X-Rays in Cepheids: XMM-Newton Observations of \( \eta \) Aql*

Nancy Remage Evans\(^1\), Ignazio Pillitteri\(^2\), Pierre Kervella\(^3\), Scott Engle\(^4\), Edward Guinan\(^5\), H. Moritz Günther\(^5\), Scott Woik\(^1\), Hilding Neilson\(^6\), Massimo Marengo\(^7\), Lynn D. Matthews\(^8\), Sofia Moschou\(^1\), Jeremy J. Drake\(^1\), Joyce A. Guzik\(^9\), Alexandre Gallet\(^10,11\), Antoine Mérand\(^12\), and Vincent Hoede\(^10,14\)

\(^1\) Smithsonian Astrophysical Observatory, MS 4, 60 Garden Street, Cambridge, MA 02138, USA; nevans@cfa.harvard.edu
\(^2\) INAF-Osservatorio di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy
\(^3\) LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 Place Jules Janssen, F-92195 Meudon, France
\(^4\) Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S3H4 Canada
\(^5\) Massachusetts Institute of Technology, Kavli Institute for Astrophysics and Space Research, 77 Massachusetts Avenue, NE83-569, Cambridge, MA 02139, USA
\(^6\) Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S3H4 Canada
\(^7\) Department of Physics and Astronomy, Iowa State University, Ames, IA, 50011, USA
\(^8\) Massachusetts Institute of Technology, Haystack Observatory, 99 Millstone Road, Westford, MA 01886, USA
\(^9\) Los Alamos National Laboratory, Box 1663, MS T-082 Los Alamos, NM 87545-2345, USA
\(^10\) Nicolaus Copernicus Astronomical Centre, Polish Academy of Sciences, Bartycka 18, 00-716 Warszawa, Poland
\(^11\) Departamento de Astronomía, Universidad de Concepcion, Casilla160-C, Concepcion, Chile
\(^12\) Unidad Mixta Internacional Franco-Chilena de Astronomía (CNRS UMI 3386), Departamento de Astronomía, Universidad de Chile, Camino El Observatorio 1515, Las Condes, Santiago, Chile
\(^13\) European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany
\(^14\) Universidad Cote d’Azur, Observatoire de la Cote d’Azur, CNRS, Laboratoire Lagrange, Boulevard de l’Observatoire, CS 34229 F-06304 Nice Cedex 4, France

Received 2021 January 25; revised 2021 May 19; accepted 2021 May 24; published 2021 August 6

Abstract

X-ray bursts have recently been discovered in the Cepheids \( \delta \) Cep and \( \beta \) Dor modulated by the pulsation cycle. We have obtained an observation of the Cepheid \( \eta \) Aql with the XMM-Newton satellite at the phase of maximum radius; the phase at which there is a burst of X-rays in \( \delta \) Cep. No X-rays were seen from the Cepheid \( \eta \) Aql at this phase, and the implications for Cepheid upper atmospheres are discussed. We have also used the combination of X-ray sources, as well as Gaia and 2MASS data, to search for a possible grouping around the young intermediate mass Cepheid. No indication of such a group was found.

Key words: Cepheid variable stars

Supporting material: machine-readable tables

1. Introduction

Cepheids are particularly important because the Leavitt (period-luminosity) law provides distances that are the first step in the extragalactic distance ladder. Despite this, Cepheids are still poorly understood. X-ray observations are a valuable tool for understanding Cepheids since they provide insights into the physics of the upper atmosphere. Their properties as members of multiple systems also provide information about star formation and evolution for intermediate mass stars.

1.1. X-rays in Cepheids

Recently XMM-Newton observations of the Cepheid archetypic \( \delta \) Cep itself have found an increase in X-rays in a very limited pulsation phase range (Figure 1 in Engle et al. 2017). For most of the pulsation cycle, X-ray flux is modest (\( \log L_x = 28.5-29.1 \text{ erg s}^{-1} \)), appropriate for a coronal super giant. However, near the maximum radius (phase 0.5), the X-ray flux rises rapidly and then falls rapidly 0.10 later in phase. Maximum luminosity (\( \log L_x = 29.23 \text{ erg s}^{-1} \)) is four times minimum luminosity. The phase in the pulsation cycle at which this occurs is particularly surprising. At phases just after the minimum radius (the “piston phase”) when the atmosphere is given a “push” by the envelope pulsation cycle, many disturbances are seen in the photosphere and chromosphere: ultraviolet lines in emission (see Figure 1 in Engle et al. 2017) and increased turbulence. Near the maximum radius, however, such signs of disturbance are absent and, in fact, the spectra of Cepheids are indistinguishable from nonvariable stars.

The pattern of the increased X-ray emission at maximum radius has been confirmed in two cycles of \( \delta \) Cep (pulsation period of 5.4\( \text{d} \), Engle et al. 2017). \( \beta \) Dor, on the other hand, has a pulsation period of 10\( \text{d} \) where the light curve is distorted at maximum light (the standard fiducial for calculating phases) by the coincidence of primary and secondary pulsation maxima. If instead we use the appearance of chromospheric emission lines to mark the phase of minimum radius (as for \( \delta \) Cep), the resulting phase of X-ray emission (after minimum radius) is the same in both \( \delta \) Cep and \( \beta \) Dor; that is, just after the maximum radius, as shown in Figure 6 of Evans et al. (2020a).

The occurrence of increased X-rays at a specific phase of the pulsation cycle ties the phenomenon to pulsation. The link to pulsation has long been suspected in possible mass-loss scenarios, and X-rays may now tie upper atmosphere activity to pulsation. Since the photosphere and chromosphere are quiescent at this phase (maximum radius), the reasonable explanation is that the disturbance results as pulsation expansion progresses to the outer atmosphere. Based on this interpretation, a reasonable velocity (35 km s\(^{-1} \)) and the time between the minimum and maximum radius indicates that the X-ray activity occurs at about 0.3 \( R_{\odot} \) above the photosphere.

There are two possible causes of the X-ray bursts. (1) One possibility is that the pulsation cycle itself generates a shock wave. Velocities seen in Cepheid photospheric pulsation are

* Based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA).
typically 35 km s\(^{-1}\), which would have to accelerate outward (e.g., due to a pressure gradient) to explain the X-rays. (2) The other possibility is a coronal reconnection event (flare) such as the ones that frequently occur on the Sun. A magnetic field is required for this. However, the occurrence of X-rays at all phases of Cepheids (albeit at a low level; Engle 2015) is a strong indication of a magnetic field. We have undertaken a theoretical modeling program to explore these possibilities. Moschou et al. (2020) have modeled the pulsation driven shock corona of δ Cep using the code PLUTO (Mignone 2014) for a pure hydrodynamic (HD) setup. Models include atmospheric stratification in spherical geometry and a simple sinusoidal driver for the pulsation at the bottom of the stellar corona. The models indicate that under specific conditions shocks are able to reproduce a phase-dependent X-ray luminosity enhancement for pulsation driven outflow.

We have embarked on a program of X-ray observations of Cepheids to explore the parameter dependence of X-rays (Cepheid Outer Atmospheres; X-rays). The observation of η Aql discussed here is part of this program.

1.2. Circumstellar Envelopes

The pattern of X-ray observations may provide a clue to upper atmosphere phenomena in the pulsating atmosphere of Cepheids. Another recently observed phenomena that may be related is circumstellar envelopes (CSEs). Excess infrared (IR) emission around Cepheids was first identified in interferometric results, as summarized by Gallenne et al. (2021). The first cases were 1 Car (Kervella et al. 2006), Polaris, and δ Cep (Mérand et al. 2006). It was subsequently found in IR photometry, including from the Spitzer satellite. Recent discussions are found in Gallenne et al. (2020), Groenewegen (2020), Marengo et al. (2010a, 2010b), Schmidt (2015), Barmby et al. (2011), and Scowcroft et al. (2016). A comprehensive fit of photometry, velocities, and angular diameters are provided by the SpectroPhoto-Interferometry of Pulsating Stars (SPIPS) from Mérand et al. (2015), which included IR excesses. The IR excess is small (mean values from Gallenne et al.: 0.09 ± 0.03 mag at 2.2 μm, 0.14 ± 0.04 mag at 10 μm).

The source of the emission is uncertain. The most recent discussion (Hocdé et al. 2020a) has examined energy distributions including Spitzer spectra. They find hot or cold dust cannot explain the spectral distribution, however free–free emission from a thin shell of ionized gas at about 0.15 R\(_{\text{Cep}}\) does match the emission. Hocdé et al. (2020b) used lines of H\(_{\alpha}\) and the IR Ca triplet to study the chromosphere. For Cepheids with periods longer than 10\(^4\), they find that the thickness of the chromosphere is about 50% of the radius of the star. This could possibly contain a hot inner chromosphere where the lines are found and a cold outer chromosphere seen in interferometry. Furthermore, for most of the long period Cepheids they find a motionless H\(_{\alpha}\) absorption feature at the stellar rest frame, which could come from the outer CSE. This is similar to the stationary absorption line found in the Mg II profiles by Böhm-Vitense & Love (1994).

CSEs are related to two aspects of Cepheids. First, IR flux must be taken into account for the most accurate application of the Leavitt law. Second, pulsation may cause mass loss, even at a very low level (see Neilson et al. 2012 for a recent summary). This would affect the evolution of the Cepheid and the interpretation of evolutionary tracks.

1.3. Outer Atmosphere

To emphasize the important niche that the X-ray observations play in understanding the upper atmosphere of Cepheids, we summarize the phenomena and what can be inferred about stratification between them, particularly as they are seen in δ Cep.

1. In the inner region of a Cepheid atmosphere we have many diagnostics for the pulsation related disturbances in the photosphere and chromosphere at minimum radius.
2. The layer related to X-ray increase is above this and does not participate in the disturbances at minimum radius, nor do the photosphere or chromosphere show any disturbance at the time of X-ray maximum (maximum radius).
3. The CSEs are identified by IR emission. At present we are accumulating diagnostics for the outer atmosphere CSEs and X-ray region, but it is not clear how they are related.
4. Beyond the CSE and X-rays, η Aql has two companions (see below) that may sculpt any mass-loss flow.
5. In δ Cep itself there is a spectacular shell (bow shock) that appears to surround the Cepheid that could be created by a mass-loss wind from the Cepheid interacting with the ISM (Marengo et al. 2010b). However, this has not been seen in η Aql.

1.4. η Aql

The target of the XMM-Newton observations, η Aql, is one of the brightest Cepheids, and has been extensively observed. It has a pulsation period of 7.18\(^4\), an E(B-V) of 0.12 mag, and a distance of 273 pc (Evans et al. 2016; based on the HST parallax scale of Benedict et al. 2007).

Available data for η Aql are assembled in Mérand et al. (2015) in the demonstration of the SPIPS program. These include interferometry from Kervella et al. (2004) and Lane et al. (2002). Mérand et al. (2015) found an excess of 0.018 ± 0.002 mag in the K band and 0.016 ± 0.003 mag in the H band. This analysis was recently redone by Gallenne et al. (2021) adding new observations from the VISIR instrument at the Very Large Telescope. They find IR excesses increasing with a wavelength from 0.077 ± 0.005 at K to 0.20 ± 0.01 mag at 25 μm.

η Aql has two companions. The closest is a B9.8 V star (Evans et al. 2013). The orbit is not yet known but, as postred giant stars, all known Cepheid binaries have separations of at least 1 au. The more distant companion is an early F star 0\(^6\)66 or 180 au from the Cepheid (Gallenne et al. 2014). Stars in the spectral range late B through early F do not in general produce X-rays, so neither of these companions is expected to produce X-rays.

The purpose of of the XMM-Newton observation was to determine whether there is an X-ray burst at maximum radius as is seen for δ Cep.

1.5. Possible Companions?

Reasonably massive stars like Cepheids (typically 5 M\(_{\odot}\)) are frequently found in binary or multiple systems (e.g., Evans et al. 2020a). In addition a number are known in open clusters, which have been an important source of calibrators for the Leavitt Law. Anderson et al. (2013) provide a recent assessment of Cepheid membership in clusters. Gaia data
make it possible to investigate whether there are any associations with low densities between recognized clusters and multiple systems. X-ray observations add an important element. Low-mass stars at the age of Cepheids are X-ray active. This means X-ray observations are particularly useful at distinguishing low-mass stars related to Cepheids from the older field star population. This is demonstrated, for instance, for the Cepheid S Mus (Evans et al. 2014). We have used the XMM-Newton observation of η Aql combined with 2MASS and Gaia data to search for any low-mass X-ray active stars in the field.

The following discussion of the XMM-Newton observations of η Aql has the following sections: the observation and data analysis, the X-rays at the position of the Cepheid, identification of counterparts to X-ray sources in 2MASS and Gaia, and discussion and conclusions.

2. Observation and Data Analysis

η Aql was observed by the XMM-Newton for 75 ks on 2019 May 12 from JD 2,458,615.584–2,458,616.452 (OBSID 0840510201). Data analysis was carried out using standard data reduction tasks in scientific analysis subsystem (SAS) software version 17.0, as in Pillitteri et al. (2013). This involved a reduction starting from the Observation Data Files of the observation, filtering the events according to their grades and screening out bad pixels. Only events between 0.3 and 8.0 keV were used. Using the recipe given in the SAS guidelines, the reduction was restricted to good time intervals and low background periods, based on the light curve of the events above 10 keV. Figure 1 shows the detected sources. The X-ray positions have a median uncertainty in position of 2″9 with a range of 2″3–4″0 (25%–75% range of the distribution).

A full list of the X-ray sources is provided in the electronic version, with a section in Table 1 below to illustrate form and content. The columns show Id, R.A., Decl., position error, distance from the aim point, the significance of detection in units of standard deviation of the local background, the rate with error scaled to the sensitivity of MOS, and the exposure time. The exposure time is the sum of MOS and pn exposures.

3. The Cepheid

The observation covered phases 0.406–0.527 using the ephemeris from Engle (2015) for the epoch $E_0 = 2,455,856.689 + 7.177025 \times E$. This covers the phase range of the X-ray burst in the 5th Cepheid, δ Cep.

The Cepheid η Aql was not detected. Figure 2 shows a zoom of the center of the XMM-Newton image with the location of the Cepheid marked with +. The upper limit on the X-ray luminosity from this was estimated as follows. In a region of 30″ around the optical position of the star there are 528 ± 23 counts in the PN energy band 0.3–8.0 keV. The region should contain about 80% of the PSF. Using 3σ from the 23 counts and correcting for the 80% factor results in 86 counts in 75 ks. Using the Portable Interactive Multi-Mission Simulator (PIMMS) with an APEC component of 0.5 keV and $N_H = 7 \times 10^{20}$ cm$^{-2}$, the upper limit of the flux is...
2.01 \times 10^{-15} \text{ ergs s}^{-1} \text{ cm}^{-2}. The upper limit results in an upper limit to the luminosity of \( L_X \leq 1.8 \times 10^{28} \text{ erg s}^{-1} \) using a distance of 273 pc, which is lower than the luminosity \( \delta \text{ Cep} \) in its quiescent phases (3.2–12 \times 10^{28} \text{ ergs s}^{-1}) and certainly less than at its maximum phase, where the luminosity is 1.7 \times 10^{29} \text{ ergs s}^{-1}.

We have investigated to see how much this upper limit can be varied. In particular, we have used narrower wavelength bands for comparison, as shown in Table 2. Since Cepheids and other supergiants have soft X-ray spectra, their flux is concentrated below 2 keV. Thus, the second row in Table 2 shows the upper limit to the count rate for the band between 0.3 and 0.8 keV. The bottom row in Table 2 shows the much narrower band between 0.45 and 0.67 keV, which contains the O VII triplet. To interpret the count rate we provide the example for the 0.3 and 1.0 keV band of the flux provided by PIMMS for a series of temperatures in Figure 3. For the range of temperatures between 0.4 and 0.8 keV, the flux is essentially

---

**Table 1**

Sources in the XMM-Newton Image Around \( \eta \) Aql

| R.A. (J2000) | Decl. (J2000) | Pos Err \( \alpha \) | Offaxis \( \delta \) | Significance \( \sigma_{\text{bg}} \) | Rate (counts ks\(^{-1}\)) | \( \pm \) (counts ks\(^{-1}\)) | Exp Time (ks) |
|--------------|---------------|---------------------|---------------------|----------------|----------------|----------------|--------------|
| 1 298.13559  | 0.77763       | 1.2                 | 14.89               | 11.6           | 1              | 0.16           | 54.14        |
| 2 298.15073  | 0.79184       | 2.9                 | 14.23               | 5.5            | 0.61           | 0.15           | 58.38        |
| 3 298.14593  | 0.79717       | 1.8                 | 13.86               | 6.8            | 0.62           | 0.12           | 60.28        |
| 4 298.17638  | 0.81929       | 4.8                 | 13.13               | 7.3            | 1.3            | 0.21           | 66.91        |
| 5 298.02853  | 0.82115       | 2.6                 | 12.72               | 35.8           | 9.3            | 0.45           | 73.99        |
| 6 298.12188  | 0.82154       | 2.9                 | 12.16               | 24.6           | 5.7            | 0.35           | 69.57        |
| 7 297.97294  | 0.83689       | 3.1                 | 13.33               | 10.5           | 1.8            | 0.26           | 53.65        |

**Table 2**

\( \eta \) Aql Upper Limits

| Energy (keV) | Count Rate (\( \times 10^3 \)) | Flux (ergs s\(^{-1}\) cm\(^{-2}\)) | Lum (ergs s\(^{-1}\)) |
|--------------|---------------------------------|-----------------------------------|------------------------|
| 0.3–8.0      | 1.15                            | \( \approx 1.7 \times 10^{-15} \) | \( \approx 1.5 \times 10^{28} \) |
| 0.3–1.0      | \( \approx 1.0 \)                | \( \approx 1.4 \times 10^{-15} \) | \( \approx 1.2 \times 10^{28} \) |
| 0.45–0.67    | 0.5                             | 0.7 \times 10^{-15}               | 0.6 \times 10^{28}     |

*Note.* Table 1 is published in its entirety in machine-readable format. A portion is shown here for guidance regarding its form and content.

(This table is available in its entirety in machine-readable form.)

Figure 2. A zoom of the center of the image in Figure 1 with the position of the Cepheid marked with +.
the same, so the flux of $1.4 \times 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$ in Table 2 is temperature independent. Luminosities are given in the final column of Table 2, which are further below the luminosities of $\delta$ Cep in either its quiescent or maximum state.

4. Identification of Counterparts to X-ray Sources

4.1. 2MASS Sources

We have used the Two Micron All Sky Survey (2MASS) catalog (Cutri et al. 2003) to find the near-IR counterparts to the X-ray sources. 34 have a 2MASS source within 5″. The full list of the 2MASS counterparts detected in the $\eta$ Aql field is provided in the electronic version, with a short list in Table 3 to indicate the content of the table. The columns show the XMM-Newton source ID, the R.A., the Decl., the 2MASS ID, the 2MASS magnitudes and errors (J, H, and K; K is referred to as K below), the 2MASS quality indicators, and the separation between the X-ray source and the 2MASS source. Figure 4 shows the $J$–$(J-K)$ color–magnitude diagram for the 2MASS counterparts for sources where the errors on the photometry are less than 0.1 mag. An M0 star at the distance of $\eta$ Aql (273 pc) with the reddening of the Cepheid ($E(B-V)) = 0.12$ mag would have a $J = 13.3$ mag and $(J-K)_0 = 0.85$ mag using the main-sequence calibration of Drilling & Landolt (2000), and the colors calibrations of Bessell & Brett (1988) and Carpenter (2001). Figure 4 shows that most of the 2MASS sources are fainter and/or redder than these values, with only a few sources which could be at the same distance as the Cepheid. Since the Cepheid is at a low galactic latitude ($b = 13°$), it is likely that there are a number of young stars at larger distances and with larger reddenings, which would constitute the majority of the 2MASS X-ray sources. Furthermore, it is likely that sources without 2MASS counterparts are background AGN.

The bright star in Figure 4 is HD 187900, which is a K2 star with $V = 9.28$ mag.

4.2. Gaia Sources

The X-ray source list was also matched against the catalog produced by the Gaia satellite (Gaia Collaboration et al. 2016, 2018). The full list of possible matches is provided in the electronic version of this paper, with a few entries in Table 4 to indicate the form and content. Of 126 X-ray sources, 54 (43%) had at least one possible match with a Gaia source. The

![Figure 3](image_url) The flux computed from the count rate for the 0.3–1.0 keV band in Table 2 for a range of temperatures (see text). The temperature $kT$ is in keV; the flux is in $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$.

![Figure 4](image_url) The color–magnitude diagram for X-ray sources with 2MASS counterparts (in magnitudes) for 2MASS errors less than 0.1 mag.

| R.A. (J2000) | Decl. (J2000) | 2MASS ID | $J$ (mag) | $H$ (mag) | $K$ (mag) | Qual | Sep |
|-------------|--------------|----------|-----------|-----------|-----------|------|-----|
| 17          | 298.23307    | 0.868617 | 19525599+0052070 | 15.7430 | 0.0910 | 15.3750 | 0.1150 | 15.1300 | 0.1450 | ABB | 1.3929 |
| 24          | 298.051844   | 0.903709 | 19521236+0054133 | 14.0700 | 0.0780 | 13.5690 | 0.1130 | 13.5390 | 0.0580 | ABA | 1.0000 |
| 24          | 298.052582   | 0.903914 | 19521261+0054140 | 14.7210 | 0.0450 | 14.0680 | 0.0580 | 14.1160 | 0.0610 | AAA | 1.0000 |
| 27          | 298.021759   | 0.914922 | 19520521+0054537 | 14.3140 | 0.0290 | 13.7460 | 0.0410 | 13.6970 | 0.0360 | AAA | 1.2030 |

Note. Table 3 is published in its entirety in machine-readable format. A portion is shown here for guidance regarding its form and content. (This table is available in its entirety in machine-readable form.)
Table 4  
Gaia Counterparts to XMM-Newton Sources

| R.A.  | Decl. | Sep | Gaia ID                  | X Src # | Px (mas) | ± (mas) | G (mag) | ± (mag) | BP (mag) | ± (mag) | RP (mag) | ± (mag) |
|-------|-------|-----|--------------------------|---------|----------|---------|---------|---------|----------|---------|----------|---------|
| 298.17575892226 | 0.81915965345 | 0.45 | 4240251955274546176 | 4       | −0.2996  | 0.3579  | 19.3837 | 0.0036  | 19.6484  | 0.0707  | 18.7031  | 0.0462  |
| 298.0286373075  | 0.82085522581 | 0.3  | 424026292033547008     | 5       | 0.5077   | 1.1782  | 20.6907 | 0.0097  | 20.5658  | 0.1153  | 20.0888  | 0.1044  |
| 298.12175960105 | 0.8213431695  | 0.22 | 4240252470670622720 | 6       | 0.7396   | 1.0290  | 20.5027 | 0.0093  | 20.471   | 0.1214  | 19.4289  | 0.0448  |
| 297.97295268783 | 0.83683043657 | 0.06 | 4240263122188744704  | 7       | 0.1319   | 0.6752  | 20.1036 | 0.0095  | 20.3039  | 0.0777  | 19.5392  | 0.0558  |

Note. Table 4 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content.  
(This table is available in its entirety in machine-readable form.)
columns show the R.A., the Decl., the separation of the XMM-Newton source and the Gaia source, the Gaia ID, the XMM-Newton source number, the parallax and error, and the Gaia magnitudes and errors (G, BP, and RP).

The distribution of parallaxes is shown in Figure 5. For comparison, the dashed line indicates the parallax of \( \eta \) Aql, which corresponds to a distance of 273 pc. There are other determinations of the distance (e.g., 296 pc from the SPIPS method; Mérand et al. 2015). Ultimately, it is anticipated the Leavitt law will be improved by Gaia, however adjustments to Figure 5 will be small. The possible matches largely correspond to distances of a kpc or more, well beyond the location of the Cepheid. There are in fact only a couple of stars that might be at the Cepheid distance. To identify possible structures in lines of sight in the galactic plane, it is valuable to have parallaxes and photometry, though in this case no structures were identified within 1 kpc.

As part of the exploration of the population in the direction of \( \eta \) Aql, we made an additional comparison, using a list of stars with Gaia parallaxes drawn up in the same way as in Kervella et al. (2019) to look for wide common proper motion companions of Cepheids. This search covered approximately the same area as the XMM-Newton field. We examined stars at approximately the distance of \( \eta \) Aql with parallaxes between 2.5 and 4.5 mas (corresponding to distances between approximately 220 and 400 pc), and further restricted the list to those with parallax errors less than 0.2 mas. The resulting sample is shown in Figure 6. As would be expected for this distance-restricted sample, the color–magnitude diagram forms a sequence. For comparison, we show the XMM-Newton sources that matched Gaia sources. Although there are three XMM-Newton sources consistent with the cmd sequence, the Gaia objects in general are not X-ray sources. This suggests that while sharing a similar distance they are stars older than the Cepheid (50 Myr), and thus less X-ray luminous and not related to it. X-ray activity is typical in young low-mass stars at the flux that would be detected in this observation. However for a young high mass star, such as a Cepheid, X-rays occur at this level only in a restricted phase range, such as for \( \delta \) Cep. In \( \eta \) Aql, the observation does not detect X-rays in this phase range.

5. Discussion and Conclusions

In this paper we have found that the Cepheid \( \eta \) Aql is not an X-ray source in the phase range at which an X-ray burst was seen in \( \delta \) Cep. Furthermore, \( \eta \) Aql has a stronger IR excess than \( \delta \) Cep indicating a CSE. Thus we do not seem to duplicate the pattern of X-ray occurrence and CSE seen in \( \delta \) Cep.

The Cepheids \( \eta \) Aql and \( \delta \) Cep have many characteristics that are similar: pulsation periods, amplitudes, and pulsation modes. The pulsation periods imply that the masses and ages are similar. The pulsation period of \( \delta \) Cep is decreasing implying that it is on the second crossing of the instability strip, in contrast to \( \eta \) Aql that has an increasing period, implying that it is on the third crossing (Engle 2015). This, however, is not a sign of different or abnormal evolution, rather just part of the standard evolutionary sequence. One parameter that might differentiate them is a magnetic field. Little is known about the magnetic fields in Cepheids. Grunhut et al. (2011) find a Zeeman signature in \( \eta \) Aql but not in \( \delta \) Cep. What role this might play in X-ray production or CSEs is not known.

This raises the question of whether X-ray bursts are common or exceptional among Cepheids since we see them in two (\( \delta \) Cep and \( \beta \) Dor) but not in \( \eta \) Aql. Alternately, is there anything about \( \eta \) Aql that would make it exceptional? The general properties of \( \eta \) Aql (period, amplitude pulsation mode) are all common among many other Cepheids. An example of a property that might affect X-ray production and be unique to \( \eta \) Aql is a companion that comes close to the Cepheid at
periastron because of high eccentricity. \( \eta \) Aql does have a close companion, but the orbit has not so far been determined.

The X-ray peaks from the theoretical simulation do not all occur at the same phase. Among other things, the phasing depends on the number of terms in the Fourier representation of the pulsation wave. This suggests another way the occurrence of an X-ray increase may depend on stellar parameters, and may differ from star to star.

In summary, the pattern of an X-ray burst in \( \delta \) Cep is not repeated in \( \eta \) Aql, despite the fact that they are similar in many physical parameters. The links between upper atmosphere phenomena are apparently not simple.

Stars in the region of \( \eta \) Aql that are young enough to be associated with the Cepheid are expected to be X-ray sources. Figure 6 shows sources in the XMM-Newton field of view that have reasonably accurate Gaia parallaxes, indicating that they might be at a distance similar to \( \eta \) Aql. These cool stars are overwhelmingly not X-ray sources; that is, not young enough to be associated with the Cepheid. In this way X-ray observations are valuable in sorting out possible structures in a crowded field in the galactic plane.

This research is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA). We thank the referee for comments that improved the presentation of the results. Support was provided to NRE by the Chandra X-ray Center NASA Contract NAS8-03060. The observations were associated with program 84051 with support for this work from NASA grant 80NSSC20K0794. J.J.D. was supported by NASA contract NNX08AD89G. Support was provided through grant HST-GO-15861.005-A from the STScI under NASA contract NAS5-26555.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC; https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

The SIMBAD database and NASA's Astrophysics Data System Bibliographic Services were used in the preparation of this paper.

References

Anderson, R. I., Eyer, L., & Mowlavi, N. 2013, MNRAS, 434, 2238
Barnby, P., Marengo, M., Evans, N. R., et al. 2011, AJ, 141, 42
Benedict, G. F., MacArthur, B. E., Feast, M. F., et al. 2007, AJ, 133, 1810
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Böhm-Vitense, E., & Love, S. G. 1994, ApJ, 420, 401
Carpenter, J. M. 2001, AJ, 121, 285
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, yCat, II, 246
Drilling, J. S., & Landolt, A. U. 2000, Astrophysical Quantities (New York: Springer), 381
Engle, S. G. 2015, PhD thesis, James Cook Univ.
Engle, S. G., Guinan, E. F., Harper, G. M., et al. 2017, ApJ, 838, 67
Evans, N. R., Bond, H. E., Schaefer, G. H., et al. 2013, AJ, 146, 93
Evans, N. R., Bond, H. E., Schaefer, G. H., et al. 2016, AJ, 151, 129
Evans, N. R., Güenther, M., Bond, H. E., et al. 2020b, ApJ, 905, 81
Evans, N. R., Pillitteri, I., & Molnar, L. 2020a, AJ, 159, 121
Evans, N. R., Pillitteri, I., Wolk, S., et al. 2014, ApJ, 785, L25
Gaia Collaboration, Prusti, T., et al. 2016, A&A, 595, A1
Gaia Collaboration, Brown, A. G. A., et al. 2018, A&A, 616, A1
Gallenne, A., Kervella, P., Mérand, A., et al. 2014, A&A, 567, A60
Gallenne, A., Mérand, A., Kervella, P., et al. 2021, submitted
Groenewegen, M. A. T. 2020, A&A, 635, A33
Grunhut, J. H., Wade, G. A., Hanes, D. A., & Alecian, E. 2011, MNRAS, 408, 2290
Hocdé, V., Nardetto, N., Lagadec, E., et al. 2020a, A&A, 633, A47
Hocdé, V., Nardetto, N., Lagadec, E., et al. 2020b, A&A, 641, A74
Kervella, P., Gallenne, A., Evans, N. R., et al. 2019, A&A, 623, A117
Kervella, P., Mérand, A., Perrin, G., & Couté du Foresto, V. 2006, A&A, 448, 623
Kervella, P., Nardetto, N., Bersier, D., et al. 2004, A&A, 416, 941
Lane, B. F., Creech-Eakman, M. J., & Nordgren, T. E. 2002, ApJ, 573, 330
Marengo, M., Evans, N. R., Barnby, P., et al. 2010a, ApJ, 709, 120
Marengo, M., Evans, N. R., Barnby, P., et al. 2010b, ApJ, 725, 2392
Mérand, A., Kervella, P., Breitfelder, J., et al. 2015, A&A, 584, A80
Mérand, A., Kervella, P., Couté du Foresto, V., et al. 2006, A&A, 453, 155
Mignone, A. 2014, JCoPh, 270, 784
Moschou, S.-P., Nektarios, V., Drake, J. J., et al. 2020, ApJ, 900, 157
Neilson, H. R., Langer, N., Engle, S. G., et al. 2012, ApJ, 760, L18
Pillitteri, I., Evans, N. R., Wolk, S. J., & Syal, M. B. 2013, AJ, 145, 143
Schmid, E. G. 2015, ApJ, 813, 29
Scowcroft, V., Seibert, M., Freedman, W. L., et al. 2016, MNRAS, 459, 1170

ORCID IDs

Nancy Remage Evans https://orcid.org/0000-0002-4374-075X
Ignazio Pillitteri https://orcid.org/0000-0003-4948-6550
Pierre Kervella https://orcid.org/0000-0003-0626-1749
Scott Engle https://orcid.org/0000-0001-9296-3477
Edward Guinan https://orcid.org/0000-0002-4263-2650
Scott Wolk https://orcid.org/0000-0002-0826-9261
Hilding Neilson https://orcid.org/0000-0002-7322-7236
Massimo Marengo https://orcid.org/0000-0001-9910-9230
Soifa Moschou https://orcid.org/0000-0002-2470-2109
Jeremy J. Drake https://orcid.org/0000-0002-0210-2276
Joyce A. Guzik https://orcid.org/0000-0003-1291-1533