A DETAILED X-RAY INVESTIGATION OF ζ Puppis. II. THE VARIABILITY ON SHORT AND LONG TIMESCALES

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ABSTRACT

Stellar winds are a crucial component of massive stars, but their exact properties still remain uncertain. To shed some light on this subject, we have analyzed an exceptional set of X-ray observations of ζ Puppis, one of the closest and brightest massive stars. The sensitive light curves that were derived reveal two major results. On the one hand, a slow modulation of the X-ray flux (with a relative amplitude of up to 15% over 16 hr in the 0.3–4.0 keV band) is detected. Its characteristic timescale cannot be determined with precision, but amounts from one to several days. It could be related to corotating interaction regions, known to exist in ζ Puppis from UV observations. Hour-long changes, linked to flares or to the pulsation activity, are not observed in the last decade covered by the XMM observations; the 17 hr tentative period, previously reported in a ROSAT analysis, is not confirmed either and is thus transient, at best. On the other hand, short-term changes are surprisingly small (<1% relative amplitude for the total energy band). In fact, they are compatible solely with the presence of Poisson noise in the data. This surprisingly low level of short-term variability, in view of the embedded wind-shock origin, requires a very high fragmentation of the stellar wind, for both absorbing and emitting features (>10³ parcels, comparing with a two-dimensional wind model). This is the first time that constraints have been placed on the number of clumps in an O-type star wind and from X-ray observations.

Key words: stars: early-type – stars: individual (zeta Pup) – X-rays: stars

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1. INTRODUCTION

Stars more massive than 20 suns are the true “cosmic engines” of our universe. Through their winds and final explosions as supernovae, they shape the interstellar medium and largely contribute to its chemical enrichment. Besides, those stars are the most luminous ones, the only ones seen from afar. Studying distant galaxies or our close neighborhood thus requires a good knowledge of these objects. However, one of their most crucial physical properties, the stellar wind, remains poorly constrained.

In recent years a large debate arose in the massive star’s community regarding the structure and strength of such winds. Based on the analysis of resonance lines in UV and FUV spectra, Bouret et al. (2005) and Fullerton et al. (2006) revised mass-loss rates of a sample of O-type stars by orders of magnitude down compared to those obtained from Hα and radio diagnostics. Oskinova et al. (2007) showed that including wind clumping in the analysis of UV resonance lines yielded mass-loss rates in agreement with those derived from Hα (see also Sundqvist et al. 2011; Šurlan et al. 2012). These estimates crucially depend on the degree of wind clumping and exact properties of these clumps.

In this debate, X-ray observations may well play a crucial role. Indeed, the first high-resolution spectra of massive stars revealed line profiles which were more symmetric and less blueshifted than expected (e.g., Kramer et al. 2003), triggering (for a large part) the current mass-loss debate. The first global fitting of high-resolution X-ray spectra has just been attempted and it is showing the clumps to be rather spherical (and not “pancake-like”), the non-porosity of the wind, and some of the plasma emitting components to be distributed over large regions (up to a hundred stellar radii in size, Hervé et al. 2012, and A. Hervé et al., submitted).

Another observable parameter, the variability, could also be used to learn about the wind structure. Indeed, the intrinsic instability of line-driven stellar winds generates clumps and shocks between clumps, which in turn produce high-energy emission over a large zone (Lucy & White 1980; Feldmeier et al. 1997b). This “embedded wind-shock model” currently is the standard model for X-ray production. Because the X-rays are directly born in the winds, their variability provides strong constraints on the wind structure. Hydrodynamical simulations showed the highly changing level of the produced X-rays, a variability which could only be lowered if many clumps were present (Feldmeier et al. 1997b). A quantitative, theoretical assessment of the interplay between clump number and variation level, for different energy ranges, was performed only recently (Oskinova et al. 2004).

On the observational side, searches for such high-energy variations were undertaken with several facilities, the most thorough work having been done with ROSAT (Berghöfer & Schmitt 1994b), but no significant short-term variation was detected in O-stars. However, the sensitivity of these early observations was poor, with relative error bars in ROSAT light curves amounting to several tens of percent, and they thus only provided weak constraints.

In the last decade, XMM-Newton has obtained an exceptional 1 Ms data set for a massive star, ζ Puppis. To date, there exists no more sensitive data set, or a data set with a better (time and spectral) coverage, for a massive star. We have thus undertaken the analysis of this data set, with the aim of constraining the
wind structure using X-ray variability. A first paper (Natzé et al. 2012, hereafter Paper I) has presented these data, explained their reduction, and provided some first results (notably the analysis of EPIC spectra). This second paper focuses on the detailed variations recorded with EPIC and RGS instruments. It is organized as follows: the target is presented in Section 2, and the observations in Section 3; the observed changes found on long, intermediate, and short timescales are described in Sections 4–6; the results are finally summarized in Section 7. The Appendix provides details on the results for each exposure.

2. ζ Puppis as a Variable Star

Being one of the closest and brightest massive stars, ζ Puppis (O4Ifnp) provides the opportunity to perform an in-depth investigation of its properties, notably its variability.

For example, ζ Puppis is well known for its spectral variations in the visible and UV domains. Some impressive variations have been reported, e.g., a 50% decrease of Hα strength over 2 years (Conti & Niemelä 1976) and a doubling of the H He ii λ 4686 and Hα line profiles over successive nights (i.e., from single line to double-peaked profiles; Wegner & Snow 1978). Periodic changes have also been detected, on short as well as longer timescales. A 5-day modulation found in the UV and optical data (Hα line, Si iv doublet at 1400 Å; photometry in the Strömgren b band) was interpreted as linked to the stellar rotation (Moffat & Michaud 1981; Balona 1992; Howarth et al. 1995; Berghöfer et al. 1996). Moffat & Michaud (1981) then further proposed that the inner wind regions are magnetically confined and forced to corotate with the star. Spectropolarimetric observations did reveal an equatorial compression of the stellar wind of ζ Puppis (Harries & Howarth 1996) but failed to indicate the presence of a strong magnetic field (Schnerr et al. 2008). Shorter-term changes of the UV and optical light profiles with periods in the range 2–20 hr were also reported by several authors (Baa de 1991; Reid et al. 1993; Howarth et al. 1995; Berghöfer et al. 1996; Reid & Howarth 1996, and references therein) and usually attributed to non-radial pulsations. Finally, Eversberg et al. (1998) detected stochastic substructures in the H He ii λ 4686 emission line moving away from the line center with time, which they interpreted as the signature of small-scale clumps.

In the X-ray domain too, the variability of ζ Puppis was investigated. Despite several early claims (Collura et al. 1989), Einstein observations did not reveal any significant variations: the false detections could be explained by instrumental effects (Snow et al. 1981; Berghöfer et al. 1996). ROSAT data, however, told another story (Berghöfer et al. 1996). Variations of the mean count rate at high energies (0.9–2.0 keV) were detected between the five ROSAT exposures, but only at a 2% significance level (i.e., lower than a 3σ detection). The longest ROSAT exposure (56.7 ks spread over 11 days) was also analyzed to look for short-term variations. While χ^2 and Kolmogorov–Smirnov methods did not yield definitive results, period folding techniques revealed the presence of a 1.44 day−1 frequency (=16.7 hr period) in the ROSAT high-energy band (i.e., 0.9–2.0 keV band). These high-energy variations have a small amplitude (about 6%), hence the period is detected with only “95% confidence,” but an additional fact reinforced the confidence in their presence: the X-ray variations appeared in phase with changes in the Hα profile. Berghöfer et al. (1996) then proposed that the periodic modulation of the wind density in the lower wind layers (as traced by Hα) triggers wind instabilities which, in turn, produce wind shocks and therefore X-rays. Berghöfer et al. (1996), however, cautioned that their results should be checked with better quality X-ray data, and a later study of an ASCA data set of ζ Puppis did not confirm the previous result (Oskinova et al. 2001a). Using the best X-ray data set available at the present time (18 XMM-Newton exposures spread over a decade), we now try to investigate in detail the X-ray variability of ζ Puppis.

3. XMM-Newton Observations and Their Reduction

In the past decade of XMM-Newton observations, the star ζ Puppis was observed during 18 exposures, mostly for calibration purposes. These data sets are excellent for studying the variability of ζ Puppis since (1) the scheduled exposure times were often long (up to ∼70 ks) and (2) the observing dates probe weekly, monthly, and yearly timescales. Unfortunately, many observations were affected by soft proton background flares, resulting in total exposure times reduced by about 30%. A summary of the observations, as well as a detailed discussion of the reduction process (using SAS v10.0.0) and of the spectra generation, is given in Paper I.

Up to five instruments aboard XMM-Newton simultaneously record the X-ray emission of sources (three with low spectral resolution: EPIC-pn, EPIC-MOS1, and EPIC-MOS2; and two with higher spectral resolution: RGS1 and RGS2). Because of their separate optical paths and detector characteristics, they can be considered as five independent instruments observing simultaneously. Indeed, the very different point spread function (PSF) observed with MOS1 and MOS2 is a clear example that no two instruments are identical aboard XMM-Newton, even if their names are similar. Furthermore, each observation corresponds to a particular realization of the noise: therefore, it is possible (and even expected!) that each realization will slightly differ from another one. In the case of the XMM-Newton observations of ζ Puppis, this means that a light curve recorded by one instrument will slightly differ from that recorded by another one, though they are compatible within the uncertainties. Having five independent data sets could be seen at first as a disadvantage, since any test or fitting will yield five not exactly identical answers, but that actually reinforces the conclusions. Indeed, it reminds us that looking at a single observation with a single instrument, as so often is done except when working with XMM-Newton, does not allow any cross-checking and thus leaves room for spurious signal—in such cases, one must always be very careful not to overinterpret the data. Having multiple data sets enables us to check any detected signal, and in what follows, we emphasize only the secure variations, i.e., the significant changes observed by all instruments (EPIC+RGS).

Our analysis is mainly based on the count rate light curves as they provide the most model-independent approach to the data. The EPIC light curves are composed of equivalent on-axis, full-PSF count rates, so that any offset or bad pixel problem was corrected to provide comparable light curves for all exposures (this possibility is not available for RGS). With this correction, all three EPIC detectors are considered to be stable over the spacecraft’s lifetime by the XMM calibration team. Therefore, the flux found from spectral fitting and the count rate derived in the same energy band are always related by a constant factor for a source with a constant spectral shape (which is the case for ζ Puppis; see Paper I): using one or the other will yield exactly the same result, and fluxed light curves will thus not convey more information than those made from count rates. It should also be noted that fitting the spectrum of ζ Puppis is actually not an easy task (see Paper I), since we are reaching the limits of the instruments and atomic data precision. Within these
limits and within the errors, the spectral shape of ζ Puppis is not changing from one observation to the next (see Paper I), but one could wonder whether this is true within an exposure. However, this would imply fitting spectra extracted in short time bins, and hence very noisy. Such fitting would be highly unreliable, unstable and it may even cause spurious changes in the spectral parameters, due to the complex spectral shape of ζ Puppis, the many local minima, and the uncertainties in atomic data. These spurious changes will thus blur the actual source variations, rendering the task of studying them impossible in practice. Working with count rates avoids these problems, yielding clear and direct information on a given energy band, if not on a given spectral parameter other than flux.

3.1. EPIC Light Curve Production

Light curves of the source and background were extracted using the SAS task epiclcorr for four time bins (200 s, 500 s, 1 ks, and 5 ks) and in seven energy bands: total (0.3–4 keV), Berghöfer’s band (0.9–2 keV), soft (0.3–0.6 keV), medium (0.6–1.2 keV), hard (1.2–4 keV), very hard (4–10 keV), and grand total (0.3–10 keV). The background and source regions are the same as for the spectral analysis (see Paper I).

The choice of the energy bands results from a compromise, taking into account the appearance of the ζ Puppis spectrum, count rates in each band, and previous results. Indeed, one has to test bands for which results were reported before. As explained in Section 2, a periodicity was found using ROSAT in the 0.9–2 keV band. This is why we define a “Berghöfer’s band,” to be able to confirm (or not) the presence of this signal in our much higher quality data. Another obvious choice is the total band, which enables us to use all available counts, and therefore get the smallest error, performing the most sensitive test of the overall level of the X-ray emission. Additional narrower bands (soft, medium, hard) are defined by taking into account the general spectral energy distribution (Figure 1). The soft and medium bands probe the brighter part of the spectrum (with count rates above ~0.6 counts s⁻¹ keV⁻¹), while the hard band enables us to investigate the tail of the spectrum. EPIC spectra showed a dim region around 0.6 keV, hence the choice of this energy to split soft and medium energy bands. Count rates are rather similar for these “narrow” bands: 0.8, 0.4, 1, and 0.4 counts s⁻¹ for MOS (respectively 2, 2, 3.5, and 1 counts s⁻¹ for pn) in the Berghöfer, soft, medium, and hard bands, respectively. The spectra appear very noisy above 4 keV, hence the choice of that energy as an upper limit for the main energy bands. Nevertheless, a (double) check was made as we want to ensure that including all data with >4 keV does not change the conclusions. Indeed, the grand total and total bands provide indistinguishable results. The very hard band would reveal the presence of very high energy phenomena (transient or not). For ζ Puppis, however, this band always presents a very low count rate, of the order of ~10⁻³ counts s⁻¹ for MOS (1 or 2), i.e., three orders of magnitude below the total band count rate, and similar to the background count rate in the same band for pn. This means that no bright emission at very high energies is present in this star, and we will therefore focus the analysis of ζ Puppis on the five main energy bands.

The choice of the time bins was also made by taking several factors into consideration. First, we considered the problem of sampling different timescales. As one wished to study ζ Puppis on as many timescales as possible, both short bins and longer bins are highly desirable. However, the upper limit on the time bin length is dictated by the length of the individual exposures (13 ks for the shortest ones) since at least a few bins are required for a meaningful analysis within the exposure itself. Second, we looked at the impact of errors. Our goal is to detect the most subtle variations of ζ Puppis. To this aim, we need to combine the smallest possible errors. Considering the count rates for the different bands and instruments (see above), we can reach a 5% error on MOS data in 200 s for the total band, in 500 s for the medium and Berghöfer bands, in 1 ks for the soft and hard bands; a 3% error on pn data in 200 s for the total band, in 500 s for the soft, medium, and Berghöfer bands, in 1 ks for the hard band. A time bin of 5 ks has been added to get 1% or less error on the total band and enhance the detection of longer-term changes within one exposure.

To check the influence of the background (which is much fainter than the source in all observations), three sets of light curves were produced and analyzed individually: the raw source+background light curves, the background-subtracted light curves of the source, and the light curves of the sole background region. The results found for the raw and background-subtracted light curves of the source are indistinguishable. An example of a light curve set is given in Figure 2.

Finally, two remarks must be made. To avoid very large errors and bad estimates of the count rates, we discarded bins displaying effective exposure time <50% of the time bin length. Our previous experience with XMM-Newton has shown us that including such bins degrades the results. It should also be noted that the SAS task epiclcorr provides equivalent on-axis, full PSF count rates, so that problems such as the presence of an offset or of bad pixels were corrected to provide comparable light curves for all exposures.

3.2. RGS Light Curve Production

The task rgslcorr yielded raw source+background light curves, background-corrected light curves for the source, and background light curves for 10 wavelength bins: total (6–30 Å, equivalent to 0.4–2 keV), Berghöfer’s band (6–14 Å, equivalent to 0.9–2 keV), soft (20–30 Å, equivalent to 0.4–0.6 keV), medium (14–20 Å, equivalent to 0.6–0.9 keV), N vi (28–30 Å), N vii (24.3–25.5 Å), O vii (21.3–22 Å), O viii (18.75–19.2 Å), Ne ix (13–14 Å), and Ne x (11.8–12.5 Å). They were calculated for each instrument (with both orders combined) and for the whole RGS (with both instruments and both orders combined). Note that the wavelength of the O vii line is at a gap of RGS2 while Ne x is in a gap of RGS1 (order 1).

As for EPIC, there were obvious choices, such as the total band or bands covering the strongest lines, but also choices dictated by previous reports (Berghöfer’s band), and compromises (soft and medium bands—the soft band is similar to its “twin,” the EPIC soft band, while the medium band appears in between soft and Berghöfer’s bands). The limits of the wavelength intervals were carefully chosen taking into account the global aspect of the high-resolution spectra (Figure 3). Limits of the bands fall in regions as free of lines as possible; the overall lower and upper limits are dictated by the increasing noise toward short and long wavelengths. It may be noted that count rates for the soft, medium, and Berghöfer bands are similar (about 0.5 counts s⁻¹). The bands covering lines were chosen to enclose the brightest isolated lines without enclosing too much of the neighboring continuum.

Again, as for EPIC, the choice of time bins represents a compromise between getting a sufficient number of counts to perform an analysis with a few percent relative error only and having enough bins within each exposure (of length 30 ks for...
bins of 500 s and 2 ks yield errors in the total band, for each RGS, of 7% and 3.5%, respectively; bins of 2 ks and 5 ks give errors in the soft, medium, and Berghofer bands of 7% and 3.5%, respectively; bins of 5 ks and 10 ks ensure errors of 10% and 5%, respectively, for bands linked to specific lines.

Note that, contrary to epiclccorr, the SAS task rgslccorr does not correct for lower recorded fluxes if the source appears off-axis. While this does not appear to be a problem for small offsets (<1.5'), the count rate of ζ Puppis during Rev. 0731 (where the offset reaches nearly 6') is clearly reduced, by about 25% in the total band. In addition, the count rate from Rev. 0091 at highest energies (shortest wavelengths) appears too high by about 20%. The origin of this problem is unknown (poor calibration at the earliest times of XMM-Newton operations or true brightening?—there is no EPIC data to confirm what happened). To avoid any interpretation problems, both data sets were discarded from global analyses (see Sections 4 and 5).

It is also important to remember that rgslccorr performs a randomization of the time tags, i.e., all runs of the same task, with the same parameters and input files, will produce slightly different results (the difference remaining within the error, of course). This is not the case for epiclccorr since a randomization is applied during the initial processing of the raw files (tasks epproc, emproc).

Figure 1. Position of the EPIC bands compared to the spectra from Rev. 1983 (top green points: pn, bottom black and red points: MOS).

(A color version of this figure is available in the online journal.)
4. LONG-TERM VARIATIONS (MONTHS TO YEARS)

4.1. Count Rates

To search for the long-term variations on timescales of months to years, we computed the average count rates for each exposure and checked their constancy using $\chi^2$ tests. We remind the reader of a few cautions. For RGS, the data points associated with Rev. 0731 are discarded from global analyses since the effective area changes due to the off-axis position of $\zeta$ Puppis are not taken into account in rgsleccorr. The data from Rev. 0091 are also discarded since they yield suspiciously high count rates (see XMM user handbook\(^5\) and Section 3). For EPIC, the pn data taken with the Medium filter are most probably still slightly affected by pileup (see also Paper I). Indeed, they yield clearly erratic results: while Revs. 535, 538, and 542 provide very similar count rates for their Thick filter data, this is not the case for their Medium filter data. Thereby considering only the best (i.e., most reliable) data, it clearly appears that the count rates are not stable over timescales of years (Figures 4 and 5). The light curves obtained by each detector decline. The rate of decline however differs among them. Over the $\sim$3800 days covered by the data sets, the EPIC-pn count rate decreased by about 6% in the total, soft and medium energy bands, 2% for the hard band and 4% for Berghöfer’s band. The count rates of EPIC-MOS decreased by about 10% in the total, medium, and Berghöfer’s bands, 6% in the hard band, and 15% in the soft band. The RGS count rates decreased by 18% in the total band, 28% in the soft band, 16% in the medium band, and 12% in Berghöfer’s band. These variations are significant at the $<1\%$ level\(^6\) as the error bars on the average count rates are very small.

The fitting of EPIC spectra also showed a small decrease in flux of a few percent (Paper I). Moreover, the supernova remnant 1E0102–72, observed independently from $\zeta$ Puppis (though also for calibration purposes), shows a decrease in its MOS count rate and flux similar to what is seen for $\zeta$ Puppis (M. Guainazzi 2011, private communication). The exact origin of this systematic trend is not known (investigations are under way by the calibration teams), but such long-term effects are reminiscent of detector sensitivity ageing problems. Up to now, the pn and MOS are considered to be stable by the XMM-Newton calibration team (M. Guainazzi 2011, private communication).\(^7\) but there are apparently remaining imperfections in the long-term calibration. Since the decline of the registered count rates is currently not taken into account in the XMM calibration, we removed this trend by hand for further analyses and conclude that it is instrumental in nature.

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\(^5\) http://xmm.esac.esa.int/external/xmm_user_support/documentation/uhb/index.html

\(^6\) A significance level of 1% implies that there is only 1% chance to get the observed deviation from the hypothesis by coincidence.

\(^7\) See also Section 1.3.2 and Figure 1.14 of the EPIC calibration status which can be found at http://xmm.vilspa.esa.es/docs/documents/CAL-TN-0018.pdf as well as Section 5 and Figure 5 of the XMM cross-calibration status available at http://xmm.vilspa.esa.es/docs/documents/CAL-TN-0052.ps.gz
Note that true variations of the source may be superimposed on these global decreasing trends. For example, ζ Puppis appears brighter during Rev. 1620 for both count rates and fluxes (derived from spectral fits, see Paper I). This is linked to the changes observed on intermediate timescales (see Section 5)—with trends on the course of days, the source may indeed appear brighter or fainter sometimes, depending on the observational sampling of these changes.

Finally, we also calculated the ratios between the RGS count rates associated with lines of the same elements: O\textsuperscript{vii}/O\textsuperscript{viii}, Ne\textsuperscript{ix}/Ne\textsuperscript{x} and N\textsuperscript{vi}/N\textsuperscript{vii}. Comparing globally the 16 secure RGS exposures (see above and Section 3), there is no obvious correlation between the different elements: the Ne\textsuperscript{ix}/Ne\textsuperscript{x} and N\textsuperscript{vi}/N\textsuperscript{vii} ratios do significantly vary, but only the N\textsuperscript{vi}/N\textsuperscript{vii} is clearly decreasing. The N lines constitute the most widely separated pair: as the long-term trend is instrumental in origin, such a calibration problem could affect some wavelengths more than others and a larger separation would then lead to larger differences in lines. The average values of these ratios, based only on count rates (i.e., not on dereddened fluxes) and excluding Revs. 0091 and 0731, are 1.44 ± 0.01 for nitrogen (both RGS, both orders), 1.28 ± 0.01 for oxygen (RGS1, both orders), and 1.86 ± 0.01 for neon (RGS2, both orders)—the choice of instruments takes into account the fact that RGS2 could not record any information on O\textsuperscript{vii}, whereas the first order of RGS1 contains no data on Ne\textsuperscript{x} (see Section 3).

4.2. X-Ray Lines

High-resolution X-ray spectra of good quality can be derived for each exposure, and used to search for variations. The lines recorded for each observation can first be compared to the average spectrum obtained when combining all observations (Figure 6). No large, significant variation is detected. Small changes in flux (of the order of one sigma) can be spotted from time to time. They are similar to those recorded at optical wavelengths (Eversberg et al. 1998; Rauw et al. 2010), with double peaks where the blue to red ratio slightly changes. Their small amplitude and the low signal to noise of the data however prevent us from making a detailed analysis: this must await the advent of more sensitive observatories.

To be more quantitative, a temporal variance spectrum (TVS) analysis (Fullerton et al. 1996) was performed on the combined and fluxed RGS spectra (output of \texttt{rgsfluxer}). The TVS computes the squared difference between individual spectra and the average one, taking the signal-to-noise ratios into account, which allows the detection of statistically significant deviations from the average. Note that the spectra are calibrated both in flux and wavelength within \texttt{rgsfluxer} (see Paper I for details), so that the pointing problems have no impact here. The relative weights for the different spectra in the TVS were chosen equal to the count rate errors on the total band. The TVS appears overall flat (implying constancy), with only a few distinctive features (Figure 7). For example, some peaks are found in the 20–24 Å region. This region is affected by gaps and missing CCDs, and there are therefore undefined values for wavelengths where no exposure exists. The exact position (in wavelength) where that occurs varies from one exposure to the next, notably because of pointing differences, and that results in apparent variability in the spectral set (hence peaks in the TVS). Increased noise at the shortest wavelengths (below 7 Å) and longest wavelengths (above 24 Å) is also producing a larger TVS, unrelated to intrinsic variability of the source (though the peak at 7.7 Å
remains unexplained). Globally, the TVS thus indicates that the lines in the X-ray spectrum of $\zeta$ Puppis are not significantly varying from one exposure to the next. Very small changes are not excluded, however. Indeed, two small peaks of the TVS occur at 13.5 and 15 Å, i.e., at the wavelength of the strongest lines: this indicates that the line profile variations of $\zeta$ Puppis are just beyond the reach of current facilities, and they may thus be detected in the future with the better sensitivity of new X-ray observatories.

5. INTERMEDIATE-TERM VARIATIONS (DAY TO MONTHS)

In this section, we investigate the data for the presence of variations with timescales of day to months. Within each exposure, the same set of tests was applied to each light curve. We first performed a $\chi^2$ test on all available individual light curves (i.e., 4 time bins and 7 energy bands for EPIC, 10 energy bins and 2 time bins for RGS, see Section 3) for several null hypotheses: constancy, linear variation, quadratic variation. We further compared the improvement of the $\chi^2$ when increasing the number of parameters in the model (e.g., linear trend versus constancy) thanks to $F$-tests (see Section 12.2.5 in Lindgren 1968). A variability test using Bayesian blocks (BBs; Scargle 1998) was also performed, through the FTOOLS battblocks. It was made on the 200 s full (i.e., including bins with $<50\%$ effective exposure time) EPIC light curves in the total energy band—those are the data with the largest signal to noise. For the most varying cases, a check was made by testing the event arrival times of the source, though this does not take into account the background, non-uniformities, or bad time intervals: results were similar to those derived from binned light curves. Unless otherwise stated the adopted critical significance level is 1% throughout this paper. The individual results for each exposure are detailed in the Appendix, and we only summarize them below.

In general, the background is found to be variable. This is expected since many observations were affected by flares and some variations remain, despite the fact that the largest and narrowest ones have been cut out during the processing (see Paper I and the Appendix for details).

For the source itself, however, only one thing is obvious: $\zeta$ Puppis does not vary much. For example, BBs are particularly useful to detect bursts, but there are none in $\zeta$ Puppis, and a single block is found in most cases to be the best representation of the data.
of the light curves. The absence of bursts is confirmed by the $\chi^2$ analyses.

The error bars on each time bin are smaller for longer bins: small variations will thus be most easily detected for long bins. On the other hand, variations with timescales much smaller than the exposure duration will be smoothed out when using long time bins. Therefore, if short-term variations were dominating the overall variability of $\zeta$ Puppis, the lowest variability level should be found for long time bins. What we find is the opposite trend: for both EPIC and RGS data, the longest time bins often yield the most variable light curves (see Figure 8)—though they rarely reach a significance level of 1%. This indicates that trends with timescales similar to or larger than the exposure duration are more common in $\zeta$ Puppis than very short-term events.

In fact, only six exposures show a significant non-constancy of their (mostly EPIC) light curves: Revs. 0795, 1164, 1343, 1620, 1814, and 1983 (Figure 8). Moreover, in eight cases (Revs. 0156, 1071, and the six previously quoted), modeling by a trend (linear and/or quadratic) yields a significant improvement of the $\chi^2$ over constancy, even if the significance levels attached to the individual $\chi^2$ (for the constancy hypothesis) are not <1% in the additional two cases. It should be noted that five out of these data sets are amongst the longest exposures (see Paper I).

Indeed, if we cut the data of Rev. 1983 to keep only the first 10, 20, 30, 40, 50, or 60 ks, the $\chi^2$ (for the constancy hypothesis) never reaches a significance level <5% and there is no significant improvement by fitting a line of non-zero slope rather than a constant! It thus seems that $\zeta$ Puppis appears variable each time one looks at it for a sufficiently long time. For the most varying cases, i.e., Revs. 1343, 1620, 1814, and 1983, a splitting of the light curves into two or three BBs is found (see, e.g., Figure 9). Again, this favors the existence of longer-term shallow trends over that of shorter-term “bursting” events.

The performed tests can also provide information on the energy at which variations occur, when they are detected. Usually, it is expected that the hard band would be the most often variable in O-stars, as highly variable phenomena such as colliding winds or magnetically-confined winds mostly produce hard X-rays. However, this seems not to be the case in $\zeta$ Puppis, as there is no coherent behavior for this band—in some exposures, the hard band appears as the most variable (i.e., that with the largest dispersion or $\chi^2$), in others as the least variable. In contrast, the soft band has a more consistent behavior: it is only detected as variable when all other bands

Figure 5. Same as Figure 4, but for the RGS data. The point which is systematically lower than others is associated with Rev. 0731, for which $\zeta$ Puppis was 6’ off-axis (see the text for details).
are varying too; it can therefore be classified as the least often variable one. Within the observational limitations, the variations in \( \xi \) Puppis therefore appear as globally affecting its spectrum, rather than being particular to a specific (narrow) energy band.

5.1. Fourier Analysis

The characteristic timescale of these intermediate-term variations is difficult to assess on individual exposures using \( \chi^2 \) tests or BBs. These first analyses can only conclude that the timescale is longer than the typical exposure length (i.e., a day or more). Looking further at the individual light curves, no obvious oscillation is detected by eye, despite the full coverage of the putative \textit{ROSAT} 17 hr period by individual exposures and the large improvement in quality over the \textit{ROSAT}\textsuperscript{1} data. It thus seems that a sinusoidal variation of several hours and an amplitude of a few percent, such as that detected by Berghöfer et al. (1996), are transient, at best.

To give a more quantitative assessment of the variability timescale, we have performed period searches on global light curves (created by putting all individual-exposure light curves after one another, keeping their individual time tags), corrected for the long-term instrumental trend described in Section 4.1. We used the algorithms of Heck et al. (1985, see also correction by Gosset et al. 2001). As in previous sections, we considered only the best data sets (see Paper I), i.e., the 15 MOS exposures and the 10 pn exposures taken in small window + Thick filter mode, as well as the 16 RGS exposures (i.e., excluding Revs. 0091 and 0731). The small time bins were favored (200 s for EPIC, 500 s for the total RGS band, and 2 ks for the other RGS bands) since the Fourier-period-search algorithms are more affected by a small number of points than by large individual errors. Note that a more general period search technique which attempts to fit a period simultaneously with its harmonics does not yield additional insights.

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**Figure 6.** Examples of “large” variations in X-ray lines for a few observations (identified by their revolution number in each panel). The individual spectrum, combining both instruments and both orders for a given revolution, is plotted with its errors and compared to the combined, full RGS spectrum at the same wavelength (red line) in each top panel. Their difference (in the sense individual spectrum minus combined spectrum) is given in each bottom panel.

(A color version of this figure is available in the online journal.)
Figure 7. Upper panels yield the mean spectrum of ζ Puppis, while the lower panels display the TVS. The dotted line corresponds to a significance level of 1%.

The resulting periodograms are shown in Figure 10, along with the spectral window (i.e., the aliasing structure appearing naturally because of the temporal sampling). The periodograms consist of narrow peaks (since the data set covers more than 10 years) tightly disposed in much broader features (because there are only a few exposures, of max. 70 ks, within this 10 year timescale), which hamper an accurate determination of any period. However, two features are apparent for all bands except the hard one: (1) the highest peak occurs at about 0.3–0.4 day^{-1} and (2) the right wing of this peak decreases much more slowly than that of the spectral window—some additional power is thus present around 0.7–1.3 day^{-1}.

To assess the significance of these signals, we performed a formal iterative decomposition in frequencies—we here illustrate only the analysis for the pn total bandpass. A first extracted frequency at ν₁ = 0.365 day^{-1} (period P = 2.74 day, semi-amplitude a = 0.25 counts s^{-1}) is significant against the null hypothesis of white noise as deduced from ad hoc simulations. The following frequencies are ν₂ ∼ 0.89 day^{-1} (P ∼ 1.12 day, a = 0.12 counts s^{-1}) and ν₃ ∼ 0.4 day^{-1} (P ∼ 2.5 day, a = 0.08 counts s^{-1}; the last values are rather uncertain because they depend on the selected binning). These peaks in the Fourier periodogram are still characterized by a significance level lower than 0.001. The white noise hypothesis is thus formally rejected.

However, these frequencies do not correspond to the true content of the signal of the star. For example, when phased with the 0.365 day^{-1} frequency, individual light curves appear one after another, with no common phase interval. As explained above, some individual runs exhibit shallow trends. The time spanned by these runs combined with their scarcity over the covered decade has an unfortunate consequence: the Fourier transform is always able to find a few frequencies that are combining the various trends in a very constructive way. However the plethoric presence of gaps in the time series and the concomitant large number of degrees of freedom is responsible for the positive combination more than the possible coherency of the signal. As a test, we detrended the individual runs with a linear function before merging them. We computed the periodogram for the new time series. All the previously reported candidate frequencies disappear from the list of frequencies. The dominant one, for the 200 s binning, is ν₄ = 1.42 day^{-1} (P = 0.70 day, a = 0.054 counts s^{-1}) which corresponds to a peak whose significance level is around 0.001. If we detrend the X-ray light curves over the individual runs with a second degree polynomial, we obtain a time series that exhibits no outstanding peak and is thus in perfect agreement with the white noise hypothesis. Therefore, although the white noise hypothesis is rejected, the alternative hypothesis to adopt remains unclear. The star exhibits weak although significant variations at a time scale between 0.7 days and several days but the sampling does not allow us to conclude the existence of a coherent, fully deterministic signal above Poisson noise. The signal could be dominantly stochastic with some coherency at short timescale (some kind of red noise<sup>8</sup>). It is also possible that these changes are transient: they would then not appear as a strictly periodic signal in the global light curve. Another possibility is that any signal could be not strictly stationary, in phase or frequency, from one observing run to the next, as often seen for changes of the optical spectra in Oef stars (Rauw et al. 2003; it must be recalled that our target, ζ Puppis, belongs to this spectral type category!).

In summary, it is certain that ζ Puppis displays variations with relative amplitudes up to 10%–15% on the timescales of days—not hours (i.e., there is no trace of the signal attributed to white noise has, on average, the same amplitude whatever the frequency, red noise displays stronger amplitudes at low frequencies.)
non-radial pulsations; see Reid & Howarth 1996). However, our data set suffers from the misfit between the possible frequencies and the actual sampling. Therefore, despite its exceptional quality, it is still insufficient to detect confidently evidence for the presence of a coherent signal with daily timescales. A modulation of the X-ray flux with such daily timescale was reported for the O-type dwarf ζ Oph, and potentially associated with the corotating interacting features found through
Figure 9. Evolution of the total count rate in Rev. 1814, with the Bayesian blocks superimposed. To ease the comparison, the corresponding light curves with 1 ks time bins are shown. The x-axis corresponds to elapsed time (in seconds) since the beginning of the MOS1 observation.

(A color version of this figure is available in the online journal.)

UV observations (Oskinova et al. 2001a). ζ Puppis shows a 5 day modulation also attributed to corotating regions (Moffat & Michaud 1981). New, continuous X-ray observations of ζ Puppis would be required to better characterize the timescale of the detected variability, and to establish whether these variations can be associated with such features.

5.2. Autocorrelation Analysis

To search for temporal links between the photon arrival times, the data corrected for the instrumental effect were also analyzed using autocorrelation methods (Edelson & Krolik 1988). The resulting autocorrelation functions are shown in Figure 11. Note that the binned functions were normalized by the number of points used and, as usual, by the dispersion around the mean (observed variance $s_n^2$). The former normalization is needed as the individual exposure times range from 15 to 77 ks (Paper I), so that more data points can be used for some time shifts.

A slight positive correlation appears for the total and medium bands for time shifts below 20 ks. A slight anticorrelation is then detected for shifts of 50–60 ks, i.e., similar to the typical duration of an exposure. A similar behavior, though with even smaller amplitude, is seen for the soft, hard, and Berghöfer energy bands. This slow evolution toward lower correlation values confirms the existence of weak coherent variations with timescales of tens of ks.

The correlation amplitudes are however small, hence not highly significant, statistically speaking. However, a strong positive correlation for small shifts is expected since the wind configuration remains the same for some time (about one flow time, which is $R_*/v_\infty = 5.8$ ks for ζ Puppis, as $v_\infty = 2250$ km s$^{-1}$ and $R_*=18.6$ $R_\odot$, using the parameters of Oskinova et al. 2006 and references therein). For longer shifts, two behaviors are then possible. On the one hand, the time bins could be independent for shifts longer than a flow time, as in a fully stochastic wind. In this case, the correlation function would rapidly drop to zero. On the other hand, if the time bins are coherently linked by a shallow trend, the correlation function should slowly decrease. This decrease is indeed what is observed, but we would thus expect a correlation signal with larger amplitudes.

In practice, however, even a perfectly correlated signal (i.e., with a correlation of 1) will be diluted by the observational Poisson noise. The expected correlation value will then be given by

$$C = 1 - \frac{s^2}{s_n^2}$$

where the observed variance $s_n^2$ comprises the noise and the coherent variations of the source, whereas $s^2$ only corresponds to the noise. For the pn light curve in the total band with 200 s time bins (globally detrended, i.e., corrected for the instrumental effect), $s_n^2$ is 0.089 counts$^2$ s$^{-2}$ and the variance due to Poisson noise is estimated to be around 0.049 counts$^2$ s$^{-2}$. The peak height $C$ should then reach 0.45, which is in good agreement with the value observed in Figure 11 for small time shifts. This implies that the intrinsic correlation of the noisless signal could be nearing one: the trends are thus real.

5.3. X-Ray Lines

As already mentioned in Section 3, RGS light curves were also extracted for the brightest isolated X-ray lines, enabling us to determine whether these lines vary over shorter timescales. The observed variations are small, generally within 1σ error bars. The only significant and coherent results are found for Revs. 0156 and 1814. For the former, a linear trend with a positive slope provides a much better fit to the Ne ix line flux. For the latter, the Ne ix line appears variable while the O viii clearly increases. Note however that these changes are detected with more significance using RGS2 data than with RGS1 data.

Since the individual count rates are available, we also calculated the ratios between lines of the same elements: O vii/O viii, Ne ix/Ne x, and N vi/N vii (Figure 12). These ratios reflect the temperature (Blumenthal et al. 1972; Waldron & Cassinelli 2007), and any change in the ratios would therefore be linked to temperature variations. Formally, opacity variations may also play a role in changing these ratios. However, the latter are not as sensitive to absorption as to temperature: a change in temperature by 15%–20% results in a doubling of these ratios (note that the temperature dependence is similar for all ratios), whereas change of the absorbing column of a smooth wind by a factor of two (from 0.1 to 0.2 × 10$^{22}$ cm$^{-2}$) yields variations of 7.5%, 25%, and 35% in the Ne, O, and N ratios, respectively. As for count rates, the ratios were tested using $\chi^2$ tests. For the individual exposures, only two features appear significant. For Rev. 0156, the Ne ix/Ne x is better fit by a line with negative slope. Similar but shallower possible trends are detected by eye for the two other ratios, but they are not formally significant. For Rev. 1814, the Ne ix/Ne x appears much better fit by a concave/U-shaped parabola, but no similar signal is seen for the two other ratios. Note that these two revolutions are amongst the variable ones (see above), and that the reported changes may be linked to slight changes in spectra (see Section 4.2), for which higher-sensitivity instruments are needed for a detailed characterization.

6. SHORT-TERM VARIATIONS (HOURS)

Once the long-term instrumental decrease and the daily trends are removed, what signal is left? In principle, this is where the variability due to embedded wind shocks should appear. In what
follows, we will first present the new observational results, then
the theoretical predictions of ζ Puppis variability, and finally
compare the two to derive constraints on the wind structure.

6.1. Observed Light Curves

Relative dispersions were calculated for each of the observed
light curves. These light curves have two specific features which
do not exist in the models (see next subsection): a temporal
binning and a binning over a range of energies. In principle,
this somewhat smoothes out any variability if it is present with
timescales shorter than the time-bin length or if it changes
strongly with energy (e.g., the light curves at 0.3 and 0.4 keV
being uncorrelated). However, the Poisson noise inevitably
impacts on the data and therefore prevents us from detecting
low-level variability (i.e., a few percent) with time bins smaller
than 200 s (see last line of Table 1)—this limit would only be
changed if a more sensitive instrument was used. In addition,
the emitting parcels contain plasma emitting over a range of energies, even if isothermal, and this implies some correlation over different ranges of energies. A comparison with synthetic curves can thus provide useful insights into the structure of the wind.

As mentioned below, the steps in the synthetic light curves correspond to different wind configurations. The dispersion calculations for the data were thus performed in the following way: (1) the original light curves of each exposure were first detrended using the best-fit linear trend derived from $\chi^2$.
Figure 12. Ratios of count rates recorded for He-like and H-like elements (top: RGS; bottom: green triangles for RGS1 and red squares for RGS2). Note that the signal for RGS is the sum of counts recorded for both RGS1 and RGS2, divided by the full exposure time. It is thus a kind of average between the two instruments (i.e., \([\text{RGS1 + RGS2}] / 2\)). However, when no signal is recorded in one instrument, as is the case for O\textsc{vii} in RGS2, the RGS data are not shown.

(A color version of this figure is available in the online journal.)

calculations (see above) as the simple model (presented in next section) does not predict nor model such features; (2) the count rate values of the 200 s light curves were then sampled at 5 and 10 ks intervals (corresponding to about one and two wind flow times, respectively), i.e., only considering every 25th or 50th value; and (3) the relative dispersions of these new, reconstructed light curves were finally evaluated using

\[
\text{rel. disp.} = \left[ \sqrt{\sum (CR_i - a - b \times t_i)^2 / (N - 2)} \right] / \text{mean},
\]

where \(a\) and \(b\) are found from the best-fit trend, see Section 3.2.1, and mean = \(\sum (CR_i / \sigma_i^2) / \sum (1 / \sigma_i^2)\). This enables us to try to reproduce the “independent wind configurations” of the successive “time steps” in the synthetic curves. Dispersions were also calculated for the full (i.e., considering all time bins) 200 s, 500 s, 1 ks, and 5 ks light curves (after detrending). When one compares the dispersions of the full 200 s light curves to these of the reconstructed light curves, they appear very similar. The maximum differences amount to ±4% in the worst cases, or smaller (<1% in absolute value) when the observations are longer. This is unsurprising since dispersion estimates on, e.g., 2 or 3 bins are less precise than on, e.g., 50 bins: when one samples the light curves every 25 or 50 steps, a particularly discrepant realization of the noise has more impact when there are fewer bins. The sparse sampling therefore does not change the results much, so Table 1 reports only the dispersions of the full light curves. This table gives in the first column the revolution number, in Columns 2–6 the dispersions measured for the main five energy bands and the 200 s binning, and in the 7th column the number of data points used; Columns 8–13 report similar values, but for the 5 ks binning. The last line provides for comparison the expected Poisson error, relative to the mean (i.e., \(1 / \sqrt{\text{count rate} \times \text{bin length}}\)). Note that only the EPIC data were used here, as the noise of the RGS light curves is even larger and would more easily mask subtle variations.

Looking at Table 1, one thing is obvious: despite the fact that the exposure-long trends mentioned above are often not perfectly linear, the measured relative dispersions around the best-fit lines are close to that expected on the sole basis of the Poisson noise. This means that the true short-term variability of \(\xi\) Puppis—and its potential wavelength dependence—remains hidden in the noise, implying a very small amplitude for these “intrinsic” short-term changes.

Figure 12. Ratios of count rates recorded for He-like and H-like elements (top: RGS; bottom: green triangles for RGS1 and red squares for RGS2). Note that the signal for RGS is the sum of counts recorded for both RGS1 and RGS2, divided by the full exposure time. It is thus a kind of average between the two instruments (i.e., \([\text{RGS1 + RGS2}] / 2\)). However, when no signal is recorded in one instrument, as is the case for O\textsc{vii} in RGS2, the RGS data are not shown.

(A color version of this figure is available in the online journal.)
These results should now be translated into constraints on the wind structure. Considering X-rays to be emitted by many hot parcels, one may naively think that it is sufficient to notice that a 1% dispersion “naturally” corresponds to $10^4$ “emitters,” using simple Poisson statistics. However, reality is not as simple: emitters suffer from different amounts of absorption depending on their location and, worse, the absorption may be clumped too. In both cases, the simple reasoning completely fails to apply, and a dedicated model is thus needed.

6.2. A Simple Wind Model

Embedded wind shocks are considered to be responsible for the X-ray emission of O-type stars. In these expanding and unstable winds, fast material encounters slow-moving material, giving rise to zones of dense gas, and the mutual collisions of such dense features then give rise to the X-rays. The radiation hydrodynamic (RHD) models (e.g., Feldmeier et al. 1997a, 1997b) predict that the collision, and thus the heating, occurs quickly (tens of seconds), and the cooling of the resulting hot plasma is also rather rapid, as the cooling time remains lower than the wind flow time for distances of several tens of stellar radii. A strong X-ray variability (two orders of magnitude in amplitude) was predicted. However, early ROSAT and Einstein observations failed to show such a strong variability of X-ray fluxes from massive stars (Berghöfer & Schmitt 1994a, 1994b, and references therein). To reconcile the results of the early observations with wind-shock theory, it was suggested that lateral breakup of the shells can lead to the presence of many parcels, resulting in low variability (Cassinelli et al. 1983; Feldmeier et al. 1997a): therefore two-dimensional (2D) or 3D models were needed. First attempts for 2D wind models were made by Dessart & Owocki (2003, 2005) but only isothermal winds (i.e., without X-ray generation) have so far been considered. Another example is the recent work of Cassinelli et al. (2008) on bow shocks, but the model is not yet self-consistent in terms of production and evolution for an

| Rev. | 200 s Binning | 5 ks Binning |
|------|---------------|--------------|
| MOS1 | Total Soft Medium Hard Berghoef N | Total Soft Medium Hard Berghoef N |
| 0156 | 5 10 7 12 8 189 | 1.4 3 1.6 2 1.3 8 |
| 0156 | 5 11 7 12 8 211 | 0.7 1.5 0.9 1.0 1.3 8 |
| 0380 | 6 13 7 12 9 163 | 0.8 3 1.0 3 1.2 7 |
| 0542 | 5 13 7 13 9 217 | 1.3 2 0.7 5 2 9 |
| 0636 | 5 13 7 13 10 95 | 1.2 1.2 1.5 2 2 4 |
| 0795 | 6 13 8 14 9 96 | 0.1 2 1.7 4 1.8 4 |
| 0903 | 6 13 7 15 9 109 | 0.7 4 2 1.8 1.2 4 |
| 0980a | 6 14 7 11 9 147 | 0.4 2 1.1 1.3 1.1 6 |
| 0980b | 6 13 7 12 8 69 | 0.4 1.9 1.3 3 0.3 3 |
| 1096 | 5 13 7 13 9 238 | 1.2 3 1.9 3 2 10 |
| 1164 | 6 12 8 12 9 203 | 1.9 2 2 4 2 8 |
| 1343 | 6 13 8 13 9 243 | 1.9 3 2 2 3 10 |
| 1620 | 6 13 8 13 9 275 | 1.2 3 1.6 1.9 1.8 11 |
| 1814 | 6 14 7 13 9 320 | 1.8 4 1.7 3 2 13 |
| 1983 | 6 13 8 13 9 383 | 1.5 3 1.7 4 3 15 |

| Total | Soft | Medium | Hard | Berghoef | N |
|-------|------|--------|------|----------|---|
| Poisson | 5 12 7 11 8 | 1.0 2 1.4 2 1.6 |

Notes. For the pn, the first five lines correspond to the data taken with the Medium filter (i.e., influenced by pileup).
ensemble of clumps. Unfortunately, no new, multi-dimensional hydrodynamical model has thus tackled the problem of X-ray generation in stellar winds, and we are thus left with alternative modeling paths.

In this context, Oskinova et al. (2001b) considered a spherically symmetric smooth cool wind permeated with discrete zones of hot X-ray emitting gas. It was found that X-ray variability depends on the frequency with which hot zones are generated, and on the cool wind opacity for the X-rays. It was shown that in such smooth cool wind, the variability in the soft band is expected to be smaller than in the hard band. Oskinova et al. (2004) further developed a 2D wind model where not only are hot parcels discrete, but the cool absorbing wind can be clumped too. We apply this model in the present paper to investigate the resulting X-ray variability. We only briefly recall here its basic features.

Our model was designed to correctly perform the radiative transfer of X-rays in stellar winds, and it also reproduces the features derived from RHD simulations. In this model, the X-ray emission originates from discrete zones of hot gas randomly distributed in an X-ray production zone extending from \(1.2 \text{ to } 100 \, R_\odot\). The choice of such a large zone may at first seem surprising, since the prediction of the 1D hydrodynamical model places the X-ray emitting regions within a few stellar radii of the stellar surface. However, a detailed global analysis of the high-resolution spectrum of \(\zeta\) Puppis (A. Hervé et al., submitted) shows that the X-ray emission zone must actually extend up to \(\sim 85 \, R_\odot\) to reproduce the observed spectrum, hence our choice of a large emission zone. Note that the lower boundary of the region was chosen taking into account the analyses of individual \(\text{Fe} \, \text{H}\) tripletts, which place onset radii in that range (e.g., Waldron & Cassinelli 2007; note that these analyses also consider large emitting zones, with emission formally extending to infinity). All emitting parcels of gas contain the same amount of matter. The line emission is powered by collisional excitation and therefore scales with the density squared. The density of the wind is derived based on the stellar mass-loss rate: from the mass conservation, it is \(\rho(r) = \frac{M}{4\pi r^2 v(r)}\) where \(M\) is the mass-loss rate and the wind velocity \(v(r)\) is \(v_\infty(1 - \frac{R_0}{r})^\beta\) (with \(\beta = 1\) and \(R_0\) chosen so that the photospheric velocity \(v(R_\odot) = 0.01 \, v_\infty\), as commonly used for a massive star wind. During motion, each hot fragment expands according to the continuity equation. Hence, the intrinsic unattenuated X-ray luminosity of each hot fragment scales as \(1/r^2 v(r)\). The probability of finding a hot fragment in the radius interval \([r, r + dr]\) scales with \(1/v(r)\), i.e., emitters are concentrated at inner radii, where the wind is slow. The random radial location of fragments is determined by von Neumann’s rejection method (e.g., Press et al. 1992) and their angular distribution is also random, with a uniform distribution over the sphere. Absorption and emission are decoupled: there is no self-absorption for the emitting material and no re-emission of X-rays after absorption. The model allows for further sophistications, i.e., emissivity can have a different scaling with density and density can also be a parameter. However, these parameters affect the shape of X-ray emission line profiles, not relative variability, so in the present study, we use the simplest emissivity.

Once produced, the X-ray emission propagates through the cooler stellar wind which can absorb it. The velocity of this cool wind is assumed to follow the same velocity relation as for the hot wind component (the so-called beta law, see above). The cool stellar wind is assumed to be either a smooth cool wind or a set of cool clumps (randomly distributed over the 1.5–316 \(R_\odot\) range), both cases having the same overall mass-loss rate and optical depth. For the fragmented wind model, we use the “cones” model of Oskinova et al. (2004), with a lateral extent of 1 degree for the spherical absorbers. A sketch of the model geometry is shown in Figure 13. Random radii are generated for each cone using the \(1/r(r)\) probability and von Neumann’s rejection method, again. The total mass of a homogeneous wind enclosed between two subsequent radii is considered to be swept up in a dense fragment with the same optical depth as the homogeneous wind material, so that the fragment location is given by \(r^2 = \left(\int_a^b dr'/v(r')\right)/\left(\int_a^b dr'/r^2 v(r')\right)\) where \(a\) and \(b\) are two subsequent random radii in the set determined by von Neumann’s method. Note that, depending on the set of radii, cool clumps do not have all the same density, some being optically thick while others are not blocking much light.

The wind parameters \((v_\infty, M, \text{ abundances})\) are derived from a non-LTE atmosphere model specific to \(\zeta\) Puppis (Oskinova et al. 2006), matching the optical/UV spectrum of the star. All these fix the clump location, size, density and optical depth, leaving as the only free parameter the number of hot and cool clumps. It may be noted that this model reproduces well the observed X-ray line profiles, despite its simplifications (Oskinova et al. 2004).

Our analysis of observational data did not reveal strong spectral trends in the variability. Therefore, for simplicity and clarity we simulate here only the monochromatic X-ray flux at a few selected representative wavelengths: 6 Å (~2 keV, midpoint of the total EPIC band), 14 Å (~0.9 keV, midpoint of the medium EPIC band), and 19 Å (~0.65 keV, midpoint of the total RGS band).

Some comments should be made about the synthetic light curves. First, the calculated flux is monochromatic and in arbitrary units. Only relative dispersions, for example, can be calculated and compared to the data. Second, these variability light curves are not, strictly speaking, functions of time. The time-dependent radiative hydrodynamic simulations of Feldmeier et al. (1997b) show that on a timescale longer than the flow time (5.8 ks for \(\zeta\) Puppis, as \(v_\infty = 2250 \, \text{km s}^{-1}\) and \(R_\odot = 18.6 \, R_\odot\), see Oskinova et al. 2006 and references therein), the wind structure is renewed and is independent of the previous wind configuration. Our model reproduces this situation: each realization of our 2D stochastic wind model is independent of the previous one and each model run represents the wind configuration on a timescale shorter than the cooling time. In other words, we model the wind at some arbitrary moment of time, and compute the X-ray emergent flux at this moment; the next data point is calculated for a randomly different wind configuration for both absorbing and emitting parcels. We do not follow the wind expansion (this will be the subject of a paper by L. M. Oskinova et al., in preparation). While this approach does not allow us to model the detailed time evolution of the X-ray flux on timescales of hours, it allows us to model the relative amplitude of the X-ray variability for long stretches of randomly distributed observations, as appropriate for this XMM-Newton observing campaign. Examples of such “light curves” are shown in the right panel of Figure 13, while relative dispersions are presented in Table 2.

Several conclusions can be drawn from Table 2.

1. As the number of emitting or absorbing parcels increases, the variability decreases, as could be expected. However, it is important to note that dispersions of 1% are only found when these numbers approach \(10^5\).

2. A smooth wind is less variable than an otherwise equivalent clumped wind.
Figure 13. Left: a snapshot showing the wind structure in the model for a small number of parcels. Black dots represent the absorbing clumps (which, despite their color, are not totally optically thick), while crosses correspond to the emitting regions. Note that the size increases with distance to the star, as the parcels keep their angular size, as seen from ζ Puppis. Only a small number of clumps is shown, for clarity. Right: excerpts of synthetic variability curves at 14 Å for a set of wind configurations. Next to each synthetic light curve are indicated the numbers of emitting zones followed by the number of absorbing clumps. For clarity, the light curves have been vertically shifted.

Table 2

| λ    | No. of Absorbing Clumps | No. of Emitting Clumps | Relative Dispersion (%) |
|------|------------------------|------------------------|-------------------------|
| 6 Å  | Smooth                 | 2000                   | 16                      |
| 6 Å  | 144000                 | 2000                   | 23                      |
| 14 Å | Smooth                 | 2000                   | 6.9                     |
| 14 Å | Smooth                 | 5000                   | 4.2                     |
| 14 Å | Smooth                 | 20000                  | 2.1                     |
| 14 Å | Smooth                 | 50000                  | 1.4                     |
| 14 Å | Smooth                 | 100000                 | 1.0                     |
| 14 Å | 72000                  | 2000                   | 33                      |
| 14 Å | 144000                 | 2000                   | 27                      |
| 14 Å | 144000                 | 2000                   | 16                      |
| 19 Å | 144000                 | 2000                   | 12                      |
| 19 Å | 144000                 | 2000                   | 25                      |
| 19 Å | 288000                 | 2000                   | 26                      |
| 19 Å | 144000                 | 20000                  | 12                      |

Notes.

a In all other runs the smooth wind starts after 316 $R_*$, while in this run the cool fragment zone of the wind ends at 100 $R_*$, which decreases the variability.
b In this run, the number of clumps in the radial direction is the same (400) as in the previous case but the lateral size of each clump is 0.5. No strong impact on the variability is found.

3. As wavelength increases (or energy decreases), the relative dispersion for a clumped wind remains stable or slightly increases whereas it decreases for a smooth wind (as already reported in Oskinova et al. 2001b). In a clumped wind, the variability is thus less energy dependent than in a smooth wind—in the extreme limiting case of a wind consisting of only opaque X-ray clumps, no energy dependence is expected (Oskinova et al. 2004, 2006).

4. If absorbing clumps are distributed over a smaller region ($R_{\text{max}}$ of 100 rather than 316 $R_*$), then the variability decreases. This is the effect of a smaller radial separation between clumps.

Comparing these theoretical predictions with the observational results (see previous subsection), we found that the number of emitting and absorbing parcels is huge. Indeed, even in the most favorable case of smooth cool wind absorption, which is the least variable case, more than 100,000 hot X-ray emitting zones must be present and contribute to the X-ray emission so that the relative flux variations remain below 1%. This number further increases when the cool wind fragmentation is also included in the model.
It must be underlined that no previous study has put direct constraints on the number of clumps in O-stars. Some studies exist, however, for evolved massive stars. For example, Lépine & Moffat (1999) report that “between 10^3 and 10^4 clumps in the line emission region are needed to account for the line profile variability of the WR stars” that they analyzed. The X-ray data of ζ Puppis suggest an even larger number, though this should apply to a larger zone than formation regions of optical lines. In addition, Davies et al. (2007) explained the polarization level of luminous blue variables by either a few massive, optically thick clumps (ejection rate of ≤0.1 clump per flow time) or many small, optically-thin clumps (ejection rate of ≥10^3 clumps per flow time), with the latter option usually favored in the literature. Considering that the X-ray emission region and the cool wind absorption region cover several tens of stellar radii, our conclusion appears consistent with Davies’ result, despite the different nature of the objects under consideration.

Thus, the sensitive XMM observations reveal that the stellar winds of O-stars are highly structured on small scales. It remains to be seen whether the theory of stellar wind instability can explain such a high degree of fragmentation. Some 2D models of the line-driven instability (LDI) in isothermal stellar winds “show that radially compressed shells that develop initially from the LDI are systematically broken up by Rayleigh–Taylor or thin-shell instabilities as these structures are accelerated outward” (Dessart & Owocki 2003), hence producing a lot of small-scale 2D structures, but the same authors later found “lateral coherence of wind structures” (Dessart & Owocki 2005) and the question of the size and number of clumps therefore remains unsettled. The hydrodynamical simulations of Feldmeier et al. (1997a; to this day the sole ones that tackled the problem of X-ray generation, though in 1D) predicted that only a few strong shocks, simultaneously present in massive star winds, are responsible for most of the X-ray emission, whereas our results strongly challenge this. The lateral break-up of the X-ray emitting shells, advocated by Feldmeier et al. (1997a) for lowering the X-ray variability, cannot provide an explanation (see Table 2). Moreover, if clumping is induced by sub-surface convection, hydrodynamical stellar evolution codes indicate that the total number of clumps in O-stars should typically amount to 6 × 10^3–6 × 10^4 (Cantiello et al. 2009). Our data indicate values of an order of magnitude larger, therefore prompting further investigation on the nature of radiatively-driven stellar winds.

7. SUMMARY AND CONCLUSION

We have analyzed an exceptional set of X-ray observations of ζ Puppis: to date, there exists no more sensitive data set nor a data set with a better (time and spectral) coverage for a massive star.

Over the decade of observations of ζ Puppis, a decreasing trend is clearly seen in the count rates. As a comparison with the fluxes determined from spectral fits (see Paper I) and with other X-ray sources shows, this is mostly due to instrumental/calibration problems (probably the ageing detector, whose sensitivity decreases with time), and is not yet taken into account in the data calibration process.

Comparing the X-ray line profiles appearing in the 18 available high-resolution spectra yields again no significant, true long-term changes. Some shallow, 1σ line profile variations are however reminiscent of those seen in the optical—more sensitive observations should confirm this, and pinpoint the timescales on which that occurs.

Once the instrumental effect is taken out, we do not detect flare-like bursts of X-ray emission nor short-term variations (<1 d, like, e.g., the stellar pulsations detected in the optical domain) in the individual exposures. However, we detect statistically-significant variations of the count rates of ζ Puppis on timescales of >1 day. Indeed, the light curves with the longest time bins appear more variable than those with shorter bins, and the longest data sets are systematically found to be variable. The detected changes appear as shallow increasing (Revs. 0156, 1071, 1620, 1814, and 1983) or decreasing (Rev. 1343) trends, or a mix of both (Rev. 1164). No clear dependence with energy is found: in particular, the hard band is not the most often variable one. This suggests that the bulk of the X-ray emission is affected, not only a high-energy emission tail linked to phenomena such as magnetic confinement. Furthermore, no evidence for a coherent, systematic periodicity is found either. These slow modulations cannot be explained by the embedded wind-shock scenario but are consistent with the presence of large-scale, slowly-moving structures in the wind, which may, for example, result from corotating interaction regions in the wind. Clearly, more data, specifically covering the full rotation period, are needed to settle the question of the origin of such features.

Once instrumental and daily trends are taken out, ζ Puppis shows a surprisingly low level of variability. This places stringent constraints on the wind structure. A wind variability model tailored to ζ Puppis has been undertaken. It shows that only a very large number of emitting and absorbing clumps (>10^5) are able to reproduce the observed light curves of ζ Puppis. This is the first time that such a limit has been placed for an O-type star. The stringent limit on number of clumps that we established questions some results from existing models of stellar winds (link clumping-convection, fragmentation level) and X-ray production (number of hot gas zones), but these models were not calculated in 3D. Future model developments should be done, taking into account our high clumpiness result.

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APPENDIX

RESULTS FOR INDIVIDUAL EXPOSURES

In this Appendix, we present the variability properties of each exposure. We also remind the reader about background flares affecting the exposure (though they have been cut out during the processing; see Paper I).

A.1. Rev. 0091

This data set only comprises data from the RGS. There were narrow background flares scattered all over the exposure and a broad flare affected the mid-exposure. At a significance level of 1%, no trend or deviation from a constant is detected. Count rates may be higher toward the end of the exposure, but only at the
A narrow background flare affected the pn data at mid-exposure. This data set shows a trend toward increasing count rates. Though less obvious in MOS2 and RGS1, this trend is clearly detected through the significant improvement of the $\chi^2$ rates. When using a linear rather than a constant fit. This trend is detected for the total, soft, and medium bands (EPIC), and for the medium band (RGS), i.e., it concerns photons with energies below 1 keV. For the EPIC-MOS1 light curve in the total band, the increase rate is $1.7 \pm 0.7 \times 10^{-6}$ counts s$^{-1}$ (i.e., a 3% increase over the $\sim 40$ ks exposure). For EPIC, count rates in the total band and/or calculated using the longest time bin appear as the most variable; for RGS, the medium band data and/or the light curves with the longest time bins are the most variable.

A large flare occurred during the second half of the observation. The count rate recorded in the hard band is not compatible with a constant—it shows a shallow decreasing trend—but only at significance levels of $1\% - 10\%$ (i.e., not formally significant). For EPIC, the hard band light curves (especially those obtained with the smallest time bin) are the most variable; on the contrary, for the other bands, the light curves calculated using the longest time bins are the most variable. RGS data do not yield any coherent result as to which time bin and energy band is the most variable.

A large flare occurred during the last third of the observation. Only pn data are available for EPIC. Data are compatible with a constant count rate, without any trend detected or any obvious oscillation. For RGS, the medium band light curve calculated with the 2 ks bin appears as the most variable; for EPIC, the hard band data are the most variable except for the longest time bins.

A large flare occurred during the second half of the observation. The count rate recorded in the hard band is not compatible with a constant—it shows a shallow decreasing trend—but only at significance levels of $1\% - 10\%$ (i.e., not formally significant). For EPIC, the hard band light curve appears as the most variable, but conclusions are unclear for the time bins: MOS data show more variability in the smallest time bins, while pn data favor variability in the longest ones. For RGS, the soft band favors the most variable.

A large flare occurred at the end of the MOS data sets, or in the middle of pn and RGS data sets. Data are compatible with a constant, without any trend detected or any obvious oscillation. There is no time bin or energy band favoring variability.

A large flare occurred during the last third of the observation. Only pn data are available for EPIC. Data are compatible with a constant count rate, without any trend detected or any obvious oscillation. For RGS, the medium band light curve calculated with the 2 ks bin appears as the most variable; for EPIC, the hard band data are the most variable except for the longest time bins.

A large flare occurred during the second half of the observation. The count rate recorded in the hard band is not compatible with a constant—it shows a shallow decreasing trend—but only at significance levels of $1\% - 10\%$ (i.e., not formally significant). For EPIC, the hard band light curve appears as the most variable, but conclusions are unclear for the time bins: MOS data show more variability in the smallest time bins, while pn data favor variability in the longest ones. For RGS, the soft band favors the most variable.
A few narrow background flares are scattered over the exposure, and a larger one occurs at the end of the observation. Data are compatible with a constant rate, without any trend detected or any obvious oscillation. For RGS, there is no time bin nor energy band favoring variability; for EPIC, the most variable data are found for the longest time bin in the hard band.

A large flare occurred during the first third of the observations. Data in the medium, total, and Berghöfer’s EPIC bands are incompatible with a constant and significantly better fitted by a linear increase. The trend in the total band is also detected in the RGS data. For EPIC, the total and medium band data appear as the most variable, especially at small time bins.

A small flare occurred at the beginning of the RGS observation. Data in all EPIC bands but the hard one are incompatible with a constant and significantly better fitted by a large linear increase or, even better, a quadratic increase. The non-constancy and the improvement by an increasing trend are also detected in the RGS data for the total and medium bands. For EPIC, the hard data appear as the least variable, while the light curves calculated with the longest time bins are the most variable. For RGS, the medium band data are the most variable.

A large soft proton flare occurred near the end of the RGS observation. Data in the total and medium EPIC bands are significantly better fitted by a linear, or even quadratic, increase, while the hard and Berghöfer’s bands are only better fitted by a quadratic increase. The increasing trend is also detected in the RGS data for the total band. An oscillation is visible in Berghöfer’s band on both RGS and EPIC, with a recurrence time of about 50 ks. In general, the longest time bins yield the most variable light curves.

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