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Rotationally modulated X-ray emission from the single O star ζ Ophiuchi

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Abstract. Archived measurements by the X-ray Telescope on board the ASCA satellite of the single runaway O9.5V star, ζ Ophiuchi, are analysed. The data set is unique as it covers just more than one full rotational period of the star. We report a clearly detected periodic X-ray flux variability with amplitude ∼20% in the ASCA passband (0.5–10 keV). The detected period $\sim 0\overset{\mathrm{d}}{.}77$ possibly indicates a connection with the recurrence time ($0\overset{\mathrm{d}}{.}875 \pm 0\overset{\mathrm{d}}{.}167$) of the discrete absorption components (DACs) in UV spectra of the star, thought to be due to the presence of large scale structures in the stellar wind modulated by rotation. We attribute the X-ray fluctuation with an uneven distribution of X-ray absorbing material. We also report that an analysis of similar ASCA observations of ζ Puppis failed to confirm earlier reported variability of X-rays from this star based on ROSAT observations.

Key words. stars: early-type – stars: individual: ζ Ophiuchi – stars: individual: ζ Puppis – X-rays: stars

1. Introduction

Supersonically expanding winds of hot early type stars are known to be highly variable on different time scales. Detailed and extensive monitoring of UV resonance lines formed throughout the stellar wind and subordinate lines (e.g. de Jong et al. 2001) lead to recognition that the variability is cyclical. Stellar rotation contributes one of the key parts in the induction and maintenance of the wind-variability mechanisms (Kaper 1998).

The overall description of stellar winds of hot stars ought to include X-rays because their transfer in the stellar wind and the distribution of emerged flux are genetically connected with the processes producing wind-variability as observed in the optical and UV lines. In some ways, all proposed mechanisms of X-ray production in the atmospheres of hot stars predict temporal variability of the X-ray emission. Nevertheless, so far there were only few detections of X-ray variability leaving the question about the influence of stellar rotation on the X-ray production open.

A large amplitude, periodic X-ray emission from the O7V star, θ^1 Ori C, was reported by Gagné et al. (1997) based on ROSAT observations. The observations covered more than 20 days. A period $16\overset{\mathrm{d}}{.}0 \pm 3\overset{\mathrm{d}}{.}8$ days was detected and attributed to stellar rotation. The time scale of changes in X-ray emission is very similar to the DACs recurrence period $15\overset{\mathrm{d}}{.}41 \pm 0\overset{\mathrm{d}}{.}02$ (Walborn & Nichols 1994). Gagné et al. (1997) discussed several possible explanations for the X-ray fluctuations including absorption in a co-rotating wind. The recent discovery of a secondary close low-mass companion for θ^1 Ori C (Weigelt et al. 1999) leave open the questions of interpretation of periodic X-ray changes as being due to the presence of a low-mass coronal companion.

In this paper we report the first ever X-ray observations of a single O star sampled continuously over one rotational period. The monitoring of ζ Oph by ASCA reveals a rotationally modulated X-ray luminosity.

2. ζ Oph

Amongst O stars, the main-sequence O9.5 star ζ Oph (HR 6175) is particularly interesting. Taking into account all the available observational material and recalling that ζ Oph is a runaway star, it is almost certain that it is a single star. The almost complete absence of multiplicity is suggested by the evolutionary scenario of the production of runaway stars. ζ Oph received its large space velocity (∼30 km s^{-1}) after the explosion of the primary in a massive binary system. The possibility of a compact object remaining bound to the star is ruled out by the recent identification of the pulsar PSR J1932+1059 as the former primary component (Hoogerwerf et al. 2001). Confirming the binary-supernova scenario, ζ Oph has a high rotation velocity ($v_{\mathrm{rot}} \sin i = 348$ km s^{-1}); in fact one of the

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highest among O stars (Massa 1995). Other physical properties of the star can be found in e.g. Howarth et al. (1993).

From data obtained over five consecutive years, the single period for travailing features, attributed to stellar rotation, was deduced as $P_{\rm DAC} = 0^{\rm d}\!.643$ (Harmanec 1989). There is a discrepancy, however, with the period obtained later from IUE time-series, HST spectroscopy and archival results. Howarth et al. (1993) observed the discrete absorption components at high velocities ($\simeq 0.8\ v_\infty$) which migrate bluewards. The recurrence time scale for this phenomenon was determined as $P_{\rm DAC} = 0^{\rm d}\!.875 \pm 0^{\rm d}\!.167$ and we use this value for our analysis.

ζ Oph is a nonradial pulsator (Jankov et al. 2000) with a variety of modes. In spite of its high helium abundance due to the mass exchange in the binary phase, ζ Oph has a comparably small mass loss rate producing a relatively low density wind. Taking into account that density and heavy element abundance in an outflow are the crucial parameters determining X-ray production (Owocki & Cohen 1999; Ignace et al. 2000), the low density and high velocity wind of ζ Oph are especially apt for studying any fluctuation of the emission.

ζ Oph has been observed by all major X-ray satellites. The first observations by EINSTEIN (0.2 − 4.0 keV) gives a ratio $\log L_{\rm X}/L_* = -7.12 \pm 0.27$. The ROSAT (0.2−2.4 keV) all-sky survey provides a ratio $= -7.68 \pm 0.61$. For ASCA, we deduce a mean ratio $= -7.73 \pm 0.16$. These values are self consistent and in the expected range for runaway stars.

3. ASCA observations of ζ Oph and ζ Pup

The ASCA X-ray satellite (0.5–10 keV) performed pointing observations of ζ Oph on 18/02/1995 14:36 to 19/02/ 19:03. The run duration was 28.444 hours or $1^{\rm d}\!.185$ which covers the single period of DAC recurrence, thus making these observations unique. The data entered the public domain on 17/04/96. We made use of the binned light curves extracted from the filtered event files. The binning was set to give means of at least 50 counts per bin but to be no smaller than the coarsest time resolution of the parent event files. ASCA carried two solid-state imaging spectrometers (SIS0 and SIS1) as well as two gas-imaging spectrometers (GIS2 and GIS3). All four instruments acquired data simultaneously. We retrieved light curves provided by all four detectors. The data have been dead-time corrected with the background subtracted. Although the effective areas of GIS and SIS are quite similar in the range 2–10 keV, SIS is more sensitive to softer X-rays and its effective area expands up to 0.5 keV, while for GIS, it falls below 0.8 keV. As Table 1 demonstrates, the weighted mean count rates of GISs are lower than those of SISs. This significant discrepancy in count rates may be indirect evidence of a rather low temperature for the bulk of the X-ray emitting plasma with emission maximum being below 1 keV.

Direct inspection of the immediate data available in graphical form in the ASCA archive shows that the records of the four detectors display bunching in the data acquisition with typically 5 to 10 grouped measurements closely spaced in time, with quiet intervals in between. Despite the large error bars carried by the individual measurements, there is an impression, particularly for SIS0 and SIS1, that the signals display an oscillation. By determining the weighted means of each well-defined group, this undulation is more apparent – see Fig. 1, where the time dependent count rates of ζ Oph from all four detectors are illustrated. Each data point represents the weighted mean of each group with its weighted standard error. Over the observing window, the X-ray count rates display a smooth undulation.

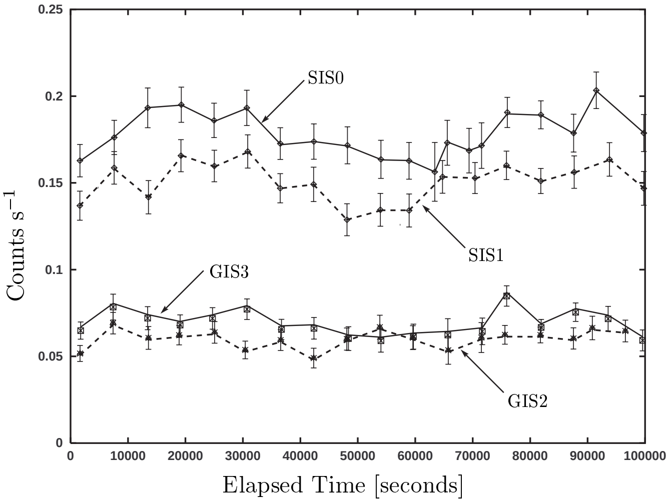

Fig. 1. Binned time sequence of observations of ζ Oph as observed by SIS0 (upper full line), SIS1 (upper dashed line), GIS3 (lower full line), GIS2 (lower dashed line). Data points are weighted means (see text), with a weighted error bar.

ASCA observed ζ Pup on 14/10/ 1993 13:08 to 15/10 17:20. The continuous run was 28.204 hours or $1^{\rm d}\!.175$ days. This is much shorter than $5^{\rm d}\!.075$ variation in Hα attributed to rotation but covers the 16.667 hour ±6% amplitude modulations reported by Berghöfer et al. (1996) using ROSAT observations.

4. Data analysis and period searching

Tests on whether measurements, m_i, can be considered as being drawn at random with time from a Gaussian distribution with sample mean, $\overline{m}$, were made by applying the string-length statistic of Lafler & Kinman (1965) modified to being an unbiased sample estimator defined as

$$T = \frac{\sum\limits_{i=1}^{N}\left(m_{i+1} - m_i\right)^2}{\sum\limits_{i=1}^{N}\left(m_i - \overline{m}\right)^2} \times \frac{(N-1)}{2N}. \qquad (1)$$

Full utilization of the data is made by including the vector length between the last and first measurement of the sequence by letting $m_{N+1} = m_1$ where N is the number of measurements. The T value is independent of the data sample size and equal to unity for measurements originating from a Gaussian distribution (Clarke 2001 – in prep.). Departures from unity can be ascribed a probability according to the size of the data sample. For the three detectors SIS0, SIS1 and GIS3, the the string-lengths (T values) were significantly shorter than unity suggesting that the data taken in time sequence were correlated and not representative of the measurements about a mean taken at random. Confidence levels of the non-randomness were 93%, 90% and 99% respectively. For the GIS2 detector, the T value was close to unity suggesting the data were indistinguishable from a random sample, with no temporal variation.

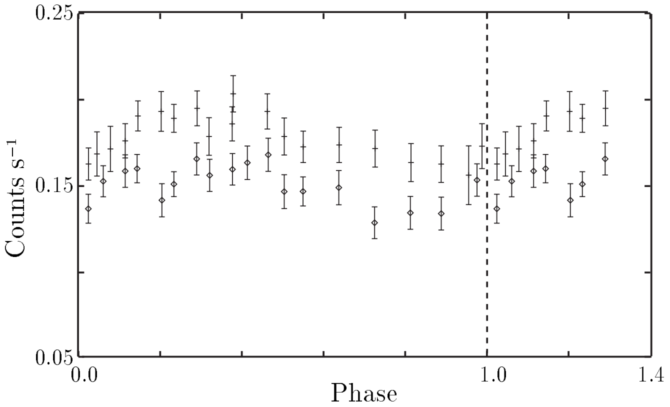

Fig. 2. The signal variations phased on the determined period of ζ Oph as observed by SIS0 (bars) and SIS1 (circles). Data points are weighted means (see text) with a weighted error bars.

The above estimator can also be used to undertake period searches and provide periodograms by re-ordering the measurements according to their determined phases for each of the trial periods and calculating the revised $T(P)$ values. The minimum T provides the estimate of the period. Application of the algorithm provided the results collected under Table 1. Error estimates for the period have been taken according to the periodogram interval over which the minimum $T(P)$ was constant. Examination of the mean periodogram from the four detectors provided the most likely period of $0\overset{\mathrm{d}}{.}768$ although there is another very similar minimum in the periodogram at $P = 0\overset{\mathrm{d}}{.}791$. We believe, therefore, that it is safe to use the value $0\overset{\mathrm{d}}{.}77$ allowing at least 5% band of uncertainty on this value.

Further confidence in the notion that the undulation is real is obtained by applying least squares fits of the measurements to a sinusoidal variation, using the determined period, and calculating the amplitude and phase. The data for SIS0 and SIS1 provided amplitudes of 21.7% and 21.1% respectively. Importnatly, the phases are closely matching. The signal variations phased on the determined period are presented for these two channels in Fig. 2.

Table 1. Count rates and periods as detected by ASCA.

	SIS0	SIS1	GIS2	GIS3
Weighted mean (cps)	0.1795	0.1504	0.0601	0.0686
Weighted error (cps)	0.0023	0.0021	0.0014	0.0015
Period (days)	0.768	0.728	0.801	0.736
Estimated error (±)	0.035	0.058	0.023	0.052
Period confidence (%)	>99.9	>99.9	92	99.3

It may be noted also that a similar exercise on measurements of ζ Pup provided no hint of variability over a similar time window. Although, detectors SIS0 and SIS1 provided data with similar S/N ratio as for ζ Oph , the values of T are marginally greater than unity with no suggestion other than that they appear to originate from a Gaussian distribution sampled at random. Thus, our attempts to detect periodic variability of the X-ray emission for ζ Pup based on ASCA provided a null result. XMM-NEWTON observations of ζ Pup (Kahn et al. 2001) did not confirm the period reported by Berghöfer et al. (1996) (pointing out that the upper limit to the percentage variation is not inconsistent). CHANDRA observed ζ Pup for $\approx 0\overset{\mathrm{d}}{.}775$; so far, no variability of X-ray emission has been reported (Cassinelli et al. 2001).

5. Discussion

Continuous ASCA monitoring of ζ Oph covering its full rotational period provides the first evidence of a correlation between stellar rotation and X-ray emission. Such a correlation is new evidence of a link between the global structure of stellar wind and X-rays.

Rotationally modulated X-ray emission from single star ζ Oph resembles θ^1 Ori C and thus supports the idea of Gagné et al. (1997) that the bulk of X-rays comes from the primary O star companion. Nevertheless, we argue that the presence of a coronal companion may be responsible for the specific features observed in the high resolution spectrum of θ^1 Ori C as reported by Schulz et al. (2000).

To begin with, one may attribute the light curve variation with changes of the emission measure or the location of the emitting material. The widely accepted mechanism of shock propagation in energetic stellar winds predicts the existence of stochastic small time scale variability rather than significant periodic fluctuations (e.g. Feldmeier et al. 1996a,b; Oskinova et al. 2001). So far, no reasonable mechanism for periodic variations of emission measure of X-ray emitting material in hot early type stars has been put forward. Nevertheless, one may speculate that the presence of co-rotational interaction regions (CIRs) (see Cranmer & Owocki 1996) can affect the production of X-ray emission and potentially lead to a correlation between stellar rotation and X-ray emission and absorption. The alternative idea is that if the X-ray source is located near the base of the wind, one would observe periodic changes in X-ray luminosity due to stellar rotation, as in solar-type stars.

Based on recent Chandra and XMM-Newton observations of hot stars, the proposal of the existence of an X-ray corona at the base of the wind has been rejuvenated by Waldron & Cassinelli (2001). At the same time, the accreting neutron-star X-ray sources orbiting near the surfaces of HD 153919 (O6If) and HD 77581 (B0.5Ib) (Haberl et al. 1989) show that this is unlikely; their X-ray spectra show such comprehensive low-energy absorption by the wind that any surface corona would be quite invisible (Pollock & Oskinova 2001 – in prep.).

Different missions have observed that the X-rays from a number of hot stars suffer from photoelectric absorption caused by K-shells of heavy ions (e.g. Corcoran et al. 1994; Cassinelli et al. 2001) in the cool general stellar wind. Stellar wind itself is not homogeneous but structured on small and large scales which are observationally revealed, e.g., in the presence of DACs in the absorption lines of numerous ions. The reasonable question to address, therefore, is whether variation in the distribution of absorbing material can lead to fluctuations of X-ray emission?

The absorption edges in the soft part of the X-ray spectrum of ζ Oph are clearly seen (ζ Oph spectra can be readily retrieved on-line using HEASARC facilities). Unfortunately, the effective area of SIS is very non-linear below 1 keV due to the presence of a strong OVII K-edge and the effective area of GIS falls quickly below 1 keV. This makes it difficult to distinguish between absorption due to the circumstellar material and the non-linear instrumental response.

In order to infer information about spectral time variability, we retrieved the energy of the detected photons and the times of their arrival from the SIS0 event file. The low count rate and the poor data quality do not allow high temporal resolution. We define a “hardness ratio” as the quotient of counts of photons above 1.2 keV over the those below that threshold. We constructed two hardness ratios by binning observations around the maximum and the minimum of the detected X-ray lightcurve. The rationale for doing so was that the opacity of the wind rises dramatically with wavelength but the wind is almost transparent for the X-rays in the hard part of the spectra. Thus the time dependence of the hardness ratio indicates varying absorption. We find indeed that the ratios (hard/soft) differ by $\sim$20% (0.68 near maximum versus 0.83 near minimum), giving a pointer to the suggestion that the cause of X-ray variability may result from changing absorption.

The striking similarity of time-scales for X-ray variability and slow moving DACs in the UV spectra which is confirmed for at least two O stars is justified when adopting the presence of CIRs in the stellar outflow. In this model, there is the only one period which corresponds to the period of stellar rotation or an integer fraction of it (Hamann et al. 2001 – accept. by A&A). Although, uncertainties in the determination of the rotational period are quite large, mainly due to uncertainties of the stellar radii, (Fullerton 1998), the number of other variable features observed in the optical and UV spectra of O type stars, such as fast modulations or line profile variations due to non-radial pulsations, seem not to have any relevance to the rotation of the star and differ significantly in their time scale (Jankov et al. 2000; Howarth et al. 1993).

To conclude, we emphasize that, although there is a very high confidence on the detection of an undulation of the X-ray output, it is impossible at this stage to put forward any firm interpretation of the determined period without accruing data over a much longer timespan.

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References

Berghöfer, T. W., Baade, D., Schmitt, J. H. M. M., et al. 1996, A&A, 306, 899

Cassinelli, J. P., Miller, N. A., Waldorn, W. L., MacFarlane, J. J., & Cohen, D. H. 2001, ApJ, 554, L55

Corcoran, M. F., Waldron, W. L., MacFarlane, J. J., et al. 1994, ApJ, 436, L95

Cranmer, S. R., & Owocki, S. P. 1996, ApJ, 462, 469

Gagné, M., Caillault J.-P., Stauffer, J. R., & Linsky, J. L. 1997, ApJ, 478, L87

Haberl, F., White, N. E., & Kallman, T. R. 1989, ApJ, 343, 409

Harmanec, P. 1989, Bull. Astron. Inst. Czechoslovakia, 40, 201

Hoogerwerf, R., de Bruijne, J. H. J., & de Zeeuw, P. T. 2001, A&A, 365, 49

Howarth, I. D., Bolton, C. T., Crowe, R. A., et al. 1993, ApJ, 417, 338

Ignace, R, Oskinova, L. M., & Foullon, C. 2000, MNRAS, 318, 214

Feldmeier, A., Kudrizki, R. P., Palsa, R., et al. 1997a, A&A, 320, 899

Feldmeier, A., Puls, J., & Pauldrach, A. W. A. 1997b, A&A, 322, 878

Fullerton, A. W. 1998, in Proc. IAU Coll. 169, ed. B. Wolf, O. Stahl, & A. W. Fullerton, Heidelberg, 3

Jankov, S., Janot-Pacheco, E., & Leister, N. V. 2000, ApJ, 540, 535

de Jong, J. A., Henrichs, H. F., Kaper, L., et al. 2001, A&A, 368, 601

Kahn, S. M., Leutenegger, M. A., Cottam, J., et al. 2001, A&A, 365L, 312

Kaper, L. 1998, in Proc. IAU Coll. 169, ed. B. Wolf, O. Stahl, A. W. Fullerton, Heidelberg, 193

Lafler, J., & Kinman, T. D. 1965, ApJS, 11, 216

Massa, D. 1995, ApJ, 438, 376

Oskinova, L. M., Ignace, R., Brown, J. C., & Cassinelli, J. P. 2001, A&A, 373, 1009

Owocki, S. P., & Cohen, D. H. 1999, ApJ, 520, 833

Schulz, N. S., Canizares, C. R., Huenemoerder, D., & Lee, J. C. 2000, ApJ, 545, L135

Walborn, N. R., & Nichols, J. S. 1994, ApJ, 425, L29

Waldron, W. L., & Cassinelli, J. P. 2001, ApJL, 548L, 45

Weigelt, G., Balega, Y., Preibisch, Th., et al. 1999, A&A, 347, L15