A close look at the RGS spectra of the O4Ief star ζ Pup

G. Rauw[1], A. Flores[2,1], Y. Nazé[1], A. Hervé[1], & L. Oskinova[3]

([1]Institut d'Astrophysique et de Géophysique, Université de Liège, Belgium; [2]Universidad de Guanajuato, Mexico; [3]Astrophysik, Universität Potsdam, Germany)

ζ Puppis (O4Ief) is the visually brightest O-star in the sky and has been extensively studied over all wavelengths. The UV and visible spectra display recurrent variations on various time scales :

- 8.5 hrs: non-radial pulsations (Reid & Howarth 1996, A&A 311, 616)
- 17 – 19 hrs: discrete absorption components in the UV (Howarth et al. 1995, ApJ 452, L65) and 0.9 – 2.0 keV ROSAT count rate (Berghöfer et al. 1996, A&A 306, 899)
- 5 days: rotational modulation of the Hα emission line (Moffat & Michaud 1981, ApJ 251, 133).

ζ Pup was observed frequently as a calibration source with the RGS. We have extracted all public data with sufficient exposure time (see table).

XMM Revolution	HJD – 2 450 000	Duration (ksec)
0091	1703.90	57.5
0156	1832.78	40.6
0535	2589.49	42.4
0538	2595.80	43.1
0542	2603.36	43.7
0552	2623.74	40.2
0636	2790.32	72.9
0903	3323.52	65.7
0980	3477.12	64.2
1096	3708.52	53.7
1164	3843.42	56.9
1343	4200.46	63.9
1620	4753.54	64.1

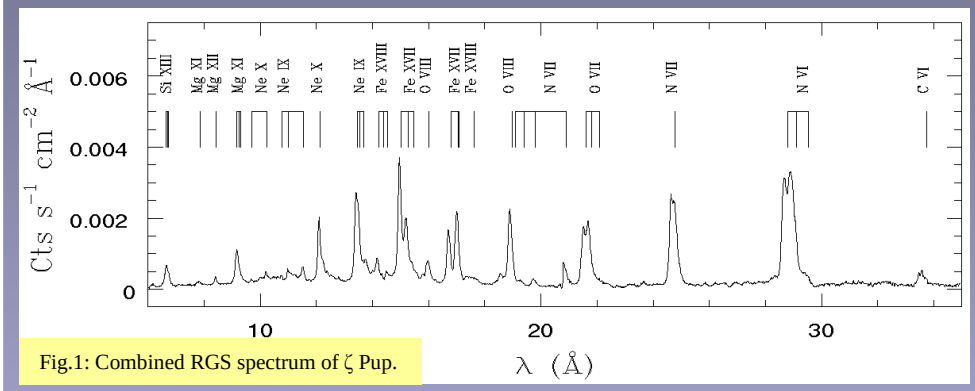
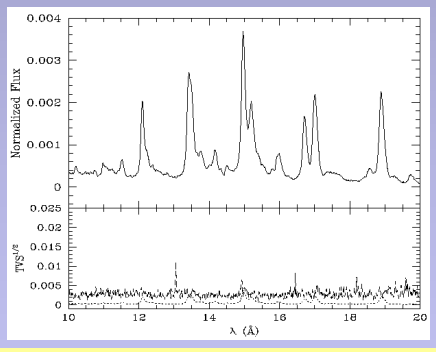
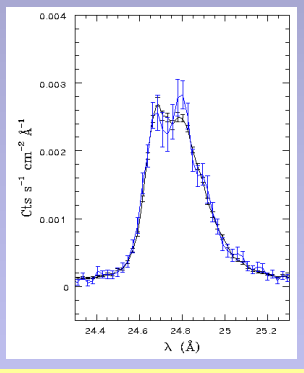


Fig.1: Combined RGS spectrum of ζ Pup.

We have investigated the X-ray variability of ζ Pup on time scales from weeks to years using the Temporal Variance Spectrum (a weighted mean of the deviations between individual spectra and the mean spectrum; see Fullerton et al. 1996, ApJS 103, 475). No significant variability is detected in any of the lines, although comparison of individual observations with the mean line profiles suggest the existence of marginal variability, especially in the (apparently) double-peaked N VII λ 24.78 Ly α line. Although this line is affected by a blend with a weaker N VI λ 24.90 line and could be optically thick, we note that this possible variability is reminiscent of the one seen in the optical He II λ 4686 line (see Fig. 2).





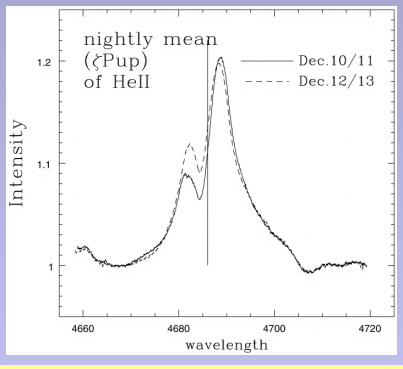


Fig.2: Left: TVS of a subsection of the spectrum of ζ Pup. No significant variability is detected. Middle: comparison between the N VII Ly α line on the mean spectrum and on the observation from revolution 1096 (blue line). Marginal variability of the relative intensity of the emission peaks is seen. Right: for comparison an example of the nightly variations of the He II λ 4686 line (from Eversberg et al. 1998, ApJ 494, 799).

We are currently analysing the shapes of individual X-ray lines using a dedicated code that accounts for absorption by the wind (either homogeneous, porous or clumpy). In this initial analysis we consider the hot plasma to be optically thin, and account only for the cool wind absorption. Some examples with a smooth wind model are shown for the O VIII λ 18.97 Ly α and N VII λ 24.78 Ly α lines. Here, the main parameters are R_0 the inner radius of the X-ray emitting plasma and $\tau_* = (\kappa\, dM/dt)/(4\,\pi\, R\, v_\infty)$, the optical depth of the wind. Our best-fit parameters differ from those of Cohen et al. (2010, arXiv:1003.0892) based on a similar fit to much lower S/N Chandra data. Our mean RGS spectrum is by far the highest quality X-ray spectrum of an O-type star to date and a more sophisticated analysis with clumpy wind models is currently under way.

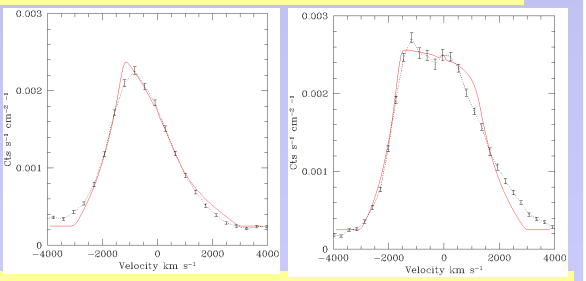


Fig.3: Smooth wind model fit of the Ly α line of O VIII (left) and N VII (right). The best fit parameters are R_0 = 1.65 and 2.5 R_* and τ_* = 1.2 and 0.2 respectively.

Conclusions: The existing XMM-Newton RGS data of ζ Pup provide the highest quality X-ray spectrum of an O-star. We find some indications of low-level line profile variability similar to what is observed in the optical and UV domain. However, the current generation of high-resolution X-ray spectrographs lack the sensitivity to investigate this phenomenon in detail. The quantum leap in collecting area expected from IXO will allow us to perform the first in-depth studies of this kind.