



The Secret Lives of Cepheids: δ Cep—The Prototype of a New Class of Pulsating X-Ray Variable Stars*

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Abstract

From our Secret Lives of Cepheids program, the prototype Classical Cepheid, δ Cep, is found to be an X-ray source with periodic pulsation-modulated X-ray variations. This finding complements our earlier reported phase-dependent FUV–UV emissions of the star that increase ~ 10 – 20 times with highest fluxes at ~ 0.90 – 0.95ϕ , just prior to maximum brightness. Previously δ Cep was found as potentially X-ray variable, using *XMM-Newton* observations. Additional phase-constrained data were secured with *Chandra* near X-ray emission peak, to determine if the emission and variability were pulsation-phase-specific to δ Cep and not transient or due to a possible coronally active, cool companion. The *Chandra* data were combined with prior *XMM-Newton* observations, and were found to very closely match the previously observed X-ray behavior. From the combined data set, a ~ 4 increase in X-ray flux is measured, reaching a peak $L_X = 1.7 \times 10^{29}$ erg s⁻¹ near 0.45ϕ . The precise X-ray flux phasing with the star’s pulsation indicates that the emissions arise from the Cepheid and not from a companion. However, it is puzzling that the maximum X-ray flux occurs $\sim 0.5\phi$ (~ 3 days) later than the FUV–UV maximum. There are several other potential Cepheid X-ray detections with properties similar to δ Cep, and comparable X-ray variability is indicated for two other Cepheids: β Dor and V473 Lyr. X-ray generating mechanisms in δ Cep and other Cepheids are discussed. If additional Cepheids are confirmed to show phased X-ray variations, then δ Cep will be the prototype of a new class of pulsation-induced X-ray variables.

Key words: stars: activity – stars: atmospheres – stars: individual (δ Cep) – stars: variables: Cepheids – ultraviolet: stars – X-rays: stars

1. Introduction

Classical Cepheid variables are a well-studied class of pulsating, yellow supergiant stars that are of fundamental importance to astronomy and cosmology (e.g., see Freedman & Madore 2010; Ngeow et al. 2015; Riess et al. 2016, and many included references). Cepheids undergo periodic changes in size, temperature, and brightness as a result of their pulsations, with periods typically ranging from 2 to 60 days. Over the past century, Cepheids have become key cornerstones of the cosmic distance scale by way of the Leavitt law—in which the star’s luminosity correlates with its pulsation period.

In the present era of “high precision” cosmology (see Riess et al. 2016), it is important to exploit the full potential of Cepheids as precise extragalactic distance indicators for determining the expansion rate of the universe and setting constraints on cosmology models. To achieve these goals, a deeper understanding and characterization of Cepheids is needed. Recent discoveries such as circumstellar environments (Nardetto et al. 2016), infrared excesses (Mérand et al. 2015), and ultraviolet emission line variability and possible more

recent X-ray emissions (Engle et al. 2014) show that some important aspects of Cepheids may not be well understood. Cepheids have also been found to show additional complications that include cycle-to-cycle variations in their light and radial velocity curves (see Evans et al. 2015b; Anderson 2016; Anderson et al. 2016; Smolec & Śniegowska 2016; Derekas et al. 2017). These newly discovered properties and time-dependent phenomena of Cepheids, unless better understood and accounted for, could place impediments on achieving the challenging goal of determining the local Hubble constant (H_0) with a precision of $\sim 1\%$, as suggested by Suyu et al. (2012). Great efforts are being undertaken to achieve this level of precision, and hopefully resolve the developing “Hubble Discrepancy” (see Riess et al. 2016), where theoretical values of the Hubble constant (H_0) derived via the Lambda-cold dark matter (Λ -CDM) cosmology model (Λ = the cosmological constant), including cosmic microwave background data (e.g., *Planck*, *WMAP* (*Wilkinson Microwave Anisotropy Probe*)), show a small (albeit statistically significant) disagreement with the value of H_0 will be derived via standard candles (e.g., Cepheids, SNe Ia (type Ia Supernovae)). As discussed by Suyu et al. (2012) and more recently by Riess et al. (2016), improved measurements of H_0 provide critical independent constraints on dark energy and the validity of the present Λ -CDM model.

This paper focuses on the efforts of the *Secret Live of Cepheids* program to study the activity and variability of Cepheid outer atmospheres (specifically δ Cep). The previously

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observed phase-dependent UV emission line variability of Cepheids can be well ascribed to the passage of a shock front through the outer atmosphere (e.g., Bohm-Vitense & Love 1994; Sasselov & Lester 1994a, 1994b, 1994c; Engle et al. 2014). Cepheid shock generation and propagation has been theorized and modeled for some time now (see Willson 1988; Fokin et al. 1996, and references therein). However, the shock mechanism has difficulty accounting for X-ray variations and the high heating energies such emissions would require.

The paper is organized in the following way: Section 2 provides background information on δ Cep and recent relevant studies of Cepheids. Section 3 discusses our previous X-ray and far-ultraviolet–ultraviolet (FUV–UV) observations of δ Cep from the *XMM-Newton* and *Hubble Space Telescope (HST)*, as well as our follow-up confirmation visit obtained by *Chandra*. Section 4 summarizes the results of this study and discusses their importance and possible cause(s). Section 5 gives the final conclusions, broader impacts, and future prospects.

2. δ Cep and the Importance of Being a Cepheid

In 1785, δ Cep ($V = +3.89$ mag; $d = 273$ pc; F5 Ib–G1 Ib; $P_{\text{pulsation}} = 5.366$ days) was discovered as a periodic variable star by Goodricke (1786). Since that time, δ Cep has become the prototype of Classical Cepheids (Cepheids hereafter), an important class of pulsating F–K supergiants whose period–luminosity law (now named the Leavitt law; Leavitt 1908) has become a crucial cornerstone of the cosmic distance scale. Recent summaries of δ Cep are given by Engle et al. (2014), Anderson et al. (2015), and references therein.

Even though Sasselov & Lester (1994a, 1994b, 1994c) predicted that Cepheids could theoretically be X-ray sources, prior to 2007, Cepheids were generally viewed as X-ray quiet. Observations carried out by previous generation X-ray satellites (*Einstein* and *ROSAT*) resulted in no reported detections of several nearby Cepheids (including δ Cep). However, Polaris (the nearest Cepheid) was later discovered as a weak X-ray source by reanalyzing archival *ROSAT High Resolution Imager* data (Engle et al. 2009; Evans et al. 2010; Engle 2015). This provided the impetus to observe Polaris and several other bright Cepheids with the *XMM-Newton* and *Chandra* X-ray satellites. Since then, an increasing number of Cepheids have been identified as soft (0.3–2.5 keV) X-ray sources (typically $\sim 5 \times 10^{28} < L_X < \sim 5 \times 10^{29}$ erg s $^{-1}$; see Tables 1 and 2; Engle et al. 2014; Evans et al. 2016).

For main sequence stars in the cool half of the Hertzsprung–Russell (H–R) diagram, those with photospheric temperatures below ~ 7000 K, coronal X-ray activity is commonplace. It is particularly strong for young, rapidly rotating stars (Micela et al. 1985; Güdel et al. 1996; Guinan et al. 2016). This is because most cool main sequence stars have “solar-like” magnetic dynamos (known as α – ω dynamos) that generate magnetic fields via each star’s differential rotation and interior convective motion (Güdel & Nazé 2009). These stars possess hot X-ray emitting coronae: regions of magnetically confined and heated, optically thin plasmas above their photospheres with temperatures typically in the range of ~ 2 – 20×10^6 K (Güdel & Nazé 2009, and references therein). Cool supergiant stars like Cepheids have relatively long rotation periods (e.g., $P_{\text{rot}} = 200$ days for δ Cep: $v \sin i = 11.4$ km s $^{-1}$ (De Medeiros et al. 2014); $d = 273$ pc (Benedict et al. 2007); radius $\approx 43 R_{\odot}$ (Mérand et al. 2015)) and for that reason were not expected to be significant coronal X-ray sources. However, possible weak

to moderate magnetic fields have been observed for a few F–G–K supergiants (Grunhut et al. 2010). There have been a small number of non-pulsating cool supergiants detected in X-rays (Ayres 2005), though many of the detections have often been met with initial skepticism (see Ayres 2011, and references therein).

The primary reason for this skepticism is that many intermediate-mass stars, including Cepheids, can have lower-mass, magnetically active F–M companions (Evans et al. 2015a) with outer convective zones. Cepheids are young stars with typical ages of less than ~ 200 Myr (Bono et al. 2005; Marsakov et al. 2013). Hence, any physical companions would also be young, rapidly rotating, and if cooler than $\sim F0$ V, would most likely be coronal X-ray sources. For comparison, F–G–K main sequence members of the Pleiades (age ≈ 125 Myr) have rotation periods typically less than 10 days (Stauffer et al. 2016).

In the case of δ Cep, Anderson et al. (2015) recently found evidence that it is a single-line spectroscopic binary with a period of ~ 6 years. The radial velocity solution indicates a possible companion mass in the range of $\sim 0.2 M_{\odot} < M < \sim 1.2 M_{\odot}$. This implied mass range corresponds to approximate spectral types between M4 V and F9 V. However, a recent interferometric study of δ Cep by Gallenne et al. (2016) failed to detect the companion. Based on the limits imposed by the data, Gallenne et al. determined that the potential companion would have a projected angular separation of $\lesssim 24$ mas from δ Cep and a spectral-type later than F0 V. Because δ Cep is young (age ≈ 80 Myr; Matthews et al. 2012), if this companion is confirmed, it should be rapidly rotating and a coronal X-ray source with an X-ray luminosity (L_X) similar to Pleiades F–M stars ($L_X \approx 0.5$ – 10×10^{29} erg s $^{-1}$; Micela et al. 1996). The possible X-ray activity of this companion will be discussed in Section 4.1. In addition, δ Cep has a wider (40'' separation) resolved companion, HD 213307, which is itself a close binary star (B7–8 V + F0 V) with a period of 1.07 days (Benedict et al. 2002). HD 213307 has been detected as an X-ray source in all our *XMM-Newton* and *Chandra* observations. These X-ray emissions most likely arise from the coronal X-ray activity of the cooler component.

Cepheids are known to have FUV–UV emission lines that vary in phase with the stellar pulsation periods (Schmidt & Parsons 1982, 1984a, 1984b; Bohm-Vitense & Love 1994; Engle 2015). This has been investigated with an observing campaign by the *Cosmic Origins Spectrograph (COS)* onboard the *HST* (Engle et al. 2014; Engle 2015, Neilson et al. 2016). The fact that these FUV–UV emissions phase with the Cepheids’ respective pulsation periods confirms that they originate from the Cepheids themselves, and not from the outer atmospheres of unresolved cool main sequence companions. These emission features (e.g., O I 1358 Å, the Si IV ~ 1400 Å doublet, the N V ~ 1240 Å doublet) originate in plasmas with temperatures of up to $\sim 200,000$ K, approaching soft X-ray emitting temperatures. It was this pulsation-induced variability of FUV–UV emitting plasmas that led us to initiate a program to search for similar X-ray variability. Representative FUV emission line fluxes from our previous study (Engle et al. 2014) are plotted versus pulsation phase in Figure 1, showing a clear period of enhanced activity during 0.90–0.96 ϕ . For comparison purposes, also plotted are the X-ray measures, V-band photometry, radial velocity data, and model-derived angular diameter measures.

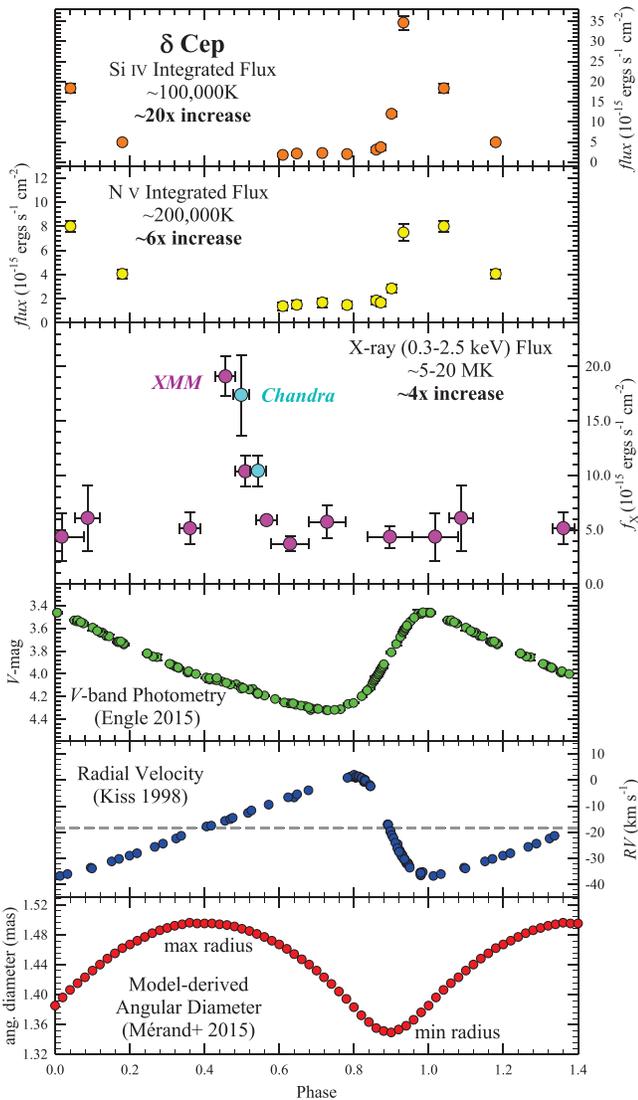


Figure 1. Atmospheric and photospheric variations of δ Cep are plotted against its pulsation phase. The top two panels show FUV emission line variations with phase, and the third panel shows variations of the star’s X-ray flux. Pink data points in the third panel represent measures made by *XMM-Newton*, and cyan data points show the follow-up observations made in 2015 with *Chandra*. For reference, the fourth and fifth panels show the *V*-band light curve and radial curve, respectively (RV curve from Kiss 1998). The bottom panel shows the variations of the star’s angular diameter with the pulsation phase from Mérand et al. (2015).

3. X-Ray Observations

3.1. X-Ray Variability from Previous Observations

Although Cepheids are luminous at optical wavelengths, their moderate levels of X-ray activity ($L_X \approx 10^{29}$ erg s $^{-1}$) combined with their distances make them comparatively faint at X-ray wavelengths ($f_X < 10^{-14}$ erg s $^{-1}$ cm $^{-2}$). Relatively long exposures (and the need for multiple visits) are required to achieve sufficient data quality and phase sampling, and this has slowed the X-ray studies progress. Over the past decade (Polaris having been observed with *Chandra* in 2006 February), only two Cepheids have been observed with sufficient pulsation phase coverage for potential X-ray variability to be uncovered. The first is δ Cep, and the second star is β Dor ($\langle V \rangle = 3.78$; $d = 318$ pc; F4–G4 Ia–II; $P_{\text{pulsation}} = 9.843$ days), which has the more symmetric light

curve common to Cepheids with pulsation periods near ~ 10 days; it will be the subject of a future paper in preparation.

From 2010 to 2013, five independent pointings to δ Cep were carried out with *XMM-Newton* (Engle et al. 2014; Engle 2015). One of the program’s early observations with *XMM-Newton* showed a much higher X-ray flux at the beginning of a long ~ 73 ks exposure, which then declined to a lower flux level similar to that observed at other pulsation phases (see Engle et al. 2014). Although searching for X-ray variability was the initial goal, the phase at which it was found to occur was very surprising. All FUV–UV emission lines peak near phase $\phi \approx 0.90$ – 0.96 , just before δ Cep reaches maximum visual brightness and just after the phase in the star’s pulsation where it has begun to expand again. This expansion forms a shock front that then propagates through the Cepheid’s outer atmosphere, compressing and heating atmospheric plasmas to produce the observed strong phase-dependent FUV–UV emissions. To our surprise, however, the phase of the enhanced X-ray emissions occurred ~ 2.7 days later, at $\phi \approx 0.45$. This is just after the Cepheid reaches its maximum size and coolest temperature, and begins to shrink again. It was an unexpected phase for enhanced X-ray activity, and relied on a single sub-exposure, so confirmation was necessary to prove that the X-ray variability was pulsation-phase-specific, and not transient or arising from a companion star.

3.2. Confirmation of Pulsation-induced X-Ray Emissions from *Chandra*

In 2015 May, a ~ 42 ks visit of δ Cep was carried out with the *Chandra* Advanced CCD Imaging Spectrometer (ACIS-I). The visit was constrained to occur at the phase of increased X-ray flux previously observed with *XMM-Newton*. The data were reprocessed with the *Chandra* Interactive Analysis of Observations (CIAO) v4.9 suite to ensure the latest calibrations were applied. Analyses of the data were made using the Sherpa modeling and fitting package (distributed as part of CIAO), and MEKAL models (Drake et al. 1996) were used for the final fitting and flux calculations.

To increase phase resolution, the observation was divided in half, creating two equal 21 ks sub-exposures that were analyzed separately. The distance and activity level of the target resulted in relatively low count rates, so single temperature plasma fits were applied to the resulting energy distributions, as two-temperature models showed no improvement in the fits. As shown in Table 1 and Figure 1, the *Chandra* data confirm the X-ray flux peak found previously with *XMM-Newton*. A steady decline in X-ray flux is observed over the course of the *Chandra* exposure, with the second subdivision displaying just over half the X-ray flux of the first subdivision. Figure 2 compares the X-ray energy distributions of the *Chandra* subdivisions. Both distributions peak around 1 keV, with peak plasma temperatures from 1.1 keV ($T \approx 13$ MK = 1.3×10^6 K) to 1.7 keV ($T \approx 20$ MK). But the first subdivision, in addition to higher overall activity, shows an increase in harder X-ray counts, in the 1.2–1.5 keV range, and potentially in the 2.4–2.9 keV range as well, although the signal is very weak at these energies.

δ Cep is a relatively weak X-ray source, whether it is in a phase of high X-ray activity or not. Thus, the plasma temperature values returned by the model fits are less certain because of the low count rates. The X-ray luminosities (L_X) of δ Cep (as well as other Cepheids; see Tables 1 and 2) are approximately the same as observed for young,

Table 1
X-Ray Observations of δ Cep

| ObsID | Start Time (UT) Start Time (JD) | End Time (UT) End Time (JD) | Phase Range | kT (keV) | kT Ratio | f_X (0.3–2.5 keV) (10^{-15} erg s $^{-1}$ cm $^{-2}$) | f_X error (10^{-15} erg s $^{-1}$ cm $^{-2}$) | L_X (10^{28} erg s $^{-1}$) | log L_X |
|------------------------------------|-------------------------------------|-------------------------------------|-------------|---------------|---------------|--|--|--------------------------------------|-----------|
| Previous <i>XMM-Newton</i> Results | | | | | | | | | |
| 552410401 | 2008 Jun 05 14:26 2454623.101 | 2008 Jun 05 21:53 2454623.412 | 0.33–0.39 | 1.00 | 1.00 | 5.14 | 1.40 | 4.56 | 28.66 |
| 0603741001 I | | | 0.43–0.48 | 0.63 | 0.57 | 19.08 | 1.80 | 16.92 | 29.23 |
| | | | | 1.83 | 1.00 | | | | |
| 0603741001 II | 2010 Jan 22 18:05 2455219.254 | 2010 Jan 23 14:17 2455220.095 | 0.48–0.54 | 0.33 | 1.00 | 10.36 | 1.40 | 9.19 | 28.96 |
| 0603741001 III | | | 0.54–0.59 | 0.79 | | 5.87 | 0.40 | 5.21 | 28.72 |
| 603740901 | 2010 Jan 28 18:04 2455217.253 | 2010 Jan 21 12:37 2455218.026 | 0.05–0.12 | 0.25 | 1.00 | 6.07 | 3.00 | 5.38 | 28.73 |
| 0723540301 I | 2013 Jun 28 6:34 2456471.774 | 2013 Jun 29 13:49 2456473.076 | 0.84–0.96 | 0.32 | 0.97 | 4.34 | 1.00 | 3.85 | 28.59 |
| 0723540301 II | | | 0.96–0.08 | 0.41 | 1.00 | 4.35 | 2.20 | 3.86 | 28.59 |
| | | | | 1.38 | 0.65 | | | | |
| 0723540401 I | 2013 Jul 02 6:17 2456475.762 | 2013 Jul 03 7:51 2456476.827 | 0.58–0.68 | 0.61 | 1.00 | 3.71 | 0.70 | 3.29 | 28.52 |
| 0723540401 II | | | 0.68–0.78 | 0.36 | 1.00 | 5.94 | 1.50 | 5.27 | 28.72 |
| | | | | 0.96 | 0.42 | | | | |
| <i>Chandra</i> 2015 Visit | | | | | | | | | |
| 16684 I | 2015 May 08 20:17 | 2015 May 09 07:53 | 0.48–0.52 | 1.6 | | 17.38 | 3.70 | 16.72 | 29.22 |
| 16684 II | 2457151.345 | 2457151.828 | 0.52–0.56 | 1.3 | | 10.41 | 1.50 | 10.12 | 29.01 |

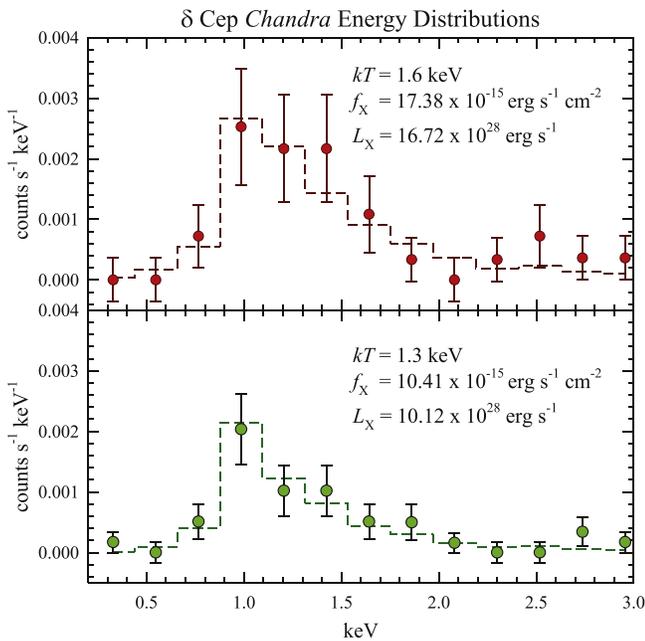


Figure 2. X-ray energy distributions for the 2015 *Chandra* observation of δ Cep are shown, along with model-derived plasma temperatures, X-ray fluxes, and luminosities. For both models (plotted as dashed lines), a neutral hydrogen (N_{H}) column density value of 3.5×10^{20} cm $^{-2}$ ($\log N_{\text{H}} = 20.5$) was adopted (Engle et al. 2014).

chromospherically active G–M stars, and about $100\times$ larger than the mean X-ray luminosity of the Sun. However, despite the large radii and thus very large surface areas of Cepheids, their X-ray surface fluxes (F_X) are much smaller than even inactive coronal X-ray sources like the Sun.

Adopting the mean interferometric radius of $\langle R \rangle = 43.0 R_{\odot}$ (Mérand et al. 2015) and the observed minimum and maximum L_X values of $\sim 4.0 \times 10^{28}$ and 17.4×10^{28} erg s $^{-1}$, respectively, for δ Cep (see Table 1) returns minimum and maximum surface X-ray fluxes of $F_X \approx 360$ and 1550 erg s $^{-1}$ cm $^{-2}$, respectively. Compared to the Sun (assuming $\langle L_X \rangle_{\odot} \approx 1 \times 10^{27}$ erg s $^{-1}$ from Ayres 2005), the surface X-ray flux is $\langle F_X \rangle_{\odot} = 1.6 \times 10^4$ erg s $^{-1}$ cm $^{-2}$. So, even for the maximum X-ray activity level of δ Cep, the surface X-ray flux is ~ 10 times less than the Sun’s (while at minimum, it is 50 times less). To further illustrate the relative X-ray activity levels, the average bolometric luminosity (L_{bol}) of δ Cep is ~ 1800 times that of the Sun. Taking this into account, and using δ Cep’s average $L_X = 10.8 \times 10^{28}$ erg s $^{-1}$, the ratio $L_X/L_{\text{bol}} = 1.57 \times 10^{-8}$, which is $\sim 6\%$ that of the Sun. When compared to younger, chromospherically active G–K stars with $L_X \approx 10^{29}$ erg s $^{-1}$, the X-ray surface fluxes (F_X) of δ Cep are nearly 10^5 times weaker.

Further comparisons can be made to the other stellar residents of and around the Cepheid region of the instability strip. For several G and early-K supergiants, distances and

Table 2
Cepheid X-Ray Detections

| Observed Cepheid | Start Time (UT) Start Time (JD) | End Time (UT) End Time (JD) | Start Phase | End Phase | kT (keV) | f_X (0.3–2.5 keV) (10^{-15} erg s $^{-1}$ cm $^{-2}$) | L_X (10^{28} erg s $^{-1}$) | Possible Companion ^a |
|------------------|------------------------------------|----------------------------------|-------------|-----------|---------------|--|--------------------------------------|---------------------------------|
| V659 Cen | 2013 Sep 07 20:11 2456543.341 | 2013 Sep 08 02:22 2456543.599 | 0.15 | 0.20 | 0.88 | 4.74 | 32.4 | Yes |
| R Cru | 2014 Jan 04 19:57 2456662.331 | 2014 Jan 05 02:30 2456662.604 | 0.75 | 0.79 | 1.24 | 7.67 | 63.1 | Yes |
| V473 Lyr | 2013 Sep 22 09:49 2456557.909 | 2013 Sep 22 12:03 2456558.002 | 0.53 | 0.59 | 0.66 | 20.5 | 75.9 | No |
| S Mus | 2013 Jan 05 14:37 2456298.109 | 2013 Jan 05 21:48 2456298.408 | 0.01 | 0.04 | 0.93 | 34.6 | 288.4 | Yes |
| Polaris | Multiple | | | | 0.1–0.6 | 28–76 | 6.31–15.85 | Yes |
| β Dor | Multiple | | | | 0.3–2.1 | 5.3–44.3 | 6.31–50.12 | No |
| δ Cep | See Table 1 | | | | 0.3–2.1 | 4.3–19.4 | 3.16–15.85 | Yes |

Note.

^a Possible Companion: This column indicates which Cepheids have companions that the currently available X-ray images cannot resolve. For these stars, at present the X-ray activity can be attributed to either the Cepheid or the companion, with the exception of δ Cep, where the phasing of the X-ray variations allows us to attribute them to the Cepheid.

X-ray fluxes were obtained from Ayres (2005) and Ayres et al. (2005), along with angular diameter measures from Bourges et al. (2017). The resulting surface fluxes show a large spread. The K-type supergiants π Her (K3 Iab) and γ Aql (K3 II) have very low surface X-ray fluxes of $F_X \approx 50$ and 40 erg s $^{-1}$ cm $^{-2}$, respectively. By contrast, the seemingly hyperactive G-type supergiants β Cam (G1 Ib–II) and β Dra (G2 Ib–II) have surface X-ray fluxes of $F_X \approx 4.7 \times 10^4$ and 5.8×10^4 erg s $^{-1}$ cm $^{-2}$, respectively. In this context, δ Cep falls near the quieter end of cool supergiant X-ray emissions. The X-ray detections of some supergiants carries important implications for the Cepheids and, specifically, their X-ray generating mechanisms, as discussed in Section 4.2.

The very low surface fluxes of δ Cep, coupled with moderately high kT values of 0.4–1.6 keV, imply that if the X-rays from δ Cep originate from quasi-uniform coronal structures, as happens for the Sun, the layer of emitting plasma is likely relatively shallow. However, another possibility is that the X-ray emissions of δ Cep originate in tightly confined, heated regions, covering a small fraction of the Cepheid’s surface, as a result of pulsation-induced magnetic fields and structures. In this case the observed X-ray emissions could arise from the interactions of turbulent plasmas and the resulting magnetic fields via magnetic reconnection mechanisms that occur in solar flares (see Drake et al. 2006).

4. Discussion

4.1. Possible X-Ray Contributions from a Cool Companion

Because Cepheids are young (ages <200 Myr; Bono et al. 2005; Marsakov et al. 2013), cool companion stars would also be young and thus rapidly rotating. As such, they would be chromospherically active stars and likely coronal X-ray sources. As mentioned earlier, cool members of the ~ 125 Myr old Pleiades cluster typically have L_X values of $\sim 0.5\text{--}10 \times 10^{29}$ erg s $^{-1}$ (Micela et al. 1996). Because $\sim 50\%$ or more of Cepheids are members of binary or multiple systems (Evans et al. 2015a, and references therein), it is important to ascertain whether X-ray emissions (if detected from a Cepheid) indeed originate from the Cepheid itself or from a companion. Because Cepheids are luminous in visible light, any close main

sequence G–K–M companions, if present, are very difficult to resolve, since they are at least ~ 8 mag fainter than their corresponding bright Cepheid hosts and thus contribute insignificantly to the Cepheid’s optical flux. However, at wavelengths below ~ 1400 Å, including X-rays, the photospheric continuum fluxes of the Cepheids and any cool companions are no longer significant. At these high energies, the companion’s X-ray emissions will not be overwhelmed by those of the Cepheid.

It is possible that an unresolved, active cool companion star (as proposed by Anderson et al. 2015) could contribute to the X-ray emission and variability. Cool main sequence stars (especially younger ones) are also X-ray variable (see Guinan et al. 2016; Stelzer 2016, and references therein) on timescales of hours (flares), days (stellar rotation bringing spots and active regions in and out of view), years (magnetic activity cycles), and even on timescales of millions to billions of years (weakening of the stellar magnetic dynamo as the star evolves and spins down). However, although the pulsation period of δ Cep is ~ 5.37 days, as shown in Figure 3 the phase of enhanced X-ray activity is tightly confined, with the enhancement diminishing in a matter of several hours. This timescale excludes long-term variations such as magnetic activity cycles and evolutionary weakening of the magnetic field. This leaves only flares from, or the rotational X-ray variability of, the companion star as a possible explanation.

Rotational X-ray variability has been observed in a small number of young, cool dwarfs. Flaccomio et al. (2005) used 10 days of *Chandra* integration time, spread over a time span of 13 days, to study X-ray variability of cool dwarfs in the Orion Nebula Cluster (ONC). At ~ 1 Myr, this cluster is much younger than δ Cep, but this is one of the most thorough studies of rotational X-ray variability, which is why it is used as reference. Flaccomio et al. found several cool dwarfs with probable, periodic X-ray variability closely matching their optically determined rotation periods, with X-ray amplitudes of ~ 2 times and even ~ 3 times in some cases. At first, this would appear to be a promising alternative explanation for the observed X-ray variability of δ Cep. However, as shown in Figure 3, in ~ 420 ks of X-ray observations obtained over 6 years, only the observations within ± 0.1 of 0.45ϕ show X-ray

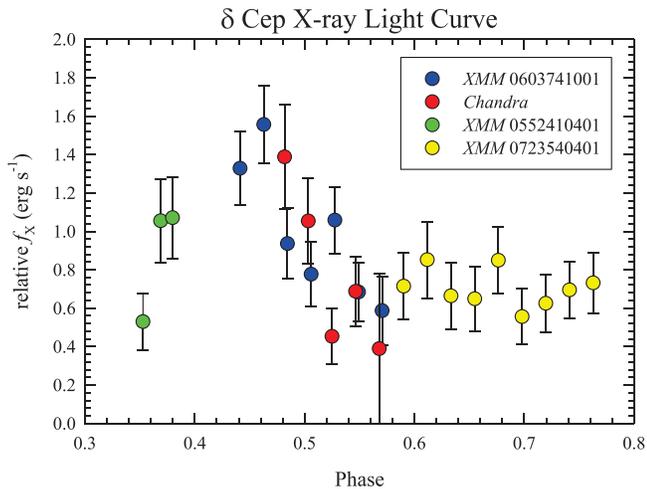


Figure 3. Relative X-ray flux curve of δ Cep. The observations in this plot were obtained over nearly 7 years. Although X-ray activity is present at all observed phases, there is a $\sim 4\times$ increase in activity centered at $\sim 0.45\phi$. This is just after the star’s maximum diameter and prior to attaining minimum photospheric temperature (see Figure 1). The *XMM-Newton* data have been phased to the ephemeris used in Engle (2015), Engle et al. (2014): $2455479.905 + 5.366208(14) \times E$. The *Chandra* data have been phased to the newly determined ephemeris: $2456859.039 + 5.366279(21) \times E$. The close agreement in the phasing, flux levels, and behaviors of the data sets are the strongest evidence that the X-ray variations are tied to the pulsation period of the Cepheid.

variability. The X-ray flux ranges are similar to the X-ray amplitudes of the known rotation-variable dwarfs. This would imply that the rotation period of the companion is ~ 1 day, which is entirely possible for a young, cool dwarf. However, if the rapid rotation of a companion star was responsible, then observations at other phases would also show X-ray variability. This is not observed for δ Cep. Finally, if the rotation period of the companion was close to the pulsation period of δ Cep, then the X-ray curve would also show a smoother, quasi-sinusoidal variation, as opposed to the X-ray flux curve of δ Cep. This leaves flare activity from the companion as the only remaining alternative explanation.

For comprehensive studies of X-ray flare properties of cool dwarfs, we again reference the *Chandra* ONC data (Favata et al. 2005; Getman et al. 2008, and references therein). The *Chandra* ONC data is one of the best data sets for efficiently carrying out an X-ray flare study of multiple targets. Typically, compiling a statistically significant sample of cool, main sequence star flare characteristics is rather difficult at present, due to the high demand on X-ray satellite observing time and the large amounts of said time required to comprehensively study flares. However, the K dwarf AB Dor has a particularly rich X-ray data set, due to it lying in the foreground of the often observed Large Magellanic Cloud. Lalitha and Schmitt (2013) presented the light curves of 32 separate *XMM-Newton* observations of this star. With an age of ~ 50 Myr, AB Dor is somewhat younger than δ Cep (or any companion stars), but nevertheless has an incredibly rich X-ray data set. Flares of various intensities and durations are present in nearly all of the 32 independent exposures. However, for δ Cep only, X-ray observations occurring in the range of ~ 0.35 – 0.55ϕ show significant variations. The X-ray exposures at other phases show no significant variations.

As a further, more precise check on the timing of the X-ray variations apparent near 0.45ϕ , we subdivided all exposures in

the range of 0.3 – 0.8ϕ into 10 ks bins (see Figure 3). This was the smallest bin size with a consistent signal to noise value above ~ 3 for all data sets plotted. It also provides much better time and phase resolution, as shown in Figure 3. The *XMM-Newton* observations were phased according to the recent ephemeris used by Engle et al. (2014): $T_{\max} = 2455479.905 + 5.366208(14) \times E$. In the interest of thoroughness, because the period of δ Cep is continually undergoing small changes (see Engle et al. 2014), recent AAVSO photometry was analyzed to ensure that the newly acquired *Chandra* data were correctly phased. The ephemeris measured from the AAVSO photometry analysis, and applied to the *Chandra* data, is $T_{\max} = 2456859.039 + 5.366279(21) \times E$. This amounted to an essentially insignificant change of $\sim 0.001\phi$. As shown in Figure 3, when the recent *Chandra* X-ray data are combined with our previous *XMM-Newton* data, the data sets (taken more than 5 years apart) almost exactly match each other in flux levels as well as variability. The resulting X-ray flux curve leaves little doubt that the X-ray activity of δ Cep is indeed periodic and varies by up to a factor of four, peaking at $\phi \approx 0.45$. The precise phasing of the X-ray fluxes with the Cepheid’s pulsation period indicates that the X-ray emission arises from the Cepheid itself and not from a companion.

4.2. The Origins of the FUV and X-Ray Emissions

As discussed in Engle et al. (2014), and previously by others (see Bohm-Vitense & Love 1994, and references therein), the phased FUV–UV emissions are best explained by pulsation-induced collisional shocks. These shocks originate near the He II ionization boundary, within the star’s interior, and are produced shortly after the star is most compressed and poised to rebound to rapid expansion. As recently measured by Anderson et al. (2015), δ Cep has a radial velocity amplitude of $K \approx 39 \text{ km s}^{-1}$. Also, the interferometric study of Mérand et al. (2015) found the angular diameter of δ Cep to vary by $\sim 10\%$, with minimum radius occurring near $\sim 0.9\phi$ and maximum occurring near $\sim 0.4\phi$ (see Figure 1). The resulting kinetic energies associated with this pulsation could be sufficient to heat atmospheric plasmas and account for the FUV–UV emission lines with the observed plasma temperature from $\sim 10^4$ to 3×10^5 K. The emitting plasma is heated by a fast moving shock front arising from the rapid expansion of the interior of the star after maximum compression during the “piston-phase” of the stellar expansion, beginning at phase $\sim 0.9\phi$. The observed phasing of the FUV–UV emissions prior to maximum brightness of the star is in general accord with this model. Moreover, emission lines show additional broadening at these phases for δ Cep (Engle et al. 2014) and for several other Cepheids (see Bohm-Vitense & Love 1994), which arises from increased turbulence of the gas as the shock front propagates outward through the less dense layer of the stellar atmosphere. From our study, for example, measures of the FUV Si IV 1393 Å line broadenings from *HST-COS* spectra indicate turbulent velocities of up to 225 km s^{-1} near $0.9 \pm 0.1\phi$, when these emissions reach maximum strength. The other FUV line emissions show similar behavior and broadenings. In addition, from the analysis of high dispersion *International Ultraviolet Explorer (IUE)* spectra of the Mg II $h+k$ emissions, Schmidt and Parsons (1984b) report radial velocity elements displaced up to $\pm 100 \text{ km s}^{-1}$ from the photospheric velocities.

This may indicate the presence of fast moving, heated plasmas in the outer atmosphere of the star.

Identifying the X-ray mechanism operating in δ Cep is, at this time, unfortunately not straightforward. Hot plasmas with $T \gtrsim 10^5$ K are indicated in δ Cep (and other Cepheids) by FUV emission lines such as N V 1240 Å. The presence of X-ray emission with plasma temperatures $T > 5$ MK is surprising, given that Cepheids were not known to be X-ray sources until recently. As shown in Figure 1, the FUV emission lines show a strong pulsation phase dependence, attaining peak emissions near $0.9\text{--}0.95\phi$ in the case of δ Cep. It was initially assumed that X-rays (if present) would also peak at or near these phases. As shown in this study, this is not the case. The X-rays are present at all phases but reach maximum strength near 0.45ϕ , i.e., nearly 3 days after the FUV lines peak. Though δ Cep is the first Cepheid to be identified so far as a definite X-ray source, we are attempting to confirm suspected X-ray variability in several other Cepheids to determine their X-ray properties. With additional observations of other Cepheids with different properties (masses, ages, pulsation periods, etc.), it should be possible to arrive at a better understanding of the X-ray mechanism. In what follows, we briefly discuss several of the most promising mechanisms and theories to explain the X-ray properties of δ Cep (and perhaps other Cepheids as well).

With our current understanding of the complex δ Cep atmosphere, it is difficult to successfully apply the shock model to explain the X-ray activity and variability. In addition (as shown in Figure 1), we have not yet obtained COS spectra of δ Cep near 0.45ϕ to search for broadening or increased FUV emissions from the X-ray emitting plasmas as they cool. *IUE* measures of the Mg II 2800 Å $h+k$ emission lines (Schmidt & Parsons 1984b) peak near 0.9ϕ (as do other FUV emissions) but show no apparent secondary enhancements near 0.45ϕ , where the X-ray emission peaks. Shock-heating the Cepheid's atmospheric plasmas to the point of generating the observed X-ray emissions (in the range of $\sim 3 \times 10^6$ to 20×10^6 K, as found from the best fitting plasma models; see Table 1 and Figure 2) would require large (>200 km s $^{-1}$) shock velocities. It is possible that the shock wave accelerates as it moves through the rarefying outer atmosphere of the Cepheid (Ruby et al. 2016). This acceleration, combined with the potential in-falling material expelled from the Cepheid during previous pulsations, could achieve such high relative velocities. However, as discussed later, the generation of magnetic fields in the outer convective atmospheres of Cepheids that commonly occurs throughout the cool half of the H–R diagram (Güdel & Nazé 2009) for main sequence stars may also be responsible (directly or indirectly) for the X-ray emissions.

As previously discussed, the measured large FUV emission line broadening values indicate that velocity fields are present and are much higher than the photospheric pulsation motions estimates of ~ 39 km s $^{-1}$. The large velocities of >200 km s $^{-1}$ observed in the FUV emission lines suggest high Alfvénic velocities, and hence the presence of hot magnetized plasma (via $B = v\sqrt{4\pi\rho}$) that could subsequently generate X-ray emission. In this expression, B is magnetic field strength, v is velocity, and ρ is the density of the plasma.

The role of short-scale magnetoacoustic convective modes, entailing the generation of longitudinal tube waves, has also been explored in detail, as pursued in the framework of time-dependent simulations. By considering photospheric-level magnetic parameters (Fawzy & Cuntz 2011), as well as the

detailed treatment of shock formation and dissipation (Fawzy et al. 2012), it was found that processes associated with those modes are insufficient to explain the X-ray observations.

Another possible mechanism for generating magnetic fields and the resulting X-ray emission in δ Cep (and perhaps other Cepheids) are via a convective zone, or through a combination of convective and pulsation-driven motions and turbulence, within the stellar interior (Narain & Ulmschneider 1996, and subsequent work). The X-ray variability of δ Cep requires a periodic amplification of the magnetic field, heating the atmospheric plasmas and increasing X-ray activity. There are a number of potential (still qualitative) theories for this magnetic mechanism, such as a post-shock increase of turbulence in the stellar interior and chromosphere that strengthens the magnetic dynamo effect, or magnetic reconnection events (Christensen et al. 2009). In the case of δ Cep (and maybe also for β Dor), the X-ray emissions peak near the maximum diameter of the star. Thus the enhancements in X-ray emission near this phase could be explained by a turbulent magnetic dynamo that strengthens in the expanding, cooling, and increasingly convective atmosphere of the stars.

We have also considered the hypothesis previously advanced by Ayres et al. (2003) to account for X-ray emissions in some cool giants and supergiants. Ayres et al. theorized that these stars could have magnetic features that scale in extent to those of the Sun and other cool main sequence stars, but their lower gravities would allow for much more extensive chromospheres. These chromospheres would act as X-ray absorbers, explaining why so few red giants were observed to be X-ray active. Cepheids are comparable to red giants in terms of gravity, but have larger masses, diameters, and higher surface temperatures. This could result in magnetic features large enough to extend beyond the Cepheids' bloated chromospheres, generating the persistent X-ray activity found at all phases observed. Further, several cool non-pulsating supergiants have also been detected in X-rays. Because these stars do not appear to pulsate, they should not be generating strong shocks. Their X-ray activity, therefore, appears likely to arise from solar-like dynamo-generated magnetic fields. This makes it possible that the Cepheids' pulsations are not responsible for generating the X-ray activity. Rather, the X-ray activity is persistent in a number of cool supergiants (certain Cepheids included), and the Cepheid pulsations simply serve to enhance the X-ray activity as a specific phase. FUV–UV emission lines and X-ray activity have also been observed in a small number of non-pulsating F and G supergiants (Ayres 2007). Although the number of detections is still small, the FUV–UV emission fluxes and X-ray luminosities of the Cepheids and non-pulsating supergiants are similar. This indicates that the same X-ray heating mechanism may be at work in both classes of supergiants, and the pulsations of the Cepheids then serve to periodically modulate or amplify this stellar dynamo driven mechanism.

5. Conclusions and Future Prospects

From an analysis of more than 420 ks of *XMM-Newton* and *Chandra* X-ray observations spanning nearly 7 years, the prototype Classical Cepheid δ Cep has been found to undergo phased pulsation-modulated X-ray variations. δ Cep was previously indicated as a possible, periodic variable X-ray source from an analysis of earlier *XMM-Newton* observations (see Engle et al. 2014). Additional phase-constrained X-ray

observations were secured with *Chandra* in 2015 May to determine if the observed X-ray emission and variability are pulsation-phase-specific to δ Cep and not transient or arising from a possible chromospherically active, cool companion star. However, as shown in Figures 1 and 3, the recent *Chandra* data very closely match the prior X-ray measurements in phase, flux values, and variability. From the combined data, a fourfold increase in X-ray flux is measured, reaching a peak of $L_X = 1.7 \times 10^{27}$ erg s⁻¹ near 0.45ϕ . As shown in Figures 1 and 3, the star shows X-ray emissions at all pulsation phases presently observed, and $\sim 70\%$ of the X-ray flux curve has been observed to date. As shown in Figure 3, unlike the typical skewed (steep rise/slower decline) light curves of the Cepheid, the flux is nearly constant (flat) at all phases covered, except in the range of ~ 0.35 – 0.55ϕ , where the X-ray flux attains a narrow ($\pm 0.10\phi$) “inverted V” shaped peak. This result complements our previously reported periodic phase-dependent FUV–UV emissions of the star that increase ~ 10 – $20\times$, reaching maximum strengths at ~ 0.90 – 0.95ϕ . The shape of the FUV emission line flux curves are similar to the X-ray flux curve but have more pronounced maxima that occur $\sim 0.5\phi$ earlier than where the X-rays peak.

As shown in Figures 1 and 3, the precise phasing of the X-ray fluxes with the star’s pulsation now leaves little doubt that the phased X-ray variations arise from the Cepheid and not from a companion. However, it is puzzling that the X-ray maximum occurs $\sim 0.5\phi$ (~ 2.7 days) later than the peak of the FUV–UV emission lines. It is possible that the G–M companion indicated by the high precision radial velocity study of δ Cep of Anderson et al. (2015) could contribute some fraction of the baseline X-ray flux observed at other times and phases. However, as discussed previously, it is highly improbable that a companion star could have a rotation period and corresponding X-ray period identical to the Cepheid.

Though questions still exist about what contribution δ Cep’s potential companion may have on the observed X-ray activity, we can now conclude that the pulsation-phased X-ray variability is caused by the Cepheid itself. Thus δ Cep can now be classified as a pulsating X-ray variable. Though δ Cep is the first Cepheid to carry this distinction, there are several other Cepheids with X-ray detections (see Table 2), and the current X-ray data for β Dor also show likely pulsation-phased variability. A shock-heating mechanism satisfactorily explains the FUV–UV emission line properties (Engle et al. 2014; Engle 2015), and is also a potential explanation for the X-ray activity, though a magnetic origin is also possible.

Before resources can be devoted to developing a robust theoretical model of either the shock or magnetic mechanisms, however, further observations are necessary to better constrain the candidates. Fortunately, as derived from radial velocity curves, β Dor has a different phase of maximum stellar radius (0.33ϕ) than δ Cep (0.40ϕ) and a longer pulsation period. Further observations of β Dor can determine whether the X-ray maximum is associated with the phase of maximum radius, or with the continued propagation of the shock responsible for the FUV–UV maximum, or perhaps neither of them. This will be the subject of a future study. It is possible that all Cepheids, or perhaps those within a certain period-range, are X-ray sources but too distant to be readily detected with the present generation of X-ray telescopes. Only further observations can tell.

In addition to Cepheids, the X-ray variability of δ Cep has important implications for other pulsating variables, though most also lie at distances that would make it difficult to detect X-ray activity if their X-ray fluxes are of similar levels to the detected Cepheids. In 2009 November, a 20 ks *Chandra* observation of RR Lyr was carried out (ObsID: 11014; PI: Guinan) to search for similar X-ray activity and variability. However, no X-ray emission was detected. From this null result, an upper X-ray limit of $L_X < 10^{30}$ erg s⁻¹ was established. Although knowing now how narrow the phase range of enhanced X-ray activity can be from our observations of δ Cep, additional X-ray observations may be warranted.

Although δ Cep is the first Cepheid to show pulsation-phased X-ray variability, it may not be the first star to do so. Oskinova et al. (2014, 2015) have reported pulsational X-ray variability from the β Cep variable ξ^1 CMa. As a magnetic B0.5 IV star, ξ^1 CMa is very different from δ Cep. Oskinova et al. theorize that the periodic X-ray variations arise from small pulsation-induced changes in the wind structure, possibly coupled with changes in the magnetic field.

As given in Table 2, several additional Cepheids have also been detected as potential X-ray sources with properties (L_X and kT) similar to δ Cep. Surprisingly, the low amplitude 3.97 day Cepheid Polaris also shows an X-ray enhancement that is near 0.5ϕ , though it is just a single X-ray observation that shows a possible enhancement. Follow-up X-ray observations (PI: Evans) have recently been approved with *Chandra*, and we plan to apply for additional observing time on *Chandra* and *XMM-Newton* to confirm the variability of β Dor and continue searching for X-ray activity and variability in other Cepheids. The confirmation of pulsation-induced X-ray variations in additional Cepheids with different pulsation and physical properties to δ Cep will be necessary to understand the mechanism(s) at work.

We dedicate this paper to Erika Böhm-Vitense, who passed away on 2017 January 21. She pioneered the early development of convection theory and stellar atmospheres and carried out extensive work on Cepheid stars.

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Facilities: XMM-Newton, Chandra, HST (COS), AAVSO.

Software: Specview, IRAF, CIAO, Sherpa, SAS.

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