High time resolution multi-band photo-polarimetric observations of the binary millisecond redback pulsar J1023+0038 with the BTA

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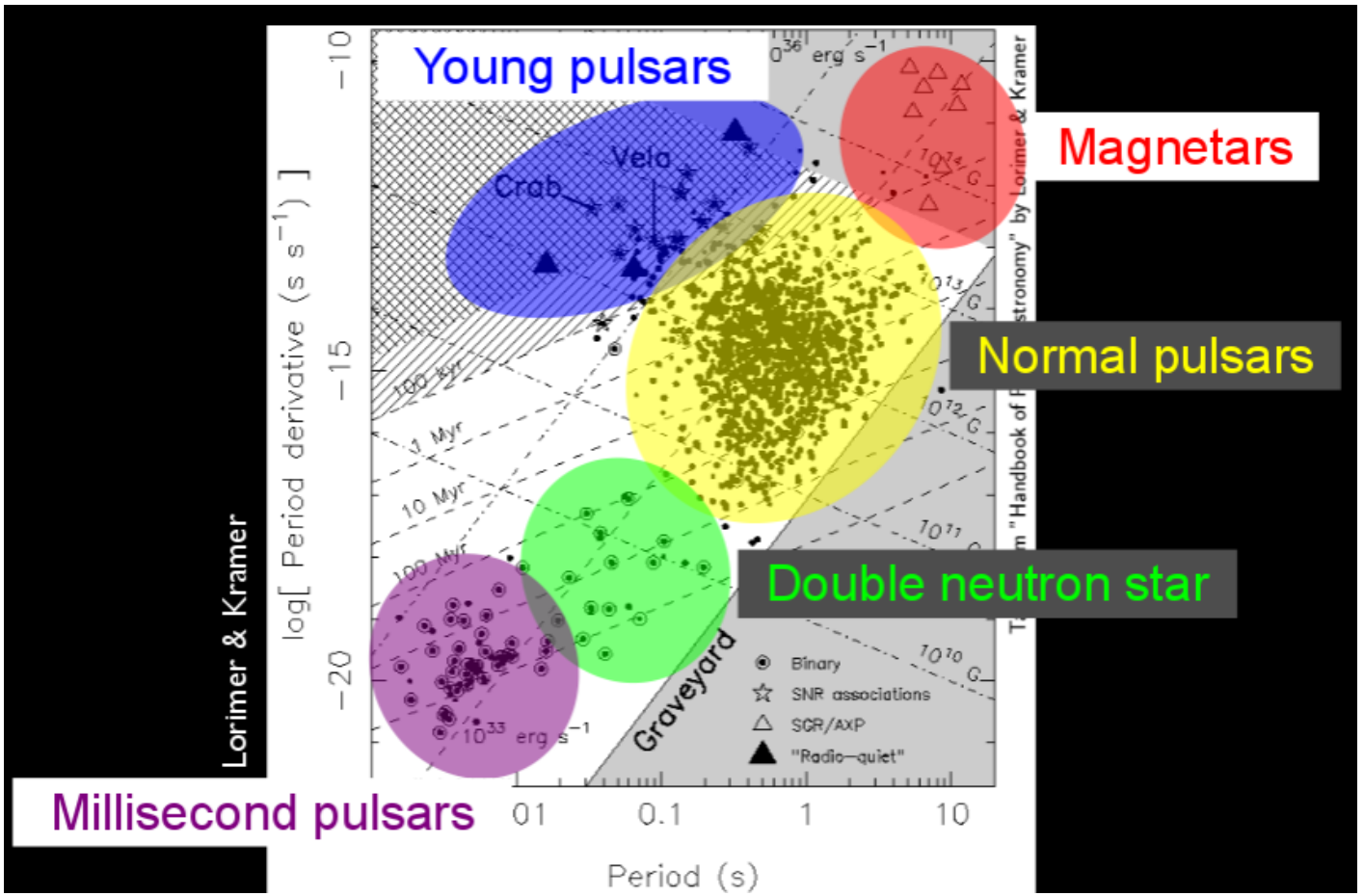
Preliminary Results

Observation Date: 17.02.2017. Duration: 3.5 h.

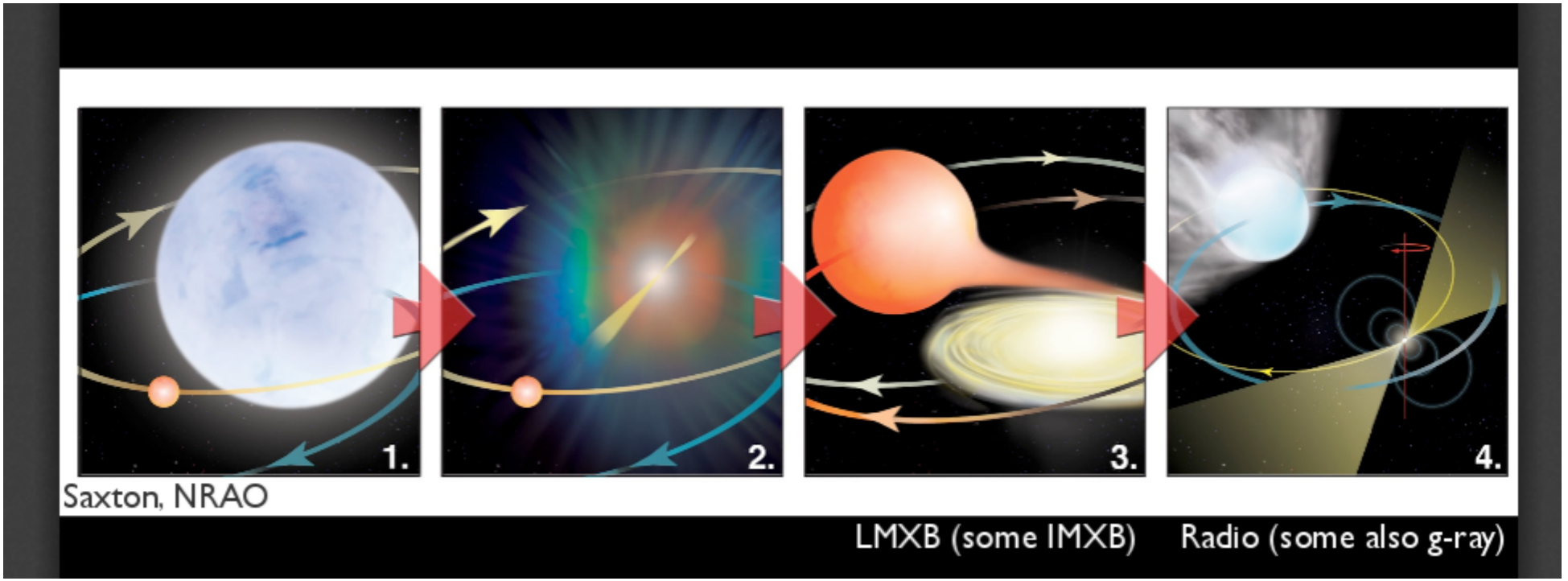
Instrument: MANIA.

A short history

- Rotation powered millisecond pulsars (RMSPs) were discovered in the radio about 35 yr ago, the first one was PSR B1937+21 (Backer et al 1982)



- Two independent groups immediately suggested that MSPS were spun-up ("recycled") by accretion in binary systems (Alpar et al. 1982; Rhadakrishnan & Srininvasan 1982).



- A long time this idea was only supported by the fact that most RMSPs are in binary systems with ordinary stellar companion.
- The discovery of 408 Hz X-ray coherent pulsations in the accretion powered NS SAX J1808.4-3658 (Wijnands & van der Klis 1998) was the first direct evidence of the accretion spin-up. Currently, the total number of such AMXP =19.

- Compact RMSPs binaries (Pb<1 day) show two distinct sub-classes: **black widows (BWs;** Fruchter et al. 1988**)** with substellar companion masses **M< 0. 1M⊙** and **"redbacks" with M>0. 1M⊙** bloated companions close to filling their Roshe lobes (Roberts 2013). **Total BWs = 40 (+2 candidates)**, **total redbacks = 22** (from the list compiled and last updated by A. Patruno in May 2 2017 https://apatruno.wordpress.com/about/millisecond-pulsar-catalogue).

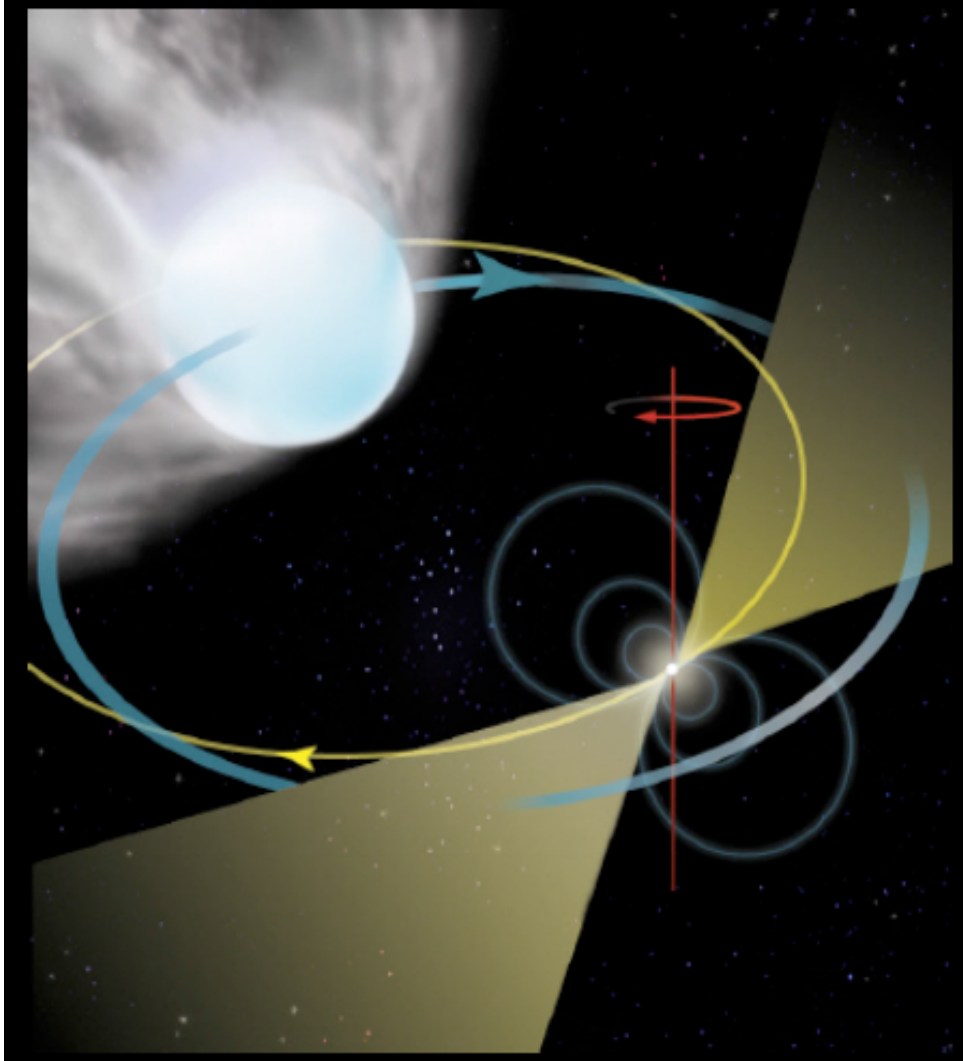
  In these systems NSs consumes their companions, as we can see in the life!

  The prototype is the Australian redback spider (Latrodectus hasselti) demonstrating sexual cannibalism - female just eats male while maiting continues! The same occers for BW spiders.

MSP "Spiders"

Blame Mallory Roberts

'Black Widow' and 'Redback' Pulsar Binaries



So named because these pulsars are 'devouring' (ablating) their companions

Black widows:
<< $0.1 M_{Sun}$ (semi) degenerate companion

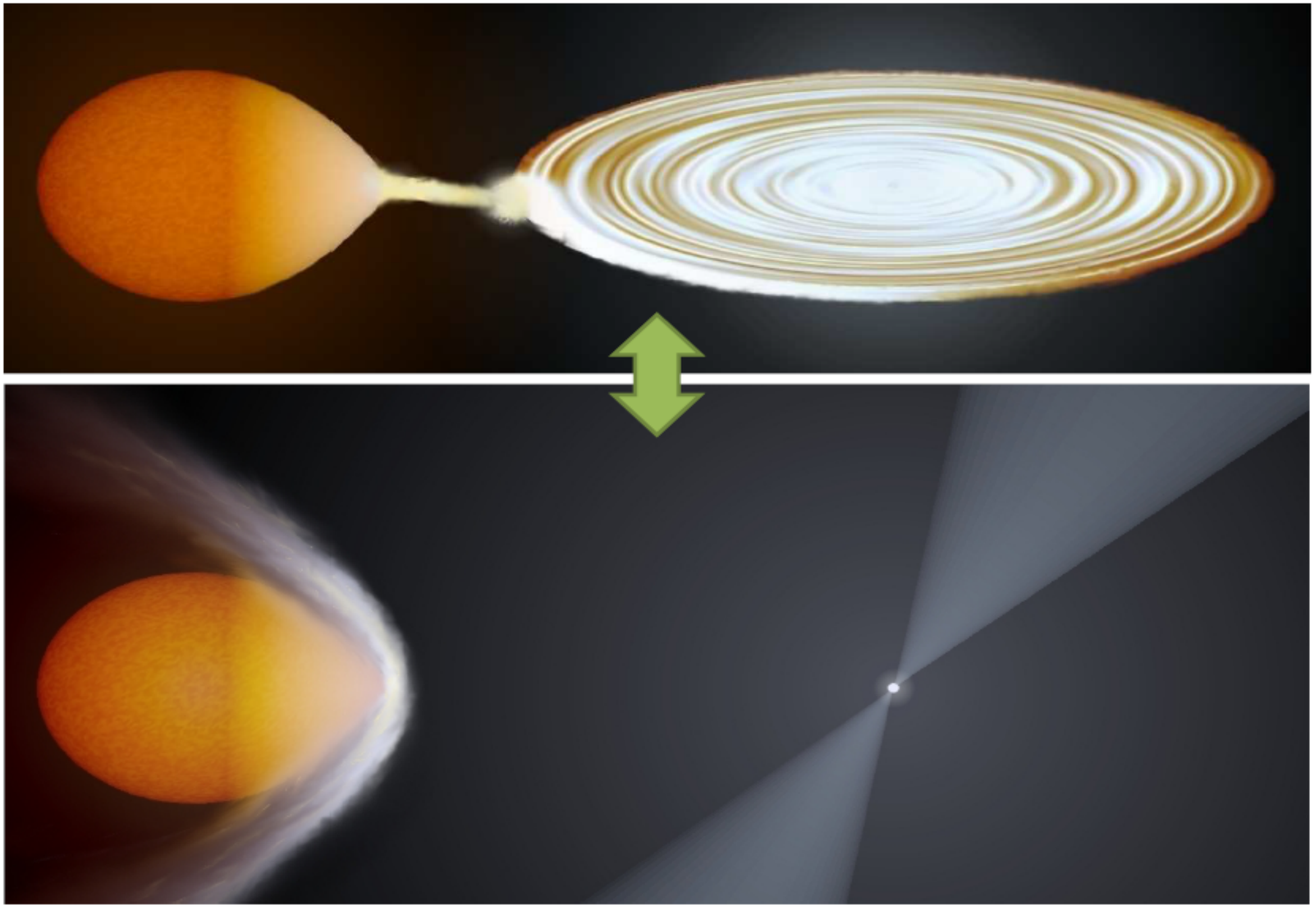
Redbacks:
~ $0.2 M_{Sun}$ non-degenerate companion

- The final point in establishing the LMXB - RMSP connection was provided by three recently discovered redbacks directly demonstrating the transformation from the accretion to the rotation powered stages:**PSR J1023+0038** (Archibald et al. 2009), **XSS J12270-4859** (Bassa et al. 2014; Roy et al. 2015), and **PSR J1824-2452I** in the globular cluster M28 (Papitto et al. 2013).

- **Congratulations to Ali Alpar and Indian groups with this event, which came to us only 20(1) yr after the idea was published!**

PSR J1023+0038 has shown the LMXB--> radio RMSP transition in 2003, and than a sudden return back to the LMXB in 2013.

This demonstrates that the transition itself is a complicated process challenging additional studies.



"Normal MSPs" vs. Spiders

- Gravity tests
- EOS constraints

- Accretion physics
- Pulsar wind
- Particle acceleration
- Shocks
- MSP formation and evolution
- EOS constraints?
- ...

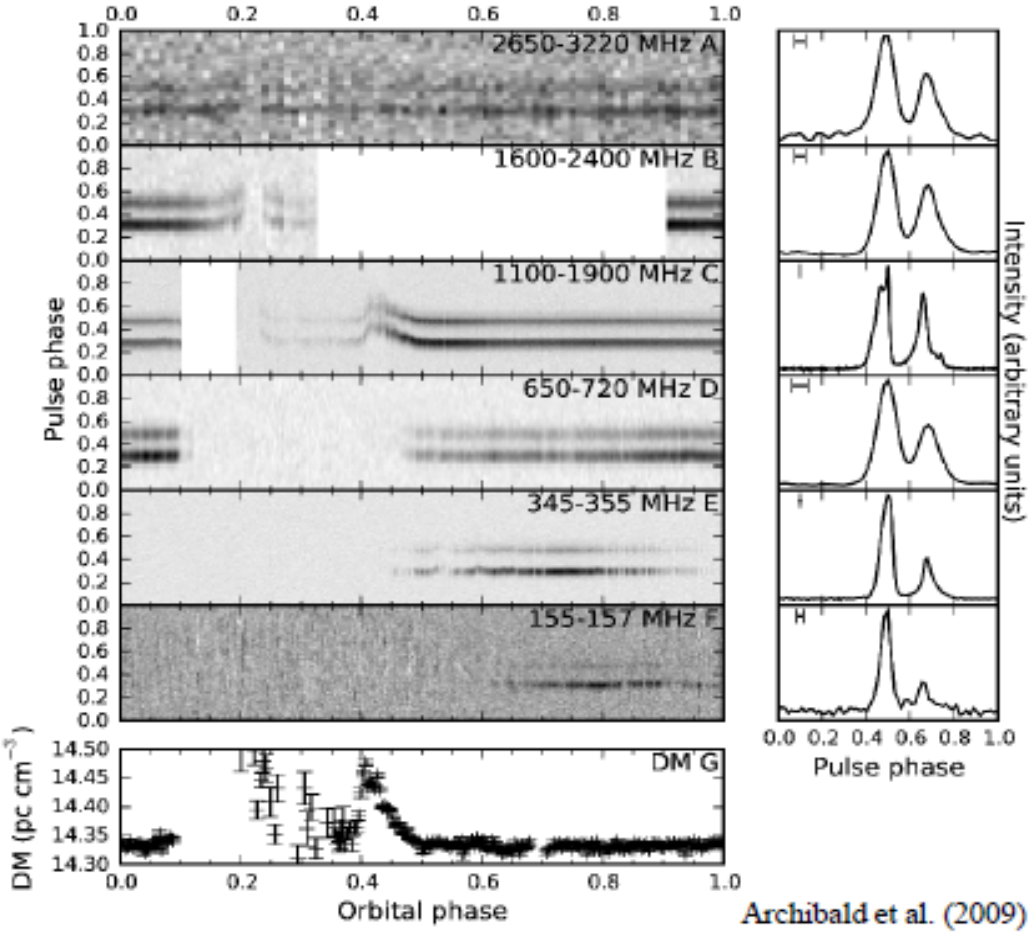
J1023+0038

Among 3 redbaks mentioned above, this is a most intriguing and studied object with its own dramatic history.

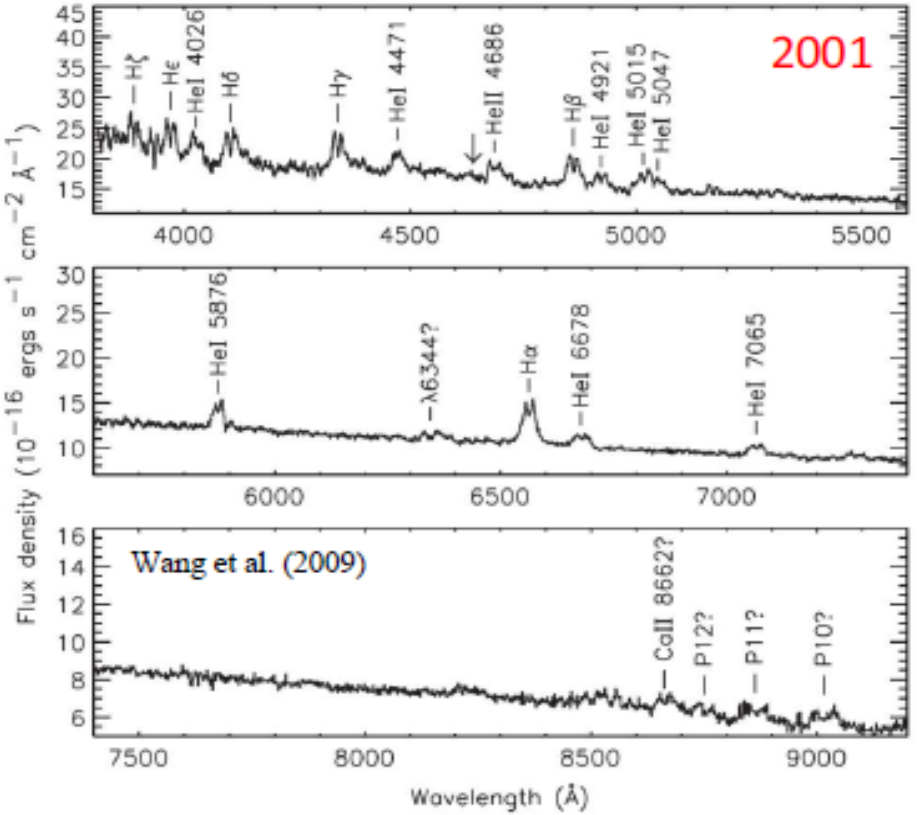
- Initially identified as a CV FIRST J102347.6+003841 (Bond et al. 2002).
- Thorstensen & Armstrong (2005): a LMXB with the accretion disc.
- The optical-X-ray observations: disc is absent (Woudt et al. 2004; Homer et al. 2006).
- Archibald et al. (2009): eclipsing binary radio RMSP with P=1.69 ms, Porb=4.8 h, and a G-class companion of $\mathbf{M=0.2M_{\odot}}$.

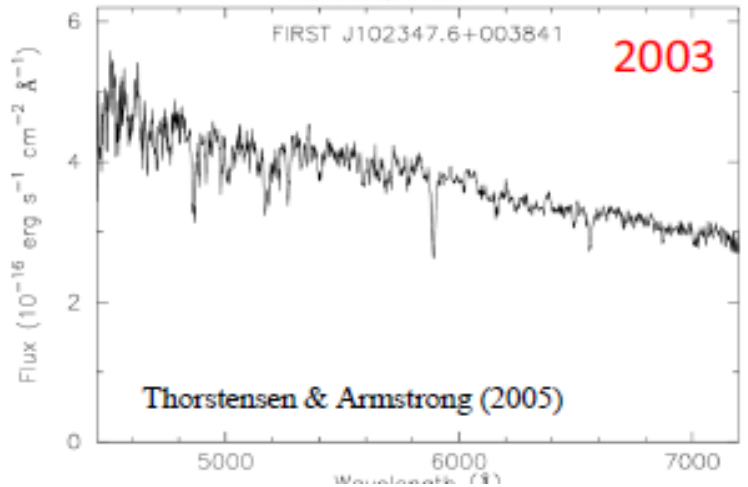
PSR J1023+0038: The "Missing Link"

- Eclipsing ("redback") binary radio MSP ($P = 1.69$ ms) discovered in 2009
- System had accretion disk in 2001 but not after 2003

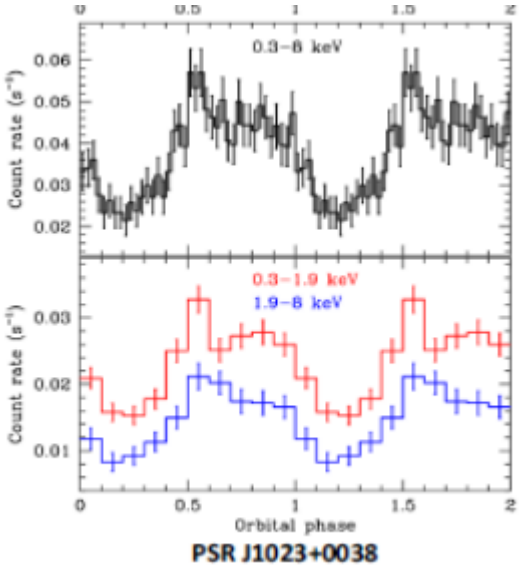


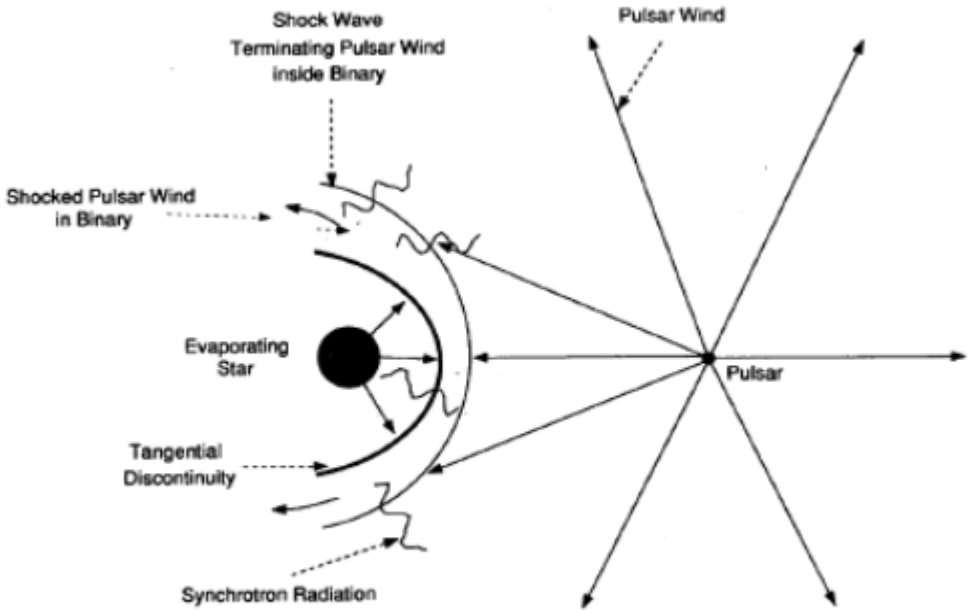
Archibald et al. (2009)





- X-ray modulation with Porb due to an intrabinary shock near the internal Lagrange point (Archibald et al. 2010)



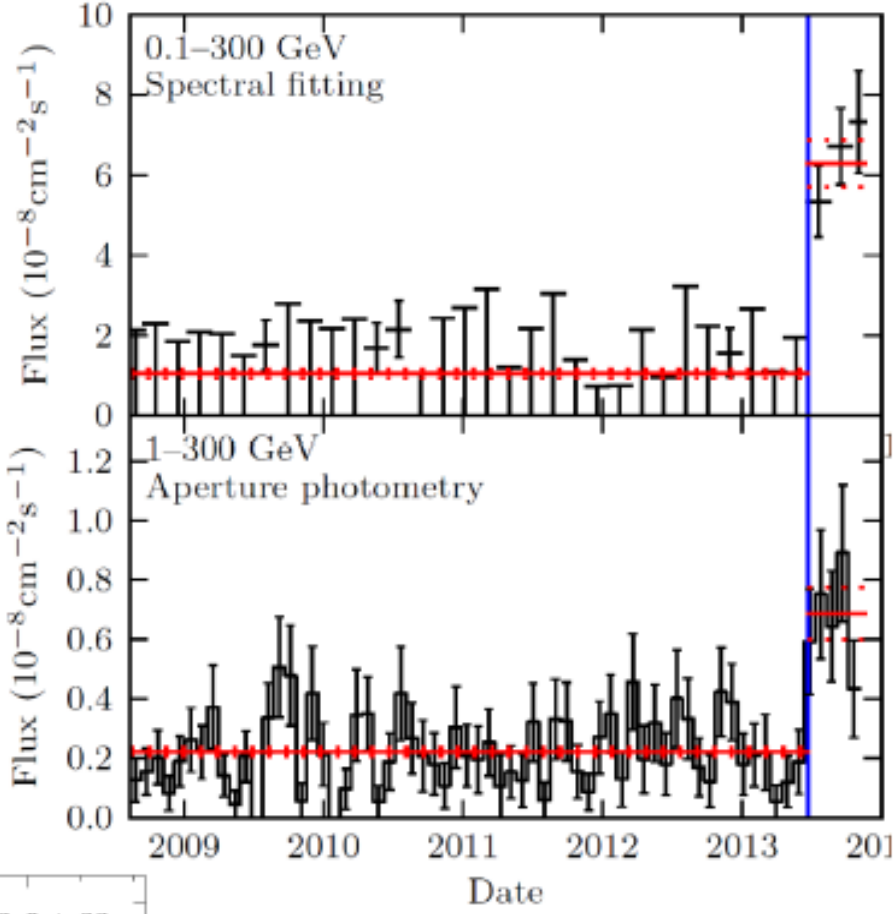


Arons & Tavani, ApJ, 403, 249 (1993)

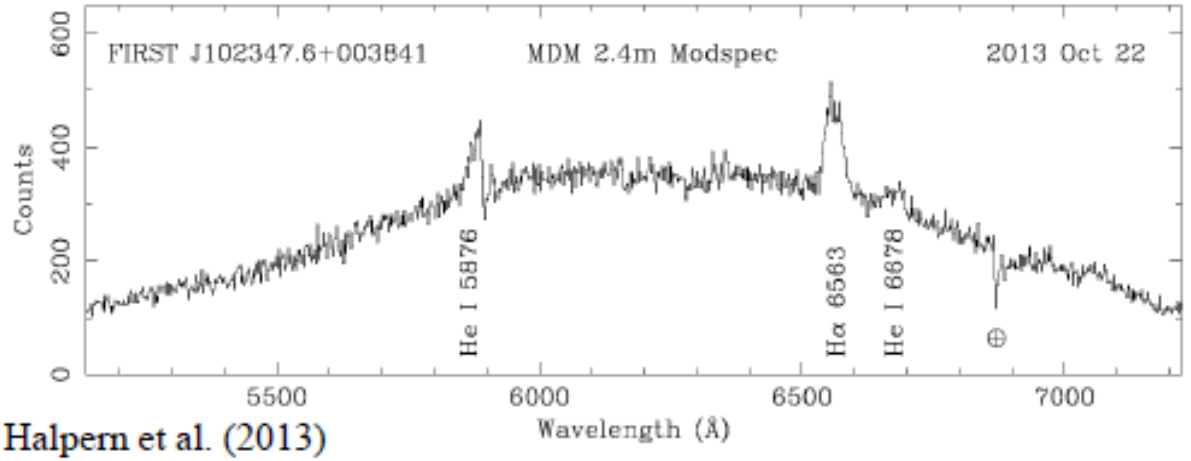
- 3-sigma gamma-ray periodic pulsations (Archibald et al. 2013, outer gaps?).
- Coherent X-ray pulsations from hot magnetic pulsar polar caps (Archibald et al. 2015).
- Disappearence of the radio MSP and reapearence of the accretion disc in the optical (Halpern et al. 2013; Szkody et al. 2013)

PSR J1023+0038: The Accretion Disk Returns

- Radio emission ceased on June 23rd, 2013
- Optical brightness increased by ~1 mag
- Double-peaked optical emission lines reappeared
- *Fermi* LAT flux increased ~5-fold
- Average X-ray flux increased by order of magnitude



Stappers et al. (2013)



Halpern et al. (2013)

• Sporadic flares in X-rays with a gradual flux increase (Archibald et al. 2014).

• Strong flux increase in gamma-rays by a factor of 5 (Stappers et al. 2014; increaes shock activity?).

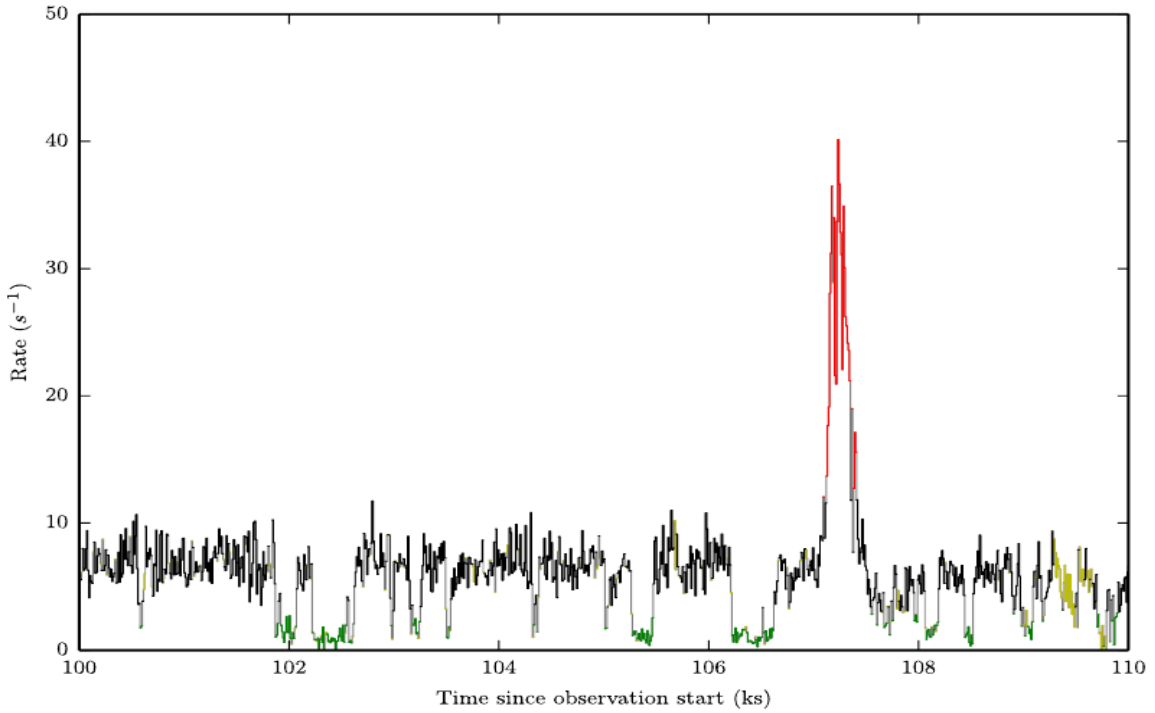
• Optical flux increase by two mag (Patruno et al. 2014).

• Modulation of the optical flux and color with Porb (redback feature) and occational optical flares and deeps at 0.1-1 mag level and time scales from 20 s to 10 min (Shahbaz et al. 2015).

• A variable flat spectrum of the radio continuum due to a possible jet (Deller et al. 2015).

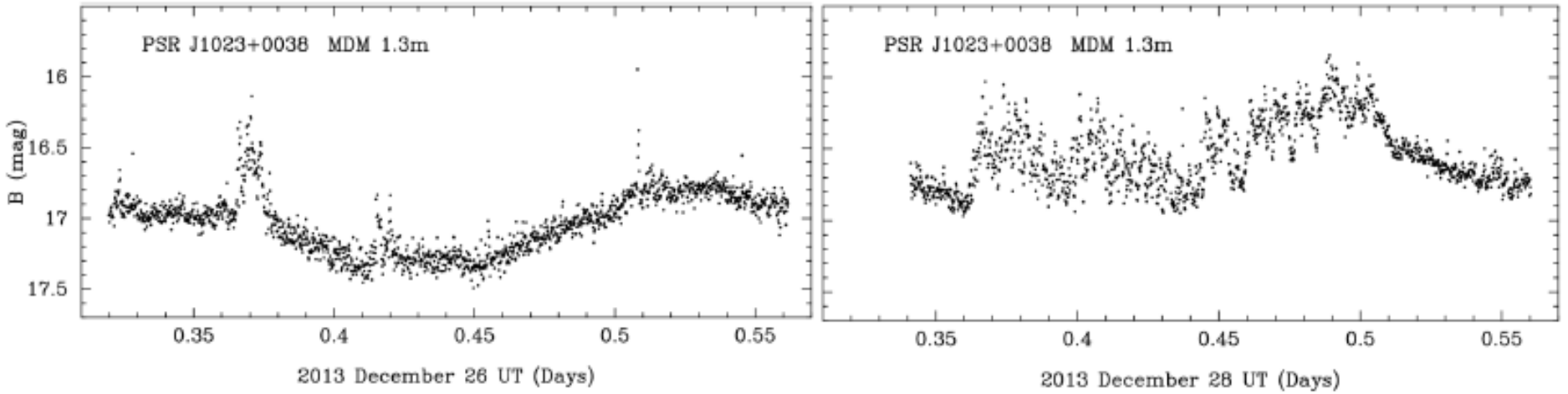
- X-ray flux increase by two orders of magnitude (Linaries 2016).

  Three X-ray brightness LMBX modes: high (Lx ~10e33 erg/s, ~70 – 80% of the time; low (LX ~5 × 10e32 erg/s, ~20% of the time}; and occasional flares (LX ~5 × 10e34 erg/s, about 2% of time). Switching from one to another mode occers on timescale from minutes to hours. Detection of intermitten coherent X-ray pulsations in the high mode (likely due to matter channeling onto magnetic poles of the NS).

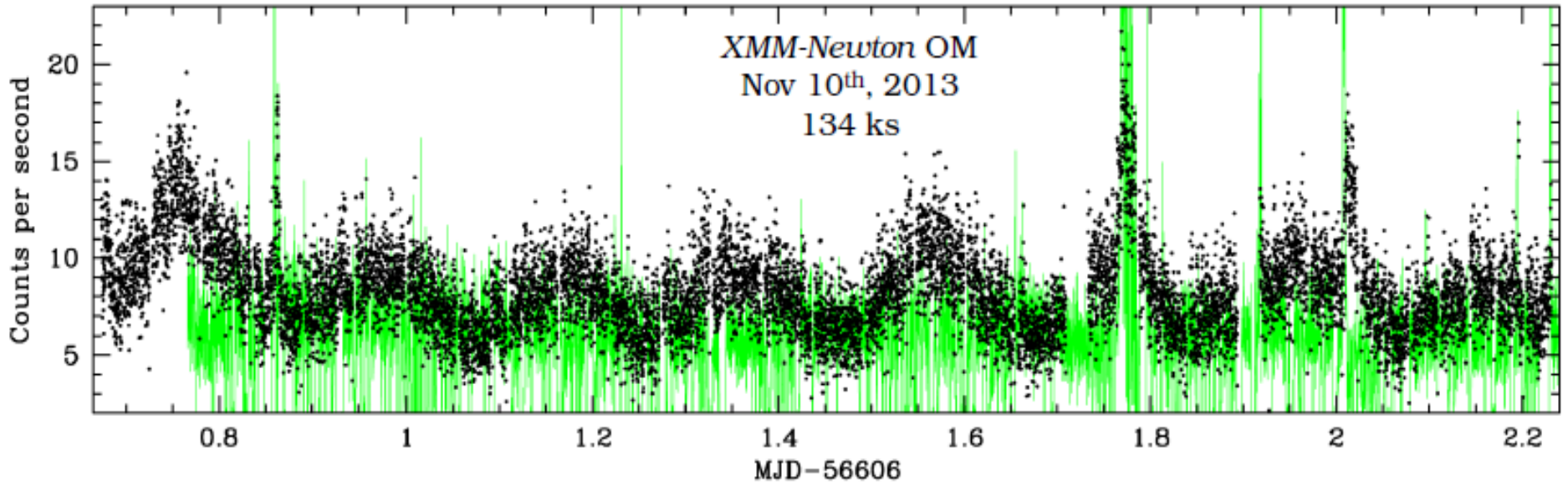


LMXB spin-down rate is 26.8% faster than in RMSP state (Jaodand et al. 2016) – pulsar wind continues to operate !!!

PSR J1023+0038: Optical Variability



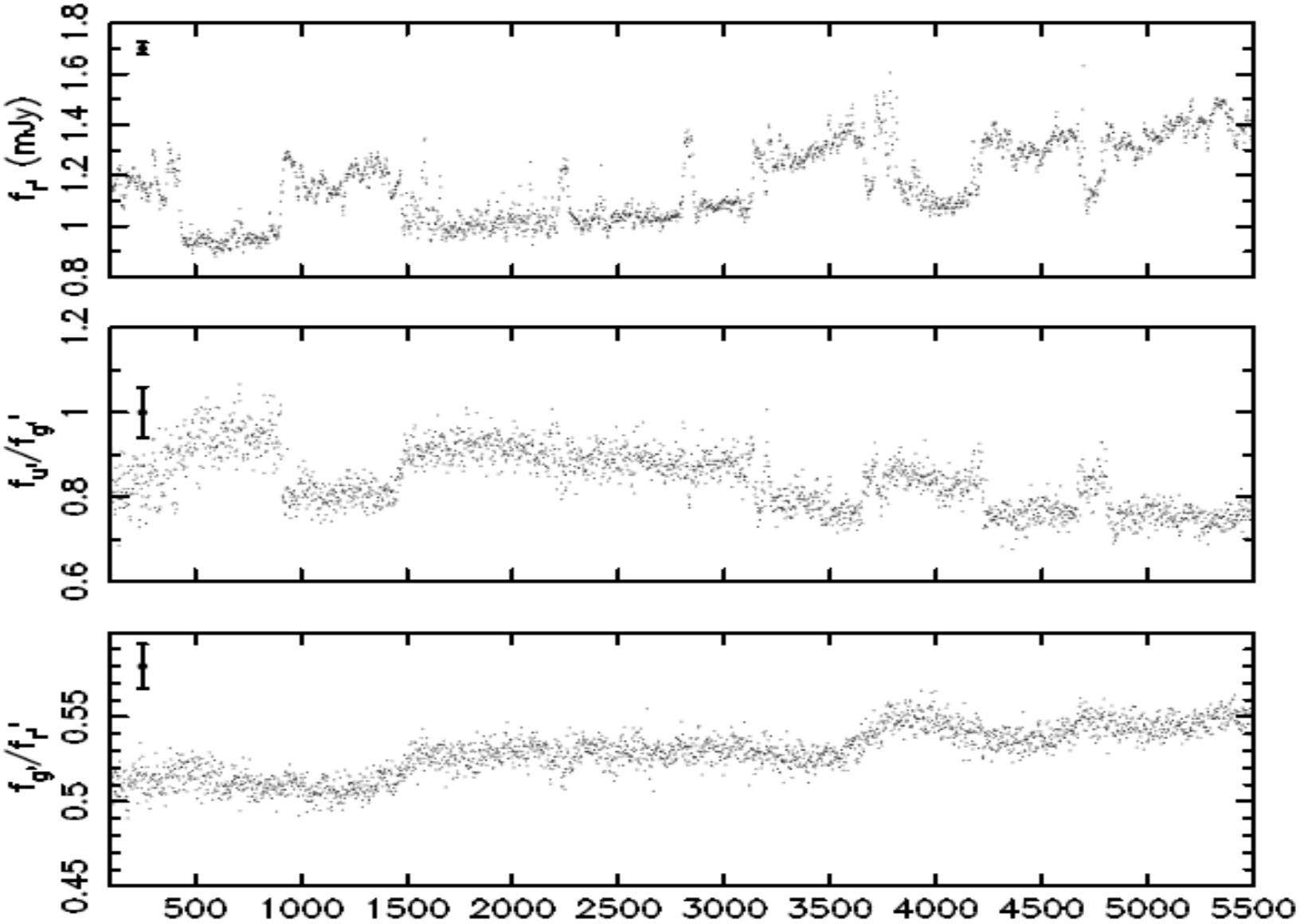
Bogdanov et al. in prep.



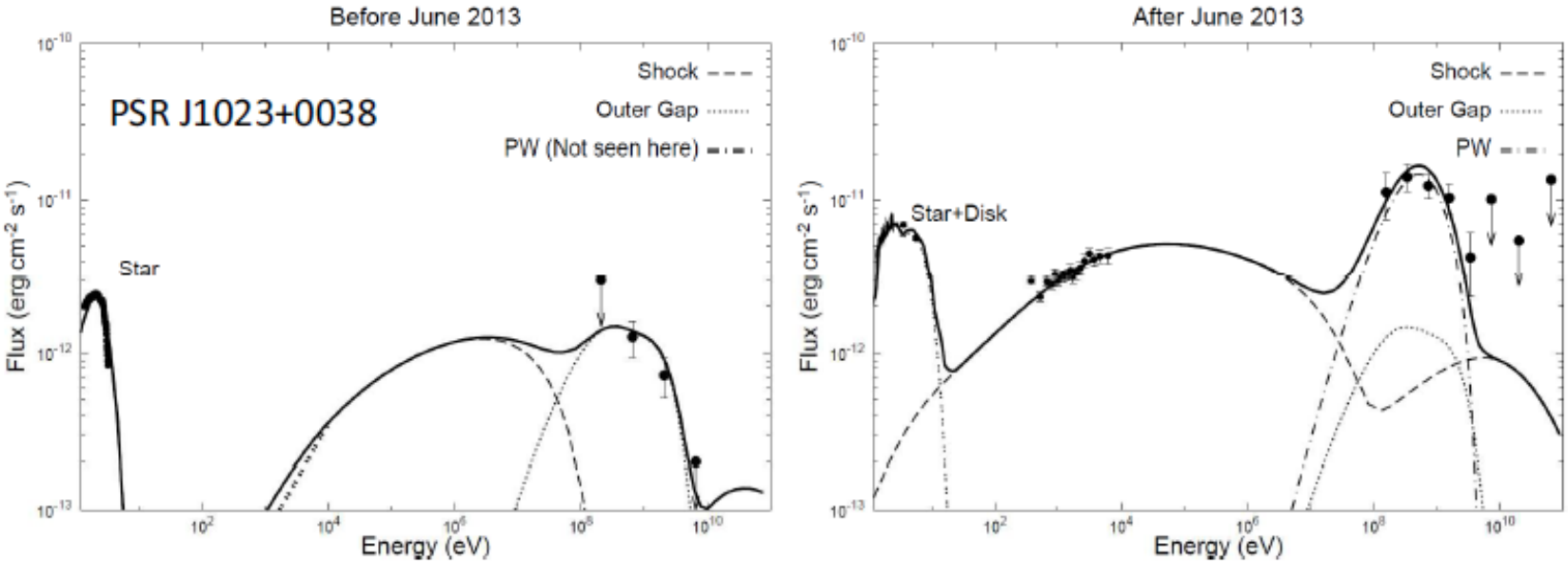
OPTICAL VARIABILITY

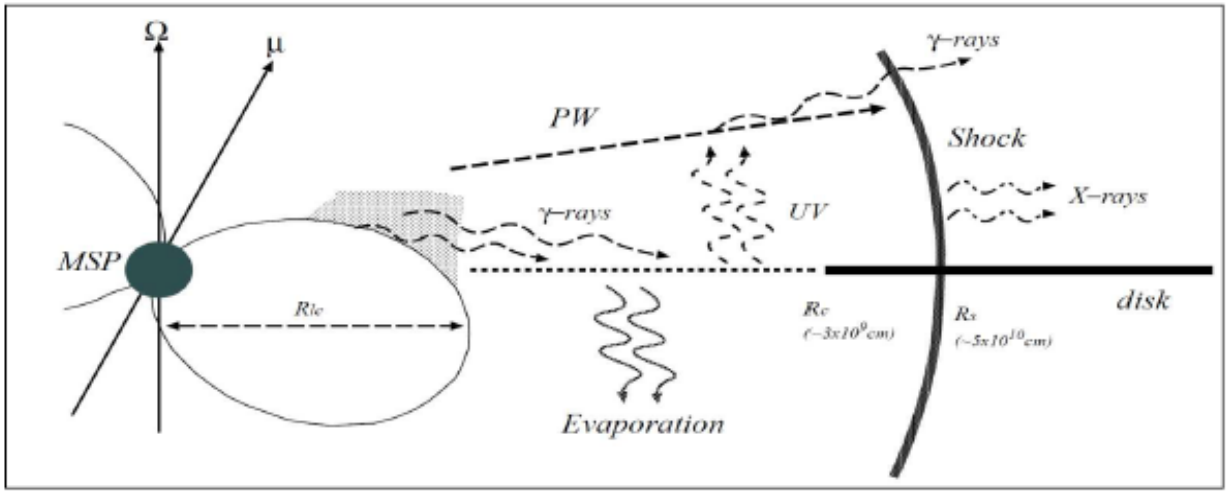
WHT- Tmin ~ 10-20 c, Apr 2014

T. Shahbaz et al, 2015



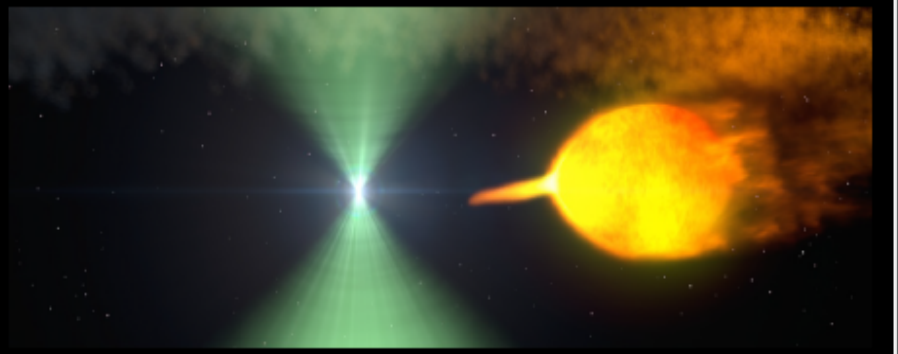
Intra-binary Shock





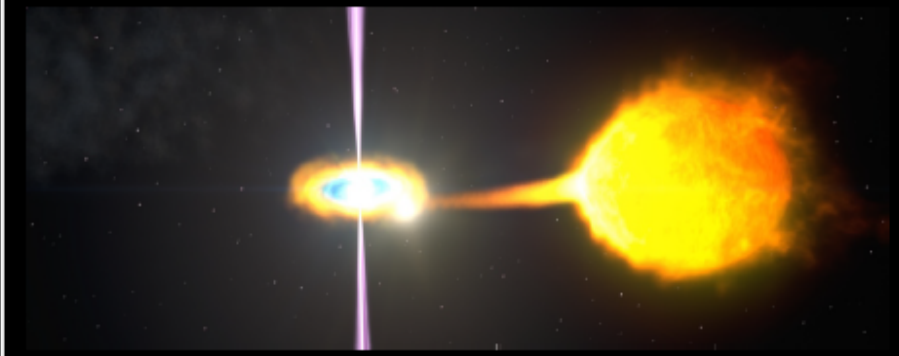
Takata et al. (2014)

Radio Pulsar State



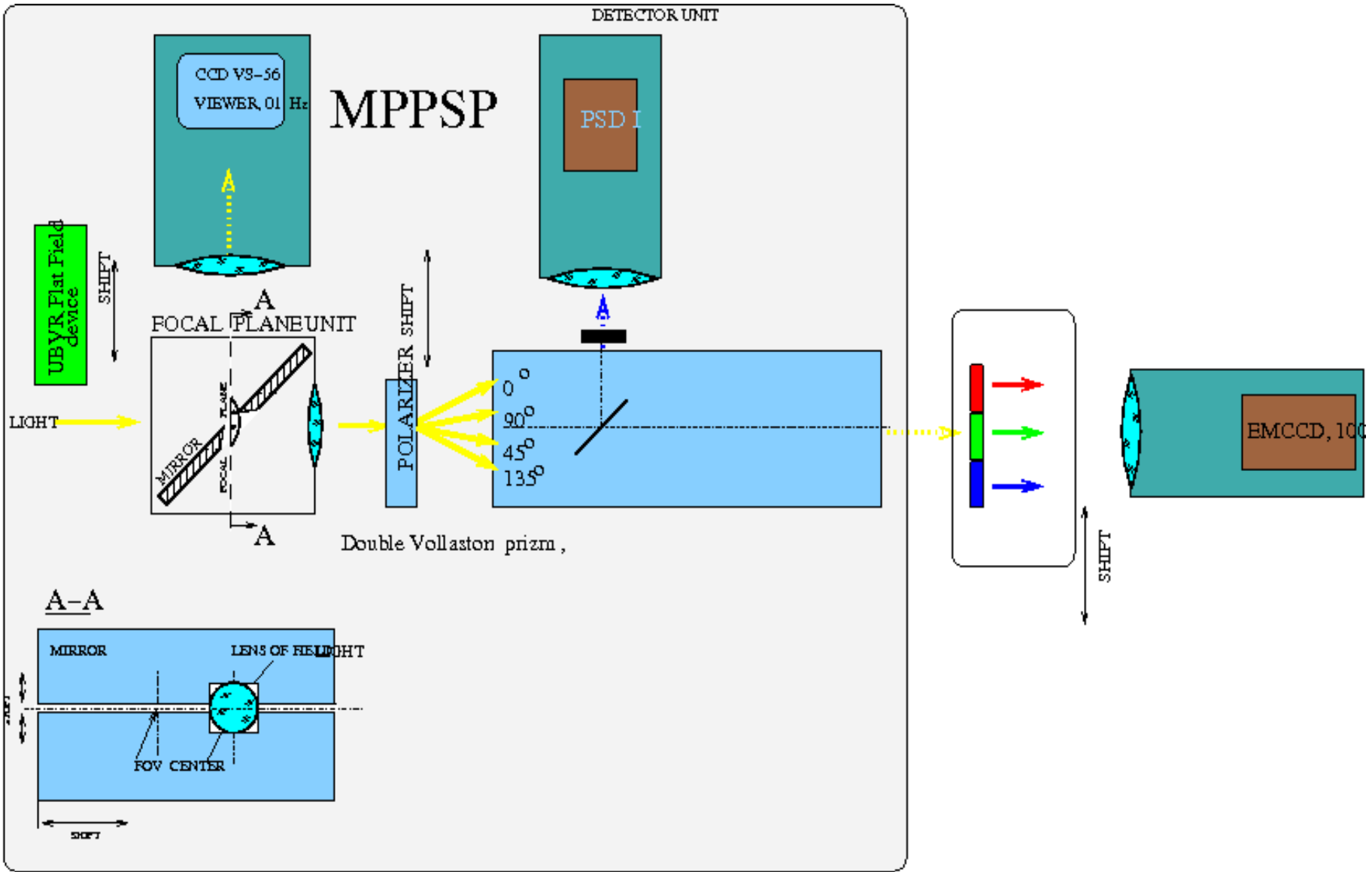
- Observed radio/gamma-ray pulsar.
- Likely radio eclipses.
- Lots of orbital timing noise.
- Modulation of X-rays at orbital period (shock).

Disk State

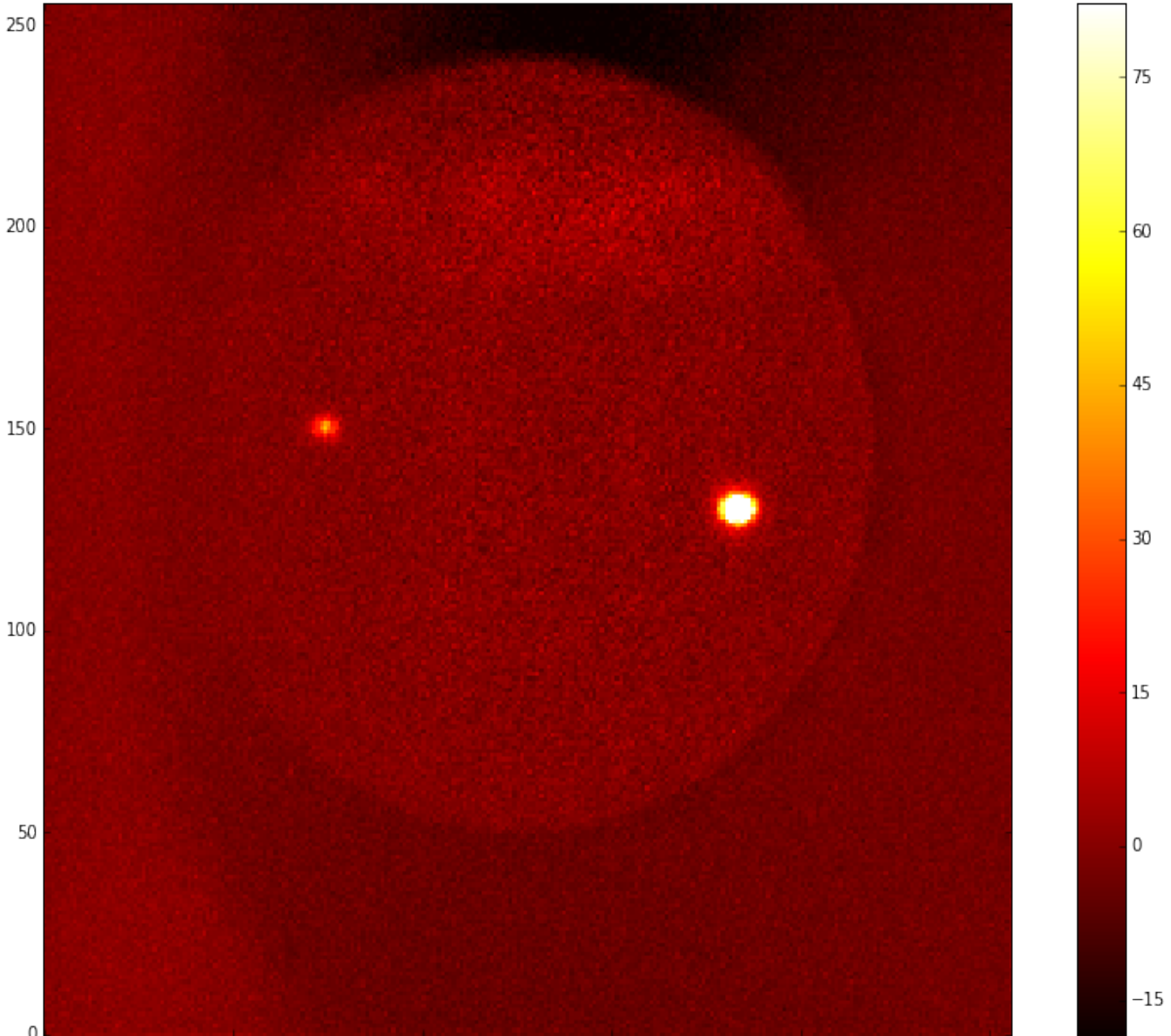


- No visible radio pulsar (off?).
- Increased optical, X-ray, and gamma-ray brightness.
- Double peaked optical emission lines.
- Flat-spectrum radio continuum source (jet?).
- No X-ray orbital modulation.
- X-ray dropouts and flares.

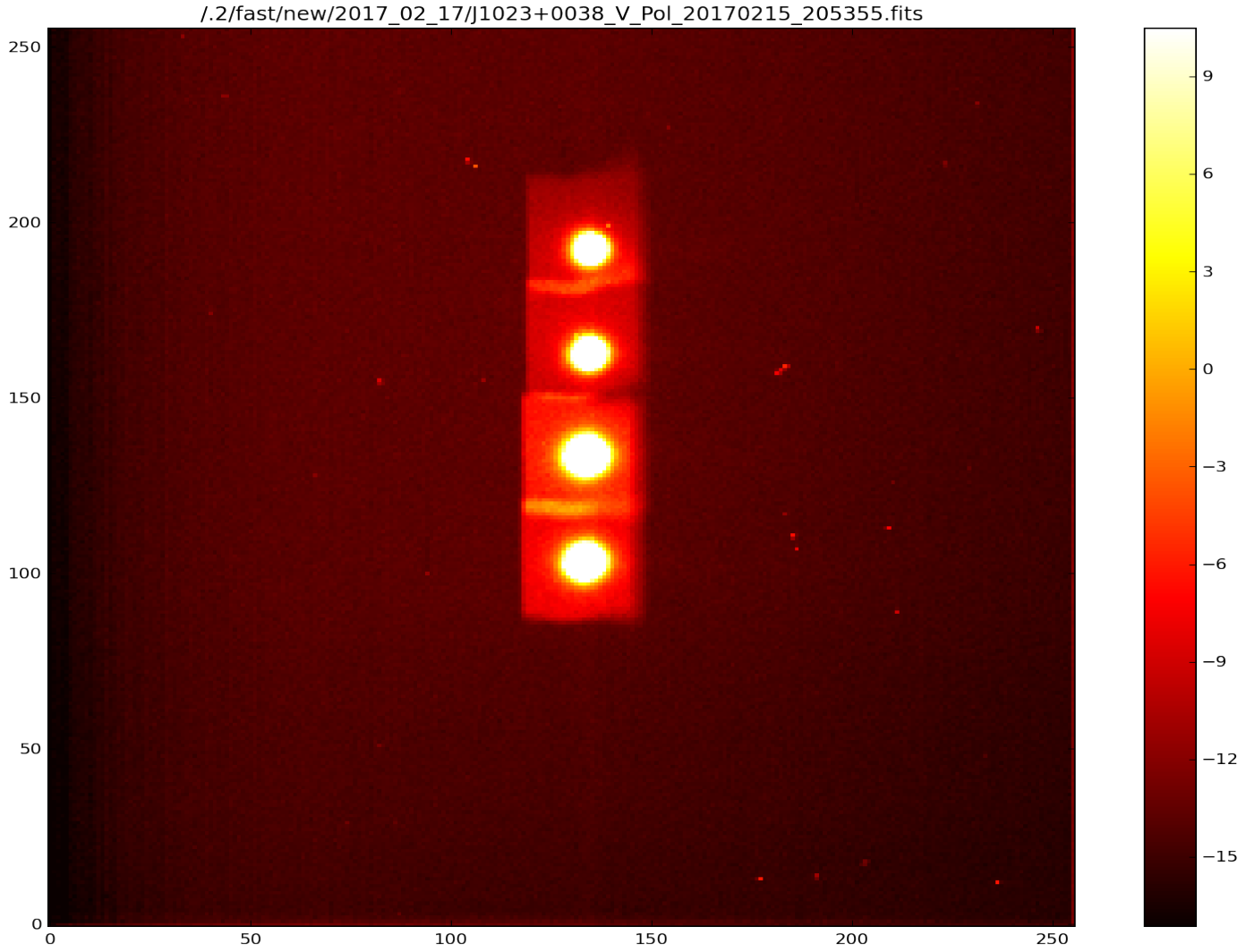
MPPP, Delta t_min=100 ns !



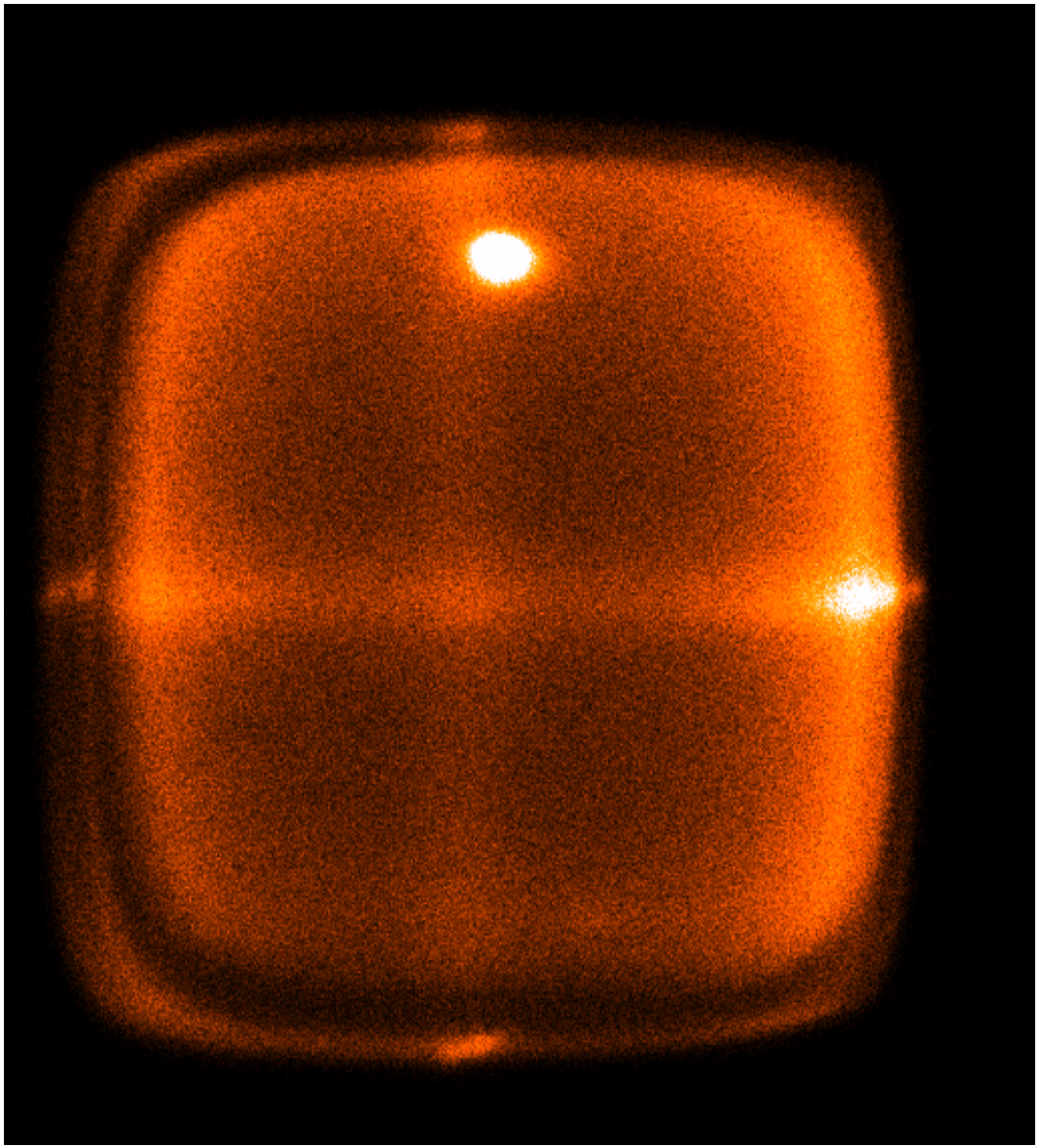
J1023+0038 (B=17.2, EBV=0.07) + comparison star, EMCCD



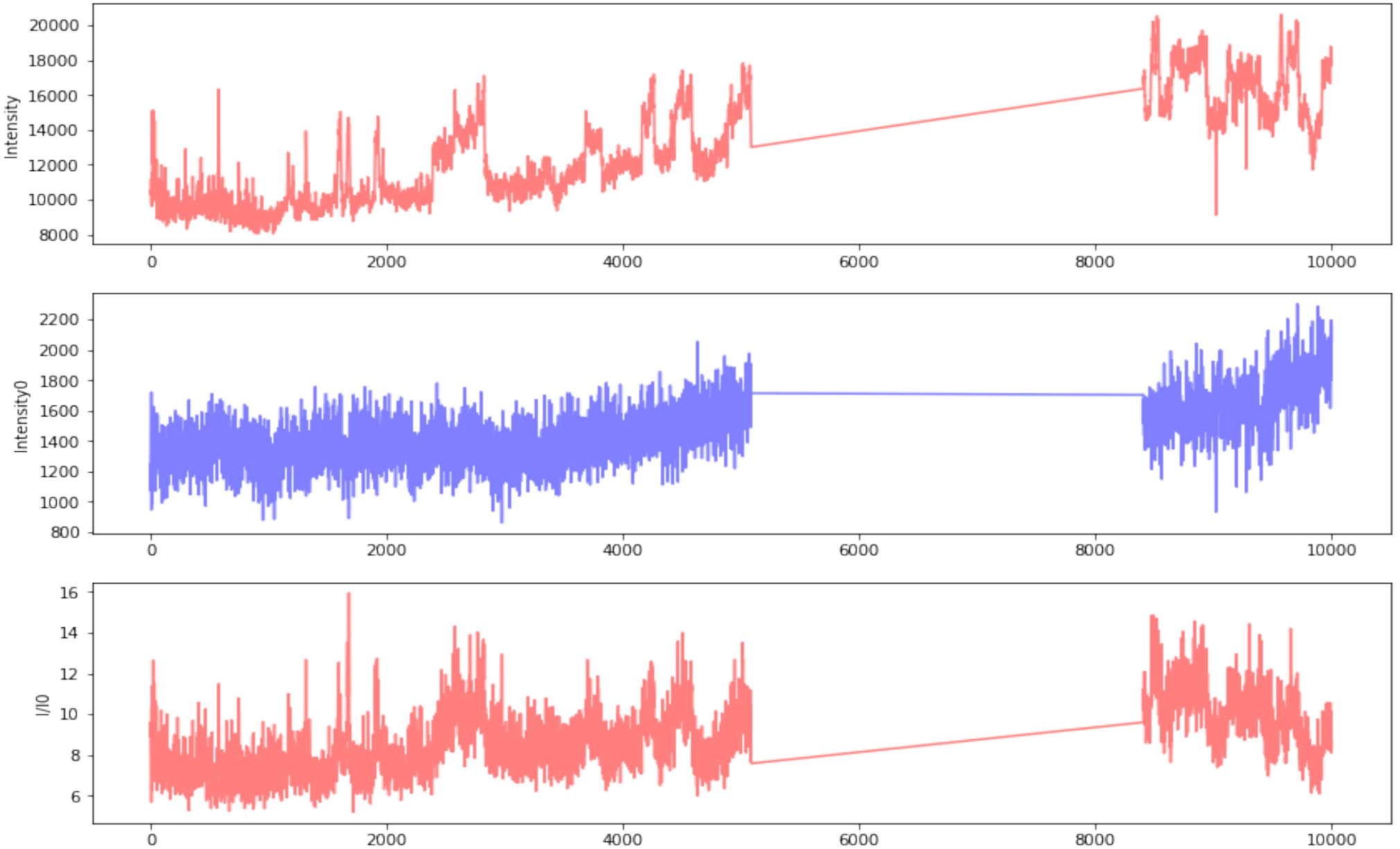
Polarimetry J1023+0038, B-band, EMCCD



J1023+0038 , U-band, PSD

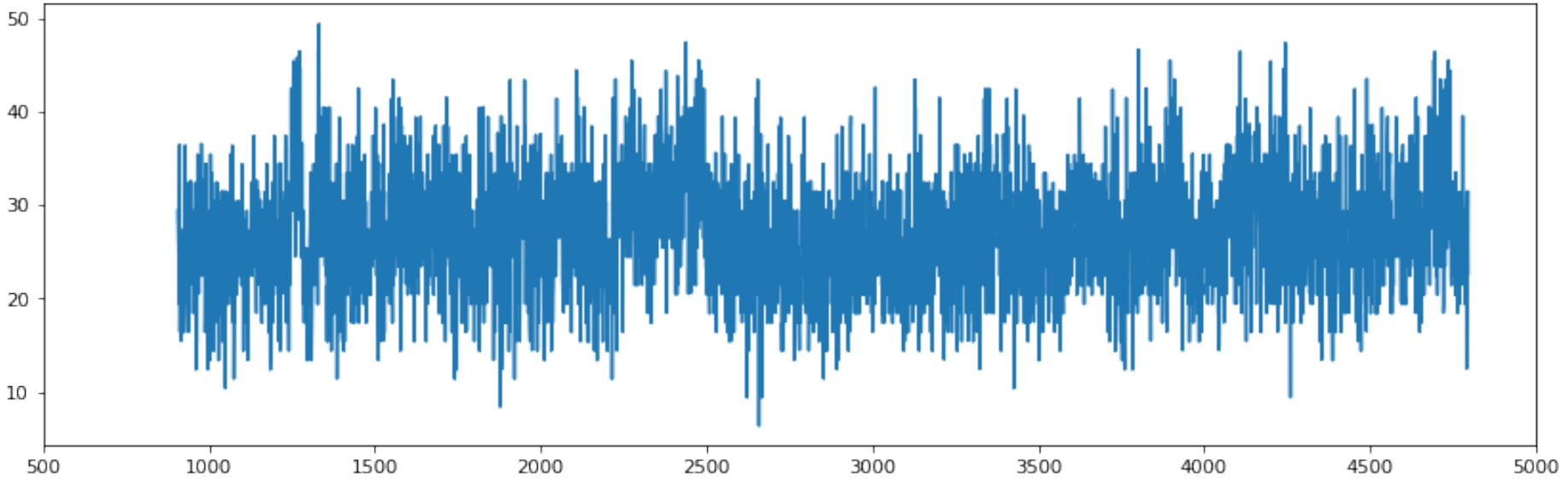


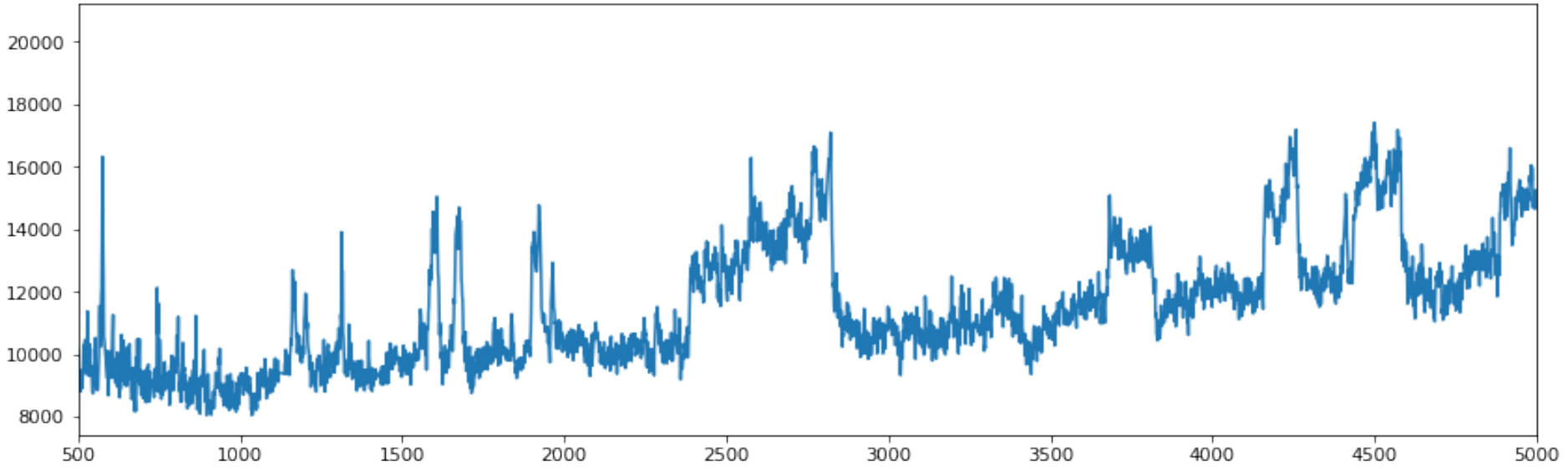
Total light curve (3.5h). B-band (psr, star, psr/star), window – 1.2 s



Light curve fragment

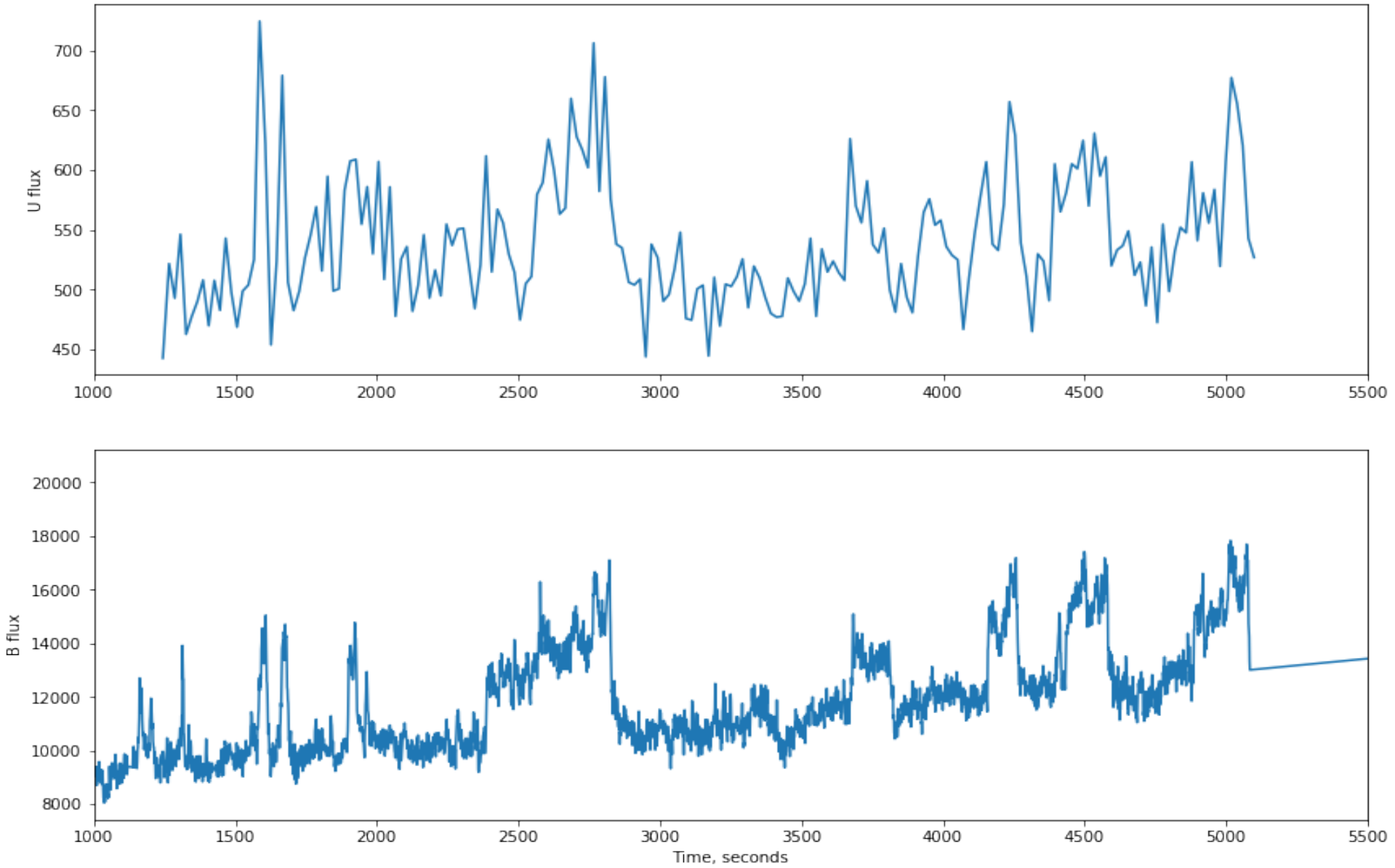
U(1s) & B(1.2s)





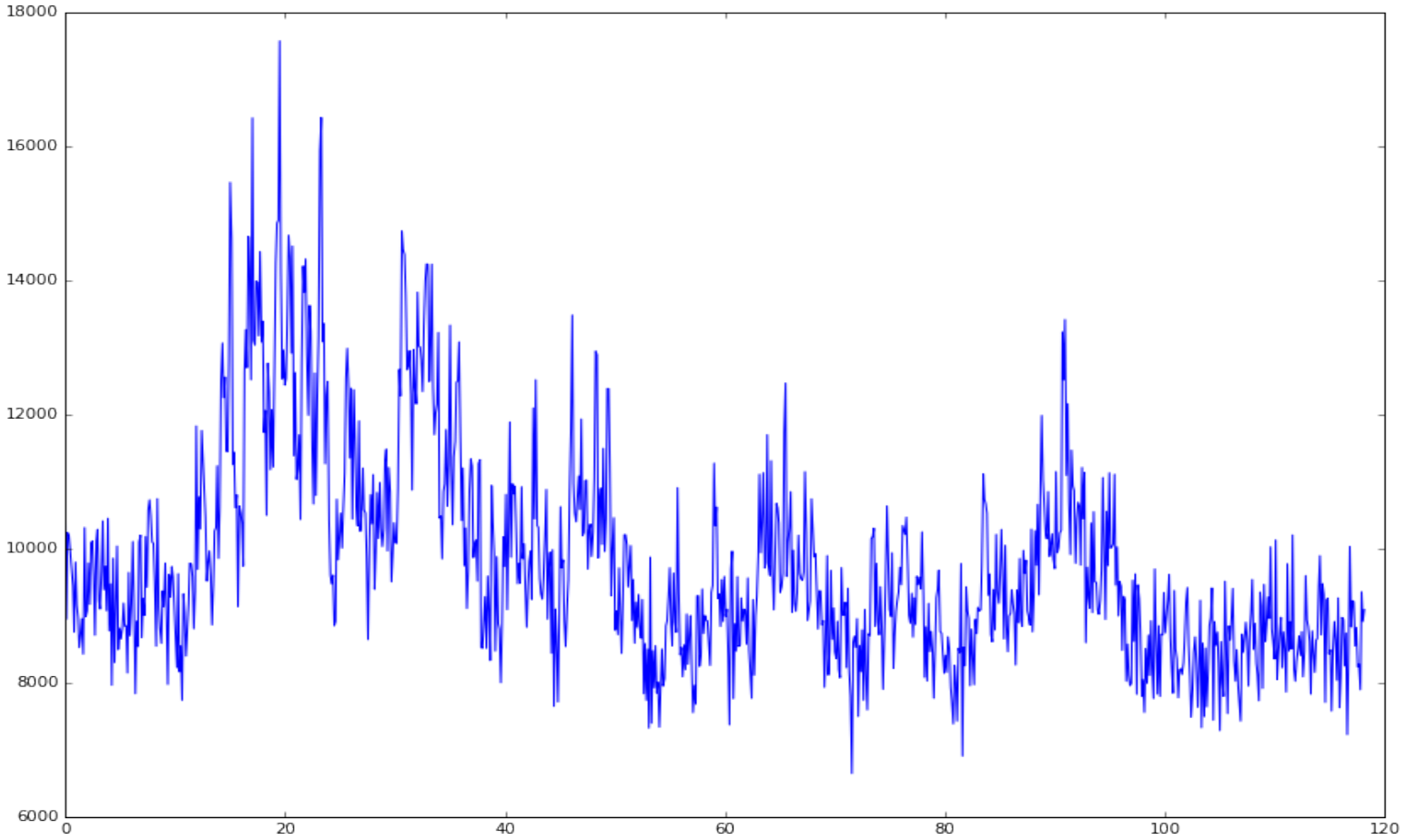
Light curve fragment,

U(20s)&B(1.2s), U/B(20s), brigther parts are redder

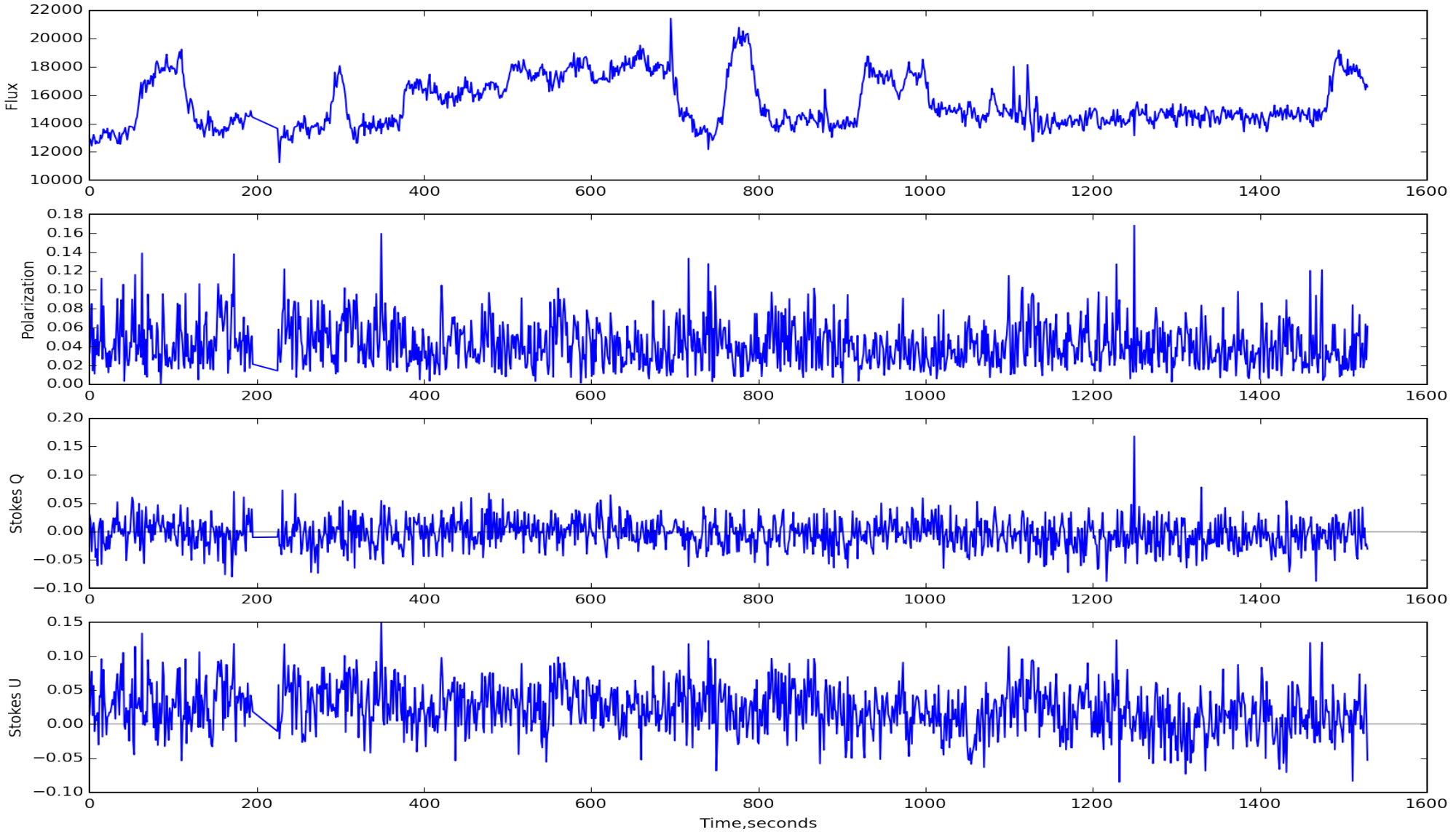


Light curve fragment,

B (0.12s)



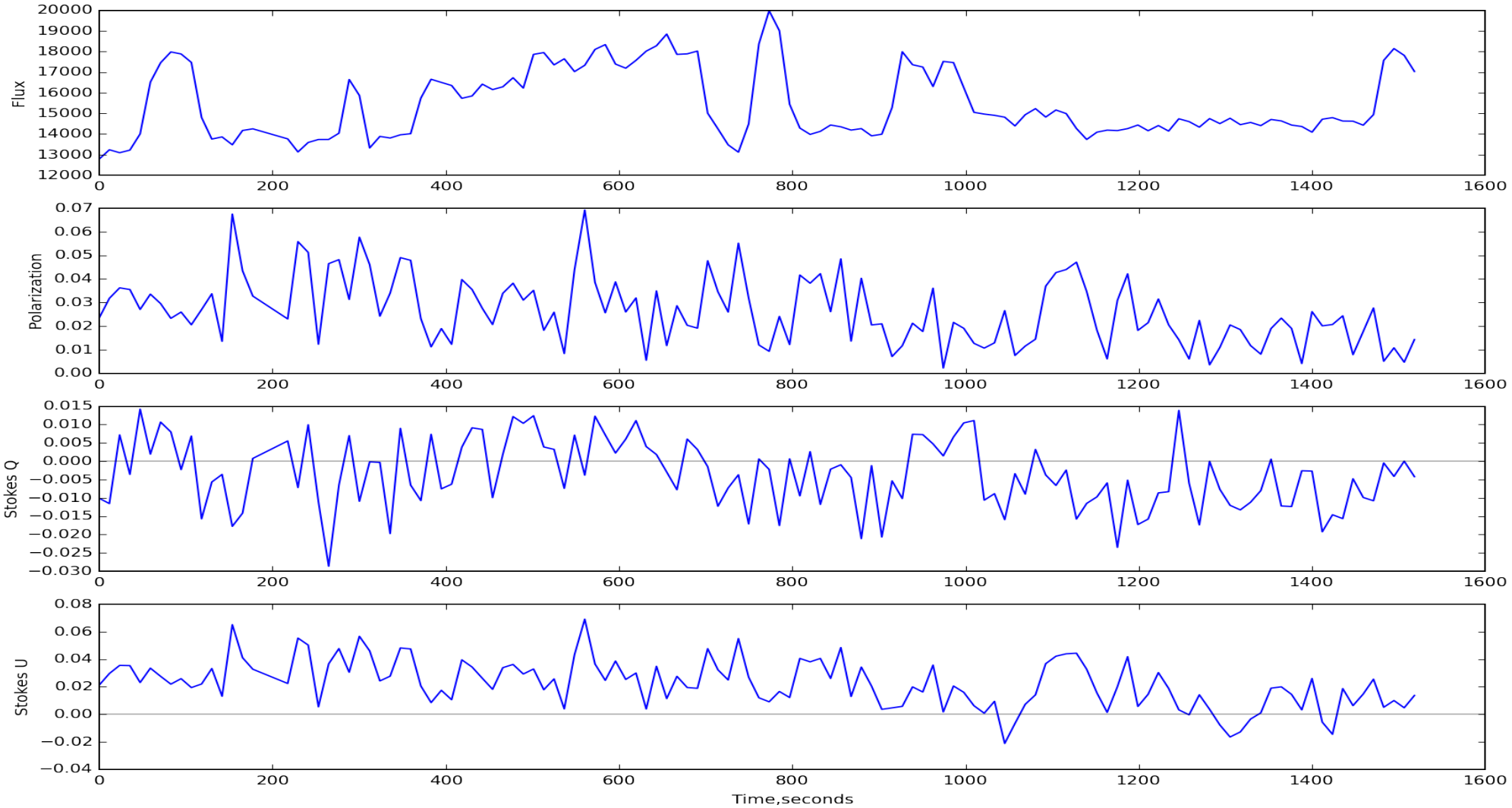
Polarimetry, B-band (1.2 s), upper limit- 6%



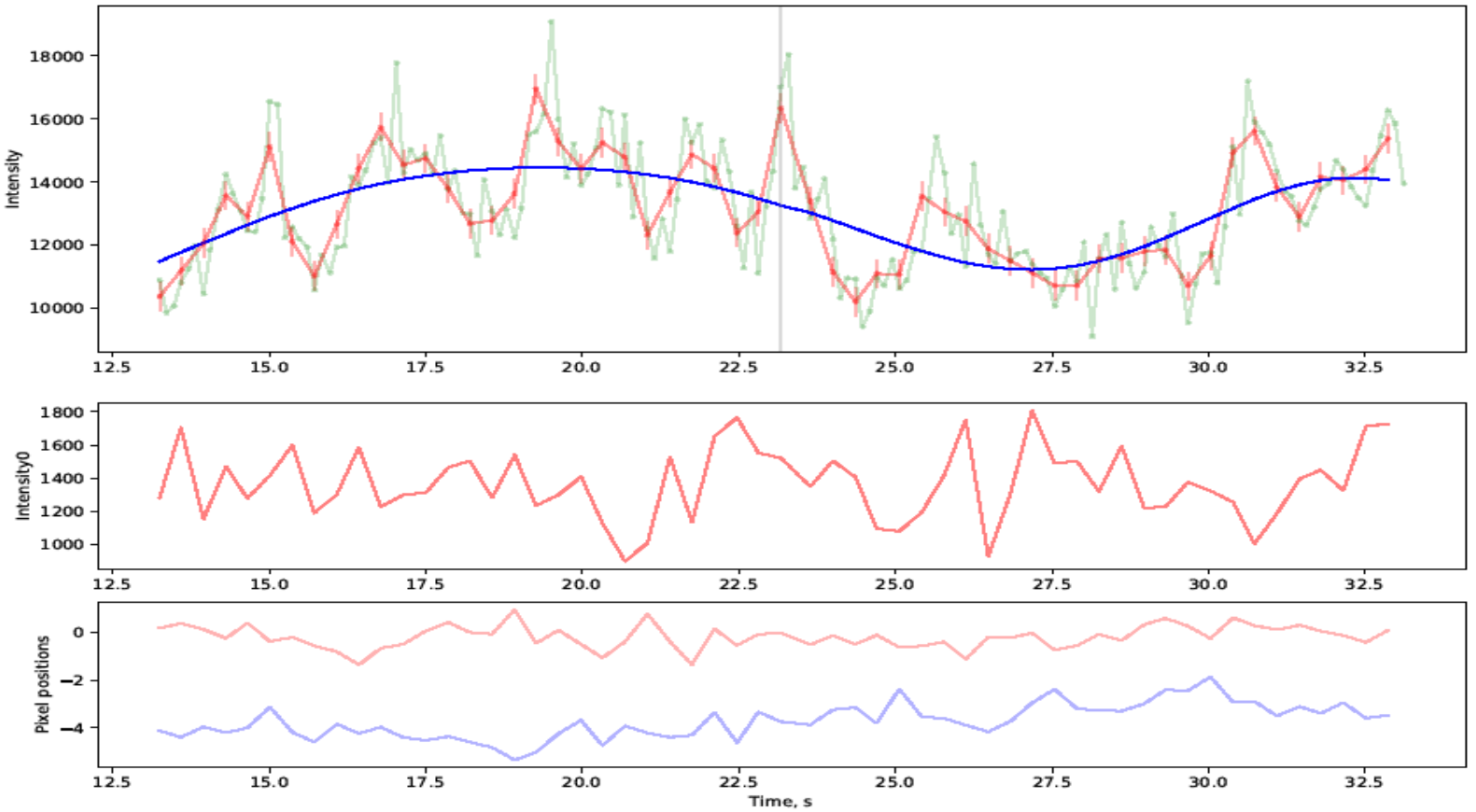
Polarimetry,

B (12 s),

P = 1.5 ± 0.5 %



Flares(--0.12s,--0.4s), rising time 0.2 – 1s, duration 0.5 – 30 s



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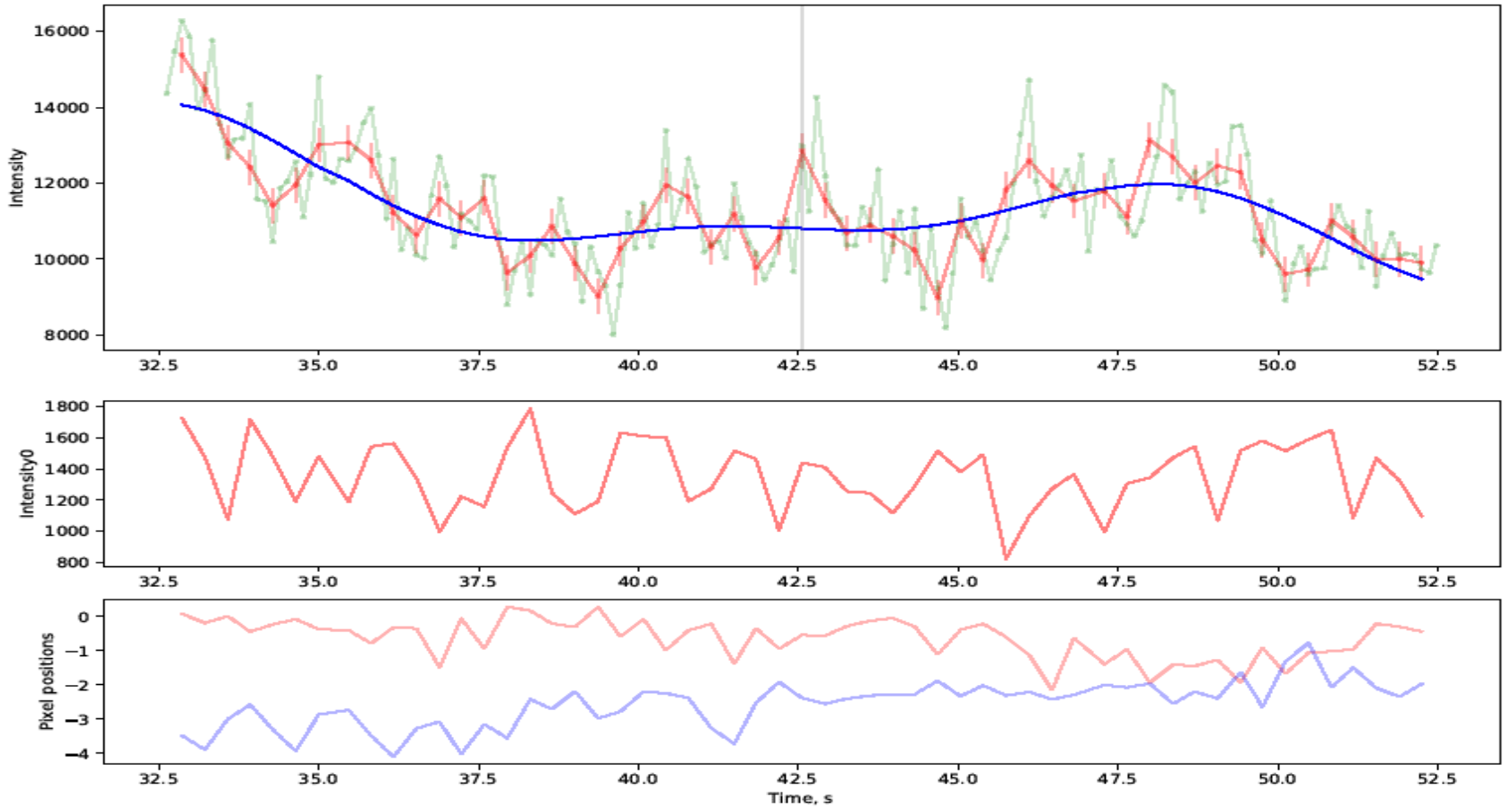
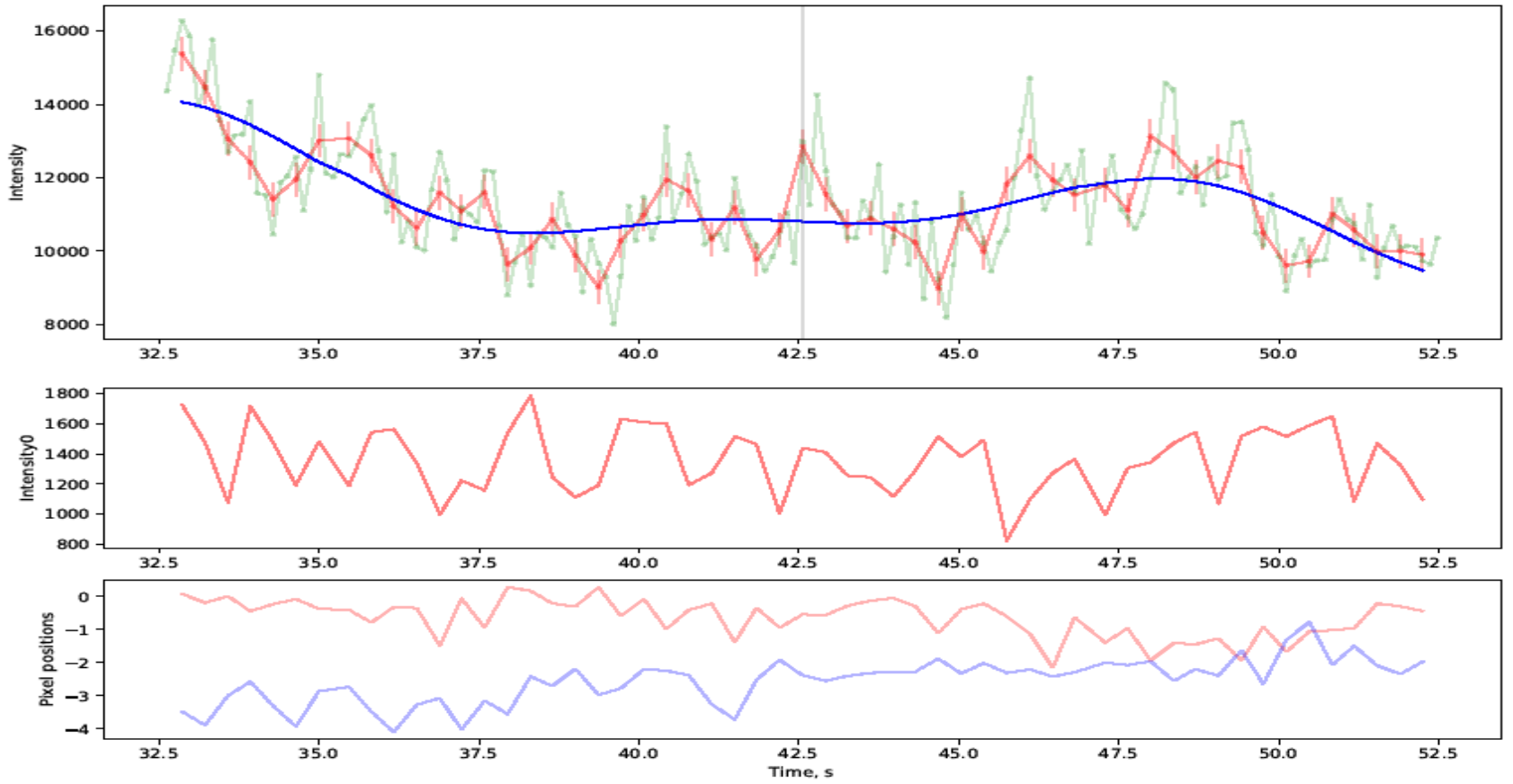
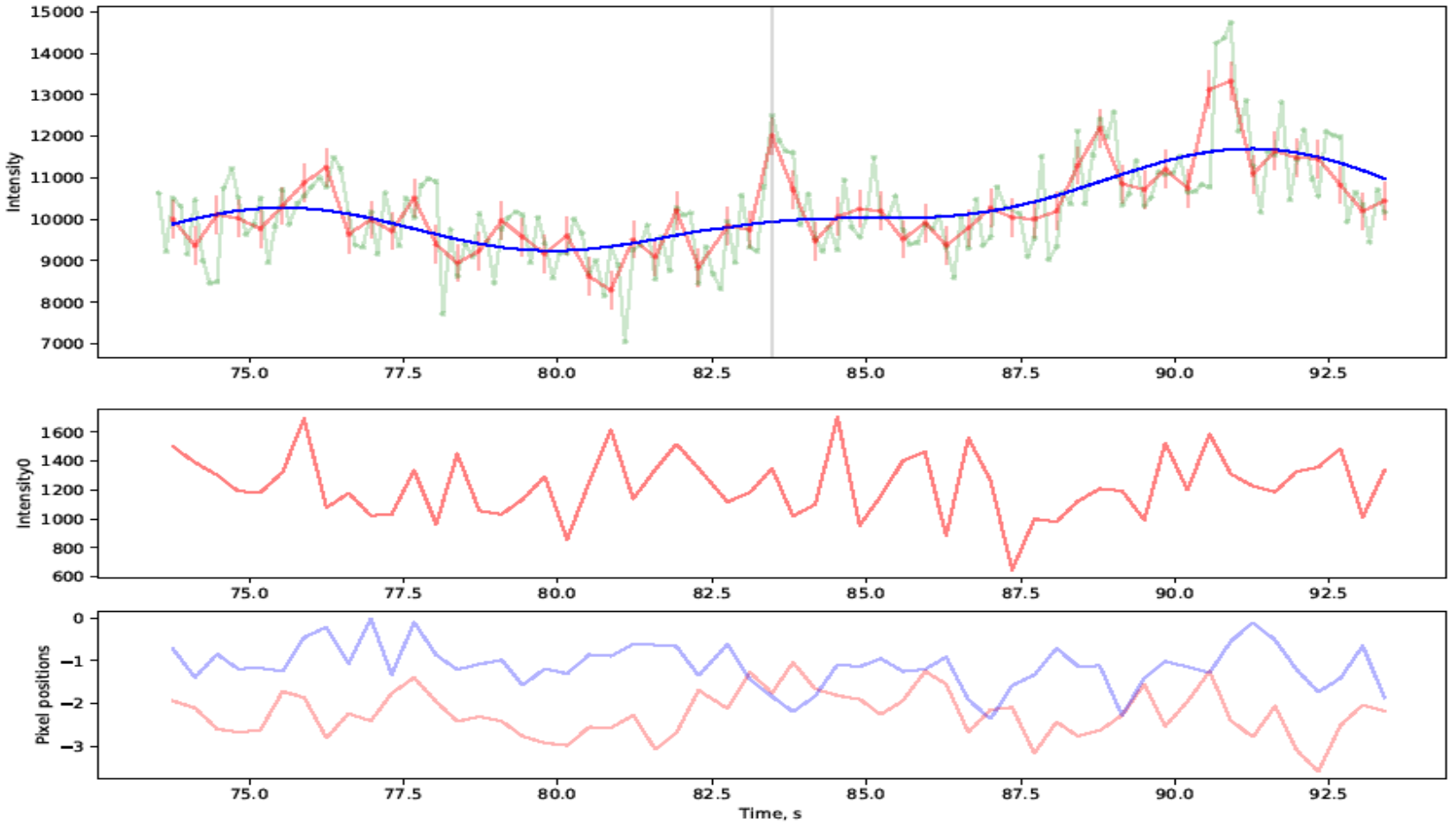


Flares(--0.12s,--0.4s), rising time 0.2 – 1s, duration 0.5–30 s



Flares(--0.12s,--0.4s), rising time 0.2 – 1s, duration 0.5–30 s



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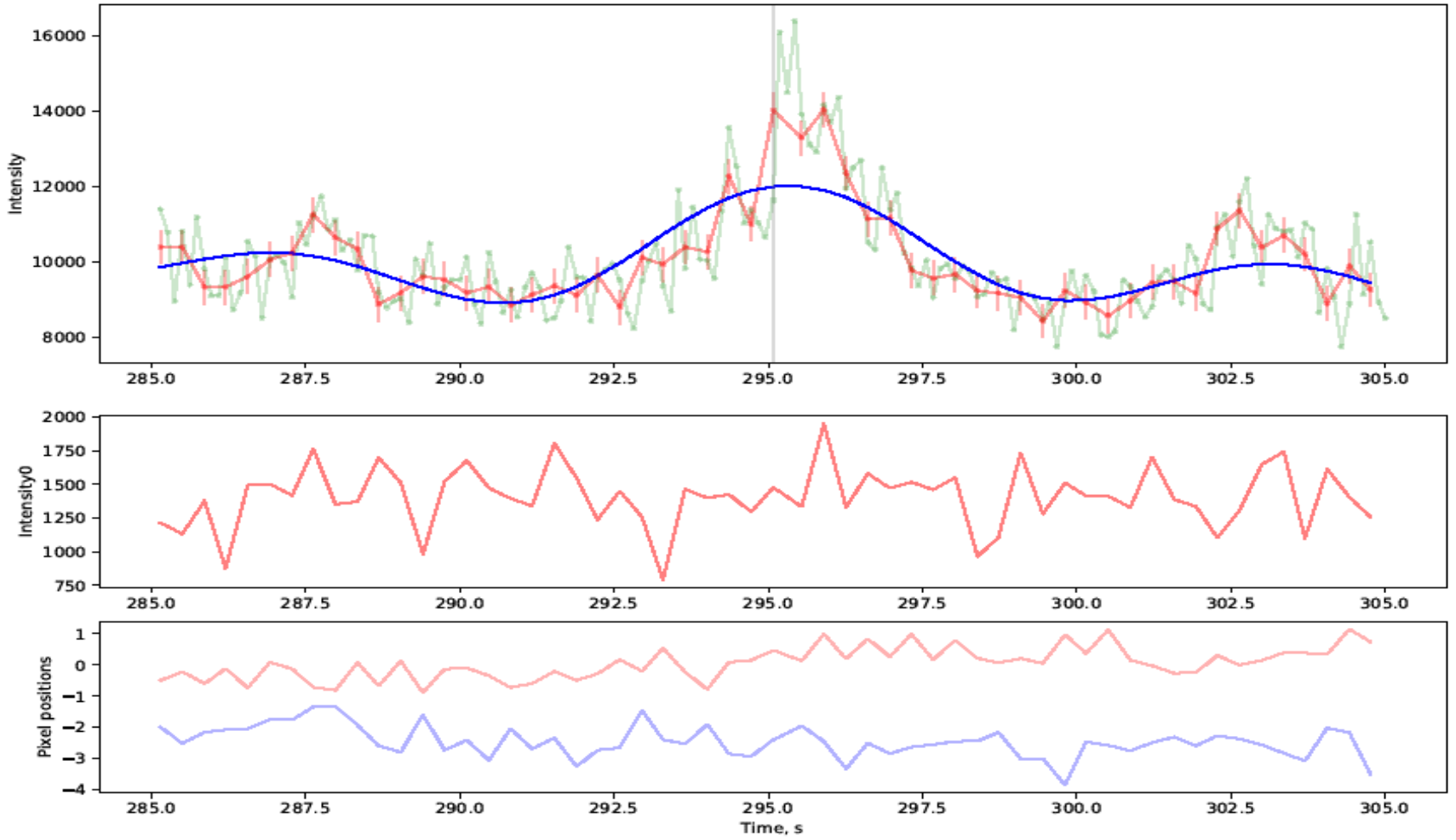
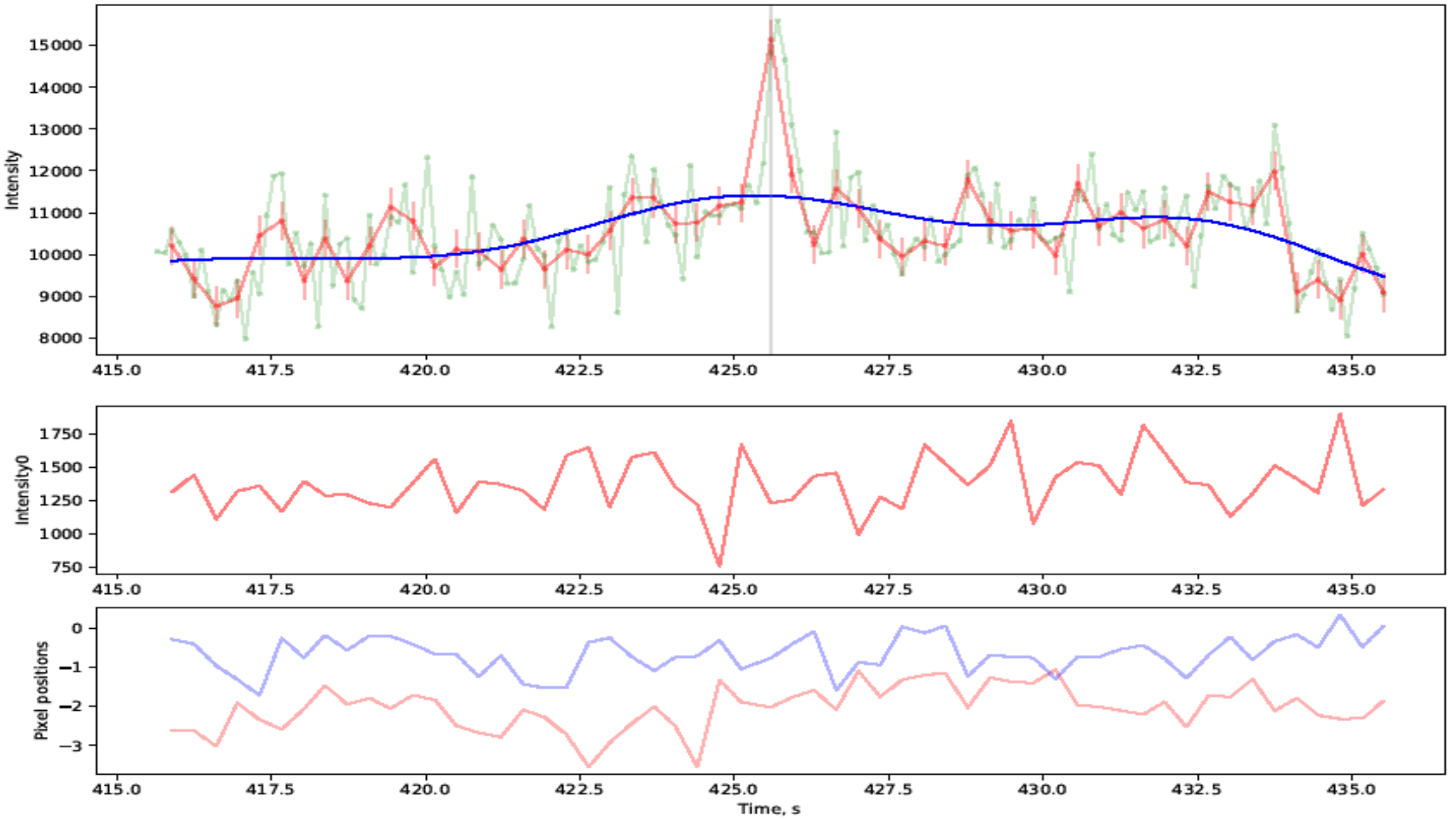
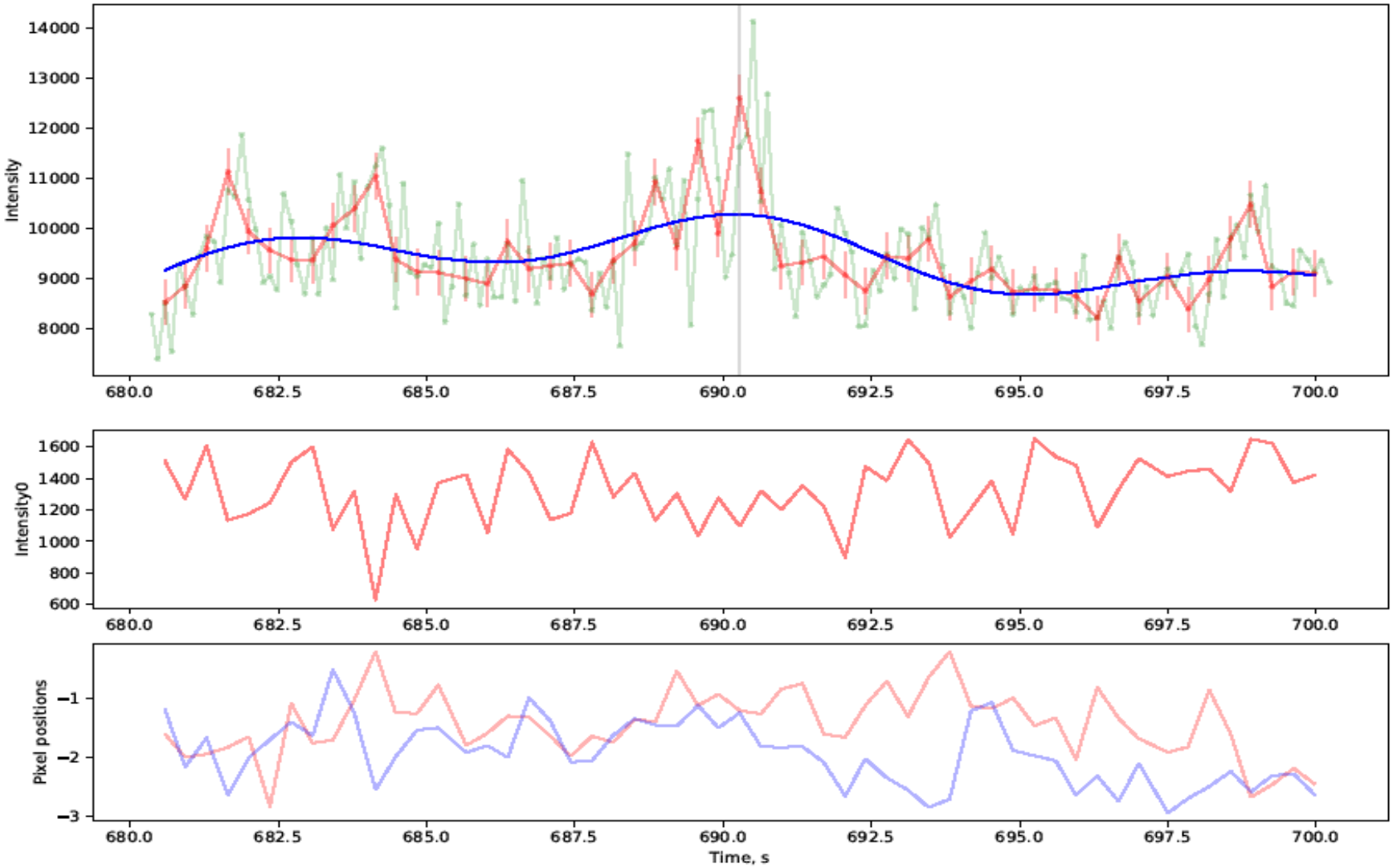


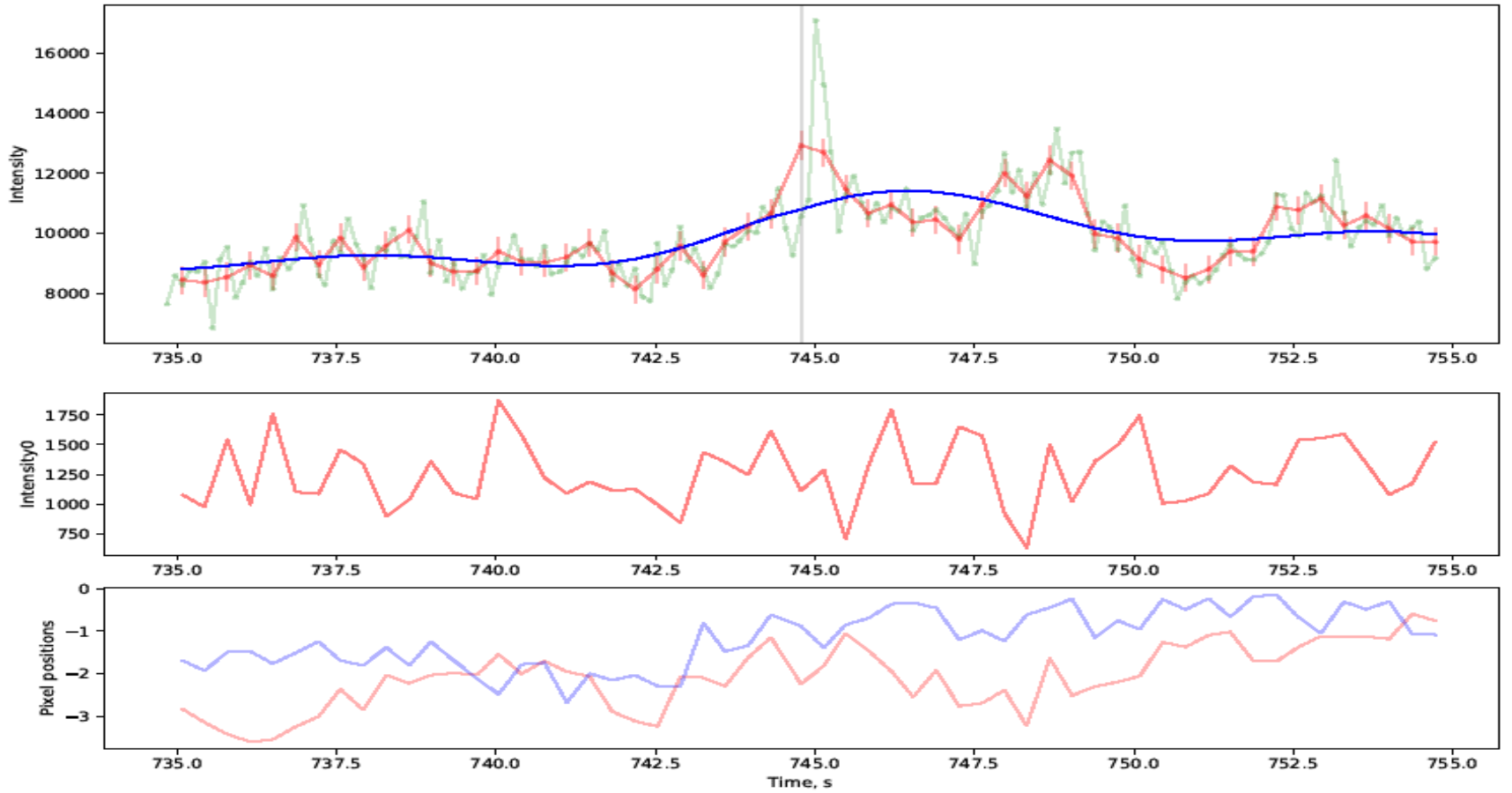
Flares(--0.12s,--0.4s), rising time 0.2 – 1s, duration 0.5 –30 s



Flares(--0.12s,--0.4s), rising time 0.2 – 1s, duration 0.5 –30 s



Flares(--0.12s,--0.4s), rising time 0.2 – 1s, duration 0.5 –30 s



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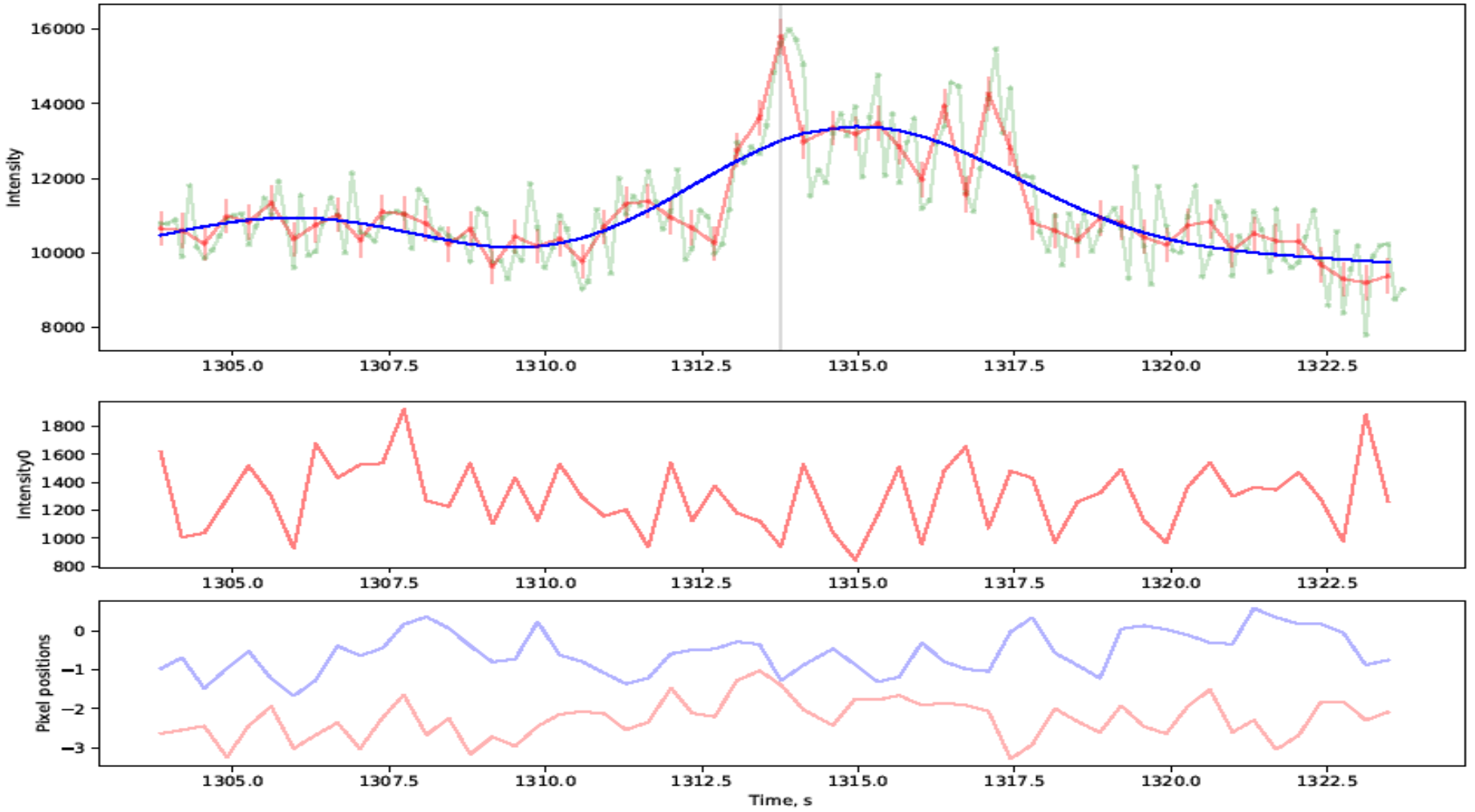
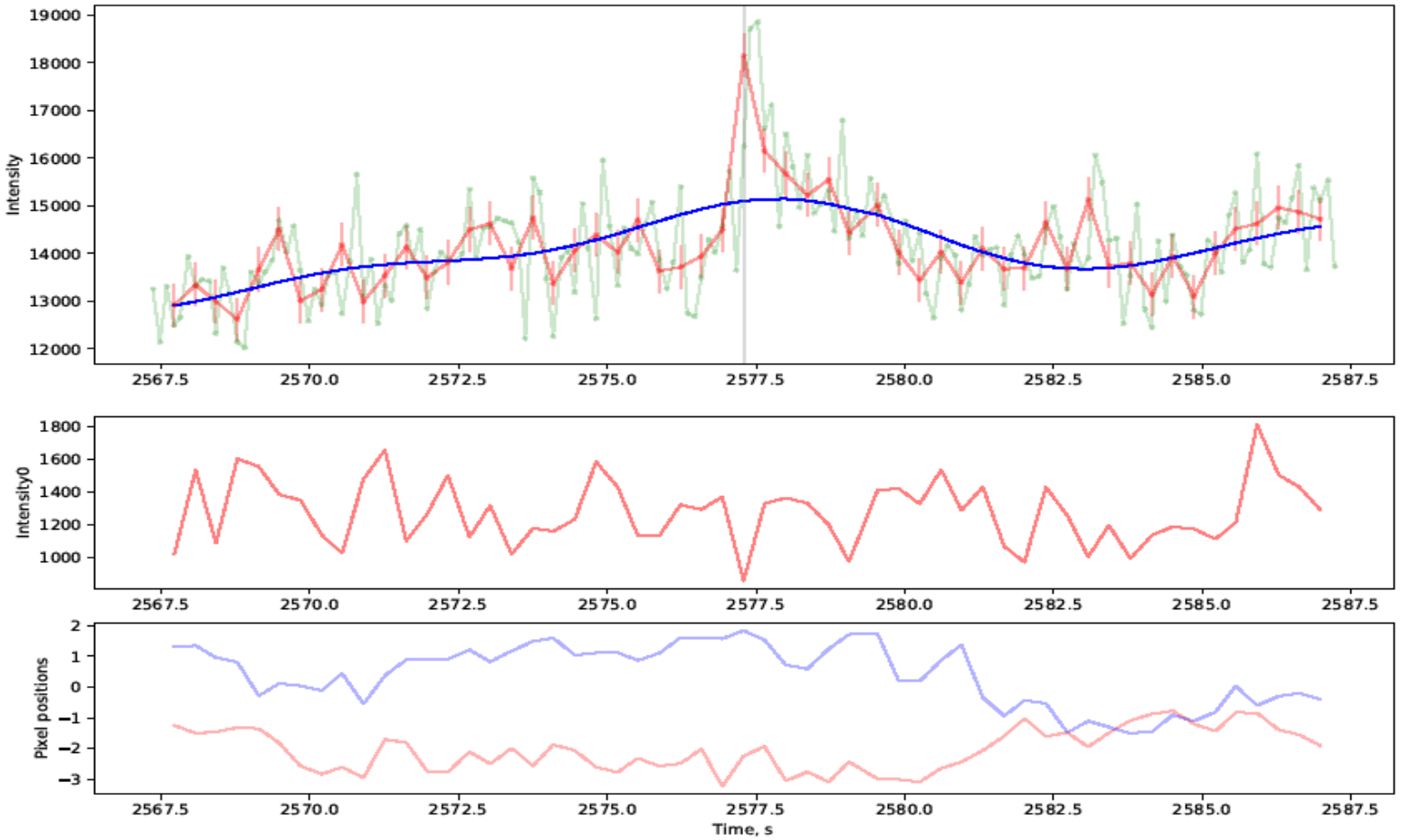


Flares(--0.12s,--0.4s), rising time 0.2 – 1s, duration 0.5 –30 s



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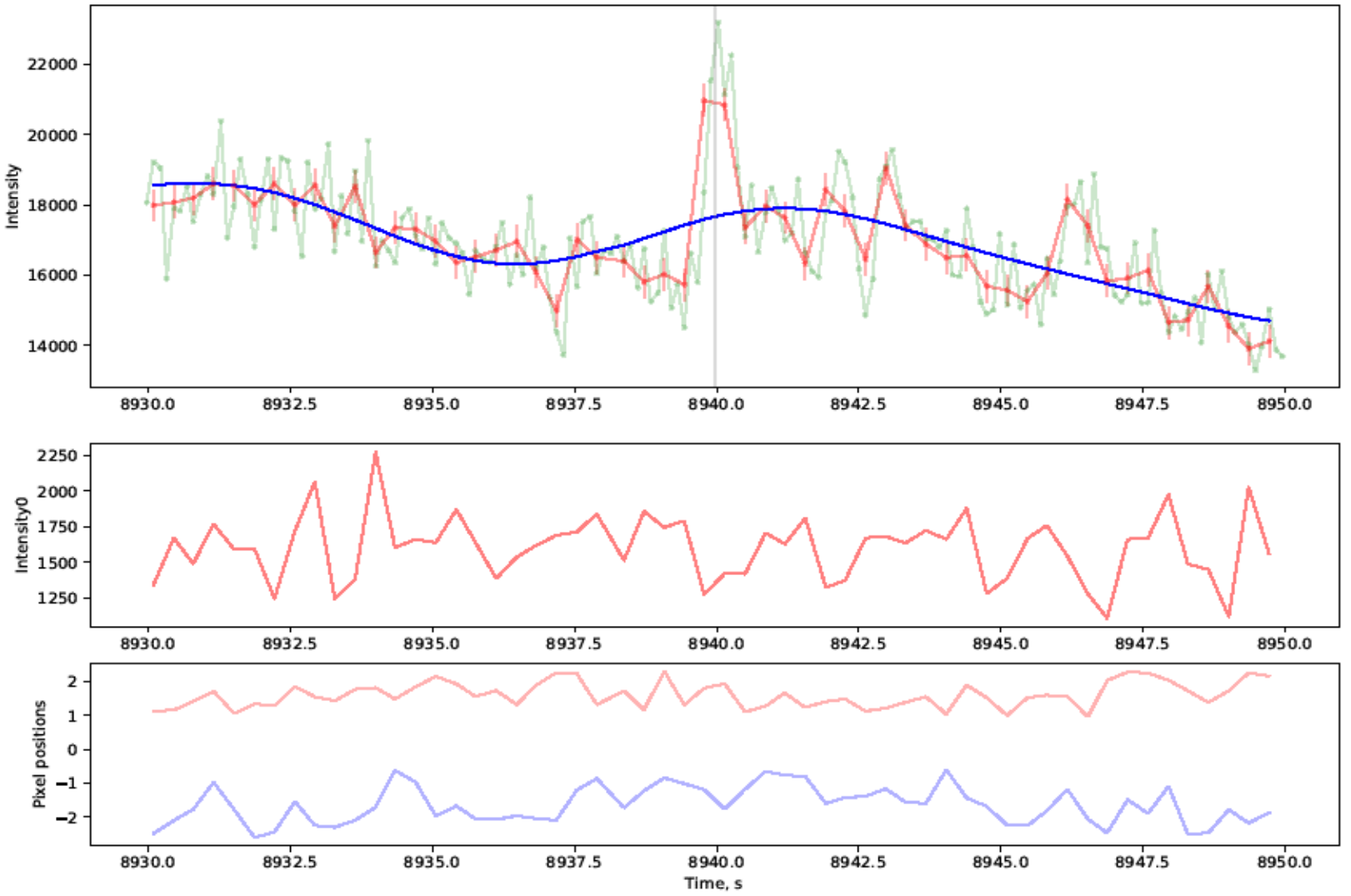

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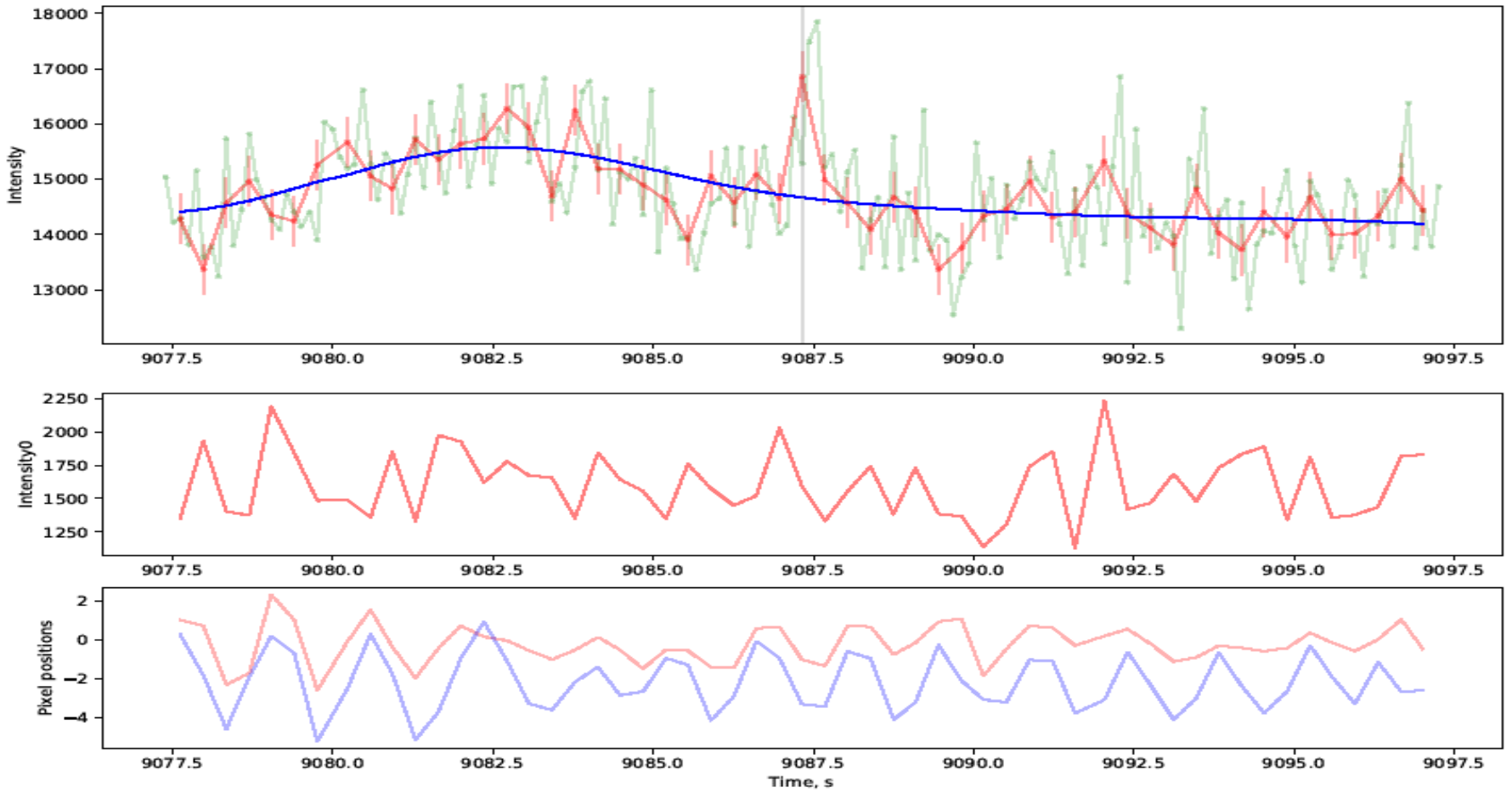
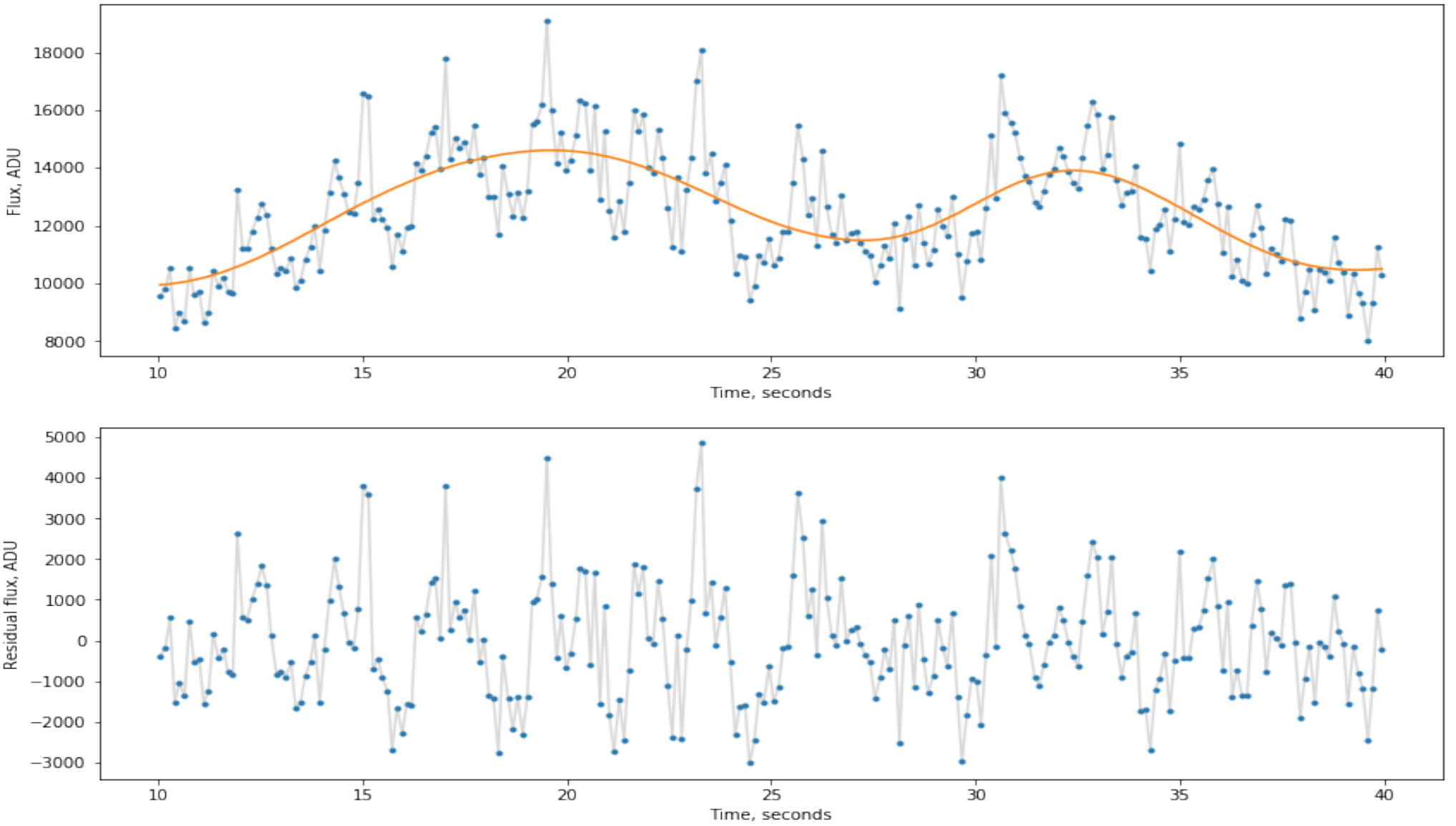
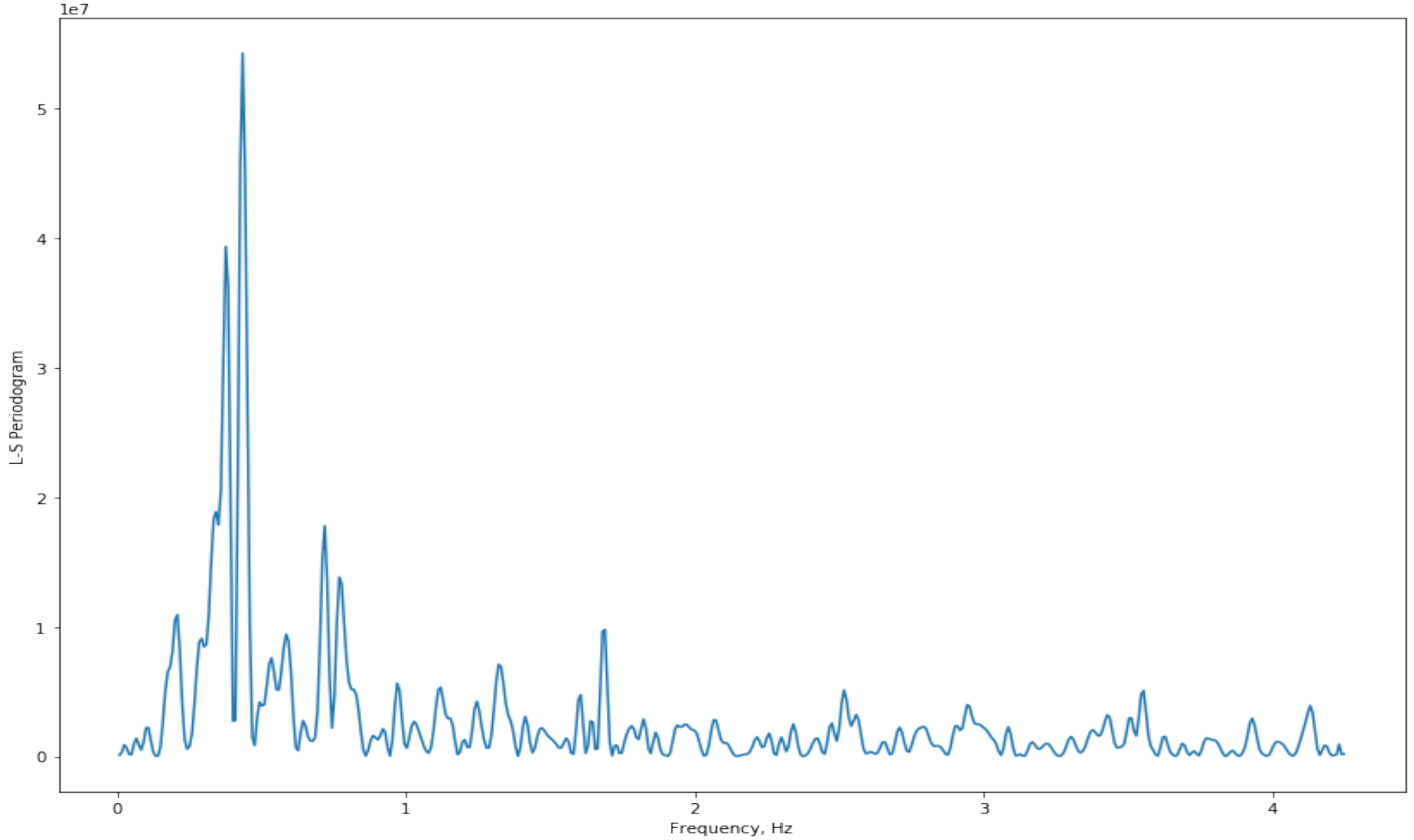


Periodical variations?



Lomb-Scargle Periodogram
P = 2.3-2.8 s



Summary

1. Generally first MANIA results are consistent with those of the ULTRACAM obtained in 2014:

J1023 is still in the LMXB state.

2. Stochastic variability at the times scales of 0.5s – several minutes, with amplitudes of 1.2 – 1.5, and the typical rising time or FWHM of 0.2s not previously resolved with the ULTRACAM at 3 times lower time resolution.

3. Sometimes unresolved spikes <0.12 s

4. Possible linear polarization 1.5 % (3 sigma) at time scales of 10 min. Too small for the jet ?

5. Correlation of U and B ~ 0.7, and flux increase - "reddening"

6. Sometimes quasi-periodical variations with P= 2.3 – 2.8 s

Nature: thermal ? fluctuations in the disc working in an unstable propeller regime??? a signature hot spots on the magnetosphere cusp ? **Needs deeper study and modelling!**

Plans

- Variability at different orbital phases and comparison with X-rays
- Specta (or SEDs) of flares
- Deeper polarization studies.
- Observations of other redbacks.