HST GO12600:

The Most Comprehensive study of the UV Spectra of Galactic Planetary Nebulae to Date

Reggie Dufour
Rice University

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The Most Comprehensive study of the UV Spectra of Galactic Planetary Nebulae to Date "work in progress!"

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GO12600: Cycle 19 HST Program (32 orbits)

The goal of this project is to assess the role played in carbon production by low and intermediate mass stars (LIMS), i.e. the progenitors of planetary nebulae (PNe). One of the most pressing problems in galactic chemical evolution today is understanding the relative roles of LIMS (1-8 Mo) versus massive stars (8-120 Mo) in affecting the cosmic level of the element C. We are launching a fresh, ambitious project whose purpose is to employ STIS to obtain UV spectra of unprecedented-quality of 10 carefully chosen, bright solar metallicity PNe spanning a broad range in progenitor mass. Line strength measurements of important emission lines of C, N, and O such as OIII] 1660-6Å, NIII] 1747-54Å, CIII] 1907-9Å, and (when He++ is strong) CIV] 1550Å and OIV] 1400Å in each object will be used along with our own in-house abundance software to determine ion and element abundances for these three species. In turn, these results will be used to assess stellar yields (productivity rates) available in the literature. Favored yield sets will be used to calculate our own chemical evolution models to assess the importance of LIMS in the cosmic evolution of C.

OUTLINE

1. THE "CHARACTERS"
2. SCIENCE DRIVERS
3. STIS OBSERVATIONS
4. RESULTS: EXAMPLE SPECTRA
5. ANALYSIS EXAMPLE: NGC 3242
6. FUTURE PLANS

1. THE CHARACTERS

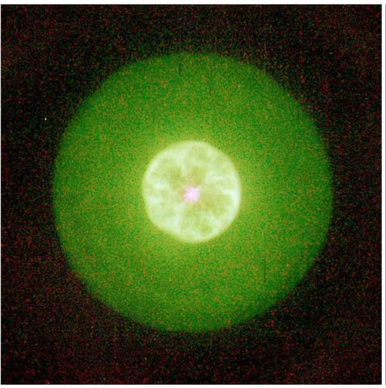
A. The People

Reggie Dufour (Rice University), PI
Dick Henry (Univ. Oklahoma), CoPI
Karen Kwitter (Williams College), CoI
Bruce Balick (Univ. Washington), CoI
Dick Shaw (NOAO), CoI
Romano Corradi (IAC, Spain), CoI

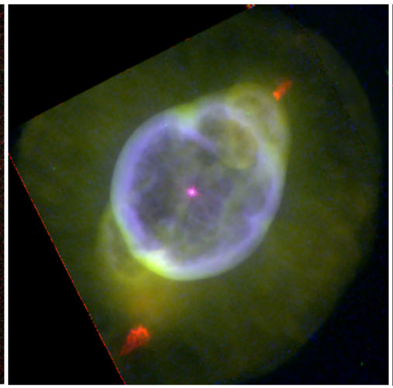
B. The Nebulae

Observed to date: NGC 3242, IC2165, NGC 5882, NGC 5315, NGC 6537, & PB6

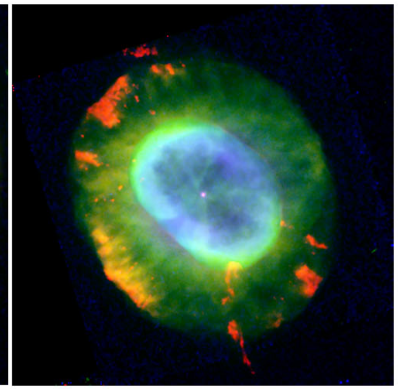
round core → *← elliptical core*



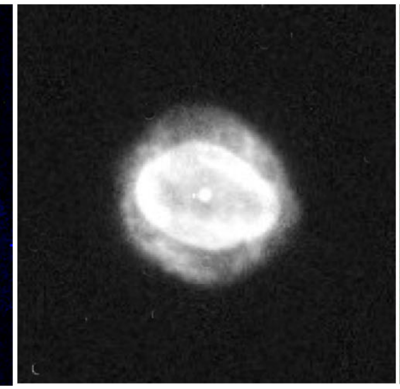
IC 3568



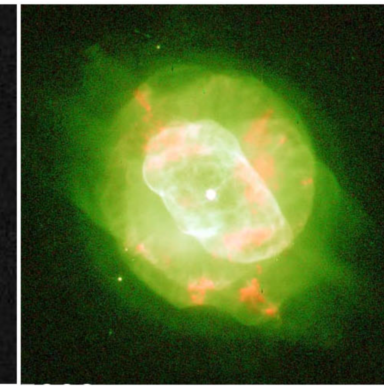
NGC 3242



NGC 7662



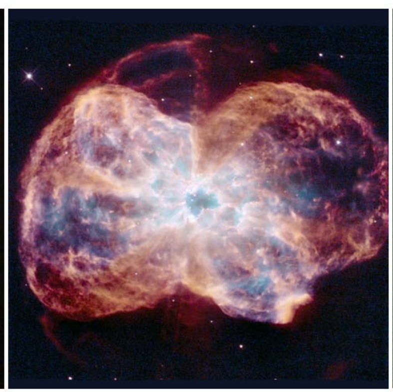
IC2165



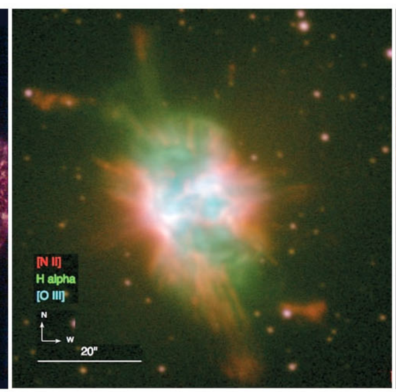
NGC 5882

bipolar / multipolar, closed lobes → *← open lobes* *irregular*

NGC 5315

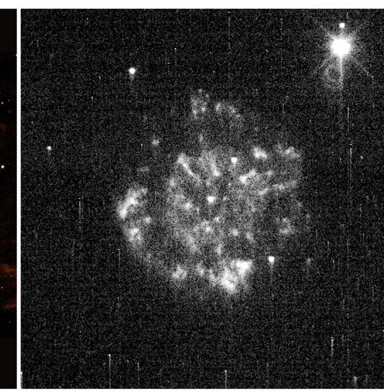


NGC 2440



NGC 6778*

NGC 6537



PB 6 = ESO 213-7

* = ground-based image

2. SCIENCE DRIVERS -- C&O in HII Regions

Spectroscopic observations of HII regions in star-forming galaxies indicate a Significant variation in N/O & C/O vs. O/H ==> C & O has secondary sources in addition to SNe.

All C abundances (in HII regions And BCGs) come from UV spectroscopy of CIII] 1909A. Most studies were with HST FOS (not STIS) due to larger Entrance apertures (but 1D).

Most N abundances come from Optical spectroscopy of [NII] 6583A (large ICF's).

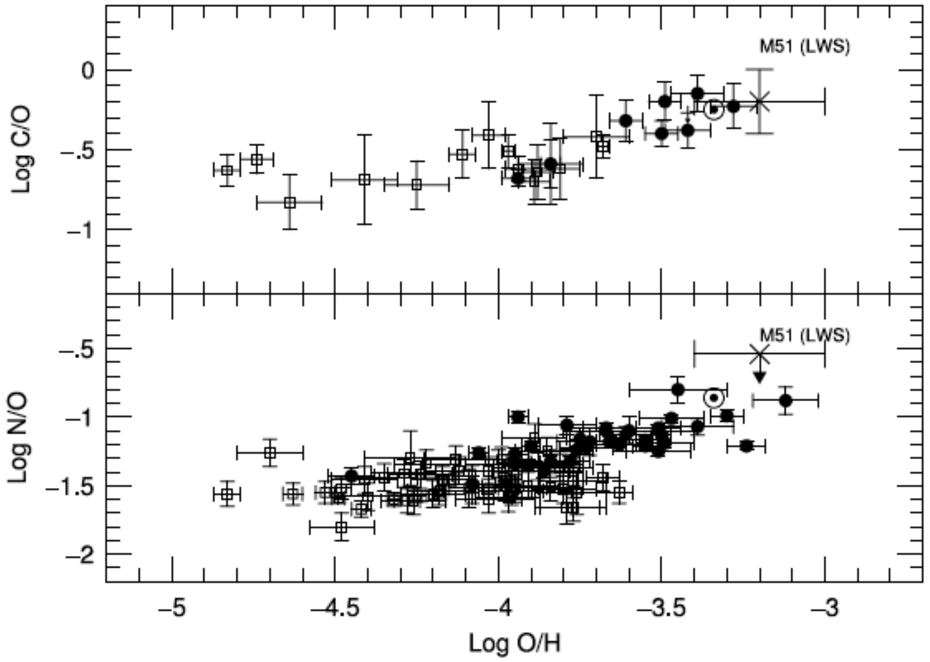


FIG. 6.—*Top:* C/O vs. O/H from spectroscopy of H II regions. Filled circles are data for H II regions in spirals (Garnett et al. 1999), and open squares are H II regions in irregular galaxies (Garnett et al. 1995, 1997). Our *ISO* results for M51 are shown by the cross. *Bottom:* N/O vs. O/H from observations of H II regions. Symbols as in the top panel. References for data points: Garnett et al. 1997; Kennicutt et al. 2003; Castellanos et al. 2002; Garnett 1990; Thuan et al. 1995.

But little known ancient IUE results:

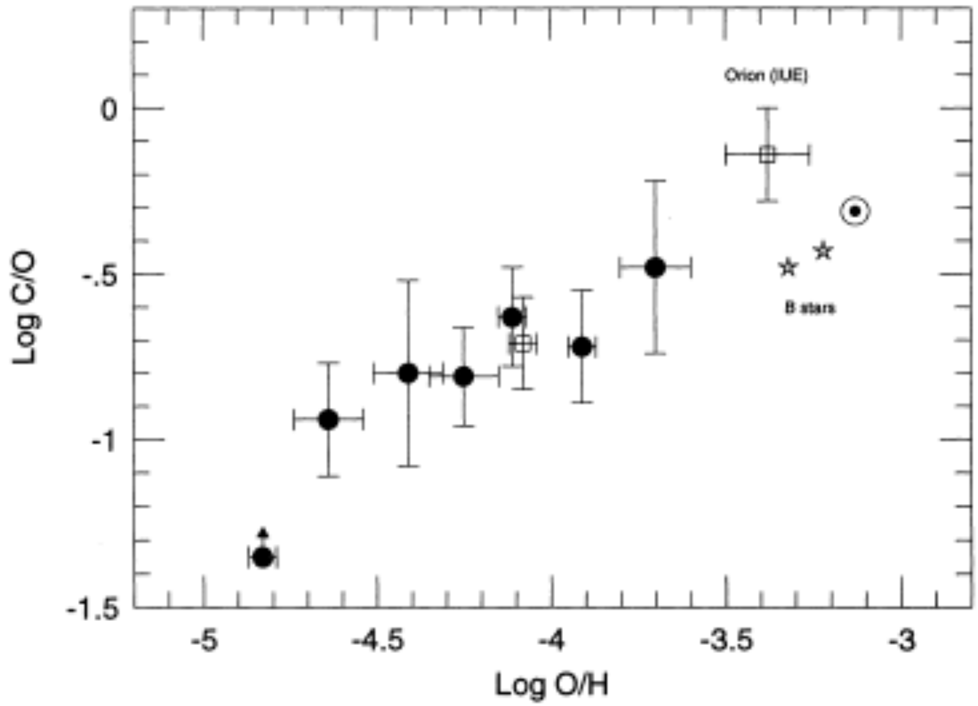


FIG. 3.—The C/O abundance ratio in irregular galaxies vs. O/H. Filled circles are the data from our FOS spectra; unfilled squares are data for Orion and NGC 2363 obtained from *IUE* spectra. The stars represent the mean abundances in B stars determined by GL92 and CL94.

Dufour (1984)

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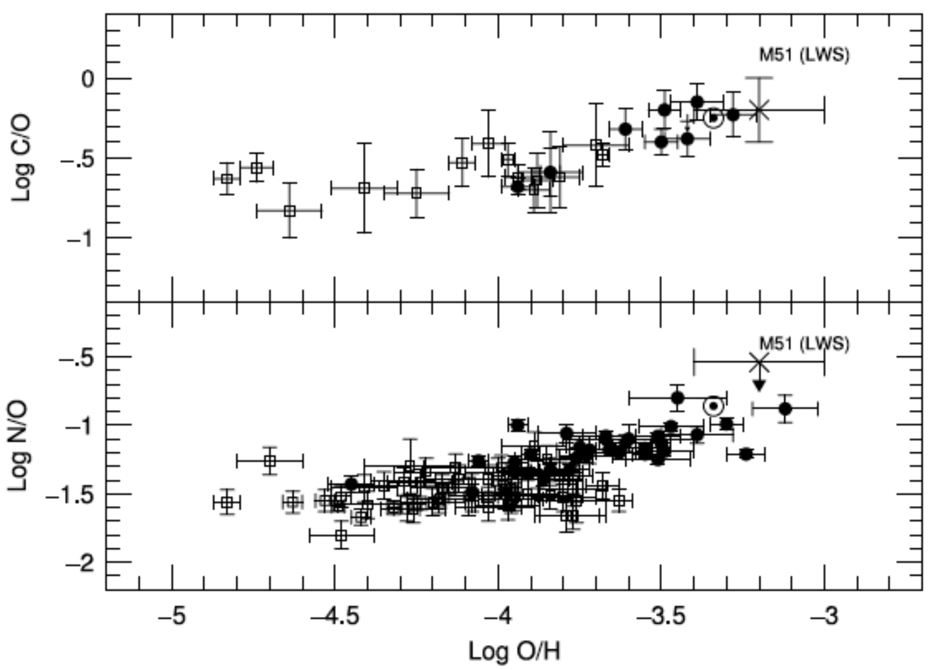

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2. SCIENCE DRIVERS -- UV spectroscopy of PNe

(a)Planetary Nebulae (PNe) are important sources of carbon and nitrogen enrichment in galaxies.

(b)The major emission lines of the dominant ionization states of C & N are in the ultraviolet for photoionized nebulae.

C+2 C III] 1907,1909 Å	N+2 [N III] 1747-1754 Å
C+3 C IV 1548,1550 Å	N+3 [N IV] 1483,1487 Å
	N+4 N V 1239,1243 Å

{also lines from ions other astrophysically significant elements:
He+,+2, O+,+2,+3,+4, Ne+2,+3,+4, Ar+3,+4, Mg+, Si+,+2}

(c)Abundances for PNe derived from visible light spectra alone involve large Ionization corrections for N {only [N II] lines} and are very suspect for C based on the (weak) C II 4267 Å recombination line.

(d)Accurate C & N abundances in PNe are necessary for comparison with theoretical yields of low-to-intermediate mass stars (LIMS; 1-5Mo).

…but not everyone appreciates the UV carbon lines:

Comments from an HST cycle 20 panel(?) report forwarded email by a nebular spectroscopy colleague:

…but get this, the weakness they quoted for our M31 PNe COS proposal was :

"The COS spectra target the doublet of C III@1906+09, and the doublet of C IV@1548+50. However, the panel felt that it was not clear how efficient those lines are for abundance determination."

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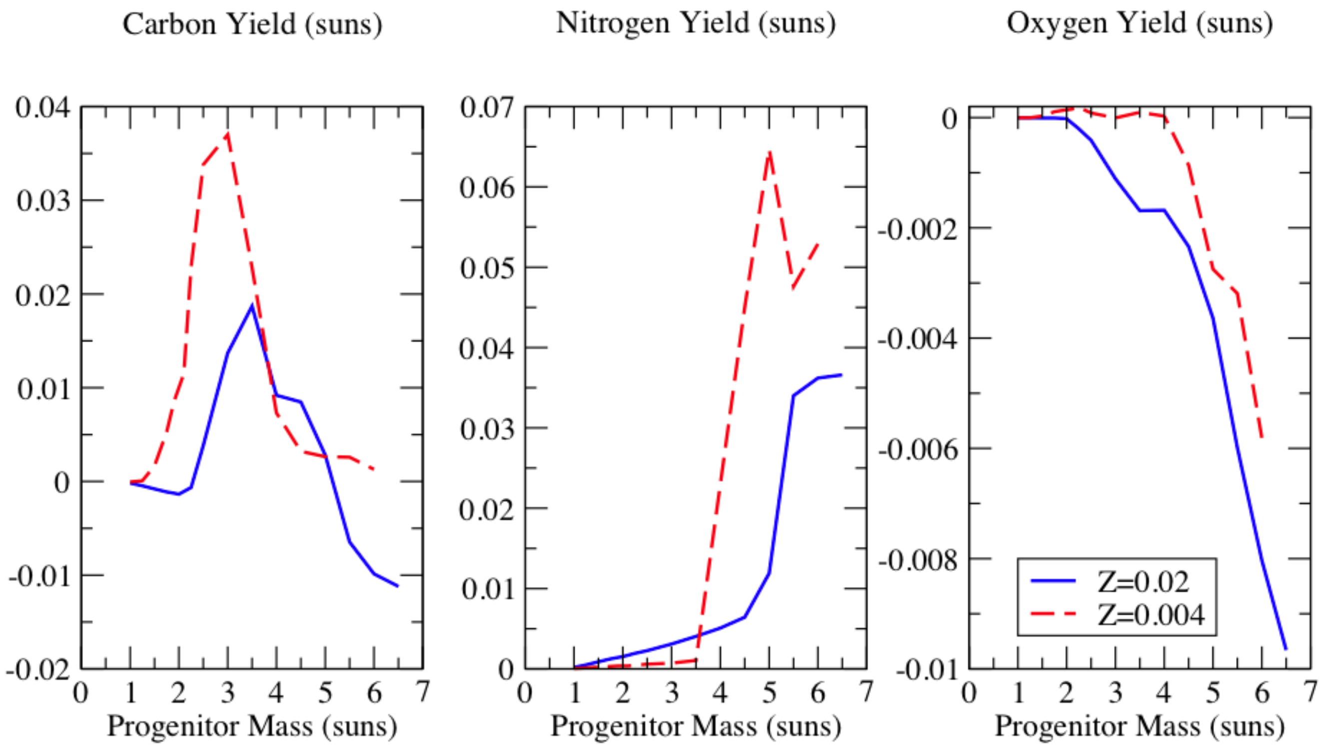
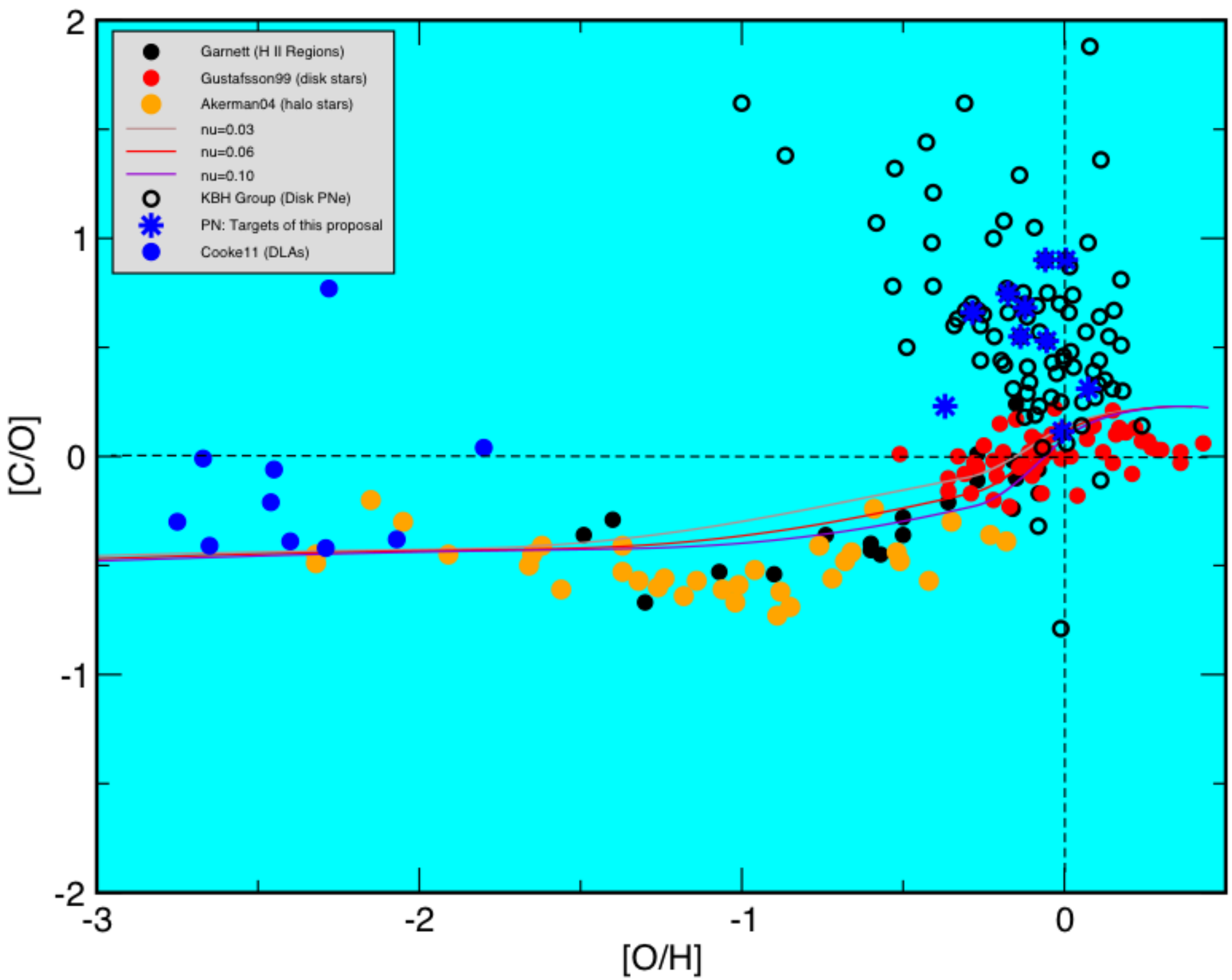
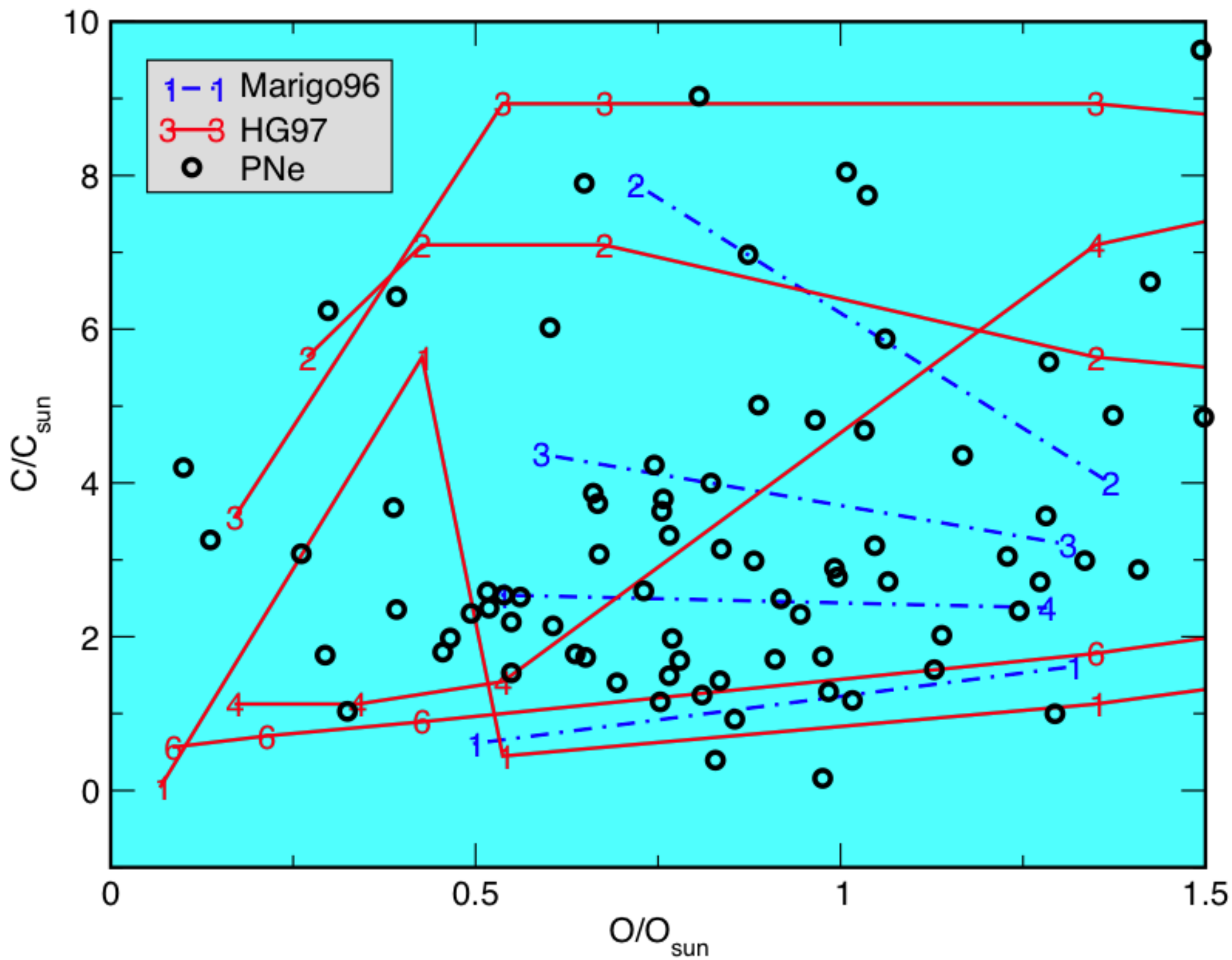


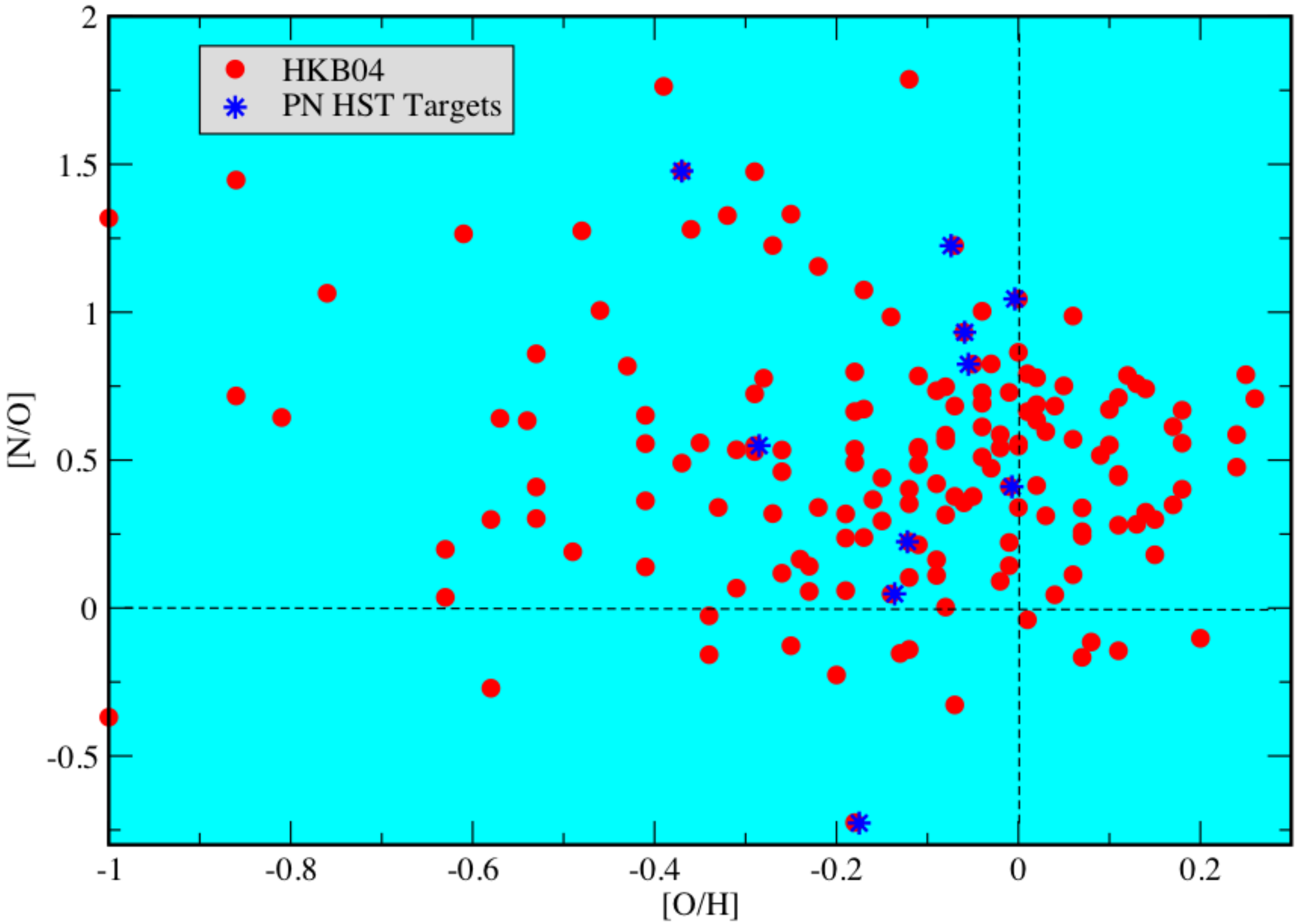
Computed yields of LIMS of C, N, and O versus progenitor mass, both in solar masses, from Karakas (2010). Examples for solar (0.02; solid line) and LMC (0.004; dashed line) metallicities are shown. Note that below about 3.5 suns the C yield is high while the N yield is small, but above this mass threshold the situation is reversed. Changeover is due to the onset of hot bottom burning, as described in the text. Note also that higher mass LIMS are predicted to consume O in the CNO cycle.



Log(C/O) versus log(O/H), both normalized to solar values (Asplund et al. 2009). The dashed lines show solar values. Objects in this plot include dwarf galaxy H II regions (Garnett et al. 1995), Galactic disk stars (Gustafsson et al. 1999), metal-poor Galactic halo stars (Akerman et al. 2004), and metal-poor damped Lyman alpha systems (Pettini et al. 2008). Together these objects define a strikingly narrow track. Given the diversity of object types, clearly the processes for synthesizing C and O are universal. The obvious deviation of PNe from this universal track results from self-contamination by LIMs. Solid lines are unpublished chemical enrichment models by Henry.



A confrontation between theory and observation! C/C$_{sun}$ versus O/O$_{sun}$ for the updated Henry, Kwitter, & Bates (2000) sample of PNe along with model predictions from v.d. Hoek & Groenewegen (1997; solid lines) and Marigo et al. (1996; dot-dashed lines). The relevant progenitor mass is indicated on each model track. A successful set of models should span the entire region occupied by the observed PNe, indicating that progenitor mass and metallicity determine the position of any one PN. In this case both sets appear to be reasonably successful in spanning the area of the data shown. The point of the current proposal is to greatly improve the C abundances by employing 21st century techniques and instrumentation, and then reevaluating all existing model sets.

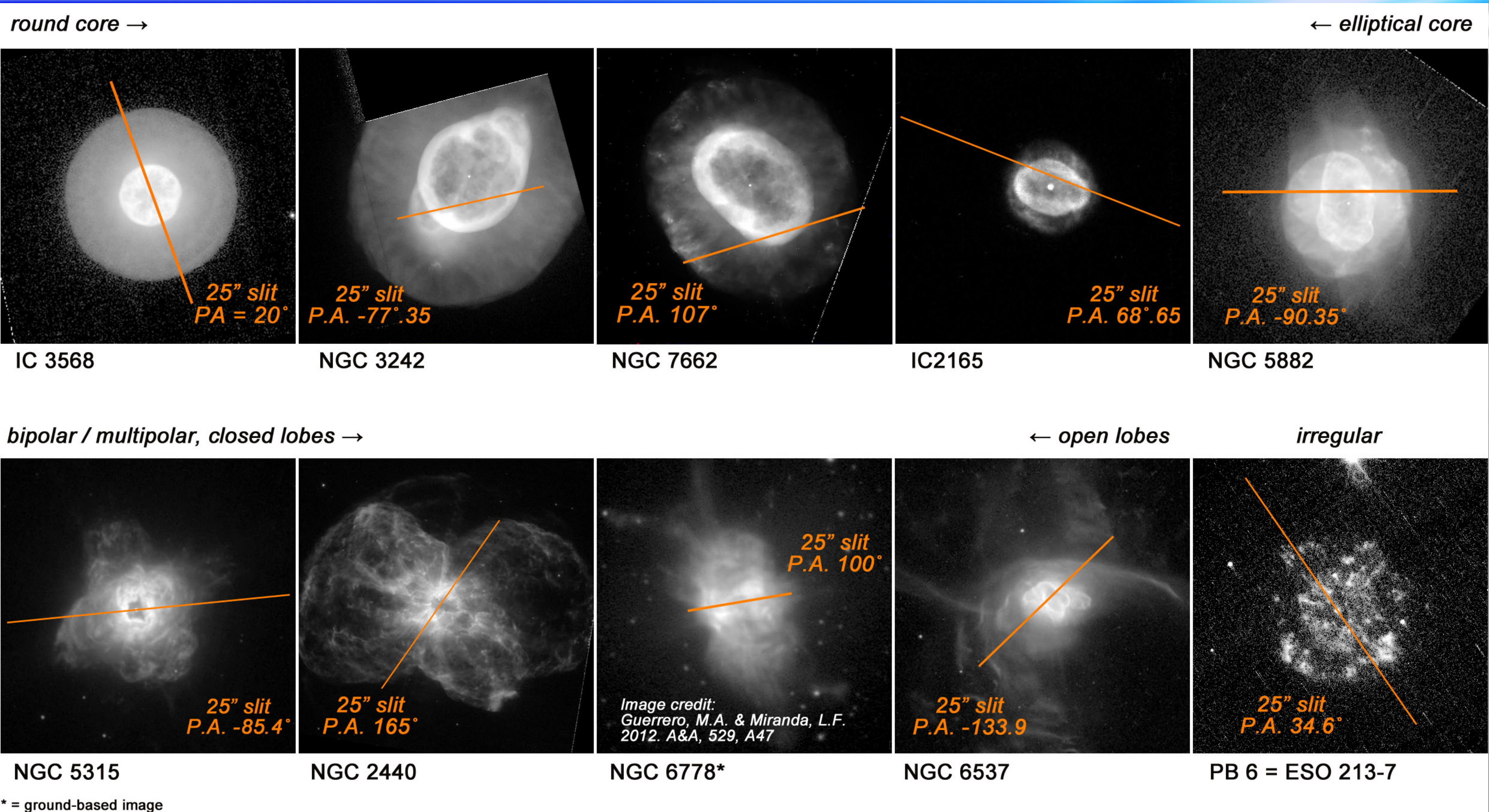


Log(N/O) versus log(O/H) relative to the solar values for the Henry, Kwitter, & Balick (2004) sample of PNe. The 10 objects chosen as targets in this proposal are indicated with stars. The dashed lines show solar abundance values by Asplund et al. 2009. The range of N/O ratios for our 10 PNe targets vary from N/O = 0.06 to ~7.2 (compared to the solar value of N/O = 0.13); that is, from ~1/2 to ~55 times solar.

3. STIS OBSERVATIONS (32 orbits granted)

- Co-spatial longslit spectra of 10 extended PNe covering the full UV-optical range (1150-10,000A)
- High spatial resolution (~0.05" along the 0.2-0.5" wide slit)
- High S/N and dynamic range (>10X IUE)
- Good spectral purity (R~300 STIS L; R~1000 STIS M)
- Good ionization structure coverage across nebulae (effectively ~25")
- 10PNe, 32 orbits, 1 STIS with CCD, 2-3 STIS with UV-MAMAs
- G140L, G230L, G230M/1907-1909, G430L, G430M/4363, G750L, G750M/6563-6583(also 6717-6730)

Slit Positions*



*STIS UV-MAMA safety concerns limited slit positions close to central stars for several Pne and even required 3 substitute nebulae from original target list (HST orbit observability limited slit PA ranges as well).

Observations Schedule

DONE:

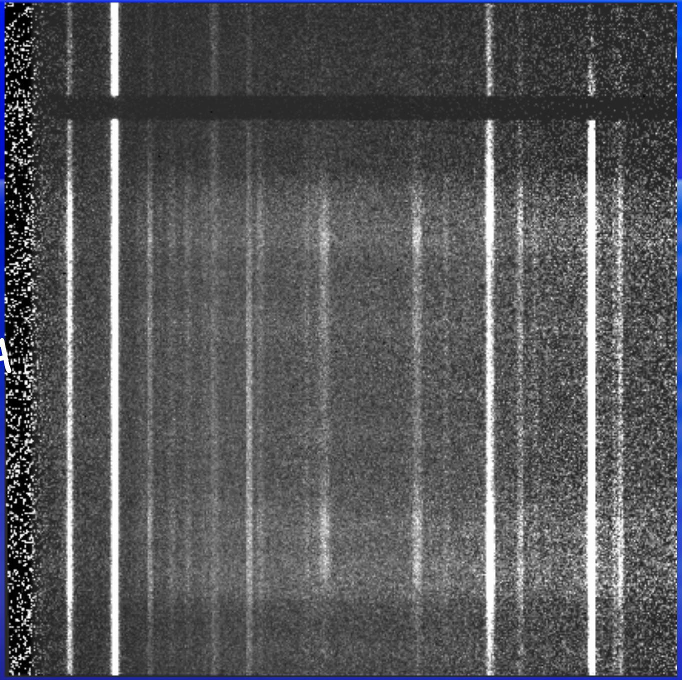
NGC 3242 - January 15,21
NGC 5315 - February 26,27
NGC 6537 - February 29,March 1
(G230L redo April 20)
NGC 5882 - April 21, 25
PB6 (ESO 213-7) - April 25, 26
IC 2165 - April 28, 30

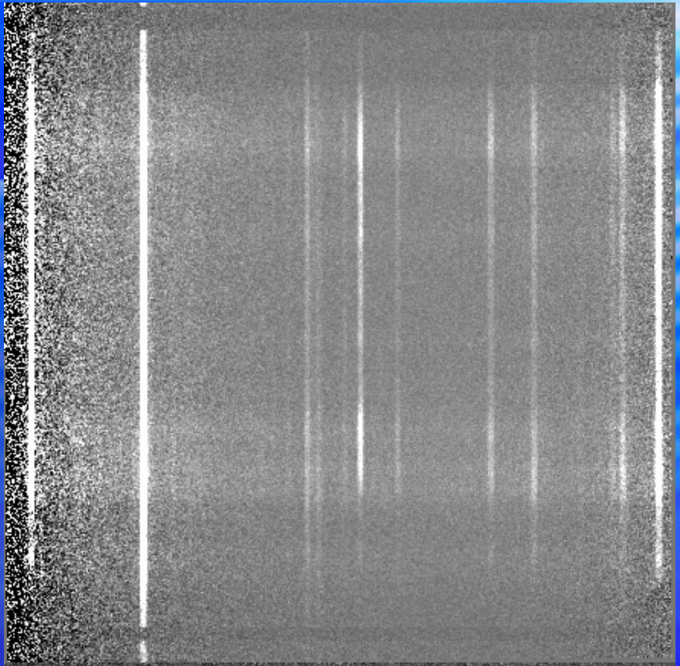
SCHEDULING:

IC 3568 - July 12 - 21
NGC 6778 - July 29 - August 12
NGC 7662 - October 1 -19
NGC 2440 - January 20 - February 17 (2013)

4. EXAMPLE SPECTRA: NGC 3242 (UV-MAMAs; 25" slit)

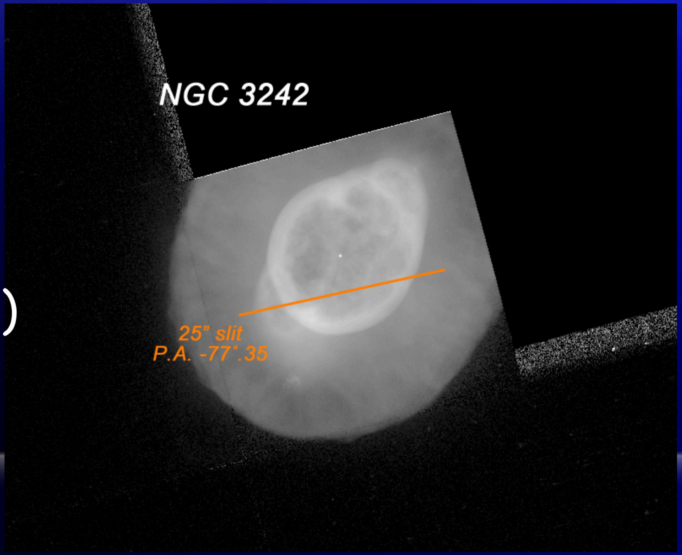
G140L
1150-1730A





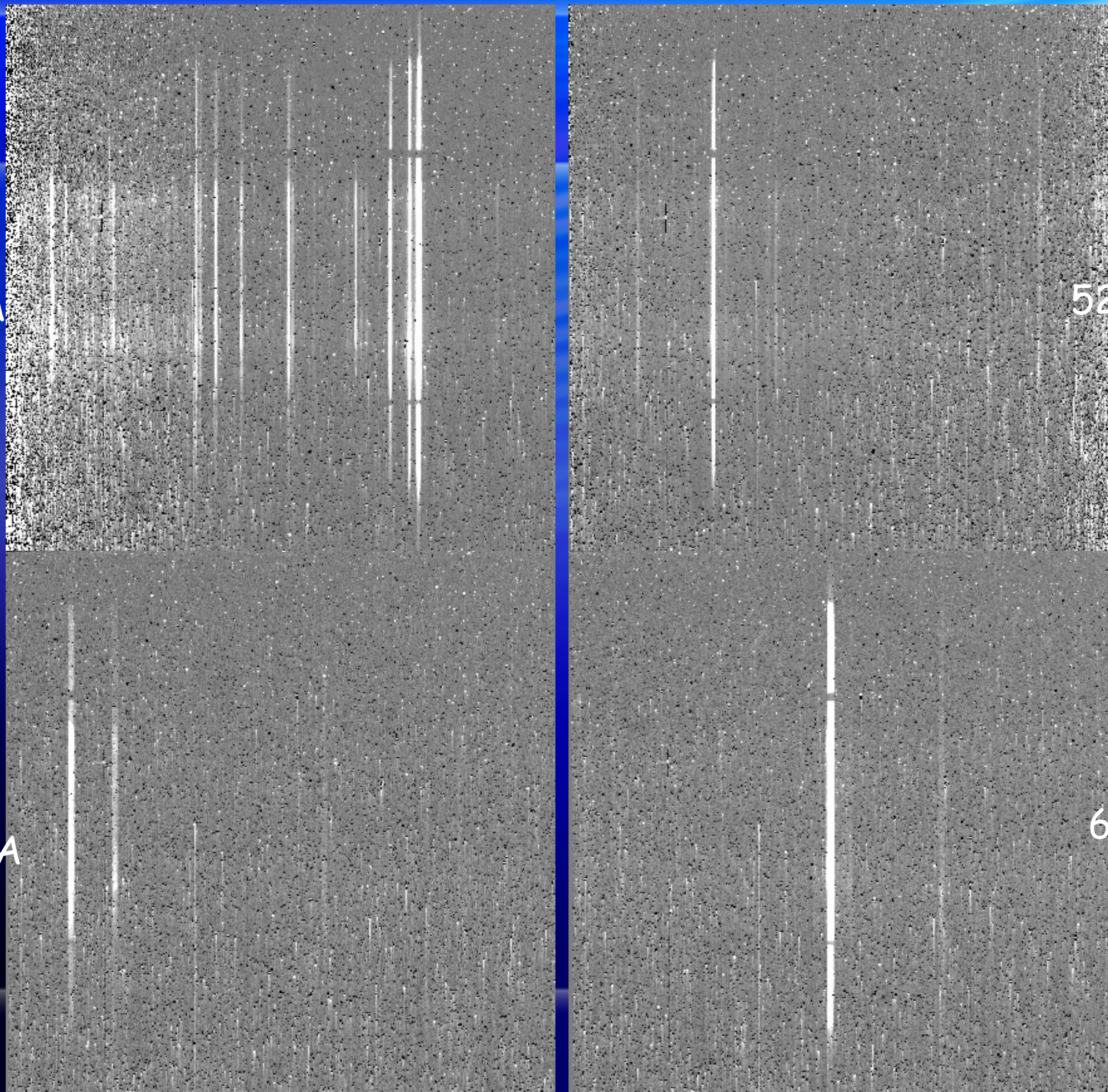
G230L
1570-3180A

SLIT
25" MAMA)



G230M
1839-1929A

STIS CCD Spectra: NGC 3242 (52” slit; 2X MAMA)

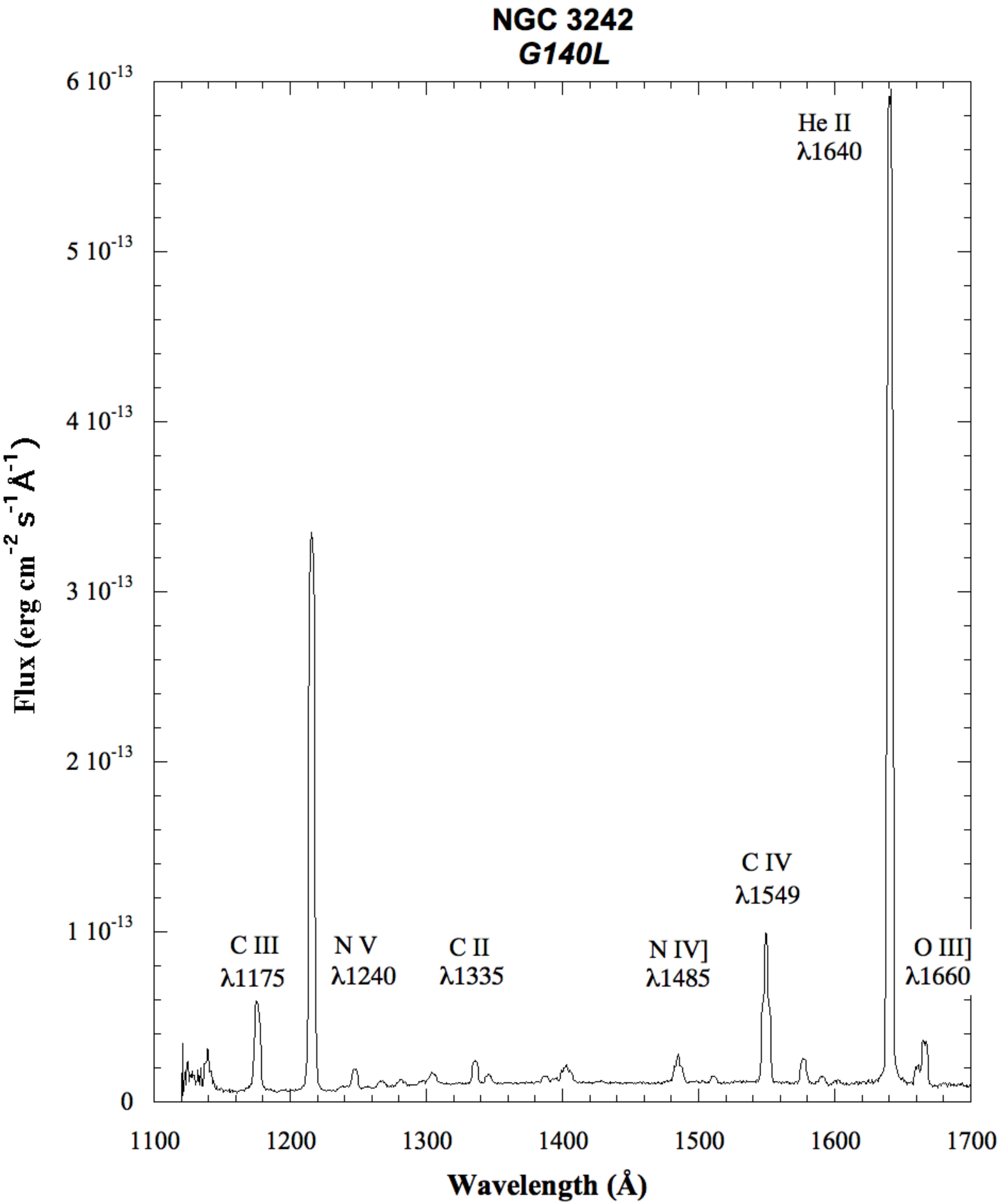


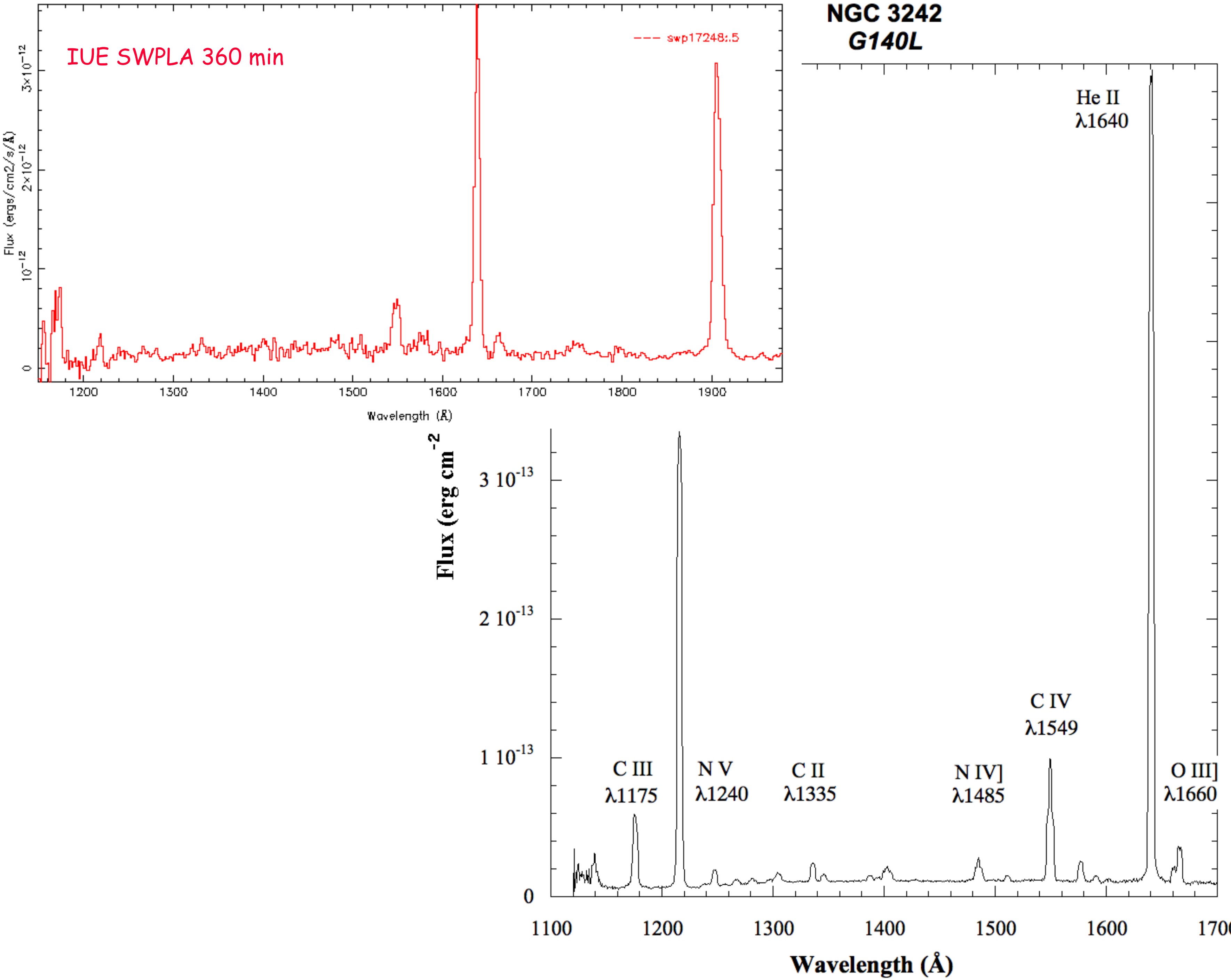
G430L
2900-5700A

G750L
5240-10270A

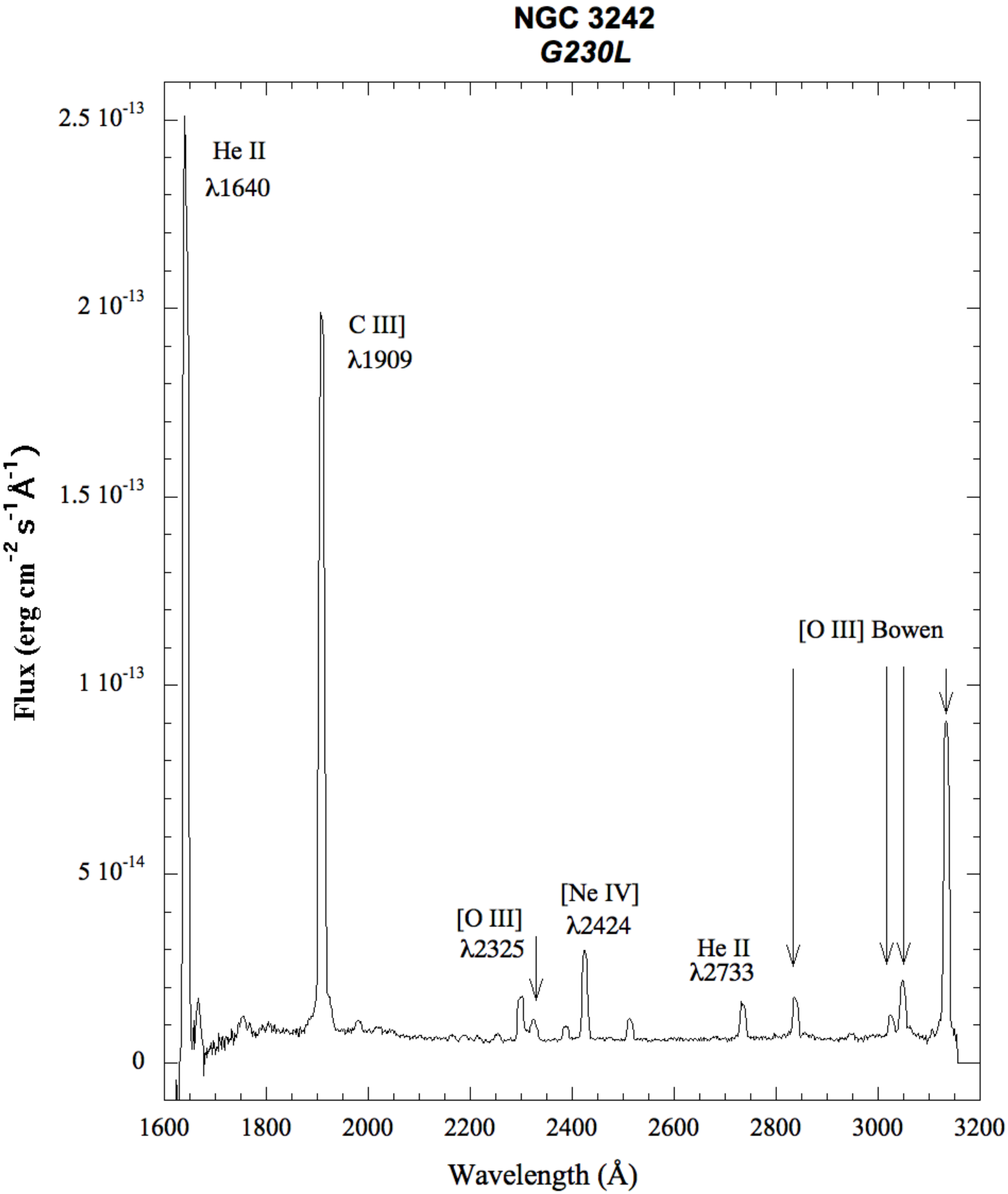
G430M
4308-4594A

G750M
6482-7054A

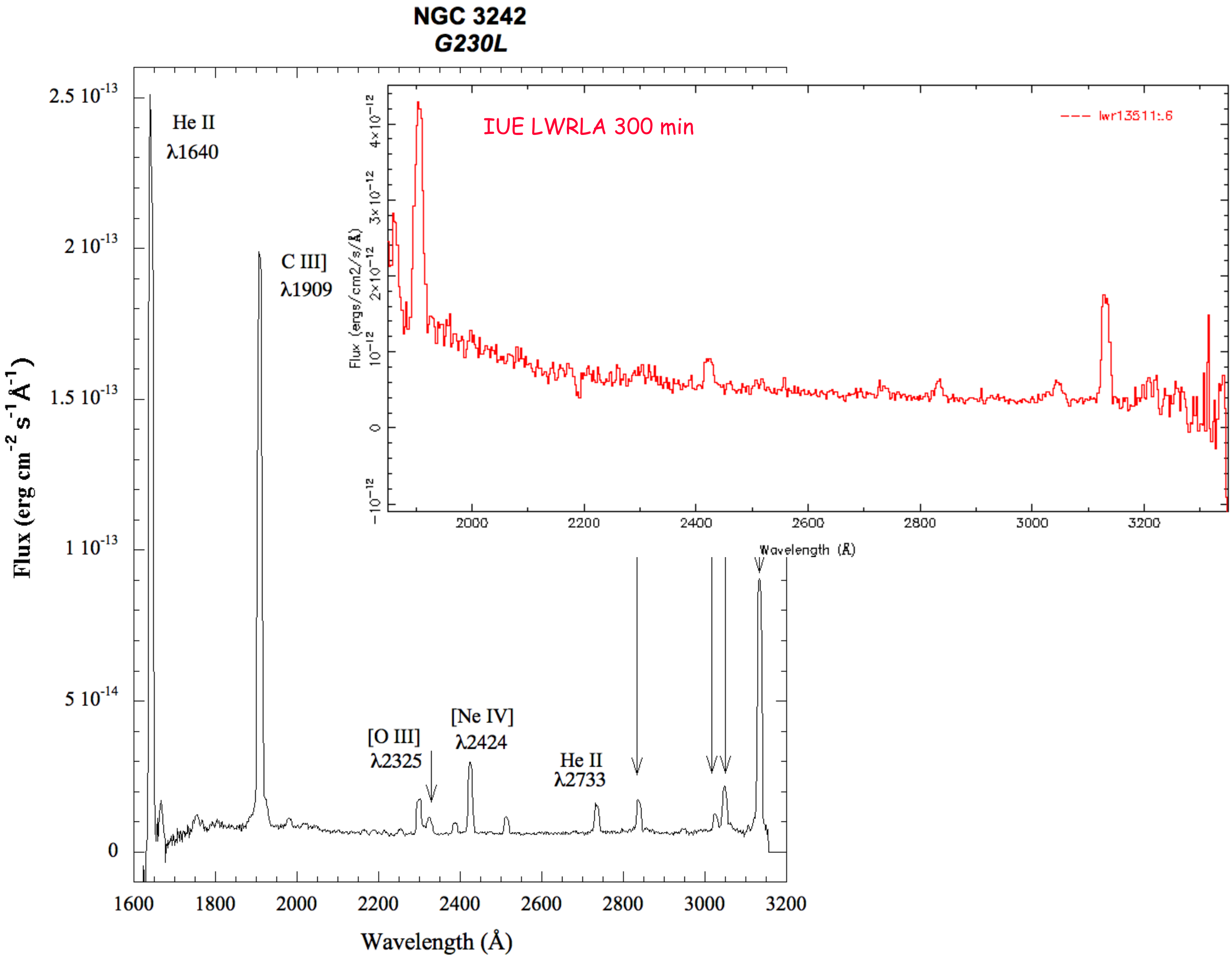

NGC 3242
G140L
He II
λ1640
C III
λ1175
N V
λ1240
C II
λ1335
N IV]
λ1485
C IV
λ1549
O III]
λ1660
Flux (erg cm-2 s-1 Å-1)
Wavelength (Å)
0
1 10-13
2 10-13
3 10-13
4 10-13
5 10-13
6 10-13
1100
1200
1300
1400
1500
1600
1700

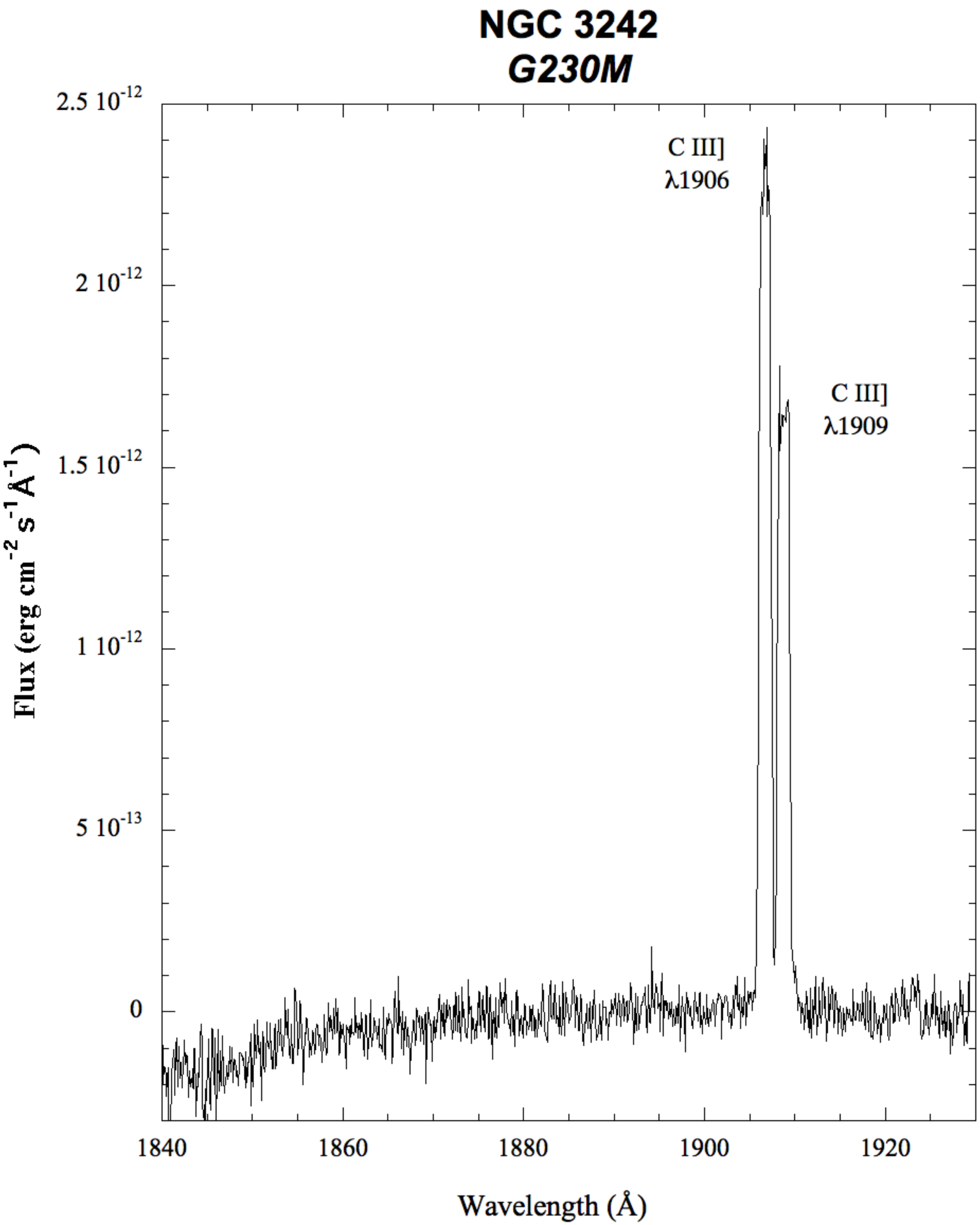


IUE SWPLA 360 min
swp17248:.5
Flux (ergs/cm2/s/Å)
Wavelength (Å)
NGC 3242
G140L
He II
λ1640
C III
λ1175
N V
λ1240
C II
λ1335
N IV]
λ1485
C IV
λ1549
O III]
λ1660
Flux (erg cm^{-2}
Wavelength (Å)

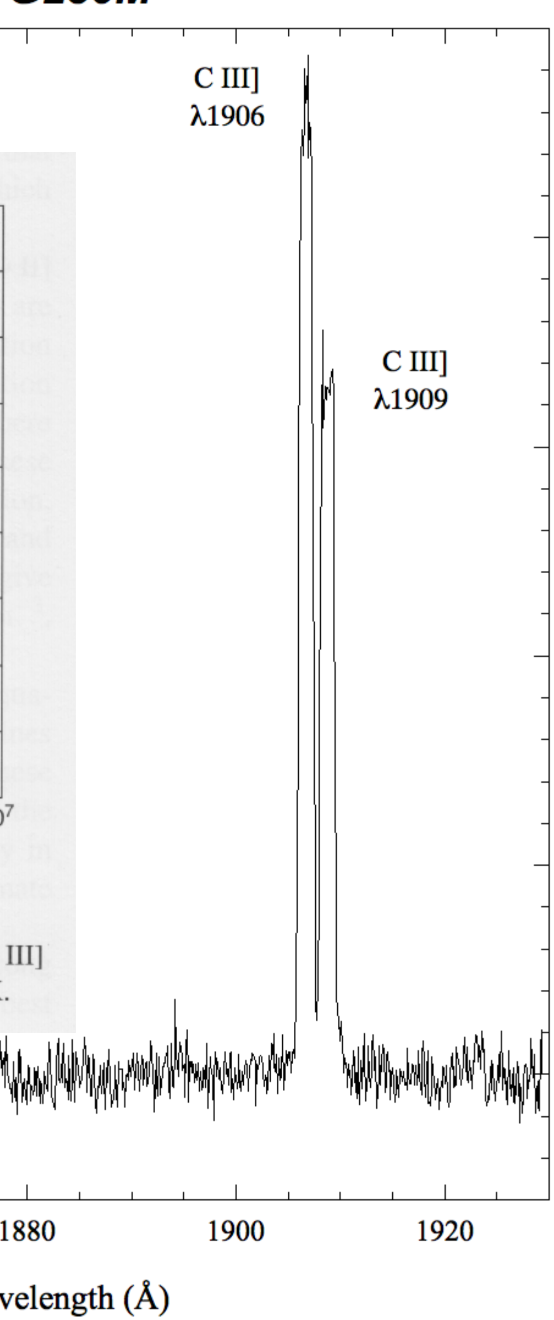


NGC 3242
G230L
He II
λ1640
C III]
λ1909
[O III]
λ2325
[Ne IV]
λ2424
He II
λ2733
[O III] Bowen
2.5 10^-13
2 10^-13
1.5 10^-13
1 10^-13
5 10^-14
0
Flux (erg cm^-2 s^-1 Å^-1)
1600
1800
2000
2200
2400
2600
2800
3000
3200
Wavelength (Å)


NGC 3242
G230L
He II
λ1640
C III]
λ1909
[O III]
λ2325
[Ne IV]
λ2424
He II
λ2733
Flux (erg cm^-2 s^-1 Å^-1)
Wavelength (Å)
IUE LWRLA 300 min
lwr13511:6
Flux (ergs/cm2/s/Å)
Wavelength (Å)


NGC 3242
G230M
C III]
λ1906
C III]
λ1909
2.5 10-12
2 10-12
1.5 10-12
1 10-12
5 10-13
0
Flux (erg cm-2 s-1 Å-1)
1840
1860
1880
1900
1920
Wavelength (Å)

NGC 3242
G230M



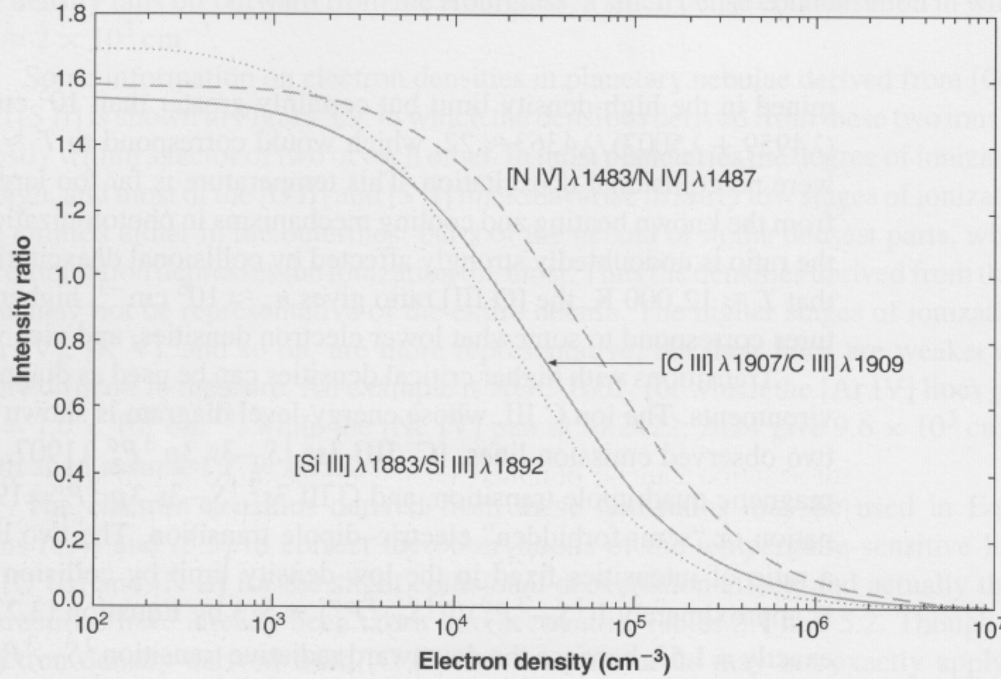
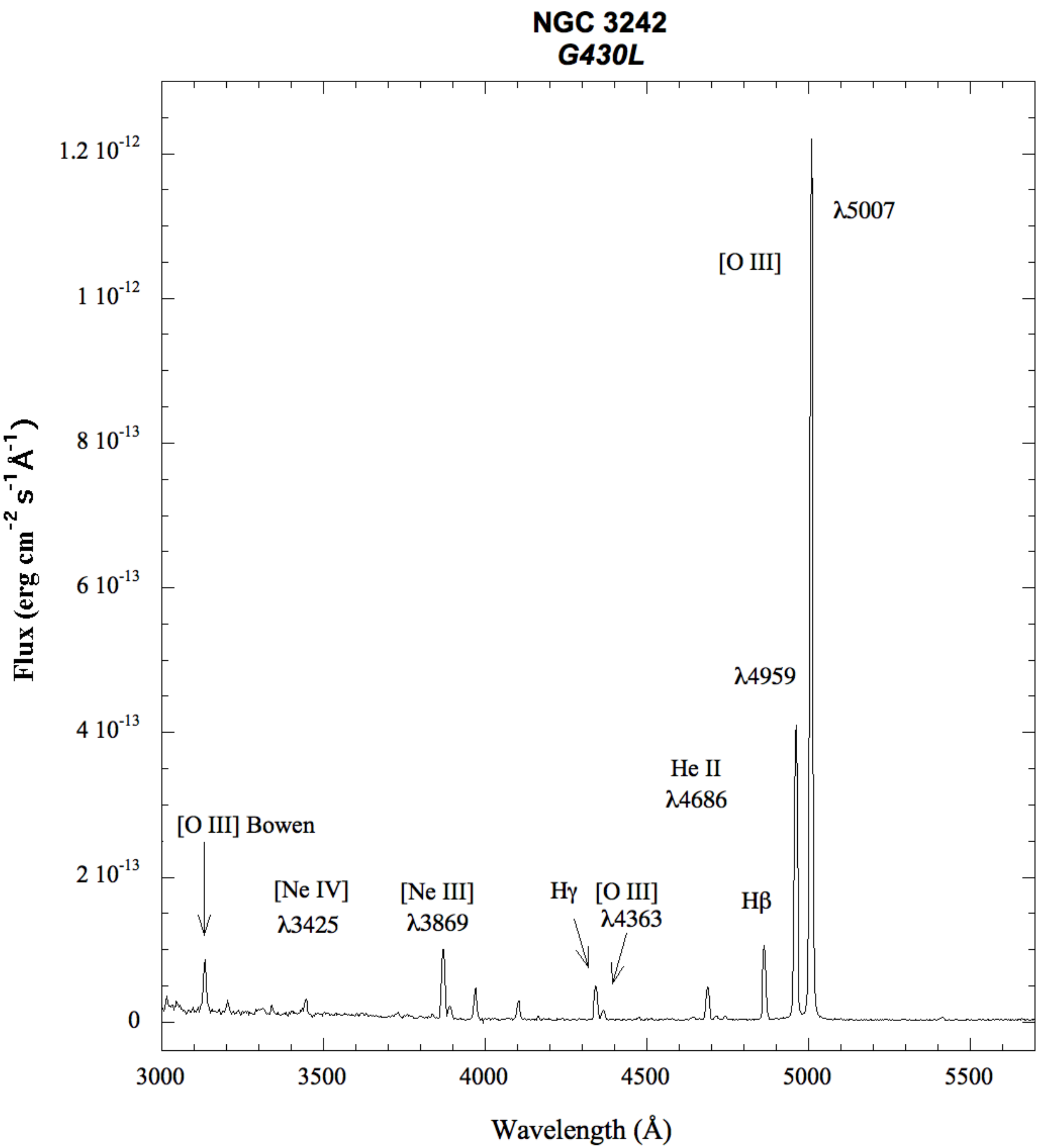
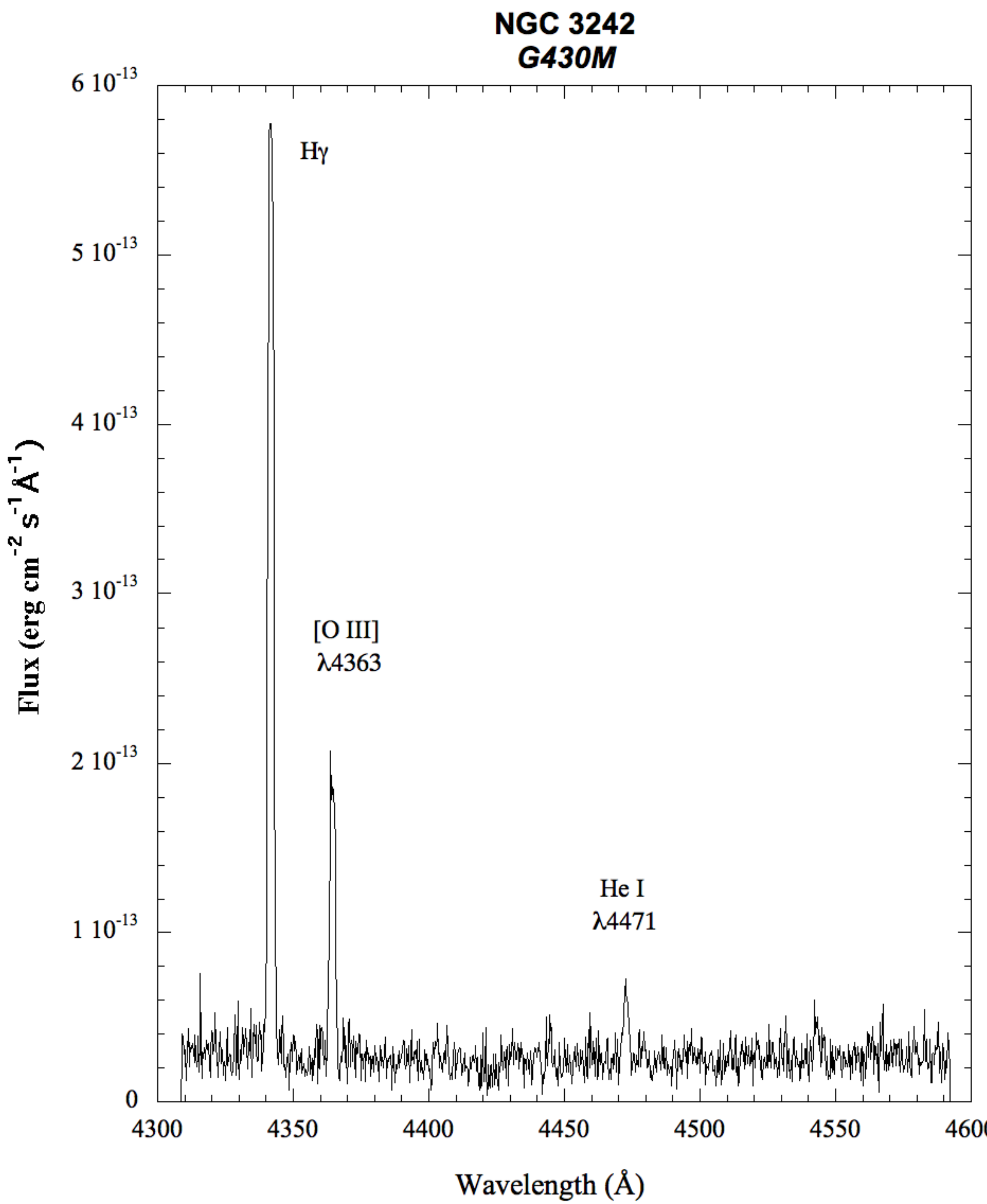
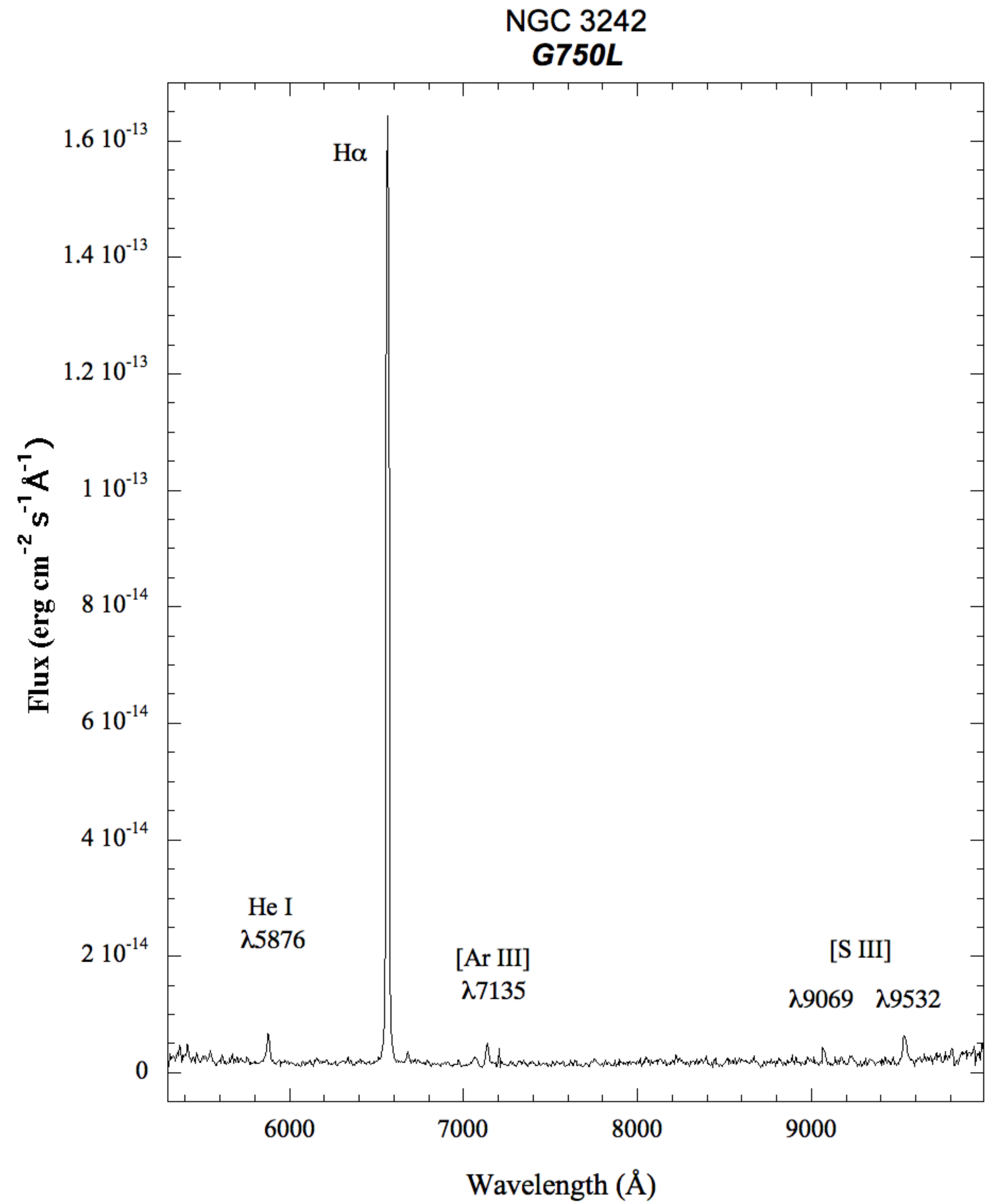
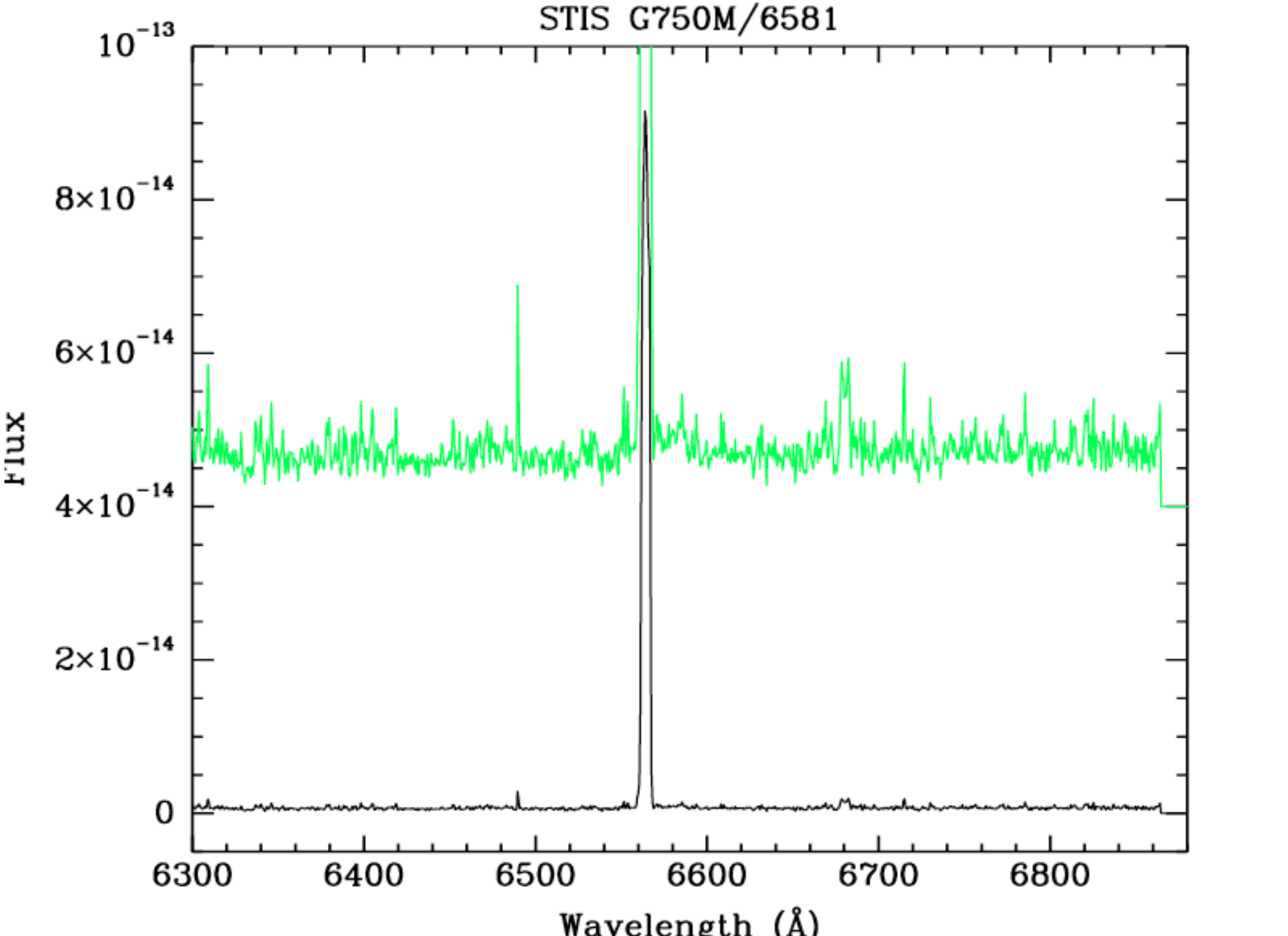


Figure 5.11
Calculated variation of [C III] λ1907/C III] λ1909, [N IV] λ1483/N IV] λ1487, and [Si III] λ1883 / Si III] λ1892 intensity ratios as a function of electron density n_e at T = 10,000 K.

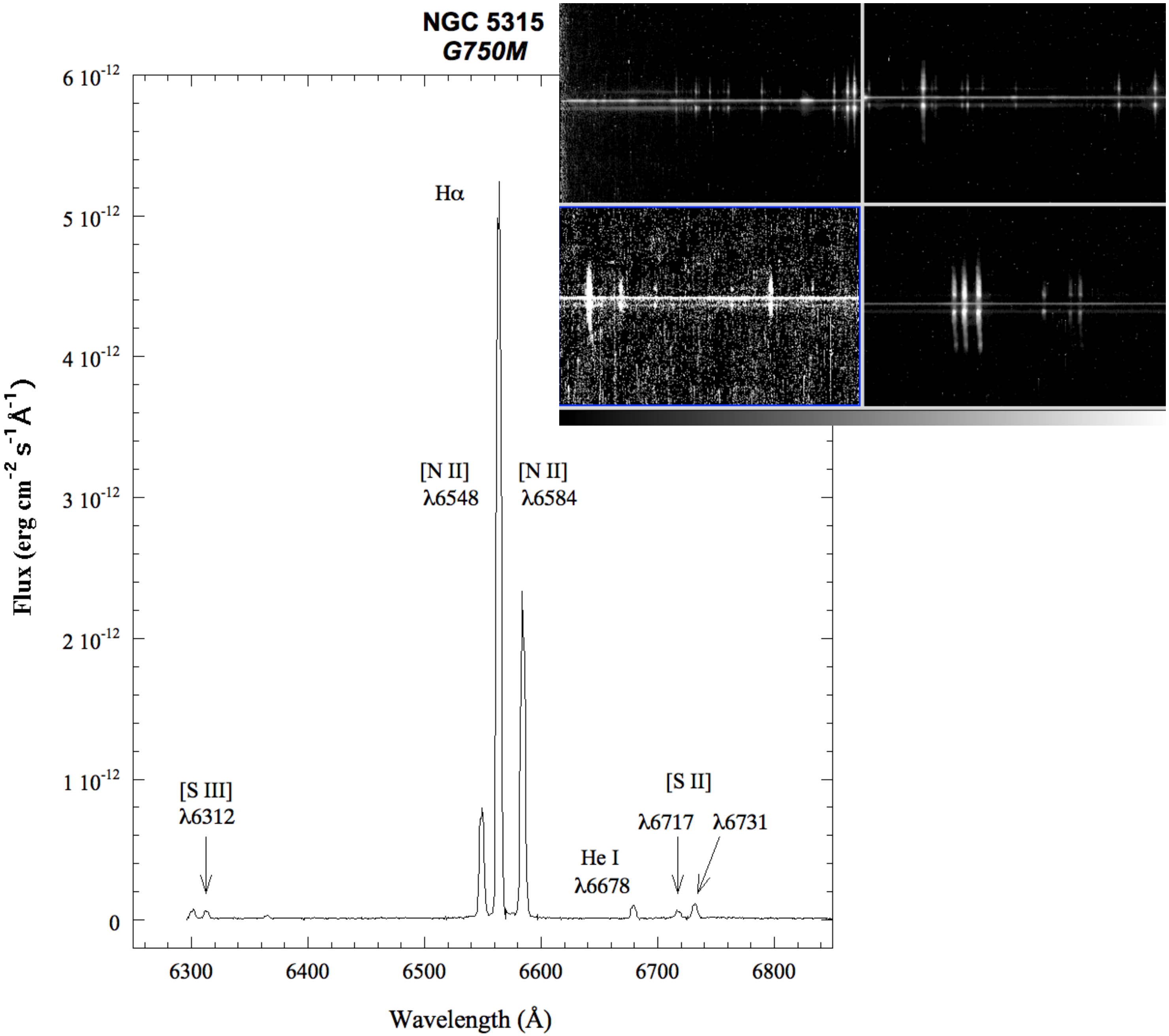

NGC 3242
G430L
Flux (erg cm^{-2} s^{-1} Å^{-1})
Wavelength (Å)
1.2 10^{-12}
1 10^{-12}
8 10^{-13}
6 10^{-13}
4 10^{-13}
2 10^{-13}
0
3000
3500
4000
4500
5000
5500
[O III] Bowen
[Ne IV] λ3425
[Ne III] λ3869
Hγ
[O III] λ4363
He II λ4686
Hβ
λ4959
[O III]
λ5007


NGC 3242
G430M
Hγ
[O III]
λ4363
He I
λ4471
Flux (erg cm-2 s-1 Å-1)
Wavelength (Å)
0
1 10-13
2 10-13
3 10-13
4 10-13
5 10-13
6 10-13
4300
4350
4400
4450
4500
4550
4600


NGC 3242
G750L
Hα
He I
λ5876
[Ar III]
λ7135
[S III]
λ9069
λ9532
Flux (erg cm-2 s-1 Å-1)
1.6 10-13
1.4 10-13
1.2 10-13
1 10-13
8 10-14
6 10-14
4 10-14
2 10-14
0
6000
7000
8000
9000
Wavelength (Å)



STIS G750M/6581
Flux
Wavelength (Å)
10^{-13}
8×10^{-14}
6×10^{-14}
4×10^{-14}
2×10^{-14}
0
6300
6400
6500
6600
6700
6800


NGC 5315
G750M
Flux (erg cm^{-2} s^{-1} Å^{-1})
6 10^{-12}
5 10^{-12}
4 10^{-12}
3 10^{-12}
2 10^{-12}
1 10^{-12}
0
Hα
[N II] λ6548
[N II] λ6584
[S III] λ6312
He I λ6678
[S II]
λ6717
λ6731
6300
6400
6500
6600
6700
6800
Wavelength (Å)

5. ANALYSIS

EXTRACTION: Spectra extracted from 2D to 1D for integrated line measurements. (requires careful attention paid to extracting same slit lengths between UV and optical; also avoid stellar contamination)

MEASUREMENTS: Emission line strengths in 1D spectra measured with IRAF/STSDAS software using both direct line areas and gaussian fitting of profiles (also S/N estimates made)

DEREDDENING: Use observed H Balmer and He recombination line strengths to derive magnitude of interstellar reddening and apply corrections to emission line measurements

DENSITY/TEMPERATURES: Derive Ne and Te from various emission line diagnostics (hopefully for both low and high ionization zones).

ABUNDANCES: Derive ionic concentrations directly with 5-level atom codes (ELSA & Nebular). Correct for unseen ionization states using ICF's to derive final elemental concentrations.

Nebular Emission-Line Diagnostic Software

nebular.iraf - 5-level (7 for some ions with UV lines) software package embedded into IRAF/STSDAS (Shaw & Dufour 1995, PASP, 107, 896) and also the web:

(http://stsdas.stsci.edu/nebular/)

New version being developed by Shaw using python/pyraf and updated atomic data coming in 2013.

ELSA - Emission Line Spectrum Analyzer - Code similar to nebular developed by Kwitter & Henry (2001, ApJ, 562, 804) with convenient additional options for error propagation and producing directly publishable LaTex tables of spectrum line measurements and abundance results. Code and documentation available at:

(http://www.williams.edu/Astronomy/research/PN/elsa/)

Abundance diagnostics using additional UV lines currently being added into the code.

NGC 3242

Emission-line Measurements and extinction corrections:

(using ELSA)

Example S/N

wavelength	ion	ROUGH SNR
1175	C III	30
1336	C II	12
1402	O IV]	10
1485	N IV]	12
1640	He II	300
1663	O III]	20
1909	C III]	80
3727	[O II]	3
4363	[O III]	12
4686	He II	30
Hbeta	H I	30
5007	[O III]	300
5876	He I	8
Halpha	H I	100
6584	[N II]	2

		3242in	
Line	f(λ)	F(λ)	I(λ)
C III λ1175	1.849	22.2	24.7
C II λ1336	1.415	5.48	5.94
O IV] λ1402	1.307	5.99	6.45
N IV] λ1485	1.231	7.70	8.26
C IV λ1549	1.184	37.9	40.5
[Ne V] λ1575	1.168	6.29	6.73
Ne IV] λ1602	1.153	1.14::	1.22::
He II λ1640	1.136	244	261
O III] λ1662	1.129	15.5	16.5
C II λ1760	1.121	8.18	8.72
C III] λ1909	1.229	224	241
HeII Pa6 λ2253	1.542	2.15	2.35
[O III]/C II] λ2325	1.356	8.42	9.10
HeII Pa eps λ2385	1.204	3.50	3.76
[Ne IV] λ2423	1.118	25.7	27.4
He II Pa delta λ2511	0.955	5.97	6.31
He II Pa gamma λ2733	0.701	9.54	9.95
O III Bowen fl λ2837	0.619	10.1	10.5
He I λ2945	0.550	1.51	1.56
O III Bowen fl λ3025	0.506	6.12	6.32
O III Bowen fl λ3048	0.494	17.0	17.5
O III Bowen fl λ3133	0.454	86.5	89.0
He II Pa beta λ3203	0.424	17.4	17.9
[Ne V] λ3346	0.371	9.62	9.86
He I λ3448	0.337	17.2:	17.6:
[O II] λ3727	0.292	8.27::	8.43::
He II + H9 λ3835	0.262	3.87:	3.94:
[Ne III] λ3869	0.252	97.6	99.3
He I + H8 λ3889	0.247	17.5	17.8
[Ne III] λ3968	0.225	30.1[a]	30.6[a]
Hε λ3970	0.224	15.0[a]	15.3[a]

		3242in	
Line	f(λ)	F(λ)	I(λ)
[S II] λ4071	0.196	2.53::	2.57::
He II λ4100	0.188	0.437[a]	0.443[a]
Hδ λ4101	0.188	27.6[a]	28.0[a]
He II λ4339	0.124	0.788[a]	0.797[a]
Hγ λ4340	0.124	45.9[a]	46.4[a]
[O III] λ4363	0.118	13.1	13.2
He I λ4472	0.090	4.02:	4.05:
[K IV] λ4511	0.080	1.68??	1.70??
He II λ4542	0.072	1.03	1.04
N III + O II λ4640	0.048	3.92:	3.95:
He II λ4686	0.036	43.0	43.3
He I + [Ar IV] λ4711	0.030	4.98	5.00
[Ar IV] λ4740	0.023	4.40	4.42
He II λ4859	0.000	1.71[a]	1.72[a]
Hβ λ4861	0.000	100[a]	100[a]
[O III] λ4959	-0.030	409	410
[O III] λ5007	-0.042	1230	1232
He II λ5412	-0.134	3.92::	3.90::
He I λ5876	-0.231	8.78	8.70
He II λ6560	-0.360	5.54[a]	5.45[a]
Hα λ6563	-0.360	291[a]	286[a]
[N II] λ6584	-0.364	2.61::	2.56::
He I λ6678	-0.380	6.93::	6.81::
He I λ7065	-0.443	3.86	3.79
[Ar III] λ7136	-0.453	6.44	6.30
[O II] λ7324	-0.481	0.853::	0.834::
[Ar III] λ7751	-0.539	1.02::	0.996::
[S III] λ9069	-0.670	3.90	3.77
P9 λ9228	-0.610	2.18	2.12
[S III] λ9532	-0.632	8.98	8.71
P8 λ9546	-0.633	2.16	2.09

Temperatures Densities Abundances

ELSA produces publishable tables directly from inputted spectral measurements

There are also options for error propagation from line strengths accuracies and extent of extinction corrections

Table 1. Ionic Abundances

Ion	T_{used}	Abundance (3242in)	Notes (3242in)
He^+	[O III]	5.73(-2)	
He^{+2}	[O III]	4.00(-2)	
icf(He)		1.00	
O^+(3727)	[N II]	*4.49(-6)	
O^+(7325)	[N II]	*4.47(-6)	
O^+	wm	4.49(-6)	
O^{+2}(5007)	[O III]	*2.56(-4)	
O^{+2}(4959)	[O III]	*2.46(-4)	
O^{+2}(4363)	[O III]	*2.56(-4)	
O^{+2}	wm	2.54(-4)	
icf(O)		1.70	
Ar^{+2}(7135)	[O III]	*4.09(-7)	
Ar^{+2}(7751)	[O III]	*2.68(-7)	
Ar^{+2}	wm	3.90(-7)	
Ar^{+3}(4740)	[O III]	*5.06(-7)	
icf(Ar)		1.71	
C^{+2}(1909)	[O III]	*1.82(-4)	
C^{+3}(1549)	[O III]	*2.58(-5)	
icf(C)		1.73	
icf(Cl)		1.70	
N^+(6584)	[N II]	*4.41(-7)	
N^{+3}(1485)	[O III]	3.66(-5)	
icf(N)		97.5	
Ne^{+2}(3869)	[O III]	*5.40(-5)	
Ne^{+2}(3967)	[O III]	5.54(-5)	
Ne^{+3}(1602)	[O III]	*3.24(-5)	
Ne^{+4}(1575)	[O III]	*3.04(-5)	
icf(Ne)		1.73	

Table 2. Temperatures and Densities

Parameter	Value (3242in)	Notes (3242in)
$T_{[OIII]}$	11820	
$T_{[NII]}$	10300	Default.
$T_{[OII]}$	10270	
$Ne_{[SII]}$	5000	Default.

Table 3. Total Elemental Abundances

Parameter	3242in	Solar Ref	Orion Ref
He/H	9.73(-2)	8.50(-2)	9.70(-2)
C/H	3.14(-4)	2.69(-4)	3.31(-4)
C/O	0.717	0.550	0.616
N/H	4.30(-5)	6.76(-5)	5.37(-5)
N/O	9.82(-2)	0.138	0.100
O/H	4.38(-4)	4.89(-4)	5.37(-4)
Ne/H	9.34(-5)	8.51(-5)	1.12(-4)
Ne/O	0.213	0.174	0.209
S/H	1.05(-6)	1.32(-5)	1.66(-5)
S/O	2.41(-3)	2.70(-2)	3.09(-2)
Ar/H	1.54(-6)	2.51(-6)	4.17(-6)
Ar/O	3.51(-3)	5.13(-3)	7.77(-3)

6. FUTURE

2013 February - STIS observations completed

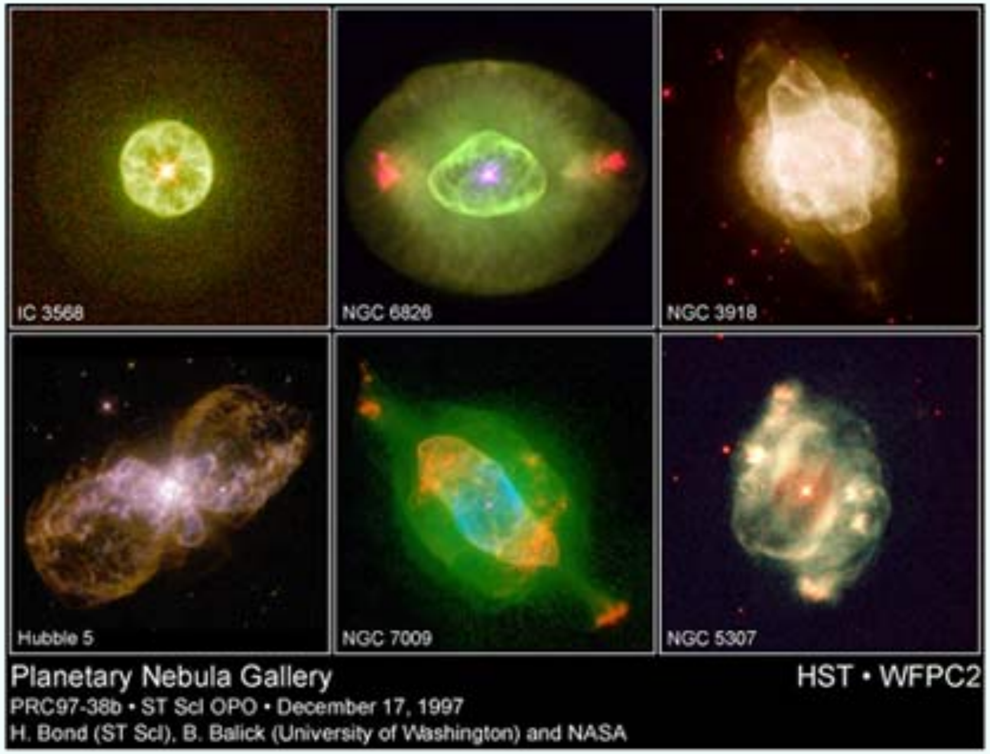
2013 summer - Complete 1D integrated spectra line measurements and abundance analyses (ApS publication); make available on the web at the Williams' s PNe spectra atlas site.

2013/2014 - Perform analyses of spatial line variations across slits for individual nebulae; compare with HST imagery to model ionization structure, physical conditions, and abundances across nebulae.

2014 - Theoretical analysis of the "confrontation between observation and theory" for LIMS. Also, possibly an appraisal of older C & N abundance studies of PNe based on more limited emission line data of past UV spectroscopic studies.

2014 - Apply for more STIS time...!!

MAHALO!



Karen B. Kwitter & Richard B.C. Henry

(bookmark: *tinyurl.com/63ed7tx*)

Spectra, Atlas Data, and Image Links for Over 160 Galactic Planetary Nebulae

COMING SOON: M31 Planetary Nebulae!