# X-ray emission from O-type stars: DH Cep and HD 97434

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## ARTICLE INFO

## ABSTRACT

We present X-ray emission characteristics of the massive O-type stars DH Cep and HD 97434 using archival XMM-Newton observations. There is no convincing evidence for short-term variability in the X-ray intensity during the observations. However, the analysis of their spectra reveals X-ray structure being consistent with two-temperature plasma model. The hydrogen column densities derived from X-ray spectra of DH Cep and HD 97434 are in agreement with the reddening measurements for their corresponding host clusters NGC 7380 and Trumpler 18, indicating that the absorption by stellar wind is negligible. The X-ray emission from these hot stars is interpreted in terms of the standard instability-driven wind-shock model.

## 1. Introduction

Massive, hot and luminous O-type stars have powerful stellar winds, with mass-loss rates of the order of $10^{-6}$–$10^{-4}$ $M_\odot$ yr$^{-1}$ and velocities of several thousand km s$^{-1}$. These winds play a crucial role both in the stellar evolution as well as the galactic evolution. The existence of strong winds is supposed to be a primary reason for X-ray emission in the early-type stars. Study of the X-ray emission from O-type stars is important for understanding the high energy processes that generate hot gas in the wind or in the atmosphere of hot stars. X-ray emission from O-type stars was first discovered serendipitously with the Einstein observatory (Harnden et al., 1979). Most O-type stars are reasonably bright ($10^{31} < L_X < 10^{34}$ erg s$^{-1}$) and have a soft thermal spectrum with kT <1 keV. The X-ray luminosity of these sources is found to scale with their bolometric luminosity as $L_X/L_{bol} \sim 10^{-6}$ to $10^{-8}$ (Long and White, 1980; Pallavicini et al., 1981; Singh and Naranan, 1982; Berghöfer et al., 1997; Sana et al., 2006). It is generally thought to be produced as a result of shocks, with velocity jumps up to a few hundred km s$^{-1}$. These shocks are generated throughout the stellar wind because of dynamic instabilities (Lucy and White, 1980; Owocki and Cohen, 1999; Kudritzki and Puls, 2000). This scenario is now called a standard model for X-ray emission from early-type stars (Rauw, 2008). Although, most of the X-ray emission is dominated by soft X-rays as expected from wind-shock

model (e.g., Feldmeier et al., 1997), a significant and an unexpected harder component is also seen in the X-ray spectra (e.g., Leutenegger and Kahn, 2003; Broos et al., 2007; Stelzer et al., 2005). High quality observational data from XMM-Newton and Chandra observatories are indeed crucial to provide a strong test of the latest models. In order to understand the X-ray emission processes from O-type stars, we have analyzed XMM-Newton data for two O-type stars DH Cep and HD 97434. The results of our analysis are presented here.

DH Cep is an O6 V + O7 V spectroscopic binary system and a member of the cluster NGC 7380 (distance = 3.7 kpc, age = 10 Myr; Underhill, 1969; Massey et al., 1995; Hilditch et al., 1996). It has an orbital period of 2.11 d (Penny et al., 1997). A low signal, Einstein X-ray observation is reported by Chlebowski et al. (1989) with $L_X \sim 5.37 \times 10^{33}$ erg s$^{-1}$ in the energy band 0.2–3.5 keV.

HD 97434 is an O9 V star (Skiff, 2007), with a membership probability of 78% (Dias et al., 2006) in the cluster Trumpler 18 (distance = 1.5 kpc; age = 90 Myr; Vázquez and Feinstein, 1990). The Einstein X-ray data for the source are cataloged by Chlebowski et al. (1989) with $L_X < 3.4 \times 10^{32}$ erg s$^{-1}$ (corrected for the distance of 1.5 kpc) in the energy band 0.2–3.5 keV.

## 2. XMM-Newton observations and data reduction

We present analysis of the archival data obtained with the XMM-Newton observatory. Table 1 summarizes the XMM-Newton observations. Our analysis is based on CCD images, lightcurves and spectra from the European Photon Imaging Cameras (EPIC). Data were acquired simultaneously with EPIC-PN camera (Strüder

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**Table 1**
Journal of XMM-Newton observations of the objects.

| Object name | DH Cep | HD 97434 |
|---|---|---|
| Observation ID | 0205650101 | 0051550101 |
| Exposure time (s) | 31413 | 40822 |
| Start time UT | 19 December 2003 | 06 February 2002 |
| (hh:mm:ss) | 02:02:12 | 01:13:19 |
| Usable time (ks) (MOS1)[a] | 25.23 | |
| Usable time (ks) (MOS2) | 25.46 | 39.20 |
| Usable time (ks) (PN) | 19.52 | 35.85 |
| EPIC filter | Thick | Medium |
| Offset from target (arcmin) | 0.000 | 3.68 |

[a] The observations have not done in Prime Full window mode for MOS1 detector.

et al., 2001) and two nearly identical EPIC-MOS (MOS1 and MOS2; Turner et al., 2001) cameras. Data reduction followed standard procedures using XMM-Newton Science Analysis System software (SAS version 8.0.0) with updated calibration files (Ehle et al., 2004). A detailed description of the data reduction and analysis procedure is given in Bhatt et al. (2010). Owing to poor counts below 0.3 keV and above 7.5 keV, our analysis is limited to the energy band 0.3–7.5 keV. For the star HD 97434, the observations are not made with the MOS1 detector, therefore we used only the data from PN and MOS2 detectors for further analysis. The binary phases of DH Cep were determined using the ephemeris HJD = 2441905.805 + 2.110932E (Hilditch et al., 1996; Penny et al., 1997) and the observations have been taken during the binary phase of 0.08–0.25.

Source photons were extracted from circular region of 20″ around the star position of DH Cep and HD 97434 to generate the light curves and spectra. Background was estimated from a number of empty regions close to the X-ray source in the detector. X-ray spectra of the sources were generated using SAS task ESPECGET, which also computes the photon redistribution as well as the ancillary matrix. Finally, the spectra were re-binned to have at least 20 counts per spectral bin for both the sources.

## 3. Analysis

Fig. 1 shows the background and the background subtracted X-ray lightcurves of the stars DH Cep and HD 97434. We have binned the event lists into 1000 and 1500 s time intervals for the stars DH Cep and HD 97434, respectively. We have performed $\chi^2$ test to measure the significance of the deviations from the mean count rates. The probability of the variability ($P_{var}$) to quantify the constancy of the data over the time scale of observations was calculated. The results are displayed in the respective panels of Fig. 1. The value of $P_{var}$ was calculated to be >99% for the star DH Cep. However, it was calculated to be <50% for the star HD 97434. It indicates that the light curves of the star DH Cep show significant variability. We further analysed the light curves of DH Cep and found that the observed variability may arise due to a few outlier points. If we neglect the four outlier points of the light curves of DH Cep, the probability of variability decreases to 80%. Therefore, we have plotted the 3σ limit in Fig. 1 represented by a shaded region around the constant count rate, i.e., mean value of count rate for the data sample. Here, σ represents the standard deviation in count rates. This analysis shows that none of the data points in any of the light curves were lying outside of 3σ limit. Further, the variability trend seen in the PN data was not correlated with the MOS data and all the data points in the light curves were within 3σ limits. Therefore, it appears that the significance of the vari-

ability in the light curves is very poor and cannot be detected by the present data set.

X-ray spectra of DH Cep and HD 97434 are shown in Fig. 2. Emission lines of Fe XVII (0.8 keV), Ne X (1.02 keV), Mg XII (1.47) and Si XIII (1.853 keV) are seen in their respective spectra. X-ray emission from massive stars is thought to be produced from thermal emission, generated from shock-heated plasma. These hydrodynamic shocks may occur in the stellar winds from massive stars. However, in massive binaries they may occur in wind–wind collision zone (Bhatt et al., 2010 and references therein). Therefore, we have modeled the spectra using (a) plane-parallel shock model (PSHOCK; Borkowski et al., 2001), and (b) models of Astrophysical Plasma Emission Code (APEC; Smith et al., 2001), as implemented in the XSPEC version 12.3.0. A $\chi^2$ – minimization gave the best fitted model to the data. We corrected for the local absorption in the line-of-sight to the source ($N_H$) using the photoelectric absorption cross sections according to Balucińska-Church and McCammon (1992) and modeled it as PHABS (photoelectric absorption screens). The abundances in the absorber were allowed to vary during the fitting procedure. The abundances were varied with respect to solar abundances adopted from Lodders (2003).

First, we fitted PSHOCK plasma model to derive their spectral features. The constant temperature PSHOCK plasma model was considered without incorporating mass-loss and orbital parameters of massive stars. However, the model does account for non-equilibrium ionization effects and assumes an equal electron and ion temperature. The best fit PSHOCK models to the data are shown in left and right top panels of Fig. 2 and the best-fit parameters are given in Table 2. The best-fit X-ray temperatures deduced from X-ray spectra are found to be $0.64^{+0.02}_{-0.02}$ keV and $0.64^{+0.04}_{-0.04}$ keV for DH Cep and HD 97434, respectively.

Second, the simplest spectral APEC model was used for the spectral fitting. Here, we first considered the case of an isothermal hot ionized gas as the one temperature (1T) APEC model. This model is expressed as PHABS × APEC. The 1T APEC models with either solar or subsolar photospheric abundances were found to be unacceptable for both the stars due to high value of $\chi^2_\nu$. Therefore, for the next level of complexity, we used models with two temperatures (2T) expressed as PHABS (APEC + APEC). In 2T models the first component represents the "cooler" ionized gas and the second component represents the "hotter" ionized gas. The 2T models were found to be acceptable but required subsolar abundances, i.e., $Z \approx 0.2 \, Z_\odot$. The subsolar abundances have also been reported for 15 other massive stars by Zhekov and Palla (2007). The best fit 2T models are displayed as histograms along with the data in the left and the right bottom panels of Fig. 2 for the stars DH Cep and HD 97434, respectively. The best-fit parameters for these models were obtained by $\chi^2$-minimization technique and are given in Table 2 with their corresponding $\chi^2_\nu$. We noted that 2T APEC model fitted these spectra better than PSHOCK model with a smaller value of $\chi^2_\nu$ (see Fig. 2 and Table 2). The cooler and hotter X-ray temperatures deduced from X-ray spectra are found to be $0.62^{+0.02}_{-0.02}$ keV and >1.89 keV for DH Cep and $0.32^{+0.07}_{-0.17}$ keV and $0.74^{+0.13}_{-0.12}$ keV for HD 97434, respectively. The best-fit values of $N_H$ for DH Cep and HD 97434 are in agreement with the values of $N_H$ derived from optical data for NGC 7380 ($0.32 \times 10^{22}$cm$^{-2}$; Massey et al., 1995), and Trumpler 18 ($0.14 \times 10^{22}$ cm$^{-2}$; Vázquez and Feinstein, 1990), respectively. The $N_H$ from optical data was estimated using the relation, $N_H = 5.0 \times 10^{21} \times E \, (B - V)$ cm$^{-2}$ (Vuong et al., 2003), where $E(B - V) = A_V/3.1$, assuming a normal interstellar reddening law towards the direction of the cluster. The extra absorbing hydrogen column density in addition to the interstellar contribution was not needed in the spectral fits implying that the absorption by the stellar wind is negligible (see also Zhekov and Palla, 2007; Sana et al., 2006).
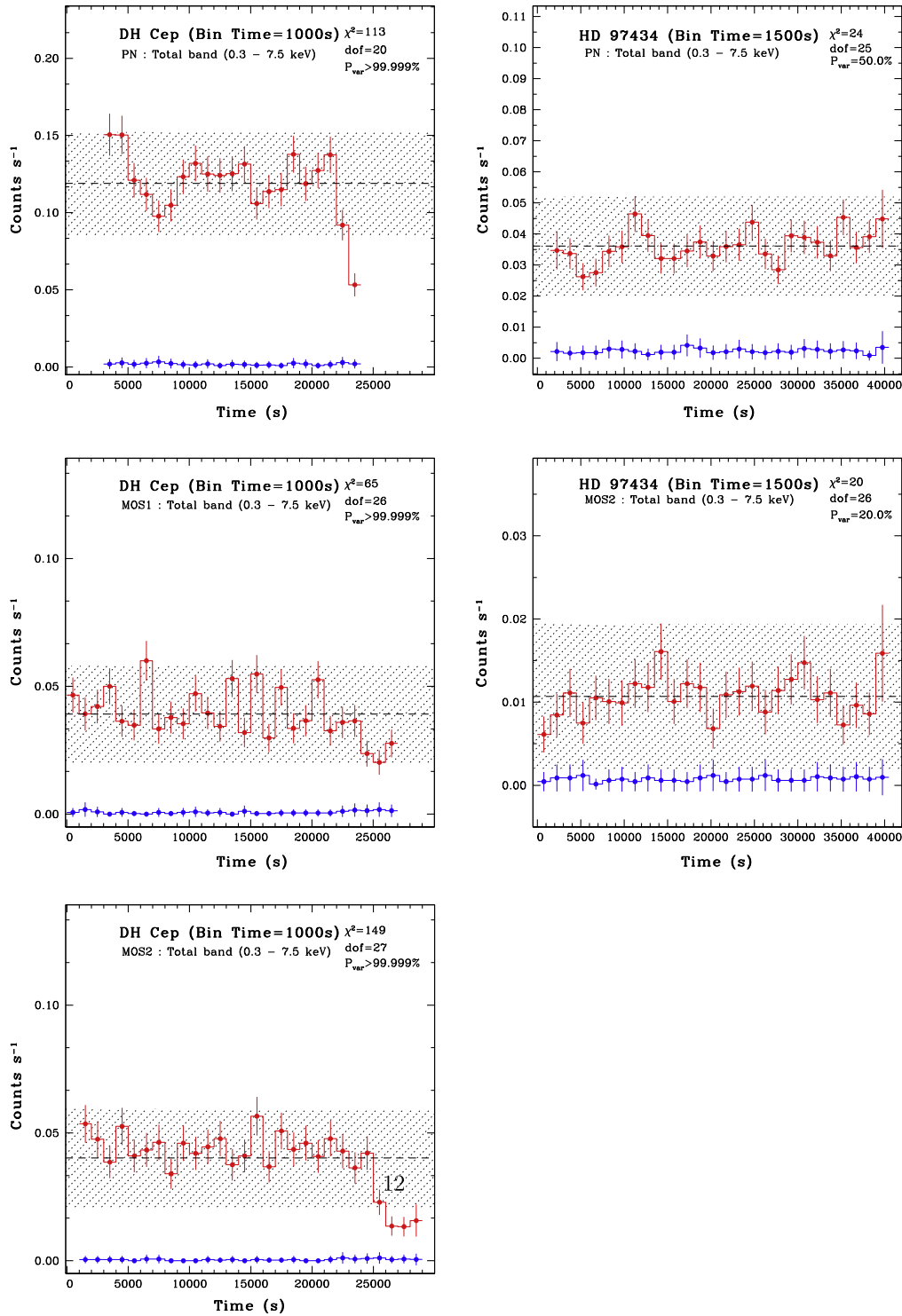
**Fig. 1.** X-ray light curves for the stars DH Cep (left panel) and HD 97434 (right panel). The background subtracted lightcurves are shown by top set of circles and the background in the same XMM-Newton/EPIC field of view represented by bottom set of circles in each panel.

## 4. Discussion

### 4.1. X-ray variability

The wind-shock model predicts a significant short-term variability in the X-ray flux as the shocks fade and grow on short time scales. However, it has not been observed so far. We have also explored the possibility of short-term X-ray variability of DH Cep and HD 97434 over the observation time span (<40 ks). The timing analysis reveals a lack of short-term variability in the X-ray intensity for both the massive stars. The lack of short-term variability could be due to the wind fragmentation, so that individual X-ray fluctuations are smoothed out over the whole emitting volume, leading to a rather constant output (Feldmeier et al., 1997). Several
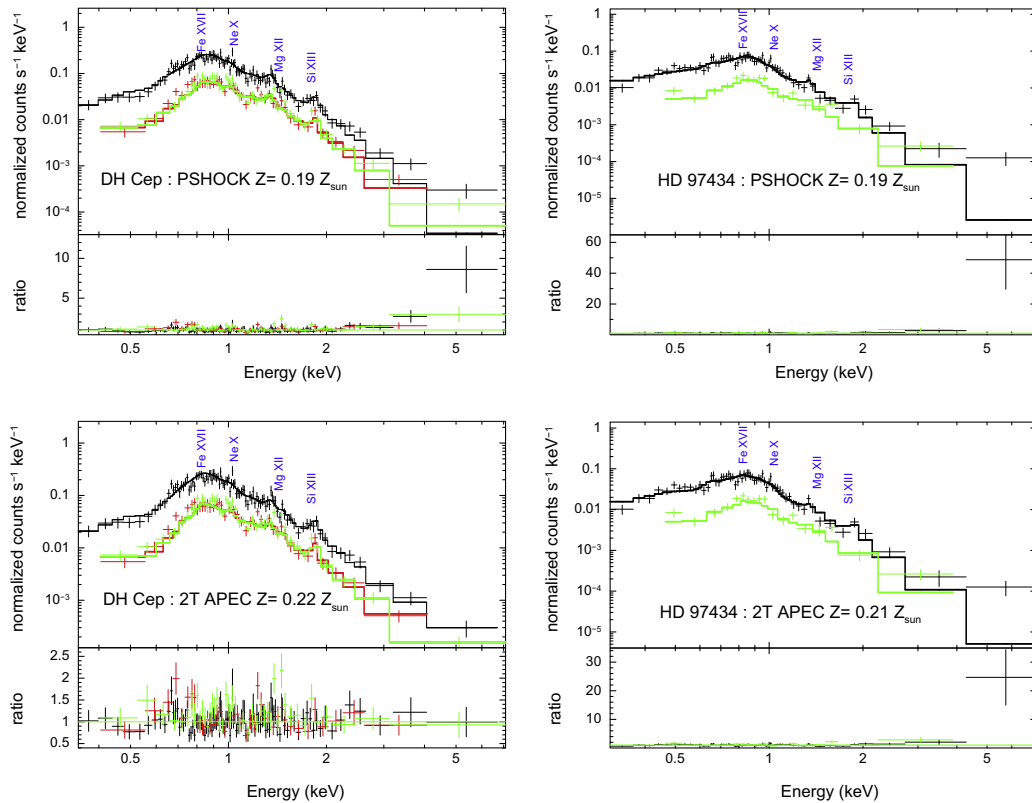
**Fig. 2.** Best-fit X-ray spectra of massive stars. left panel: for DH Cep. right panel: for HD 97434. The solid line histograms represent the best fit PSHOCK (in upper panels) and 2*T* APEC model (in lower panels) with absorption model PHABS for PN, MOS1 and MOS2 data.

**Table 2**
The best-fit spectral parameters of the stars DH Cep and HD 97434.

| Parameters | DH Cep | | HD 97434 | |
|---|---|---|---|---|
| | PSHOCK | 2*T* APEC | PSHOCK | 2*T* APEC |
| $N_H$ ($10^{22}$ cm$^{-2}$) | $0.42^{+0.04}_{-0.04}$ | $0.39^{+0.03}_{-0.03}$ | $0.17^{+0.04}_{-0.04}$ | $0.18^{+0.05}_{-0.04}$ |
| $kT_1$ (keV) | $0.64^{+0.02}_{-0.02}$ | $0.62^{+0.02}_{-0.02}$ | $0.64^{+0.04}_{-0.04}$ | $0.32^{+0.07}_{-0.17}$ |
| $kT_2$ (keV) | | >1.89 | | $0.74^{+0.13}_{-0.12}$ |
| $Z/Z_\odot$ | $0.19^{+0.02}_{-0.02}$ | $0.22^{+0.06}_{-04}$ | $0.19^{+0.07}_{-0.05}$ | $0.21^{+0.11}_{-0.06}$ |
| $\tau$($10^{11}$ s cm$^{-3}$) | $15.14^{+59.94}_{-9.26}$ | | $9.61^{+11.39}_{-4.23}$ | |
| $EM_1$ ($10^{54}$ cm$^{-3}$) | $240.26^{+28.85}_{-33.79}$ | $215.49^{+30.15}_{-43.86}$ | $5.09^{+1.62}_{-1.21}$ | $4.09^{+3.18}_{-2.02}$ |
| $EM_2$ ($10^{54}$ cm$^{-3}$) | | $4.95^{+9.28}_{-2.34}$ | | $3.43^{+2.02}_{-1.28}$ |
| $\chi^2_\nu$/d.o.f. | 1.32(181) | 1.18(180) | 1.36(75) | 1.31(74) |
| $F_X$ ($10^{-12}$ erg cm$^{-2}$ s$^{-1}$) | 0.33 | 0.34 | 0.08 | 0.08 |
| log $L_X$ (erg s$^{-1}$) | 32.73 | 32.75 | 31.31 | 31.32 |
| log ($L_X/L_{bol}$)[0.3 − 7.5] | −6.73 | −6.71 | −7.29 | −7.29 |
| log ($L_X/L_{bol}$)[0.3 − 2.0] | −6.77 | −6.77 | −7.31 | −7.31 |
| log ($L_X/L_{bol}$)[2.0 − 7.5] | −7.76 | −7.55 | −8.56 | −8.48 |

other massive stars, e.g., HD 159176 (De Becker et al., 2004) and HD 47129 (Linder et al., 2006) have also shown lack of variability in their light curves.

The longer-term variability can not be probed using present data. The long-term variability (few days) from O-type stars was reported by Snow et al. (1981) for the first time, but their results were based on the low sensitivity detectors available at that time. No significant variability was detected by the ROSAT All-Sky Survey in the X-ray emission of 57 OB stars over a time-scale of ≈2 d (Berghöfer and Schmitt, 1995).

### 4.2. X-ray temperatures of plasma

Our analysis of XMM-Newton data reveals two-component X-ray temperature structure for massive stars. The temperatures

corresponding to the cool and the hot components of HD 97434, and the cool component of DH Cep are found to be less than 1 keV. However, the temperature corresponding to the hot component of DH Cep was found to be more than 1.89 keV. The derived values of temperatures are similar to the O-type stars in the NGC 6231 cluster (Sana et al., 2006) and in the Carina OB1 association (Antokhin et al., 2008). Generally for O-type stars, the best fits to good quality data can usually be achieved by the sum of two thermal components at about 0.3 and 0.7–1 keV (Güdel and Nazé, 2009). The observed soft X-ray emission could originate from radiation-driven instabilities in stellar winds (Lucy, 1982). The wind-shock model predicts the intrinsic instability of the line driving mechanism. Indeed, the velocity in an unstable wind is not the same everywhere and the fast-moving parcels of material will overcome the slow moving material, generating shocks between them. This model estimates the shock velocities ($v_{shock}$) by the relation (Lucy, 1982; Luo et al., 1990)

$$v_{shock} = \sqrt{\frac{kT_{sh}}{1.95\mu}}. \qquad (1)$$

Adopting the mean particle weight $\mu \approx 0.62$ for O-type stars (Cassinelli et al., 2008) we derive the "average" value of shock velocities correspond to the cool components ($kT_1$) $716^{+12}_{-12}$ km s$^{-1}$ and $514^{+54}_{-162}$ km s$^{-1}$ for the stars DH Cep and HD 97434, respectively. However, the shock velocities correspond to the hot components ($kT_2$) are found to be >1563 km s$^{-1}$ and $782^{+66}_{-66}$ km s$^{-1}$ for DH Cep and HD 97434, respectively. These values are about a factor of 2 larger than the predicted by radiative shock model of Lucy (1982). However, the evolved version of the standard model by Owocki et al. (1988) predicts X-ray emission up to 1 keV from wind-shock model. The temperature corresponding to the hot component of DH Cep is found to be more than 1.89 keV. It may

arise from wind collision zone of the binary system (see Bhatt et al., 2010 and references therein), but we are not able to draw any firm conclusion on the basis of it alone. Therefore, it appears that the cool as well as hot temperature components from DH Cep and HD 97434 could be generated by instabilities in radiation-driven wind shocks.

### 4.3. X-ray Luminosity

For massive stars DH Cep and HD 97434, the ratios of X-ray to bolometric luminosities, $\log(L_X/L_{bol})$, are found to be $-6.7$ and $-7.3$ (see Table 2) in the energy band 0.3–7.5 keV, respectively, which are broadly consistent with the relation derived for similar kind of O-type stars (Sana et al., 2006).

X-ray luminosities derived from XMM-Newton data are found to be an order of magnitude lower than the $L_X$ derived from Einstein observations for both the massive stars (see Table 2 and Section 1). These discrepancies can not be explained by difference in sensitivity ranges of the various instruments. A similar results have been found by De Becker et al. (2004) for the star HD 159176 after the comparison of XMM-Newton, Einstein and ROSAT data. We found the X-ray luminosity $4.82 \times 10^{32}$ and $1.95 \times 10^{31}$ in energy range 0.3–2.0 keV for the DH Cep and HD 97343, respectively, using XMM-Newton data. The choice of the energy range is nearly a similar to the energy range in Einstein observations, i.e., 0.2–3.5 keV. We further converted the Einstein IPC count rates into flux using the WebPIMMS,[1] where we assumed a thermal plasma model with temperature of 0.5 keV, and the hydrogen column density of $3.9 \times 10^{21}$ for DH Cep and $1.8 \times 10^{21}$ for HD 97434 (see Table 2). The Einstein IPC count rates are 0.0166 and <0.0103 counts s$^{-1}$ for the stars DH Cep and HD 97343, respectively (Chlebowski et al., 1989). The X-ray luminosity thus caluated was $2.3 \times 10^{32}$ and <$1.2 \times 10^{31}$ for the stars DH Cep and HD 97434, respectively. These values are consistent with that obtained from XMM-Newton observations. Therefore, it appears that the model used by Chlebowski et al. (1989) to convert the Einstein count rates into luminosities may be responsible for these discrepancies.

## 5. Summary and conclusions

Using the archival XMM-Newton observations, we present, for the first time, the temporal and spectral analysis of X-ray emission from O-type stars DH Cep and HD 97434. The main results are as follows:

1. There is no firm evidence for short-term variability in the X-ray intensity during the observations time span (<40 ks) for both the stars.
2. The values of $N_H$ derived from the best-fit X-ray spectra are consistent with the optical estimates of reddening.

3. X-ray spectra of these stars are fitted consistently with two-temperature plasma models. The X-ray emitting plasma is found to be generated at a temperature of lesser than 1 keV. It could originate from small shocks in the radiation-driven outflows. A hotter component is indicated in DH Cep.
4. The best-fit values of abundances are found to be 0.2 times of the solar abundances.

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[1] http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html