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# CATACLYSMIC BINARIES IN STAR CLUSTERS. I. A SEARCH FOR ERUPTING DWARF NOVAE IN THE GLOBULAR CLUSTER M92

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## ABSTRACT

Globular clusters are reputed to contain many capture (and possibly primordial) binaries. Close white dwarf–main sequence binaries should be particularly plentiful. Such systems can give rise to dwarf nova eruptions, which are indisputable indicators of interacting, close binaries. We have therefore surveyed the rich Galactic globular cluster M92 (NGC 6341) for erupting dwarf novae. CCD images with limiting magntide ~21.5 on 10 of 13 consecutive nights yield zero erupting dwarf novae. Artificial dwarf novae inserted into the CCD frames allow us to assess our completeness of detection. We should have detected 50% of all erupting dwarf novae at 6 core radii from the cluster center and 90% of such events further out. The lack of detections limits the number of dwarf nova binaries in M92 with $6r_c < r < 20r_c$ to $\leq 7$ with 92% probability. Our upper limit of $\leq 7$ is the first observational quantitative limit on globular cataclysmics.

A simple model (based on two-body tidal capture theory and binary evolution) is used to predict the number of cataclysmic binaries in M92. The globular should contain ~70 systems; roughly 11 should lie outside $6r_c$. Our observed upper limit suggests that an expanded observing program will soon detect or rule out large numbers of cataclysmics in globulars.

*Subject headings:* binaries: close — globular clusters: individual (M92) — novae, cataclysmic variables — stars: statistics

## 1. INTRODUCTION

Astronomers have finally embraced the concept of globular clusters (GCs) rich in, and dynamically driven by, close binary stars. The binding energy of just a few close binaries rivals that of an entire cluster of $10^5$ stars. Thus, the discoveries of X-ray binaries, eclipsing binaries, millisecond pulsars, radial velocity variables, thickened main sequences, and variable blue stragglers have revolutionized the study of GCs. An exhaustive review of the observations and theory of binaries in GCs has recently appeared (Hut et al. 1992) and the reader is referred to it for an in-depth review of the subject.

Cataclysmic variables (CVs) are the rarest binaries known in GCs. Only two classical novae (Sawyer 1938; Hogg & Wehlau 1964), one dwarf nova (Margon, Downes, & Gunn 1981), and one likely magnetic, X-ray emitting CV (Paresce, de Marchi, & Ferraro 1992) are near-certain members of Galactic GCs. Hertz & Grindlay (1983) suggested that GC CVs should be considerably more plentiful than low-mass X-ray binaries, as white dwarfs are more common than neutron stars. Hut & Verbunt (1983) and Verbunt & Meylan (1988) predicted much lower numbers of globular CVs on the basis of the lower capture probability of WDs relative to neutron stars. Rappaport & Di Stefano (1993) note that white dwarfs are less likely than neutron stars to be ejected from clusters during their formation and predict the presence of order 100 cataclysmics (mostly low mass transfer rate systems) in each of $\omega$ Cen and 47 Tuc.

Better observational evidence concerning globular CVs is sorely needed and is the motivation of the present study. We have searched for erupting dwarf novae (DNs) in the globular cluster M92. This was done because DN light curves are unique and indisputable proof of the presence of a cataclysmic binary.

With brightnesses near outburst peak of $M_B \sim +4.5$ (and little spread in this value; see Vogt 1982), erupting dwarf novae should reach $B \sim 19$ in M92—easily detectable on CCD frames outside the dense cluster core. Their expected brightness increases of 3–5 mag in just one or two nights (from ~22 mag in M92 quiescence) should help pinpoint candidates.

The observations are described in § 2, and the search for variables is discussed in § 3. The results of the search, and the implications for the number of cataclysmics in M92 and other globulars are summarized in § 4.

## 2. OBSERVATIONS

Images of M92 were taken on 10 of 13 consecutive nights between 1991 September 2 and 14, with the Wise Observatory 1 m telescope and 1024 × 1000 pixel TI CCD. The detector has a scale of 1″ per pixel.

Three images of the cluster, each of 30 minutes duration through a liquid $CuSO_4$ filter (essentially a broad-band $U + B + V$ filter), were made on each of the nights, except for September 11, which has only two good images, and September 13, which has only one. No data were obtained on September 3, 9, and 10. Stars brighter than $B \sim 14$ are saturated, as is the cluster core. The frames were debiased and flat-fielded, and the three images on each night were medianed together to produce a single frame. The two September 11 images were

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averaged. There was a residual sky background variation along the $x$-axis in the September 12 images after flat-fielding. It was removed by fitting a surface to the background and subtracting the fit from the data. Hereafter, we refer to the "nightly frames" as the medianed, averaged, or sole frame, as the case may be.

## 3. DATA ANALYSIS

### 3.1. *Searching for Variables*

DAOPHOT (Stetson 1987) was used to obtain profile-fitting photometry and positions for all the stars in each of the nightly frames. Since the position of the center of the cluster on the CCD was slightly different from night to night, small corrections were applied to the coordinates to put them all in the reference frame of the September 8 image (which was best centered in the aperture). The coordinates from each frame were then matched to all the other frames. Stars whose positions were separated by $\leq 3''.0$ were considered to be the same star on successive frames. A master list was then generated which contained only one entry for each possible star in the entire 10 night set. This gave each star a unique identification and position. DAOPHOT was then run again on all the frames using the master coordinate list. This ensured that stars which were found above the plate limit, on only one or a few frames initially, would at least be looked at by DAOPHOT in the second pass on *all* the frames to see if they were really there. Note that due to the differences in centering the cluster from night to night, some stars near the edges of the frames were sampled on some nights and not on others, but these stars were still included in the search. Our master list contained 5634 stars.

A plot of magnitude variability index (Shara et al. 1988) $\sigma$ versus mean magnitude (Fig. 1) was then made to separate anything that might be variable from the rest of the set. The variability index (essentially a $\chi^2$) is most sensitive to smoothly varying objects (such as dwarf novae on the decline from eruption). Stars with $\sigma$ above the mean curve (above $\sigma \sim 0.15$ to 0.45 mag, depending on magnitude) were considered candidates as variables and were inspected individually to see if the apparent variability was caused by an intrinsic brightness change in the star or by some artificial factor in the data. The 1203 high $\sigma$ stars were visually inspected individually. Embedded cosmic rays, "blooming" from nearby saturated stars or mismatching by the ALLSTAR profile fitting in DAOPHOT were all causes for false variability of stars in the set. All six previously known RR Lyrae type variables with $r \geq 6r_c$ were easily found. No other variable stars of any kind brighter than $B \simeq 20.5$ (see below) were found in this search.

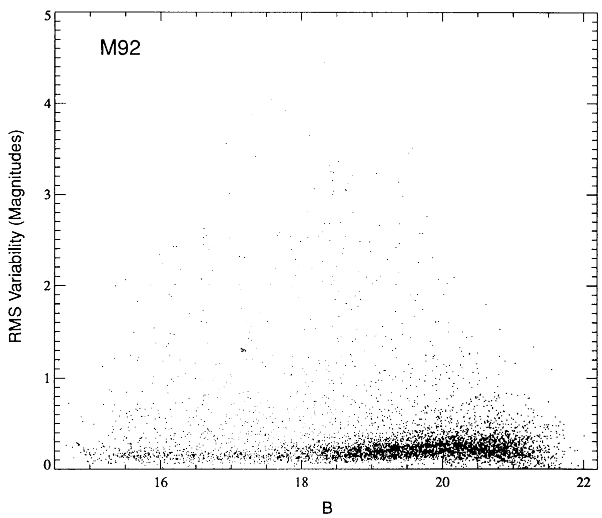


FIG. 1.—The mean magnitude of each star vs. the rms of its magnitude over the nights for which DAOPHOT returned a valid magnitude. Stars with only one night of valid magnitude are, of course, not shown here but were examined separately.

A second search was made specifically to find dwarf novae erupting between successive nights—or stars eclipsed by binary companions on only one or a few nights of our observing run. The absolute magnitude difference for each star between successive nights of observation was calculated. All 605 stars which showed large apparent variability ($\gtrsim 3.5\ \sigma$ at the mean magnitude of each considered star, typically 0.5 mag) were examined individually. None was found to be variable.

### 3.2. *Magnitude Limits and Completeness*

Our complete lack of detection of variables in M92 would have little value without a discussion of the completeness of the search as a function of magnitude and distance from the cluster core. This is given below.

#### 3.2.1. *Magnitude Limit*

The liquid $CuSO_4$ filter we used has transmission very close to unity from the atmospheric limit to 6200 Å, and zero redward. Dwarf novae typically display $U-B \sim -1.0$, $B-V \sim 0.0$ during outburst. Our filter is thus a good match to the colors of DNs and helps suppress the light of cluster red giants and low-mass dwarfs.

The broad-filter response precludes assigning a well-defined magnitude in a standard photometric system to each observed star. As a reasonable compromise, we assigned the published $B$ magnitudes of Sandage (1970) to a sequence of 25 stars and used the resulting instrumental versus $B$-magnitude curve to calibrate all other stars.

Figure 2 is a histogram of the 5634 detected stars. It is apparent that (outside the saturated core—see below) we are

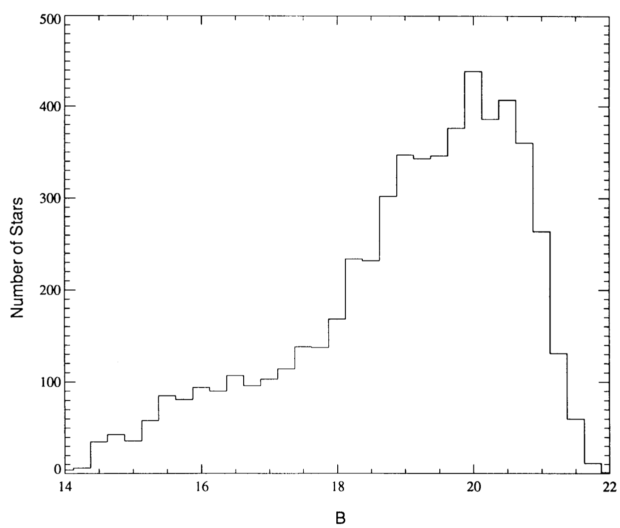


FIG. 2.—Histogram of all 5634 detected stars

90% complete in our detection limit to $B \approx 20.5$, roughly 50% complete from $B = 20.5$ to $B = 21$, and reach the detection limit at $B \approx 21.5$.

As an independent check on the above magnitude completeness limit, we added sets of 80 artificial stars to one image. Each set of 80 stars had 10 stars at each half-magnitude step from 18.0 to 21.5, inclusive. The 80 stars were added simultaneously on concentric rings, with radii of 12 to $30r_c$ in steps of $3r_c$. The first search process of § 3.1 was repeated to try to find these stars; the result is shown in Figure 3. This confirms that our detection completeness limit is $B \sim 20.5$. A series of images of artificial stars of increasing magnitude is shown in Figure 4. This figure visually confirms that stars with $B \lesssim 20.5$ are straightforward to locate, while fainter stars are increasingly difficult. The $\sim$90% completeness limit to $B \approx 20.5$ did not vary significantly from night to night, *and it is adequate to guarantee nearly complete detection of erupting dwarf novae in M92* (*see next section*).

#### 3.2.2. *Completeness of Detection of Erupting Dwarf Novae*

Three sets of 110 stars each, at 19.0, 19.5, and 20.0 magnitude, were added in three separate trials to one image. These artificial stars (with expected magnitudes of DNs within a few nights of eruption maximum) were added in concentric circles of radius increment $3r_c$, centered on the cluster core (10 stars at each of 3 mag in each of 11 rings). A search was conducted as above to determine the fraction of artificial variables found as functions of distance from the cluster center and of magnitude. The result is shown in Figure 5 for all 330 artificial stars. Our detection completeness rises from 10% at 3 core radii to 50% at $6r_c$ and is then $\geq$90% for $9r_c < r < 21r_c$. There is little dependence on source brightness except for $r < 6r_c$, where most of the located sources are the brightest (19th magnitude) ones. As a check, we note again that all six known RR Lyrae variables with $r \geq 6r_c$ (Nassau 1936) were easily rediscovered. Eight RR Lyraes with $2.5r_c < r < 5.4r_c$ were not rediscovered. (Two small amplitude suspected variables [0.30 and 0.25 mag amplitudes, according to Nassau] at 9.1 and 14.3 core radii, respectively, were also not found. These are, of course, much smaller amplitudes than exhibited by DNs.)

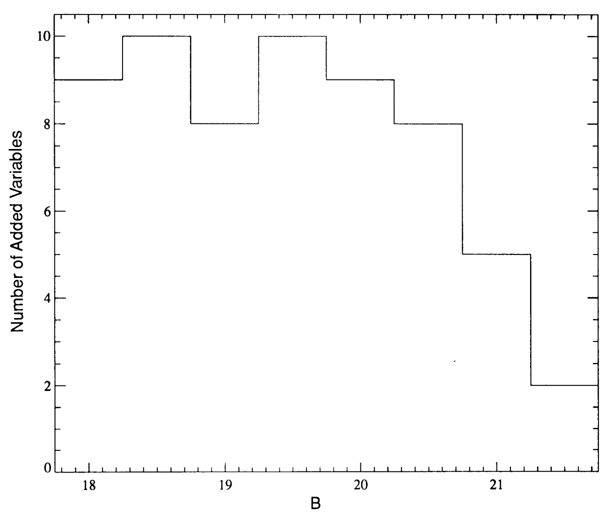


FIG. 3.—Histogram of the found, added variables. Ten of each from 18.0 to 21.5 in 0.5 magnitude steps (a total of 80) were actually added.

In summary, we believe that we are 90% complete in detection to $B = 20.5$ outside $9r_c$, and at least 50% complete for $6r_c < r < 9r_c$.

## 4. DISCUSSION

The outcome of our observations of M92 is that we detected zero erupting dwarf novae during the interval 1991 September 2–14. This negative result permits us to place an interesting upper limit on the number of dwarf novae in M92 (outside its core) as follows.

The distance modulus of M92 is 14.5, with essentially zero reddening (Harris & Racine 1979). DNs reach $M_B \simeq +4.5$ at maximum (Warner 1976; Vogt 1982), or $B \simeq 19$ in M92.

The time $t_r$ to rise to maximum light, and to remain at maximum $t_m$, varies from DN to DN. Szkody & Mattei (1984) have summarized the properties of the best studied DN and find $t_r$ and $t_m$ to average 2 days and 3 days, respectively (75% of systems have $t_r$ between 1 and 3 days, and $t_m$ between 2 and 5 days). The decline rates from maximum rarely exceed 1 mag day$^{-1}$. It is therefore common to find DNs within 1 mag of maximum for 5 days (1 day on the rise, 3 at maximum, 1 in decline) and only rarely for less than 3 days. We thus expect erupting DNs in M92 to display $B \lesssim 20$ for 3–5 days around maximum light (assuming of course, that globular DNs resemble those in the field).

In support of these statements we note that the well-documented eruption brightness of the only known DN in a globular cluster (V101 in M5) exceeded $B = 19.0$ for 5 consecutive nights in June 1985 (Shara, Moffat, & Potter 1987). The distance and reddening of M5 are practically identical to those of M92. If a V101-like DN had erupted in M92 during our 1991 observations, we would have easily detected it.

Two important conclusions can now be drawn. First, the one-night (1991 September 3) and two-night (1991 September 9 and 10) gaps in our 13 night run should not have caused us to miss any eruptions. Second, our $\gtrsim$90% completeness detection limits of suddenly appearing stars with $B \lesssim 20$ guarantee that we would have detected $\sim$90% of erupting DNs in M92 outside its core (see Fig. 5).

A simple model now permits us to place an upper limit on the number of DNs outside the GC core. Szkody & Mattei (1984) found that the average length of time between successive DN outbursts is 39 days. The probability that we should have detected any given DN in the outer regions of M92 is just $13/39 \times 0.9 = 0.30$. Then the probability of missing any given DN (because it is in quiescence throughout our 13 day period of coverage) is 0.70. The eruption epochs of every DN are independent of those of every other DN. Thus, the probability of our having missed $N$ DNs in M92 because of unlucky eruption timing is just $(0.7)^N$. For example, we can say that there are $\leq 7$ DNs outside $6r_c$ in M92 with 92% probability.

We can now compare our observational upper limit with a simple, theoretically predicted number of DNs in the outer part of M92. We base the M92 model on the work of Di Stefano & Rappaport (1993, hereafter DR), who calculated the expected number of CVs in 47 Tuc and $\omega$ Cen with tidal capture theory (Fabian, Pringle, & Rees 1975) and a binary evolution model. We note that 47 Tuc is only slightly more centrally concentrated than M92 but has 3 times more mass and suffers 2.5 times more collisions (and thus DN binaries) during a Hubble time. We simplistically scale down the number of DR predicted CVs in 47 Tuc by a factor of 3, to

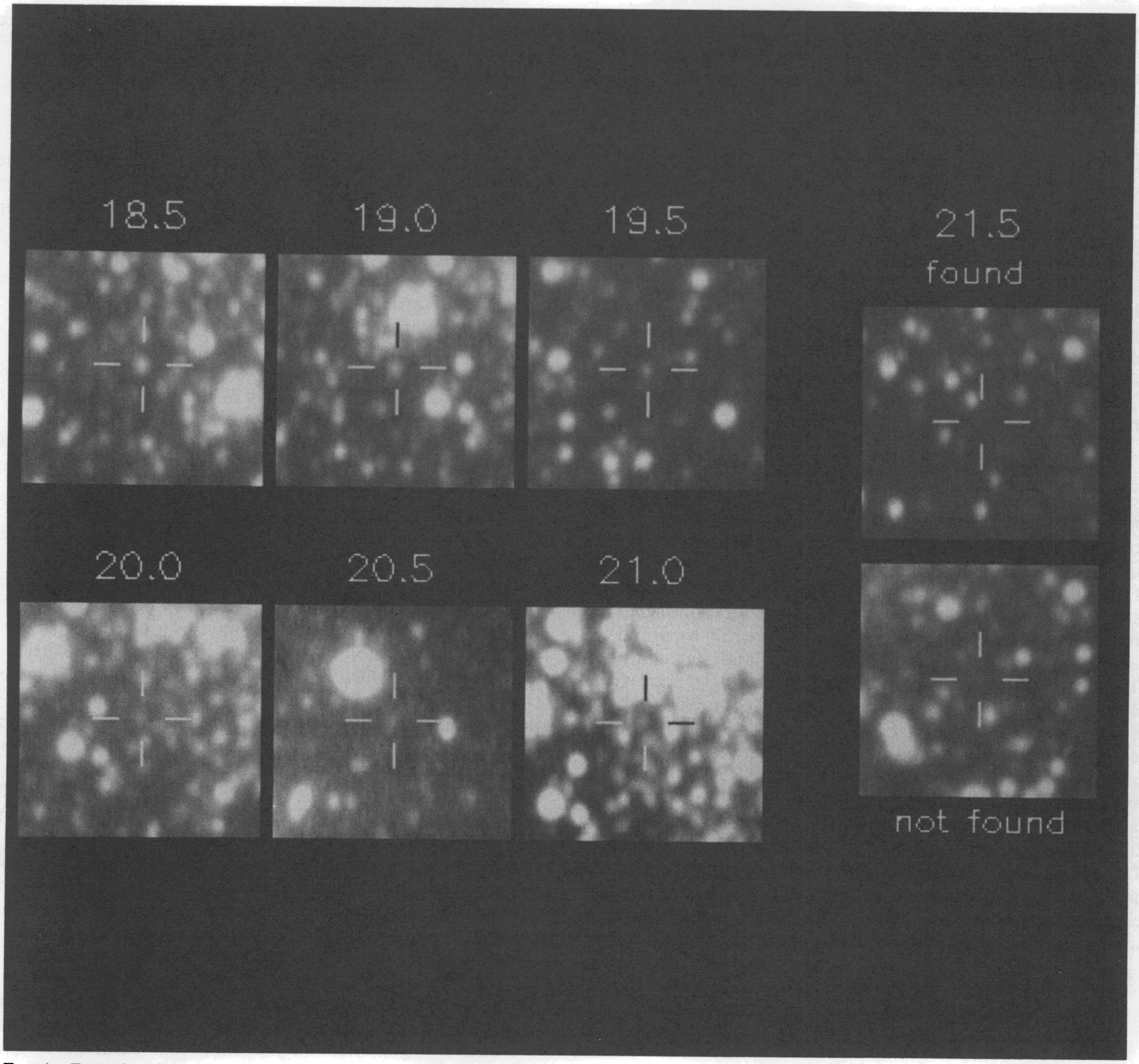


FIG. 4.—Examples of the added variables, ranging from 18.5 to 21.5 magnitudes. The 21.5 magnitude stars show the two cases: one which was found by the search, another which was not.

derive a rough estimate of the number of CVs in M92. In defense of adopting this crude approximation, we note that the estimated number of CVs in 47 Tuc depends linearly on the numbers and mass distribution of white dwarfs near the globular core. These numbers are uncertain by at least an order of magnitude; a more sophisticated model of the M92 CV population has no observational basis.

DR predict about 200 active mass-transfer binaries with $L$(x-rays) $> 10^{30}$ergs s$^{-1}$to now be present in 47 Tuc. (Low mass-transfer rate DNs [e.g., U Gem] typically emit $\gtrsim 10^{30}$ ergs s$^{-1}$ during quiescence [Cordova & Mason 1983].) DR also find that roughly $\frac{2}{3}$ of such systems should have white dwarfs with masses $\lesssim 0.75$ $M_{\odot}$. Figure 2*b* of Verbunt & Meylan (1988) suggests that $\sim\frac{1}{4}$ of these CVs should be formed outside $\approx 6r_c$. We adopt the above values for M92 and assume that $\frac{2}{3}$ of these moderate mass CVs retain their radial distance distribution after formation ($\frac{1}{3}$ capture heavy companions and migrate to the cluster center).

We can now predict that the number of CVs $N_{\rm M92}$ outside $6r_c$ is

$$N_{\rm M92} \sim 200 \times \tfrac{1}{3} \times \tfrac{2}{3} \times \tfrac{1}{4} \times \tfrac{2}{3} = 11. \qquad (1)$$

This value is comparable to our observed upper limit of 7 (with 92% probability).

Di Stefano and Rappaport (1993) concluded: "Our calculations of the numbers and luminosities of CVs are not obviously at odds with the lack of optical detection of numerous dwarf novae in globular clusters, but this needs to be quantified further." We have now done so, and agree with DR that there is not yet a strong disagreement between observations and theory. The limits presented here are on the verge of seriously constraining the predictions of CVs in globulars.

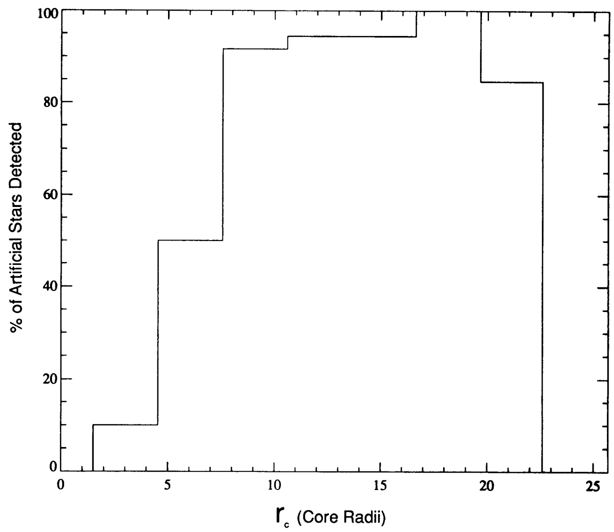


FIG. 5.—Percentage of added variables (artificial dwarf) novae) detected as a function of distance from the center of M92 (in units of core radii).

A factor of 4–8 reduction of our upper limit is clearly achievable with a 2 week run on a 1 m telescope (by observing 4–8 GCs nightly with a 2048 × 2048 CCD). A null result would imply $\lesssim 1$ DN per cluster outside $\approx 6r_c$, disconcertingly less than the (simple model's) prediction of 11. It is worth emphasizing, however, that the approximations and estimates that went into the model are sufficiently crude that even a reduction of 8 in the upper limit would by no means be fatal to tidal capture theory or the predictions of the existence of CVs in globular cores.

Even more exciting are *Hubble Space Telescope* observations now in hand. Several groups now have data sufficient to locate CVs in globular cores, or unambigously show that they are very rare or absent. We expect an observational resolution of the 20 year-old problem of the existence of globular core catalysmic binaries in the next one to two years.

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