The Anatomy of a Murder

The spectroscopic development of a nova outburst

Stella Novae 2013

The Prequel: Some history

- mid-1920s-1950: H II regions - Forbidden lines as diagnostics, recombination theory; Fluorescence; Multiplets for heavy elements (RMT, stellar spectroscopy), MK classification (series "Physical Processes in Gaseous Nebulae")
- Stratton & Manning (1939, *Atlas of spectra of Nova Herculis 1934* Solar Phys. Obs. Cambr.)
- McLaughlin (1942, ApJ, 95, 428; 1943, Publ. Obs. Mich., 8, 149); soon after the start of modern laboratory spectroscopy
- Payne-Gaposchkin (1957, *The Galactic Novae*) presented the first major summary
- Merrill (1958, *Lines of the Chemical elements in Astronomical Spectra* CIW Publ. 610)
- The CTIO taxonomy (Williams et al. 1991, ApJ, 376, 721; 1994, ApJS, 90, 297)
- IAU Symp. 3: Non-stable Stars (1955), *The Classical Novae* (1989), Sitges 2002, *The Classical Novae 2nd Ed* (2008)

More milestones:

- Ne III in novae – even a small sample showed variations, some never showed the line
- The *enhanced* aspect: something increases the strength of metallic spectra relative to stellar atmospheres
- Multiple absorption line systems
- Symmetries of the line profiles
- Relative timings of photometric and spectroscopic variations

Why spectroscopy? Basic issues of photometry

- Photometry is essential but only partial information, it isn't just very (!) low dispersion spectroscopy
- Interpretation based on assumptions about geometry, filling factors, and structure
- Depends on the filters and variations of line profiles in a complicated way

Also sprach McLaughlin

"The attempt to draw a generalized picture of the spectroscopic development of a typical nova is handicapped by the fact that only seven bright objects of this class have been observed in great detail, and there are important interruptions in each observatory's record of even those seven stars. ... Each object has its idiosyncracies, and no one of them can be adopted as typical in every respect. On the other hand, we must face the risk of eliminating something important if we try to "average" the seven bright novae".
McLaughlin 1943, Publ. Obs. Univ. Michigan, 8(12), 149

A. Pre-maximum spectrum (V<V_{min}): This set of lines lasts through the observed rise, over the maximum, and for at least a day or two after maximum light

B. Principal absorption (ΔV = 0.6-4.1): Emerges soon after maximum and is present simultaneously with the PMS for a short time, its displacement is a little greater than the PMS. In composition it resembles a supergiant star

C. Diffuse enhanced absorption (1.2 -3): This set of very strong and diffuse hydrogen and enhanced metallic lines has a displacement roughly double that of the PS

D. Orion absorption (2.1 - 3.3): These lines of He I, O II, N IIm with or without H, emerge later with a velocity similar to, but not always equal to, the DES

E. Nitrogen absorption (3 - 4.5): The strong lines of N III 4097, 4103Å belonging to the Orion spectrum but they persist after the rest have disappeared. Lines of N IV occur with N III in some novae

F. Nebular (4 - 11): The NS is simply a development from the principal emission spectrum

G. Post-nova narrow stellar emissions (ΔV = 8 - min)

The Expanding Ejecta

The velocity and structure

- The velocity as the main difference
- Beals (1950): application of the theory to WR stars
- Sobolev (1950's): constant velocity gradient is not just a simplification, although it has algorithmic advantages as well
- Rediscovery: also called the Large Velocity Gradient approximation, "on-the-spot" transfer, all of this is related to Monte Carlo modeling now possible for the ejecta.
- Going beyond the Sobolev methods: moving atmospheres

Enter Sobolev

"The presence of a velocity gradient leads to very serious theoretical difficulties. However, there are very fundamental simplifications, chiefly connected with the fact that, owing to the presence of the velocity gradient, the line radiation reaches the observer not only from the external regions of the medium but also (on account of the Doppler effect) from the internal regions. Hence we can go much further in the theory of radiative equilibrium of a moving medium than in the theory of a stationary atmosphere. In particular, it is possible to construct a theory of polychromatic radiative equilibrium for a moving medium (that is, for atoms with a large number of levels)."
Sobolev 1947, *Moving Envelopes of Stars* Leningrad State Univ. (1960; trans. G. Gaposchkin); see also Chandrasekhar 1945, RvMP, 17, 138: "The formation of lines in a moving medium"

The atmosphere analogy

The differences

A stellar atmosphere is a (1) hydrostatic structure, (2) completely filled, and (3) in some kind of global thermal balance (radiative+convective). Ejecta are "none of the above", essential for modeling:

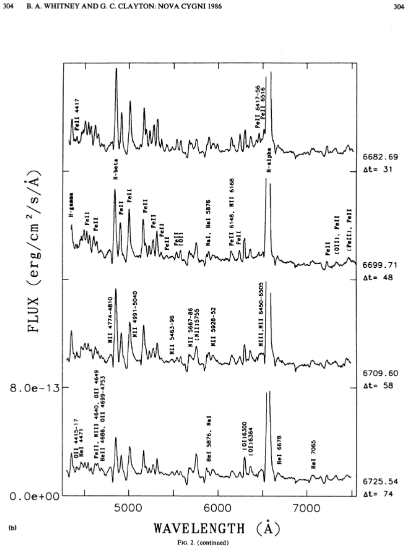
- No limits for velocities, the ejecta are already in free expansion.
- No limits on temperatures, the time dependence of the environment allows for wildly non-equilibrium conditions
- No limits on vacuity, there is nothing preventing fragmentation and very large density contrasts

… and a profound counsel by McLaughlin

"The existence of several different emission systems is not so well known as the multiplicity of the absorptions, mainly because the bright lines are essentially *undisplaced* and hence not immediately separable on the basis of velocity. But the different widths of the bands, or their different character, as well as their times of appearance and disappearance, allocate them to groups which correspond to those of the absorption systems"

" If we are going to understand the physical processes in novae,we must differentiate features from one another not only in terms of excitation but also in terms of the locality of their origin. Neither physics nor geometry alone will "explain" a nova. Perhaps the judicious use of both – each in its proper place, or together – will do so. Similarity of structure is a proper guide to use in unravelling the complexities of the nova emission spectrum."

example – V1819 Cyg 1986 (Whitney & Clayton), optical



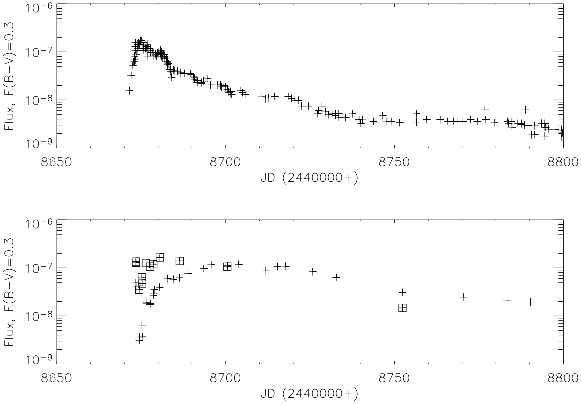
304 B. A. WHITNEY AND G. C. CLAYTON: NOVA CYGNI 1986 304

(b)

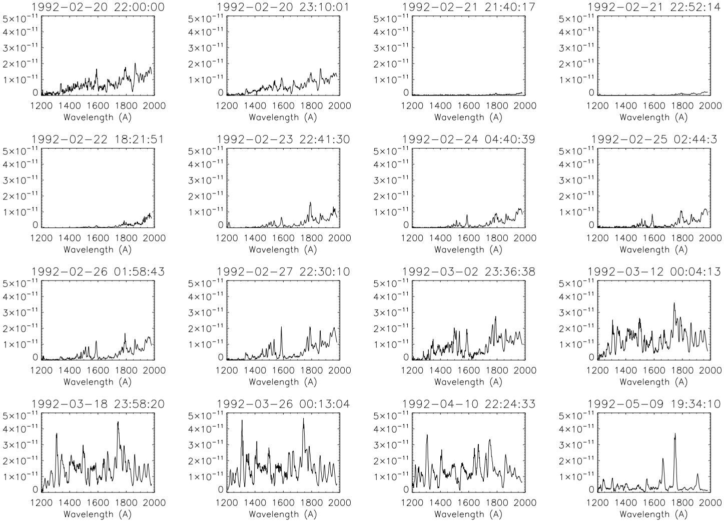
FIG. 2. (continued)

The UV-optical connection (antique but still (!) relevant)

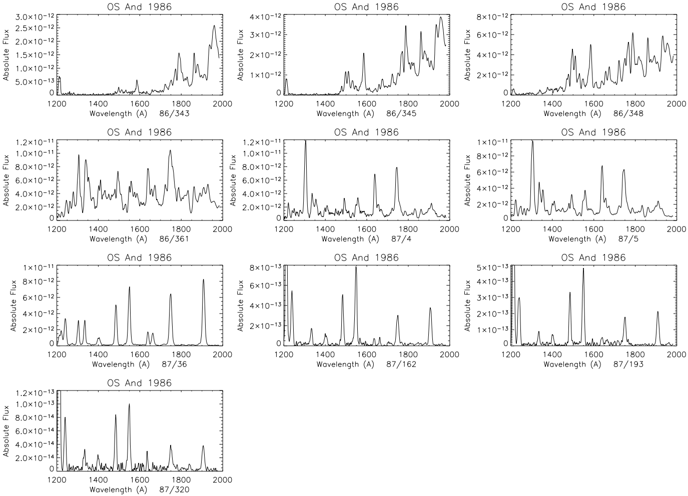
The sort of data we won't have in the future: variability of the UV and optical



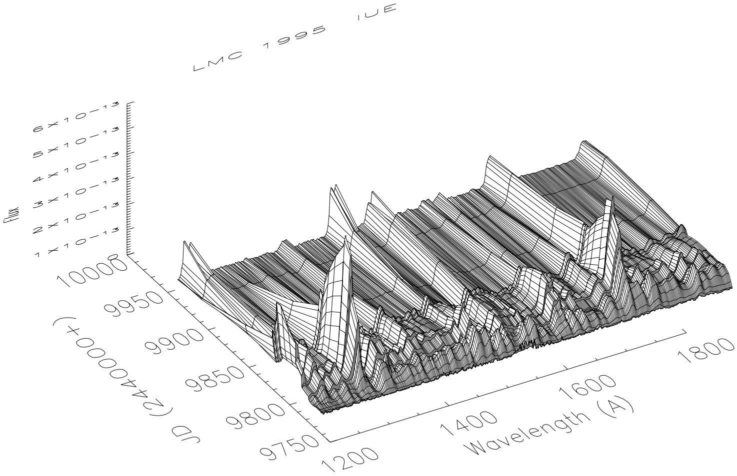
example – V1974 Cyg 1992 – the Fe-curtain



example – OS And 1986 - the Fe-curtain



The UV in a CO nova, an example of what we've lost



The optical taxonomic classes are useful descriptors of stages but it's best not to over-interpret them:

- The "Fe II" novae are caught in an optically thick stage, whatever the structure of their ejecta
  → If you see that spectrum the strong coupling among the metallic species dominates the spectrum formation and the covering factor is indicated by the absorption/emission .
- "He/N" novae are, at the time of observation, already in the optically thin stage (or already completely ionized).
- The original morphological taxonomy, including the B star-like spectrum, already includes the possible presence of highly ionized species.
  → This is the fireball stage whatever the wavelength region.

- Since the line profiles are neither Gaussian nor Lorentzian, the characterization of the profile by standard measures used in stellar atmospheres is potentially misleading.
- The optical depth is not dominated by a microturbulent field even if the word is still used. There's *no* turbulence in a supersonic freely expanding medium. structures imposed at the launch, whether in a wind or ejecta, are advected without dynamical evolution.

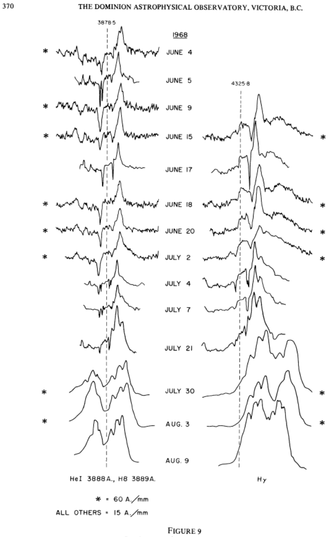
Line widths are related to:

- Changes in the column density as a function of time, which in turn depends on the imposed velocity gradient.
- Coupling between lines of the same or different species, depending on depth in the shell, and their respective cross-excitations.
- Collisional de-excitations and radiative excitations that dominate the inner portion of a wind won't occur in ejecta after a critical density is reached.
- **NB**: All of these don't apply to the formation of the emission/absorption spectra in symbiotic-like systems
- Changes in the central object happening sufficiently quickly can probe the structure of the shell
- Recombination and ionization fronts are strongly time dependent phenomena within the individual structures.

NACs, DACs, and TACs

a. The multiple absorption systems in novae when optically thick are (arguably) the strongest evidence *against* a windK
b. The DACs, when observed in a wind, are either the result of co-rotating regions or transported structures. Either way, they are not observed in the α Cyg type spectra.
c. In a stellar wind, the *discrete absorption components* are advected and strengthen as they narrow, an effect of the saturation induced by $dv(r)/dr \rightarrow 0$ as $r \rightarrow \infty$; strong NLTE in all senses.
d. NACs, in contrasty, separate as they extend to higher v_{rad} and don't sustain the deceleration effect seen in DACs.
Another essential difference: they are strong at the start, during the *classical* "principal" and "diffuse-enhanced" stages.

Narrow absorption features and their development: HR Del 1967: Hutchings (1970, DAO)



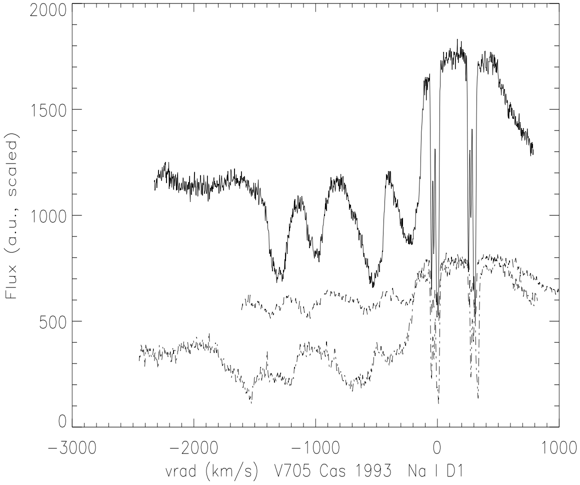
370 THE DOMINION ASTROPHYSICAL OBSERVATORY, VICTORIA, B.C.

FIGURE 9

Development of nebular lines, phase III

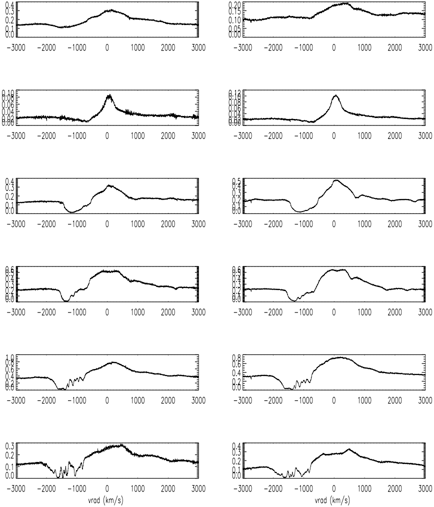
Narrow absorption features and their development

V705 Cas 1993 Na I D1,D2 lines during the optically thick stage near maximum



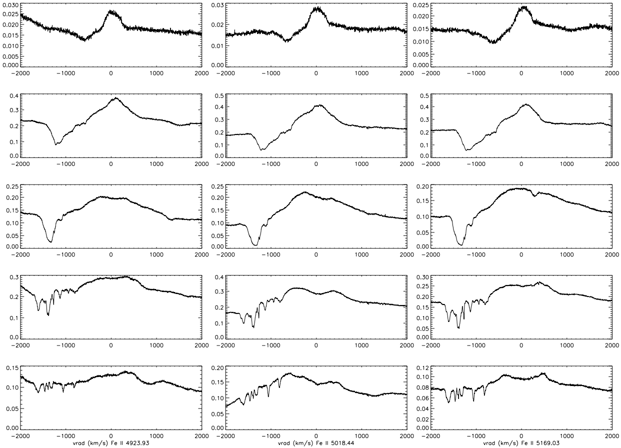
Narrow absorption features and their development

T Pyx 2011 Balmer lines



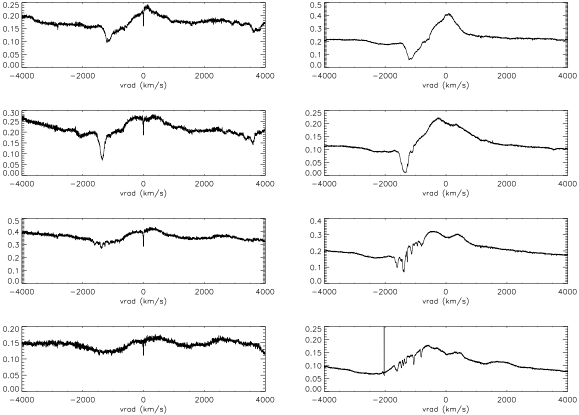
Narrow absorption features and their development

T Pyx 2011: narrow features, Fe II RMT 42



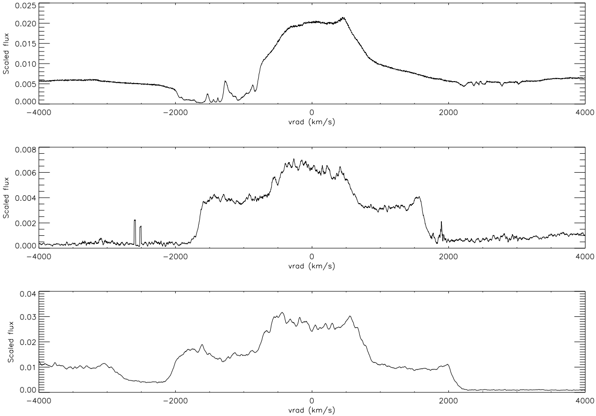
Narrow absorption features and their development

T Pyx 2011: comparison between multiplets - narrow features, Fe II RMT 26, 42



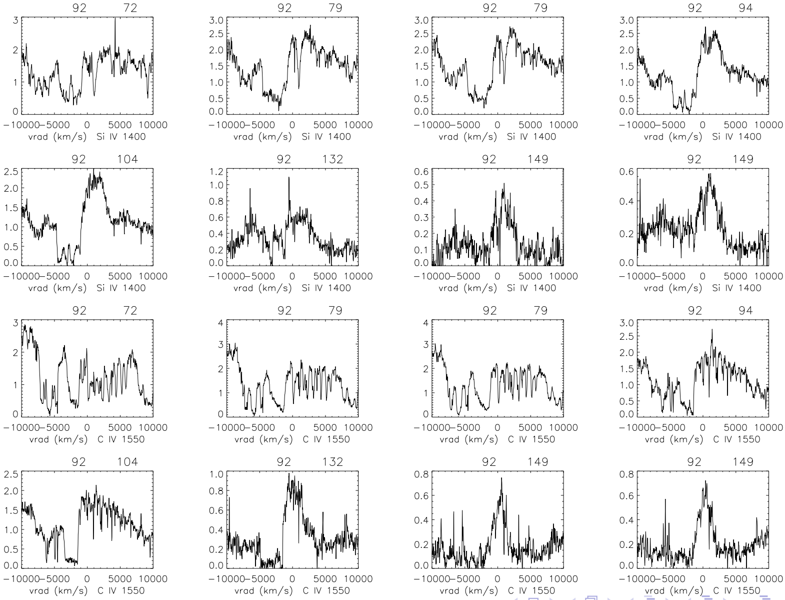
Narrow absorption features and their development

T Pyx 2011: comparison of absorption on Hβ (2011 May, 2011 Oct) and emission on [O III]5007Å (2011 Oct)



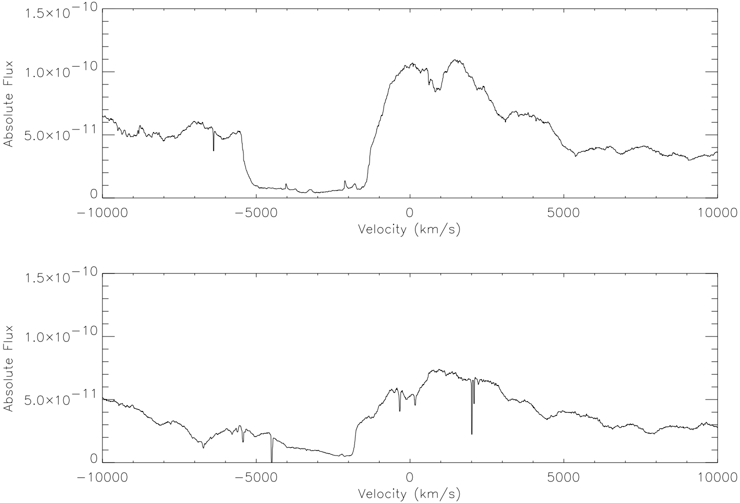
Broad absorption features and their development

V1974 Cyg: Si IV, C IV during the transition stage



Broad absorption features

V382 Vel: Si IV, C IV at a similar stage

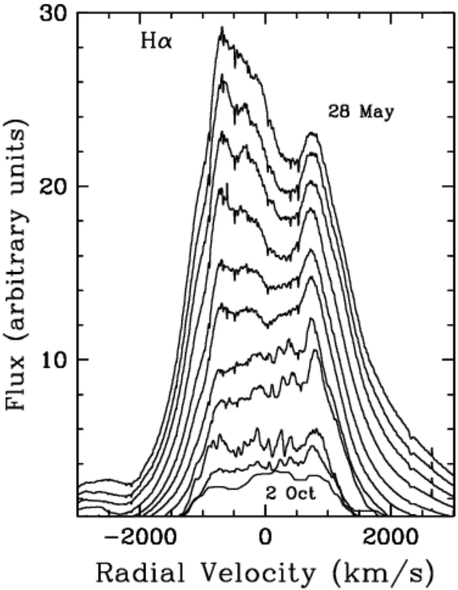


Allora ha parlato Payne-Gaposchkin

"If the bright line profiles of novae are to be interpreted in terms of Doppler effect, the observations suggest that we explore the possibility that there are departures from spherical symmetry in the emissivity. Such departures might stem from differences in mass density in different parts of the envelope, as pictured by Menzel & Payne (1933), or as differences in excitation as suggested by Grotrian (1937). Both these causes will in fact be found to be at work, but their discussion involved physical as well as geometrical considerations."
Payne-Gaposchkin 1957, *The Galactic Novae*, p. 61 (the section on spectra of novae)

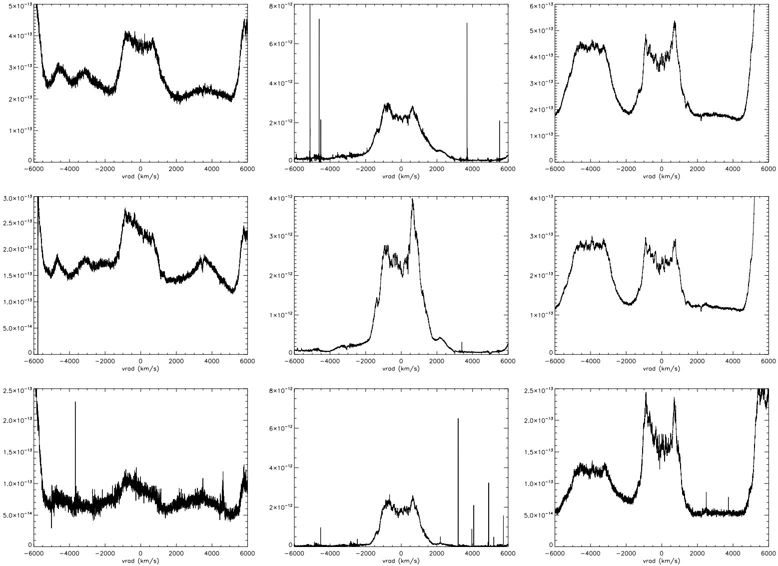
Systematic variations in profiles

V382 Vel Balmer line sequence: Della Valle et al. (2002, A&A)

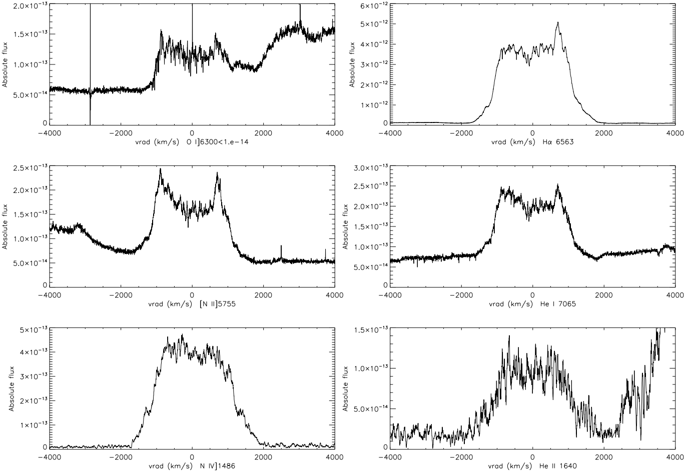


Time dependence of line profiles

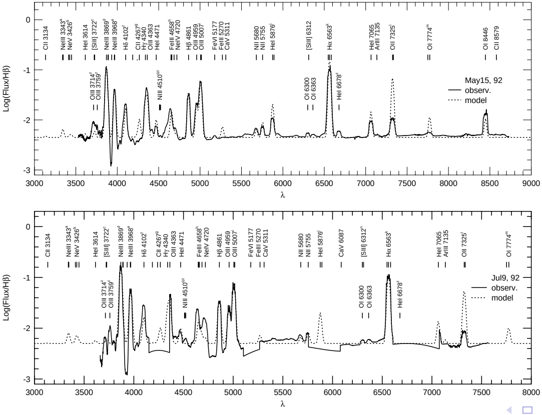
Nova Mon 2012: He I 4471Å, [Ne III] 3869Å, [N II] 5577Å between 2012 Sept. - Dec.



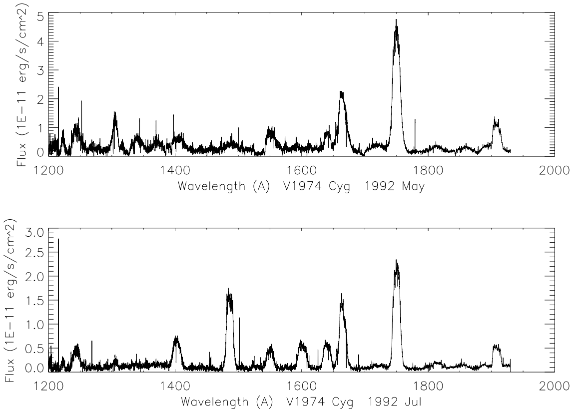
Nova Mon 2012 optical, UV comparative profiles



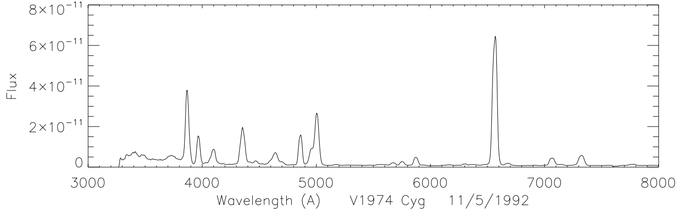
V1974 Cyg : Optical spectrum, onset nebular Moro-Martín et al. (2001)

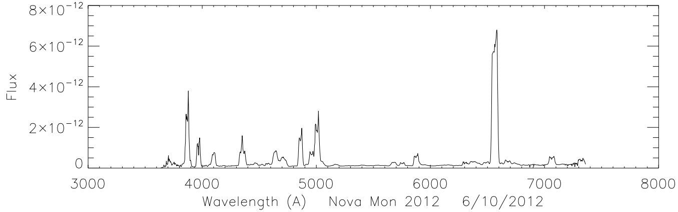


V1974 Cyg: 1200-2000Å spectrum, onset nebular stage

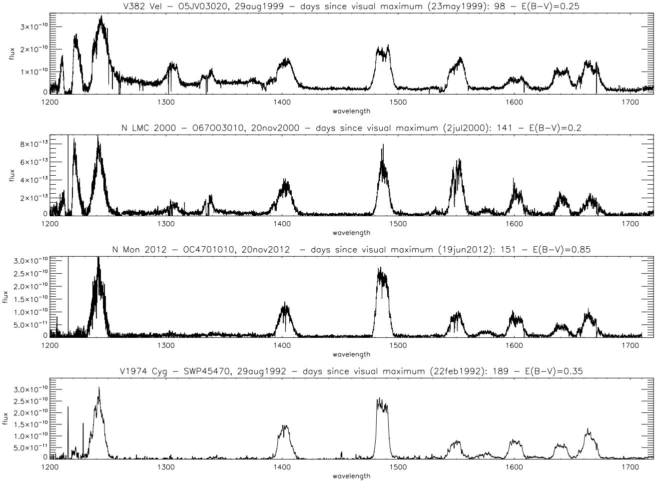


ONe novae: V1974 Cyg (day 93) and Nova Mon 2012 (day 106) optical

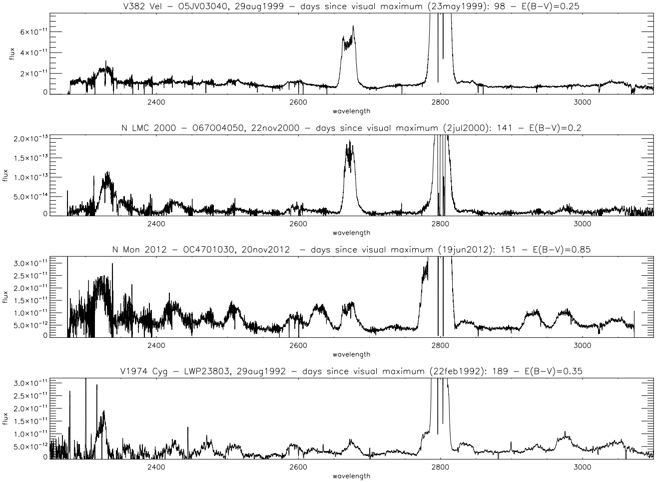




The Fabulous Four: 1200-2000Å spectrum, nebular stage



The Fabulous Four: 2000-3100Å spectrum, nebular stage



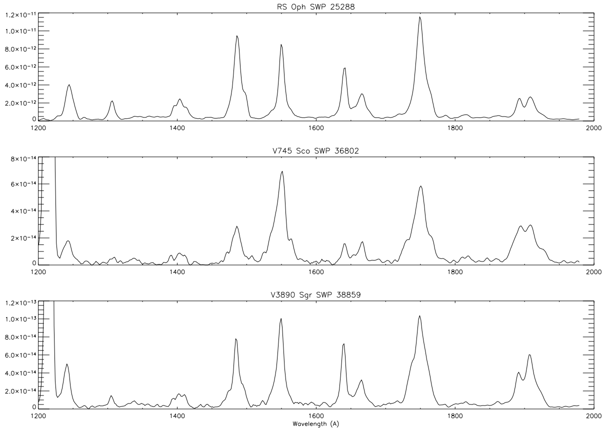
V382 Vel – 05JV03040, 29aug1999 – days since visual maximum (23may1999): 98 – E(B–V)=0.25

N LMC 2000 – 067004050, 22nov2000 – days since visual maximum (2jul2000): 141 – E(B–V)=0.2

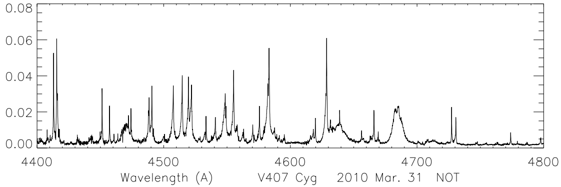
N Mon 2012 – 0C4701030, 20nov2012 – days since visual maximum (19jun2012): 151 – E(B–V)=0.85

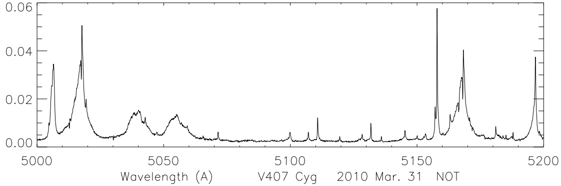
V1974 Cyg – LWP23803, 29aug1992 – days since visual maximum (22feb1992): 189 – E(B–V)=0.35

Symbiotic-like recurrent novae 1200-2000Å spectrum



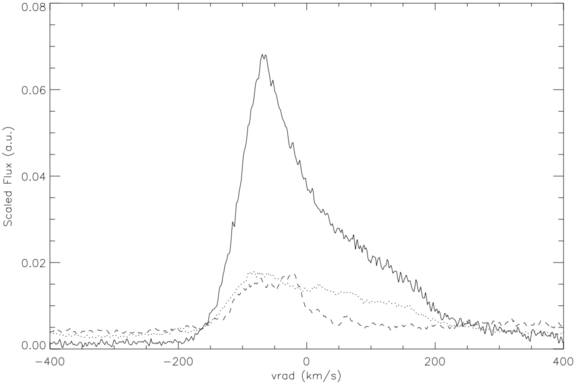
V407 Cyg, optical spectrum near start of the event, two sample intervals





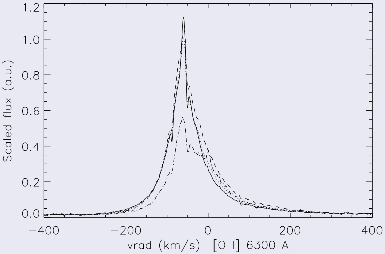
Dynamical tracer of the shock expansion

V407 Cyg [Ca V]; He II 4686Å showing the shock front

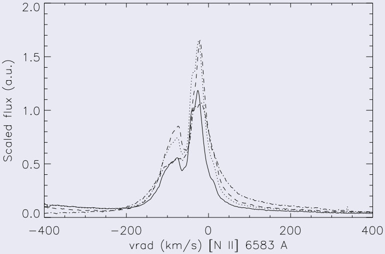


Late environmental response: V407 Cyg 2010-2011

[O I] 6300Å development in the later spectra

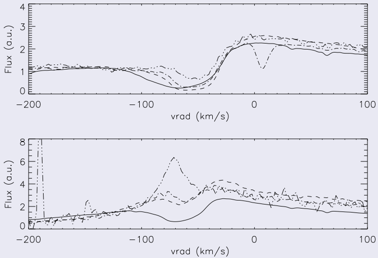


[N II] development at the same time

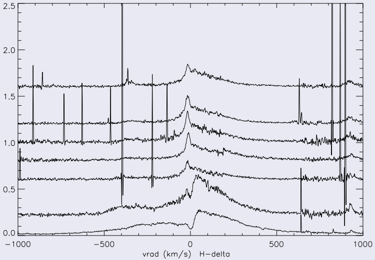


V407 Cyg 2010: environmental (wind and more) Balmer line variations

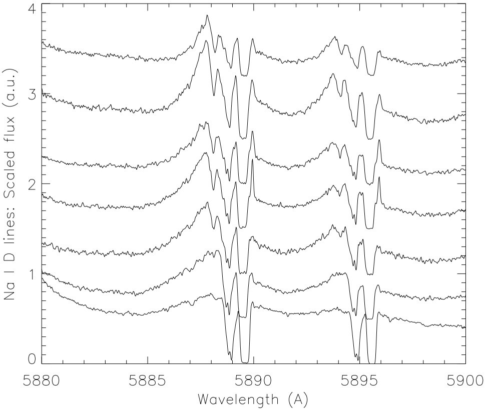
Balmer line variations: local (wind) absorption, H*alpha* - Hδ for two different stages of outburst



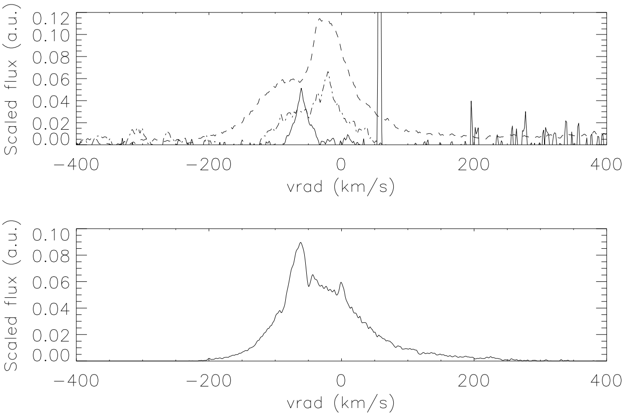
Hδ sequence, note the transition from absorption to emission (time from bottom)



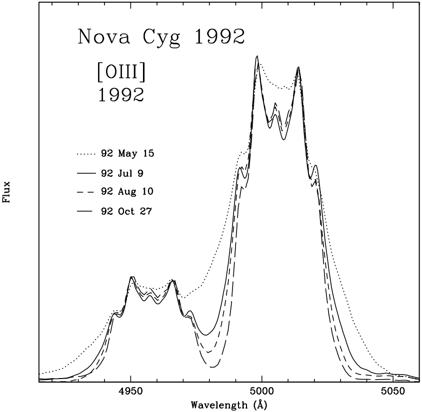
V407 Cyg: Na I D line sequence; two contributing factors - wind and environment and the SN Ia/GRB connection?

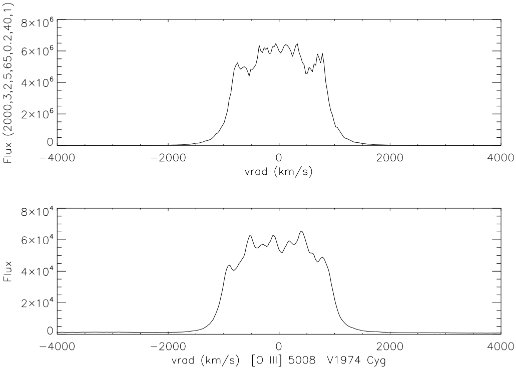


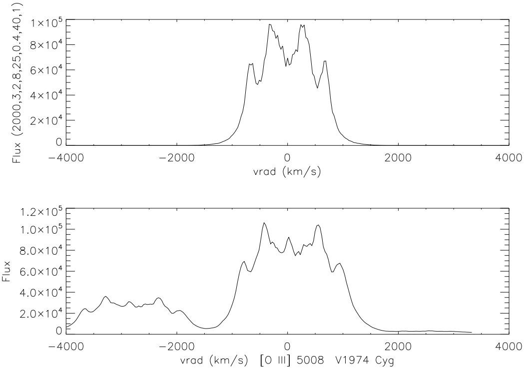
V407 Cyg: contributors to the composite line profiles



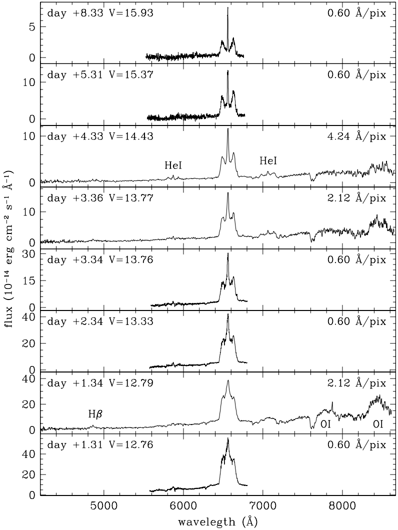
Fine structure and filling factors: V1974 Cyg: Line structure: [O III] in early transition and nebular stage, V1974 Cyg, Moro-Martín et al. (2001)




Flux (2000,3,2,5,65,0.2,40,1)
8×10^6
6×10^6
4×10^6
2×10^6
0
−4000
−2000
0
2000
4000
vrad (km/s)
Flux
8×10^4
6×10^4
4×10^4
2×10^4
0
−4000
−2000
0
2000
4000
vrad (km/s) [O III] 5008 V1974 Cyg

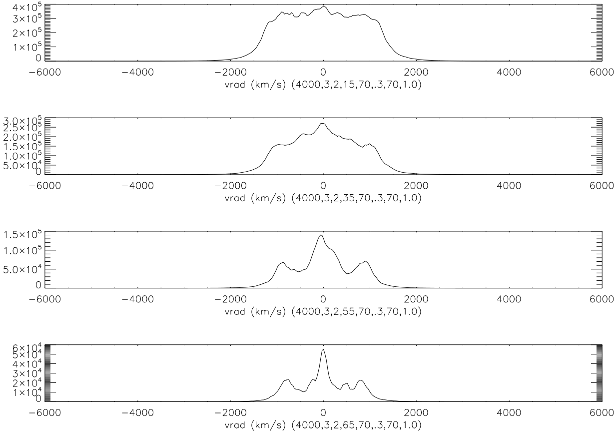

Flux (2000,3,2,8,25,0.4,40,1)
1×10^5
8×10^4
6×10^4
4×10^4
2×10^4
0
−4000
−2000
0
2000
4000
vrad (km/s)
Flux
1.2×10^5
1.0×10^5
8.0×10^4
6.0×10^4
4.0×10^4
2.0×10^4
0
−4000
−2000
0
2000
4000
vrad (km/s) [O III] 5008 V1974 Cyg

Line profile time development: V2672 Oph, Munari et al. (2010)



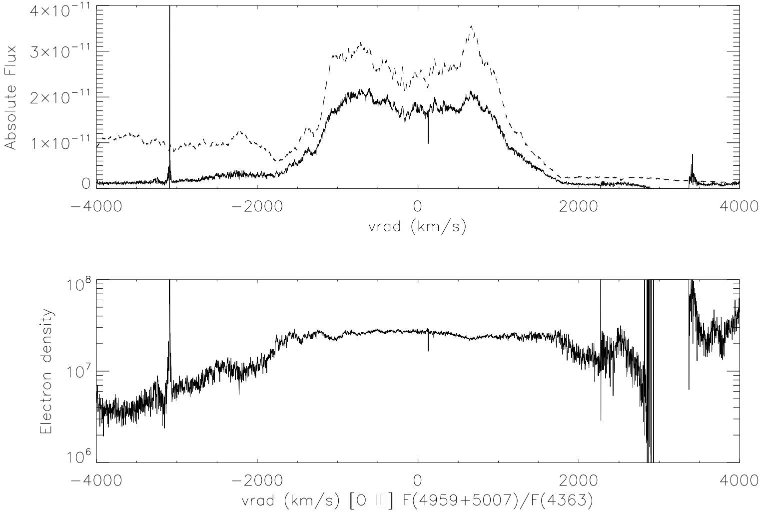
Line profile time development

Simulations: V2672 Oph – compare with Munari et al. (2010)



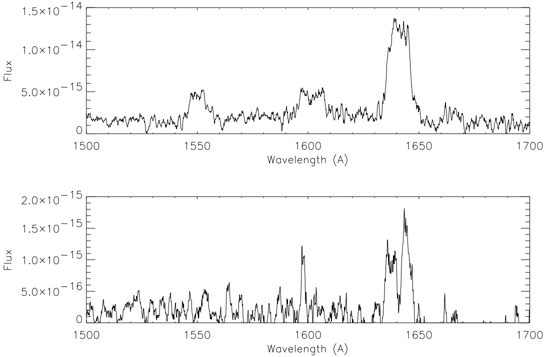
Plasma diagnostics: spatial inhomogeneities

Nova Mon 2012, n_e from [O III] 2012 Nov. 21



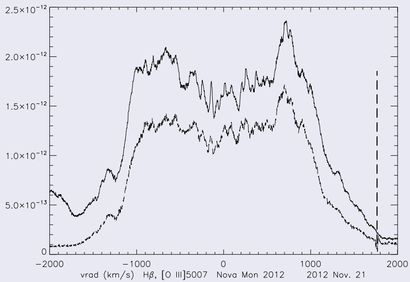
Inhomogeneities and structure - An old but now significant observation

V1974 Cyg: large vs. small aperture, 1995 (GHRS)

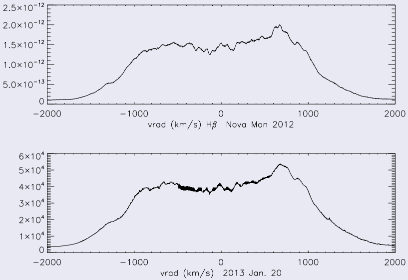


The fine structures (a.k.a. knots and filaments)

Nova Mon 2012: Forbidden (dash) vs. recombination permitted (solid) transitions

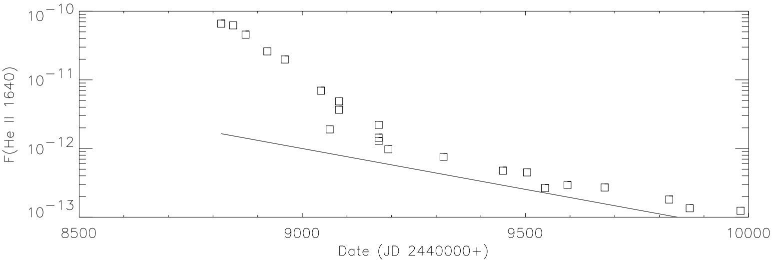


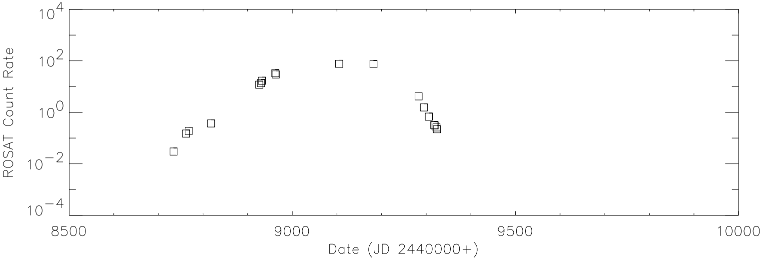
Persistence (Nova Mon 2012: 2012 Sep. - 2013 mid-Jan)

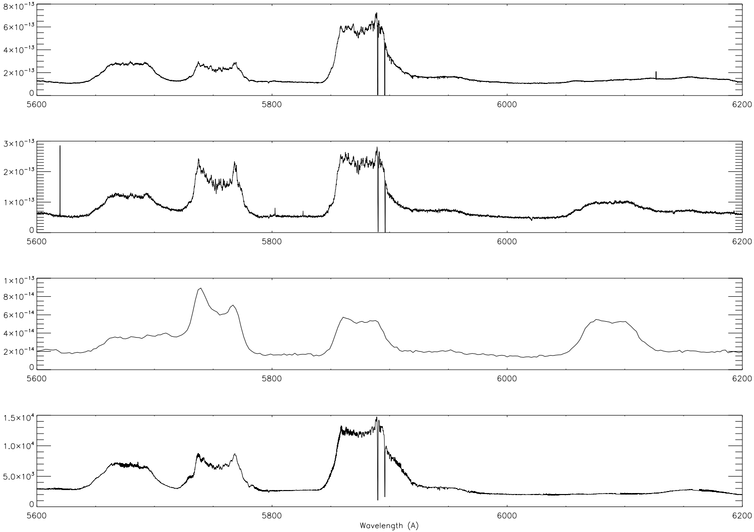


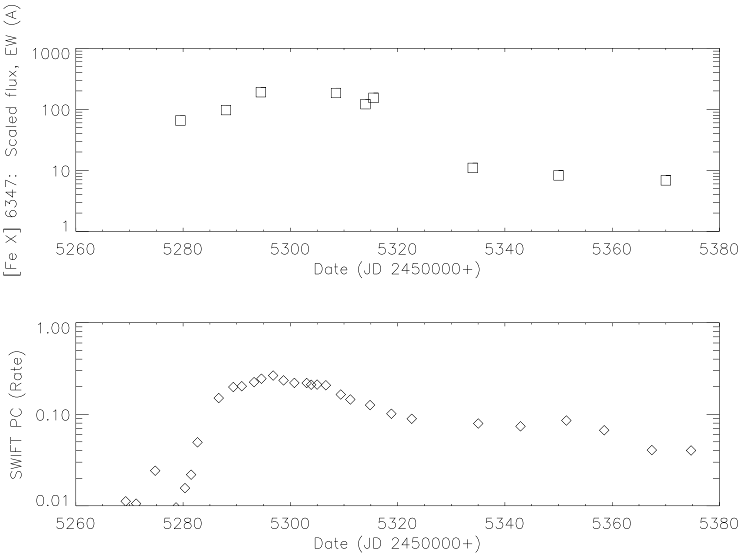
Plasma diagnostics: time dependence

V1974 Cyg: He II 1640Å and ROSAT XR variations






8×10⁻¹³
6×10⁻¹³
4×10⁻¹³
2×10⁻¹³
0
5600
5800
6000
6200
3×10⁻¹³
2×10⁻¹³
1×10⁻¹³
0
5600
5800
6000
6200
1×10⁻¹³
8×10⁻¹⁴
6×10⁻¹⁴
4×10⁻¹⁴
2×10⁻¹⁴
0
5600
5800
6000
6200
1.5×10⁴
1.0×10⁴
5.0×10³
0
5600
5800
6000
6200
Wavelength (A)


[Fe X] 6347: Scaled flux, EW (A)
1000
100
10
1
5260
5280
5300
5320
5340
5360
5380
Date (JD 2450000+)
SWIFT PC (Rate)
1.00
0.10
0.01
5260
5280
5300
5320
5340
5360
5380
Date (JD 2450000+)

Some questions

- Why, if the ejecta aren't spherical, is there (apparently) a *bolometrically constant* stage? What sets the covering factor for the highly inclined systems?
- What is the origin of the fine structure? What determines the filling factor of the fragmentation?
- What is the origin of the bipolar symmetry?
- What mixes the ejecta? Is there a signature in the ejecta?
- Is there a wind at *any* stage of the outburst?
- Are there feedback effects from the companion (is it just the proverbial "innocent bystander" who happens to witness the crime)?

Some unbridled speculation (it's a conference, right?)

- Are there *any* standard candles?
- Is the boundary layer as simple as we want it to be?
- Is the MMRD relation related to ejecta geometry and orientation?
- Is there a pulsational (shell flash) instability possibly due to sporadic re-start of accretion?
- Do magnetic fields control the initiation of the explosion (is this the mechanism for the pile-up)?

“Last scene of all, that ends this strange, eventful history, is second
childishness and mere oblivion,
sans tooth, *sans* eyes, *sans* taste,
sans everything.”
Shakespeare, W. (1600, *As You Like It* Act II, Sc. 7)