Spectroscopic & Photometric Development of T Pyxidis (2011) from 0.8 to 250 Days after Discovery

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Brief Introduction to T Pyx

- Shortest P_{orb} recurrent nova (~$0^d.076$ or $1^h.824$)
- high
- Unusual luminous RN (MS+WD) at quiescence
  - $M_{WD}=1.25\text{-}1.4M_{sun}$ (Selvelli et al. 2010)
  - $M_{WD}=0.7\pm0.2M_{sun}$ (Uthas et al. 2010)
- low i=10 ° - 15° (Uthas et al. 2010, Chesneau et al. 2011)
- 6 previous recorded outbursts
  - 1890, 1902, 1920, 1944, 1966/1967, and 2011
- Extensive nova shell associated with previous outbursts.

T Pyx outburst in 2011

V=13.0 on 2011 Apr 14.27 (JD 2455665.7931, *t*=0 d)

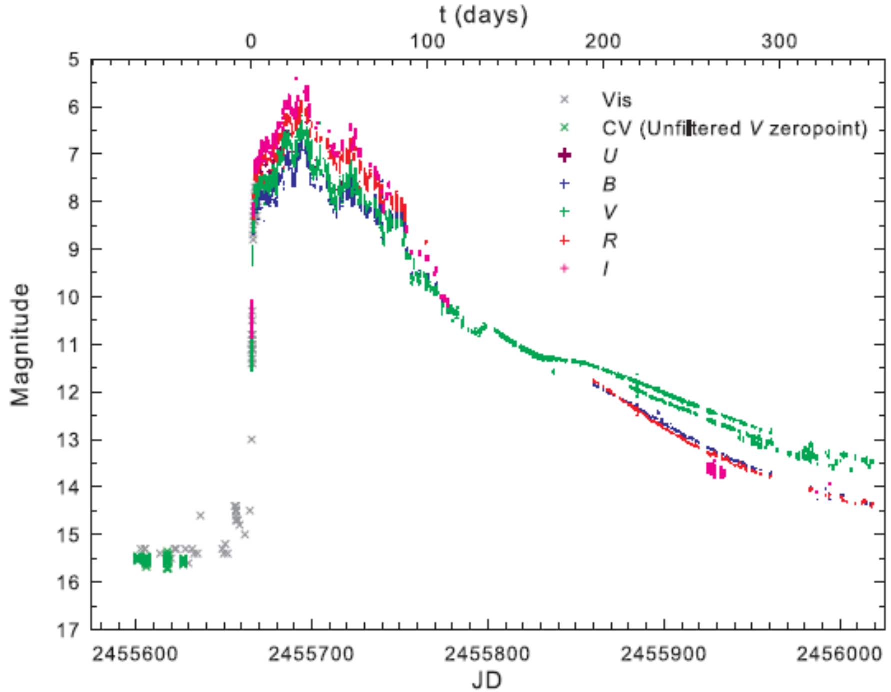
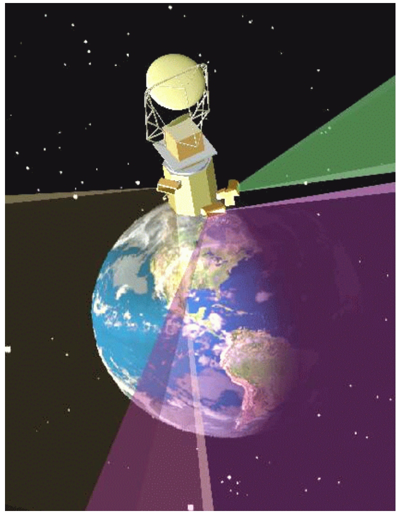


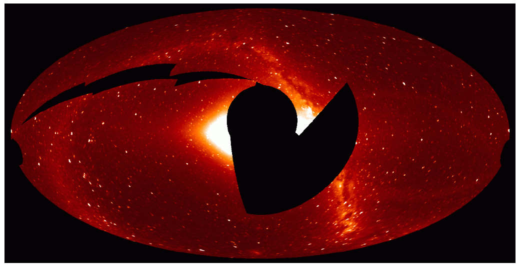
Figure 1.1: The AAVSO optical light curves of T Pyx in its 2011 outburst

Photometric observations from SMEI

- <u>Solar Mass Ejection Imager (SMEI)</u>
  - all-sky, white-light CCD-based camera system.
  - observing the inner heliosphere from Earth orbit
  - on board the U.S. Air Force *Coriolis* spacecraft
  - 840 km Sun-synchronous orbit on 6th January 2003 (Hick et al. 2005)
  - ceased operation in September 2011

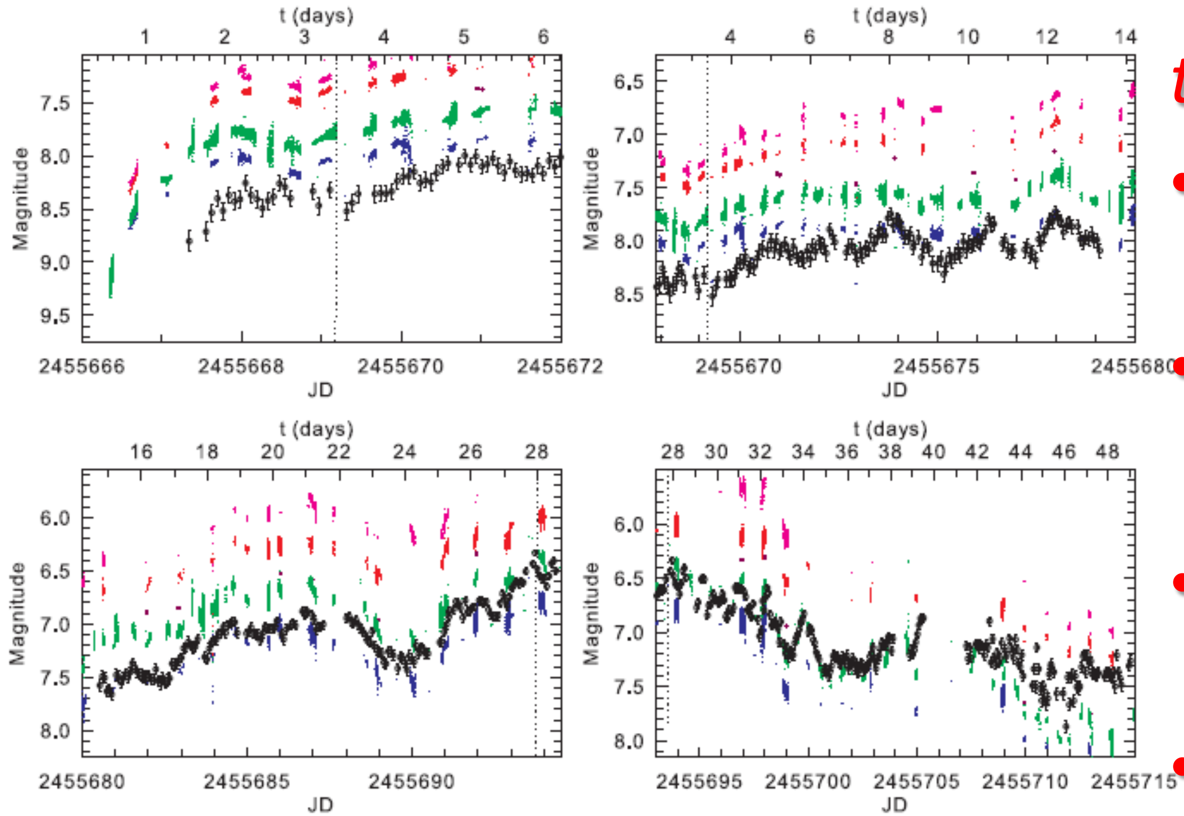


- SMEI consists of 3 CCD cameras
  - 60°x3° field of view each
  - 4-second exposures every 102 minutes.
  - peak quantum efficient at ~700 nm and FWHM ~300 nm.
  - detect brightness changes in point sources down to m_{SMEI}~8.



- **SMEI high-cadence observations can investigate bright nova explosions (m_{SMEI}<8) during 2003-2011 and produce extremely detailed light curves.**

Light curve from SMEI



t=1.5-49.0 d

- Initial rise

  (t=1.5-3.3 d)

- Plateau (halt ?)

  (t=3.3-13.3 d)

- Final rise

  (t=14.7-27.9 d)

- Early decline

  (t=27.9-90.0 d)

Figure 1.3: Four idealised phases of the SMEI light curves including the initial rise (top left), the pre-maximum halt (top right), the final rise (bottom left), and the early decline (bottom right). Vertical dotted lines separate each phase of the light curve.

Light curve from SMEI

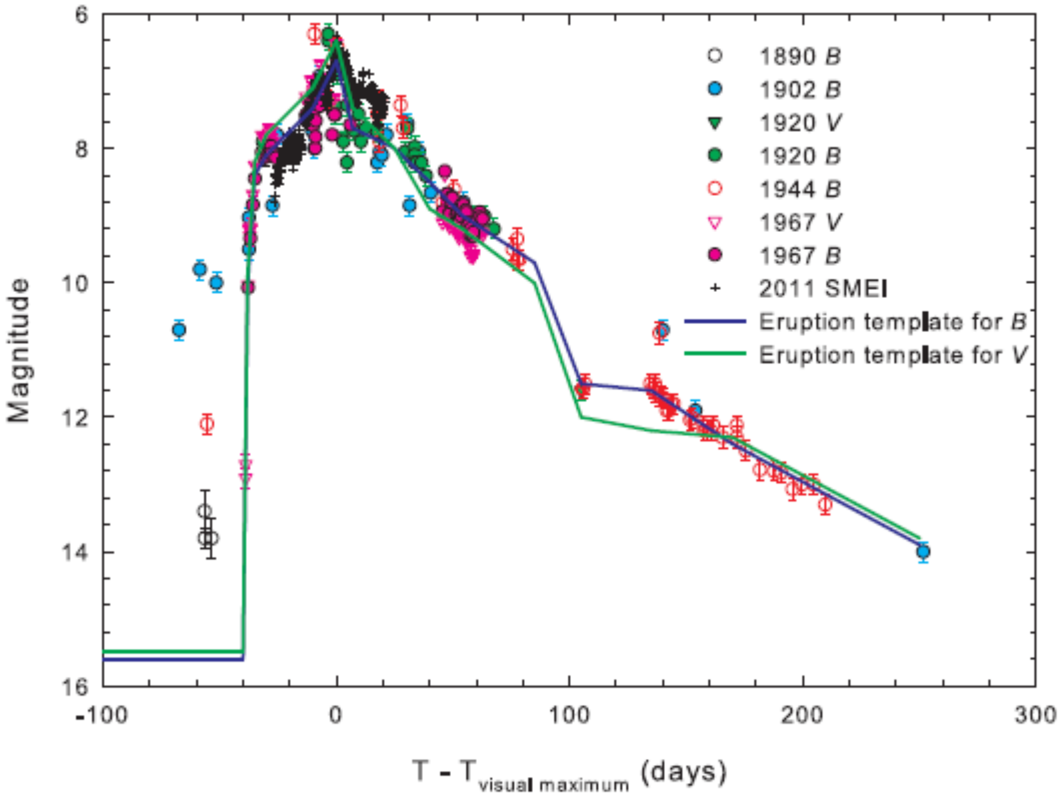


Figure 1.4: The outburst in 2011 from SMEI (plus signs) compared to the previous outbursts. The *B* (circles) and *V* (triangles) observations are highlighted in different colours to represent each year of outburst (1890:open black, 1902:blue, 1920:green, 1944:open red, 1967:pink). Data for the previous outbursts are taken from Schaefer (2010).

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Light curve from SMEI

Early time periodicity and possible cause – precession of disk?

by using *PERIOD04*

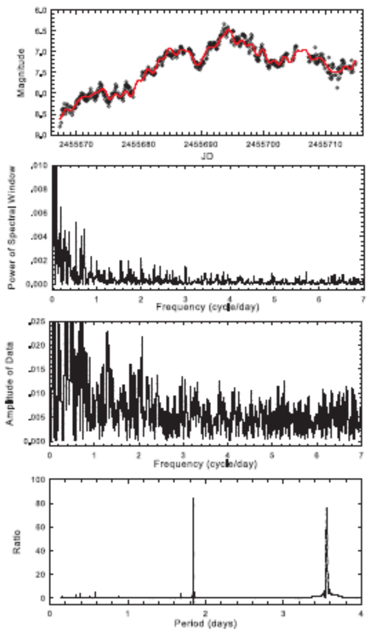


Figure 1.5: Period found by analysing the SMEI light curve from the beginning to the last observation. The observation points were fitted (top) and yielded the ratio of the spectral window (below) over the observational data (middle) which gives us the possible periods (bottom).

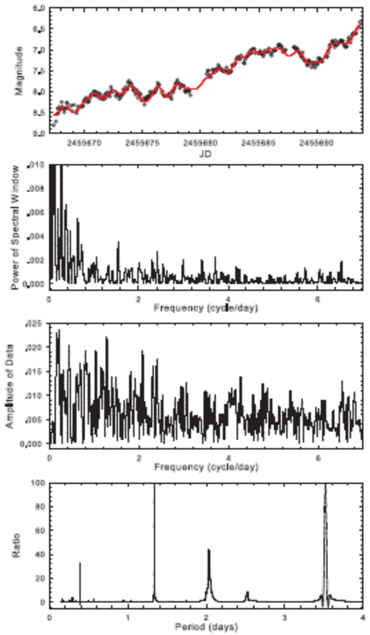


Figure 1.6: As Figure 1.5 but from the the beginning to visual maximum.

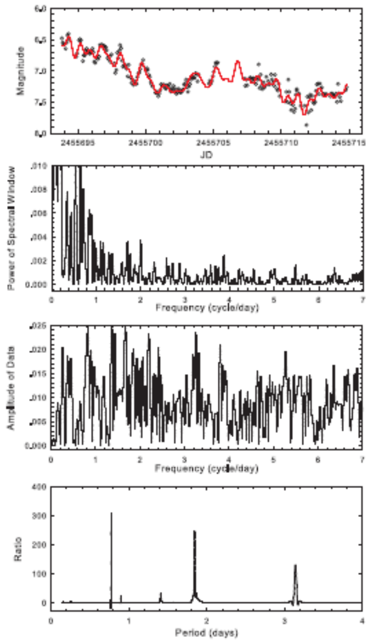


Figure 1.7: As Figure 1.5 but from the visual maximum to the last observation.

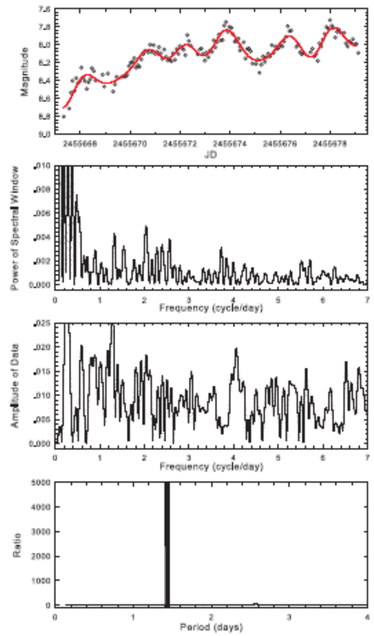


Figure 1.8: As Figure 1.5 but from the beginning to the end of the plateau phase.

Table 1.3: Results from *PERIOD04*

Cases	Parts in light curve	t (days)	Most prominent period (days)
(a)	first observation - last observation	1.5-49.0	1.8±0.4, 3.2±0.9
(b)	first observation - visual maximum	1.5-27.9	3.5±0.05, 1.3±1
(c)	visual maximum - last observation	13.4-49.0	0.7±6, 1.8±9
(d)	first observation - end of plateau	1.5-27.9	1.44±0.04

$P_{orb}/P_{precession}$ =5.3% corresponding to q~0.125-0.15

Hirose& Osaki (1990)

Spectroscopic observations from SMARTS and LT

- Small and Moderate Aperture Research Telescope System (SMARTS) *t*= 0.8 – 80, 155-250 d
  - 1.5m at CTIO + long-slit R-C spectrograph
  - Obtained 99 (300<R<3400) optical spectra
    - 49 moderate-res. in blue
    - 37 moderate-res. in red
    - 13 low-res. in a wide wavelength
- Liverpool Telescope (LT) *t* = 8.6-11.6 d
  - Fully robotic 2m at La Palma + FRODOSpec
  - Obtained 8 optical spectra
    - 4 in blue (R~2200)
    - 4 in red (R~2600)

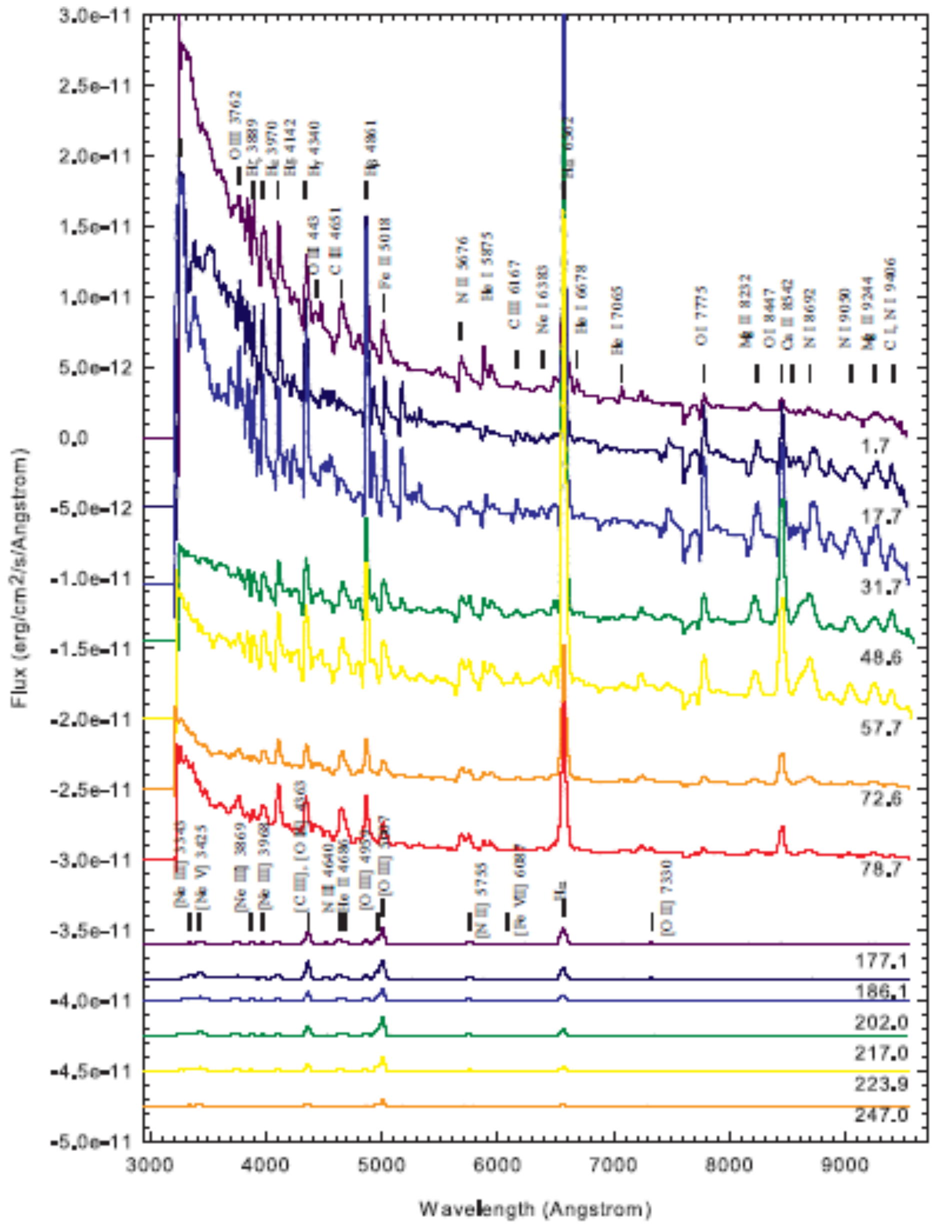
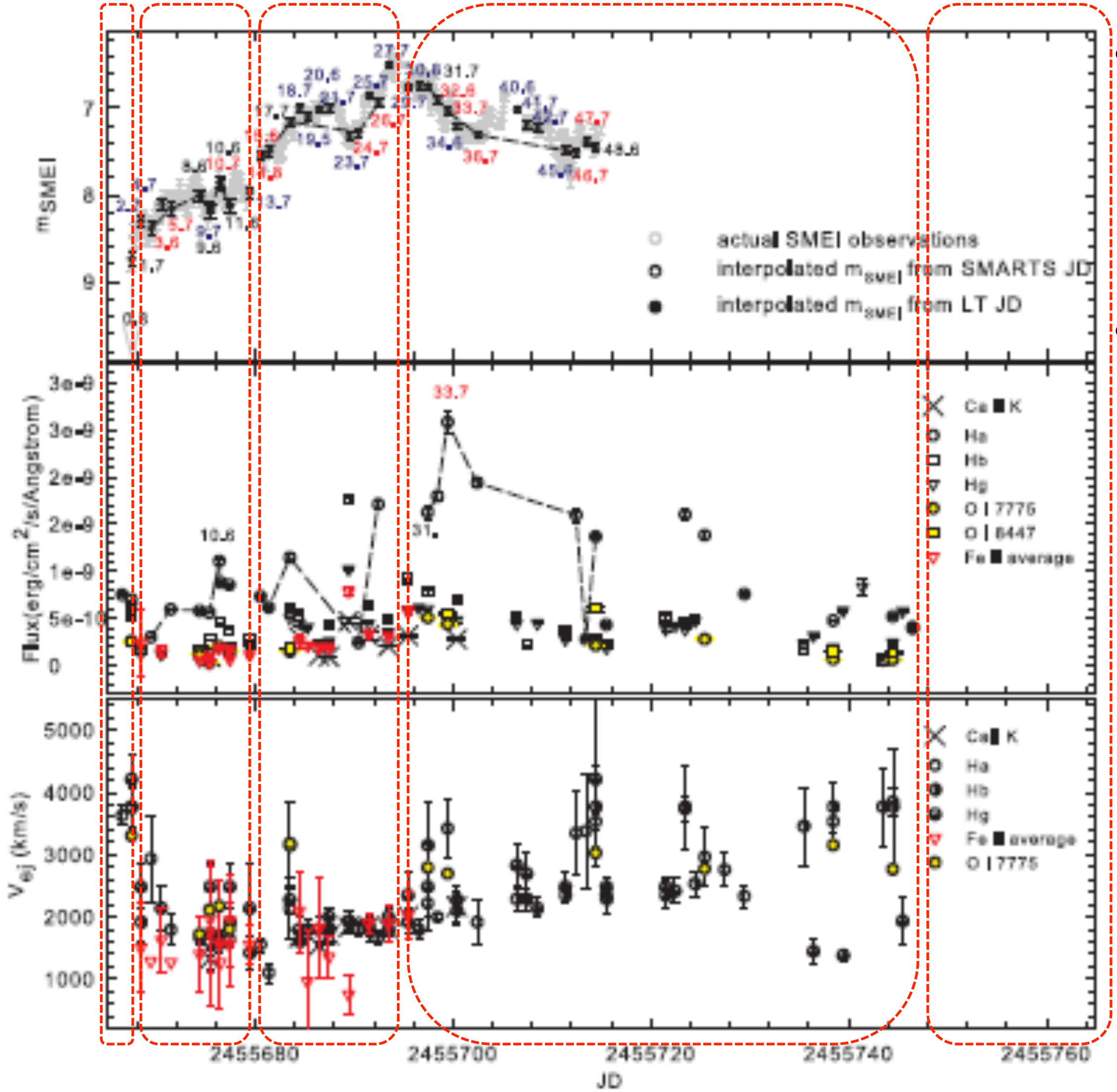


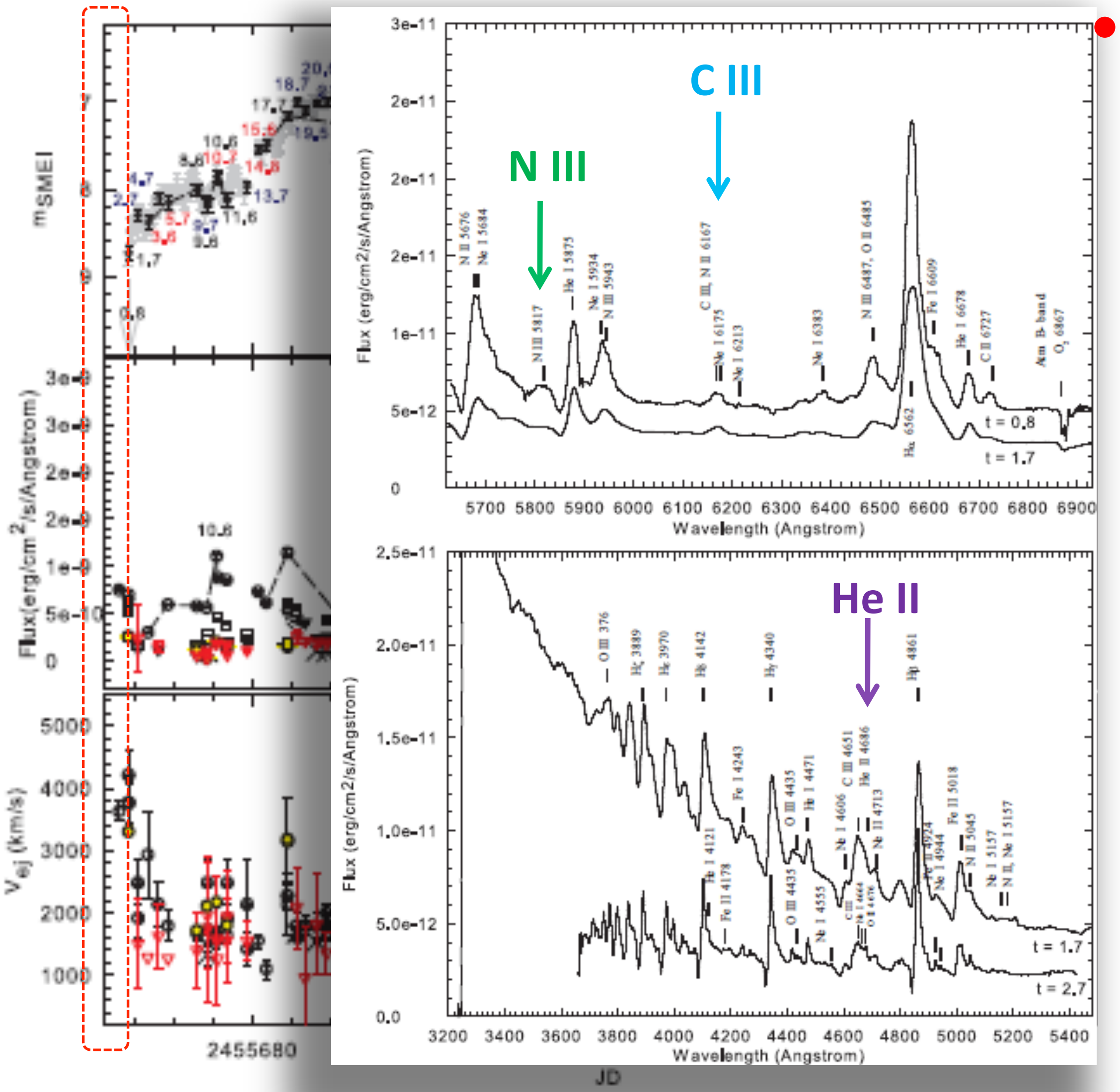
Figure 1.11: Low-resolution spectra of T Pyx taken from t=1.7-247 days.

Spectra from SMARTS and LT



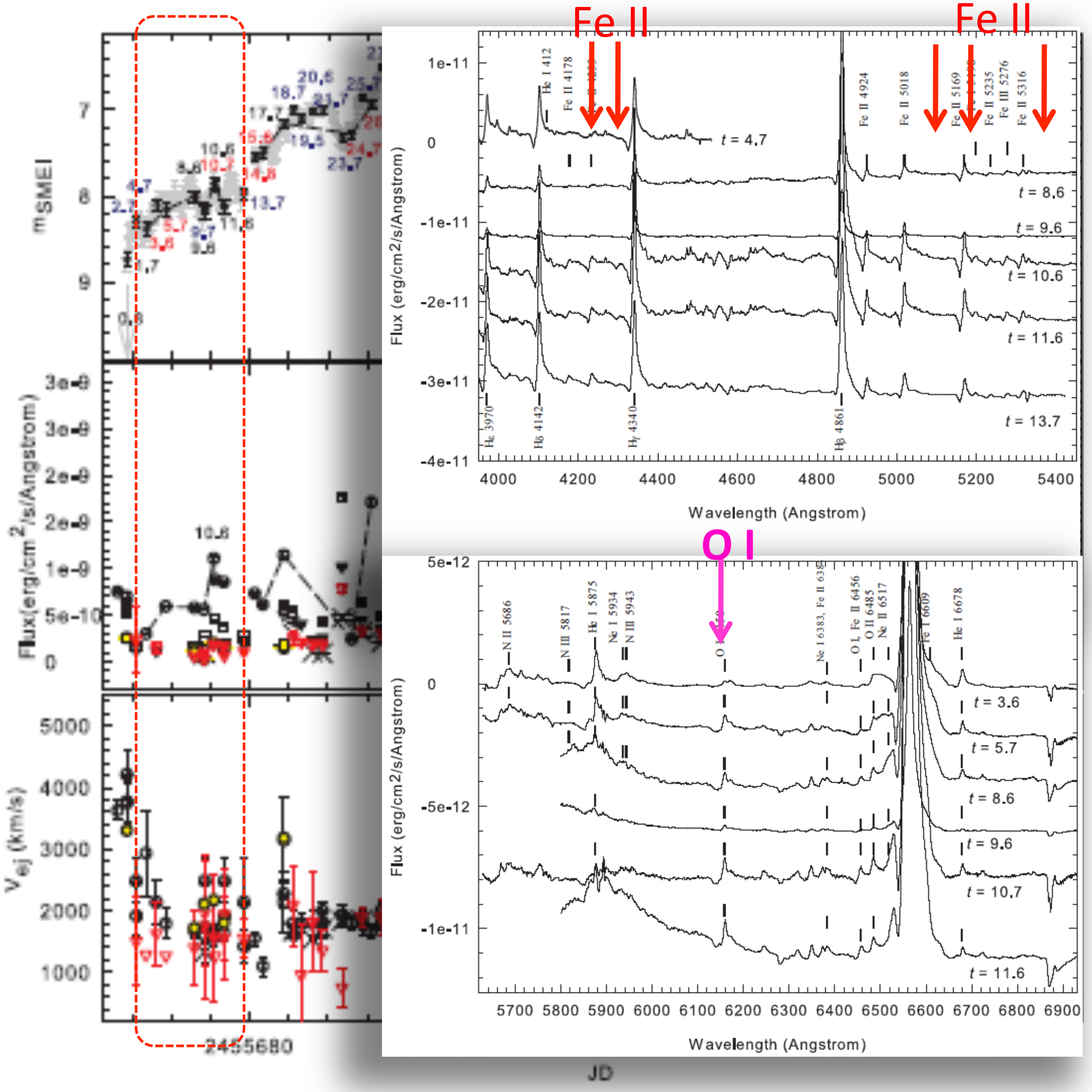
- Measured Flux and derived implied V_{ej} (from P Cygni profile)
- 5 light curve phases:
  - Initial rise (t=0.8-3.3 d)
  - Plateau (t=3.6-13.7 d)
  - Final rise (t=14.7-27.9 d)
  - Early decline (t=27.9-90 d)
  - Transition phase (t=90-250d)

Spectral evolution



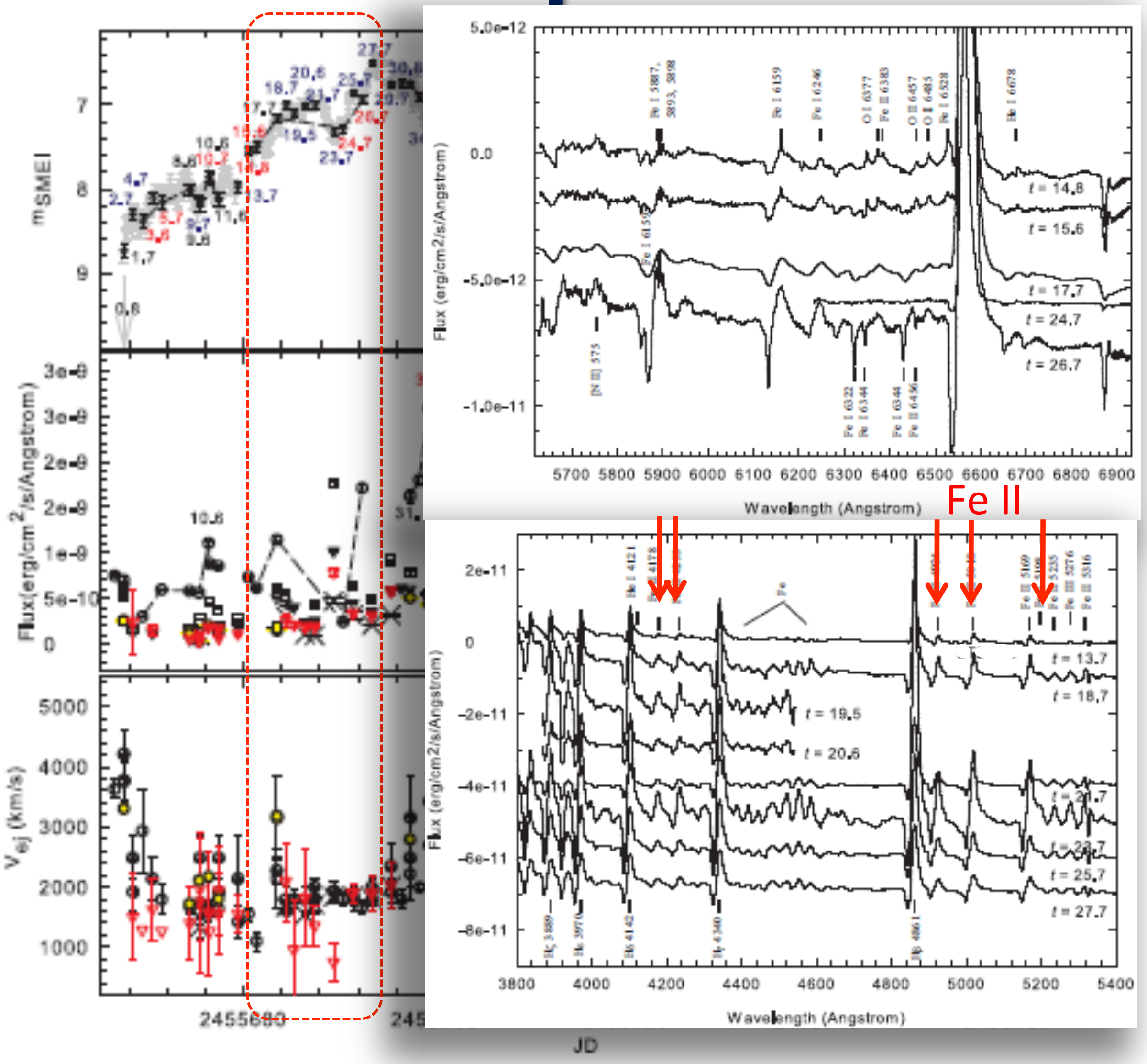
- **Initial rise** (t=0.8-3.3 d)
  - High ionization (He II, C III, N III)
  - 'fireball' stage
  - Brightness comes almost entirely from continuum.
  - Marked drop V_{ej} (eg. DQ Her, LMC 91) 4000 -2000 km/s (t=0.8-2.7)
  - If initial ejection is a Hubble flow → see high apparent V_{ej} initially
    - i.e. mass loss rate may decrease.
    - Comparible with HVFs in Type Ia SNe? (Interaction of initial highest velocity ejecta with circumstellar envelope)
  - Suggest 2 different stages of mass loss.
    - a short-lived phase immediately after outburst
    - a more steadily evolving and higher mass loss phase

Spectral evolution



- **Plateau** (t=3.6-13.7d)
  - Fe II & O I increase in intensity
    (Spectral type change B to A)
  - iron curtain begins at t=8.6 d
  - Light curve variation seems consistent with line strengths of Hα, Hβ, Hγ, Fe II.
  - Derived V_{ej} decreases and starts to be stable at ~1500 km/s during this halt.

Spectral evolution

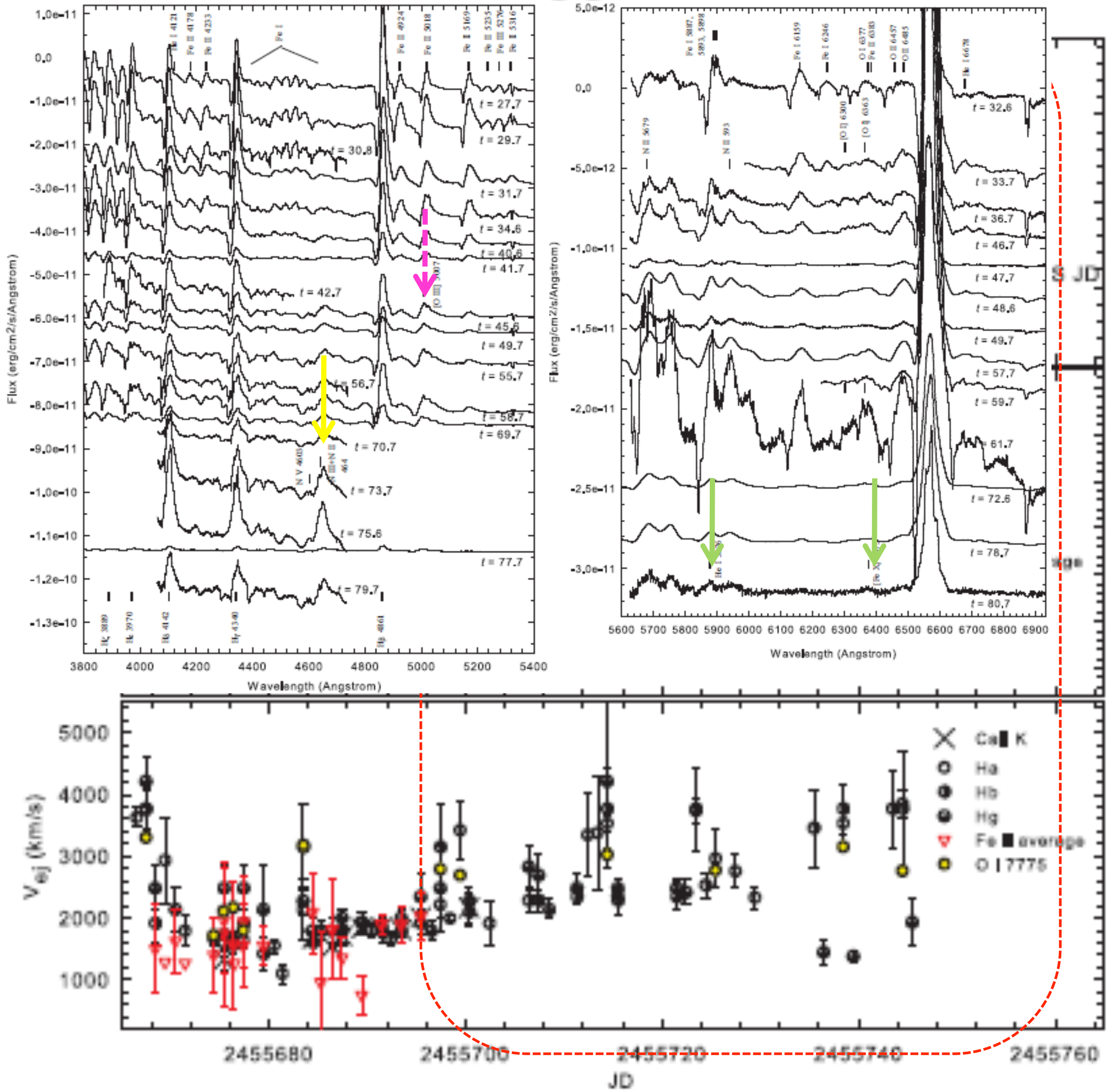


- Final rise (t=14.7-27.9d)
  - O I flash begins at t~17 d.
  - Principal spectrum apparent

    (Iron curtain still persists.)
  - major dip at t=23.7 d due to Hα flux.
  - Visual max at t=27.9 d
  - Gradual increase in V_{ej}
  - i.e. relative size of pseudo-photosphere to the ejecta was shrinking revealing higher velocity material.

Spectral evolution

- Early decline (t=27.9-90 d)
  - Principal spectrum persists until t ≤ 48 d
  - Balmer lines began double-peak structure at t=42.7 d
  - forbidden lines, eg. [O III] at t=45.6 d
  - Orion spectrum at t~70 d (N III+ N II 4640 emission)
  - Weak He I 5876 , [Fe X] 6375 marginally deteced at t~80 d
  - Pseudo-photosphere is shrinking and T_{eff} is increasing.
  - Ultimately the envelope is optically thin.



Spectral evolution

- Transition phase (t=90-250 d)
  - SSS revealed at t=111 d.
  - Nebular spectrum is apparent.

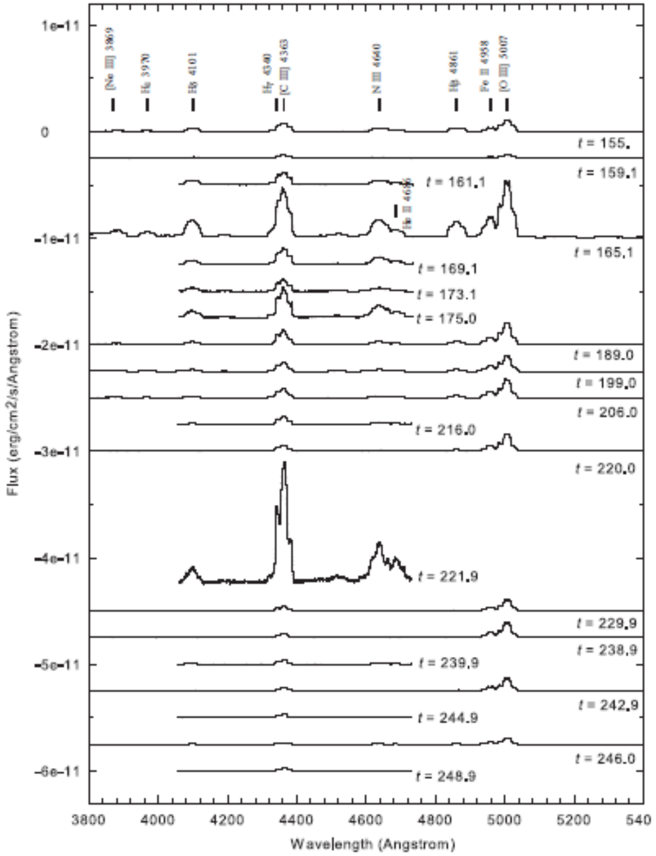


Figure 1.20: The blue spectra during the transition phase.

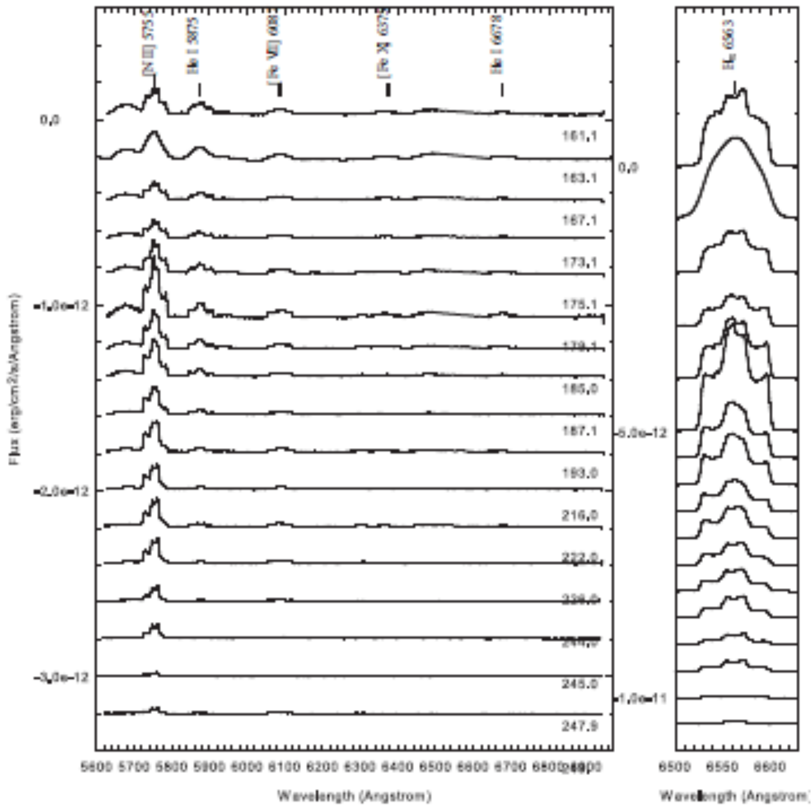


Figure 1.21: The red spectra during the transition phase.

The simple pseudo-photosphere model

- Properties of a nova spectrum are expected to be similar at the same magnitude below peak (ΔV) (Bath & Harkness, 1989)
- We found the detected ionized elements agree well with those expected at the same ΔV.

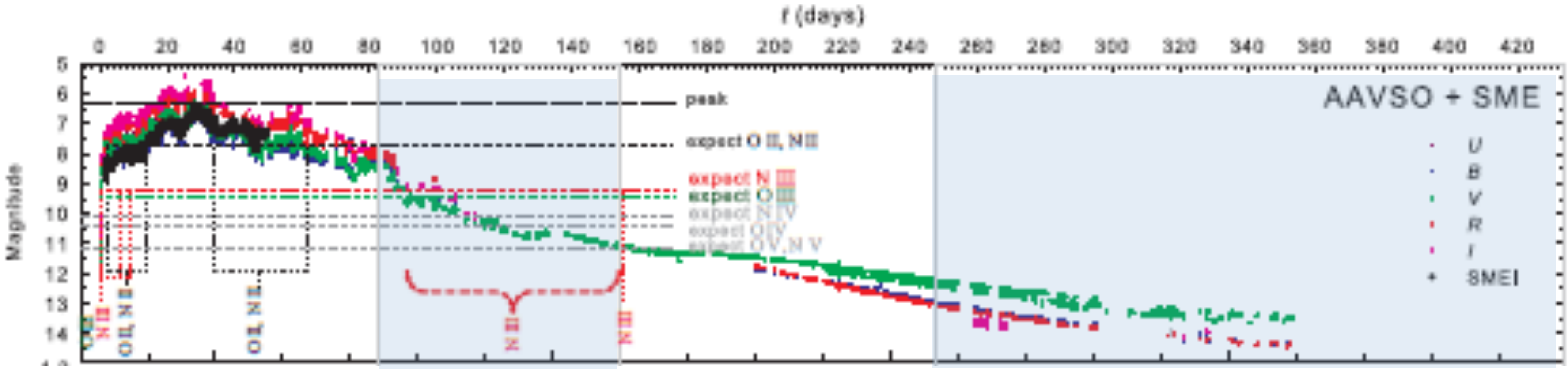


Table 1.5: Ionization levels at various decline stages according to Bath and Harkness (1989).

ΔV	V	Element ionization level	t (days)	T_{eff} (K)
1.45	7.78	O II	2.7, 3.6-13.6, 33.7-61.7	30000
1.55	7.88	N II	2.7, 3.6-10.7, 36.7-80.8	33000
2.85	9.18	N III	0.8-2.7, 5.7, 8.6, 155.1-221.9	110000
3.15	9.48	O III	0.8-1.7, ([O III] began at 45.6)	145000
3.75	10.08	N IV	not detected	253000
4.10	10.43	O IV	not detected	350000
4.85	11.18	O V, N V	not detected	700000

Comparison to X-ray and Radio Light Curves

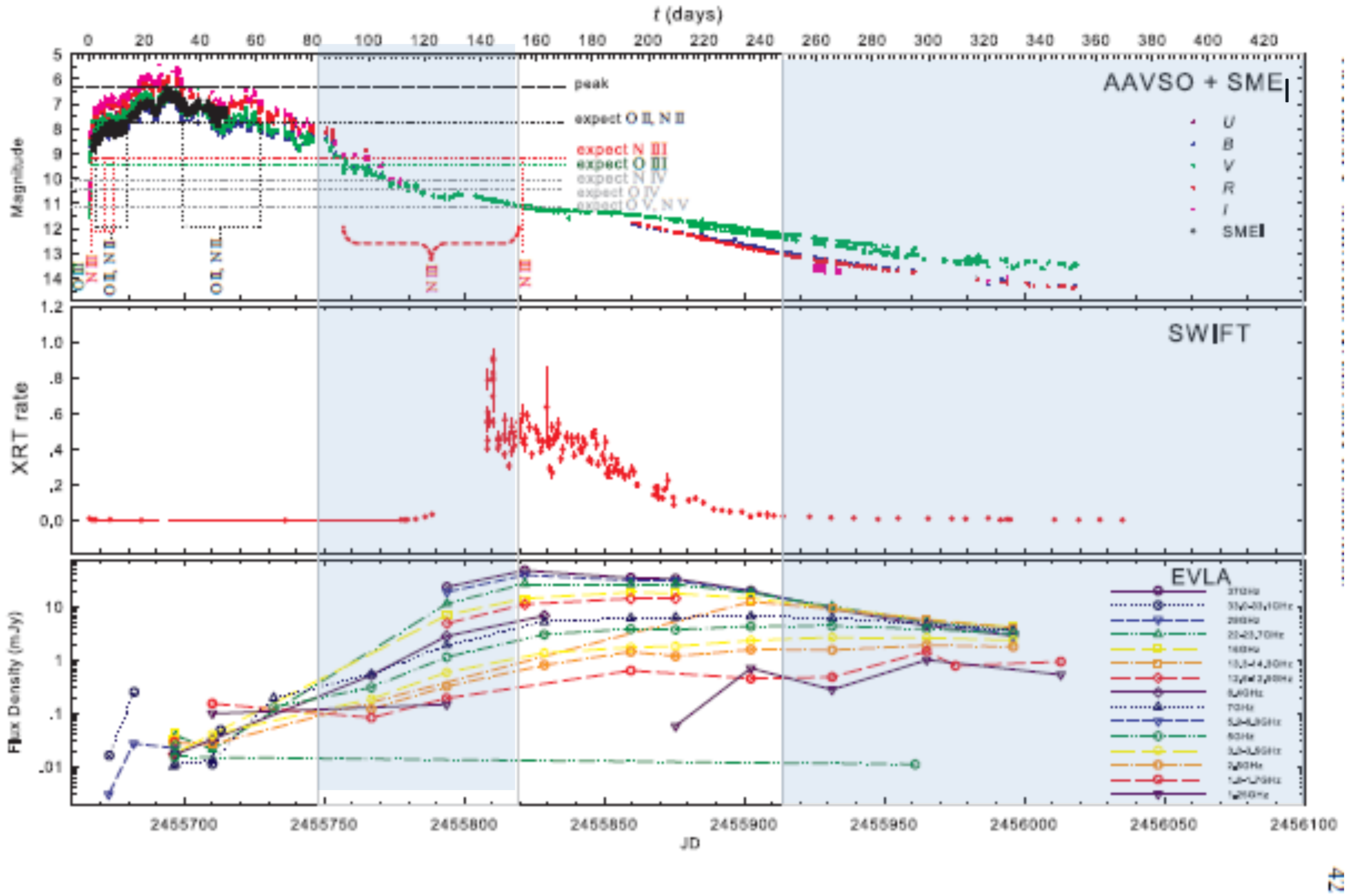


Figure 1.22: Comparison between optical, radio and X-ray light curves.

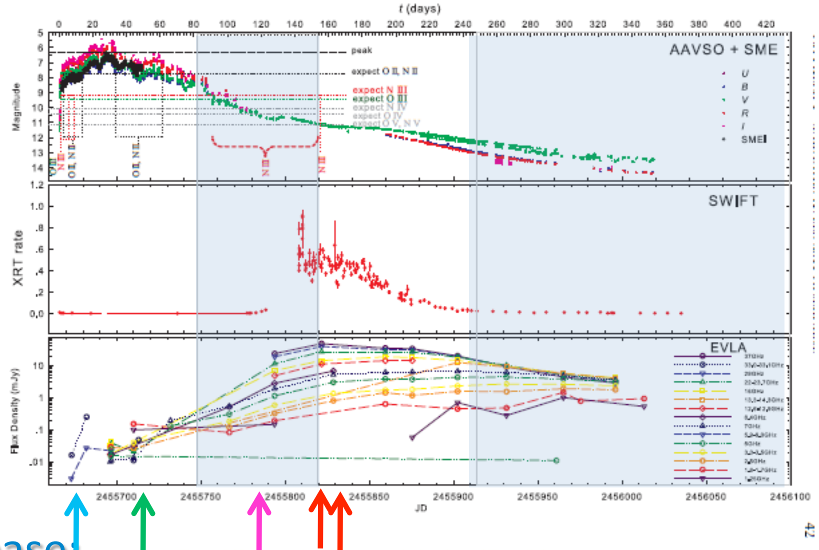


Figure 1.22: Comparison between optical, radio and X-ray light curves.

- During plateau phase:
  - ➢ The rise of high frequency radio emission (37 GHz) at t=7-15 d.
- During Early decline:
  - ➢ Radio emission rose steeply (where [O III] 5007 was first present at t~45 days)
- SSS began at t=111 and peaked at t=144 d.
  - ➢ Consistent with appearance of [Fe X] 6375 found marginally earlier (at t=80 d) and high ionization species found later on (at t=155.1 d).
- middle of the plateau in the X-ray light curve (t~155 d)
  - ➢ Consistent with high frequency (37 GHz) radio flux peaked
  - ➢ and appearance of coronal lines [Fe X] 6375 and [Fe VII] 6087 in optical spectra (t=161.1 d).
- X-ray emission was finally undetectable at t~222 days then low frequency radio (1.25 GHz) reached a peak later at t~250 d.

Conclusions

- The SMEI light curve provides unprecedented detail with high cadence data of T Pyx in 2011 during t=1.5-49 days.
  - ➢ A strong period of $1^{d}.44\pm0.04$ before visual maximum was detected.
- The spectra from the LT and SMARTS were investigated during t=0.8-80 d and 155-250 d.
  - ➢ The nova was observed spectroscopically very early in its rise

    – a distinct high velocity ejection phase was evident at this time.
  - ➢ The overall spectral development follows that typical of a Classical Nova and comparison to the photometric behaviour reveals consistencies with the simple evolving pseudo-photosphere model of the nova outburst.
  - ➢ Weak He I 5876 and [Fe X] 6375 marginally detected before the rise in SSS.
  - ➢ Middle of plateau in the X-ray light curve is consistent with appearance of high ionization species and the peak of high frequency radio flux