THE ASTROPHYSICAL JOURNAL, 356:174–183, 1990 June 10

THE PULSAR CONTENT OF GLOBULAR CLUSTERS

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Received 1989 July 24; accepted 1989 December 14

ABSTRACT

Recent surveys of Galactic globular clusters have been very effective at discovering radio pulsars. By a careful analysis of selection effects in the various surveys, and after estimating the relative efficiency of pulsar production in the individual clusters, we obtain a census of the cluster population of pulsars. We find that there are $\sim 10^4$ pulsars in the Galactic globular clusters, subject to uncertainties in pulsar beaming and binarity. Such a large population poses severe problems for the standard model of pulsar production in clusters, unless the uncertain factors due to beaming and binarity are pushed to values inconsistent with our present expectations. This suggests the need for a substantial modification of the standard model, either by including accretion-induced collapse of massive white dwarfs or by increasing the retention of primordial neutron stars in the clusters. We also find that the birthrate of pulsars exceeds that of their presumed progenitors, the cluster low-mass X-ray binaries, by a large factor. This discrepancy, and a similar discrepancy for the binary and millisecond pulsars in the Galactic disk, can be resolved if the X-ray lifetime of low-mass X-ray binaries is ~ 100 times shorter than generally assumed. Finally, we present a table of the estimated numbers of pulsars in the rich globular clusters visible from the northern hemisphere. This table should be of interest to observers involved in pulsar searches.

Subject headings: clusters: globular — pulsars — stars: evolution — stars: neutron — X-rays: binaries

I. INTRODUCTION

Neutron stars have been discovered in globular clusters, as low-mass X-ray binaries (LMXBs) and as radio pulsars. The LMXBs are among the brightest X-ray sources in the sky, and consequently the ~ 10 LMXBs discovered in globular clusters represent a complete sample. In contrast, radio pulsars are intrinsically faint objects and are particularly hard to find in globular clusters because of the large distances. To date, seven pulsars have been discovered in the globular cluster system, but ongoing radio searches will undoubtedly uncover a few dozen more pulsars in the years to come as sensitivity and algorithms improve. Thus radio pulsars will increasingly become our prime window to study neutron stars in globular clusters.

The origin of pulsars and, in general, neutron stars in globular clusters is presently under dispute. The simplest hypothesis, hereafter the "standard" model, is that the neutron stars were born in the earliest epoch of star formation. Like the young pulsars observed in the disk of the Galaxy, the primordial neutron stars probably started with large magnetic field strengths, but the fields decayed rapidly (time scale $\sim 10^7$ yr) to an asymptotic value of 10^8–10^{10} G (Battacharya and Srinivasan 1986; Kulkarni 1986; van den Heuvel, van Paradijs, and Taam 1986) and the pulsars faded away from the radio sky. Subsequently, some fraction of the neutron stars, aided by the high stellar density, tidally captured field stars. Mass transfer from the companion then spun up the neutron star to a high rotation rate (see van den Heuvel 1988 for a review); during this phase, the system would have been visible as an LMXB (see Lewin and Joss 1983 for a review of LMXBs). If the final spin rate was rapid enough after accretion ceased, the neutron star reappeared in the radio sky as a fast pulsar in a binary system with a white dwarf companion. We refer to these as low-mass binary pulsars (LMBP); here the term "low mass" refers to the low-mass function of the binary. LMBPs are members of a new class of pulsars, the "recycled pulsars," which are defined to be pulsars that have undergone accretion at some stage in their life. If, as appears to be the case, the asymptotic magnetic fields do not decay further on a Hubble time scale, LMBPs with initial periods of tens of milliseconds or less will remain visible for the age of the Galaxy.

Following the discovery of the first pulsar PSR 1821−24 in the globular cluster M28 (Lyne *et al.* 1987) it was immediately realized that there should be many more pulsars in globular clusters. The 400 MHz flux density of this pulsar, $S_{400} \sim 25$ mJy, corresponds to a radio luminosity, $L_{400} = S_{400} d(\text{kpc})^2 \sim 700$ mJy kpc^2, which is nearly three orders of magnitude greater than the minimum luminosity of pulsars, ~ 1 mJy kpc^2 (Dewey *et al.* 1985). This, coupled with the L_{400}^{-1} luminosity law of observed pulsars (Lyne, Manchester, and Taylor 1985), suggested that PSR 1821−24 represented only the "tip of the iceberg" (Goss, Kulkarni, and Lyne 1988). The presence of a large number of faint pulsars in clusters would be quite difficult to understand, and other channels of pulsar production, such as accretion-induced collapse (AIC) of massive white dwarfs, may then have to be considered. Clearly, an observational

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determination of the pulsar content of globular clusters would therefore be most useful for further discussion of this question.

An additional issue is the birthrate of the pulsars in the globular clusters. In the framework of the standard model, the birthrate of the LMXBs should be equal to that of the LMBPs. However, in the disk of the Galaxy, the birthrates of LMBPs with orbital periods $\lesssim 25$ d exceeds that of their progenitor LMXBs by *at least a factor of 100* (Kulkarni and Narayan 1988). A similar comparative study in the cluster would be useful in shedding more light on this puzzling problem.

These two issues, viz., carrying out a census of the pulsar population and estimating the birthrates of the pulsars and their progenitors, constitute the principal goals of this paper. The completion of a fair number of pulsar searches toward clusters from Arecibo, Jodrell Bank, the VLA, and Green Bank provides sufficient observational data to make this study meaningful. These two issues were considered earlier by Grindlay and Bailyn (1988) and Bailyn and Grindlay (1990) using limited data. Our results, based on a large amount of observational data, are in fair agreement with their preliminary findings.

The organization of the paper is as follows. In § II we briefly describe the features of the five pulsar searches which constitute the basic observational material of this paper. The assumptions and the model adopted for the radio pulsars, such as the radio luminosity law, selection effects of pulsar searches, etc., are explained in § III and the results are given in § IV. Conclusions and implications for the origin and evolution of LMBPs are summarized in § V.

II. BASIC OBSERVATIONAL DATA

We included the following five major surveys in our analysis. The globular clusters searched by these surveys are listed in Table 1.

Jodrell Bank Survey.—This extensive survey was done at Jodrell Bank by Lyne and collaborators (Biggs, Lyne, and Brinklow 1989; Lyne and Biggs 1989) using the 76 m Lowell telescope. The target clusters were observed in one or more observing configurations ("rf" is radio frequency): $\nu_{\rm rf} = 610$ MHz central frequency with a 32×1 MHz filterbank ("low dispersion measure" search); $\nu_{\rm rf} = 610$ MHz, 32×250 KHz ("high-dispersion measure" search); $\nu_{\rm rf} = 1420$ MHz, 32×1 MHz. Details of the surveys may be found in the above papers, and Table 1 gives the minimum detectable flux, S_J, for each cluster. The 1400 MHz search discovered a 3 ms pulsar, 1821−249, in M28 (Lyne *et al.* 1987), and the "high dispersion measure" search discovered a 11 ms binary pulsar, 1620−264, with $P_{\rm orb} \sim 191$ day, in M4 (Lyne *et al.* 1988).

Arecibo Survey.—All the rich globular clusters accessible with the Arecibo telescope ($-1° \leq \delta \leq 38°$) were searched at a radio frequency, $\nu_{\rm rf} \sim 1400$ MHz. Details of this survey can be found in Kulkarni *et al.* (1990). Table 1 gives the flux limits, $S_{\rm A}$, down to which each cluster was searched. An isolated pulsar, 2127+11A, with a period of 110 ms was discovered in M15 (Wolszczan *et al.* 1989*a*). A second survey is now being done at 1400 MHz with faster sampling than before, and also at 430 MHz. This survey has already discovered two new pulsars in M15: 2127−11B, a 56 ms single pulsar with a flux density one-third that of PSR 2127+11A (Anderson *et al.* 1989*a*), and 2127+11C, a 30 ms pulsar in an 8 hr binary system with a flux density one-half that of PSR 2127+11A (Anderson *et al.* 1989*b*). The data from other clusters are currently being analyzed. We have included the new survey in our calculations only in the case of M15.

Green Bank Survey.—This survey was done using the NRAO 100 m telescope at Green Bank at $\nu_{\rm rf} = 1400$ MHz (Backer and Dey 1988). No pulsars were detected down to the limit of the survey ($S_G = 2$ mJy).

VLA Surveys.—Hamilton, Helfand, and Becker (1985) used the VLA to carry out an *imaging* search, at $\nu_{\rm rf} \sim 1.4$ GHz, for point sources within the cores of a dozen nearby clusters. Their flux limits, S_V, are given in Table 1. In comparison to normal searches that look for pulsation, imaging searches have the advantage that they are insensitive to pulse broadening due to dispersion or scattering by the interstellar plasma (see § III*b*) and limits on point sources place firm upper bounds on the flux of any undiscovered pulsar. This survey drew attention to an interesting point source in M28 which eventually led to the discovery of the first millisecond pulsar in a globular cluster, PSR 1821−24 in M28, at Jodrell Bank.

Deep VLA Survey.—Kulkarni *et al.* (1990) present results from long VLA observations of four clusters at $\nu_{\rm rf} \sim 1.4$ GHz. The 1 σ point source flux density values in the images of these four clusters are GC 1339+286 (M3; $\sigma_S \sim 45$ μJy); GC 1620−264 (M4; $\sigma_S \sim 60$ μJy); GC 1715+432 (M92; $\sigma_S \sim 24$ μJy); and GC 1821−249 (M28; $\sigma_S \sim 50$ μJy). Kulkarni *et al.* (1990) claim that a point source at the level of 3.5 σ_S would have been readily detected in their images. To this sensitivity limit, a total of three sources were found within the core regions of the four clusters; two of these are the known pulsars in M4 and M28, and the third is an intriguing point source in M3 with a flux density of 180 μJy. So far, Arecibo searches of M3 have not yielded any pulsations, but further processing of the data is underway.

III. BASIC MODEL AND CALCULATIONS

The aim of this paper is to infer the total number of pulsars in the globular clusters using the known pulsar detections and our knowledge of the searches and their selection effects. There are a number of elements in the calculations, which we now describe.

a) Luminosity Law

It has been found empirically that there is a relation between the mean observed 400 MHz luminosity of a pulsar, L_m, and the quantity, $Q \equiv \log (\dot{P}_{-15}/P^3)$, where P is the pulsar period in seconds and $\dot{P}_{-15}$ is the period derivative in units of 10^{-15} s s^{-1}. Proszynski and Przybicien (1984) suggested a relation of the form $\log (L_m) = \frac{1}{3}Q + A$. Figure 1*a* (taken from Narayan and Ostriker 1990) shows that this model fits the observations quite well. Stollman (1986) (see also Taylor and Stinebring 1986) suggested a modification where L_m saturates at a constant value for $Q > 1.5$. Although both of these models were developed for the single pulsars in the Galactic disk (§ III*e*), the recycled pulsars too obey a similar luminosity law (Fig. 1*c*). Adopting the Proszynski-Przybicien model, which gives a slighly better fit than the Stollman model, we find for 11 recycled pulsars (disk and cluster),

$$\log (L_m) = \tfrac{1}{3}Q + 1.1 . \quad (1)$$

This fit is indicated by the solid line in Figure 1*c*. Narayan and Ostriker find $A = 1.6$ for normal single pulsars (Fig. 1*a*) rather than the 1.1 we find for the recycled pulsars. This means that, at a given Q, the recycled pulsars are a factor ~ 3 fainter than single pulsars.

It is empirically observed that virtually no pulsars are found with $Q < -1$. This has led to the concept of a "death line" in the P-$\dot{P}$ plane, given by $Q = -1$, beyond which pulsars effec-

TABLE 1

DETAILS OF PULSAR SEARCHES IN GLOBULAR CLUSTERS FROM THE NORTHERN HEMISPHERE

Cluster	DM (cm^{-3} pc)	τ_{scatt} (μs)	log (W^1)	S_J (mJy)	S_A (mJy)	S_G (mJy)	S_V (mJy)	n_{psr}	n_{det}
0443+313......	140	270	−1.9	5[a]	0.05	...	...	16	0.11
0522−245......	61	38	−2.6	5[a]	...	...	...	3	...
1003+003......	46	20	−6.0	...	0.12	...	...	0	...
1126+292......	32	9	−6.0	...	...	2	...	0	...
1207+188......	32	9	−3.5	1.5[b]	...	2	...	0	...
1236−264......	54	27	−3.7	3[c]	...	...	...	0	...
1310+184......	32	9	−3.0	...	0.10	2	...	1	...
1339+286......	32	9	−2.5	3[c]	0.05	2	0.16[d]	4	0.07
1403+287......	33	9	−4.8	...	0.10	2	...	0	...
1427−057......	42	16	−3.2	3[c]	...	2	...	1	...
1436−263......	64	39	−2.5	3[c]	...	...	...	4	...
1500−328......	88	77	−1.7	1.5[b]	...	...	...	22	...
1516+022......	44	17	−2.3	5[a]	0.10	2	...	6	0.07
1608+150......	48	20	−6.0	...	0.10	...	...	0	...
1614−228......	100	100	−1.7	6[c]	...	...	1[e]	25	0.06
1620−264......	63	52	−2.9	6[a]	...	...	0.21[d]	2	0.40
1629−129......	86	71	−3.3	3[c]	...	2	...	1	...
1639+365......	48	21	−2.7	3[c]	0.06	2	...	3	0.07
1644−018......	74	53	−3.2	3[c]	...	2	...	1	...
1645+476......	48	22	−3.0	1.5[b]	...	...	...	1	...
1650−220......	150	240	−3.3	1.5[b]	...	...	...	1	...
1654−040......	85	70	−2.9	3[c]	...	2	1[e]	1	0.02
1657−004......	80	63	−6.0	...	...	2	...	0	...
1658−300......	190	600	−1.4	...	...	...	1[e]	48	0.23
1659−262......	240	600	−2.0	...	...	...	1[e]	11	0.01
1701−246......	220	510	−2.6	3[c]	...	...	...	3	...
1702−226......	190	400	−3.0	3[c]	...	...	...	1	...
1707−265......	250	770	−2.3	...	...	...	1[e]	6	0.02
1711−294......	190	990	−2.4	1.6[b]	...	...	...	5	...
1713−280......	440	2.2 × 10^3	−2.3	4[c]	...	...	...	6	...
1714−237......	190	550	−2.8	6[a]	...	...	...	2	...
1715+432......	55	29	−2.2	...	...	2	0.08[d]	7	0.36
1716−184......	200	430	−2.4	6[a]	...	...	...	5	...
1718−195......	220	540	−2.8	1.5[b]	...	...	...	2	...
1720−263......	230	1.2 × 10^3	−2.7	7[a]	...	...	...	3	...
1720−177......	210	480	−2.4	6[c]	...	2	...	5	...
1724−307......	370	2.4 × 10^4	−3.1	2[b]	...	...	...	1	...
1725−050......	110	140	−4.0	5[a]	...	2	...	0	...
1727−315......	630	7.7 × 10^5	−3.2	13[c]	...	...	...	1	...
1727−299......	350	3.3 × 10^4	−2.4	13[c]	...	...	...	4	...
1730−333......	380	1.4 × 10^7	−1.0	14[a]	...	...	...	130	...
1735−032......	140	190	−2.5	...	...	2	1[e]	4	0.01
1740−262......	210	5.1 × 10^4	−2.9	1.7[b]	...	...	...	2	...
1742+031......	120	150	−4.9	3[c]	0.10	2	...	0	...
1745−247......	260	7.7 × 10^4	−0.9	11[a]	...	...	...	150	...
1746−203......	240	2.8 × 10^3	−1.1	8[a]	...	...	...	86	005
1747−312......	500	4.1 × 10^4	−2.0	12[a]	...	...	...	11	...
1751−241......	440	1.4 × 10^7	−2.3	2[b]	...	...	...	7	...
1758−268......	250	3.3 × 10^4	−3.5	2[b]	...	...	...	0	...
1759−089......	190	650	−1.8	7[a]	...	2	...	17	0.02
1800−300......	220	2.4 × 10^3	−2.0	...	...	...	1[e]	13	0.05
1800−260......	560	9.5 × 10^4	−2.3	7[a]	...	...	...	5	...
1801−300......	220	2.1 × 10^3	−2.2	8[a]	...	...	...	8	0.01
1801−003......	200	440	−3.8	3[c]	...	2	...	0	...
1802−075......	93	270	−2.8	3[c]	...	2	...	2	0.03
1804−250......	92	6.7 × 10^3	−2.3	10[a]	...	...	...	5	0.02
1806−259......	190	4.4 × 10^3	−2.0	10[c]	...	...	...	12	0.01
1808−072......	320	1.6 × 10^3	−3.7	3[c]	...	...	...	0	...
1810−318......	300	1.2 × 10^3	−2.5	1.5[b]	...	...	...	4	...
1812−121......	350	1.6 × 10^4	−6.0	...	...	2	...	0	...
1820−303......	260	830	−1.9	6[a]	...	...	...	15	0.01
1821−249......	120	880	−1.8	...	...	...	0.18[d]	18	0.68
1827−255......	210	710	−2.5	7[a]	...	...	...	3	...
1828−323......	210	470	−2.5	1.5[b]	...	...	...	4	...
1828−235......	170	640	−2.5	7[a]	...	...	...	4	0.01
1832−330......	190	370	−2.6	6[c]	...	...	...	3	...
1833−239......	92	230	−2.4	...	...	...	1[e]	5	0.11
1838−198......	340	1.4 × 20^3	−3.5	6[c]	...	...	...	0	...
1840−323......	170	290	−2.4	6[c]	...	...	...	4	...
1850−087......	190	1.5 × 10^3	−2.8	1.5[b]	...	2	...	2	...
1852−227......	190	400	−2.6	6[a]	...	...	...	3	...

TABLE 1—*Continued*

Cluster	DM (cm^{-3} pc)	τ_{scatt} (μs)	log (W^1)	S_J (mJy)	S_A (mJy)	S_G (mJy)	S_V (mJy)	n_{psr}	n_{det}
1902+017......	410	1.7×10^4	−3.3	2[b]	0.06	...	...	1	...
1908+009......	130	970	−2.5	7[a]	0.07	2	...	3	0.25
1914−347......	99	97	−4.7	2[b]	...	...	...	0	...
1914+300......	220	660	−3.3	...	0.06	2	...	1	0.01
1916+184......	310	4.3×10^3	−3.7	...	...	2	...	0	...
1936−310......	84	69	−3.7	3[c]	...	...	...	0	...
1942−081......	130	170	−4.0	...	...	2	...	0	...
1951+186......	130	520	−3.5	...	0.07	...	1[e]	0	0.02
2003−220......	76	55	−2.0	5[a]	...	...	...	13	...
2031+072......	100	110	−2.9	1.5[b]	0.05	2	...	2	0.01
2050−127......	60	33	−3.8	3[c]	...	2	...	0	...
2059+160......	96	97	−3.5	...	...	2	...	0	...
2127+119......	65	47	−1.8	5[a]	0.10	...	...	21	1.20
2130−010......	54	28	−2.3	5[a]	0.10	2	...	6	0.02
2137−234......	44	17	−2.2	...	...	...	1[e]	8	0.03
2305−159......	35	11	−5.7	...	...	2	...	0	...

[a] 610 MHz; high-resolution DM search.
[b] 61420 MHz.
[c] 610 MHz; low-resolution DM search.
[d] 1400 MHz search with the VLA by Kulkarni *et al.* 1989.
[e] 1400 MHz search with the VLA by Hamilton, Helfand, and Becker 1985.

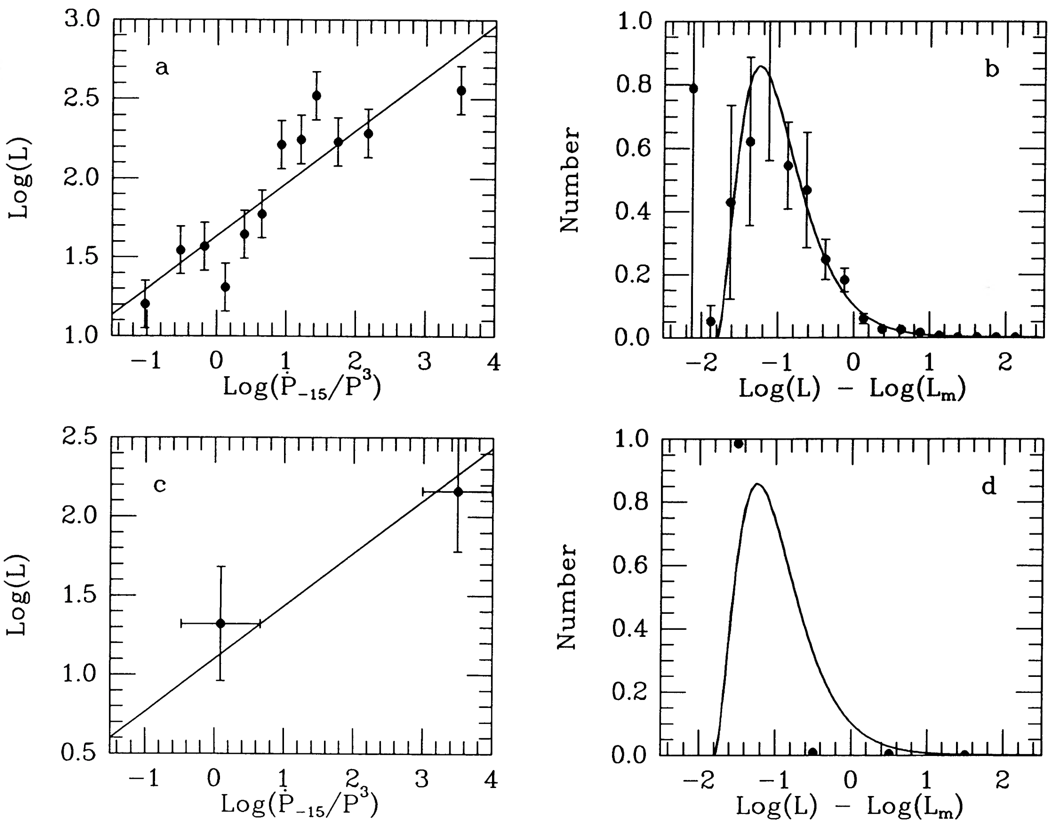

FIG. 1.—(*a*) The mean observed 400 MHz luminosity of single pulsars, L, plotted as a function of $Q = \dot{P}_{-15}/P^3$, where $\dot{P}_{-15}$ is the period derivative in units of 10^{-15} s s^{-1} and P is the period in units of seconds. The solid line is a fit to the data (from Narayan and Ostriker 1989). (*b*) The distribution of the luminosities, L, around the mean observed luminosities, L_m, of the true, unbiased pulsar population. This distribution was inferred from analysis of eight flux limited pulsar surveys by Narayan and Ostriker (1989). The solid line corresponds to eq. (2). Note that the average observed pulsar ($\log L = \log L_m$) is nearly a factor of 20 more luminous than the typical object of the true, unbiased underlying population. (*c*) Similar to (*a*), but for 11 recycled pulsars in the disk and globular clusters. The two data points correspond to six pulsars (*left*) and five pulsars (*right*), respectively. The solid line is the model described by eq. (1). (*d*) Similar to (*b*), but for nine recycled pulsars in the disk, divided into four equal bins. The solid line corresponds to eq. (2) and is the model used in the present calculations. The data points, though, too few to constrain the model significantly, are not inconsistent with it.

tively become undetectable. We have incorporated this limiting line in our calculations.

The model luminosity L_m that is fitted by equation (1) represents the *mean* luminosity of the *observed* pulsars at a given value of Q. We also need the *distribution* of luminosities around this mean, and it is important to realize that this should refer to the true unbiased pulsar population, not just the observed sample, which tends to be strongly biased in favor of brighter objects. Narayan and Ostriker (1989) have used eight flux-limited pulsar surveys and obtained (see Fig. 1*b*) for the single pulsars in the Galaxy the following model for the distribution of $X \equiv \log(L/L_m)$,

$$h(X) = 0.036(X + 1.8)^2 \exp(-3.6\,X)\,, \quad X > -1.8\,. \quad (2)$$

To first order, they find that $h(X)$ is independent of Q. Note that the function peaks at $X \sim -1.3$, showing that the average observed pulsar is nearly a factor of 20 more luminous than the typical object of the underlying population. The small numbers of recycled pulsars precludes us from deriving $h(X)$ independently for these pulsars. However, the available data on 11 recycled pulsars do seem to be consistent with the above equation (Fig. 1*d*). Hence we assume that equation (2) is applicable to the recycled pulsars as well.

Equations (1) and (2) provide a complete description of the distribution of 400 MHz luminosity of pulsars of given P and $\dot{P}_{-15}$. Since many of the pulsar searches have been done at frequencies other than 400 MHz, we need to convert the luminosity model to these frequencies. The spectral index α of a typical pulsar [where $S(\nu) \propto \nu^{-\alpha}$] is 1.5 (e.g., Narayan 1987). However, it now appears that the recycled pulsars, especially the millisecond pulsars, have $\alpha \sim 2.4$ (Fruchter 1989). We have used a compromise value of $\alpha = 2$ in our calculations. Our choice errs on the side of being conservative since it leads to pulsars in our model being brighter at higher frequencies than they really are and therefore easier to detect; consequently, our estimate of the true number of pulsars in the clusters ($N_{\rm psr}$ in §§ III*f* and IV) would be an underestimate.

b) Selection Effects of Pulsar Surveys

Pulsar surveys are affected by many selection effects. The finite sampling interval of the data restricts the search to pulsar periods greater than a few times the sampling interval. The number and bandwidth of the filter channels restrict the maximum dispersion measure up to which pulsars of a given period P can be detected. Scattering in the interstellar plasma leads to pulse broadening, which reduces the effective signal-to-noise ratio further. Also, the Galactic synchrotron radiation background introduces additional noise. Fortunately, all of these effects can be modeled reasonably well (see Narayan 1987 for details). Table 1 gives the estimated dispersion measure, DM (cm^{-3} pc), and pulse scatter-broadening at 400 MHz, $\tau_{\rm scatt}$ (μs), for the various clusters.

It is important to note that the imaging surveys are immune to many of these selection effects such as dispersion, scattering and binarity (see § III*c* below). Thus the absence of a point source within the core region of a cluster necessarily implies that the cluster has no pulsar to the limit of the continuum image.

In addition to the sensitivity limit of the searches another selection effect is introduced by the beamed nature of pulsars. It is usual to assume that only one out of 5 pulsars is beamed toward the Earth (e.g., Manchester and Taylor 1977). Consequently, any estimate of the number of pulsars based on the number of detections must be finally multiplied by a factor of 5. However, there is fairly compelling evidence (see Narayan and Ostriker 1989 for a brief review; also Lyne and Manchester 1988) to suggest that the beaming factor varies with pulsar period; the factor appears to be close to unity for fast pulsars. Hence, throughout our analysis we retain a factor $\bar{f}$, which is the mean fraction of pulsars in the globular clusters that are beamed toward the Earth.

c) Selection Effect due to Binary Acceleration

Pulsars in binary systems are selected against in standard pulsar search algorithms because the changing velocity blurs the pulse peaks in the power spectrum. This loss in sensitivity can be avoided only if the Fourier frequency shift over the course of the integration interval, $T_{\rm obs}$, is smaller than the spectral resolution of the Fourier transform, $1/T_{\rm obs}$, this leads to a restriction on the acceleration a:

$$|a| \ll \frac{1}{T_{\rm obs}^2}\,\frac{Pc}{m}\,; \quad (3)$$

here m is the number of significant harmonics of the pulsar and varies between 4 and 16, depending upon the thoroughness of the search algorithm. Accordingly, if M_2 is the mass of the pulsar's companion (in units of 0.3 $M_\odot$) then Kepler's law and equation (3) imply that pulse detection will be reduced in sensitivity for orbital periods shorter than

$$P_{\rm orb} \sim 1.7\, d[M_2(m/4)(10\ {\rm ms})/P]^{3/4}(T_{\rm obs}/1000\ {\rm s})^{3/2} \times (M_T/1.8\ M_\odot)^{-1/2}\,, \quad (4)$$

where the total mass of the system is $M_T = 1.8\ M_\odot$ and we have averaged over orbital inclinations. Thus deep searches with their large $T_{\rm obs}$ will be necessarily deficient in binary periods of less than several days. Of course, systems at very small sin i, with large orbital eccentricity or at orbital phases near conjunction will suffer smaller apparent accelerations. Similarly, in a small fraction of tidal captures most of the secondary mass can be lost, leaving only an extremely low mass ($\ll 0.1\ M_\odot$) degenerate core. For these binaries, the acceleration of the pulsar is less of a factor. One of the biggest advantages of the continuum imaging surveys, such as the VLA observations, is their complete immunity from the acceleration limit.

In order to overcome the acceleration limitation, some groups have recently designed algorithms to look for pulsars in binary systems. Specifically, the assumption is made that, over the time $T_{\rm obs}$, the acceleration is constant. With this proviso, a two-dimensional search (P, and a) is made. The discovery of an $\sim$8 hr binary in M15 (Anderson *et al.* 1989*b*) suggests that a number of high-acceleration pulsars remain to be discovered.

d) Cluster Weighting Function

There is a wide range in the properties of the $\sim$150 known globular clusters in the Galaxy, which should be reflected in their pulsar content. We account for these variations by ascribing a weight to each cluster, W_j, normalized such that $\sum_j W_j = 1$. The weights are calculated based on various observed parameters of the clusters. Throughout this work we have used the parameters quoted by Webbink (1985). We understand that Webbink's compilation includes data from disparate sources and hence not all the parameters are equally reliable (S. Djorgovski, personal communication), but this is the most complete source at this time.

The simplest scheme is to have the weights be proportional to the optical luminosity (L_j); i.e., $W_j^0 \propto L_j$ which, assuming a constant M/L ratio, translates to a weighting function proportional to the mass of the cluster.

The second level of sophistication is to recognize that in either the standard model or the AIC model the number of pulsars is directly proportional to the number of tidally captured binary systems. The time scale for a given compact star to be tidally captured is

$$\tau_{tc} = (n_{star}\,\sigma v)^{-1} \sim 5 \times 10^{10}\, v_6/(R_* M_T \rho_5)\ \mathrm{yr}\ , \qquad (5)$$

where the cluster velocity dispersion and central density are in units of 10^6 cm s^{-1} and 10^5 $M_\odot$ pc^{-3}, respectively, and the total binary mass (M_T) and the noncompact stellar radius (R_*) are in solar units (e.g., Verbunt 1988). The total number of binaries formed to data by tidal capture is thus proportional to $r_c^3\, n_{co}\, \tau_H/\tau_{tc}$ where n_{co} is the density of appropriate compact objects and τ_H is the Hubble time. Thus the number of recycled pulsars in a cluster will be proportional to $n_*^2\, r_c^3/v_{rms} \equiv W^1$ where n_* is the density of stars in the core, r_c is the core radius, and v_{rms} is the velocity dispersion in the core.

The next level of sophistication is relevant only to the standard model, where the pulsars are spun-up primordial neutron stars. If the primordial neutron stars were born with the same high-velocity dispersion, $v_{rms} \sim 200$ km s^{-1}, as we see in the disk pulsars then only a small fraction will be retained by the shallow potential well of the globular cluster, for which $v_{esc} \lesssim 50$ km s^{-1}. This suggests a weighting $W_j^2 \propto W_j^1 \times f(v_{esc})$ where f gives the fraction retained in the cluster and depends on the underlying velocity dispersion of the pulsars at birth. We choose a simple functional form for the retention factor, $f = [1 - e^{-(v_{esc}/v_{rms})^2}]$. Note that neither the full velocity distribution function nor the cluster escape velocities at the early epoch of neutron star birth is well known, so this estimate is uncertain. Also the origin of large pulsar velocities in the disk is not well understood, and in some models only pulsars born in binary systems are supposed to have large velocities and the pulsars born from single stars are supposed to have small velocities. Thus the value of v_{rms} is itself uncertain. Moreover, there are additional important dynamical effects having to do with the history of the cluster (which may have passed through core collapse), with mass segregation in the cluster core (Verbunt and Meylan 1988) and with upper main-sequence IMFs that may vary between clusters. We are investigating such effects, but their study often requires detailed models of individual clusters, which are generally not available. For these reasons, we concentrate on calculations with the second weighting function W^1, which seems the most robust estimator at this juncture. At appropriate points we will state results with other weighting functions.

e) Model of Pulsar Birth and Evolution

The final element in our calculation is a model for the distribution of P and $\dot{P}$ of pulsars in globular clusters. The dipole magnetic field of a pulsar in units of 10^9 G is given by the relation (e.g., Manchester and Taylor 1977),

$$B_9^2 = 10^6 P\dot{P}_{-15}\ . \qquad (6)$$

Instead of P and $\dot{P}$, we use P and B_9 as our basic parameters.

Recycled pulsars with low-mass companions (or no companions) have been found with magnetic field strengths in the range log B = 8–10. This is a much lower field strength than that seen in normal single pulsars. It is believed that the fields are lower because these systems are old and their fields have decayed. Moreover, there seems to be good evidence that once the field reaches such a low strength, further decay is arrested (see Kulkarni and Narayan 1988 for a review). Using these ideas as a guide, we assume that recycled pulsars are born in globular clusters with a uniform distribution of log B in the range $8 < \log B < 10$.

A histogram of the *observed* recycled pulsars appears to peak at the lower end of this range. Some of this is certainly due to selection effects. The shorter period pulsars are expected to be more luminous (eq. [1]) and by virtue of equation (7) (see below), shorter period pulsars will also have smaller magnetic field strengths. Thus, the true distribution of the underlying population is expected to be flatter than the observed distribution, as long as surveys maintain sensitivity to short period pulsars. We also note that pulsars discovered since the completion of this paper (a 7.9 ms pulsar in M5, Wolszczan *et al.* 1989*b*; a 10 ms pulsar in M13, Anderson *et al.* 1989*c*; a 33 ms pulsar in M53, Anderson *et al.* 1989*d*) are most likely pulsars with $B_9 \gtrsim 10$. An accurate determination of $\dot{P}$ is necessary to derive B_9; however, from luminosity considerations it can be argued that pulsars are discovered close to the birthline (eq. [7]). Thus the above uniform distribution of log B_9 is quite reasonable. We also assume that the field strength does not vary during the life of the pulsar.

Since it is believed that recycled pulsars are spun up by accretion from a companion, their period at birth is expected to be equal to the Keplerian period of the inner edge of the accretion disk. This leads to the following estimate of the initial periods of these pulsars,

$$P_i = 1.9 B_9^{6/7}\ \mathrm{ms}\ . \qquad (7)$$

This relation defines the so-called "rebirth line" in the *B-P* plane.

After birth, the pulsar will spin down as a function of time. The variation of P with time is obtained by integrating equation (6) with a constant value of B_9; hence, the spin period at time t_9 Gyr after birth is given by

$$P^2(t_9) = P_i^2 + 6 \times 10^{-5} B_9^2\, t_9\ . \qquad (8)$$

We assume in our calculations that pulsars have been born in globular clusters at a constant rate over the last 10 Gyr (the Hubble lifetime). This assumption, combined with equations (7) and (8) and our assumed distribution of field strengths, uniquely determines the present distribution of pulsars in the $P - \dot{P}$ plane. Further, using the luminosity model described in § III*a*, we can determine the distribution of luminosities of these pulsars. We find that our derived luminosity function does, in fact, follow an L^{-1} law, with a cutoff at $L_{400} \sim 3$ mJy kpc^2, so our model is in agreement with observations of the Galactic disk population. Finally, by including in detail the various selection effects described in § III*b*, we can estimate, for each cluster j, the fraction f_j of this population of pulsars that would have been discovered by the various surveys.

f) Number and Birthrate of Pulsars

Let N_{psr} be the total number of potentially visible pulsars in all the globular clusters combined; by "potentially visible" we mean that we do not include those pulsars that are beamed away from Earth or have large accelerations. The number of pulsars in, say, the jth cluster is given by $N_{psr}\, W_j$, where W_j is the appropriate weighting function as discussed in § III*d*. The number of pulsars expected to have been discovered in this cluster by the various surveys is then given by $N_{psr} W_j f_j$, where the fraction f_j includes our pulsar evolution model, luminosity model, and selection effects (see § III*e*). The expected total number of discoveries in all the clusters combined is $N_{psr} \Sigma_j W_j f_i$. If the actual number of pulsars detected in the clusters is N_{det}, then we can estimate the true number of pulsars N_{psr} by

$$N_{psr} = \frac{N_{det}}{\Sigma_j W_j f_j} . \quad (9)$$

This number needs to be multiplied by a further factor of $(1 + \beta)/\bar{f}$, where $\bar{f} < 1$ is the mean beaming fraction (§ III*b*) and β allows for those pulsars that were missed because of binary-induced Doppler shifts (§ III*c*).

Once we have calculated N_{psr}, the model in § III*e* directly gives also the birthrate of recycled pulsars in the globular clusters. If there were no death line, the birthrate would be given exactly by $(N_{psr}/10)$ Gyr^{-1} because of our assumption of a constant birthrate during the last 10 Gyr. In our calculations, we did allow for the effect of the death line in detail, but the results turned out to be almost identical to the simpler "no-death" estimate. (This merely means that only a small fraction of the recycled pulsars in the globular clusters have lived long enough to cross the death line and "die.")

In a previous paper (Kulkarni and Narayan 1989) we estimated the number of recycled LMBPs and their birthrate in the Galactic disk, but the method employed there was very different from the one used here. In that case, for each observed pulsar of period P_j and luminosity L_j, we calculated a scale factor $S(P_j, L_j)$; this represents an estimate of the ratio of the total number of such pulsars in the Galaxy to the number that would be discovered with the given surveys. The total number of potentially visible pulsars in the Galaxy was then estimated by summing the scale factors of all the observed pulsars, $N_{psr} = \Sigma_j S(P_j, L_j)$. An important feature of this approach is that it does not need to assume a model of pulsar luminosity or a distribution of P and B.

Unfortunately, we are unable to use this method in the case of the globular cluster pulsars. Because the solar system is embedded in the disk we can, in principle, expect to discover representatives of even very faint disk pulsars provided these are sufficiently numerous that the nearest one is bright enough to fall within the sensitivity limits of the surveys. Therefore, by scaling the observed sample through $S(P_j, L_j)$, we can hope to generate a crude but realistic representation of the true pulsar distribution in the disk. In contrast, since the nearest globular cluster is over 1 kpc away, there is an absolute luminosity cutoff below which we cannot discover any pulsars using current surveys. Unfortunately, this cutoff is fairly severe. For instance, in the disk, the two observed pulsars that contribute most to N_{psr} [i.e., have the largest $S(P_j, L_j)$] are PSR 1855+09 and PSR 1957+20 (Kulkarni and Narayan 1988; Fruchter 1989). Neither of these pulsars, which in a sense represent the bulk of the population, would have been discovered if they were located in any one of the globular clusters. Consequently, we have had to develop the alternative approach of this paper. Here we use a model of pulsar luminosity, coupled with a reasonable assumption regarding the distribution of P and B, to estimate the fraction of essentially undetectable low-luminosity pulsars. Our previous experience with this kind of modeling leads us to believe that the calculations are realistic.

IV. RESULTS

Seven pulsars have been discovered by mid-1989 in globular clusters. Two of these, in 47 Tuc, were found by Ables *et al.* (1989) using a search whose details are not available. None of the surveys included in our calculations looked at 47 Tuc (which is visible only from the southern hemisphere) and therefore, in order to be consistent, we ignore these two detections. Of the remaining five pulsars, PSR 2127+11C was discovered only when an acceleration search was used. Since we have not modeled such a search in our treatment of the selection effects, we eliminate this pulsar as well. We are thus left with four detections. Setting $N_{det} = 4$, our results are as follows.

Using the weighting function W^1 (§ III*d*) and a spectral index $\alpha = 2$ (§ III*a*), we estimate the total number of pulsars in the globular clusters (see eq. [9]) to be $N_{psr} \sim 1100(1 + \beta)/\bar{f}$. The factor $(1 + \beta)$ is to allow for pulsars that were missed because of excessive acceleration, and $\bar{f}$ is to correct for beaming. Using the weighting functions W^0 and W^2, the results are $N_{psr} \sim 800(1 + \beta)/\bar{f}$ and $N_{psr} \sim 2000(1 + \beta)/\bar{f}$, respectively. If we use W^1 and a spectral index $\alpha = 2.4$ (Fruchter 1989) then the result is $N_{psr} \sim 1600(1 + \beta)/\bar{f}$. Within these uncertainties we adopt $N_{psr} \sim 1500(1 + \beta)/\bar{f}$ as a good estimate.

The conventional choice for the mean beaming factor, $\bar{f}$ is 0.2, independent of period (e.g., Lyne, Manchester, and Taylor 1985). However, as briefly discussed in § III*b*, there is much evidence for a period-dependent beaming factor with a value equal to unity for millisecond pulsars. In the framework of our model, most of the pulsars in clusters are old pulsars with attendant long periods and hence beaming factor closer to that of conventional pulsars, 0.2. On the other hand, the observed pulsars are the more luminous younger and shorter period pulsars, characterized by a beaming factor closer to unity. We have not estimated the model-averaged beaming factor but $1/\bar{f}$ of 2.5 seems quite reasonable, and this is the value we adopt for the rest of the discussion.

From naïve consideration of the tidal capture scenario, we expect fewer than $\sim$0.1 of these binaries to have $P_{orb} \gtrsim 3$ day (Verbunt *et al.* 1987; Romani, Kulkarni, and Blandford 1987; Romani 1989). From equation (4), binaries with orbital periods smaller than this value will be undetectable to single-dish pulse searches (some binaries can be detected if sophisticated acceleration correction can be applied but most of these binaries are essentially undetectable in single-dish pulse searches). This suggests that $\beta \gtrsim 10$. However, we can set observational constraints on β as well. In M15, two low-acceleration pulsars were discovered without an acceleration search and one moderately accelerated pulsar was found when an acceleration search was carried out even though this search was by no means the most complete, being insensitive to very short orbital-period binaries and fast pulsars in binary systems. We think that the immediate success with the acceleration search probably means that β is at least of order unity. An approximate upper bound on β can be derived from the VLA imaging searches as follows. From our model we estimate that we should have found $\sim 2\beta$ nonpulsing sources so far with the two VLA surveys. The actual number found is one (in M3; Kulkarni *et al.* 1989). Let us make the optimistic assumption that this source is really an accelerated pulsar. We can then ask what values of β are consistent, within some specified confidence interval, with this single detection. This leads to the constraint, $\beta \lesssim 2$, at the 90% confidence level. Combining the two limits, we thus have $1 \lesssim \beta \lesssim 2$. Thus we estimate that the total number of pulsars in the globular clusters to be $\sim 10^4$.

In Table 1 we list our estimates of n_{psr} $(= N_{psr} W_j)$, the numbers of pulsars present in each of the clusters according to our calculations (for W^1, $\alpha = 2$). We have ignored the factor of $(1 + \beta)/\bar{f}$. We also give in Table 1 our estimates of n_{det} $(= N_{psr} W_j f_i)$, the expected number of detections according to our model. It is very heartening that the three highest values of n_{det} from our models correspond to M15 (2127+119), M28 (1821−249), and M4 (1620−264), which have two, one, and one actual detections, respectively. This implies that our models represent the pulsar population in the clusters reasonably accurately.

We estimate the birthrate of pulsars in the globular clusters to be one pulsar every $8 \times 10^6 \bar{f}/(1 + \beta)$ yr using W^1 and $\alpha = 2$; it is one in $5 \times 10^6 \bar{f}/(1 + \beta)$ yr for W^2 and $\alpha = 2$ and one in $6 \times 10^6 \bar{f}/(1 + \beta)$ yr for W^1 and $\alpha = 2.4$. Taking our preferred value for β (1.5) and $\bar{f}$(0.4), the birthrate becomes one in $\sim 10^6$ yr. As we discuss in the next section, this is a very high rate compared to the birthrate of LMXBs.

An interesting question is: what is the expected distribution of spin-down ages, $\tau = P/2\dot{P}$, for the observed pulsars? Figure 2 shows the distribution predicted by our model with W^1 and $\alpha = 2$. As expected, we see that young pulsars are more likely to be discovered than old ones. This is because young pulsars tend to be brighter according to our luminosity model, making them easier to find; the effect is, however, partially offset by another selection effect, viz., that young pulsars spin faster, which makes them harder to find. Among the pulsars discovered so far in globular clusters, two have reliable measurements of τ, viz., $\tau = 3 \times 10^7$ yr for PSR 1821−24 and $\tau = 3 \times 10^8$ yr for PSR 1620−26. Both ages are well below the mean age of 5 Gyr. Although this confirms our expectation that observed pulsars will be younger than average, the effect seems to be stronger than we might have anticipated, particularly in the case of PSR 1821−24.

This suggests either that many tidal binaries undergo a long gestation period, resulting in relatively recent births (H. Johnson, personal communication; Romani 1990*a*) and/or

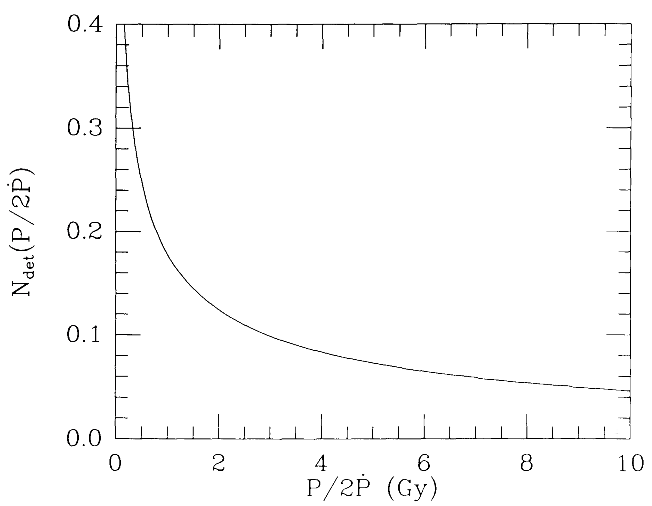

FIG. 2.—The expected distribution of spin-down age, $P/2\dot{P}$, for the pulsars detected in the four surveys discussed in the paper using our model and weighting function W^1. Pulsars with small spin-down age tend to be luminous and hence the distribution peaks at small spin-down ages. Nonetheless, more than half the pulsars are expected to be found with ages greater than 2 Gyr. Despite the peak toward smaller ages, the age of the pulsar in M28 is uncomfortably too low.

that cluster pulsars fade more rapidly with age than expected in our model. In either case, the birthrate of pulsars in globular clusters will be much higher than the already high estimate we obtained above, although this will be partly mitigated by the increased beaming factor $\bar{f}$ associated with this skew toward a younger population.

V. DISCUSSION AND CONCLUSIONS

Our principal finding is that the system of globular clusters contains an enormous number of pulsars: $N_{psr} \sim 1500(1 + \beta)/\bar{f} \sim 10^4$ (see also Bailyn and Grindlay 1990; Verbunt *et al.* 1990). Most of these, of course, will be undetectable because of the great distances to the majority of the clusters. However, over the years to come we expect radio searches, especially in the southern hemisphere, to uncover a few tens of pulsars in globular clusters.

Our census allows us to make some inferences about the initial populations of neutron stars in the globular clusters. In the standard model not all the neutron stars end up as pulsars. Indeed, only that small fraction which undergo a tidal capture may end up as spun-up pulsars (eq. [5]). Verbunt *et al.* (1987) and Romani *et al.* (1987) estimate that in a typical rich cluster, over the Hubble time scale, the number of recycled pulsars formed by tidal capture is ~ 0.1 N_{ns}, where N_{ns} is the total number of neutron stars present. Thus, from our results, the total number of neutron stars in the cluster system is $N_{ns} \sim 10^5$. The mass of the globular cluster system is estimated to be 10^8 $M_\odot$, and thus we derive $\sim 10^{-3}$ neutron stars per $M_\odot$ of visible cluster matter. This is to be compared with the efficiency of neutron star production in the Galactic disk, where the total number of neutron stars is estimated to be a few times 10^8 (Lyne, Manchester, and Taylor 1985; Narayan 1987) from a disk mass of $\sim 1.1 \times 10^{11}$ $M_\odot$ (Bahcall, Schmidt, and Soneira 1983), giving 10^{-3} neutron stars per $M_\odot$ of matter.

If the primordial neutron stars in clusters had velocities as large as that of the disk pulsars then $\sim 10\%$ of the primordial neutron stars are expected to be retained in the shallow cluster potential (see Verbunt *et al.* 1990); this statement is subject to uncertainties in the origin of pulsar velocities and the evolution of cluster potential well depths. Thus either most of the primordial neutron stars were retained in the cluster cores or that the production of neutron stars in clusters was *more* efficient than that in the Galactic disk.

However, the critical assumption inherent in the discussion above is that the initial mass function (IMF) is similar for the disk and the cluster systems. Theoretical modeling of the formation and evolution of clusters by Chernoff and Weinberg (1990, hereafter CW) does not lend support to this assumption. CW find that a cluster with a relatively flat IMF ($\alpha < 2.5$; here the standard Salpeter value is $\alpha = 2.35$) loses so much mass by the stellar evolution of the massive stars that it will quickly unbind. Only steep IMF clusters can survive to the present date, but these will not produce many neutron stars. Bailyn and Grindlay (1990) present this as strong evidence against the standard scenario. Superficially, this does indeed appear to be a serious objection. However, CW make many assumptions in their theoretical modeling some of which are crucial in this context. First, CW assume a single-exponent IMF and hence their arguments apply principally to the evolved stars dominating the total mass loss, i.e., those born with $M > 5$ $M_\odot$. With a more complicated IMF, the upper main sequence, and hence the production of neutron stars, is quite poorly constrained. Second, CW assume that clusters at $t = 0$ are just tidally stable. Assumption of more compact configurations will greatly enhance the number of primordial neutron stars retained (E. S. Phinney, personal communication). Also cluster pulsars might not share the high birth velocities of the disk population. Third, CW assume an unrealistically high low-mass cutoff which lead to an underestimate of the total mass and hence stability of the cluster. (F. Verbunt, personal communication).

On balance, the results of our analysis indicate that some amendment to the standard model is probably required, substantiating Bailyn and Grindlay's (1990) suggestion. These authors argue that cluster pulsars are produced by AIC of accreting white dwarfs. There are a number of problems with this hypothesis, several of which have been addressed by Verbunt, Lewin, and van Paradijs (1989). First, the pulsars must be produced with large rotation rates directly from the collapse of a white dwarf as opposed to an accretion-induced spin-up of a collapsed white dwarf. Narayan and Popham (1989) examine the evolution of the angular momentum and angular velocity of accreting white dwarfs and conclude "... the number of systems that lead to a low-field short-period neutron stars, similar to the known millisecond pulsars, will be small." The alternative is the formation of a typical young pulsar which subsequently gets spun up by accretion. However, this contradicts the observations since the numerous intermediate X-ray sources should have been detected when in fact less than a dozen have been detected so far. Second, recent calculations suggest that only the O-Ne-Mg white dwarfs and, perhaps, the most massive C-O white dwarfs can undergo collapse (Nomoto 1987). Only main-sequence stars with initial mass close to 8 $M_{\odot}$, if any, are expected to produce such white dwarfs. Thus, the number of neutron stars, produced can be increased by at most a factor of ~ 2. Finally, it is not clear that neutron stars produced via AIC have a velocity distribution different from that of neutron stars resulting from type II supernovae (SNs). In addition to these essentially theoretical arguments there are a number of observational difficulties with the suggestion of Bailyn and Grindlay. The large number of CVs predicted by the AIC model have yet to be observed despite a number of surveys. Thus substantial additional work is required to answer these difficulties and produce viable AIC scenarios.

Regardless of the above controversies the principal conclusion of this paper is inescapable: *the pulsar population of globular clusters is unexpectedly high.* Agreement with the standard model can be barely attained if $\beta = 1$ and $1/\bar{f} = 1$. However, these choices are not self-consistent. First, in the standard model, β is supposed to be 9. However, the VLA imaging observations led us to conclude that $\beta \lesssim 2$. Second, in the standard model, most of the pulsars are expected to be old and hence have periods of tens of ms. The beaming fraction for such periods ranges from ~ 2 to more than ~ 5 in the model of Lyne and Manchester (1988) or from ~ 1 to ~ 3 in the model of Vivekanand and Narayan (1981). Our choice of $1/\bar{f}$ of 2.5 is a reasonable compromise. Hence we conclude that the progenitor population should be enhanced either through a reduced initial velocity of the neutron stars or via alternative sources of pulsar production in addition to the primordial neutron stars.

Turning next to the birthrate, we compare the production rate of the pulsars with that of their supposed immediate progenitors, the LMXBs. In the standard model, most of these LMXBs represent captures of neutron stars with main-sequence stars and hence the mass transfer is driven by gravitational radiation/magnetic braking rather than nuclear evolution as would be the case for a binary involving a giant (see Verbunt 1988). The mean duration of the X-ray phase is estimated to be $\tau_X \sim 10^9$ yr. Since there are 10 LMXBs known in the globular cluster system we obtain a birthrate $B_X \sim 10/\tau_X \sim 10^{-8}$ yr^{-1}. In contrast, we have estimated the LMBP birthrate as $B_R \sim 1.3 \times 10^{-7}$ $(1 + \beta)/\bar{f}$ yr$^{-1} \sim 10^{-6}$ yr^{-1}. Thus, it appears that the birthrate of LMXBs is smaller than that of the LMBPs by a factor of ~ 100.

Kulkarni and Narayan (1988) showed that a similar difficulty is present even for the LMXBs and LMBPs in the disk. They found that the birthrate of disk LMBPs with short orbital periods is strongly in excess of the birthrate of the corresponding LMXBs, whereas for wide binaries which evolve from highly evolved secondaries the birthrates were in approximate agreement. Since cluster LMXBs seem to have short orbital periods, the resolution of the disk problem will also be germane to the cluster binaries. Thus we conclude that, in both Galactic components, *recycled pulsars are formed from progenitors whose bright X-ray phase is substantially suppressed compared to the predictions of the standard model.*

A number of ways of effecting this reduction in X-ray luminosity have been proposed. One solution suggested by Kulkarni and Narayan (1988) was that the accreted power predominantly comes out in bands other than X-rays, such as γ-rays and cosmic rays. However, extensive X-ray observations of globular clusters have not found any extensive number of low-luminosity X-ray sources in the cluster cores. A few faint sources that have been found, are typically outside the core region (Hertz and Grindlay 1983). Their nature is controversial (Verbunt and Meylan 1988; Margon and Bolte 1987) and their location outside the core region argues against neutron star systems. Thus even this solution does not seem likely. An alternative means of limiting the number of bright accreting neutron star progenitors is to greatly accelerate the mass transfer rates, correspondingly lowering the X-ray lifetimes τ_X. In fact, it is precisely the short orbital period systems, which presumably evolve via angular momentum losses, for which the evolution rates are least understood and for which the birthrate problem was identified in the Galactic disk.

Evidence supporting this modification of the standard scenario may be found in the recent discovery of the eclipsing, millisecond pulsar PSR 1957+20 (Fruchter, Taylor, and Stinebring 1988) and in theoretical work on accelerated evolution of LMXBs being pursued by the Columbia group (e.g., Kluzniak *et al.* 1988; Ruderman, Shaham, and Tavani 1989). In the latter model, the spin-down luminosity of the recycled pulsar heats the surface of the mass losing donor and significantly increases the mass transfer rate; alternatively, the heating may be due to the X-rays generated by the accretion disk. It remains to be demonstrated that the rate can be increased by as much as a factor of 100, as is demanded by the results in this paper and the work of Kulkarni and Narayan (1988).

Regardless of this issue of a hastened mass transfer phase, the lifetime of X-ray binaries cannot be arbitrarily decreased, at least in the framework of the standard model. In particular, the necessary decrease in X-ray lifetime requires a two order of magnitude increase in the formation rate of the tidal binaries. Mass segregation can substantially boost the tidal capture rate (Verbunt and Meylan 1988). This coupled with the uncertain number of primordial neutron stars make it possible to have a tidal capture rate of 1 in 10^7 yr in the cluster system and perhaps as high as 1 in 10^6 yr (Verbunt and Meylan 1988). Thus by substantially augmenting the neutron star population it may be possible to save the standard model.

Physical collision between compact stars and normal stars is a complication specific to the globular cluster environment.

These should result in either massive accretion disks undergoing high $\dot{M}$ or very close binaries, whose evolution may be accelerated. If such systems can produce recycled pulsars (Krolik 1984), then they may contribute a large fraction of the observed population while having relatively short-lived bright X-ray counterparts. Note, however, that this would not solve the discrepancy in the disk birthrates.

To conclude, our analysis suggests that there are several problems with the standard model. First, we find an unexpectedly large number of pulsars. Second, the age of the observed pulsars is significantly lower than that predicted by the standard model, by nearly a factor of 10. Third, the number of close binaries which escape detection by conventional pulsar searches are found to be a factor nearly one order of magnitude less than predicted by the standard model. Fourth, the birthrate of the radio pulsars is nearly two orders of magnitude larger than that of their supposed progenitors, the LMXBs. This last conclusion is also true of the disk LMXBs and recycled pulsars. We conclude that this discrepancy in both the disk and the cluster systems and the absence of a large number of faint X-ray sources in clusters strongly imply that the X-ray lifetime of LMXBs should be reduced by nearly a factor of 100.

The first three conclusions listed above warrant a critical re-examination of the production mechanisms of cluster pulsars. In this context, Bailyn and Grindlay (1989) and other authors (Michel 1987; Chanmugam and Brecher 1987) for entirely different motivations have speculated that rapidly rotating pulsars could be formed by direct collapse of an O-Ne-Mg white dwarf. However, theoretically it is unclear if such collapse occurs robustly and moreover, the limited number of appropriate (i.e., massive) white dwarfs will probably allow only modest augmentation of the pulsar birthrate. We note that, should this mechanism prove operative, it would produce recycled pulsars with an orbital period distribution rather different from that of the standard LMXB scenario (Romani 1990*b*). In addition, AIC scenarios ensure that the systems which successfully produce pulsars will be those with large mass accretion rates and hence either wide, giant-driven orbits or very tight orbits allowing accelerated evolution due to pulsar irradiation. Both types of systems will have truncated X-ray phases.

In summary, while we have established estimates for the number of recycled pulsars and the rate of their production, we are still not in a position to identify uniquely their genesis and evolution. Future studies of the orbital period distribution and other properties of the pulsar population may shed further light on this problem.

We are grateful to A. Lyne and J. Biggs for giving us complete details of the Jodrell Bank survey. We would like to thank D. Chernoff for useful discussions and the referee for clarifying comments. R. N.'s research is supported in part by the National Science Foundation under grant AST 88-14725.

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