Recent advances in the modeling of panchromatic observations of nova shells

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Outline

- What we learn from the ejecta of novae.
- Sipping highlights of the past.
- New problems from the growing panchromatic data sets.
- The future?

Fundamental questions addressed by analysis of nova shells

- Mass ejected during outburst.
  - The "missing mass" problem.
  - Mass ejected a function of WD mass?
  - The SN Ia connection.
- Abundance of the ejecta.
  - Galactic contributions and
  - Pre-solar nebular contributions.
  - different dust compositions.
  - Abundances as fingerprint of the underlying outburst?
- Structure of the ejecta.
  - How are the clumps formed?
  - Is the abundance constant in the shell?
  - Dust formation in clumpy ejecta.

Evolution of nova shell modeling

Earliest days:

- Low resolution optical spectra.
- Nebular diagnostic techniques to obtain T_e and N_e (e.g. Pottasch 1959, AnAp, 22, 412; Gorbatskii & Nitkitin 1964, SvA, 7, 656).

1980s:

- IUE opens up the ultraviolet. Low resolution IR spectra.
- Use of ionization correction factors to estimate abundances of unseen ionizations (e.g. Andrea, J.; Drechsel, H.; Starrfield, S. 1994 A&A, 291, 869)

1990s to now:

- Photoionization modeling using multiple components.
- Co-temporal X-ray/UV/Optical/IR/Radio data sets.
- Check results against other methods to constrain or confirm the mass and abundance solution.

Photoionization modeling

Model Input

- Amount of ionization.
  - Luminosity
  - SED shape
- Shell geometry.
  - shape
  - covering factor
  - filling factor
- Density structure.
- Elemental composition.

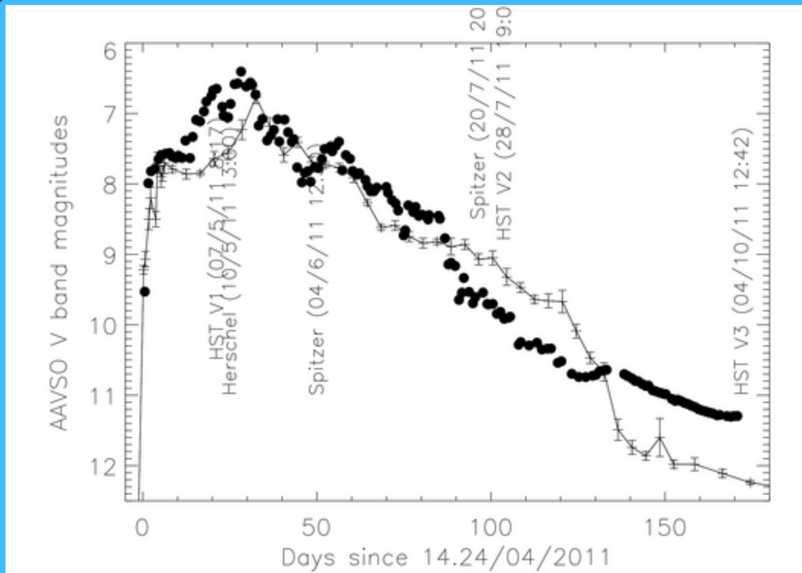
Model Output

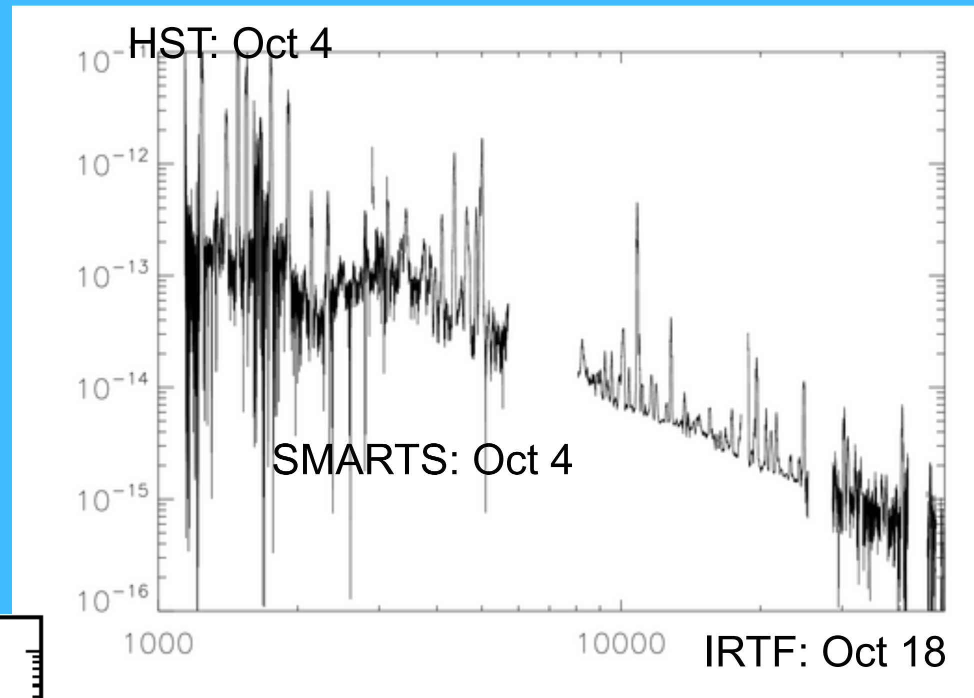
Predicted shell

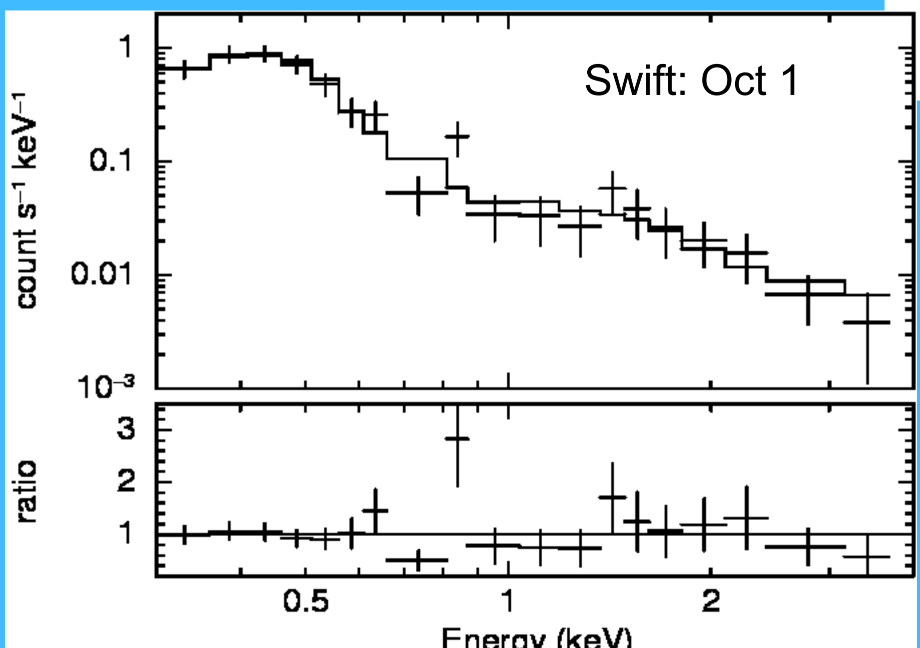
- Emission line luminosities
- continuum luminosity.

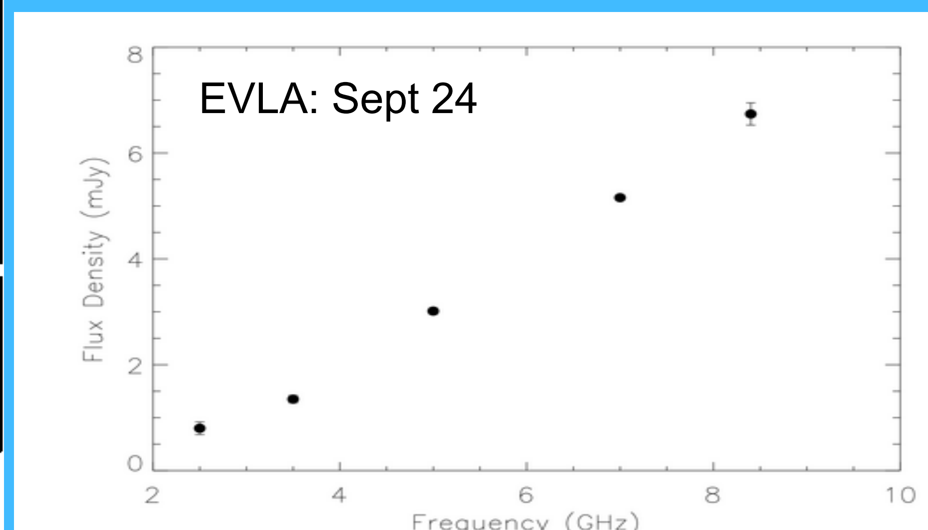
Further constrains on final solution from fitting different evolutionary epochs or other independent techniques.

Best nova SED: T Pyx



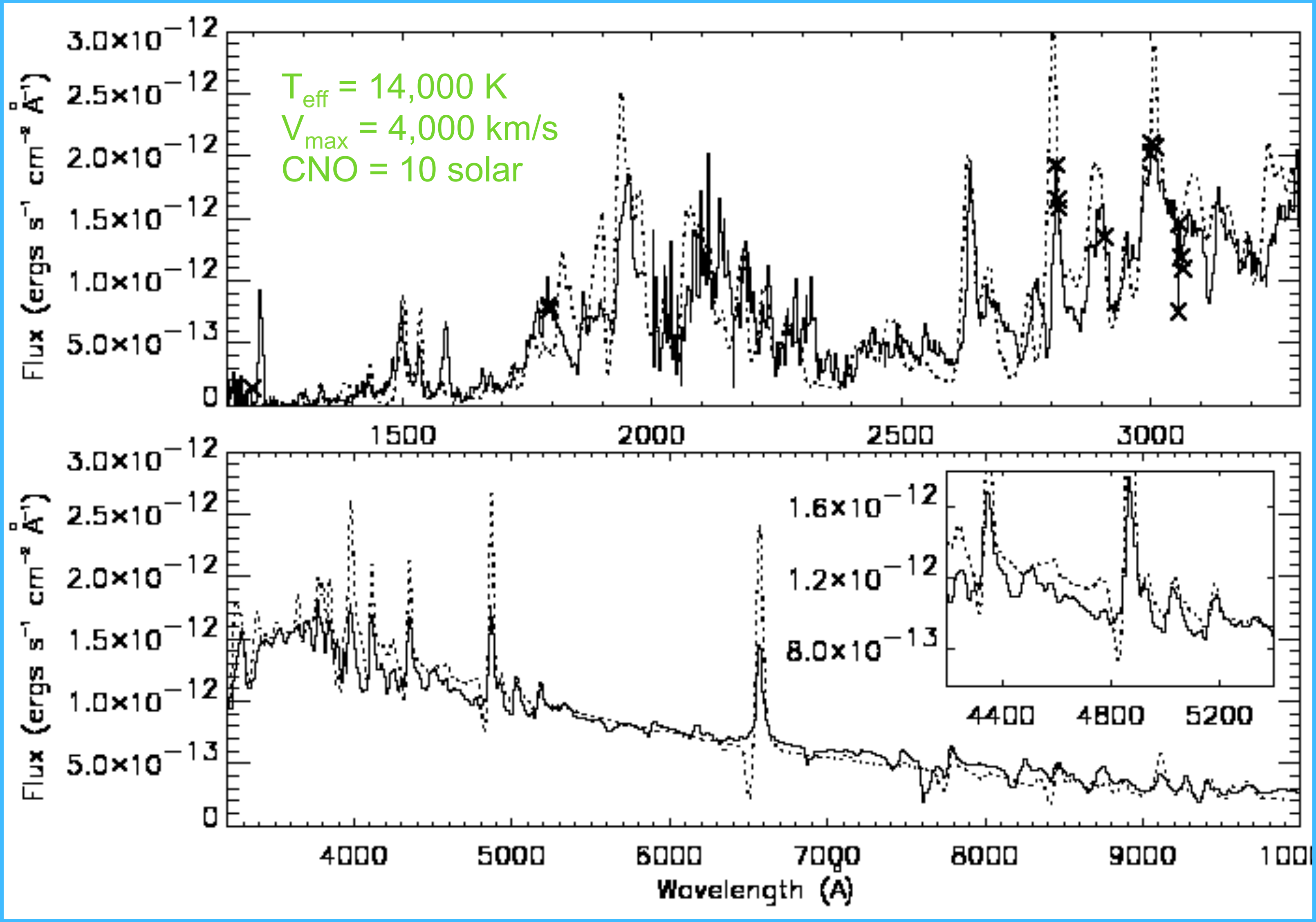






Model Atmosphere fits

Nova LMC 1991: Iron-curtain phase with Z=0.1 solar PHOENIX model



Schwarz et al. 2001 MNRAS, 320, 103

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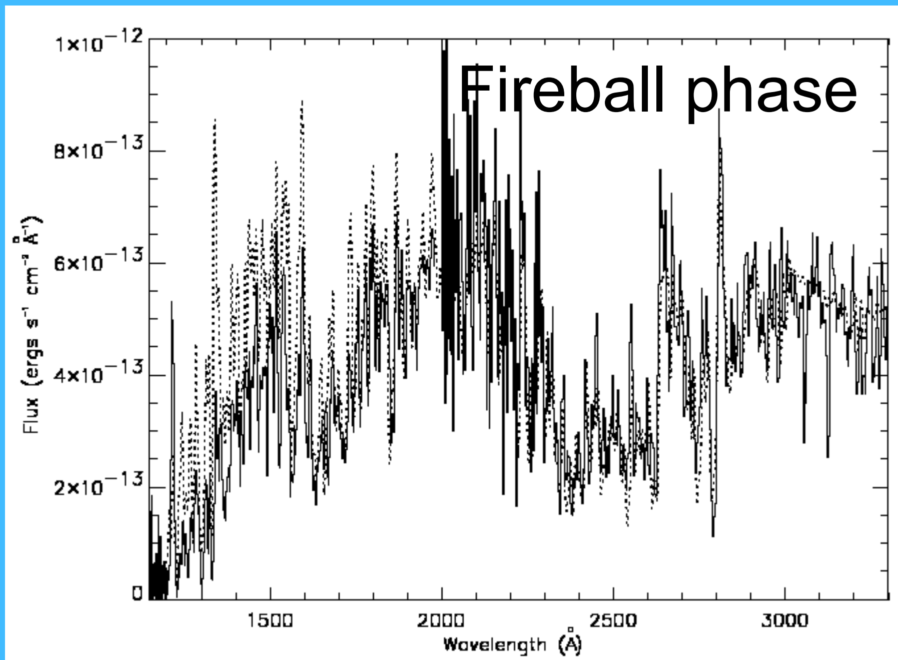
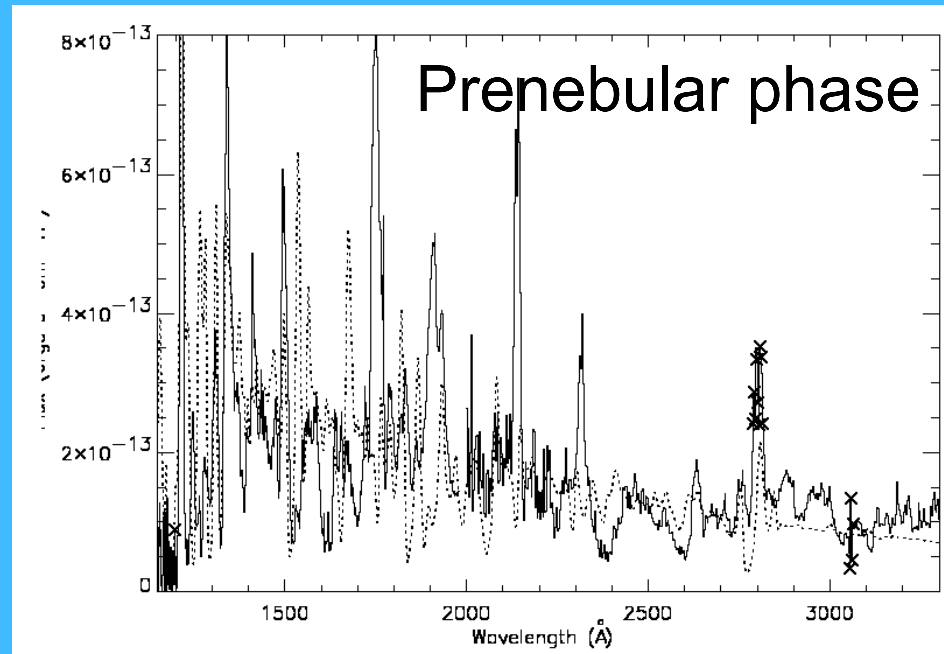




He/H = 0.8 +/- 0.2
C/H = 5 +/- 2
N/H = 85 +/- 25
O/H = 6.5 +/- 2.0
Ne/H ~ 0.2
Fe/H ~ 0.2

Consistent with CLOUDY modeling of 3 UV + 1 optical nebular spectra.

Schwarz et al. 2001 MNRAS, 320, 103

Abundances for 8 ONe novae

Table 1
Summary of Observed Abundances (in Mass Fractions) for Neon Novae from UV, Optical, and IR Spectroscopy

	LMC 1990#1[1]	V4160 Sgr[2]	V838 Her[2]	V382 Vel[3]	QU Vul[4]	V693 CrA[5]	V1974 Cyg[6]	V1065 Cen[7]	Solar[8]
X_{He}/X_H	4.8(8)E-01	7.1(4)E-01	5.6(4)E-01	4.0(4)E-01	4.6(3)E-01	5.4(22)E-01	4.8(8)E-01	5.4(10)E-01	3.85E-01
X_C/X_H	3.7(15)E-02	1.43(7)E-02	2.28(23)E-02	2.6(13)E-03	9.5(59)E-04	1.06(44)E-02	3.1(9)E-03	...	3.31E-03
X_N/X_H	1.48(42)E-01	1.27(8)E-01	3.29(47)E-02	2.28(54)E-02	1.61(10)E-02	1.84(67)E-01	6.0(15)E-02	1.40(33)E-01	1.14E-03
X_O/X_H	2.4(10)E-01	1.35(9)E-01	1.42(38)E-02	4.13(38)E-02	3.2(14)E-02	1.63(66)E-01	1.55(85)E-01	4.7(15)E-01	9.65E-03
X_{Ne}/X_H	1.6(10)E-01	1.38(5)E-01	1.22(5)E-01	4.0(7)E-02	5.1(4)E-02	6.7(34)E-01	9.7(40)E-02	5.34(98)E-01	2.54E-03
X_{Mg}/X_H	1.37(71)E-02	≈8.4E-03	1.2(7)E-03	2.45(14)E-03	1.02(49)E-02	9(7)E-03	4.3(28)E-03	4.4(13)E-02	9.55E-04
X_{Al}/X_H	2.3(11)E-02	...	1.8(13)E-03	1.63(16)E-03	4.1(11)E-03	5.0(46)E-03	>7.8E-05	...	8.74E-05
X_{Si}/X_H	4.8(39)E-02	1.09(6)E-02	7(2)E-03	5(3)E-04	2.4(18)E-03	2.4(18)E-02	...	...	1.08E-03
X_S/X_H	...	...	1.48(15)E-02	...	...	...	...	2.3(13)E-02	5.17E-04
X_{Ar}/X_H	...	...	...	...	4.0(3)E-05	...	...	4.6(17)E-03	1.29E-04
X_{Fe}/X_H	...	2.4(8)E-03	2.35(63)E-03	...	9.53(54)E-04	...	8.8(72)E-03	1.16(40)E-02	1.81E-03
X_H[9]	4.7(9)E-01	4.65(37)E-01	5.63(36)E-01	6.6(4)E-01	6.3(3)E-01	3.8(14)E-01	5.5(8)E-01	3.6(10)E-01	7.11E-01

Notes. All abundances are given here in terms of mass fraction ratios, X_{el}/X_H (or mass fraction for hydrogen; see last row), by converting the "number abundances relative to hydrogen relative to solar" from the original literature (references provided below). The abundance uncertainties are given in parentheses.

[1] From Vanlandingham et al. (1999).

[2] From Schwarz et al. (2007).

[3] From Shore et al. (2003).

[4] From Schwarz (2002).

[5] From Vanlandingham et al. (1997).

[6] From Vanlandingham et al. (2005); solar abundances assumed in their analysis are not listed; their adopted values were $\log(N_{el}/N_H)_\odot = -1.0$ (He), −3.45 (C), −4.03 (N), −3.13 (O), −3.93 (Ne), −4.42 (Mg), −5.53 (Al), −4.45 (Si), −4.79 (S), −4.49 (Fe) (K. M. Vanlandingham 2012, private communication).

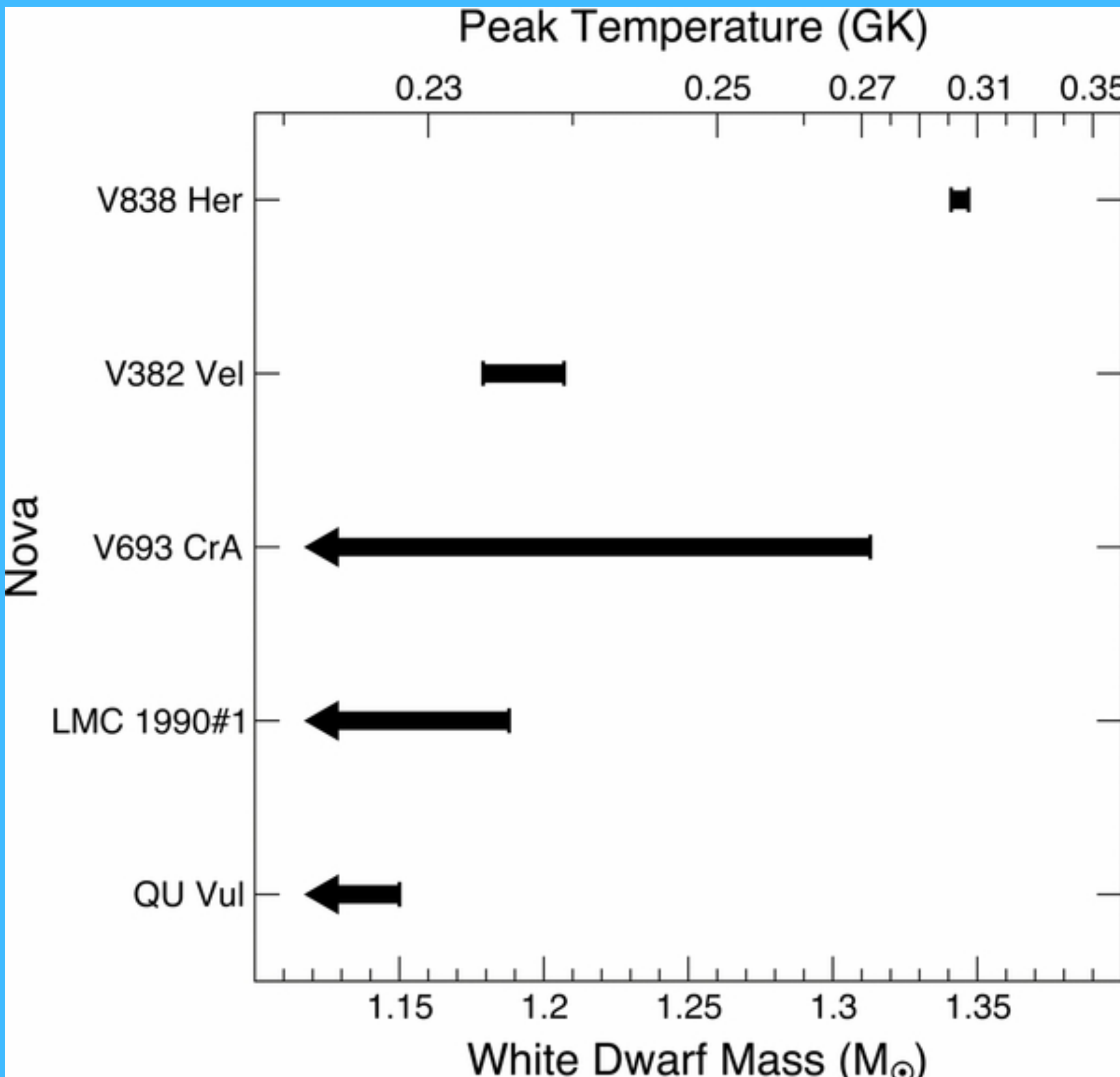
[7] From Helton et al. (2010).

[8] From Lodders et al. (2009).

[9] Calculated from $X_H = [1 + X_{He}/X_H + X_C/X_H + \cdots + X_{Fe}/X_H]^{-1}$.

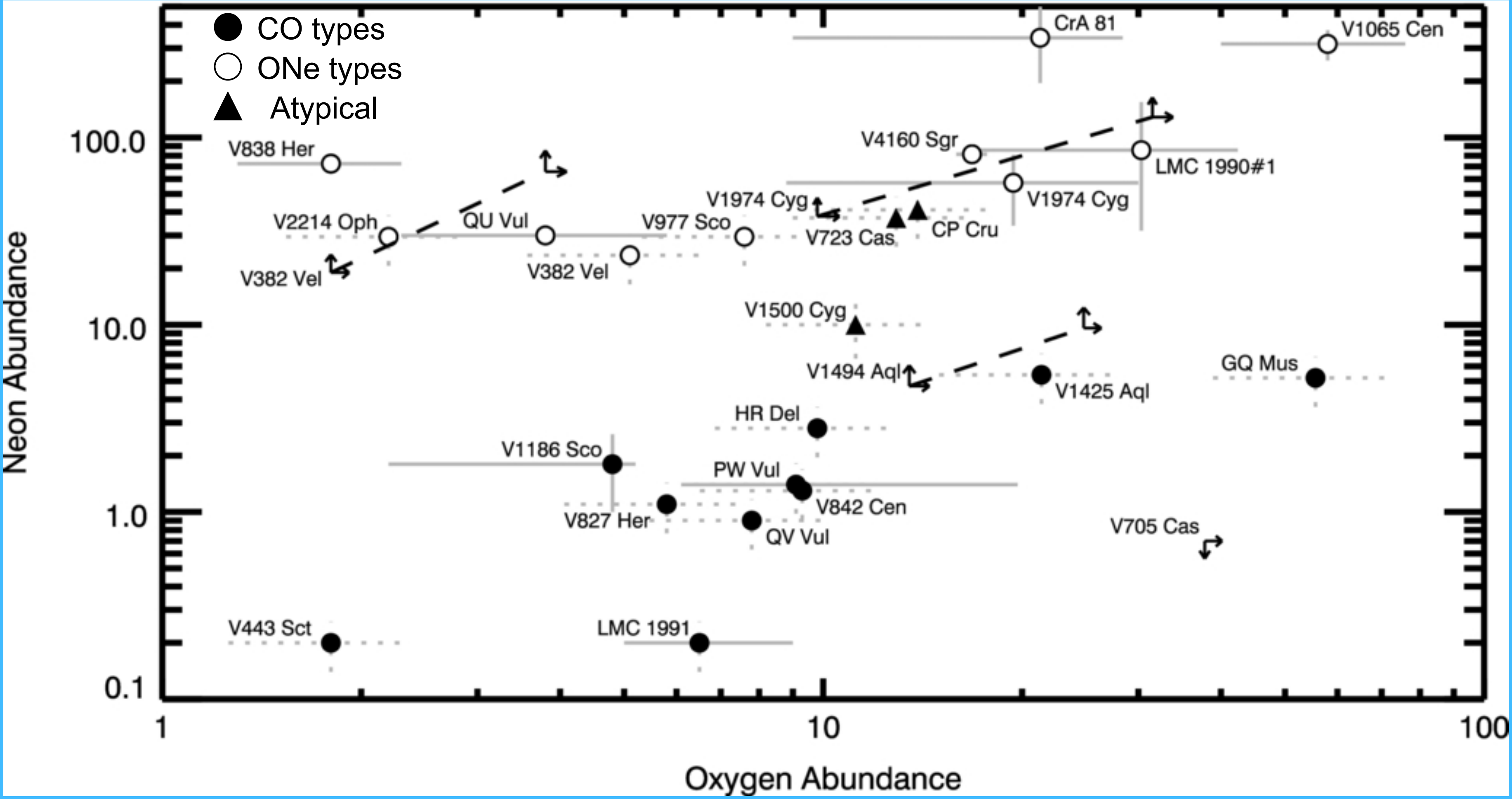
As summarized in Downen et al. 2013, ApJ, 762, 105

From abundance to WD mass



Estimated WD masses from the published photoionization abundances (Downen et al. 2013, ApJ, 762, 105)

Abundance patterns: O vs Ne



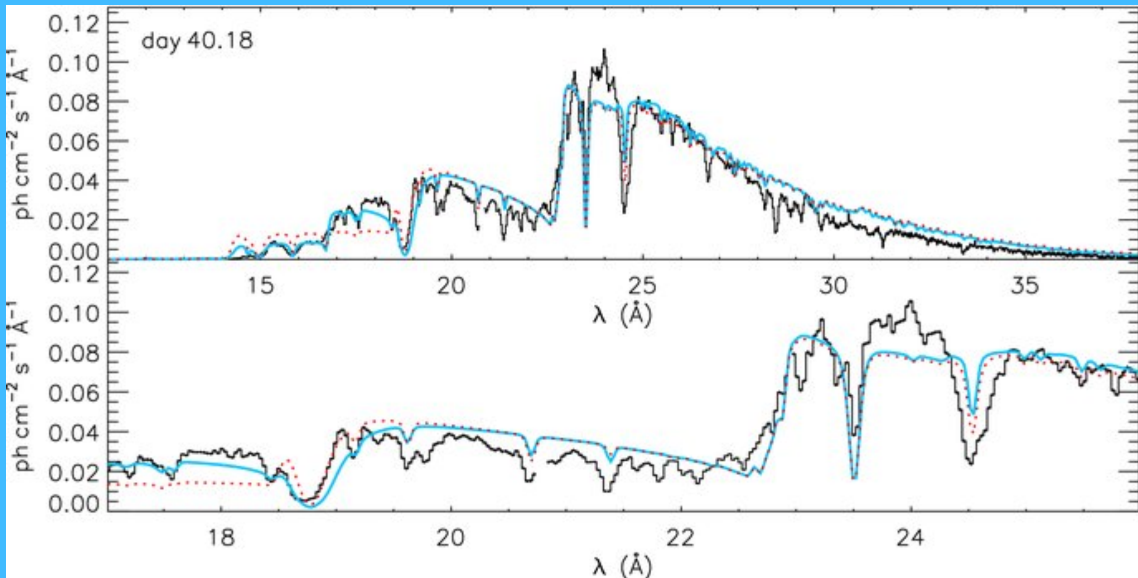
A clear difference between the ONe and CO type novae (Helton et al. 2012, ApJ, 755, 37)

Ejected mass in the ONe sequence

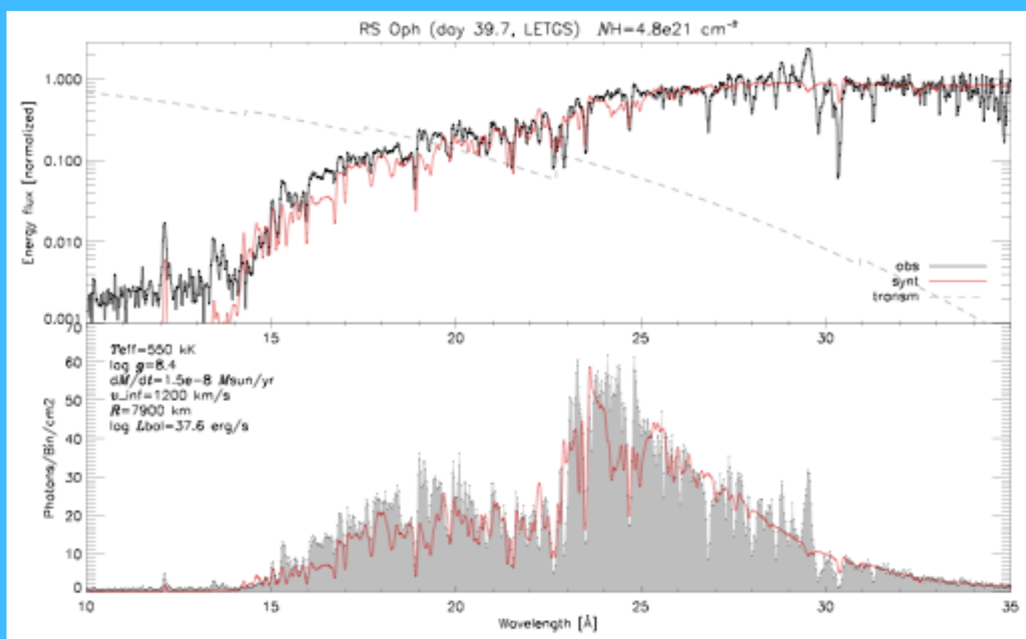
	QU Vul	V1974 Cyg	V1065 Cen	V382 Vel	V4160 Sgr	V838 Her
t_2 (days)	25	17	11	4	2	2
M_{eject} (1e-5 M_{sun})	>35	19	14-17	18-50	~3.6	0.73

Adapted from Schwarz et al. 2007, ApJ, 657, 453 plus Helton et al. 2010, AJ, 140, 1347

Modeling X-ray grating spectra



TMAP model fit to a XMM spectrum of V2491 Cyg (Ness et al. 2011, ApJ, 733, 70). C=0.25, N=11.5,O=35.0.



A dynamical PHOENIX model fit to a Chandra spectrum of RS Oph with solar abundances (van Rossum & Ness 2019, AN, 331, 175).

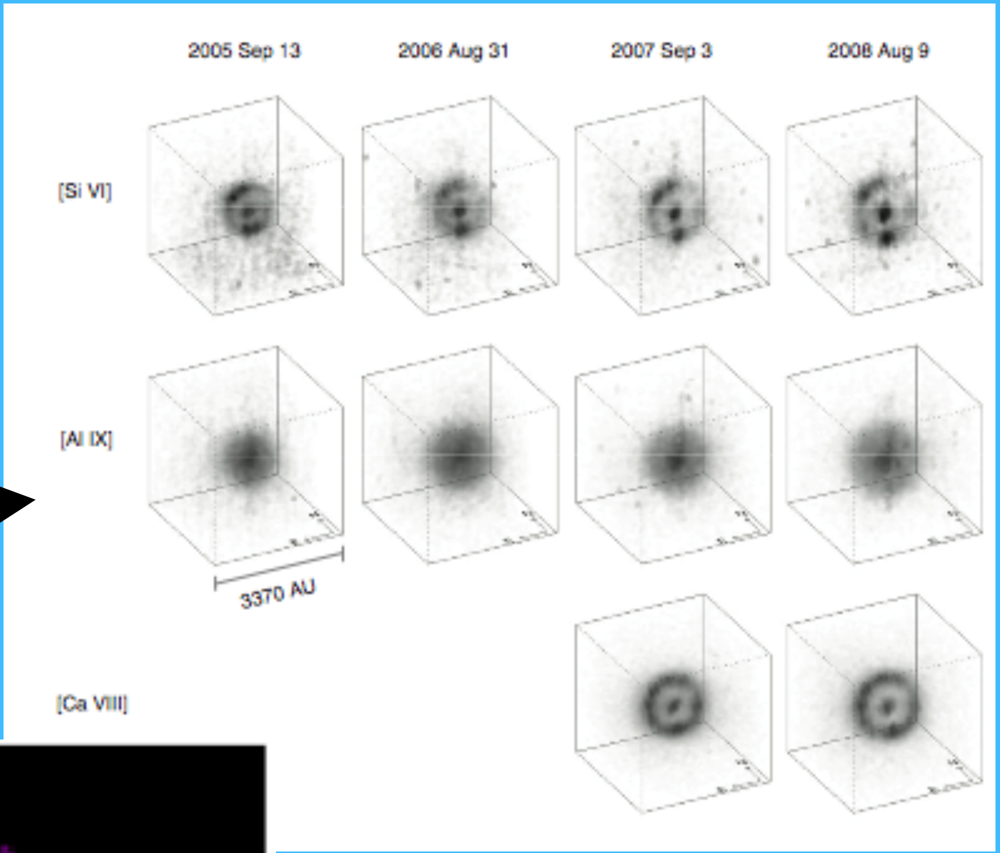
Panchromatic observations have raised more questions!

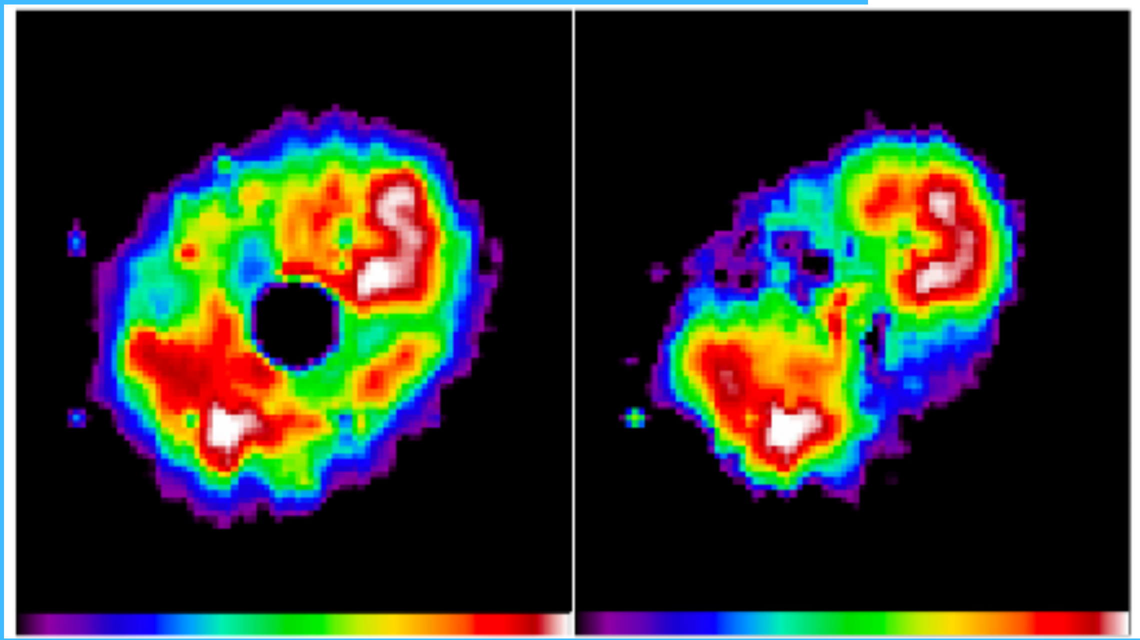
- The more ionizations observed the harder it becomes to fit a single photoionization model to the data. Multi-components become necessary.

- Imaging shows shells deviate from spherical symmetry.
  - Known for a long time that old, resolved ejected shells show deviations from spheres with rings and polar caps (Gill & O'Brien 2000, MNRAS, 314, 175, Krautter et al. 2002 AJ, 124, 2888).

Recently spatially resolved novae

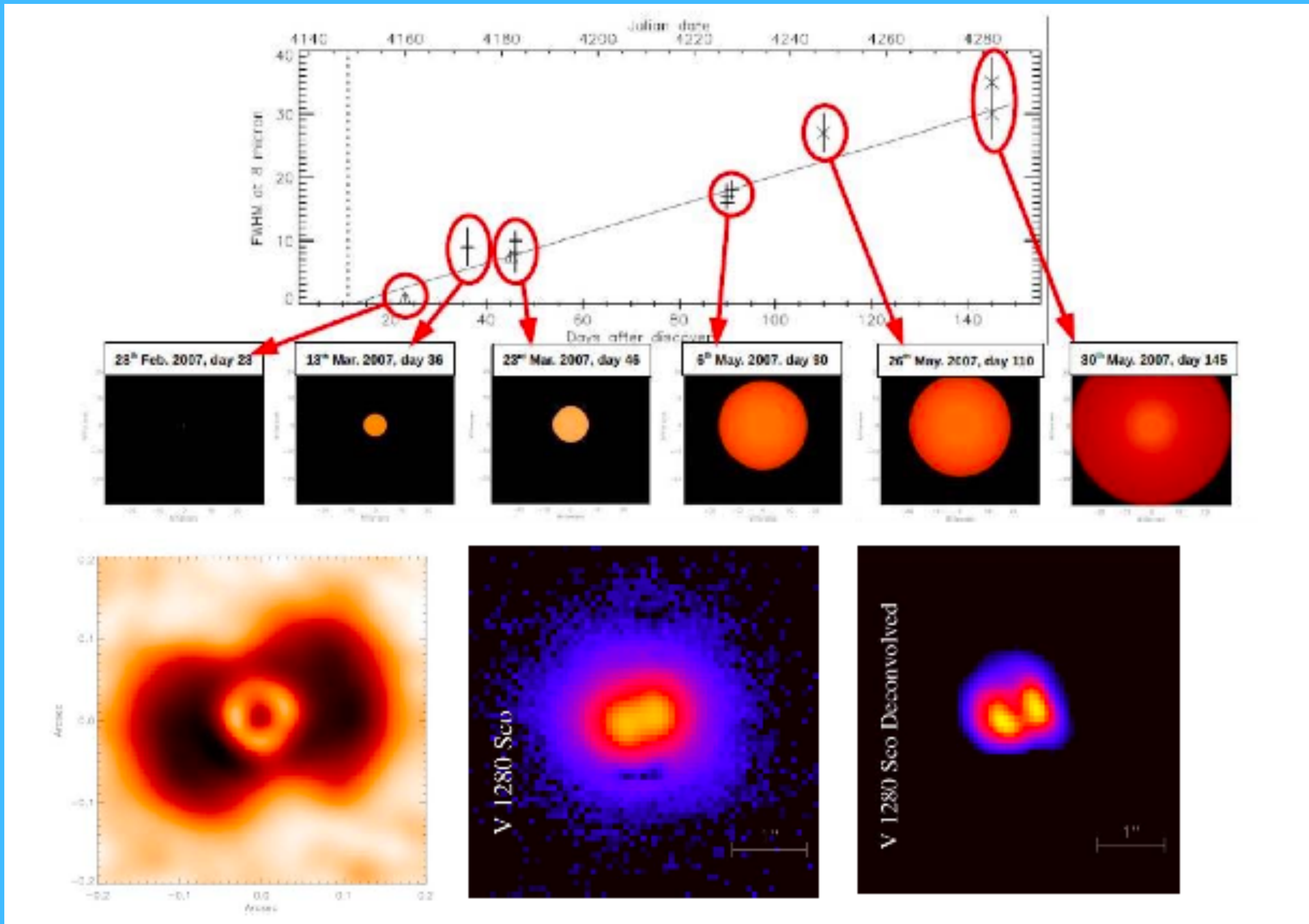
Keck AO IR spectra of V723 Cas from Lyke & Campbell 2010, AJ, 138, 1090





HR Del Halpha+[N II] (left) and [O III] (right) from Moraes & Diaz 2009, AJ, 136, 1541

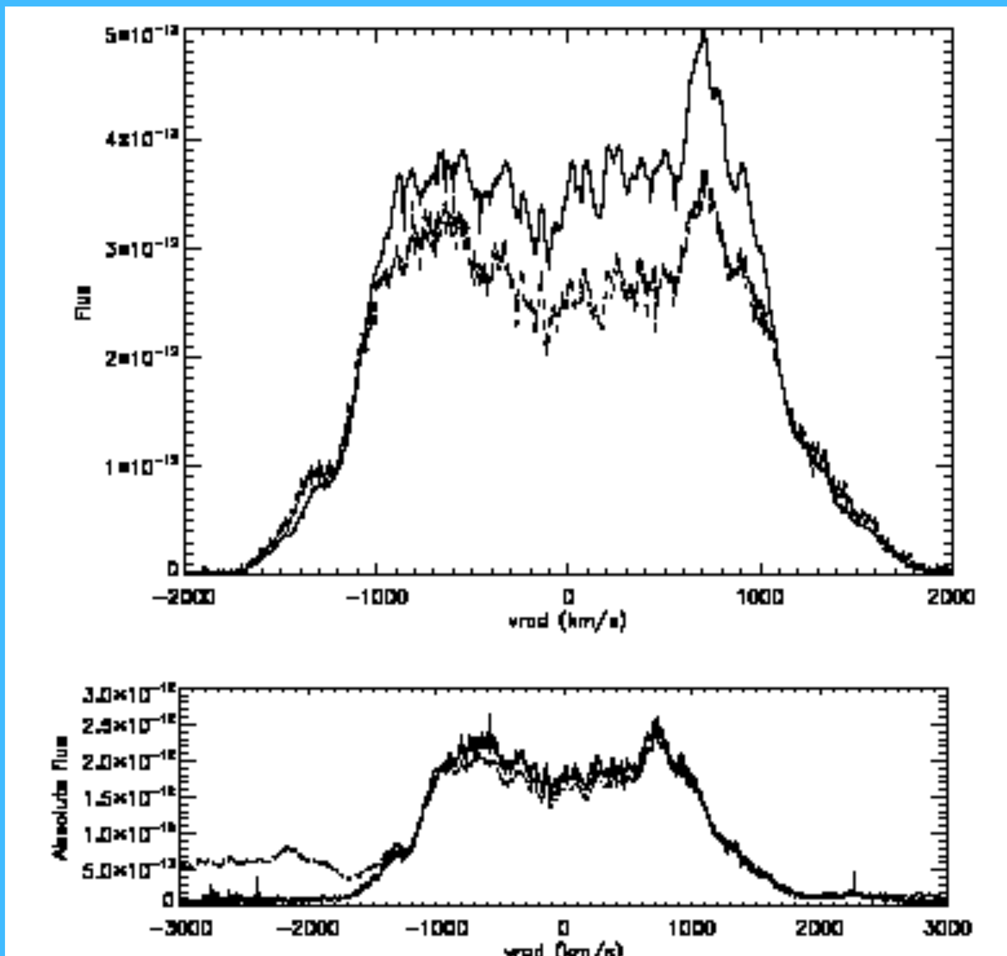
VLTI observations of V1280 Sco



Chesneau & Banerjee 2012, BASI, 1

NOT line profiles in Nova Mon 2012

Nova ejecta are clumpy with evidence of abundances deviations across the shell, HST spectra of V1974 Cyg (Shore et al. 1997 ApJ, 490, 393).

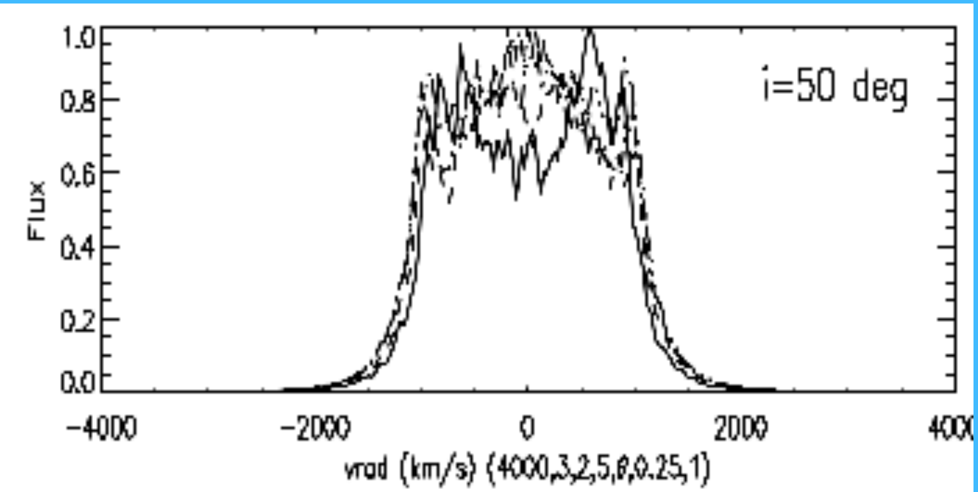


Variations in Halpha (solid) and scaled [Ne III] (3869 A; dotted) line profiles.

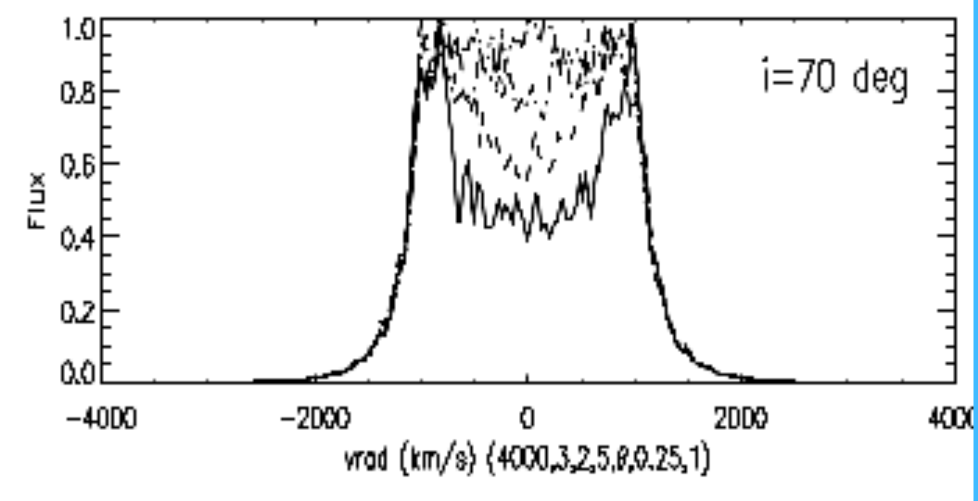
Similarities between [O III] (5007A; solid) and [Ne III] (3869 A; dotted) line profiles.

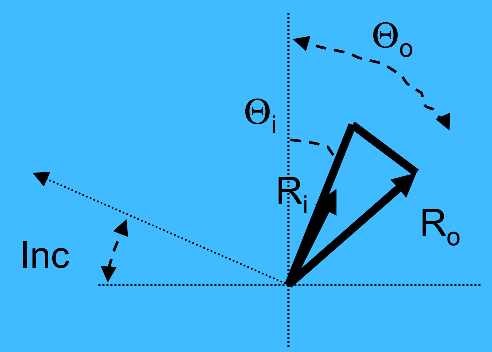
Shore et al. 2013 submitted

Monte Carlo model line profiles

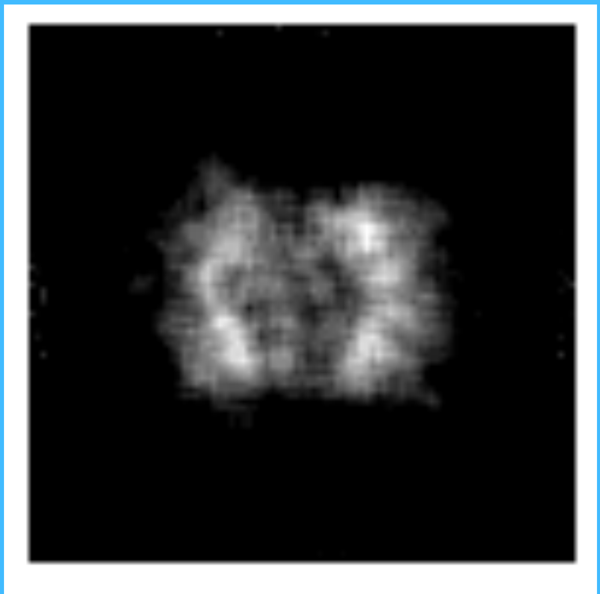


Θ_i = 5° Θ_o = 20,40,60,90°





Model assumes a ballistic velocity law and constant ejecta mass.



ΔR/R = 0.3

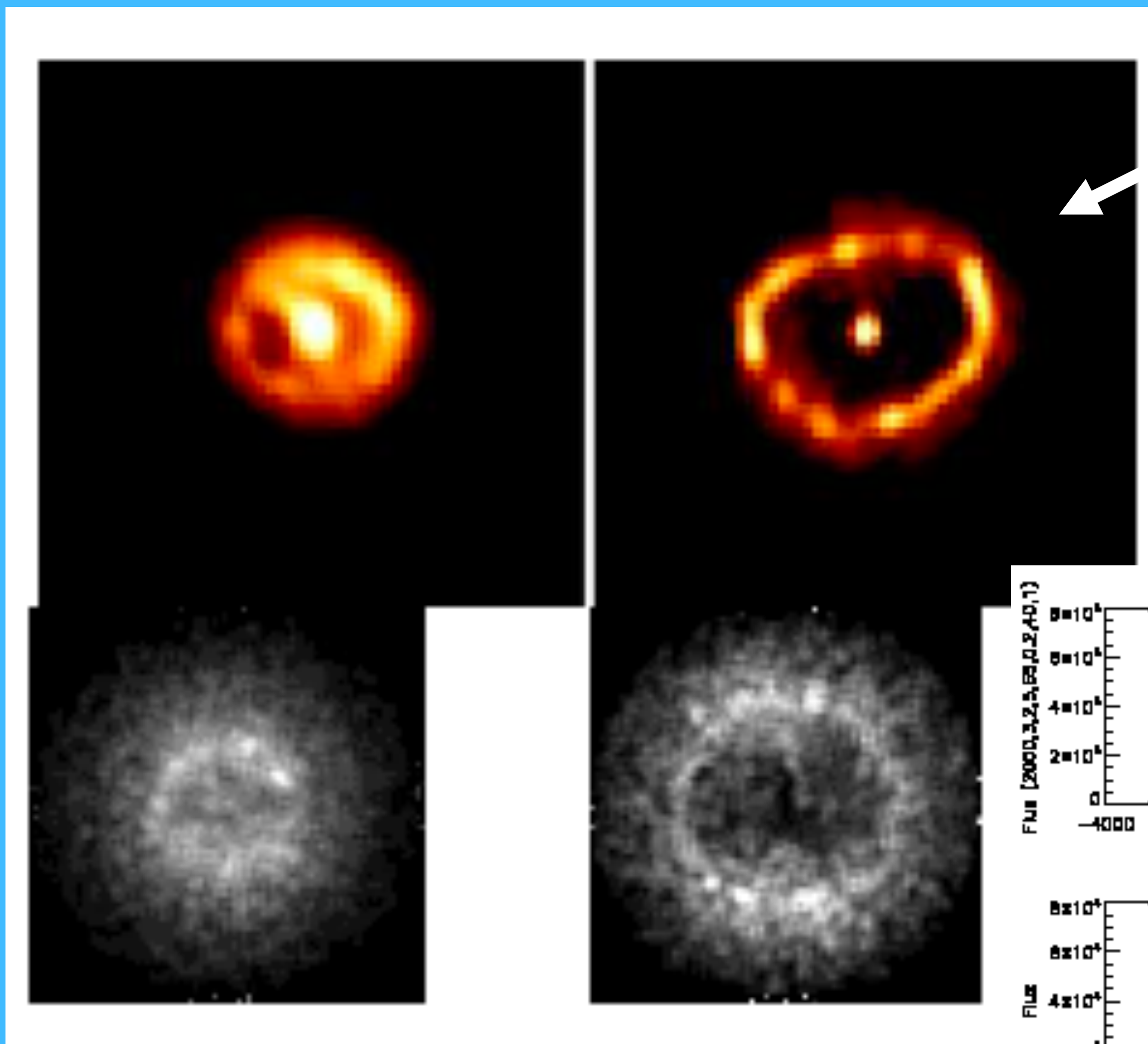
Θ_i = 5°

Θ_o = 60°

inc = 70°

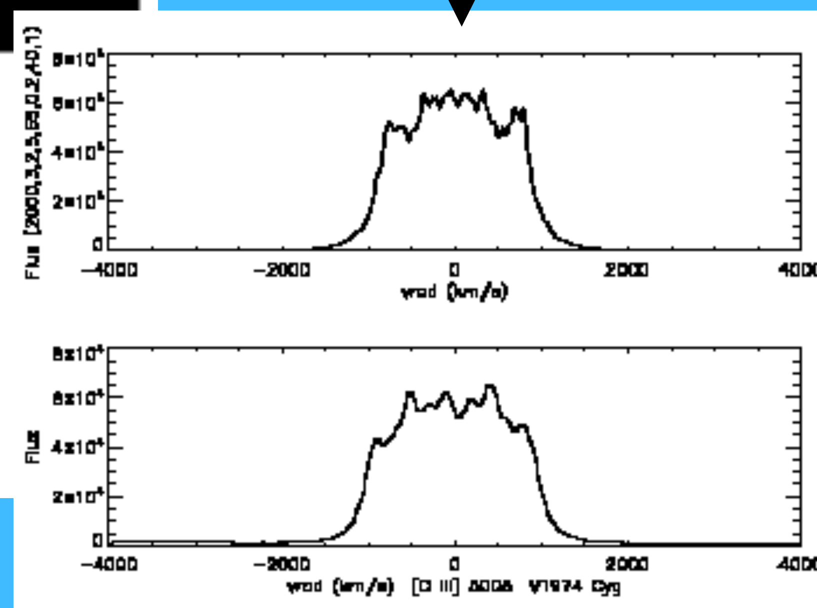
Shore et al. 2013 submitted

V1974 Cyg test



HST images of the ejecta of V1974 Cyg (top) and sample model ejecta (bottom).

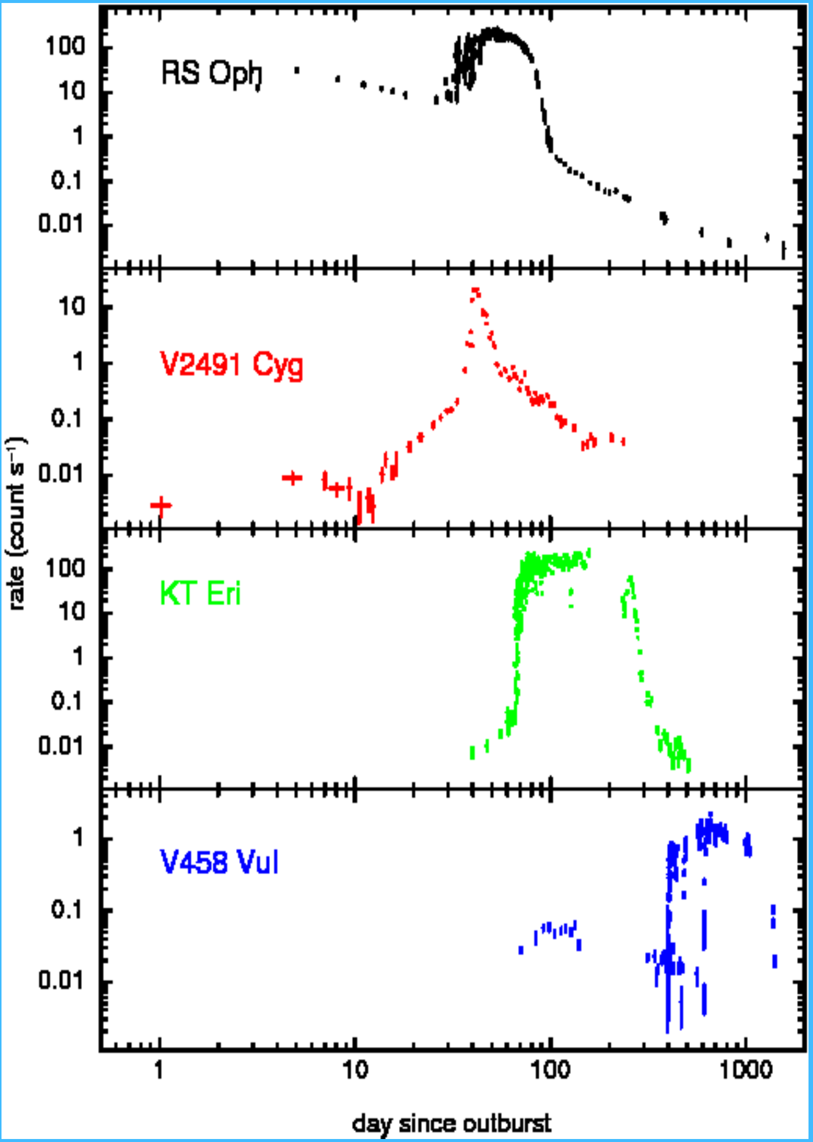
Halpha line profile of model (top) and observed (bottom).



Shore et al. 2013 submitted

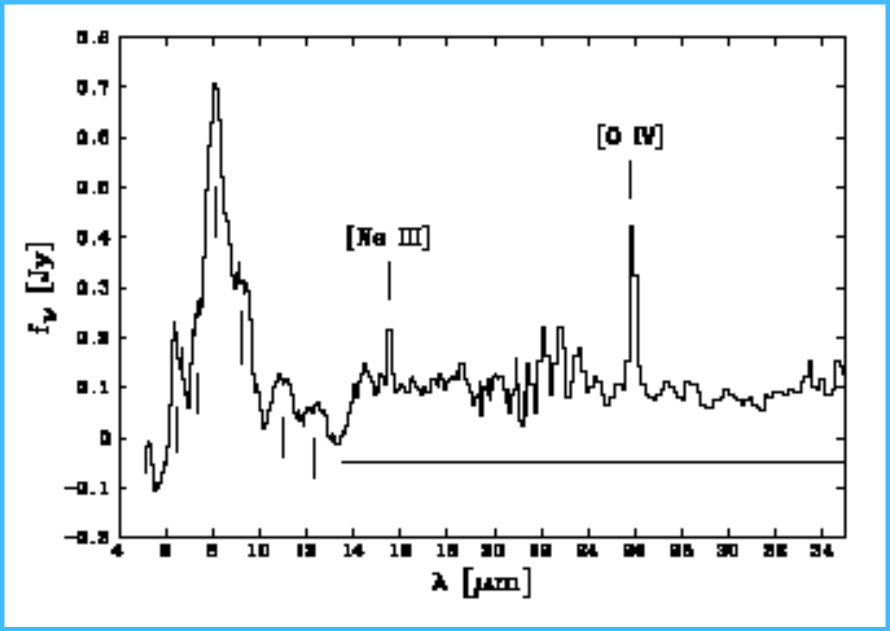
Panchromatic observations have raised more questions!

- Unexpected and (mostly) unexplained X-ray behavior.
  - ➢ Long lasting hard X-rays.
  - ➢ Variable soft X-ray emission.
  - ➢ UV/X-ray light curve (anti-)correlations.
  - ➢ Few correlations between SSS and other nova parameters (Schwarz et al., 2011, ApJS, 197, 31).



Panchromatic observations have raised more questions!

- Rapidly changing conditions (e.g. X-ray variability) means shell isn't in equilibrium.
- Surprising high energy gamma-ray early in the outburst.
  - ➢ What powers these high energy gamma-rays?
  - ➢ Are all novae gamma-ray producers?
- Unknown dust features in Spitzer spectra (e.g. Helton 2010 PhD).



DUSTY subtracted IR spectrum of DZ Cru (Evans et al. 2011, MNRAS, 406, 85)

Future developments

• Integrate ejecta geometry derived from imaging and spectrocopy into the photoionization modeling of the shell.

  ➢ RAINY3D: pseudo-three-dimensional driver for Cloudy (Moraes & Diaz 2011, PASP, 123, 844).

  ➢ SHAPE: a morpho-kinematical modeling application (e.g. Ribeiro et al. 2011, MNRAS, 412, 1701)

• Integration of shocks into energy budget.

• Are there inclination effects? How do we account for it?

• New model atmosphere for an extensive archive of early UV/Optical spectra and later X-ray SSS spectra.

• Continue to exploit multiwavelength observations.

  ➢ Especially in the UV for as long as STIS and COS survive.

  ➢ Expand collaborations among groups with specialties at different wavelengths.