The Astrophysical Journal, 438:719–723, 1995 January 10

THE FAINT X-RAY SOURCES IN AND OUT OF ω CENTAURI: X-RAY OBSERVATIONS AND OPTICAL IDENTIFICATIONS

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Received 1993 September 22; accepted 1994 July 13

ABSTRACT

We present the results of an observation of the globular cluster ω Cen (NGC 5139) with the *Einstein* high-resolution imager (HRI). Of the five low-luminosity X-ray sources toward ω Cen which were first identified with the *Einstein* imaging proportional counter (IPC) (Hertz & Grindlay 1983a, b), two are detected in the *Einstein* HRI observation: IPC sources A and D. These detections provide source positions accurate to 3″–4″; the positions are confirmed in a *ROSAT* HRI observation reported here. Using CCD photometry and spectroscopy, we have identified both sources as foreground dwarf M stars with emission lines (dMe). The chance projection of two dMe stars within $\sim 13'$ of the center of ω Cen is not extraordinary, given the space density of these stellar coronal X-ray sources. We discuss the possible nature of the three as yet unidentified IPC sources toward ω Cen, and consider the constraints that the *Einstein* observations place on the total population of X-ray sources in this cluster. The integrated luminosity from faint X-ray sources in ω Cen appears to be low relative to both the old open cluster M67 and the post–core-collapse globular, NGC 6397.

Subject headings: globular clusters: individual (ω Centauri) — stars: late-type — X-rays: stars

1. INTRODUCTION

The globular cluster ω Cen is one of two clusters in which multiple low-luminosity X-ray sources were discovered in a survey of globular clusters with the *Einstein Observatory* imaging proportional counter (IPC) (Hertz & Grindlay 1983b, hereafter HG). Five such sources were discovered in this cluster alone. These sources, together with nine found in six other clusters, form a population distinct from the much brighter low-mass X-ray binaries (LMXBs), which were already known in globulars (see Grindlay 1993a for a recent review). More sensitive observations undertaken with the *ROSAT* X-ray telescope have now more than doubled the number of low-luminosity sources known in globulars (Grindlay 1993b; Verbunt et al. 1993; Cool et al. 1993; Rappaport et al. 1994; Grindlay & Cool 1995). Hertz & Grindlay (1983a) hypothesized that the low-luminosity globular cluster X-ray sources are cataclysmic variables (CVs), the white dwarf analogs of the LMXBs. Other hypotheses that have been put forward to explain at least some of these sources include quiescent LMXBs (Verbunt, van Paradijs, & Elson 1984), RS CVn type binary stars (Bailyn, Grindlay, & Garcia 1990), and serendipitous foregound or background sources (HG; Margon & Bolte 1987).

A critical test of any of these hypotheses is to identify optical counterparts for the X-ray sources. Support for the CV hypothesis has recently been provided by the identification with the *Hubble Space Telescope* (*HST*) of a faint blue variable counterpart for the low-luminosity source in 47 Tuc (Paresce, De Marchi, & Ferraro 1992), and of faint UV stars (De Marchi & Paresce 1994) and Hα-bright stars (Cool et al. 1995) in the error circles of X-ray sources in NGC 6397. However, the large majority of the faint globular cluster sources have yet to be identified optically. Prior to the launch of *HST*, ω Cen had been a focus of efforts to identify optical counterparts of low-luminosity sources, owing in part to the existence of off-center sources at moderate radii where crowding effects were not prohibitive for ground-based studies. However, a search for blue variables among over 2000 stars in a field containing the IPC error circle of one of the ω Cen sources (IPC source A) found none (Shara et al. 1988). When this source and one other (IPC source D) were detected with the *EXOSAT* channel multiplier array (CMA), the error circles were reduced to a much more manageable $\sim 10''$ (Verbunt et al. 1986) (although see discussion of *EXOSAT* error circles in § 2.1 below). However, a search for *U*-bright objects among $\gtrsim 30$ stars in the *EXOSAT* error circles yielded no viable counterparts (Margon & Bolte 1987). The authors concluded that chance superpositions of foreground and background X-ray sources could contribute significantly to the population of low-luminosity X-ray sources toward globular clusters.

In 1980 January a long exposure of ω Cen was obtained with the *Einstein* high-resolution imager (HRI), the results of which have not been reported previously. Two of the low-luminosity sources that had been identified with the IPC (sources A and D) were detected, the same two that had been detected with *EXOSAT* (although see § 2.1 below). The high positional accuracy of the *Einstein* HRI (3″–4″; Grindlay & Barranco 1995) narrowed down the field of possible optical counterparts still further.

In § 2.1 we report the results of our analysis of this *Einstein* HRI observation of ω Cen, together with the results of a short

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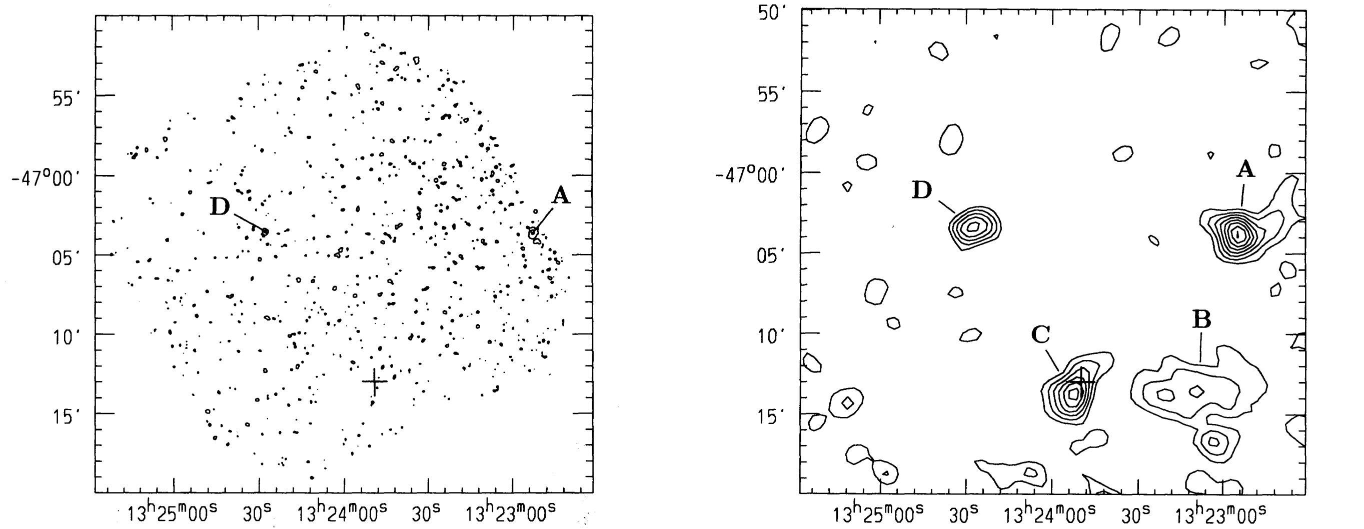

FIG. 1*a* FIG. 1*b*

FIG. 1.—*Einstein* observations of the globular cluster ω Cen (NGC 5139). The axes are labeled in B1950 coordinates; sources are labeled as in HG. The plus sign marks the cluster center in each case. (*a*) The 26.6 ks HRI exposure, showing the full HRI field of view. The image has been smoothed with a Gaussian of FWHM = 9″.4. (*b*) For comparison, the same area is shown in the 22.5 ks *Einstein* IPC exposure. This image has been smoothed with a Gaussian of FWHM = 75″.

ROSAT HRI exposure of the cluster. We describe in § 2.2 the optical photometry and spectroscopy which led to our identifications of counterparts for these two X-ray sources, and compare the optical and X-ray results in § 2.3. Finally, in § 3, we discuss the X-ray source population in and toward ω Cen as a whole, in light of the present findings.

2. OBSERVATIONS AND ANALYSIS

2.1. *X-Ray*

A 26.6 ks exposure of ω Cen was taken with the *Einstein* HRI on 1980 January 28–30. The 25′ diameter HRI field of view (Giacconi et al. 1979) covered a region containing four of the low-luminosity X-ray sources discovered with the *Einstein* IPC: sources A–D (following the nomenclature adopted in HG; see Fig. 1). Two sources are detected in the HRI exposure at significance levels of $\geq 5\ \sigma$. Their positions in the HRI image, which we derived using the algorithm of Cash (1979), are consistent with the positions of IPC sources A and D (see Table 1), and are offset 11′ and 13′ from the cluster center, respectively. These two sources are also present at the $\geq 5\ \sigma$ level in a 4.6 ks exposure of the cluster which we obtained with the *ROSAT* HRI on 1992 August 1–2, and 1993 January 21. Neither the *Einstein* nor the *ROSAT* HRI exposures were sensitive enough to detect IPC sources B and C (see discussion below).

Figures 2*a* and 2*b* (Plate 27) are *V*-band CCD images of the fields of sources A and D (see § 2.2). The large circles labeled "EI" in each figure represent *Einstein* IPC error circles (HG); the circles labeled "EX" represent *EXOSAT* error circles (Verbunt et al. 1986). The circles labeled "EH" and "RH" represent *Einstein* and *ROSAT* HRI error circles, respectively. These circles combine the centroiding uncertainties for each source with an estimated 3″.2 aspect uncertainty (90% confidence) for the *Einstein* HRI (Grindlay et al. 1984; Grindlay & Barranco 1995), and 9″.1 (90% confidence) for the *ROSAT* HRI, based on the reported 1 σ scatter between X-ray and optical positions of 6″.4 (*ROSAT* Status Report 54). The *Einstein* and *ROSAT* HRI and *Einstein* IPC positions are consistent for sources A and D (see Table 1). There is also reasonable agreement with the *EXOSAT* CMA position for source D. However, the position of the source found with the *EXOSAT* CMA in the error circle of IPC source A is clearly inconsistent with the HRI position (see Table 1 and Fig. 2*a*). Either *EXOSAT* detected a different source, or the *EXOSAT* position is in error. We note that whereas source D was

TABLE 1

ASTROMETRY

	Source A			Source D		
Instrument	α(1950)	δ(1950)	Error	α(1950)	δ(1950)	Error
Optical (CCD)......	13h22m52s.15	−47°03′32″.1	<1″	13h24m27s.27	−47°03′33″.8	<1″
Einstein (HRI)......	13 22 52.66	−47 03 31.3	3.7	13 24 27.58	−47 03 35.3	3.7
ROSAT (HRI)......	13 22 51.89	−47 03 28.0	10.3	13 24 27.52	−47 03 37.9	9.7
EXOSAT[a]	13 22 50.0	−47 04 21	10	13 24 28.3	−47 03 51	10
Einstein (IPC)[b]......	13 22 54.7	−47 04 00	60	13 24 24.4	−47 03 37	60

[a] Verbunt et al. 1986.
[b] Hertz & Grindlay 1983b.

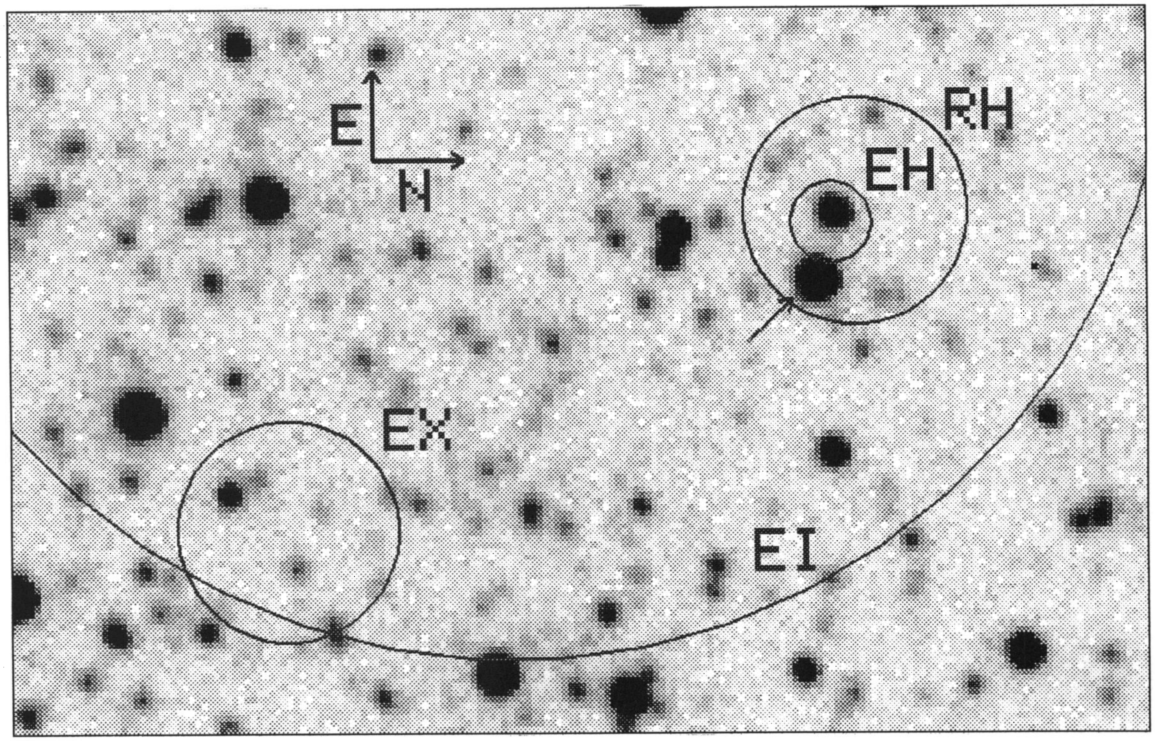

FIG. 2*a*

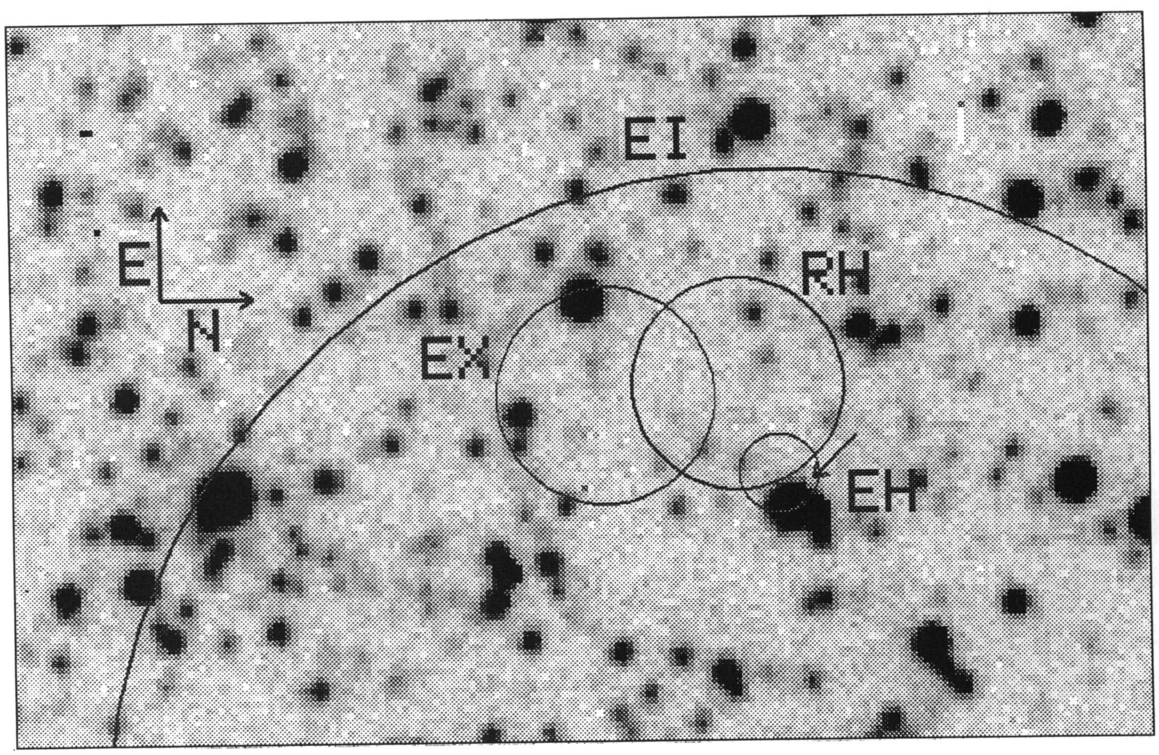

FIG. 2*b*

FIG. 2.—*V*-band CCD images of the fields of *Einstein* IPC sources A and D (HG, Table 6). The fields of view are ~1'.7 × 1'.1. Four X-ray error circles are shown in each figure and labeled as follows: EI = *Einstein* IPC (HG); EH = *Einstein* HRI (this paper); RH = *ROSAT* HRI (this paper); EX = *EXOSAT* CMA (Verbunt et al. 1986). The HRI error circles represent 90% confidence limits on the X-ray source positions. Arrows mark the stars which are identified as foreground dMe's. Astrometry was performed relative to SAO stars on an ESO plate with the measuring engine at the Harvard-Smithsonian Center for Astrophysics. (*a*) IPC source A; (*b*) IPC source D.

COOL et al. (see 438, 720)

detected at a significance level of 4.8 σ with *EXOSAT*, source A was detected at only the 2.8 σ level (Koch-Miramond & Aurière 1987). Neither the *Einstein* HRI nor the *ROSAT* HRI images show any source at the *EXOSAT* "source A" position.

2.2. *Optical*

On 1990 June 28 we obtained CCD photometry of the fields of sources A and D with the 4 m telescope at CTIO as part of a program to identify emission-line objects in globular clusters (Grindlay, Cool, & Bailyn 1991; Cool et al. 1995). Images were taken of both fields through an Hα filter and two narrowband filters on either side of Hα to sample the continuum (see Grindlay et al. 1991 for more details of the method). We determined relative magnitudes of the stars in and near the *Einstein* HRI error circles in each of the three filters using DAOPHOT II (Stetson 1987, 1991), software designed for doing crowded-field stellar photometry. Each field contained a bright star with an apparent Hα excess in or near the *Einstein* HRI error circle (see arrows in Fig. 2). We determined B and V magnitudes of these two stars using CCD images obtained in 1987 April with the 1.5 m telescope at CTIO, and calibrated our instrumental magnitudes using the B and V magnitudes of Margon & Bolte (1987) for several of the brightest stars in the *EXOSAT* error circles. The rms deviations between our magnitudes and those of Margon & Bolte were $\lesssim 0.1$ mag. The Hα-excess star in the *Einstein* HRI error circle for source D has $m_V = 14.8 \pm 0.1$; the star near the source A error circle has $m_V = 14.6 \pm 0.1$. Both have $B-V \sim 1.3 \pm 0.1$–0.2, placing them approximately 0.4 mag to the red side of the giant branch of ω Cen (e.g., Noble et al. 1991), indicating that both stars were probable foreground M stars.

In 1992 August and 1993 February we obtained spectra of these stars with the CTIO 4 m telescope using the Ritchey-Chrétien spectrograph, blue Air Schmidt camera, and Reticon CCD (see Fig. 3). Both spectra show the TiO bands characteristic of dwarf M stars, and contain strong, narrow Hα and Hβ emission lines, identifying them as dMe stars, which are well-known X-ray sources (e.g., Fleming et al. 1988). We estimate spectral types of approximately dM2e–dM3e for both stars (Turnshek et al. 1985), which is consistent with their $B-V$ colors. Given that $M_V \simeq 10$–11 for such M dwarfs (Allen 1973), they are clearly foreground stars, at distances of approximately 50–100 pc, which are by chance projected on ω Cen.

2.3. *Comparison of Optical and X-Ray*

The X-ray–to–optical flux ratios and X-ray luminosities of both objects are consistent with their identifications as foreground dMe stars. During the *Einstein* HRI observation the fluxes of sources A and D were 1.5×10^{-13} ergs cm^{-2} s^{-1} and 0.7×10^{-13} ergs cm^{-2} s^{-1}, respectively, in a 0.1–2.4 keV band. To convert count rates to fluxes, we assumed Raymond & Smith (1977) spectra with $kT \sim 0.3$ keV (see Schmitt et al. 1990) and $N_H = 3.3 \times 10^{19}$ cm^{-2} (Bohlin, Savage, & Drake 1978). These parameters provide a good fit to the *Einstein* IPC spectrum of source A (source D has too few counts to fit) and bring the *EXOSAT* and *Einstein* IPC fluxes to within a factor of ~ 2 of each other (Verbunt et al. 1986). Comparing these fluxes with the optical V-band fluxes, we find $\log (f_x/f_V) = -1.4$ and -1.8 for sources A and D, respectively. Such f_x/f_V ratios are typical of dMe stars (Vaiana et al. 1981), as are their luminosities, which we infer from their distances to be in the range $(0.2$–$2.0) \times 10^{29}$ ergs s^{-1} (Schmitt et al. 1990; Fleming et al. 1988). Both stars are variable X-ray sources. Variations by factors of 2–3 are present in our *ROSAT* observations; similar variability was seen in source D with *EXOSAT* (Koch-Miramond & Aurière 1987). X-ray variability at this level is not uncommon in dMe stars (Agrawal, Rao, & Sreekantan 1986; Ambruster, Snyder, & Wood 1984).

These factors, combined with the location of these two foreground dMe stars in or very near the *Einstein* HRI 90% confidence error circles, leave little doubt that they are the counterparts of the X-ray sources.

3. DISCUSSION

The *Einstein* globular cluster survey contains the subset of X-ray sources in the IPC fields of view which fell within 10 core radii or 3′ of the center of a cluster, whichever was larger. Of the sources which met these criteria, three were identified in the original survey paper as probable serendipitous projections (HG, Table 7). The present identifications of two sources toward ω Cen thus increase from three to five the number of known foreground or background sources among the faint

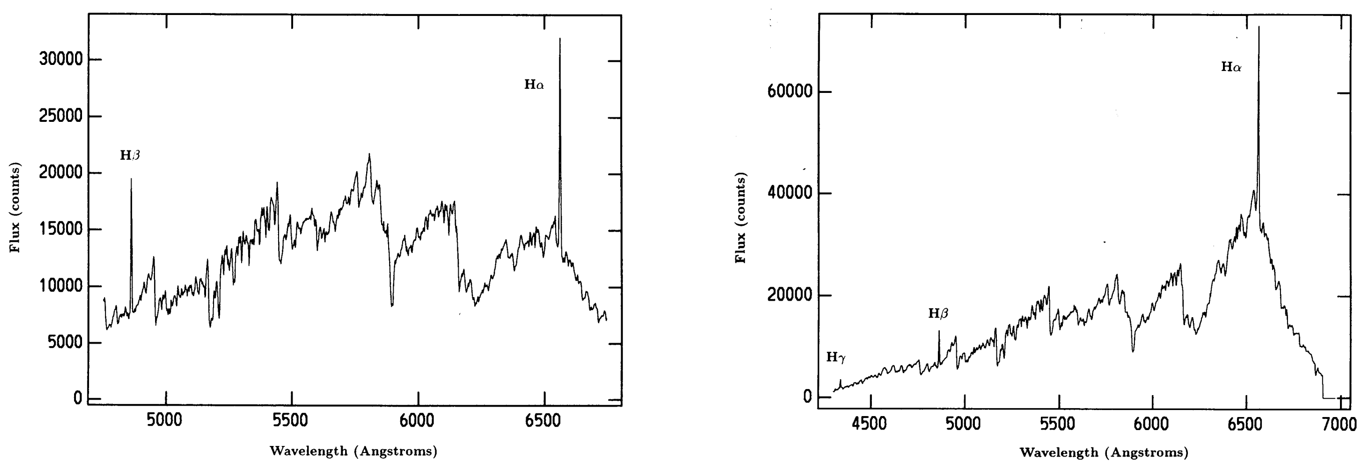

FIG. 3*a* FIG. 3*b*

FIG. 3.—Spectra of the stars marked with arrows in Figures 2*a* and 2*b*; both were taken with the CTIO 4 m telescope. (*a*) Five minute spectrum of the optical counterpart of IPC source A; (*b*) 10 minute spectrum of the counterpart of IPC source D (see text).

globular cluster X-ray sources. A third source toward ω Cen (IPC source E), offset from the cluster center by $\sim 25'$, may also be a coronal source: Margon & Bolte (1987) report a foreground K star in the IPC error circle which would have a reasonable X-ray–to–optical flux ratio were it the source of the X-rays. Several other sources at larger radial offsets, not included in the cluster survey, have also been identified as serendipitous projections by Harris et al. (1992).

The present findings are in keeping with expectations for the rate of chance projections. Omega Centauri was one of two clusters in which multiple sources were identified in the IPC survey, the other being NGC 6656 (M22). Given the large core radii of ω Cen and M22 (2'.4 and 1'.9, respectively), relatively large areas were surveyed for these two clusters. Both were exposed for ≥ 22 ks, about 10 times longer than the typical survey exposure of 2–3 ks. Combining the resulting flux limits with the survey areas and with number counts from the X-ray survey of Maccacaro et al. (1982), HG estimated that $\sim 40\%$ of the sources in these deep exposures would be serendipitous foreground or background sources. The number of foreground coronal sources in particular that is to be expected in these fields can be determined using the XCOUNT numerical model (Favata et al. 1992), which incorporates a model of the distribution of stars in the Galaxy as well as interstellar hydrogen, together with the spectral response of a given X-ray detector. In observations made with the IPC, a total of ~ 1 foreground source is expected in the combined areas surveyed in these two clusters, given their respective flux limits (Micela, Sciortino, & Favata 1993). That there may be two or perhaps three among the nine previously unidentified sources toward these clusters is therefore not extraordinary.

Neither of the two remaining *Einstein* IPC sources in ω Cen is detected in the *Einstein* HRI or *ROSAT* HRI exposures. Source C, which lies within 1' of the cluster center (see Fig. 1*b*), and thus remains a likely cluster member, appeared pointlike in the IPC observation, with $f_x \simeq 1.5 \times 10^{-13}$ ergs cm^{-2} s^{-1} (HG), or $L_x \simeq 5 \times 10^{32}$ ergs s^{-1}. We derive a 3 σ upper limit from the *Einstein* HRI image of $f_x < 1.2 \times 10^{-13}$ ergs cm^{-2} s^{-1}, or $L_x < 4 \times 10^{32}$ ergs s^{-1}, comparable to the detected IPC flux. This provides only marginal evidence for variability, however, given the uncertainties in the spectrum and the count-to-flux conversions for the two detectors. This source has recently been resolved into two, each with $L_x \sim 2 \times 10^{32}$ ergs s^{-1} (0.5–2.4 keV band), in a pointed observation with the *ROSAT* Position Sensitive Proportional Counter (PSPC) (Verbunt et al. 1993). The X-ray luminosities of these two central sources make them good candidates to be CVs (see, e.g., Patterson & Raymond 1985); optical identifications will provide the critical test.

IPC source B, which lies several arcminutes west of the cluster center (see Fig. 1*b*) and is clearly extended, had $f_x \sim 1.2 \times 10^{-13}$ ergs cm^{-2} s^{-1} in the IPC observation, or $L_x \sim 4 \times 10^{32}$ ergs s^{-1} if the source is in the cluster (HG). This extended source is only partially covered in the *Einstein* HRI field of view; for the portion within the HRI field, we derive a 3 σ upper limit of $f_x < 7 \times 10^{-13}$ ergs cm^{-2} s^{-1}, or $L_x < 2 \times 10^{33}$ ergs s^{-1}. This extended X-ray emission was noted by Hartwick, Cowley, & Grindlay (1982), who suggested that it and other extended emission features seen in two other globulars could arise from shocked cluster gas, as it interacts with the halo. The more detailed calculations of Faulkner & Smith (1991) suggest that such a mechanism would not produce the observed luminosities. This source may instead be due to a localized source of hot gas in the cluster, such as might be provided by a planetary nebula or an ablating millisecond pulsar (Grindlay 1993a); alternatively, it may be due to a chance alignment with a background galaxy cluster (see Krockenberger & Grindlay 1994 for a more detailed discussion of this possibility and of extended X-ray emission in globulars). Its location well off the cluster center (at 2–4 core radii) excludes the possibility that it is comprised of a large number of faint, unresolved X-ray sources, which would produce a more symmetrical distribution.

The *Einstein* HRI observation provides a limit on the integrated emission from any population of faint sources in the cluster. For the inner 2 core radii (4'.8), the 3 σ upper limit is $L_x < 9 \times 10^{33}$ ergs s^{-1}. The IPC observation puts the total emission from the central region (including sources B and C) at $L_x \lesssim 3 \times 10^{33}$ ergs s^{-1} (Hartwick et al. 1982). These limits of course do not preclude the existence of X-ray sources below the IPC and HRI detection thresholds, but they can be used to make rough comparisons of the X-ray source population in ω Cen to that in other clusters. NGC 6397, for example, contains four or five sources with an integrated luminosity of $L_x \sim 3 \times 10^{32}$ ergs s^{-1} (Cool et al. 1993). Scaling by cluster mass, a comparable population of faint sources in ω Cen would produce an integrated luminosity of $L_x \gtrsim 10^{34}$ ergs s^{-1}, a factor of $\gtrsim 3$ larger than the IPC limit. Viewed as an excess of sources in NGC 6397 relative to ω Cen, such a difference might be attributable to the advanced dynamical state of NGC 6397 (a probable post–core-collapse cluster; Djorgovski & King 1986), whose high central density (Pryor & Meylan 1993) should be accompanied by high rates of stellar interactions. This possible deficiency of faint X-ray sources in ω Cen is more extreme when compared to the old open cluster M67. The combined luminosity of six RS CVn stars and a CV identified in M67 is $L_x \sim 7 \times 10^{31}$ ergs s^{-1} (Belloni, Verbunt, & Schmitt 1993). Scaling by mass, a comparable population of faint sources would produce an integrated luminosity in excess of 10^{35} ergs s^{-1} in ω Cen, a factor of ~ 30 more than is observed. Future, more detailed comparisons of the X-ray source populations among clusters with varying characteristics and histories will be possible as more sensitive X-ray studies are made, which should provide valuable insight into the nature and formation mechanisms of these objects.

The identifications here of two dMe stars projected by chance 11'–13' from the center of ω Cen serve as an important reminder that as X-ray observations of globular clusters reach fainter flux limits, such serendipitous detections will only increase in frequency. They also demonstrate the great advantage that high spatial resolution X-ray imaging provides in identifying optical counterparts in crowded fields. The improved PSPC X-ray positions, or future *ROSAT* HRI positions, when combined with observations with the *HST*, should make it feasible to identify counterparts even of the sources in the crowded core of ω Cen.

We gratefully acknowledge Eric Rubenstein and Jeff McClintock for help in obtaining spectra at CTIO, and thank Mark Birkinshaw for comments on a preliminary draft. This research was partially supported by a NASA Graduate Student Researchers Program Fellowship (A. M. C.), NASA grants NAG5-1624 and NAGW-3280 (J. E. G.), NAGW-2469 (C. D. B.), HF-1003.01-90A (P. J. C.), and the Office of Naval Research (P. H.).

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