**HUBBLE SPACE TELESCOPE SNAPSHOT SURVEY FOR RESOLVED COMPANIONS OF GALACTIC CEPHEIDS***

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Received 2015 October 29; accepted 2016 February 29; published 2016 May 3

**ABSTRACT**

We have conducted an imaging survey with the Hubble Space Telescope Wide Field Camera 3 (WFC3) of 70 Galactic Cepheids, typically within 1 kpc, with the aim of finding resolved physical companions. The WFC3 field typically covers the 0.1 pc area where companions are expected. In this paper, we identify 39 Cepheids having candidate companions, based on their positions in color–magnitude diagrams, and having separations >5′′ from the Cepheids. We use follow-up observations of 14 of these candidates with XMM-Newton, and of one of them with ROSAT, to separate X-ray-active young stars (probable physical companions) from field stars (chance alignments). Our preliminary estimate, based on the optical and X-ray observations, is that only 3% of the Cepheids in the sample have wide companions. Our survey easily detects resolved main-sequence companions as faint as spectral type K. Thus the fact that the two most probable companions (those of FF Aql and RV Sco) are earlier than type K is not simply a function of the detection limit. We find no physical companions having separations larger than 4000 au in the X-ray survey. Two Cepheids are exceptions in that they do have young companions at significantly larger separations (δ Cep and S Nor), but both belong to a cluster or a loose association, so our working model is that they are not gravitationally bound binary members, but rather cluster/association members. All of these properties provide constraints on both star formation and subsequent dynamical evolution. The low frequency of true physical companions at separations >5′′ is confirmed by examination of the subset of the nearest Cepheids and also the density of the fields.

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

**1. INTRODUCTION**

Particular interest is being paid at present to the role of binaries, for instance in planet formation. Binary/multiple systems have important effects in stellar evolution, especially of massive stars, which have a high fraction of binaries (e.g., Sana et al. 2012). A substantial fraction of the massive stars in such systems exchange mass or merge during post-main-sequence evolution. Binary systems are also progenitors of X-ray sources in later stages when one component has evolved into a compact object.

An important topic currently under discussion is the question of the formation of wide binaries. Binaries are considered wide when they have separations of about 1000 to 10,000 au, corresponding to orbital periods of approximately 12,000 to 400,000 years. As discussed by Kouwenhoven et al. (2010), the typical size of a star-forming core is 103 au, which is also roughly the separation between protostars in young clusters. Forming multiple star systems wider than this does not follow naturally from a collapse process. Several scenarios have been proposed to get around this. Kouwenhoven et al. suggest that distant companions can be acquired as a star cluster disperses. Alternatively, Reipurth & Mikkola (2012) propose that distant components can result from triple systems that are formed as compact units, but then “unfold” because they are dynamically unstable, sending one component to a wider orbit (or ejecting it from the system). When discussing wide companions, it is of course possible that at least one star is itself actually a closer binary, i.e., that the system is a hierarchical triple. In this discussion, we use “binary” as shorthand for “binary or multiple.” A distant component, of course, may result from a mixture of these processes to augment the few wide systems formed in the collapse process.

The diversity of configurations in multiple systems provides insights into the evolution of the stellar population. Single stars can evolve without outside influence. Stars in binary systems may interact when the primary expands past the main sequence if their orbital separations are small enough. At wider separations, the components of binaries follow the same evolutionary paths as single stars. Triple or higher multiple systems may in addition have dynamical evolution within the system, which may result in an increased separation (typically for the smallest member) or even the ejection of a member. Thus, multiple systems provide a length (separation) measurement. In the case of triple systems, it may be altered by the internal dynamics. Finally, the widest systems are fragile and subject to destruction by external passing stars. For all these reasons, the assembly of binary characteristics, particularly as a function of the mass of the primary, provides a tool to investigate both formation conditions and subsequent interactions.

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* Based on observations with the NASA/ESA Hubble Space Telescope obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.
To probe these questions, we are making a series of studies of binary systems with a range of separation and mass ratio. Cepheid variables provide valuable information about the binary/multiple characteristics of fairly massive stars (typically \( \sim 6 \, M_\odot \)). One of our studies uses radial velocities from the sharp lines of Cepheids to derive the properties of spectroscopic-binary systems with periods between about 1 and 20 years (Evans et al. 2015). To provide data about the binary frequency among main-sequence B stars (destined to become Cepheids), we discussed the Chandra observation of the cluster Tr 16 (Evans et al. 2011).

In order to explore the widest orbital separations, we have also carried out a survey for resolved companions of Cepheids, using the Hubble Space Telescope (HST) and its Wide Field Camera 3 (WFC3). Initial results from this survey were included in Evans et al. (2013, hereafter “Paper I”), who discuss the subset of the sample with relatively high-mass companions derived using IUE observations. Paper I provides the distribution of separations for systems with mass ratios \( q = M_2/M_1 > 0.4 \), in a sample equally sensitive across the range of possible separations. The current paper (Paper II) is the second in this series.

The present paper gives full details of our WFC3 imaging survey of 70 Cepheids, which was introduced in Paper I. Because of the challenges of identifying and measuring faint close companions of much brighter Cepheids, we have divided the discussion according to the detection approach. In the current paper we discuss candidate companions located 5″ or more from the Cepheids. For these systems the light of the much brighter Cepheid does not materially affect photometry of the companions. A subsequent paper (Paper III) will report on companions closer than 5″, which are embedded in the wings of the image of the bright Cepheid; the photometry thus requires a more sophisticated point-spread function (PSF) subtraction. Since the separation in au depends both on the apparent separation and the distance, we defer discussion of the full sample to Paper III, in which we will combine both separation regimes. Several features of the current study are of note. Information about resolved companions has advanced greatly with instrumental developments such as adaptive optics (AO) and interferometry, particularly at small separations. The current study provides a uniform survey of orbital separations from several hundred au up to \( \sim 0.1 \) pc (including the systems discussed in Paper I and those to be discussed in Paper III). In this study, very low-mass stellar companions can be detected, but we limit our discussion to stars hotter than M0 for reasons of field contamination and X-ray followup. Important insight about the possible companions identified in this paper is provided by XMM-Newton (XMM) X-ray observations to identify low-mass stars young enough to be physical companions of the Cepheids (Evans et al. 2016, Paper IV).

This paper is organized as follows. First the sample of 70 Cepheids that were observed with WFC3 is described. Within this sample we then identify candidate companions with a separation greater than 5″ but still within the WFC3 40″ × 40″ aperture, and having a magnitude and color appropriate for a main-sequence star at the distance and reddening of the Cepheid (Table 4). For a subset of these candidates, we use XMM-Newton observations to select those that have the X-ray emission expected for main-sequence stars with the ages of Cepheids. Finally, we discuss the results in the context of the subset of the nearest Cepheids, and also field density.

2. HST SNAPSHOT SURVEY

2.1. Observations

We have carried out a snapshot imaging survey of nearby Galactic Cepheids, using the UVIS channel of the WFC3 camera on HST. Because of the high sensitivity of WFC3 and the fact that our targets are very bright, we elected to use intermediate-band filters instead of the broad-band ones used most often in HST imaging. The two filters we chose were F621M and F845M. Magnitudes in these filters can be transformed reasonably well into broad-band V and I, respectively.

The program was carried out in HST Cycle 18 (program ID SNAP-12215, PI N.R.E.), over the interval from 2010 September 20 to 2011 September 11. Our input list of snapshot targets contained 71 Cepheids. Remarkably, all 71 targets were observed (an unusually high yield for a snapshot program). However, due to a spacecraft data formatter error, the data from one of the observations (FM Aql) were lost. Three additional observations suffered failures to acquire one of the two guide stars, but the data are still useful. Our program therefore successfully covered 70 Galactic Cepheids.

For each WFC3 observation, we centered the Cepheid in a 1024 × 1024 pixel subarray. The WFC3 UVIS image scale is 0.0396 pixel\(^{-1}\), giving a field of view of 40″ × 40″. We obtained three dithered exposures in both of the filters. Exposure times—generally just a few seconds—were chosen such that the image of the Cepheid (at its average brightness) would be overexposed, leading to a few saturated pixels at the center of its image. This overexposure strategy results in companion stars being detectable to faint levels to within a few pixels of the primary star. The images are available from the Mikulski Archive for Space Telescopes, as are the exposure times in each filter and the dates of the observations.

The 70 Cepheids that were imaged in the survey are listed in Table 1. The input target list was compiled using the Galactic Cepheid database\(^8\) (Fernie et al. 1995). We chose primarily the nearest Cepheids, most of which are within 1 kpc. To these, we added three more luminous long-period Cepheids at larger distances (T Mon, RS Pup, and SV Vul). The pulsation period, intensity-weighted mean V magnitude, and \( E(B - V) \) listed in Table 1 were generally taken directly from the database. The exceptions were a few Cepheids with relatively bright companions, discussed in Paper I. For these stars, the values of \( V \) and \( E(B - V) \) have been corrected for the light of the companion. The data for Y Car have been taken from Evans (1992), likewise corrected to subtract the light of the companion.

To use the Leavitt (period–luminosity, or P–L) relation to derive a distance, we must first identify those Cepheids that are not pulsating in the fundamental mode. These “s-Cepheids” were identified historically based on their low-amplitude, nearly symmetric sinusoidal light curves (in contrast to the “sawtooth” light curves of fundamental pulsators). With the development of Fourier decomposition, it was realized that various combinations of amplitude and phase parameters for low-order modes could distinguish between fundamental and overtone pulsators. This interpretation was confirmed observationally with Magellanic Cloud microlensing programs such as

\(^7\) http://archive.stsci.edu

\(^8\) http://www.astro.utoronto.ca/DDO/research/cepheids/table_physical.html
| Star       | Period (days) | $(V)$ (mag) | $E(B-V)$ (mag) | Distance (pc) | Inner Limit$^a$ (au) | Outer Limit$^b$ $(\arcsec)$ |
|------------|--------------|-------------|----------------|---------------|----------------------|-------------------------|
| U Aql      | 7.02         | 6.47        | 0.35           | 613           | 184                  | 33                      |
| TT Aql     | 13.75        | 7.14        | 0.49           | 925           | 277                  | 22                      |
| FF Aql     | 4.47         | 5.37        | 0.22           | 365           | 109                  | 55                      |
| V496       | 6.81         | 7.75        | 0.41           | 989           | 297                  | 20                      |
| V1344 Aql  | 7.48         | 7.77        | 0.57           | 810           | 243                  | 25                      |
| η Aql      | 7.18         | 3.90        | 0.12           | 273           | 82                   | 73                      |
| RT Aur CO  | 3.73         | 5.45        | 0.05           | 454           | 136                  | 44                      |
| Aur$^c$    | 2.51         | 7.71        | 0.23           | 796           | 239                  | 25                      |
| RX Cam     | 7.91         | 7.65        | 0.63           | 715           | 215                  | 28                      |
| Y Car      | 3.63         | 8.08        | 0.08           | 1468          | 440                  | 14                      |
| ε Car      | 35.55        | 3.72        | 0.17           | 506           | 152                  | 40                      |
| SU         | 2.74         | 5.99        | 0.23           | 376           | 113                  | 53                      |
| Cas$^d$    | 2.14         | 7.73        | 0.11           | 900           | 270                  | 22                      |
| V636       | 8.38         | 7.20        | 0.70           | 535           | 160                  | 37                      |
| V Cas      | 5.49         | 6.84        | 0.29           | 709           | 213                  | 28                      |
| V553       | 2.06         | 8.46        | 0.22           | 1038          | 311                  | 19                      |
| V659       | 5.62         | 6.67        | 0.21           | 753           | 226                  | 27                      |
| V737       | 7.07         | 6.72        | 0.22           | 848           | 255                  | 24                      |
| IR Cep$^d$ | 2.98         | 7.83        | 0.43           | 650           | 195                  | 31                      |
| δ Cep      | 5.37         | 3.95        | 0.09           | 255           | 76                   | 78                      |
| AV         | 4.35         | 7.44        | 0.40           | 701           | 210                  | 29                      |
| Cru$^d$    | 5.27         | 6.10        | 0.25           | 527           | 158                  | 38                      |
| AX Cir     | 3.39         | 7.71        | 0.32           | 798           | 240                  | 25                      |
| BP Cir$^d$ | 5.83         | 6.77        | 0.19           | 829           | 249                  | 24                      |
| R Cru      | 4.69         | 6.60        | 0.16           | 724           | 217                  | 28                      |
| S Cru      | 6.73         | 6.57        | 0.19           | 811           | 243                  | 25                      |
| BG         | 4.76         | 5.49        | 0.05           | 521           | 156                  | 38                      |
| Cru$^d$    | 16.39        | 6.39        | 0.29           | 981           | 294                  | 20                      |
| X Cyg      | 3.85         | 6.90        | 0.08           | 857           | 257                  | 23                      |
| SU Cyg     | 3.53         | 5.77        | 0.04           | 521           | 156                  | 38                      |
| DT         | 4.74         | 5.98        | 0.07           | 630           | 189                  | 32                      |
| Cyg$^d$    | 7.94         | 3.73        | 0.04           | 335           | 100                  | 60                      |
| W Gem      | 7.91         | 6.95        | 0.28           | 905           | 272                  | 22                      |
| ζ Gem      | 10.15        | 3.92        | 0.02           | 383           | 115                  | 52                      |
| V473       | 2.62         | 6.18        | 0.03           | 553           | 166                  | 36                      |
| Lyra       | 27.02        | 6.14        | 0.14           | 1416          | 425                  | 14                      |
| R Mus      | 7.51         | 6.30        | 0.12           | 844           | 253                  | 24                      |
| S Mus      | 9.65         | 6.20        | 0.21           | 789           | 237                  | 25                      |
| S Nor      | 9.75         | 6.43        | 0.19           | 910           | 273                  | 22                      |
| Y Oph      | 17.13        | 6.17        | 0.65           | 510           | 153                  | 39                      |
| BF Oph     | 4.07         | 7.34        | 0.25           | 823           | 247                  | 24                      |
| AW Per     | 6.46         | 7.55        | 0.53           | 726           | 218                  | 28                      |
| V440       | 10.94        | 6.28        | 0.27           | 791           | 237                  | 25                      |
| Per$^d$    | 41.39        | 6.95        | 0.45           | 1543          | 463                  | 13                      |
| AP Pup     | 5.08         | 7.37        | 0.21           | 990           | 297                  | 20                      |
| MY         | 8.20         | 5.68        | 0.06           | 728           | 218                  | 27                      |

Notes:

$^a$ Minimum linear separation at which the companion could be detected, corresponding to 0$''$.3 angular separation.

$^b$ Angular separation corresponding to Galactic tidal limit of 0.1 pc linear separation.

$^c$ Adopted pulsation period is discussed in the text.

$^d$ First-overtone pulsator; period has been fundamentalized.

the MACHO project (Alcock et al. 1995), which showed two P-L sequences. While this framework is secure, there are still a few exceptions or puzzles. We have used photometric results (Antonello et al. 1990) to identify the following as overtone pulsators: SU Cas, IR Cep, BP Cir, AV Cir, DT Cyg, SZ Tau, LR TrA, and AH Vel. We have added BG Cru, MY Pup, and V950 Sco, based on results from radial-velocity curves (Kienzle et al. 1999). In addition, V1334 Cyg is classified by Evans (2000) as a first-overtone pulsator. The pulsation mode of V440 Per has been controversial, partly because it has a period of 7.57 days, long enough that some of the diagnostics become confused. Recent velocity data, however, indicate that it is an overtone pulsator (Baranowski et al. 2009), which we will adopt. FF Aql, on the other hand, has many Fourier characteristics of overtone pulsators. However, the HST Fine Guidance Sensor (FGS) parallax (Benedict et al. 2007) indicates that it pulsates in the fundamental mode, which we will use.
Two stars in the sample require further discussion. CO Aur is a double-mode Cepheid, which is excited in the first and second overtones (Antonello et al. 1986). We have fundamentalized the first-overtone period (1.78 days) using the relation from Alcock et al. (1995), as discussed above. V473 Lyr is unique as a Population I Cepheid with a large variation in pulsation amplitude over a period of approximately 1210 days (Burki & Mayor 1980). Its absolute magnitude and pulsation mode have been discussed a number of times. While they are still open to question, the consensus is that it is pulsating in the second overtone (e.g., Burki et al. 1986; Andrievsky et al. 1998), which is in keeping with its very short period. We have used the $P_2/P_1$ ratio from CO Aur (0.8007) to derive the first-overtone period from the observed period (1.49 days), and then fundamentalized that. As a point of interest, in addition to CO Aur, the stars Y Car, TU Cas, EW Set, and U TrA are also double-mode pulsators.

Distances for the targets, listed in Table 1, were computed in the same way as in Paper I, based on the Leavitt relation derived from the HST FGS parallaxes of Benedict et al. (2007). The periods in Table 1 for the overtone pulsators have been fundamentalized before computing the distance. As discussed in Evans (1991), for broad-band colors, a Cepheid is less reddened than a hot star by the same intervening material. We compensate for this by using $R = A_r/E[B-V] = 3.46$ to compute $V_0$ as needed. For these nearby Cepheids, the effect of using this value of $R$ rather than the more standard 3.1 is generally small.

In order to provide a sense of the scope of the survey, Column 6 in Table 1 gives an estimate of the smallest separation at which companions will be detected when the full reductions are complete, including the PSF correction to reveal companions within $5''$ of the Cepheid (Paper III). We have used an estimate of $0''.5$ as the radius limit outside of which companions can be detected. Column 7 provides the separation in arcseconds corresponding to 0.1 pc at the distance of the Cepheid. Systems with wider separations are thought to be disrupted by the Galactic tidal field, or through encounters with passing stars. Column 7 shows that a large part of this 0.1 pc zone is contained within the $40'' \times 40''$ WFC3 field of view for most targets.

### 2.2. Data Reduction and Analysis

As mentioned above, the analysis of the observations is divided into two parts. In this paper, possible companions more than $5''$ from the Cepheid are discussed. In such cases, standard aperture photometry can be used straightforwardly. Figure 1 is a typical image, showing that light from the Cepheid contributes a complicated background to the image inside about $5''$.

For the photometric analysis, we use the default drizzle-combined drz.fits images from the HST archive pipeline. These frames are created by combining the individual dithered exposures, and are fully processed to bias-subtracted, flat-fielded, and geometrically corrected images with cosmic rays removed. In the IRAF environment, the daofind routine was used to locate all detected stars in the frames, and measure their image coordinates. When daofind misses targets, a manual examination of the field using imexamine provides the remaining stellar coordinates. Once the coordinate list is compiled, the psfmeasure routine analyzes the stars at those coordinates and returns a list of FWHMs. An average FWHM is calculated from this list. The relevant photometric constant (magnitude scale zero point) was taken from the WFC3 manual10 for Vegamags. They are then entered into the photometry parameters file (photpars) and the average FWHM and background standard deviation are entered into the data parameters file (datapars). An aperture radius of 10 pixels ($0''.4$) was used. The IRAF photometry package (phot) is then run on the image to perform aperture photometry, using the star coordinates and parameter files as input to produce the stellar magnitudes and their errors.

Examples of the WFC3 images in the F845M filter are provided for R Cru (Figure 1), V Cen (Figure 3), and FF Aql (Figure 5).

### 3. FINDING RESOLVED PHYSICAL COMPANIONS

#### 3.1. Isochrones

The goal of our project is to identify candidate resolved physical companions of the Cepheids imaged in the survey. The selection criterion is that the candidate companion star must lie in the color–magnitude diagram (CMD) near an isochrone for the typical age of a Cepheid (50 Myr), corrected to the distance and reddening of each Cepheid.

Isochrones in the WFC3 filters that we used, and in the ground-based $V$ and Kron-Cousins $I$ bands, are available from two sources. We created a 50 Myr isochrone as follows. (1) For the unevolved lower main sequence (defined here as $V - I > 0.75$), we used the Dartmouth Stellar Evolution Database.11 This compilation gives isochrones in the WFC3 F621M and F845M filters, and in $V$ and $I$. We selected isochrones for solar metallicity ([Fe/H] = 0). Unfortunately, for the lowest available age in the Dartmouth isochrones, 1 Gyr, there is a large gap in coverage from $V - I \approx 0.9$ to 1.5. We therefore used data from the 5 Gyr isochrone, which is free of large gaps and agrees very well with the 1 Gyr isochrone in the color ranges where they do overlap. (2) For the stars with $V - I < 0.75$, which have begun to evolve off the zero-age main sequence in the available Dartmouth isochrones, we used a “Padova” 50 Myr isochrone12 for a heavy-element content of $Z = 0.0152$. We again obtained isochrones in WFC3 F621M and F845M, and in ground-based $V$ and $I$.

For the unevolved main sequence, we note that the Dartmouth and Padova isochrones agree reasonably well from $V - I \approx 0.75$ to about 1.25. But then they begin to diverge as we move further down the main sequence, with the Padova absolute magnitudes becoming progressively fainter than the Dartmouth values. At $V - I \approx 2$, the Padova $M_V$ values are fainter than Dartmouth by about 0.6 mag. By comparison with empirical absolute magnitudes for lower-main-sequence stars with accurate parallaxes (e.g., those assembled by E. Mamajek13), we find that the Dartmouth isochrones, in

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9 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

10 http://www.stsci.edu/hst/wfc3/phot_zp_lbn, the version “Prior to 2012 March 6.”

11 Dotter et al. (2008); data tables are at http://stellar.dartmouth.edu/models/index.html, retrieved 2014 June 9.

12 Bressan et al. (2012); data tables are at http://stev.oapd.inaf.it/cmd, retrieved 2014 June 11.

13 Pecaut & Mamajek (2013); data tables are at http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt.
$V, (V - I)$, give better agreement with real stars. We therefore adopted a combination of the Padova 50 Myr isochrone for $V - I < 0.75$ (and the corresponding isochrone for $F621M$ and $F845M$ magnitudes), and the Dartmouth 5 Gyr isochrone for the unevolved cooler main-sequence stars, as our standard Cepheid-age solar-composition isochrone.

In the discussion below, we will find it useful to transform the WFC3 $F621M$ magnitude and $F845M$ color index to ground-based $V$ and $V - I$. A least-squares polynomial fit to the Padova–Dartmouth tables gives the following relations, which have residuals no larger than ±0.02 mag:

$$V = F621M + 0.115637x^7 - 0.98113x^6$$
$$+ 3.09425x^5 - 4.26033x^4 + 2.03240x^3$$
$$+ 0.14579x^2 + 0.46920x + 0.041$$

and

$$V - I = -0.06353x^5 + 0.48892x^4 - 1.20278x^3$$
$$+ 0.86796x^2 + 1.36607x + 0.002,$$

where $x = F621M - F845M$.

In order to create an isochrone appropriate for each individual Cepheid, we need to correct it to the reddening and distance of the Cepheid, given in columns 4 and 5 of Table 1, respectively. To obtain the reddening law in the WFC3 $F621M$ and $F845M$ filters, we used the formulae of Cardelli et al. (1989), with effective wavelengths of 6210 and 8450 Å, respectively. This yields the relations $E(F621M - F845M) = 1.2 E(B - V)$ and $A_{F621M} = 2.9 E(B - V)$.

Examples of comparisons of the WFC3 photometry with the 50 Myr isochrone are given for the fields surrounding R Cru (Figure 2) and V Cen (Figure 4). In these figures we have highlighted the region in the isochrone where we expect to be able to detect X-ray emission from young, low-mass stars (i.e., those with spectral types of F2 V through K7 V, with unreddened $F621M - F845M$ colors ranging from 0.27 to 1.06). Young M dwarfs also produce X-rays, but the flux drops quickly with advancing spectral type, and at the distances of our Cepheids we do not expect X-ray emission to be detectable (Evans et al. 2016). We have therefore neglected candidate M dwarf companions, even though they would be easily detected in the WFC3 photometry.

### 3.2. Candidate Companions

Using the HST $F621M$ versus $F621M - F845M$ CMDs, we selected candidate physical companions in the following way. In addition to the ZAMS, a line was placed 0.75 mag above it, indicating the upper limit of binaries of identical mass (e.g., Figure 2). The region between these lines is the region where companions are expected, and a list was generated (Appendix) of stars within 2σ of this region. The identification criteria were guided by experience with the low-mass members of the S Mus cluster identified on an XMM image (Evans et al. 2014). Occasionally additional judgment was invoked. For instance, fainter stars with errors in the colors greater than 0.2 mag were dismissed as too uncertain for further consideration.

We examined the CMDs for all the Cepheids for possible companions, finding candidates for 39 out of the 70 targets. These 39 Cepheids, and their candidate companions, are listed in Table 4 in the Appendix. Table 4 contains all candidate companions lying within 2σ of the ZAMS in the CMDs, and hotter than spectral type M0. The first two columns list the $F621M$ and $F621M - F845M$ magnitudes and colors, and
their errors. For convenience, the next two columns provide the transformed $V$ and $V - I$. The following two columns give the angular separations and position angles. The final column provides the projected separations converted to au, using the distances from Table 1.

Table 4 lists possible companions $\geq 5''$ from the Cepheid, which is the sample discussed in the rest of this paper. Additional possible companions were identified by our search technique, lying less than 5$''$ from the Cepheid. These are listed in Table 5, but they will only be discussed in Paper III, together with an additional and more complete catalog of candidate companions identified in PSF-subtracted images.

Figures 2 and 4 show two examples of the F621M and F621M – F845M CMDs, for R Cru and V Cen, respectively. For these two Cepheids, there is one star within 2$\sigma$ of this part of the ZAMS, which are the potential companion candidates. These stars are circled on Figures 1 and 3. These figures are typical in two respects. The CMDs rule out all but a very few stars in the field as possible companions. That is, the companion range we were working with was something of a “sweet spot,” with relatively few interlopers. In addition, even at the low galactic latitudes of Cepheids, the field only becomes heavily populated fainter than the M0 limit.

4. X-RAY CONFIRMATION

Because faint red stars are common in the Galactic plane, it is important to confirm that our candidate companions are physical, rather than chance alignments with field stars. As discussed above, chance alignments would be much more common in a deeper survey, but it is still important to evaluate the relatively bright candidates in Table 4. Physical companions of Cepheids must be the same age as the Cepheids themselves, typically 50 Myr. Low-mass stars with a chromosphere have decreasing rotation rates as they age because of magnetic braking (e.g., Pallavicini et al. 1981). For this reason, stars young enough to be Cepheid companions are easily distinguished from old field stars by their X-ray fluxes. We are conducting a series of observations of the Cepheids in Table 4 using the XMM-Newton satellite, to be described in Paper IV (Evans et al. 2016). An example is provided by S Mus (Evans et al. 2014). So far 14 of our 39 Cepheids with possible resolved companions have been observed with XMM (ICar, V659 Cen, V737 Cen, R Cru, S Cru, X Cyg, V473 Lyr, R Mus, S Mus, S Nor, Y Oph, V440 Per, U Sgr, and Y Sgr), to a depth where essentially all the K stars (and hotter) at the distance of the Cepheid with an age of 50 Myr would be detected. There is also an upper limit on W Sgr from the ROSAT All Sky Survey (Section 5.3 below).

The X-ray results are summarized as follows:

1. Our wide candidate companions are overwhelmingly not young X-ray active stars, and hence are unlikely to be physical companions. Twenty-three candidate companions with separations $\geq 8''$ (with the exception of S Nor; see below), and three with smaller separations (V737 Cen, R Mus, and Y Sgr), were rejected because of the lack of an X-ray detection.

2. R Cru has an X-ray source in its field; however, at XMM resolution, the source could be assigned either to the Cepheid or the candidate companion star at 7$\prime$6 (6330 au). However, there is an even closer source in the WFC3 images, to be discussed in Paper III because its separation is only 1$''$9. In the following we assume that this closer source produces the X-rays.

3. S Mus similarly has an X-ray source, but again XMM observations cannot distinguish between the Cepheid and the possible companion at 5$''$0 (3950 au). We have subsequently obtained a Chandra observation of the S Mus field. Because of its higher spatial resolution, we can now conclude that the X-rays come not from the 5$''$0 companion, but from the Cepheid/spectroscopic binary. (Full discussion of the results is in preparation.) Thus at present we can say that there are no resolved physical companions of Cepheids at 4000 au or wider.

4. S Nor is our one Cepheid with an X-ray source unequivocally at the position of a resolved companion, with a projected separation of 14$''$6 (13,300 au). This is significantly wider than the companions of either R Cru or S Mus. However, S Nor is a member of a populous cluster. For this reason, and based on the discussion below in Section 6, we consider it likely that it is a chance alignment with a cluster member, rather than a gravitationally bound binary companion.

Thus our preliminary “working model” is that physical companions of Cepheids are found at separations within about 4000 au; however, in a cluster there may be wider alignments, but they are probably not bound system members.

4.1. The Most Probable Companions

One of the goals of this study is to examine the range of separations of physical companions to Cepheids. We use the X-ray results on the lack of wide physical companions to apply another filter to the list of possible companions (Table 4). Specifically, we examine in detail the Cepheids with candidates lying at separations $\geq 5''$ and $\leq 6330$ au. The 6330 au upper limit is based on R Cru, the widest of the possible X-ray companions, although we conclude in Paper IV that the X-rays are most probably produced by a closer companion (to be discussed in Paper III). Table 2 lists this subset of 11 candidate companions (of ten Cepheids). The first five columns are taken from Table 4. Column 6 in Table 2 summarizes the X-ray results.
We now examine further evidence whether the stars in Table 2 are physically related to the Cepheids. Four of the Cepheids have been observed in X-rays (V737 Cen, R Mus, W Sgr, and Y Sgr), and were not detected; these four are listed at the bottom of the table; see Section 5.3 for W Sgr). Thus, for the total sample of 70 Cepheids in our survey, ten of them have

**Table 2**

| V (mag) | V – I (mag) | Sep. (") | PA (°) | Sep. (au) | X-ray Detection | (V – I)_0 (mag) | No. of Companions^a |
|---------|-------------|----------|--------|----------|-----------------|----------------|---------------------|
| 19.22   | 2.05        | 5.2      | 77     | TT Aql   | 4810            | 1.49            | 5                   |
| 18.77   | 1.92        | 6.6      | 51     | FF Aql   | 6100            | 1.36            | 5                   |
| 11.22   | 0.85        | 6.9      | 146    | R Cru    | 2520            | ...             | 1                   |
| 16.281  | 1.17        | 7.64     | 302    | S Mus    | 6330            | 0.60            | 1                   |
| 17.94   | 1.56        | 5.0      | 182    | AP Sgr   | 3940            | ...             | 1                   |
| 17.85   | 1.72        | 6.3      | 86     | RV Sco   | 5320            | 1.32            | 1                   |
| 12.68   | 0.63        | 6.0      | 323    | V737 Cen | 4520            | 1.50            | 2                   |
| 17.22   | 1.61        | 7.3      | 295    | R Mus    | 6190            | No              | 1.36                | 2                   |
| 15.68   | 1.17        | 6.9      | 328    | W Sgr    | 5820            | No              | 1.03                | 1                   |
| 16.10   | 1.75        | 6.3      | 341    | Y Sgr    | 2580            | No              | 1.62                | 2                   |
| 17.06   | 1.85        | 10.6     | 204    |          | 5350            | No              | 1.62                | 1                   |

Note. ^a: Source of X-rays unidentified. See the text.

^a Total number of candidate companions of Cepheid listed in Table 4.
potential resolved companions ($>5\arcsec$) within 7000 au. However, when the X-ray results are folded in, four are eliminated. Of the six stars observed by XMM or ROSAT (including R Cru and S Mus), four were not detected, and hence are probably field stars. The remaining two sources that were detected (R Cru and S Mus) are so close to the Cepheid that both the Cepheid and the companion are within the XMM PSF. However, in both cases, additional evidence indicated that the resolved companion candidate is not the X-ray source. R Cru has a closer companion which we consider a more probable X-ray candidate (see Paper III). The Chandra observation of S Mus also shows that the X-rays are produced by the Cepheid/spectroscopic binary.

We can use Table 2 to make an estimate of the companion frequency ($>5\arcsec$) within 7000 au. From since none of the 6 possible companions $>5\arcsec$ which have observed in X-rays have been detected, the remaining four Cepheids (TT Aql, FF Aql, AP Sgr, and RV Sco) might have the same detection rate. However, the companions of FF Aql (Section 5.2) and RV Sco (below) are both likely to be physical companions since they appear to show a proper motion. Furthermore, anticipating the discussion for field density (Section 6), the fact that TT Aql has 2 possible companions as well as 5 possible companions in the whole field makes it unlikely that the 2 stars listed in Table 2 are bound binary companions. This leaves only 1 star (AP Sgr) in Table 2 as a possibility, but with the low X-ray detection rate, it is also unlikely. Thus, the binary rate in this separation range is 2 (RV Sco and FF Aql) out of 70 or 3%.

RV Sco has additional information from proper motions. The Washington Double Star Catalog (WDS)\(^\text{14}\) has measures for the pair in 1925 and 1987, showing no relative motion between the two stars. The total motion of the Cepheid is about half an arcsecond in that period, indicating that the two are moving together, and thus likely bound.

Column 9 in Table 2 lists the intrinsic $(V - I)_{0}$ color, using the $E(B - V)$ from Table 1 and $E(V - I)/E(B - V) = 1.15$ (assuming, of course, that the stars have the same reddening as the Cepheids). All the possible companions have the colors of K stars, except for FF Aql and RV Sco, where the possible companions have hotter colors. (These colors are hot enough that the companions would not be expected produce X-rays.) K stars are certainly reasonable companions for Cepheids. On the other hand, they are also the most plentiful field stars in the range under consideration, and hence the most likely to be chance alignments. The fact that the two most probable companions (FF Aql and RV Sco) in Table 2 are more massive than K stars suggests the companion distribution is top heavy as compared to the Initial Mass Function (IMF). This is clearly not due to the detection limit, since K dwarfs are easily detected in the WFC3 survey.

Anticipating the discussion of field density (Section 6), we list in Column 8 the number of possible companions (Table 4) with separations $>5\arcsec$ for each Cepheid. As fully discussed below (Section 6), a large number of possible companions increases the probability that the possible companions are not gravitationally bound. On these grounds, the companions of TT Aql and RV Sco are suspect. We note that the discussion of proper motions above implies that the RV Sco companion is indeed related to the Cepheid.

The following summarizes the discussion above of the frequency of resolved companions as well as the outer extent:

1. Both of the estimates of the companion frequency for separations $>5\arcsec$ are 3% or less.
2. We have identified no probable companions wider than RV Sco (4520 au). Thus 4000 au is a reasonable estimate for the extent of companions from our summary.

5. THE NEARER CEPHEIDS

In this section and the next one, we discuss tests to confirm the relative scarcity of physical companions with a projected separation from the Cepheid of $>5\arcsec$.

In order to confirm the X-ray results that stars in the outer parts of the field are chance alignments, we created Table 3, containing the subset of Cepheids nearer than 600 pc. These are the Cepheids that are least likely to be contaminated by field stars at the brightnesses expected for physical companions. Column 2 indicates whether there is a possible companion on the WFC3 images with a “Yes”; column 3 indicates whether the possible companion has not been detected in an X-ray observation with a “No.” Since the nearest Cepheids have the most complete information, we are able to discuss three of them in more detail, as follows.

5.1. δ Cep

δ Cep poses a special challenge in determining its relation to the star HD 213307, a late B star 40′′ away. Parallaxes were determined for both stars using the HST FGS by Benedict et al. (2002). They found both stars to be at the same distance within the errors, and also found that HD 213307 is itself a binary from the astrometry. Proper motions and radial velocities of δ Cep and HD 213307 are similar but not identical. Both stars are listed as members of the newly discovered Cep OB6 association (de Zeeuw et al. 1999). HD 213307 is not within

| Star       | Companion | HST/WFC3 > 5″ | Companion | XMM/ROSAT |
|------------|-----------|---------------|-----------|-----------|
| FF Aql     | Yes       | ...           | ...       | ...       |
| η Aql      | ...       | ...           | ...       | ...       |
| RT Aur     | ...       | ...           | ...       | ...       |
| ζ Car      | Yes       | No            | ...       | ...       |
| SU Cas     | ...       | ...           | ...       | ...       |
| V636 Cas   | Yes       | ...           | ...       | ...       |
| δ Cep      | see text  | ...           | ...       | ...       |
| AX Cir     | ...       | ...           | ...       | ...       |
| BG Cru     | ...       | ...           | ...       | ...       |
| DT Cyg     | ...       | ...           | ...       | ...       |
| β Dor      | ...       | ...           | ...       | ...       |
| ζ Gem      | ...       | ...           | ...       | ...       |
| V473 Lyr   | Yes       | No            | ...       | ...       |
| Y Oph      | Yes       | No            | ...       | ...       |
| W Sgr      | Yes       | No            | ...       | ...       |
| X Sgr      | ...       | ...           | ...       | ...       |
| Y Sgr      | Yes       | No            | ...       | ...       |
| EW Sct     | ...       | ...           | ...       | ...       |
| SZ Tau     | ...       | ...           | ...       | ...       |
| T Vul      | ...       | ...           | ...       | ...       |
| U Vul      | ...       | ...           | ...       | ...       |

\(^{14}\) http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/WDS
our WFC3 image, but that is because δ Cep is so nearby. At its distance, the projected separation is 10,200 au. This is larger than the separations (Table 2) for the most probable companions, set largely by the X-ray results. It is also the outlier in the separation distribution for Cepheids with reasonably massive companions (Figure 5 in Evans et al. 2013). Is HD 213307 gravitationally bound to δ Cep? If so, the separation is unusually wide. On the other hand, because they belong to an association, the possibility of a chance alignment with a star at the same distance is enhanced.

5.2. FF Aql

FF Aql has been a candidate for a wide binary for many years. It has a comparatively bright possible companion 7″ from the Cepheid (Figure 5). This small separation, however, has made it difficult to determine the colors of the companion from the ground, because of scattered light from the Cepheid. Udalski & Evans (1993) concluded that the two stars are not related based on photometry. The HST results (Table 2 and Figure 6) place the companion within the expected main-sequence band. Thus, based on the CMD and separation, the companion to FF Aql is probably a physical companion. The V − I color in Table 2 (dereddened) corresponds to a main-sequence star between F5 and G0 (Drilling & Landolt 2000). This would make the Cepheid a member of a triple system, since it is also a member of a spectroscopic binary. As with RV Sco, measurements of the positions of the two stars since 1886 (WDS) indicate no relative motion, indicating that they are a physical pair.

5.3. W Sgr

W Sgr is already known to be a member of a complicated multiple system. It is a spectroscopic binary (Petterson et al. 2004, and references therein) with a very low-amplitude orbit, but a fairly massive companion (Evans 1995). Recently Evans et al. (2009) used an HST observation to demonstrate that the hottest star in the system is actually a resolved companion (projected separation 0″16), not the secondary in the spectroscopic binary. Thus, the star with a separation of 6″3 (2580 au) in Table 2 would be the fourth star in the system if it is a physical companion.

Because W Sgr is a nearby system, the results of the ROSAT All Sky Survey15 provide useful information. No source was visible at the position of the system. From the background and exposure map, an upper limit to the count rate of 0.0012 cts s−1 was derived. (The PSF of ROSAT is ~45″.) The ROSAT PSPC (energy 0.1 to 2.4 keV) was converted to a flux in 0.5 to 8.0 keV, using PIMMS with kT = 0.48 keV and N_H = 1021 cm derived from the E(B − V). The flux upper limit derived from the count rate is 1.61 × 10−14 erg cm−2 s−1. At a distance of 409 pc, this becomes an upper limit of L_X = 3.2 × 1029 erg s−1 (log L_X = 29.51). This is slightly above the limit for X-ray flux, log L_X = 29.2, used in Paper IV (Evans et al. 2016) as the lower limit for low-mass stars young enough to be Cepheid companions. However, it is low enough that we consider it improbable that it is actually a physical companion, and treat it as such here.

5.4. Polaris

We add one additional star to the discussion of nearby Cepheids, even though it was not included in the WFC3 survey: Polaris. Like δ Cep, it has a resolved companion 18″ from the Cepheid. The companion Polaris B has a proper motion consistent with orbital motion in a wide orbit. The spectral type of the companion (summarized by Evans et al. 2010) is F3 V. A Chandra observation found that it is not an X-ray source (Evans et al. 2010), which is not surprising for an early F star. Using the distance from Hipparcos (130 pc; Feast & Catchpole 1997; van Leeuwen et al. 2007), the companion has a projected separation from the Cepheid of 2340 au, well within the range of the most probable companions (Table 2).

To complete the list of system components, Polaris is a member of a 30 year astrometric binary, whose secondary has been detected by HST (Evans et al. 2008).

5.5. The Nearer Cepheids: Summary

The sample of the nearest Cepheids in Table 3 has 21 stars, of which seven have possible companions in the WFC3 images. An additional nearby Cepheid, δ Cep, has a companion which is not on a WFC3 image because of its wide angular separation. Of the eight stars with possible companions, five have been observed with XMM or ROSAT, and the companions were not detected; hence they are classed as chance optical alignments with field stars. The three remaining possibilities in Table 3 are δ Cep, FF Aql, and V636 Cas. If we further apply the criterion from the XMM observations in the previous section that only stars closer than 6330 au are probable physical companions, V636 Cas and δ Cep are disqualified. This leaves one star out of 21 in Table 3 with a probable resolved companion (5%). This is, of course, a very small sample, but since this subsection of the sample is the least likely to be contaminated by field stars, it confirms the small companion fraction from the combined WFC3 and XMM observations. (Including Polaris, the companion fraction rises to 2 out of 22 [9%].)

We note also that the companion of Polaris is significantly more massive than a K star, like those of FF Aql and RV Sco. On the other hand, the four stars rejected by X-ray observations

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15 http://www.xray.mpe.mpg.de/cgi-bin/rosat/rosat-survey
Table 2 are all K stars, leaving two Cepheids with possible K companions (TT Aql and AP Sgr). This suggests a preference for more massive companions than the distribution of the IMF.

In our working model (Section 4), we add δ Cep to S Nor #4 as Cepheids which are members of known clusters or associations, and hence likely to have a chance alignment with a related but not gravitationally bound star.

6. FIELD STELLAR DENSITY

The second test we have made is to check whether the occurrence of a possible companion depends on the surface density of stars in the field. We generated a frequency distribution for the number of fields with 1, 2, 3, … companions from Table 4 (i.e., the companions >5′′ from the Cepheid), and similarly for Table 5 (companions <5′′ from the Cepheid). Figure 7 shows the comparison. Only a very small fraction of the fields with one or two companions have possible companions <5′′. In contrast, approximately half the more dense fields (three or more possible companions) have possible companions closer than 5′′. This is consistent with the possibility that denser fields are linked with increased chance alignment. This supports the working model that some Cepheids may have been formed in a loose grouping as well as gravitationally bound systems. Figure 7 confirms that, in the overwhelming majority of fields with 0, 1, or 2 possible companions (59 fields), the occurrence of a possible companion ≥5′′ is very rare (2%).

7. DISCUSSION

We have made a further check on the working model, specifically that in addition to gravitationally bound system members, star formation may have produced some surrounding groups with a range of densities from very low to well-populated well-known clusters. Two recent studies have identified Cepheids related to clusters based on criteria including proper motions (Anderson et al. 2013; Chen et al. 2015). Of the Cepheids that they conclude are definitely associated with clusters or associations, seven are in our survey (U Sgr, SU Cyg, S Nor, BB Sgr, V Cen, S Mus, and X Cyg—although X Cyg is only considered a definite member by Chen et al.). For these stars we examine the evidence of the existence
| $F621M$ (mag) | $F621M - F845M$ (mag) | $V$ (mag) | $V - I$ (mag) | Sep. ($^\circ$) | Position Angle ($^\circ$) | Sep. (au) |
|----------------|------------------------|-----------|---------------|----------------|--------------------------|---------|
| 17.83 ± 0.05  | 1.66 ± 0.05            | 18.49     | 2.07          | 14.1           | 129                      | 13,000  |
| 18.13 ± 0.05  | 1.69 ± 0.05            | 18.79     | 2.09          | 9.6            | 155                      | 8880   |
| 17.74 ± 0.04  | 1.27 ± 0.04            | 18.41     | 1.73          | 12.5           | 267                      | 11,600  |
| 18.56 ± 0.09  | 1.63 ± 0.09            | 19.22     | 2.05          | 5.2            | 77                       | 4810   |
| 18.11 ± 0.06  | 1.48 ± 0.06            | 18.77     | 1.92          | 6.6            | 51                       | 6100   |
| 10.81 ± 0.00  | 0.55 ± 0.00            | 11.22     | 0.85          | 6.9            | 146                      | 2520   |
| 16.57 ± 0.02  | 1.18 ± 0.02            | 17.25     | 1.64          | 6.7            | 85                       | 6620   |
| 14.81 ± 0.01  | 0.84 ± 0.01            | 15.41     | 1.26          | 20.9           | 260                      | 20,600 |
| 18.02 ± 0.05  | 1.28 ± 0.05            | 18.70     | 1.74          | 11.6           | 6                        | 17,000 |
| 14.67 ± 0.01  | 0.71 ± 0.01            | 15.21     | 1.09          | 19.1           | 10                       | 9660   |
| 16.08 ± 0.02  | 1.29 ± 0.02            | 16.76     | 1.75          | 19.9           | 153                      | 10,600 |
| 14.97 ± 0.01  | 0.87 ± 0.01            | 15.59     | 1.30          | 13.4           | 102                      | 9500   |
| 15.29 ± 0.01  | 0.79 ± 0.01            | 15.87     | 1.20          | 22.1           | 335                      | 16,600 |
| 17.42 ± 0.04  | 1.12 ± 0.04            | 18.09     | 1.59          | 14.7           | 341                      | 11,100 |
| 15.97 ± 0.02  | 0.84 ± 0.02            | 16.57     | 1.27          | 20.2           | 238                      | 15,200 |
| 15.16 ± 0.01  | 0.77 ± 0.01            | 15.73     | 1.17          | 23.8           | 81                       | 17,900 |
| 16.93 ± 0.03  | 1.01 ± 0.03            | 17.59     | 1.47          | 17.0           | 59                       | 12,800 |
| 16.55 ± 0.03  | 1.14 ± 0.03            | 17.22     | 1.61          | 7.3            | 295                      | 6190   |
| 17.00 ± 0.03  | 1.14 ± 0.03            | 17.67     | 1.61          | 17.1           | 231                      | 14,500 |
| 16.95 ± 0.03  | 1.36 ± 0.04            | 17.62     | 1.81          | 18.1           | 42                       | 11,800 |
| 13.18 ± 0.01  | 0.71 ± 0.01            | 13.72     | 1.10          | 17.4           | 133                      | 12,200 |
| 16.48 ± 0.02  | 0.98 ± 0.02            | 17.13     | 1.43          | 14.1           | 296                      | 11,200 |
| 16.92 ± 0.03  | 1.23 ± 0.03            | 17.60     | 1.70          | 21.2           | 271                      | 16,900 |
| 17.77 ± 0.04  | 1.39 ± 0.04            | 18.44     | 1.84          | 11.6           | 168                      | 9260   |
| 15.71 ± 0.02  | 0.77 ± 0.03            | 16.281    | 1.17          | 7.64           | 302                      | 6330   |
| 15.91 ± 0.02  | 1.11 ± 0.02            | 16.59     | 1.58          | 13.8           | 70                       | 9990   |
| 17.23 ± 0.04  | 1.09 ± 0.04            | 17.90     | 1.55          | 11.9           | 20                       | 8620   |
| 17.39 ± 0.04  | 1.21 ± 0.04            | 18.07     | 1.67          | 9.1            | 134                      | 7380   |
| 17.94 ± 0.06  | 1.21 ± 0.06            | 18.61     | 1.68          | 12.9           | 96                       | 12,700 |
| 15.70 ± 0.02  | 0.91 ± 0.02            | 16.33     | 1.36          | 14.8           | 298                      | 14,500 |
| 16.30 ± 0.02  | 0.81 ± 0.02            | 16.90     | 1.23          | 25.2           | 87                       | 21,600 |
| 16.24 ± 0.02  | 0.82 ± 0.02            | 16.84     | 1.24          | 14.4           | 58                       | 13,000 |
| 14.30 ± 0.01  | 0.81 ± 0.01            | 14.89     | 1.23          | 15.0           | 44                       | 8300   |
| 17.14 ± 0.05  | 0.80 ± 0.05            | 17.73     | 1.21          | 6.5            | 276                      | 9200   |
| 16.14 ± 0.02  | 0.58 ± 0.02            | 16.59     | 0.91          | 18.5           | 166                      | 26,200 |
| 15.11 ± 0.01  | 0.77 ± 0.01            | 15.68     | 1.17          | 6.9            | 328                      | 5820   |
| 17.27 ± 0.05  | 1.09 ± 0.05            | 17.94     | 1.56          | 5.0            | 182                      | 3940   |
| 13.51 ± 0.01  | 0.58 ± 0.01            | 13.95     | 0.90          | 14.6           | 289                      | 13,300 |
| 15.89 ± 0.02  | 0.76 ± 0.02            | 16.45     | 1.15          | 19.8           | 172                      | 18,000 |
| 15.73 ± 0.02  | 0.79 ± 0.02            | 16.32     | 1.20          | 20.1           | 188                      | 18,300 |

Table 4
Candidate Companions of Galactic Cepheids
| $F621M$ (mag) | $F621M - F845M$ (mag) | $V$ (mag) | $V - I$ (mag) | Sep. (") | Position Angle (°) | Sep. (au) |
|----------------|------------------------|----------|-------------|----------|-------------------|----------|
| 17.41 ± 0.04  | 0.98 ± 0.04            | 18.06    | 1.44       | 8.5      | 44                | 7740     |
| 16.70 ± 0.03  | 1.08 ± 0.03            | 17.37    | 1.54       | 13.5     | 7                 | 12,300   |
| 17.33 ± 0.04  | 1.06 ± 0.04            | 18.00    | 1.52       | 15.0     | 1                 | 13,600   |
| 16.47 ± 0.03  | 1.57 ± 0.03            | 17.13    | 2.00       | 18.1     | 212               | 9230     |
| 17.04 ± 0.03  | 1.12 ± 0.03            | 17.71    | 1.58       | 18.8     | 244               | 15,500   |
| 15.13 ± 0.01  | 0.80 ± 0.01            | 15.72    | 1.21       | 10.9     | 305               | 8620     |
| 13.33 ± 0.00  | 0.65 ± 0.00            | 13.83    | 1.01       | 10.6     | 131               | 8380     |
| 18.13 ± 0.06  | 1.16 ± 0.06            | 18.81    | 1.63       | 10.8     | 317               | 16,700   |
| 16.21 ± 0.02  | 0.85 ± 0.02            | 16.82    | 1.28       | 21.8     | 54                | 33,600   |
| 15.64 ± 0.02  | 1.06 ± 0.02            | 16.31    | 1.52       | 19.4     | 18                | 12,000   |
| 16.76 ± 0.03  | 1.52 ± 0.03            | 17.42    | 1.95       | 13.9     | 127               | 8580     |
| 17.00 ± 0.03  | 1.51 ± 0.03            | 17.66    | 1.94       | 17.1     | 164               | 10,500   |
| 15.43 ± 0.03  | 1.28 ± 0.03            | 16.10    | 1.75       | 6.3      | 341               | 2580     |
| 15.76 ± 0.03  | 1.31 ± 0.03            | 16.44    | 1.77       | 19.0     | 46                | 7,770    |
| 16.39 ± 0.03  | 1.40 ± 0.03            | 17.06    | 1.85       | 10.6     | 204               | 5350     |
| 17.47 ± 0.04  | 1.16 ± 0.04            | 18.15    | 1.63       | 23.5     | 258               | 19,900   |
| 17.18 ± 0.04  | 1.25 ± 0.04            | 17.85    | 1.72       | 6.3      | 86                | 5320     |
| 15.42 ± 0.01  | 1.11 ± 0.02            | 16.09    | 1.58       | 10.6     | 156.               | 9500     |
| 16.26 ± 0.02  | 1.03 ± 0.02            | 16.92    | 1.49       | 18.0     | 330               | 16,100   |
| 18.06 ± 0.05  | 1.37 ± 0.05            | 18.73    | 1.83       | 11.4     | 270               | 10,200   |
| 15.41 ± 0.01  | 0.81 ± 0.01            | 16.00    | 1.22       | 10.6     | 66                | 9500     |
| 12.37 ± 0.00  | 0.41 ± 0.00            | 12.68    | 0.63       | 6.0      | 323               | 4520     |
| 17.52 ± 0.04  | 1.24 ± 0.04            | 18.19    | 1.71       | 14.8     | 79                | 11,100   |
| 17.12 ± 0.03  | 1.09 ± 0.03            | 17.79    | 1.56       | 10.6     | 187               | 7,980    |
| 16.66 ± 0.03  | 1.33 ± 0.03            | 17.33    | 1.79       | 23.0     | 192               | 17,300   |
| 15.91 ± 0.02  | 0.79 ± 0.02            | 16.49    | 1.20       | 14.4     | 268               | 12,000   |
| 15.26 ± 0.01  | 0.76 ± 0.01            | 15.83    | 1.17       | 18.0     | 215               | 15,000   |
| 17.64 ± 0.04  | 1.34 ± 0.04            | 18.31    | 1.80       | 19.9     | 180               | 16,800   |
| 17.32 ± 0.04  | 1.24 ± 0.04            | 17.99    | 1.71       | 11.9     | 331               | 10,100   |
| 15.20 ± 0.01  | 0.72 ± 0.01            | 15.74    | 1.11       | 15.9     | 316               | 13,500   |
| 16.94 ± 0.03  | 1.01 ± 0.03            | 17.60    | 1.47       | 14.3     | 312               | 12,100   |
| 16.22 ± 0.02  | 0.86 ± 0.02            | 16.84    | 1.29       | 19.6     | 280               | 16,600   |
| 17.21 ± 0.03  | 1.07 ± 0.03            | 17.88    | 1.53       | 24.6     | 116               | 20,800   |
| 15.42 ± 0.01  | 0.70 ± 0.01            | 15.95    | 1.07       | 17.6     | 0                 | 14,800   |
| 15.44 ± 0.01  | 0.91 ± 0.01            | 16.08    | 1.35       | 15.0     | 48                | 12,600   |
| 17.16 ± 0.03  | 0.79 ± 0.03            | 17.74    | 1.20       | 20.5     | 360               | 22,300   |
| 16.70 ± 0.03  | 0.85 ± 0.03            | 17.31    | 1.28       | 13.4     | 256               | 14,600   |
| 13.77 ± 0.01  | 0.40 ± 0.01            | 14.08    | 0.63       | 16.8     | 65                | 17,100   |
| 17.84 ± 0.04  | 0.99 ± 0.04            | 18.49    | 1.44       | 16.5     | 56                | 16,800   |
| 18.37 ± 0.06  | 1.35 ± 0.06            | 19.04    | 1.80       | 15.1     | 241               | 22,700   |
| 18.17 ± 0.05  | 1.12 ± 0.05            | 18.84    | 1.59       | 16.9     | 131               | 25,400   |
| 18.55 ± 0.07  | 1.20 ± 0.07            | 19.23    | 1.67       | 20.9     | 68                | 31,400   |
| 14.50 ± 0.01  | 0.81 ± 0.01            | 15.09    | 1.22       | 15.1     | 86                | 22,700   |
of nearby stars at the same distance using Tables 4 and 5. None of these Cepheids are in the 30 fields (43%) which have no possible companions. Three (U Sgr, S Nor, and X Cyg) have more than one possible companion. Of the 4 which have been observed in X-rays (U Sgr, S Nor, X Cyg, and S Mus), one X-ray source at a wide companion (S Nor). Thus, even for this group there is at only one possible related star outside the separation range (4000 au) where we find gravitationally bound binaries. We draw attention to possible wide associations, particularly as low density groupings may be of particular interest when Gaia results are available.

This paper focuses on the extent of gravitationally bound systems for \( \sim 6 M_\odot \) Cepheids. The fraction with companions wider than \( 10^3 \) au is very small confirming that the frequency distribution for binary systems peaks at much smaller separations. Although full analysis of the frequency distribution as a function of separation/year awaits the discussion of closer companions (Paper III), we can compare results on the extent of companions with studies in other mass ranges. For O stars, the recent high-resolution study of Sana et al. (2014; SMASH) found a decrease in the number of comparatively bright companions at separations of approximately 2000 au, as discussed by Evans et al. (2016, Paper IV). For solar-mass stars, Raghavan et al. (2010) and Tokovinin (2014) both find a decrease in the frequency of companions at periods \( > 10^5 \) years \( (\approx 3000 \) au), also in approximate agreement with the results of the present survey.

8. SUMMARY

We report here the results of an HST WFC3 snapshot imaging survey of 70 classical Cepheids. This paper (Paper II in the series) discusses possible companions with separations \( \geq 5'' \) from the Cepheid.

1. We identify possible companions by comparison of the \( F621M \) versus \( F621M - F845M \) CMD with evolutionary tracks at the distance and with the reddening of the Cepheids with a width allowing for a binary sequence. The list of 39 possible Cepheids with companions (Table 4) should fully cover the spatial extent of possible companions and identify them through main-sequence stars of K spectral types.

2. Fourteen of the possible companions have been observed with XMM (details in Paper IV) to distinguish active stars as young as Cepheids from old field stars. From these observations, we find no young stars at a larger separation from the Cepheid than that of S Mus (5''0 or 3950 au). However, the XMM observation does not resolve the companion and the Cepheid. A Chandra observation shows that the X-rays are not produced by the star at 5''0 separation, but from the Cepheid/spectroscopic binary.

3. Based on the X-ray results (Paper IV) of a subset of 14 Cepheids with possible companions we estimate a frequency of companions \( \geq 5'' \) to be 3% or less.

4. Companions more massive than K stars predominate among the most probable companions, which cannot be due to the WFC3 detection limit.

5. We have confirmed the outer extent of gravitationally bound systems from the subset of Cepheids closer than 600 pc, which are the least susceptible to chance
alignments with field stars, and find a comparable frequency of probable companions.
6. Similarly using the list of companions closer than 5" of the Cepheids (Table 5, the most likely to be bound system members), we compare the number of close possible companions with the field density as indicated by the number of possible companions in Table 4. Fields with three or more possible companions are more likely to have close companions, which we attribute to increased probability of chance alignment in the denser fields (loose groupings).

7. The working model is that the possible companions stars in Table 4 may include both bound system members, and also stars formed at the same time in the same neighborhood. This may be the case of HD 213307 (δ Cep companion) and S Nor #4, since both the Cepheids are members of clusters or associations, which may account for their unusually wide separations.

Thus, in this paper we focus on the outer extent of Cepheid multiple systems. As noted in the introduction, systems this wide could easily support an inner binary, hence be part of a triple system. In the next paper (Paper III) we will discuss companions less than 5" from the Cepheid and then the characteristics of the combined population of resolved binary companions.

Financial support from STScI grants GO-12215.01-A and GO-13368.01-A and also Chandra X-ray Center NASA Contract NAS8-03060 is gratefully acknowledged. Vizier and SIMBAD were used in the preparation of this study. This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory.

APPENDIX

The candidate companions of the Cepheids in the survey (Section 3.2) are listed here. The columns in the table are the Vega-scale F621M magnitudes and F621M − F845M colors, followed by these values transformed to ground-based V and V − I. The final three columns are the separation from the Cepheid in arcseconds, the position angle in degrees, and the separation in au using the distance in Table 1. Table 4 lists companions which are >5" from the Cepheid; Table 5 contains possible companions <5" from the Cepheid. Table 5 will be discussed primarily in Paper III, but is included here because the search techniques are the same as those in Table 4.

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