio of -1st to +1st order at Postion 1 for P330E
ratio of spectra
residual wrt array average
Ratio of -1st to +1st order at Postion 2 for P330E
Ratio of -1st to +1st order at Postion 3 for P330E
Ratio of -1st to +1st order at Postion 4 for P330E
Ratio of -1st to +1st order at Postion 5 for P330E
Average Ratio over all Positions for P330E
ratio
0.04
0.03
0.02
0.01
0.00
-0.01
1.1•10^4
1.2•10^4
1.3•10^4
1.4•10^4
1.5•10^4
1.6•10^4
1.7•10^4
Wavelength (angstroms)

Current and Planned Experiments

- NISTstars , ground based, SI traceable (PI C. Cramer)
  - => high precision & accuracy, visible
- ALTAIR – suborbital payload, SI traceable, laser (PI J. Albert)
  - (Yorke Brown's talk on Monday)
- ACCESS – rocket, SI based (PI M.E. Kaiser)
  - high precision, calibration accuracy of 1%, 0.35-1.7μm bandpass.

Lidar and GPS systems to measure atmospheric properties

- AESOP (UNM) & gps systems TAMU

  => improved atmosphere models e.g. MODTRAN

Summary

- Vega can be observed with HST in the NIR
- Provides 'above the atmosphere' spectral data

- To do:
  - improve sensitivity function
  - resolve SED differences
  - determine error budget