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THE FORMATION AND DETECTION OF STRONGLY MAGNETIC WHITE DWARF BINARIES IN GLOBULAR CLUSTERS

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ABSTRACT

We discuss the mechanism for the formation of magnetic cataclysmic variables (MCVs) by the tidal capture of isolated magnetized white dwarfs and determine those globular clusters where the largest number of them are likely to be formed. By performing a statistical analysis of the X-ray emission of known MCVs, in the solar neighborhood, we determine the hard X-ray luminosity functions of the DQ Her and AM Her binaries and the soft X-ray luminosity function of the AM Her binaries. We find that the DQ Her binaries have a mean hard X-ray luminosity a factor of 10 higher than that for the AM Her binaries. We also estimate the X-ray fluxes of globular cluster MCVs by using a solar neighborhood survey, for the first time, and identify those globular clusters which are likely to contain MCVs which may be detectable by means of their X-ray emission.

Subject headings: clusters: globular — stars: magnetic — stars: white dwarfs — X-rays: sources

1. INTRODUCTION

Magnetic cataclysmic variables (MCVs) are close binary systems in which a magnetized white dwarf accretes matter from a red dwarf star, the magnetic field strength of the white dwarf being sufficiently strong that the accreting material is channeled onto the magnetic poles of the white dwarf (see the reviews by Berriman 1988 and Cropper 1990). All the known MCVs lie within a few hundred parsecs of the Sun and hence are considered to be Galactic disk objects. No MCVs have yet been identified in the more distant globular clusters which are several kiloparsecs away.

The MCVs may be divided into two subclasses: the AM Herculis binaries and the DQ Her binaries. The AM Her binaries are observationally characterized by the strong optically polarized radiation they emit, and contain synchronously rotating white dwarfs. The magnetic fields of the AM Her binaries have been determined from the detection of cyclotron lines (Visvanathan & Wickramasinghe 1979), Zeeman line splitting (Schmidt, Stockman, & Grandi 1986), and models for the strong optical polarization ($\sim 10\%$), which is believed to arise as a result of cyclotron emission (Chanmugam & Dulk 1981). These determinations show that they lie between about 10 and 50 MG (Cropper 1990). On the other hand, the DQ Her binaries do not in general emit detectable optical polarization or show evidence of Zeeman or cyclotron lines. In one case only (BG CMi) weak optical and infrared circular polarization has been detected (West, Berriman, & Schmidt 1987), implying a magnetic field of about 4 MG (Chanmugam et al. 1990). These binaries generally show X-ray pulsations with periods which differ from their orbital periods, showing that they contain asynchronously rotating white dwarfs. Their magnetic fields must be greater than about 0.05 MG in order for the accreting matter to be channeled onto the magnetic poles. It has been proposed by Chanmugam & Ray (1984) that the DQ Her binaries would evolve into AM Her binaries if their magnetic fields are larger than about 3 MG. They also argued that some of them could have fields of order 10 MG, while others could have weaker fields. On the other hand, Lamb & Patterson (1983) estimated the average fields of DQ Her binaries to be about 1 MG from their spin-up properties, while King, Frank, & Ritter (1985) suggested on evolutionary grounds that they have magnetic moments comparable to those of the AM Her binaries. Polarimetric searches by a number of observers, and especially Stockman et al. (1991), have failed to reveal magnetic fields in these and other known cataclysmic variables (CVs). If the magnetic field is very large ($B \gtrsim 100$ MG), then the source should produce significant UV radiation as a result of optically thick cyclotron emission. Searches for such strong UV emission with *IUE* from various CVs in the solar neighborhood have failed to reveal any such sources (Bond & Chanmugam 1982). Thus, the known MCVs in the Galactic disk have magnetic fields which are less than about 50 MG.

On the other hand, a few percent of isolated white dwarfs have detectable magnetic fields (Angel, Borra, & Landstreet 1981) lying in the range 1 MG $\lesssim B \lesssim$ 500 MG (Schmidt 1989). Recently, it was suggested by Ray & Chanmugam (1990, hereafter RC) that the majority of MCVs in globular clusters are expected to be formed by tidal capture of white dwarfs by red dwarfs, and hence their field distribution will resemble that of isolated magnetic white dwarfs in the globular clusters rather than that of the primordially formed CVs. If correct, this would imply that globular clusters will contain a new class of MCVs with high fields (50 MG $\lesssim B \lesssim$ 500 MG). In § 2 we discuss in further detail the formation mechanism for such MCVs in globular clusters and identify those clusters which are likely to have the greatest number of such systems. In order to determine whether X-ray measurements with the next generation of X-ray satellites should help reveal the brightest of these systems, we examine in § 3 the X-ray luminosities of the known MCVs. By using recent statistical techniques for astronomy which utilize information obtained from upper limits as well as detections (Feigelson & Nelson 1985), we show in § 3 that the

DQ Her binaries have a mean hard X-ray luminosity which is a factor of 10 higher than that of the AM Her binaries. We also determine the soft X-ray luminosity function for the AM Her binaries and estimate what fraction of them are likely to be detectable at globular cluster distances. This information is taken together with estimates of formation rates of MCVs to determine those globular clusters which are the best targets for X-ray observations with the next generation of space-borne X-ray observatories, such as *ROSAT*, *ASTRO-D*, and *AXAF*. We then point out how X-ray detections combined with *IUE* and *HST* observations can help identify strongly magnetic CVs among them.

2. FORMATION OF MAGNETIC CATACLYSMIC VARIABLES BY TIDAL CAPTURE

X-ray surveys of low mass X-ray binaries (LMXBs) which are fairly complete show that about 10% of all Galactic LMXBs are located in globular clusters, even though the clusters contain only 10^{-4} of the Galactic mass. This overabundance of LMXBs in globular clusters relative to those in the Galactic disk has led to the suggestion (Fabian, Pringle, & Rees 1975) that they are formed by tidal capture of a neutron star in the cluster rather than by the evolution of a primordial binary. It is possible that the globular clusters also have an overabundance of white dwarf binaries with respect to the Galactic disk, since the tidal capture cross section is roughly the same whether the compact star is a white dwarf or a neutron star (Hertz & Grindlay 1983) (except for the effects of mass segregation, which might play some significant role in centrally condensed clusters; Verbunt & Meylan 1988 and references therein).

The number of white dwarf binaries formed in globular clusters can be estimated from the cross sections for tidal captures and the number density n_T of target stars (in this case the lower–main-sequence stars) and the number of white dwarfs present in the globular cluster core. This number, integrated over the globular cluster lifetime $\tau_{\rm GC}$ ($\sim 10^{10}$ yr) is equal to $4\pi\Gamma\tau_{\rm GC} r_c^3 n_{\rm WD}/3$. Here $n_{\rm WD}$ is the number density of white dwarfs in the globular cluster core of radius r_c, while the rate Γ of tidal capture in the globular cluster core per compact star is given by equation (16) of Ray, Kembhavi, & Antia (1987).

The widest orbit upon circularization following tidal capture of a lower–main-sequence star has an orbital period $P_{\rm orb}$ slightly less than a day. On the other hand, white dwarf binaries in the Galactic disk are believed to enter the CV phase for $P_{\rm orb} \lesssim$ 0.5 day. Thus, the probability of forming a CV–like system with a main-sequence companion directly through tidal capture is roughly 0.6 times the probability of forming all white dwarf binaries. In addition, some of the wider systems ($P_{\rm orb} \gtrsim$ 0.5 day) may also evolve into CV–like systems quickly, since, in the process of binary formation, the system may go through a common envelope phase (Ray et al. 1987). To estimate the number of all white dwarf binaries formed in a globular cluster in $\tau_{\rm GC}$, one needs the number of all white dwarfs formed in the globular cluster core. This depends on the initial number of stars dN in a mass interval dM around mass M or the initial mass function (IMF): dN/dM is proportional to $M^{-\alpha}$, and varies substantially according to the metallicity of the cluster.

If α is too low, e.g., near $\alpha = 2.35$, the Salpeter value, then the heavy mass loss in the initial outburst of supernova explosions would lead to a disruption of the cluster, unless the central concentration is high enough (Chernoff & Weinberg 1990). On the other hand, clusters with steep IMF (say $\alpha = 3.5$) survive under a wide variety of initial conditions. From an analysis of the data available for the globular clusters 47 Tuc and M15, Bailyn & Grindlay (1990) have argued that α for the upper main sequence in these clusters is 3.75 or greater. Verbunt & Meylan (1988) have argued that a satisfactory fit to the observed main-sequence luminosity function in 47 Tuc can be found only for a broken IMF: for masses between 0.13 and 0.88 $M_\odot$, $\alpha \simeq 1.2$, while for more massive stars, $3.75 < \alpha < 4.5$. In Table 1 we estimate the number of white dwarf binaries, $N_{\rm WD}$, formed over 10^{10} yr, assuming $\alpha = 4$ for the upper main sequence and $\alpha = 1.2$ for the lower main sequence for 47 Tuc, and assuming a single $\alpha = 4$ for M15 and NGC 6440. For 47 Tuc we also report estimates taking account of the effects of mass segregation on the formation rate of white dwarf binaries as given by Verbunt & Meylan (1988). We emphasize that the IMF indices of the first two entries in Table 1 are only assumed ones, and they illustrate the sensitivity in the calculated number of currently active CVs. Observational evidence of the mass and velocity distribution of stars in the cluster core as a

TABLE 1

BINARY WHITE DWARFS WITH MAIN-SEQUENCE COMPANIONS FORMED IN 10^{10} YEARS IN THREE DIFFERENT GLOBULAR CLUSTERS

CLUSTER	DENSITY ($M_\odot$ pc^{-3})	CORE RADIUS (pc)	ROOT MEAN SQUARE VELOCITY (km s^{-1})	α[a]	CENTRAL NUMBER DENSITY (pc^{-3}) WD[b]	MS[c]	NUMBER OF WD MS BINARIES[d]	CURRENTLY ACTIVE CVs	MCVs	REFERENCES
NGC 6440	5×10^5	0.24	13	4	6×10^4	$\sim 10^6$	~ 2400	60	1–2	1, 2
M15	1.8×10^5	0.26	8.6	4	2.1×10^4	3.8×10^5	~ 600	15	~ 1	1, 2
47 Tuc	1.06×10^5	0.52	13.1	1.2, 4	2.5×10^4	1.6×10^5	~ 1600	40	2–3	3, 4 1, 4, 5
47 Tuc[f]	5.1×10^4	0.52	10.3	1.2, 4	...	7.6×10^4	600	15	~ 1	5, 6, 7

[a] Initial mass function index. If two indices are given, they are for the lower and upper main sequences, respectively.

[b] Assuming the white dwarfs are formed from main-sequence stars with mass 0.8–8.0 $M_\odot$.

[c] Main-sequence stars with masses in range 0.3–0.8 $M_\odot$.

[d] Number of white dwarf main-sequence binaries.

[e] Number of currently active CVs and MCVs calculated assuming a lifetime of 4×10^8 yr for CVs. The range of the number of MCVs is obtained by taking 3%–5% of the white dwarfs to be magnetized and an overall (luminosity-weighted) detection probability of 80%.

[f] With mass segregation effects.

REFERENCES.—(1) Webbink 1985; (2) Verbunt 1989; (3) McClure et al. 1986; (4) Bailyn & Grindlay 1990; (5) Meylan 1989; (6) Verbunt & Meylan 1988; (7) Meylan 1987.

function of its radius can substantially improve the theoretical estimates of the number of CVs present in globular clusters. Unfortunately, only in two clusters so far are photometry and spectrophotometry of the globular cluster central regions detailed enough to have helped model the radial distribution of stars, so that with assumptions about the mass function exponent and a few other parameters, the effects of mass segregation can be estimated (Verbunt & Meylan 1988). For all the remaining globular clusters we did not take mass segregation into account, simply because there are not sufficient data to do so at this time. Note that Kulkarni, Narayan, & Romani (1990) have, in another context (pulsars), independently done essentially the same thing.

The tidal capture rate Γ predicts that roughly 3% of the white dwarfs would be captured via tidal interactions in a cluster of canonical target star density $n_T = 10^4$ pc^{-3}, whereas 20% of the globular clusters which have unresolved cores (Djorgovski & King 1986) could have undergone collapse, in which case a larger fraction of the white dwarfs could have a captured companion (Bailyn & Grindlay 1990) owing to a substantially higher stellar density. As a global average, as much as 10% of the compact stellar remnants in the cluster cores may have been tidally captured. In the absence of mass segregation effects, and with the assumption that all clusters have roughly the same IMF index, the relative contribution of a cluster toward the binary formation rate normalized to the contribution from all clusters would scale as $W_1 \propto n_*^2 r_c^3 / v_{\rm rms}$. Here n_* is the number density of stars in the cluster core. About seven clusters like 47 Tuc have high stellar density, which together would provide approximately half the weight W_1 of the roughly 50,000 white dwarf binaries present in all the globular cluster cores.

The relative weights listed are only indicative and can be uncertain by moderate factors because of the effects mentioned above. Out of these 5×10^4 white dwarf binaries, more than 3×10^4 would be systems with $P_{\rm orb} \leq 0.5$ days which are "CV-like" at one time or another. Among these, the currently observable magnetic CVs, which may be luminous in the hard X-ray band, are estimated as follows: (*a*) Since the MCVs in globular clusters are formed from isolated white dwarfs undergoing tidal capture, the fraction of MCVs among all CVs would be the same as that of magnetic white dwarfs among all isolated white dwarfs; in the solar neighborhood, this latter ratio is 3%–5%; (*b*) the binary magnetic white dwarf system will be X-ray–active only for a CV lifetime of $\tau_X = 4 \times 10^8$ yr $\sim \tau_{\rm GC}/25$. Therefore, the total number of MCVs currently X-ray–active in the globular cluster systems by their X-ray emission is

$$N_{\rm MCV} = 100\left(\frac{N_{\rm WD}}{10^5}\right)\left(\frac{f_{\rm CV}}{0.6}\right)\left(\frac{f_{\rm MWD}}{0.04}\right)\left(\frac{\tau_X/\tau_{\rm GC}}{0.04}\right) . \qquad (1)$$

Here $f_{\rm CV}$ is the fraction of the binary white dwarfs $N_{\rm WD}$ that enter the CV phase directly, and $f_{\rm MWD}$ the fraction of white dwarfs which are magnetic; $f_{\rm CV}$ and $f_{\rm MWD}$ are likely to be greater than 0.6 and 0.03, respectively. We list in Table 1 the numbers of *currently active* CVs and magnetic CVs expected. Note that even though, on a first-order analysis, NGC 6440 is a higher weight (W_1) cluster compared to 47 Tuc (see Table 2), the latter could have a larger number of active CVs because it has a less steep lower–main-sequence IMF.

3. THE X-RAY LUMINOSITY FUNCTIONS OF MAGNETIC CATACLYSMIC VARIABLES

In order to estimate the number of systems which can be detected in a globular cluster by an X-ray instrument of a given sensitivity, we need to know the luminosity function of the MCVs. The only unbiased survey that can be used for the probable number of objects detectable is the hard X-ray band in which both the AM Her and the DQ Her binaries emit. It will be of interest to determine the soft X-ray luminosity function as well, since it is in this band that the strongly magnetized AM Her binaries predominantly radiate, whereas the DQ Her binaries do not. Because the soft X-rays are absorbed considerably more than the hard X-rays by the interstellar gas, a survey in the latter band would give a more complete representation of the magnetic CV population in the Galaxy. For this reason, the target globular clusters for strongly magnetic CVs which may be accessible through the soft X-ray band may be different from those which contain the largest number of CVs, under an a priori analysis as in § 2.

TABLE 2

POSSIBLE TARGET GLOBULAR CLUSTERS FOR WHITE DWARF MAIN-SEQUENCE BINARIES

NAME	W_1[a]	DISTANCE (kpc)	EXPECTED NUMBER OF DETECTIONS OF MCVs: Soft X-Ray[b]	Hard X-Ray[c]	COMPACT SOURCE DETECTIONS[d]
Terzan 5	0.13	7.1	...	4–6	XP
Liller 1	0.10	7.9	...	3–5	X
NGC 6440	0.08	7.1	...	3–4	XP
47 Tuc	0.06	4.6	~ 1	2–3	10P
NGC 6266/M62	0.04	6.1	...	1–2	...
NGC 6388	0.09	13.5	...	2–3	...
NGC 6626/M28	0.03	5.8	...	1–2	P
NGC 5272/M3	6×10^{-3}	10.4	<1	1	...

[a] W_1 is the weight factor for formation (which does not account for mass segregation effects mentioned in § 2).

[b] For *ROSAT* sensitivity for that particular cluster as indicated in the text.

[c] *AXAF* expected number on the basis of X-ray CCD (0.2–10 keV) for an integration time of 10,000 s.

[d] Indicates whether a compact source such as a low-mass X-ray (X) or radio pulsar (P) (Lyne 1991) has already been detected in the cluster.

We have used the fluxes, F_X, reported by Watson (1986) and Norton & Watson (1989) together with the distance, d, estimates for the AM Her binaries (Cropper 1990) and DQ Her binaries (adapted from Norton & Watson 1989) to predict their luminosity functions. In this paper we use $L_X = 2\pi d^2 F_X$. For many sources, only an upper limit to the flux is available. Recognizing the importance of the information implicit in the failure to detect some objects, which can be partially recovered under reasonable assumptions, astronomers have used statistical methods, collectively called "survival analysis" in actuarial and related fields. Software packages have been constructed to handle such data that combine detections with upper limits. We use the computer program package ASURV (see Feigelson & Nelson 1985). The program employs univariate methods to calculate the Kaplan-Meier product limit (PL) estimators for the distribution functions of randomly censored samples, e.g., the (separate) lists of AM Her and DQ Her systems with detections and upper limits. The software also provides tests (TWOST) to determine whether two censored samples are drawn from the same parent population or not. These tests are primarily generalizations of standard tests for uncensored data, such as the Wilcoxon and log-rank nonparametric two-sample tests. We use these tests to determine the level of significance at which the luminosity functions of the AM Her and DQ Her samples are distinct.

We first determine the luminosity function of the known MCVs in the two energy bands surveyed by *EXOSAT*.

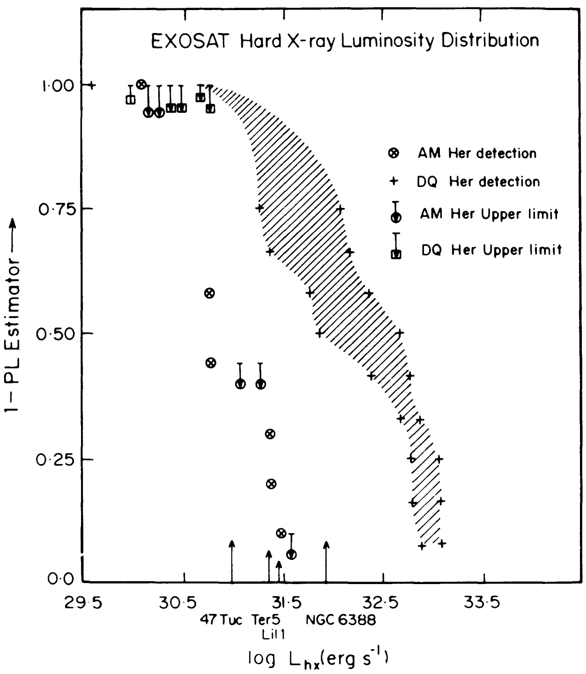

FIG. 1.—*EXOSAT* hard X-ray luminosity distribution of the AM Her and DQ Her binaries in the 2–10 keV range for the solar neighborhood. The luminosity levels down to which the distribution functions can be searched, by observing the cluster with *AXAF* for 10,000 s, are shown by upward vertical arrows on the abscissa. Included in this figure are the upper limits to the hard X-ray luminosities of a few AM Her and DQ Her binaries. The horizontal lines marked at the top of the vertical arrows ending in a square (DQ Her) or a circle (AM Her) are drawn at the same ordinate as that of the immediately preceding (in luminosity) detection. The position of the vertical arrow for each source for which only an upper limit of flux is available is drawn at the luminosity corresponding to that upper limit reported by the *EXOSAT* ME flux. The hatched region corresponds to the range of the luminosity function of DQ Her binaries that is obtained from the minimum and maximum of all distances to the various sources.

3.1. *Hard X-Rays*

The *EXOSAT* survey in the 2–10 keV hard X-ray band detected 14 MCVs in the solar neighborhood and found upper limits on the X-ray flux from 10 other cases. The MCVs constitute a high fraction (four out of five) of all CVs discovered serendipitously by *EXOSAT*.

The hard X-ray fluxes from the DQ Her binaries in the solar neighborhood and the corresponding distances are given in Table 3. Since the distances to these sources are uncertain in some cases, we give the ranges of these reported in the literature and calculate the corresponding luminosities that are reported in the last column. When we use the ASURV software to construct the hard X-ray luminosity functions for DQ Her binaries, we take two sets of luminosities corresponding to the minimum and maximum values reported in the last column of Table 3. The two luminosity functions (i.e., the cumulative maximum-likelihood estimators) thus obtained represent the boundaries of the uncertainty in the intrinsic hard X-ray luminosity functions of DQ Her binaries due to the uncertainty in distance to some of the sources. This is represented by the shaded region in Figure 1.

TABLE 3

HARD X-RAY LUMINOSITY OF DQ HER BINARIES

Source	Distance (pc)	2–10 keV Flux (ergs s^{-1} cm^{-2})	Luminosity (ergs s^{-1})	References
GK Per[a]	525	4.5×10^{-11}	7.4×10^{32}	1, 2
V1223 Sgr	540–660	5×10^{-11}	$(0.87–1.3) \times 10^{33}$	1, 3
TV Col	>500	4.1×10^{-11}	$>6.1 \times 10^{32}$	1, 4, 5
FO Aqr	200–640	3.4×10^{-11}	$(0.81–8.3) \times 10^{32}$	1, 3
BG CMi	700–1000	2.3×10^{-11}	$(0.67–1.4) \times 10^{33}$	1, 6
AO Psc	100–750	4.0×10^{-11}	$(0.024–1.3) \times 10^{33}$	1, 3
H0542−407	>500	1.9×10^{-11}	$>2.8 \times 10^{32}$	1, 4
V426 Oph	169–235	4.0×10^{-11}	$(0.68–1.3) \times 10^{32}$	1, 7
EX Hya	76–190	8.4×10^{-11}	$(0.29–1.8) \times 10^{32}$	1, 3
SW UMa	140	$<0.5 \times 10^{-11}$	$<5.8 \times 10^{30}$	1, 3
AE Aqr	28–78	$<1.0 \times 10^{-11}$	$<(0.47–3.6) \times 10^{30}$	1, 3
DQ Her	300–500	$<0.02 \times 10^{-11}$	$<(1.1–3.0) \times 10^{30}$	1, 3

[a] Quiescent flux in high state.

REFERENCES.—(1) Norton & Watson 1989; (2) Duerbeck 1981; (3) Berriman 1987; (4) Buckley & Tuohy 1989; (5) Berriman 1988; (6) McHardy et al. 1987; (7) Hessman 1988.

The hard X-ray luminosity function of the AM Her sample is also shown in Figure 1. This figure contains additional upper limits to the luminosity of AM Her stars that were not included in RC. In addition to the detections, the upper limits are shown by vertical arrows (bounded above by the preceding detection's PL estimator). It is clear as in previous work (RC, Fig. 1) that the luminosity functions are quite distinct; the distribution for the AM Her systems terminates around log $L_{hX} \simeq 31.5$, whereas that for DQ Her systems extends beyond log $L_{hX} = 32.5$. Here L_{hX} is given in ergs s^{-1}.

The mean luminosity of the AM Her systems obtained by using ASURV is log $L_{hX} = 30.696$ with a typical 1 σ error of ± 0.187. The corresponding numbers for DQ Her systems are log $L_{hX} = 31.567$ and ± 0.360 when the minimum luminosities are used and log $L_{hX} = 32.133$ and ± 0.303 when the maximum luminosities in Table 3 are used. The ASURV Gehan's generalized Wilcoxon test confirms that these two samples are distinct at the 98.2% (test statistic = 2.361) level for the minimum luminosities of the DQ Her binaries, while the log-rank test confirms this at the 93.9% level (test statistic = 1.872). Similarly, if the maximum luminosities of the DQ Her system are used, then the AM Her and DQ Her distributions are distinct at the 99.4% level according to Gehan's test and at the 96.4% level in the log-rank test. Therefore, the statistical significance of the distinction between the two classes of sources (AM Her and DQ Her) is maintained at a high level.

If we make the hypothesis that the luminosity function of globular cluster MCVs is the same as that of the known (solar neighborhood) MCVs and that the *EXOSAT* survey is complete for the portion of the sky observed down to the luminosity level indicated, then we can estimate the number of MCVs likely to be observable in a similar survey of the globular clusters. Since for DQ Her binaries, only the range of luminosity functions for sources in the solar neighborhood is known because of their uncertain distance, we have folded in this range to predict the expected number of detections reported in Table 2. For example, the *AXAF* X-ray CCD with a spectral range of 0.2–10 keV would detect in 10^4 s an object with an X-ray luminosity $L_X \sim 10^{32}$ ergs s^{-1} at a distance of 15 kpc in our Galaxy. Although this spectral range is wider than the *EXOSAT* medium-energy (ME) detector, we use these characteristics to indicate in Figure 1 (*vertical arrows*) the luminosity level down to which an X-ray–active MCV would be detectable in various globular clusters for a typical pointing time of 10^4 s. Obviously the DQ Her systems are better candidates. We combine these detection probabilities together with the expected number of systems in the various high-weight W_1 (for formation of tidal capture binaries involving white dwarfs) globular clusters listed in Table 2, to estimate the number of expected detections in *AXAF* surveys with pointing times of 10,000 s. Since W_1 denotes the overall weight factor for all CVs formed by tidal capture, we have included in the last column of Table 2 (the expected number of detections) a fraction $f_{MWD} = 0.03$ of magnetic white dwarfs consistent with equation (2) of RC. Our estimates are also useful for hard X-ray observations with *ASTRO-D*, whose sensitivities in this regard are not drastically different from those of *AXAF*.

3.2. *Soft X-Rays*

Only the AM Her binaries, among MCVs, emit substantially in the soft X-ray band. The soft X-ray measurements have been reported by Watson (1986) using the *EXOSAT* low-energy (LE) telescope with the charge multiplier array (CMA) as the detector and employing the Lexan 3000 filter. Conversion of the observed count rates to flux values requires the knowledge of spectral parameters of these objects. The measurements listed by Watson (1986) are mostly broad-band measurements, with the result that spectral parameters are poorly determined. The absorption due to the intervening interstellar medium further obscures most of the soft X-ray flux from us. For the present we assume that a blackbody shape is a good approximation to the actual soft X-ray spectrum of MCVs. For three of the objects listed here the spectral parameters have been determined fairly accurately. These are AM Her (Heise et al. 1985), QQ Vul (Osborne et al. 1987), and BL Hyi (Beuermann & Schwope 1989). The first two objects were observed using gratings on *EXOSAT*, and a blackbody temperature of $kT_{bb} = 25$ eV was measured for both of them. The analysis by Beuermann & Schwope (1989), based on the combined low-energy and medium-energy data, also gave a best fit with $kT_{bb} = 25$ eV for BL Hyi. Consequently we assume that a blackbody with a temperature of $kT_{bb} = 25$ eV is a good approximation for all the MCVs. It is also very important to know the amount of equivalent hydrogen column between us and the sources. Most of the objects listed here, with the exception of AN UMa and QQ Vul, are within a distance of 100 pc from us. The absorbing column density for all these objects has been assumed to be $N_H = 10^{20}$ atoms cm^{-2} (Paresce 1984; Frisch & York 1989). For AN UMa and QQ Vul we assumed a column of 3×10^{20} and 4×10^{20} cm^{-2} for their distances of 300 and 400 pc, respectively. With these assumptions for the spectral parameters, we converted the count rates observed using the Lexan 3000 filter with LE to flux values. The conversion scale for different N_H values was given to us by J. P. Osborne (1990, private communication). The contribution of a hard bremsstrahlung component to the soft X-ray measurements was subtracted from the count rates for all sources (except the last three in Table 4, for which only upper limits to the hard X-ray flux are available) before conversion, assuming a temperature of 20 keV for the hard component (Beuermann & Schwope 1989) in all the MCVs. This amounts to 0.007 counts in the soft X-ray band for each 0.1 s count detected in the hard X-ray channel. These fluxes and luminosities are reported in Table 4.

We also show a soft X-ray luminosity function for the AM Her binaries in Figure 2, constructed by the Kaplan-Meier method. All sources here are detections; a few have lower limits to their luminosity, $L_{sX} = 2\pi d^2 F_{sX}$, because only the lower limits to their distance are known. But for the purpose of calculating the Kaplan-Meier estimator, we have taken the lowest of these values. The mean of the distribution is at log $L_{sX} = 32.575 \pm 0.307$. Shown in the figure are arrows which denote the luminosity levels down to which *ROSAT* can survey for MCVs in different globular clusters for a typical pointing time.

Our choices of the globular clusters in the figure are guided not so much by the high weight W_1 for the formation of tidal capture binaries (although 47 Tuc is such a high-weight cluster) but rather by their high latitudes above the Galactic plane and moderate distances. This is because in the lower Galactic latitudes the interstellar gas densities are higher, which leads to enhanced absorption and reduced count rates per unit unabsorbed flux.

We use the best available estimates of the distances to the relevant globular clusters, and the Galactic column densities obtained from 21 cm observations (A. A. Stark et al. 1989, private communication; Stark et al. 1991), to estimate the

TABLE 4

EXOSAT SOFT X-RAY LUMINOSITY OF POLARS

Source	Distance (pc)	Counts s^{-1} (Lexan)	F_{sX}[a] (ergs s^{-1} cm^{-2})	L_{sX}[b] (ergs s^{-1})	References
EF Eri (2A0311−227)	≥89	1	2.6×10^{-10}	$\geq 1.23 \times 10^{32}$	1, 2
VV Pup	145	1	3.97×10^{-10}	5.01×10^{32}	1, 2
V834 Cen (E1405−451) ...	86	0.7	2.52×10^{-10}	1.12×10^{32}	1, 2
MR Ser (PG 1550+191) ...	112	0.03	6.4×10^{-12}	4.82×10^{30}	1, 2
BL Hyi (H0139−68)	128	0.03	1.08×10^{-11}	1.06×10^{31}	1, 2
ST LMi (CW 1103+254) ..	128	0.5	1.86×10^{-10}	1.83×10^{32}	1, 2
AN UMa	≥270	0.3	7.2×10^{-11}	$\geq 3.15 \times 10^{32}$	1, 2
AM Her (3U 1809+50)	75	7	2.63×10^{-9}	8.87×10^{32}	1, 2
QQ Vul (E2003+225)	≥400	0.5	4.37×10^{-9}	$\geq 4.19 \times 10^{34}$	1, 2
EXO 03314−255.4	250	0.65	1.87×10^{-9}[c]	6.61×10^{33}	2, 3
EXO 023432−5232.3	500	0.015	2.66×10^{-10}[c]	3.76×10^{33}	2, 4
DP Leo (E1114+182	≥380	0.0163	1.30×10^{-10}[c]	$\geq 1.06 \times 10^{33}$	2, 5

[a] Soft X-ray flux.

[b] Soft X-ray luminosity.

[c] Assume that the hard X-ray component's contribution (25 keV) is negligible compared with F_{sX}. For others, the hard X-ray component is subtracted out at 0.007 counts s^{-1} in the soft X-ray band for each 0.1 counts s^{-1} in the hard X-ray channel.

REFERENCES.—(1) Watson 1986; (2) Cropper 1990; (3) Giommi et al. 1987; (4) Beuermann et al. 1987; (5) Schaff et al. 1987.

absorption toward the interesting clusters. Considering the large distances to these clusters, most of the H I can be assumed to be between the clusters and the observers. Thus, the low Galactic latitude cluster M4 ($l = 350.97$°, $b = 15.974$°) is relatively nearby, at a distance of 2.1 kpc, but has a hydrogen column density $N_H = 1.21 \times 10^{21}$ cm^{-2} (Frisch & York 1989). By contrast, the high-latitude cluster M3 ($l = 42.2$°, $b = 78.707$°) is relatively far away, at a distance of 10.4 kpc, but has a hydrogen column density N_H of only 0.128×10^{21} cm^{-2}.

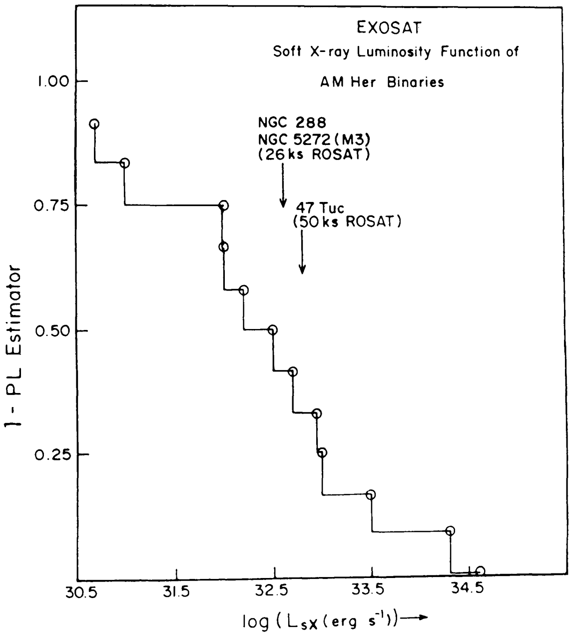

FIG. 2.—Soft X-ray luminosity function of AM Her binaries in the solar neighborhood based on the Kaplan-Meier PL estimator method. The data are taken from Table 4 for L_{sX}. Also shown, by vertical arrows, are the minimum luminosity levels to which the distribution function can be searched for a 50,000 s pointing of *ROSAT* for sources located in 47 Tuc. A similar level for NGC 288 and NGC 5272 (M3) for an integration time of 26,000 s by *ROSAT* is also shown. All three clusters are high Galactic latitude clusters.

Of the three high Galactic latitude globular clusters marked in Figure 2, 47 Tuc (distance = 4.6 kpc) has a Galactic N_H in its direction of 3.8×10^{20} cm^{-2}. Assuming a blackbody flux with $kT_{bb} = 30$ eV, the *ROSAT* high-resolution images would have a count rate of only 5×10^{-4} for an *unabsorbed* flux level of 5×10^{-13} ergs cm^{-2} s^{-1}, corresponding to $L_{sX} = 6 \times 10^{32}$ ergs s^{-1}. Hence 47 Tuc would require an exposure of about 50,000s for a 5 σ detection. In NGC 288, where $N_H = 1.5 \times 10^{20}$ cm^{-2}, a source with an unabsorbed flux of 10^{-13} ergs cm^{-2} s^{-1} ($L_{sX} \sim 4 \times 10^{32}$ ergs s^{-1}) would be detected in 26,000 s. The required time for a similar source in NGC 5272 (M3), where $N_H = 1.3 \times 10^{20}$ cm^{-2}, is comparable to that for NGC 288. Both of these possible detections assume a count rate of 1.2×10^{-3} counts s^{-1}. With the long exposure time, *ROSAT* may be able to detect ~1 strongly magnetized CV in 47 Tuc. On the other hand, the low Galactic latitude clusters such as M4, NGC 5139, and NGC 6656 would require an exposure of over 300,000 s for a source of comparable strength. Similarly, low Galactic latitude clusters such as Terzan 5, Liller 1, and NGC 6440 would be unsuitable for detection in the soft X-ray band despite their high probability of formation of MCVs.

The uncertainty in distance to some globular clusters does not, however, translate into as much uncertainty in N_H, especially for high-latitude sources, because the H I density is large only near the Galactic plane. Thus, although an uncertainty in distance of up to a factor of 2 in some cases would lead to a corresponding uncertainty in luminosity due to the inverse square law, the potentially major effect of altering N_H and affecting soft X-ray count rates drastically will be inoperative for high Galactic latitude sources as long as the distance to the source is greater than a few scale heights of H I density. In any case, the hard X-rays are not substantially affected by column densities of hydrogen, and for them only the inverse square law effect will be relevant.

4. DISCUSSION AND CONCLUSIONS

In this paper we have examined in greater detail a recent suggestion (RC) that strongly magnetic CVs may be formed in globular clusters by the tidal capture of isolated magnetic white dwarfs. In order to ascertain how these systems can be discovered, we have estimated the X-ray luminosity functions of the known MCVs which are found in the solar neighborhood. By including detections and upper and lower limits, we have deduced, using the software package ASURV (see Feigelson & Nelson 1985), that the hard X-ray luminosity of the DQ Her binaries is on the average a factor ~10 larger than that of the AM Her binaries. Although this has been suspected previously, this is the first time that quantitative support for this has been provided and suggests that the DQ Her binaries are better candidates for detection in globular clusters in the hard X-ray band. The clusters which are likely to contain MCVs detectable in the hard X-ray band by using *AXAF* and *ASTRO-D* have been pointed out in Table 2. It should be emphasized that the estimates for the numbers of such systems expected are underestimates, because they assume the systems are formed by tidal capture of isolated magnetized white dwarfs with field strengths greater than 1 MG. Because complete surveys for the 95% of white dwarfs with fields below 1 MG have not been made, it is possible that many such weak-field white dwarfs exist (J. Liebert 1985, private communication). Those with the minimum field ($\gtrsim 50$ kG) necessary to channel the flow of accreting material near the white dwarf could become weak-field DQ Her binaries by tidal capture.

We have also estimated the soft X-ray luminosity function of the known AM Her binaries using similar techniques, although the estimates are less reliable because the spectral parameters of these objects are not well known and the interstellar medium obscures the soft X-ray flux. By using our soft X-ray luminosity function, we show that some clusters, despite having a high probability of forming MCVs, would be unsuitable for detection in the soft X-ray band. With a long exposure time, *ROSAT* may be able to detect ~1 strongly magnetized CV in 47 Tuc. If a detection is made, this should be followed up with *HST* and *IUE* observations to determine whether the X-ray source has an excess UV flux characteristic of cyclotron self-absorbed high magnetic field systems.

If MCVs are detected in globular clusters, this would have a number of implications for the evolution of magnetic fields of white dwarfs and their evolution in close binaries. Thus, it would support models for the ohmic decay of white dwarf magnetic fields which show that the longest-living (fundamental) mode, for a dipole field, does not decay significantly in the Hubble time (Chanmugam & Gabriel 1972; Wendell, Van Horn, & Sargent 1987). On the other hand, it would argue against models that explain the absence of strongly magnetic CVs with fields greater than about 50 MG. These models suggest that such systems may have been formed but evolve so rapidly that they become detached and appear instead as isolated magnetic white dwarfs (see Schmidt et al. 1986 and Hameury, King, & Lasota 1989 for details). Similarly, the detection of a strongly magnetized CV in a globular cluster may have implications in delineating the evolutionary stages connected with magnetic field generation (or destruction). This is because the evolution of a white dwarf binary formed by tidal capture is different from the evolution of younger *ab initio* binaries likely to be formed in the solar neighborhood, since some of the evolutionary processes in the latter, e.g., a common envelope phase, may have been skipped by the former.

To summarize, in this paper we have estimated the X-ray fluxes of globular cluster MCVs by using a statistical analysis of the X-ray emission of solar neighborhood MCVs which also includes upper and lower limits. We then use these results to identify those globular clusters which are likely to contain MCVs that may be detectable by means of their X-ray emission.

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