RESOLVED COMpanIeNS OF CEPHeIDS: TESTING THE CANDIdATES wITH X-RaY OBSERVAtIONS

Nancy Remage Evans1, Ignazio Pillitteri1,2, Scott Wolk1, Margarita Karovska1, Evan Tingle1, Edward Guinan3, Scott Engle3, Howard E. Bond4,5, Gail H. Schaefer6, and Brian D. Mason7
1 Smithsonian Astrophysical Observatory, MS 4, 60 Garden St., Cambridge, MA 02138, USA; nevans@cfa.harvard.edu
2 INAF-Osservatorio di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy
3 Department of Astronomy and Astrophysics, Villanova University, 800 Lancaster Ave., Villanova, PA 19085, USA
4 Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802, USA; heb11@psu.edu
5 Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA
6 The CHARA Array of Georgia State University, Mount Wilson, California 91023, USA; schaefer@chara-array.org
7 US Naval Observatory, 3450 Massachusetts Ave., NW, Washington, DC 20392-5420, USA
Received 2015 November 10; accepted 2016 January 31; published 2016 April 4

ABSTRACT

We have made XMM-Newton observations of 14 Galactic Cepheids that have candidate resolved (≥5") companion stars based on our earlier HST Wide Field Camera 3 (WFC3) imaging survey. Main-sequence stars that are young enough to be physical companions of Cepheids are expected to be strong X-ray producers in contrast to field stars. XMM-Newton exposures were set to detect essentially all companions hotter than spectral type M0 (corresponding to 0.5 M☉). The large majority of our candidate companions were not detected in X-rays, and hence are not confirmed as young companions. One resolved candidate (S Nor #4) was unambiguously detected, but the Cepheid is a member of a populous cluster. For this reason, it is likely that S Nor #4 is a cluster member rather than a gravitationally bound companion. Two further Cepheids (S Mus and R Cru) have X-ray emission that might be produced by either the Cepheid or the candidate resolved companion. A subsequent Chandra observation of S Mus shows that the X-rays are at the location of the Cepheid/spectroscopic binary. R Cru and also V659 Cen (also X-ray bright) have possible companions closer than 5" (the limit for this study) which are the likely sources of X-rays. One final X-ray detection (V473 Lyr) has no known optical companion, so the prime suspect is the Cepheid itself. It is a unique Cepheid with a variable amplitude. The 14 stars that we observed with XMM constitute 36% of the 39 Cepheids found to have candidate companions in our HST/WFC3 optical survey. No young probable binary companions were found with separations of ≥5" or 4000 au.

Key words: binaries: general – stars: formation – stars: massive – stars: variables: Cepheids

1. INTRODUCTION

Binary/multiple configurations influence every phase of a star’s life: formation, the main sequence, and the post-main sequence, and they often drastically affect the outcomes. For instance, Kraus et al. (2012) find that binaries with intermediate separations (40 au) are less likely to have protoplanetary disks than both closer and wider binaries, and hence are less likely to form planets. For main-sequence stars, Sana et al. (2012) recently showed that more than 70% of O stars (≥20 M☉) are destined to undergo binary interactions with mass exchange, and a third of those undergo mergers. At later stages, many classes of X-ray sources have scenarios involving binaries containing a compact object (supernovae progenitors, X-ray binaries, novae, cataclysmic variables, and symbiotic stars). However, there are many unanswered questions about how these configurations are achieved.

Technical developments in recent years in both radial velocities and imaging have contributed greatly to the studies of binary/multiple stars. For massive stars, the velocity study of O stars in the 30 Dor (Tarantula Nebula) in the LMC (Sana et al. 2013) is of particular importance. It confirmed the large fraction of binaries, and demonstrates the importance of interaction in the their evolution (above; Sana et al. 2012). A comparable velocity survey was done on the B stars in the Tarantula Nebula (Dunstall et al. 2015), who concluded that the multiplicity properties of the B stars are essentially the same as for the O stars. An extensive high-angular-resolution study of O stars was made at the Very Large Telescope (VLT) and the Very Large Telescope Interferometer (VLTI) which covers separations from 0.5 to 10^4 mas (1 to 20,000 au at a typical distance of 2 kpc; Sana et al. 2014). Of particular importance was filling the gap between spectroscopic binaries and visual binaries which had been found by Mason et al. (1998). A further survey was made by Aldoretto et al. (2015), of O and B stars using the HST Fine Guidance Sensor (FGS). A summary of previous studies of binarity/multiplicity in massive stars can be found in Evans et al. (2013, 2016).

Binary/multiple properties reflect the processes of star formation in their extent and mass ratios. The formation of wide binaries (1000 au or greater) is a problem for star formation, since this is larger than the typical size of a star-forming core. Several mechanisms have been suggested to get around this problem. One is the “unfolding” of a triple system. In a triple, which is dynamically unstable, one component (typically the smallest) may be sent to a wider orbit (Reipurth & Mikkola 2012). Another mechanism is the acquisition of a third star during cluster dissolution (Kouwenhoven et al. 2010). Parker & Meyer (2014) concluded that over time the reduction of triple systems through disruption is balanced by acquisition of another star, keeping the binary fraction relatively constant. The stars targeted in the present study are wide resolved companions. Within such systems there is ample room for a close binary, and hence wide companions are candidates for triple systems. In the same way that early exoplanet discoveries
taught us the importance of migration, analysis of multiple systems points to dynamical evolution in which a third star plays a special role. One example of the consequences of a triple system is that spectroscopic binaries with \(< P < 12\) day are much more likely to have a third component than those with \(P > 12\) day (Tokovinin et al. 2006). This implies that dynamical evolution has shortened the periods of the first group. Conservation of total system angular momentum requires that the wider tertiary components move to wider separations. Scenarios involving a triple system have also been proposed to explain close eccentric binaries (Perets & Kratter 2012) and close binaries with small mass ratios (Moe & Di Stefano 2015), both required for exotic end-stage objects.

The present study is Paper IV in a series aimed at determining the binary/multiple properties of Cepheids. They are reasonably massive stars (typically 4–8 \(M_\odot\) stars, abbreviated to 6 \(M_\odot\) below) in a well-known evolutionary state with well-studied distances and redenning. This study builds on a Hubble Space Telescope (HST) Wide Field Camera 3 (WFC3) imaging survey of 70 Cepheids. Evans et al. (2013; Paper I) demonstrated the technique using Cepheids with reasonably massive companions \((q = M_2/M_1 \geq 0.4)\). In Papers II and III (Evans et al. 2016; N. R. Evans et al. 2016, in preparation (Paper III)), we used the WFC3 images in the F621M and F845M filters to identify candidate resolved companions as close as approximately 0″5. With this we can identify main-sequence companions typically as close as 300 au. Paper II discusses possible companions \(\geq 5″\) from the Cepheid; Paper III discusses closer companions identified after point-spread function (PSF) correction.

Possible resolved companions were identified in Paper II as follows. A color–magnitude (CMD) was formed for stars from the F621M and (F621M–F845M) data, which transform well to V and (V–I). This was compared with an isochrone at the distance and with the reddening of the Cepheid (see Paper II). Stars in the field within 2\(\sigma\) of the isochrone with colors hotter than M stars were considered candidate resolved companions, and are listed in Paper II.

Identification of resolved companions, particularly low-mass stars, is plagued by contamination from galactic field stars. However, resolved companions which are genuine physical companions of Cepheids (typically \(\geq 50\) Myr old) will be young. Stars this young are active X-ray producers as compared with old field stars. In the present study, we have observed a number of possible resolved companions from the HST survey with the XMM-Newton X-ray satellite (XMM) to identify X-ray active young stars, likely to be genuine bound companions.

Thus, the aim of this study is to identify the widest companions of Cepheids down to very small masses. One goal is to determine the maximum separation which set by star formation plus subsequent dynamical evolution. A second aim is related to the fact that a wide system may easily contain a closer binary, at least in the main-sequence phase. A wide companion certainly does not guarantee a three-star system, but it is a flag that this may be the case. As discussed above this opens a number of possibilities for its evolution.

The subsequent sections in this paper discuss the observations and data analysis (Section 2), the resolved companions, upper limits and detections (Section 3), results (Section 4), discussion (Section 5), and a summary.

### 2. OBSERVATIONS AND DATA ANALYSIS

Our XMM target list was selected from a compilation of possible resolved companions found in our HST optical imaging survey. Discussion of the results of the survey is done in two parts, determined by data-reduction challenges (Papers II and III). Possible companions at \(\geq 5″\) are good targets for XMM imaging, since this is approximately the size of the XMM PSF. Specifically, our target list was drawn from Table A1 in Paper II of such candidates, which would be resolvable by XMM. Table 1 lists the observed Cepheids, the date of observation and UT at the beginning of the integration, the exposure duration for the MOS1 CCD camera, the redening and distance (from Paper II), and the XMM filter used. In addition to XMM observations made for this study, two observations were obtained from the XMM archive: U Sgr (PI: Motch) and ℓ Car (PI: Guinan). Of the 39 Cepheids with candidate resolved companions \(\geq 5″\) (from the 70 WFC3 observations), altogether 14 of them (36%) were observed with XMM.

Data analysis was carried out as in Pillitteri et al. (2013), using standard XMM data reduction (SAS) tasks to filter events so that events in the band 0.3–8.0 keV were used. Only good time intervals were included and high-background intervals were removed. Source detection and upper-limit calculation were done using a wavelet deconvolution algorithm, as

| Star    | Date and UT | Exp. MOS1 (ks) | \(E(B - V)\) | Distance (pc) | Filter |
|---------|-------------|----------------|--------------|---------------|--------|
| ℓ Car   | 2010 Feb 08 10:32:32 | 52.9 | 0.17 | 506 | Thick |
| V659 Cen| 2013 Sep 07 20:10:37 | 20.8 | 0.21 | 753 | Medium |
| V737 Cen| 2014 Jan 26 14:29:20 | 31.7 | 0.22 | 848 | Medium |
| R Cru   | 2014 Jan 04 19:56:55 | 22.0 | 0.19 | 829 | Medium |
| S Cru   | 2013 Aug 21 21:52:30 | 11.4 | 0.16 | 724 | Medium |
| X Cyg   | 2013 Apr 26 02:46:47 | 30.9 | 0.29 | 981 | Medium |
| V473 Lyr| 2013 Sep 22 09:49:34 | 6.6  | 0.03 | 553 | Medium |
| R Mus   | 2013 Feb 15 01:19:42 | 17.4 | 0.12 | 844 | Medium |
| S Mus   | 2013 Jan 05 14:36:48 | 25.3 | 0.21 | 789 | Medium |
| S Nor   | 2015 Mar 13 09:10:05 | 33.1 | 0.19 | 910 | Medium |
| Y Oph   | 2012 Sep 12 06:52:49 | 9.5  | 0.65 | 510 | Medium |
| V440 Per| 2013 Sep 02 21:48:18 | 24.4 | 0.27 | 791 | Medium |
| U Sgr   | 2006 Oct 11 23:29:34 | 29.5 | 0.40 | 617 | Medium |
| Y Sgr   | 2013 Sep 29 04:56:27 | 13.2 | 0.20 | 505 | Medium |
implemented in the code originally written for ROSAT images (Damiani et al. 1997a, 1997b) and adapted for XMM images.

3. CANDIDATE RESOLVED COMPANIONS

The results of our XMM observations of possible resolved companions are summarized in Table 2. The successive columns are: the companion identification number for each Cepheid, V and V − I from Paper II, the separation in arcsec, the position angle, the separation converted to au using the distance from Table 1, the J2000 R.A. and decl. of the companion, and whether an X-ray source was detected at that location (Y/N/?). ? means the star responsible for the X-rays is uncertain, as discussed further in Section 3.2. The coordinates were measured from the WFC3 images.

In only three cases (S Mus, R Cru, and S Nor #4) is there possible X-ray flux at the location of the resolved companion, as shown in Figures 1–3. In two further cases (V659 Cen and V473 Lyr) a source was detected at a position indistinguishable from the Cepheid itself. These will be discussed in Section 3.2.

3.1. Detection Upper Limits

The XMM exposure times were set with the aim of detecting main-sequence companions as cool as spectral type K, which would have \( \log L_v \) of 29.2 erg s\(^{-1}\) or greater (at the distance and with the reddening of each Cepheid). X-ray fluxes for M dwarfs become much fainter as temperature decreases, and exposure times become much longer. X-ray flux, of course, depends on the age of the stars. The \( \alpha \) Per cluster is approximately 50 Myr old, making it an appropriate comparison for Cepheids which have about the same age. ROSAT observations of the cluster were discussed by Randich et al.
At approximately this limit, they detected 88% of K stars in their list. Pillitteri et al. (2003) use ROSAT data to obtain the X-ray luminosity distributions of G, K, and M stars for the α Per cluster. The X-ray detection rate at log $L_X$ of 29.2 erg s$^{-1}$ is 80%–90% for G and K stars, but falls off for M dwarfs. A deeper XMM observation of the α Per cluster was discussed by Pillitteri et al. (2013). Their luminosity function found a similar detection rate. (Note that the relevant bin in their discussion includes early M stars as well as G and K stars). Because of the dependence of X-ray flux on both age and spectral type, and, of course, the X-ray variability cycles of late-type stars, there is some imprecision in the estimate. However, this luminosity limit should ensure that most late-type stars through the K range (to 0.5 $M_\odot$) will be detected.

To quantify the non-detections in Table 2, we have computed upper limits at the positions of each of the candidate companions. Since we know the location of the possible companion stars, we used a $3\sigma$ detection limit for the upper limit. We ran the wavelet algorithm with this threshold to determine the level of count rates for a point-like source at the positions of the Cepheid companions. Table 3 (Column 3) lists the upper limit. The detections and upper limits were obtained

Figure 1. (a) Left: the XMM image of S Mus. The circles show the location of the Cepheid (black) and the possible companion (red). The orientation of both figures is the same with N up and E on the left. The scale is indicated by the $5''$ line. A log stretch is used to emphasize faint features. Circle sizes in both (a) and (b) are arbitrary. (b) Right: the HST WFC3 I image of S Mus. The possible companion is circled.

Figure 2. (a) Left: the XMM image of R Cru with circles to show the locations of the Cepheid and two possible companions. (b) Right: the HST WFC3 I image of R Cru. Both possible companions are circled. The image orientation and treatment are the same as for Figure 1.
using both MOS and pn images, using the standard relative efficiency MOS/pn cameras of 800/260 from the effective areas in the appropriate energy range. For V473 Lyr the count-rate limit is measured slightly further from the Cepheid than the position shown in Figure 5, to decrease flux from the position of the Cepheid (although there is still likely to be some contribution from the source at the Cepheid position). The ratio of $N_H$ to $E(B - V)$ used to derive the column densities in Column 4 was $5.9 \times 10^{21}$ cm$^2$ mag$^{-1}$. The corresponding flux (Column 5) was generated for this $N_H$ using an APEC plasma emission code in the PIMMS flux calculation software\(^8\) with log $T = 7.0$ and solar abundance for XMM using the filter in Table 1. The upper-limit X-ray luminosity (Column 6) was then derived using the distance.

In summary, most of the upper limits (Table 3) are close to the goal of log $L_X$ of 29.2 erg s$^{-1}$, showing that we should have detected most of the late F, G, and K stars which are young and at the distance of the Cepheids.

### 3.2. X-Ray Detections

The candidate optical companions targeted by our XMM observations are $\geq 5''$ from the Cepheid, allowing us to avoid confusion with X-ray emission from the Cepheid itself. In five

\[^{8}\text{http://cxc.harvard.edu/toolkit/pimms.jsp}\]
In Table 4 we include the median energy for each of the detections. The sources on the images are relatively weak, so full spectral analysis is not feasible. However, the median energy provides information which can help distinguish between a low-mass star and a cool supergiant, which has a softer spectrum. As an example, see Figure 3 in Evans et al. (2010), which compares the Polaris spectrum with the stacked spectrum from Orion Nebula low-mass stars (Feigelson et al. 2005). The low-mass stars have a sharp energy peak at 1 keV, with a tail extending out to 2 keV. Stars with earlier spectral type (as well as older stars), including the Polaris system, have energy peaks at about 0.9 keV.

The combination of the median energy values and $L_X$ in Table 4 provides the following information about the X-ray sources. S Nor #4 is the only undisputed X-ray source resolved from the Cepheid. Its median energy (0.95 keV) and $L_X$ are consistent with a low-mass star. In fact, the $L_X$ for all the detected sources is consistent with low-mass stars, but S Mus is the outlier in the high end. For the four systems where the position of the X-ray source is indistinguishable from the Cepheid, either it or the Cepheid could produce the detection. Thus, the Cepheid itself is a possible source. This star is one of the most unusual Cepheids known, unique among classical Cepheids in having a large-scale amplitude variation, resembling the Blazhko variations in RR Lyrae stars.

S Nor #4: This is the only X-ray source that is unequivocally from the resolved companion (Figure 3). However, since the Cepheid is a member of a populous open cluster, there is a significant chance of an alignment with a cluster star.

In this section we discuss each of the XMM detections in Table 4.

S Mus: A possible companion of S Mus lies within the PSF of the XMM image (Figure 1). From the image we cannot tell whether the X-rays come from the companion or from the Cepheid itself. We have recently obtained an observation of S Mus with the Chandra X-ray satellite. The image shows that the X-rays are not produced by the resolved companion, but from the location of the Cepheid. Full discussion of the results is in preparation. S Mus is a well-known binary system with a period of 1.38 years (Evans et al. 2006, and references therein). Velocities of the hot companion have been measured in the ultraviolet (Bohm-Vitense et al. 1997) and show no sign that the companion is itself a binary. The companion has a spectral type of B3 V, and is the one companion among the XMM observations hot enough that it could produce X-rays itself, which seems the most likely source of the X-rays.

R Cru: As with S Mus, the XMM image (Figure 2) cannot determine whether the X-rays come from the close (8") companion or the Cepheid. In addition, in Paper III, we find a possible companion 1"9 from the Cepheid. Either of the companions or the Cepheid could produce the X-rays. Figure 2 also shows that there is a small brightening in X-rays at the position of the resolved companion to the right of the Cepheid. We have examined that area carefully, and there is not a significant source at that location, but rather a fluctuation similar to other background fluctuations apparent in the figure.

V659 Cen: None of the five resolved possible companions in Figure 4 are coincident with an X-ray source. However, in Paper III, there is a possible companion at about 0"7 from the Cepheid. Either it or the Cepheid could produce the detection.

V473 Lyr: The X-rays in Figure 5 come from the vicinity of the Cepheid rather than the possible companion (separated by 15"). This raises the question whether there is a closer low-mass companion which could produce the X-rays. There are considerable data which address this topic. In Paper III there is no sign of a close companion. Conclusions from velocities are tricky because of the variable pulsation amplitude. The star has been discussed recently by Molnar & Szabados (2014), who conclude that it does not show binary motion, based largely on the 5 years of velocity data from Burki (1984). A binary companion can never be completely ruled out, but there is no evidence for one from either velocities or imaging. Thus, the Cepheid itself is a possible source. This star is one of the most unusual Cepheids known, unique among classical Cepheids in having a large-scale amplitude variation, resembling the Blazhko variations in RR Lyrae stars.
For V659 Cen a low-mass companion is consistent with both the median energy and $L_X$, and there is other evidence of such a companion. For S Mus, the median energy and $L_X$ are consistent with X-rays produced by shocks in an outflowing wind, as might be produced in the hot companion (see, for example, Stelzer et al. 2005).

Only the S Mus source has enough counts to make it reasonable to look at the spectrum (Figure 6). Although the counts warrant only crude energy bins, energy maximum is clear. The resulting energy from the fit ($kT = 0.64 \pm 0.14$ keV) is consistent with a low-mass star, although the $N_H$ ($5 \pm 2 \times 10^{21}$ cm$^{-2}$) and hence the unabsorbed flux ($6.3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the 0.3–8.0 keV band) is larger than that in Table 4.

In summary, of the five $XMM$ detections, two stars (R Cru and V659 Cen) have a close companion (<2′′ from the Cepheid) which are the most likely sources of the X-rays. For S Mus, the working model is that the X-rays are probably produced by the B3 companion. For S Nor, the late-type resolved companion is detected, though whether it is gravitationally bound to the Cepheid or a cluster member is unknown. For the final detection, V473 Lyr, the only candidate for the X-ray source appears to be the Cepheid.

We stress that the main goal of this study was to search for X-rays from young low-mass stars to identify Cepheid companions. These are coronal stars, for which the X-ray properties have been well studied. The mechanism for producing X-rays in Cepheids themselves is not well understood. They are also coronal stars. One possible mechanism is pulsation-driven shocks, as discussed by Engle et al. (2014). Another possibility is collisionless shocks (Ruby et al. 2016).
companions with XMM and found no young stars (with the exception of S Nor #4, which is most probably a cluster member). Thus, we have found no probable resolved companions with separations larger than 3950 au (S Mus, Table 2).

5. DISCUSSION

Systems containing Cepheids have undergone several periods of reorganization. As massive stars they are highly likely to be found in binary or multiple systems. Much of the dynamical adjustment from the initial configuration in a system of three or more members happens quickly and many will have already produced a hierarchical system by the time the primary reaches the zero-age main sequence (ZAMS). As stressed above, however, triple (and higher) systems can still evolve dynamically. This can result in the ejection of a star (typically the least massive) from the system.

After the ZAMS, since Cepheids are post-red-giant stars, very close binaries will have undergone Roche-lobe overflow. In extreme cases this results in mergers. Cepheids which began life as B stars have in some cases had their binary properties altered in this way, since there are no Cepheid binaries with shorter periods than a year in the Milky Way (Sugars & Evans 1996).

We stress three features of the current investigation which contribute to the understanding of binary/multiple properties in fairly massive stars (typically 6 M\textsubscript{\odot}). First, we have typically searched an area as wide as the canonical 0.1 pc (20,000 au) in our HST images for possible companions, which is the extent expected for physical companions. Second, the XMM observations provide a severe winnowing of the candidate list, and an important constraint on the extent of bound companions. Third, the magnitude difference between the Cepheid and a possible companion can be more than ΔV = 10 mag, including companions through K stars. A late K star would have a mass ratio of 0.1 with a 6 M\textsubscript{\odot} Cepheid.

Full discussion of the results of closer companion will be provided in Paper III; however we will make a preliminary comparison with other recent results, particularly of the extent of wide systems. The recent survey of resolved O star companions (Sana et al. 2014; SMASH) plans a further analysis of binary properties; however, a preliminary comparison with their results is warranted at this stage. The VLT and VLTI instruments they used cover from 0.5 through 104 mas, (1 au to 0.1 pc at the typical distance of their O stars of 2 kpc). The typical distance in our Cepheid survey is 700 pc. It is only their widest separations which are comparable to the Cepheids discussed here. An interesting change occurs for their detections at about 1″. The magnitude differences are larger (up to 8 mag in H); however while there are many comparatively faint companions, the number of bright companions drops off as compared with closer regions. Indeed, their probability analysis also concluded that the low-mass companions at separations >2″ are not physical companions. For a 20 M\textsubscript{\odot} system, the separation of ~2000 au where this happens is similar to the widest separation we find.

Tokovinin et al. (2006) made a survey of 165 solar-type spectroscopic binaries to search for wider components. They noted a decrease in third components at periods >105 years (≈3000 au). In a more recent distance-limited survey of solar-mass stars, Tokovinin (2014) finds a decrease in the widest

4. RESULTS

The distribution of separations for the possible companions investigated in Table 2 is shown in Figure 7. Appropriate to XMM’s spatial resolution, the Cepheids observed all have possible companions at separations ≥5″. In Figure 7, the optically resolved candidate companions are overwhelmingly not found to have the X-ray strength expected for a low-mass star about 50 Myr old. The star which is the exception to the finding that there are no companions in the survey at greater distances than 8000 au is the companion to S Nor. This is one of two stars in the survey (S Nor and U Sgr) which is a member of a populous open cluster. This increases the likelihood of a chance alignment with a cluster member. We thus consider the S Nor #4 companion at a projected separation of 13,300 au, to be an outlier, and most likely not to be gravitationally bound to the Cepheid.

The HST WFC3 survey covered 70 Cepheids, of which 39 were found to have possible resolved companions with separations ≥5″. We observed 14 (36%) of the possible
companions at about the same period. A similar result was found by Raghavan et al. (2010), also for solar-mass stars.

6. SUMMARY

We discuss XMM observations of possible resolved companions of Cepheids from an HST WFC3 survey. X-ray observations differentiate between young, low-mass stars (physical companions of Cepheids) and old field stars.

1. Of the possible resolved companions, only one was unambiguously detected, implying that it is a young star. The Cepheid involved is S Nor #4, which is a member of a well-populated cluster. For this reason, and because the companion is separated from the Cepheid by as much as 15″ (13,300 au), it is likely that this is a cluster member rather than a gravitationally bound companion.

2. Two of the Cepheids (S Mus and R Cru) have an X-ray source which is not resolved from the Cepheid on the XMM images. However, on a Chandra image of S Mus, the X-rays are shown to be produced by the Cepheid/spectroscopic binary.

3. R Cru and also V659 Cen have additional companions closer than the limit of 5″ for this study, which are the likely X-ray sources (to be discussed in Paper III).

4. One final X-ray detection (V473 Lyr) has no known companion; hence the prime suspect is the Cepheid itself. It is a unique Cepheid with a variable amplitude.

5. The 14 stars observed with XMM constitute 36% of the candidate companions. None were found to be young likely physical companions with a separation \( \geq 5″ \) or wider than a projected separation of 4000 au (assuming that S Nor #4 is a cluster member).

The full binary frequency will be discussed in Paper III including the entire HST WFC3 survey.

Support for this work was also provided from the Chandra X-ray Center NASA Contract NAS8-03060. Funding was provided from HST GO-13369.001-A (to NRE and IP). Vizier and SIMBAD were used in the preparation of this study.

Comments from an anonymous referee improved the clarity of the presentation.

REFERENCES

Aldoretto, E. J., Caballero-Nieves, S. M., Gies, D. R., et al. 2015, AJ, 149, 26
Anderson, R. I., Sahlmann, J., Holl, B., et al. 2015, ApJ, 804, 144
Böhm-Vitense, E., Evans, N. R., Carpenter, K., Beck-Winchatz, B., & Robinson, R. 1997, ApJ, 477, 916
Burki, G. 1984, in IAU Symp. 105, Observational Tests of the Stellar Evolution Theory, ed. A. Maeder & A. Renzini (Dordrecht: Reidel), 453
Damiani, F., Maggio, A., Micela, G., & Scioritino, S. 1997a, ApJ, 483, 350
Damiani, F., Maggio, A., Micela, G., & Scioritino, S. 1997b, ApJ, 483, 370
Dunstall, P. R., Dafton, P. L., Sana, H., et al. 2015, A&A, 580, 93
Engle, S. G., Guinan, E. F., DePasquale, J., & Evans, N. 2009, in AIP Conf. Proc. 1135, Future Directions in Ultraviolet Spectroscopy: A Conference Inspired by the Accomplishments of the Far-Ultraviolet Spectroscopic Explorer Mission (Melville, NY: AIP), 192
Engle, S. G., Guinan, E. F., Harper, G. H., Neilson, H. R., & Evans, N. R. 2014, ApJ, 794, 80
Evans, N. R., Bond, H. E., Schaefer, G. H., et al. 2013, AJ, 146, 93 (Paper I)
Evans, N. R., Bond, H. E., Schaefer, G. H., et al. 2016, AJ, submitted (Paper II)
Evans, N. R., Guinan, E., Engle, S., et al. 2010, AJ, 139, 1968
Evans, N. R., Massa, D., Fullerton, A., Sonneborn, G., & Ipinc, R. 2006, AJ, 647, 1387
Feigelson, E. D., Getman, K., Townsley, L., et al. 2005, ApJS, 160, 379
Kouwenhoven, M. B. N., Goodwin, S. F., Parker, R. J., et al. 2010, MNRAS, 404, 1835
Kraus, A. L., Ireland, M. J., Hillenbrand, L. A., et al. 2012, AJ, 745, 19
Mason, B. D., Gies, D. R., Hartkopf, W. I., et al. 1998, AJ, 115, 821
Moe, M., & Di Stefano, R. 2015, ApJ, 801, 113
Melnar, L., & Szabados, L. 2014, MNRAS, 442, 3222
Parker, R. J., & Meyer, M. R. 2014, MNRAS, 441, 3722
Perets, H. B., & Kratter, K. M. 2012, ApJ, 768, 99
Pillitteri, I., Evans, N. R., Wolk, S. J., & Syal, M. B. 2013, AJ, 145, 143
Pillitteri, I., Micela, G., Scioritino, S., & Favata, F. 2003, A&A, 399, 919
Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, ApJS, 190, 1
Randich, S., Schnitt, J. H. M. M., Prasser, C. F., & Stauffer, J. R. 1996, A&A, 305, 785
Reipurth, B., & Mikkola, S. 2012, Nat, 492, 221
Ruby, J., Engle, S. G., & Guinan, E. F. 2016, in AAS Meeting, 227, 144.21
Sana, H., de Koter, A., de Mink, S. E., et al. 2013, A&A, 550, A107
Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Sci., 337, 444
Sana, H., Le Bouquin, J.-B., Lacour, S., et al. 2014, ApJS, 215, 15
Stelzer, B., Flaccomio, E., Montmerle, T., et al. 2005, ApJS, 160, 557
Sugars, B. J. A., & Evans, N. R. 1996, AJ, 112, 1670
Tokovinin, A. 2014, AJ, 147, 87
Tokovinin, A., Thomas, S., Sterzik, M., & Udry, S. 2006, A&A, 450, 681