THE ASTROPHYSICAL JOURNAL, 350:L9–L12, 1990 February 10

STRONGLY MAGNETIC WHITE DWARF BINARIES IN GLOBULAR CLUSTERS

A. RAY
Tata Institute of Fundamental Research
AND
G. CHANMUGAM
Department of Physics and Astronomy, Louisiana State University, Baton Rouge
Received 1989 October 17; accepted 1989 November 17

ABSTRACT

We predict that globular clusters are likely to contain a new class of magnetic cataclysmic variables (CVs) with significantly high fields ($50 \lesssim B \lesssim 500$ MG) which is unknown among the CVs in the solar neighborhood. In addition, we make estimates of their expected X-ray luminosities and propose that X-ray surveys combined with optical/UV observations should lead to the detection of the brightest of them. Specific target globular clusters with high probability of detection of these sources are given.

Subject headings: clusters: globular — stars: binaries — stars: magnetic — stars: white dwarfs

I. INTRODUCTION

Cataclysmic variables (CVs) are close binary star systems in which a white dwarf accretes matter from a red dwarf star (Patterson 1984). Magnetic CVs (MCVs) are a subclass of these in which the magnetic field strength of the white dwarf is sufficiently strong so that the accreting material is channeled onto the magnetic poles of the white dwarf (Cropper 1989; Berriman 1988). All the known MCVs lie in the solar neighborhood, and little is known about their existence in the more distant globular clusters.

X-ray surveys of low-mass X-ray binaries (LMXBs), which are essentially complete because of their high intrinsic luminosities, allow LMXBs to be more easily detected at large distances than CVs, since they contain accreting neutron stars rather than accreting white dwarfs (Hertz and Grindlay 1983). About 10% of all galactic LMXBs are located in globular clusters, even though the clusters contain only 10^{-4} of the Galactic mass. The overabundance of LMXBs in globular clusters relative to those in the Galactic disk has led to the suggestion (Fabian, Pringle, and Rees 1975; Sutantyo 1975) that they are formed by the tidal capture of a field neutron star in the cluster rather than by the evolution of a primordial binary. Since the tidal capture cross section σ is roughly the same whether the compact star is a white dwarf or a neutron star (except for the effects of mass segregation in centrally condensed clusters [Verbunt and Meylan 1988]), globular clusters could also have an overabundance, with respect to the Galactic disk, of white dwarf binaries.

The globular clusters have an overabundance of millisecond pulsars as well, compared to their number in the Galactic disk (Kulkarni, Narayan, and Romani 1989). It is possible that at least some of them are formed from the accretion-induced collapse of white dwarfs (Michel 1987; Chanmugam and Brecher 1987; Grindlay and Bailyn 1988; but see also Ray and Kluzniak 1989) without passing through the LMXB phase (Bailyn and Grindlay 1989). Since the magnetic field of the neutron star produced may reflect that of the progenitor white dwarf (Chanmugam and Brecher 1987), it is clearly of interest to estimate the number of white dwarf binaries in globular clusters and especially the distribution of their magnetic fields and luminosities.

In this *Letter* we estimate the number of binaries containing magnetic white dwarfs in globular clusters. Since these are mainly formed through tidal capture, the distribution of magnetic fields will resemble those of single white dwarfs in the cluster and not those of primordial white dwarf binaries. If we assume that this single white dwarf field distribution is similar to that in the Galactic disk, then the distribution of fields of MCVs in globular clusters will be very different from their counterparts in the Galactic disk. The MCVs may be divided into two subclasses: the AM Herculis binaries which contain synchronously rotating white dwarfs, and the DQ Herculis binaries which contain asynchronously rotating ones. The magnetic fields of the AM Her binaries lie between about 20 and 50 MG (Cropper 1989), while those of the DQ Her binaries are likely to be between about 0.05 MG and 10 MG (Chanmugam and Ray 1984). Spectroscopic searches have failed to reveal magnetic fields in other known CVs (H. S. Stockman, unpublished). 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* among various CVs in the solar neighborhood have failed to reveal any such sources (Bond and Chanmugam 1982). Thus, MCVs have magnetic fields $B \lesssim 50$ MG in the Galactic disk. Although about 20% of the known CVs in the Galactic disk are magnetic (Morris *et al.* 1987), only 3%–5% of isolated white dwarfs are magnetic (Angel, Borra, and Landstreet 1981) with $1 \lesssim B \lesssim 500$ MG (Schmidt 1989). We predict therefore that globular clusters will contain a significant new class of MCVs with high fields ($50 \lesssim B \lesssim 500$ MG) not previously known. We also make estimates of their expected hard X-ray luminosities and propose that observations with the next generation of X-ray satellites combined with optical/UV measurements with the Hubble Space Telescope should target globular clusters with high probabilities for detecting such sources.

II. FORMATION OF MAGNETIC WHITE DWARF BINARIES IN GLOBULAR CLUSTERS

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 lower main-sequence stars) and the number of white dwarfs present in the globular cluster core. This number, integrated over the globular cluster lifetime τ_{GC} ($\sim 10^{10}$ yr), is equal to $\Gamma \tau_{GC} r_c^3 n_{WD}$. Here, n_{WD} is the number density of white dwarfs in the globular cluster core of radius r_c, while the rate of tidal capture in the globular cluster core per compact star is given by (Ray, Kembhavi, and Antia 1987)

$$\Gamma = n_T \sigma v = 2.9 \times 10^{-12} \text{ yr}^{-1} \left(\frac{M_T}{2\,M_\odot}\right)\left(\frac{R_m}{3.84 R_*}\right)\left(\frac{R_*}{0.65\,R_\odot}\right) \times \left(\frac{v_{rms}}{10 \text{ km s}^{-1}}\right)^{-1}\left(\frac{n_T}{10^4 \text{ pc}^{-3}}\right). \quad (1)$$

Here σ is the tidal capture cross section, and v is the relative velocity of the colliding stars, set equal to the velocity dispersion of stars v_{rms} in the globular cluster core. The rate has been normalized to the parameters relevant to a 0.6 $M_\odot$ main-sequence star taken to be a $n = 3/2$ polytrope. R_m is the periastron distance, R_* is the radius of the main-sequence star, and M_T is the total mass of the system. The cross section σ is dominated by the gravitational focusing term in the impact parameter so that $\sigma \simeq 2\pi R_m G M_T/v^2$.

The widest orbit upon circularization following tidal capture has an orbital period P_{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 $P_{orb} \lesssim 0.5$ day. Thus, the probability of forming a CV–like system directly through tidal capture is roughly 0.6 times the probability of forming all white dwarf binaries. In addition, some of the wider systems ($P_{orb} \gtrsim 0.5$ day) may also evolve into CV–like systems quickly, as in the process of binary formation the the system may go through a common envelope phase (Ray, Kembhavi, and Anita 1987). To estimate the number of all white dwarf binaries formed in globular cluster in τ_{GC}, one needs the number of all white dwarfs formed in the globular cluster core, which in turn depends on the initial mass function (IMF) of stars in the cluster core. The IMF is usually described by a power law of index α [$dN(M)/dM \propto M^{-\alpha}$] and varies substantially according to the metallicity of the cluster.

Small IMF indices ($\alpha \sim 2.5$) lead to cluster disruption due to heavy mass loss from too numerous supernovae (Chernoff and Weinberg 1990). Clusters with $\alpha = 3.5$ may, however, survive under a wide variety of initial conditions. The tidal capture rate given by equation (1) predicts 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}. However, as many as 20% of the globular clusters which have unresolved cores (Djorgovski and King 1986) could have undergone collapse, in which a larger fraction of the white dwarfs could have a captured companion (Bailyn and Grindlay 1989) due to substantially higher stellar density. An example of having a high fraction of white dwarfs in binaries may be NGC 6440, if the IMF index is $\alpha = 3$. The number of compact stellar remnants in a globular cluster and the number of binaries formed over its age depend sensitively on the IMF index. The formation rate of white dwarf binaries is also affected by mass segregation effects for centrally condensed clusters like 47 Tuc (Verbunt and Mevlan 1988). Photometry and spectrophotometry of the globular central regions have helped model the radial distribution of stars in only a few clusters so far. Further observational inputs toward white dwarf binary formation rate may become available for a larger number of clusters in the future. In a global average, as much as a fraction $\simeq 0.1$ of the compact stellar remnants in the cores may have been tidally captured.

TABLE 1

HIGH WEIGHT GLOBULAR CLUSTERS FOR WHITE DWARF–MAIN SEQUENCE STAR BINARIES

Name	W_1[a]	d[b] (kpc)	W_1/d^2 [c]	Detections[d]
Ter 5	0.13	7.1	0.0026	X
Lil 1	0.10	7.9	0.0016	X
NGC 6440	0.08	7.1	0.0016	X
47 Tuc	0.03	4.6	0.0014	2P
NGC 6266/M66	0.04	6.1	0.0011	...
NGC 6388	0.09	13.5	0.0005	...
NGC 6626/M28	0.016	5.8	0.0005	P

[a] Weight factor for formation (which does not account for mass segregation effects mentioned in § II).
[b] Distance.
[c] Weight factor (unnormalized) for detection.
[d] Indication of whether a compact source such as a low-mass X-ray binary (X) or radio pulsar (P) has already been detected in the cluster.

The relative contribution of a cluster toward binary formation rate normalized to the contribution from all clusters would scale as $W_1 \propto n_*^2 r_c^2/v_{rms}$. Here n_* is the number density of stars in the cluster core. About seven clusters like NGC 6440 have high stellar density and low velocity dispersion, which together would provide roughly half the weight W_1 of all white dwarf binaries present in the globular cluster cores. Equation (1) predicts that there would be roughly 6000 white dwarf binaries formed in NGC 6440 (which has a core radius of 0.24 pc and a velocity dispersion of 13 km s^{-1}) in its entire lifetime. This is assuming $\alpha = 3$ which gives ~ 9000 white dwarfs and $\sim 54{,}000$ main-sequence stars in the cluster core. The number of white dwarf binaries formed over 10^{10} yr in 47 Tuc, on the other hand, with a central density one-fifth that of NGC 6440, is about 330 when the mass segregation effects and the different IMF index of the former are taken into account. Thus, the globular cluster systems in all would contain roughly 100,000 white dwarf binaries, most of which are in the high-weight (W_1) clusters. Some of these are listed in Table 1.

Out of the 10^5 white dwarf binaries, more than 6×10^4 would be systems with $P_{orb} \leq 0.5$ days which are CV–like at one time or other. Among these, the currently observable magnetic CVs, which may be luminous in the hard X-ray band, are estimated as follows: (1) 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%; and (2) the binary magnetic white dwarf system will be X-ray active for only a CV lifetime of $\tau_X = 4 \times 10^8$ yr, which is roughly 1/25th the globular cluster lifetime τ_{GC}. Thus at any given time only 1/25th of the magnetic white dwarf binaries will be active as X-ray–emitting objects. Therefore, the total number of MCVs currently observable in the globular cluster systems by their X-ray emission is

$$N_{MCV} = 100\left(\frac{N_{WD}}{10^5}\right)\left(\frac{f_{CV}}{0.6}\right)\left(\frac{f_{MWD}}{0.03}\right)\left(\frac{\tau_X/\tau_{GC}}{0.04}\right). \quad (2)$$

Here, f_{CV} is the fraction of the binary white dwarfs that enter the CV phase, and f_{MWD} is the fraction of white dwarfs which are magnetic and are likely to be greater than 0.6 and 0.03, respectively. In order to estimate the number of systems which can be detected by an X-ray instrument of a given sensitivity, we have to find the luminosity distribution of the MCVs.

III. HARD X-RAY LUMINOSITY OF MAGNETIC CATACLYSMIC VARIABLES

The MCVs are found to be particularly bright sources in the X-ray band. Out of the five CVs accidentally discovered by *EXOSAT*, four were found to be MCVs (Giommi, Tagliaferri, and Angelini 1988). The *EXOSAT* survey in the 2–10 keV hard X-ray band detected 13 MCVs in the solar neighborhood and put limits on the X-ray flux from nine other sources known to be MCVs. We use these fluxes (Watson 1986; Norton and Watson 1989) and distance estimates (Cropper 1989) to construct a histogram of the luminosities of MCVs (Fig. 1). The peak of the distribution appears in the log L_X bin between 31.5 and 32.5, where L_X is in ergs s^{-1}. These are primarily the DQ Her systems. The AM Her systems are relatively underluminous in the hard X-ray band—their peak in the luminosity distribution appearing in a bin 10 times fainter than that of the DQ Her systems. Luminosities below log $L_X = 30.5$ are primarily upper limits for known MCVs. This is qualitatively consistent with the view that the accretion rate and, hence the bolometric luminosity of CVs decline with orbital period as the system evolves (Patterson 1984) and that the AM Her binaries have, in general, shorter orbital periods than the DQ Her binaries (Chanmugam and Ray 1984).

If we make the hypothesis that the luminosity distribution of globular cluster MCVs is the same as that of the known 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. As the globular clusters are a few kiloparsecs away (contrast the known CV distances of several hundred parsecs), only the fraction ($\sim 3/22$) of

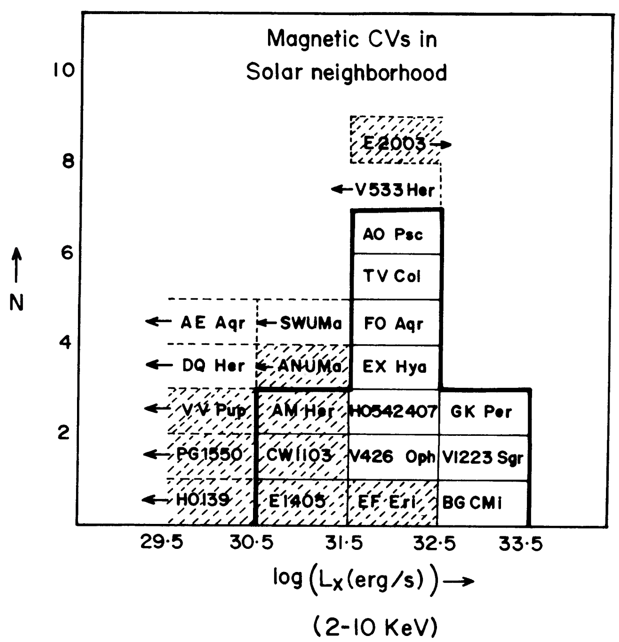

FIG. 1.—Magnetic cataclysmic variables in the solar neighborhood detected by the *EXOSAT* survey in the hard X-ray (2–10 keV) band. Shaded boxes represent which are of the AM Herculis type. Upper or lower limits of detection are indicated by arrows inside dashed boxes.

sources in the highest luminosity bin in Figure 1 may be detectable. Since there are approximately 100 currently active MCVs in globular clusters (eq. [2]), less than approximately 15 hard X-ray sources may be detectable by surveys like that of *EXOSAT*. As many globular clusters are much farther away than just a few kiloparsecs, some of them may be below the threshold for detection.

As argued in § II, a few globular clusters with high central density and large core size contain most of the binaries with magnetic white dwarfs. In Table 1 we list seven globular clusters which cumulatively are likely to contain approximately half of the MCVs in all globular clusters, arranged according to the distance-weighted detection probability at a given flux level, $W_1/r_{\rm kpc}^2$, where W_1 is the normalized weight of a cluster toward MCV population, and $\tau_{\rm kpc}$ is the distance to the cluster in the kiloparsecs. This is a relative measure of observability of MCVs at a given flux level. Thus, there would be roughly 10 high-luminosity sources in the 10 globular cluster systems.

In this connection we note that in a survey conducted by the *Einstein Observatory* using the soft X-ray band, Hertz and Grindlay (1983) found eight "low-luminosity" sources which they ascribed to white dwarf binaries. It is not immediately apparent how to correlate these sources with our estimates of hard X-ray detectable sources, since the soft X-ray distribution of solar neighborhood MCVs are poorly known even compared to their hard X-ray luminosity distribution. Additionally, one requires the relative sensitivities of the two searches by *Einstein* and *EXOSAT* in the two energy bands.

IV. CONCLUSIONS

In this *Letter*, we have proposed that most of the MCVs present in globular clusters are formed by tidal captures of isolated magnetic white dwarfs by main-sequence stars. If the isolated magnetic white dwarfs in globular clusters have similar field distributions as those in the solar neighborhood, the distribution of the magnetic fields of the white dwarfs in MCVs in globular clusters may be qualitatively different from those found locally. More specifically, we predict that there may exist a new class of MCVs with strong magnetic fields $50 \lesssim B \lesssim 500$ MG which is presently unknown in the solar neighborhood. The number of these systems would be about one-fourth that of the MCVs with $B \gtrsim 1$ MG, on the basis of local white dwarf field distribution. We estimate that the globular clusters should contain ~ 100 MCVs, with $1 \lesssim B \lesssim 500$ MG. We list in Table 1 clusters which are likely to contain about one-half of the MCV population and arrange them according to their relative weights toward detectability. Since roughly 15% of these are high-luminosity sources (Fig. 1), future hard X-ray observations with the next generation of X-ray satellites (e.g., *ASTRO-D*, *AXAF*) should reveal about 10 of the brightest of these with luminosities $\gtrsim 10^{33}$ ergs s^{-1}. Soft X-ray detectors aboard *ROSAT* should be able to detect the strongly magnetized ones among the brightest AM Her binaries.

We suggest that the low-luminosity sources ($10^{32} \lesssim L_X \lesssim 10^{34.5}$ ergs s^{-1}) detected by the *Einstein* soft X-ray survey might contain some of the MCVs with relatively strong magnetic fields $B \gtrsim 10$ MG, since the AM Her binaries have relatively strong soft X-ray fluxes compared to the DQ Her binaries. Estimates of the ratio (or upper bounds) of the soft to hard X-ray fluxes in these cases will enable one to decide whether they have strong fields ($B \gtrsim 10$ MG) or not (Beuerman *et al.* 1989; Osborne 1986). In addition, the very high magnetic field objects ($B \geq 100$ MG) would be significant sources of UV radiation by optically thick cyclotron emission. The presence or absence of strongly magnetic CVs in globular clusters has important implications for the evolution of MCVs and the distribution of white dwarf magnetic fields.

This research was supported by NSF grants AST-8822954 to LSU and INT87-15411-A01-TIFR to Tata Institute. A. R. wishes to thank LSU's Department of Physics and Astronomy for its hospitality.

REFERENCES

Angel, J. R., Borra, E. F., and Landstreet, J. D. 1981, *Ap. J. Suppl.*, **45**, 457.
Bailyn, C. D., and Grindlay, J. E. 1989, preprint.
Berriman, G. 1988, in *Polarized Radiation of Circumstellar Origin*, ed. G. V. Coyne *et al.* (Vatican City: Vatican Observatory), p. 281.
Beuermann, K., Thomas, H.-C., Giommi, P., Tagliaferri, G., and Schwoppe, A. 1989, *Astr. Ap.*, in press.
Bond, H. E., and Chanmugam, G. 1982, in *Advances in Ultraviolet Astronomy: Four Years of IUE Research* (NASA CP-2238), ed. Y. Kondo, J. M. Mead, and R. D. Chapman (Washington, DC: NASA), p. 530.
Chanmugam, G., and Brecher, K. 1987, *Nature*, **329**, 696.
Chanmugam, G. and Ray, A. 1984, *Ap. J.*, **285**, 252.
Chernoff, D., and Weinberg, M. 1990, *Ap. J.*, in press.
Cropper, M. 1989, *Space Sci. Rev.*, in press.
Djorgovski, S., and King, I. R. 1986, *Ap. J. (Letters)*, **305**, L61.
Fabian, A. C., Pringle, J. E., and Rees, M. J. 1975, *M.N.R.A.S.*, **172**, 15P.
Giommi, P., Tagliaferri, G., and Angelini, L. 1988, *Mem. Soc. Astr. Italiana*, **59**, 33.
Grindlay, J. E., and Bailyn, C. D. 1988, *Nature*, **336**, 48.
Hertz, P., and Grindlay, J. E. 1983, *Ap. J.*, **275**, 105.
Kulkarni, S. R., Narayan, R., and Romani, R. W. 1989, *Ap. J.*, submitted.
Michel, C. F. 1987, *Nature*, **329**, 310.
Morris, S. L., *et al.* 1987, *Ap. J.*, **314**, 641.
Norton, A. J., and Watson, M. G. 1989, *M.N.R.A.S.*, **237**, 715.
Osborne, J. P. 1988, *Soc. Astr. Italiana*, **59**, 117.
Patterson, J. 1984, *Ap. J. Suppl.*, **54**, 443.
Ray, A., Kembhavi, A. K., and Antia, H. M. 1987, *Astr. Ap.*, **184**, 164.
Ray, A., and Kluzniak, W. 1989, preprint.
Schmidt, G. D. 1989, in *IAU Colloquium 114, White Dwarfs*, ed G. Wegner (Berlin: Springer Verlag), p. 305.
Sutantyo, W. 1975, *Astr. Ap.*, **44**, 227.
Verbunt, F., and Meylan, G. 1988, *Astr. Ap.*, **203**, 297.
Watson, M. G. 1986, in *The Physics of Accretion onto Compact Objects*, ed. K. O. Mason, M. G. Watson, and N. E. White (Berlin: Springer-Verlag) p. 97.

GANESAR CHANMUGAM: Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803

ALAK RAY: Theoretical Astrophysics, Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India