Stars and their variability observed from space
C. Neiner, W. W. Weiss, D. Baade, R. E. Griffin, C. C. Lovekin, A. F. J. Moffat (eds)

INSTRINSIC X-RAY VARIABILITY OF O STARS AND WOLF-RAYET STARS

A.M.T. Pollock[1]

Abstract. X-rays are produced in the radiatively-driven winds of O stars and Wolf-Rayet stars and show irregular variability of a few per cent amplitude on time scales of hours and days. How this slow X-ray chaos relates to the lower amplitude, more rapid optical chaos being revealed by TESS is not known.

Keywords: X-rays: stars, Stars: early-type, Stars: Wolf-Rayet, Stars: variables: general

1 X-rays from massive stars

Only a handful of single O stars and Wolf-Rayet stars are bright enough with current technology to have high-resolution X-ray spectra. The broad emission lines with widths about $\frac{3}{4}$ of the UV terminal velocities show that the X-rays are produced out in the supersonic stellar winds. The most popular theory, although incomplete, appeals to microscopic shocks that develop from instabilities in the wind line-driving mechanism. Accumulated intermittently over several years as part of XMM-Newton calibration, the aggregated 1 Ms high-resolution X-ray spectrum shown in Figure 1 of the single O4 supergiant ζ Puppis by the Reflection Grating Spectrometer (RGS) shows strong lines from highly-ionised abundant elements and little or no electron continuum. Apart from its unusually strong lines of NVI and NVII, testament to a high nitrogen abundance, it is typical of the soft X-ray spectra intrinsic to single massive O stars and Wolf-Rayet stars.

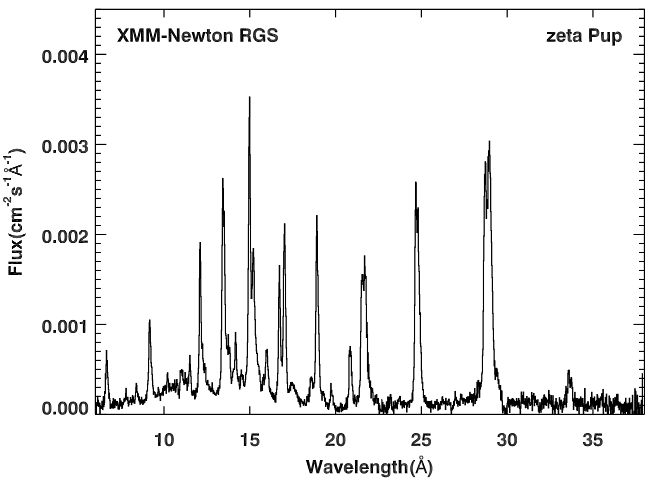

Fig. 1. XMM-Newton RGS high-resolution X-ray spectrum of the single O4 supergiant ζ Puppis.

2 X-ray variability instrument of choice

The ideal instrument combines linearity and stability with high sensitivity. The XMM-Newton EPIC-pn instrument acting as an imaging photometer is by far the best currently available. It also has the advantage of working alongside the other XMM instruments including the RGS. The pn's exceptional instrumental stability at a level of about 0.1% is demonstrated through repeated observations over many years of the very X-ray bright LMC SNR N132D shown in Figure 2.

[1] Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK

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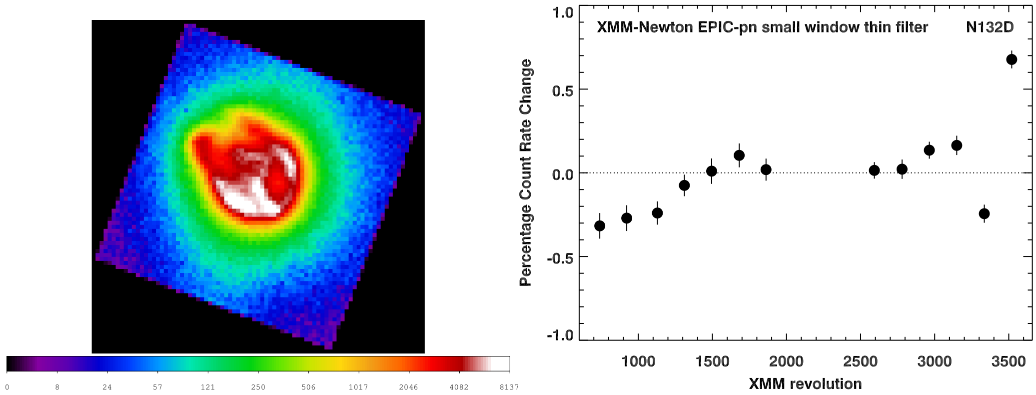

Fig. 2. XMM-Newton EPIC-pn observations of the LMC SNR N132D with the image left and the long-term light curve right.

3 X-ray variability

Even fewer massive stars have variability measurements. These all show that the X-ray brightness is not constant. XMM-Newton EPIC-pn light curves of the single O4 supergiant ζ Puppis show smooth irregular changes with an amplitude of a few percent on time-scales generally of a few days. This type of variability that might be classified as slow chaos has also been observed in all other hot stars with suitable data including δ Orionis and EZ CMa = WR6. Accumulated over several years by the EPIC-pn in parallel with the RGS spectrum above, the X-ray light curve of ζ Puppis of 1ks resolution on the left of Figure 3 has the unobserved gaps greatly reduced between typically annual observations. The Median Absolute Deviation measure of variability, or MAD, is only 3%, too small for other instruments to measure. There is no periodic signal with variations appearing stochastic or chaotic.

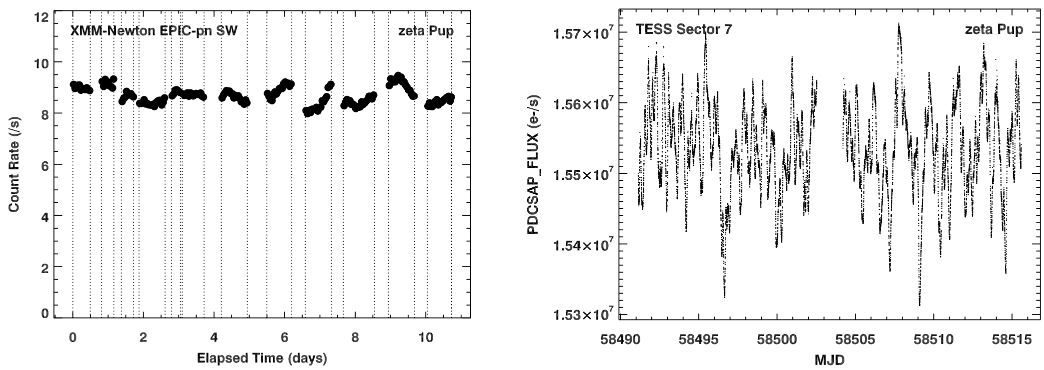

Fig. 3. Comparative X-ray and optical light curves of the O4 supergiant ζ Puppis from XMM-Newton EPIC-pn on the left and TESS on the right.

4 Towards a coherent physical synthesis

The well-developed theory of mass loss in hot stars holds that the powerful supersonic winds in O stars and Wolf-Rayet stars are driven by radiation pressure. TESS data have recently revealed the variability of the driving force through the beautiful material freely available in exemplary fashion through the MAST Archive as shown on the right of Figure 3 for ζ Puppis in one of two sectors. Here the MAD is 0.29%, an order of magnitude smaller in amplitude than in X-rays on time scales similarly perhaps an order of magnitude faster. It seems at least plausible that instead of responding to instabilities that X-rays are produced by interacting shocks out in the wind responding to variable radiation pressure. One of many unknowns concerns X-ray variability time scales because no observations have ever been long enough, a circumstance that will only be resolved through concerted community efforts.