Outward from Cepheids

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Pulsation in Cepheids is driven by a wave generated in the envelope of the supergiants. We have long had diagnostics to observe the wave as it passes through the photosphere and chromosphere. At minimum radius there are many signatures of disturbance by the wave passage including ultraviolet lines in emission and an increase in microturbulence. X-ray observations, however, provided a surprise. They have a low level of flux for most phases which persists unchanged through minimum radius. However, there is a burst of X-ray flux just after maximum radius, with a rapid rise, short duration and rapid fall similar to a stellar flare. This has been observed four times, including twice for δ Cep itself. The occurrence at a specific phase ties this to the pulsation process. This may be an upper atmosphere phenomenon (at about 0.13 stellar radii) which is related to circumstellar envelopes found via interferometry, at larger radii particularly in the infrared. These new diagnostics may ultimately answer questions about possible pulsation driven mass-loss.

Cepheids are important as the first step in the extragalactic distance scale more than 100 years after the discovery by Leavitt that the intrinsic luminosity is correlated with the pulsation period (Leavitt Law). Currently, several groups have the goal of ultimately determining the Hubble constant to 1% (Riess et al., 2011; Freedman et al., 2012). Several challenges are involved in the aim of using the infrared (IR) Leavitt Law to this precision. Interferometry has identified circumstellar envelopes (CSEs) in the infrared and visible (Nardetto et al., 2016) and IR excesses (Kervella et al., 2013). Understanding these shells as well as their effects on the inferred luminosity is an important part of the most precise use of the Leavitt Law. In addition these shells may be related to the long-standing question of whether pulsation in Cepheids results in some level of mass loss. However, the search for signs of mass loss has been elusive. This would be one way to reconcile the masses determined from pulsation and evolutionary tracks.

A series of multi-wavelength observations is being undertaken to explore these questions (as part of the program "The Secret Lives of Cepheids" Engle, 2015). The first result of this program is a thorough discussion of δ Cep (Engle et al., 2017), with particular emphasis on new far ultraviolet observations using the *Hubble* Space Telescope (*HST*) Cosmic Origins Spectrograph (*COS*) and X-ray observations using *Chandra* and *XMM-Newton*. For δ Cep they confirmed that many chromospheric lines go into emission as the pulsation wave passes through the photosphere and chromosphere at minimum radius (approximately phase 0.90; fig. 1 in Engle et al., 2017).

X-ray observations, however, remain constant at a relatively low level at this phase. Surprisingly, they have a roughly 4-fold increase just after maximum radius (phase approximately 0.5), where the photospheric spectrum is indistinguishable from a non-variable star. The occurrence of X-rays at phases when the photosphere is "quiet" implies that the X-rays are produced not in the photosphere, but above it. Furthermore, the fact that the increase happens just after maximum radius suggests that it is triggered by the collapse of the atmosphere. This increase has been observed in two cycles of δ Cep, and also in β Dor and V473 Lyr. We are pursuing a program to observe further Cepheids in X-rays to determine whether the effect occurs at the same phase and how it depends on luminosity (mass), amplitude, pulsation mode, and temperature (convective flux).

Polaris is one target star. As seen in Fig. 1, for this low amplitude Cepheid we have so far identified little variability in far ultraviolet (FUV) lines, although the phase coverage is scanty. Similarly, there is little variation in the X-ray flux even immediately after maximum radius. However, there is a gap in coverage between phase 0.4 and 0.5 (soon after maximum radius), where there could in fact be a flux increase. If this is not the case, the implication is that the very low amplitude of pulsation does not result in an X-ray increase.

A rise is seen in the X-ray flux in the 10-d Cepheid β Dor (Engle 2017, private communication). In analyzing the X-ray variation we note that the 10-d Cepheids occur in the Hertzsprung progression where the pulsation amplitude is diminished by the coincidence of the primary and secondary humps. This may distort the phase of maximum light, the standard ephemeris fiducial. We have determined the phase of the X-ray increase as follows. For δ Cep (fig. 1 in Engle et al., 2017) both the phases when the pulsation wave passes through the photosphere at minimum radius and the phase of X-ray maximum shortly after maximum radius are well determined from FUV lines and X-ray fluxes respectively. The X-ray flux maximum occurs 0.66 phase after the FUV flux maximum. Similarly, the phases of the photospheric pulsation wave and X-ray increase are well determined for β Dor. If we match the phases of UV maximum in δ Cep and β Dor (by adding 0.17 to the phase of UV maximum in β Dor), the phase of X-ray maximum becomes 0.42, as shown in Fig. 2, very similar to the phase of δ Cep.

The additional star with a large X-ray flux is found as follows. Random phase observations of 14 Cepheids (Evans et al., 2016) were made to study possible resolved main sequence companions. Since main sequence stars are stronger X-ray producers than supergiants like Cepheids (at the same age of about 50 Myr) generally upper limits were found at the positions of the Cepheids themselves. These are summarized in Fig. 2 as functions of phase. The only star at the Cepheid locations with a detection unlikely to be from a main sequence companion is V473 Lyr. Fig. 2 shows that it is at essentially the same phase as the X-ray maximum as in the two cycles of δ Cep. Furthermore, using the corrected phase of X-ray maximum, the X-ray increase in β Dor is at the same phase.

Thus, in summary, the Cepheids studied have an increase in X-ray flux which is tied to the pulsation phase. It seems to be above the photosphere and chromosphere, and is unaffected by activity there. The phasing suggests that it is triggered by the collapse of the atmosphere after maximum radius. There seem to be two possible mechanisms for the X-ray increase: a shock wave generated by the pulsation or a flare such as frequently found in cool star atmospheres. A magnetic field has been detected in η Aql (Grunhut et al., 2010). Furthermore, X-rays have been detected in δ Cep at all phases at a low level, another magnetic field indicator. Thus, a magnetic field, one of the requirements for flares, seems to be common.

Simple velocity arguments put the X-ray production at about 0.13 stellar radii, which is below the CSEs, thought to be at about 2 stellar radii. In a flare scenario, coronal mass ejection (CME) events are often linked with flares. Thus, a possible scenario is that material is moved from the X-ray layer upward to the level where CSEs are found.

In summary, X-rays are providing a new diagnostic for Cepheid upper atmospheres which may be linked with mass-loss and also influence the IR flux, and the IR Leavitt law.

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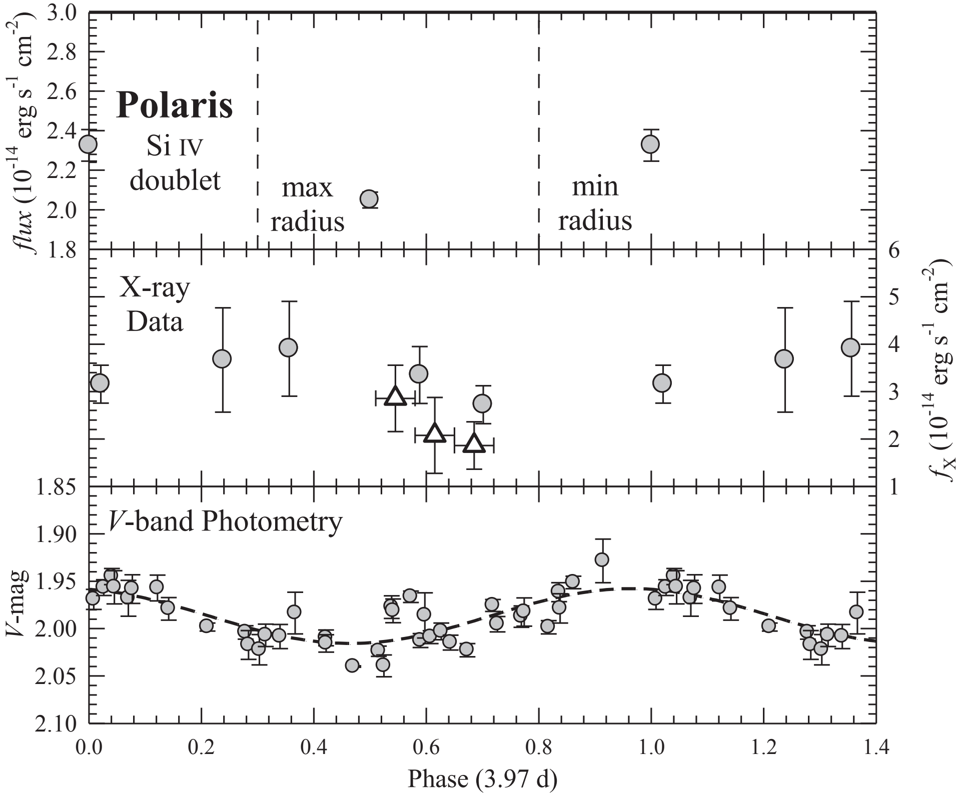

Fig. 1: Observations of Polaris. Top: observations of emission of the Si IV doublet in FUV spectra; phases of maximum and minimum radius are indicated. Middle panel: X-ray observations (*XMM*, *Chandra*, and *ROSAT*). Two separate cycles near phase 0.6 are indicated by circles and triangles. Bottom panel: the $V-$band light curve of this low-amplitude Cepheid. Most data are from Engle (2015).

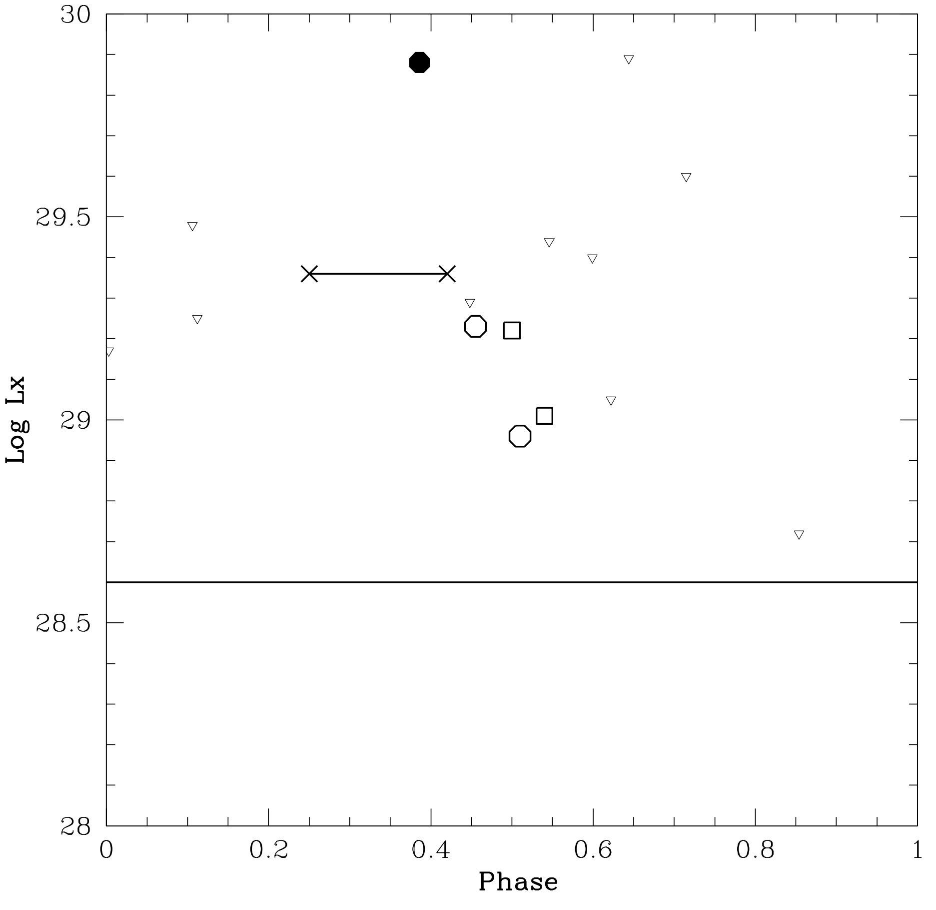

Fig. 2: X-ray luminosity as a function of phase. Open symbols: δ Cep in two different cycles; filled symbol: V437 Lyr; triangles: upper limits to Cepheid fluxes. The solid line at $\log L_{\mathrm{X}} = 29.6$ is the luminosity of δ Cep at phases outside the burst shown by the open symbols. The x markers show the increased luminosity for β Dor. Left: standard maximum light ephemeris; right: phase corrected to match the maximum UV luminosity with that of δ Cep (see text). For all stars and cycles, the phases of X-ray increase occur at the same phase, soon after maximum radius.