What can we learn from ULXs variability?

The amazing case of the Cartwheel galaxy

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1. ULXs (Ultra-Luminous X-ray sources):

- point-like
- non nuclear
- extra-galactic
- X-ray luminosity > 10^{39} erg s^{-1} (L_{Edd} for a $10M_{\odot}$ object)
- Accreting binary systems: a compact object (black hole or neutron star) plus normal star.

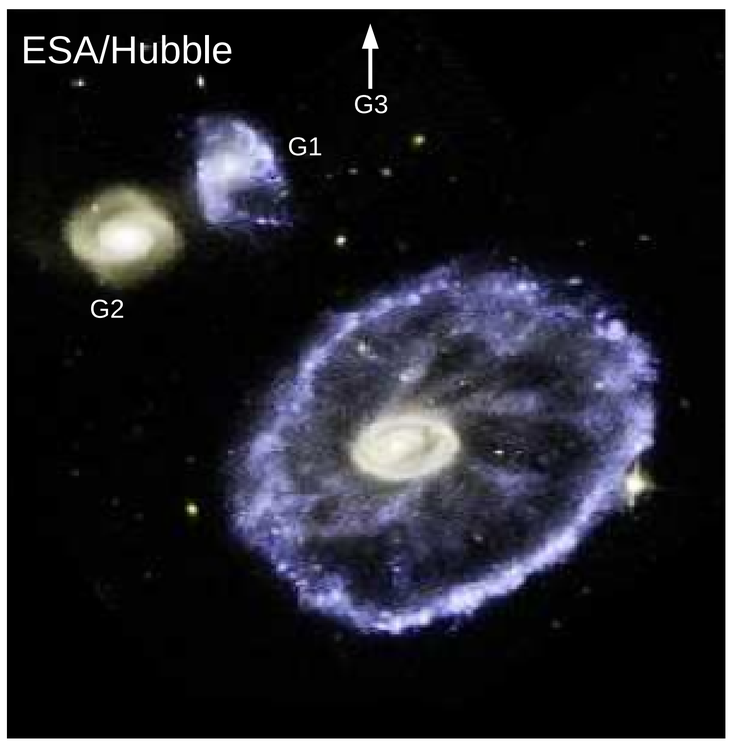
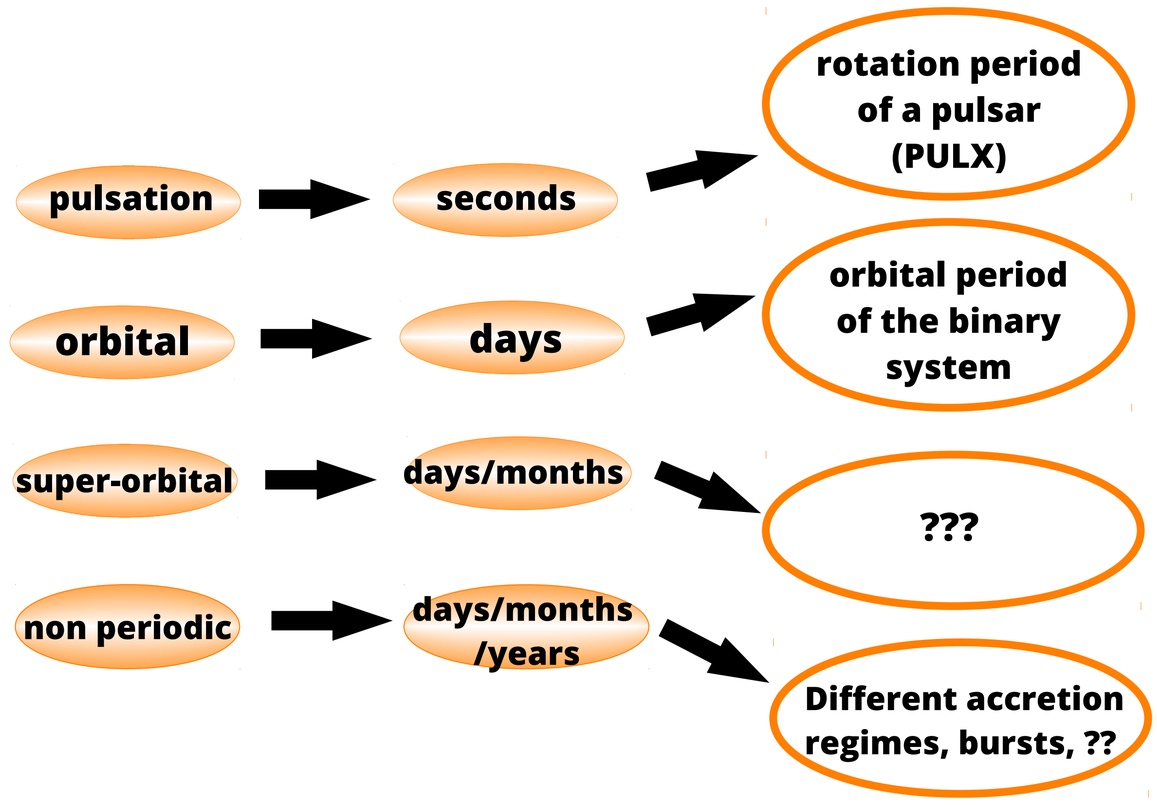


Fig.1: optical image (Hubble Space Telescope) of the Cartwheel Galaxy (on the bottom) and 2 of the companions in the upper part of the image: G1 (on the right) and G2 (on the left).
The fourth member G3 is further North. It is not included in this field of view but it is observed in X-rays.

2. VARIABILITY IN ULXs:

Flux variation - periodic or non periodic – on different time scales, from seconds to years.
(e.g. Bachetti+ 2014, Israel+ 2017, Walton+ 2016, Soria+ 2012, Heil+ 2009, Pizzolato+ 2010)



3. THE CARTWHEEL GALAXY:

- Collisional ring galaxy in a compact group of 4 members (Iovino 2002): name from its shape (origin: collision with a companion).
- Very high X-ray activity, connected with the shock wave that created the ring and triggered star formation.
- Largest number of ULXs in a single galaxy

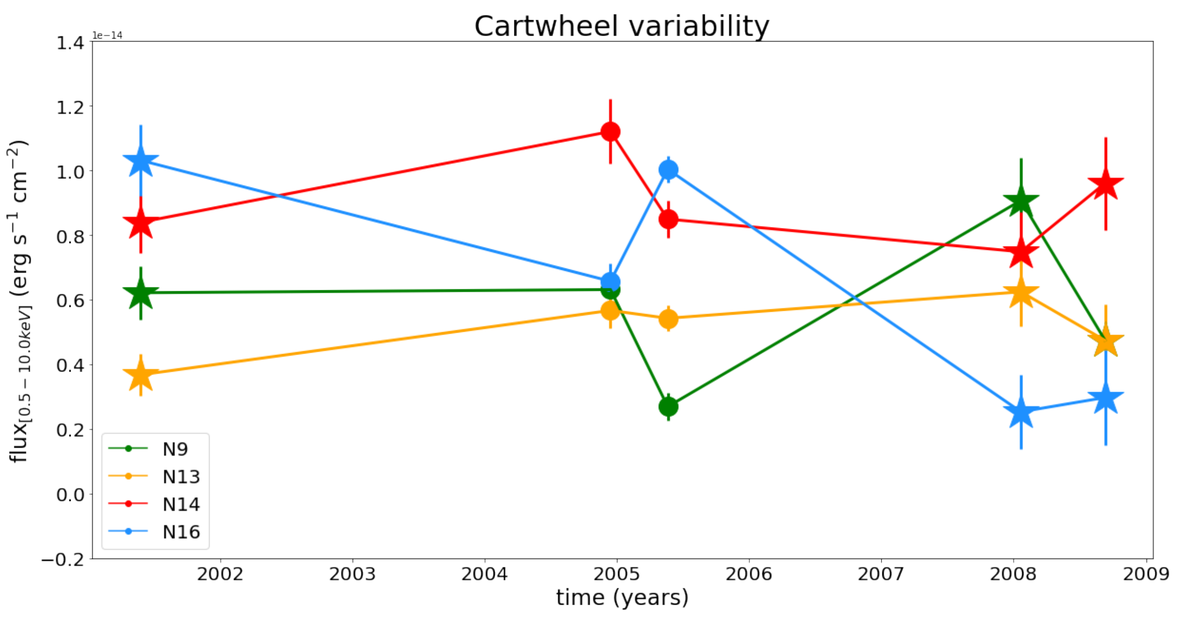


Fig.2: Long term light curve of 4 of the brightest sources in the ring of the Cartwheel galaxy: Chandra observations are indicated with a 'star', XMM-Newton observations with a 'dot'. $L_x \sim 10^{39} - 10^{40}$ erg s^{-1}.

4. OUR WORK:

- AIM: study of ULXs as a class and their variability.
- DATA: 3 Chandra (2001-2008; Wolter & Trinchieri 2004) and 2 XMM-Newton observations (2004-2005; Crivellari+ 2009).
- RESULTS: detection of 23 + 9 ULXs in the Cartwheel Galaxy and companions (7 never detected in previous works) (complete results in Salvaggio & Wolter, in prep.).

Flux and Variability:

- Assuming a power-law spectrum (Γ=2.2 and nH=1.9x$10^{21}$$cm^{-2}$ Wolter & Trinchieri 2004) we derive the flux for each source and we compare it with a constant flux, thanks to a Bayesian code based on the estimate of likelihood profiles (BLike code by Belfiore, private communication) which includes non-detections.
- The list of detected sources is different for each observation. 90.6% of the sources show non periodic variability (3σ significance) during the period of the observations (about 8 years).
- We also investigate short term variability (during the observation) with a Kolmogorov-Smirnov test. No variability is detected but the statistics is very low.

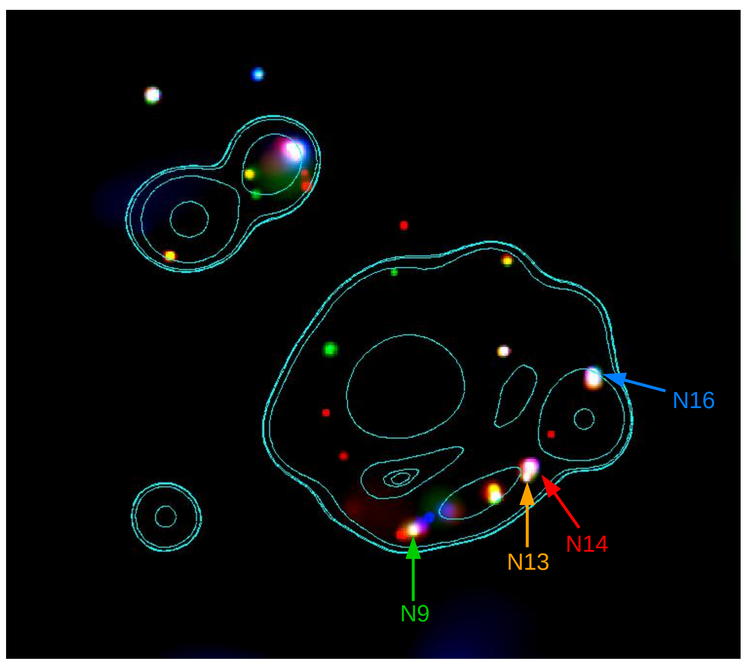


Fig.3 RGB image of the smoothed Chandra data: combination of three epochs to highlight variability – each data-set in a different color (May 2001 = red, Jan 2008 = green, Sep 2008 = blue). North is up and East to the left. We superpose optical contours from the DSS.

5. Companion Galaxies: the Cartwheel Galaxy has 3 companions: G1, G2 and G3. Also these galaxies show X-ray emission.

- 7 ULX in G1 ($L_x^{tot} \sim 6\times10^{40}$ erg s^{-1}): G1 sources are variable between observations with a behaviour similar to those in the Cartwheel.
- 2 single sources N1 and M32, associated respectively with G2 ($L_x^{tot} \sim 1\times10^{40}$ erg s^{-1}) and G3 ($L_x^{tot} \sim 5\times10^{40}$ erg s^{-1}).
- The total emission derives from the gas and the unresolved sources.