

OPTICAL IDENTIFICATION OF BINARY PULSARS: IMPLICATIONS FOR MAGNETIC FIELD DECAY IN NEUTRON STARS¹

SHRINIVAS R. KULKARNI²

Palomar Observatory and Owens Valley Radio Observatory, California Institute of Technology;
 and Department of Astronomy, University of California, Berkeley

Received 1986 January 22; accepted 1986 April 22

ABSTRACT

We report the discovery of the optical counterparts of two binary pulsar systems—0655 + 64 and 0820 + 02. In accordance with stellar evolution scenarios we find the optical counterparts to be white dwarfs. The existence of a *cool* and therefore old white dwarf in the 0655 + 64 system contradicts the standard hypothesis of exponential decay of magnetic fields in neutron stars. We resolve this contradiction by hypothesizing that the magnetic field in neutron stars consists of two components—an exponentially decaying field and a steady field. The former probably resides in the crust and the latter perhaps in the core. The consequences of this hypothesis for the lifetimes of millisecond pulsars, binary pulsars, and galactic bulge X-ray sources are discussed.

Subject headings: pulsars — stars: binaries — stars: white dwarfs

I. INTRODUCTION

Of the nearly 500 known pulsars, only six are in binary systems. The absence of X-ray emission and the presence of a *radio* pulsar in these systems is commonly interpreted to mean that the two components in such systems are no longer interacting and that the companion star of the pulsar is either another neutron star or a white dwarf (see van den Heuvel 1984 for a review). Hereafter, the pulsar will be referred to as the “primary” and the companion as the “secondary.” This terminology is appropriate since the progenitor of the pulsar is always more massive than the secondary (see § IV).

To date there has been no observational detection of the secondary stars. At optical wavelengths, there has been considerable effort to detect the famous binary system, PSR 1913 + 16 and the binary millisecond pulsar, PSR 1953 + 29 with no success owing to considerable Galactic obscuration. Optical work for the two recently discovered binary pulsars (1855 + 09, 2303 + 46) will be possible only after more precise radio positions become available. In this *Letter* we wish to report the discovery of the optical counterparts of the remaining two systems—PSR 0655 + 64 (Damashek *et al.* 1982) and PSR 0820 + 02 (Manchester *et al.* 1983). The former is a short orbital-period system and the latter, a long orbital-period system (see Table 1 for other measured and derived parameters).

Earlier we issued a short, preliminary report (Kulkarni 1986). Here we report our findings in detail and discuss some implications. In § II we present the optical data. From an analysis of this data we conclude that the proposed optical counterparts are indeed white dwarfs (§ III). However, the white dwarf in the 0655 + 64 system is a *cool* white dwarf which implies that PSR 0655 + 64 is a very old pulsar (§ IV).

The implications of this finding for the evolution of surface magnetic fields of neutron stars are discussed in § V.

II. OPTICAL OBSERVATIONS AND IDENTIFICATION

The optical data for this project were obtained from Cassegrain CCD cameras on three telescopes: the Lick 3 m Shane (1985 November), the Hale 5 m (1985 December), and the KPNO 4 m (1985 December). The data are of varying quality with the KPNO³ images having the best seeing (about 1”) and the Lick images, the worst seeing (3”–4”).

In Figure 1, the star marked H at $\alpha(1950.0) = 06^{\text{h}}55^{\text{m}}49^{\text{s}}50 \pm 0^{\text{s}}.1$, $\delta(1950.0) = 64^{\circ}22'23''.2 \pm 0''.7$ coincides, within astrometric errors, with the best radio position obtained from timing observations (Damashek *et al.* 1982). Likewise, in Figure 2, the star marked K at $\alpha(1950.0) = 08^{\text{h}}20^{\text{m}}34^{\text{s}}.1 \pm 0^{\text{s}}.03$, $\delta(1950.0) = 02^{\circ}08'53''.4 \pm 0''.45$ coincides with the best radio position obtained using the VLA (Fomalont *et al.* 1984). The density of stars as faint as stars H and K can be estimated by counting the stars in the two fields. In both these fields, the chance coincidence of an arbitrary star within 1” of a given radio position is $\leq 1\%$. Thus we propose stars H and K to be the optical counterparts of the secondary stars of 0655 + 64 and 0820 + 02 systems, respectively.

During the course of writing this *Letter* we came to know of a considerable amount of optical work done by Dr. J. Kristian and colleagues. A report of their work along with details of pulse search towards stars H and K is in preparation (J. Kristian, personal communication).

For photometry we used the KPNO data which consisted of a pair of frames, one in *V* and the other in *R*, for each field; each frame is a 600 s integration. The seeing was a little

¹Based in part on research done at Lick Observatory, University of California.

²Millikan Fellow.

³KPNO (Kitt Peak National Observatory) is operated by the Association for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1
MEASURED AND DERIVED PARAMETERS

Parameter	0655+64	0820+02
P (s)	0.196	0.865
DM (cm^{-3} pc)	8.0	23.7
$P/2\dot{P}$ (yr)	3.6×10^9	1.1×10^8
τ_m (yr)	4.6×10^7	1.1×10^7
P_{orb} (days)	1.03	1232.3
M_{sec} (M_{\odot})	~ 0.7	0.3^a
E_{B-V}	0.045	0.028^b
m_R	22.1	22.8
$V - R$	0.1	-0.2
T_{BB} (K)	$\sim 8 \times 10^3$	$\geq 2 \times 10^7$
d (pc)	640^a	1920^a
M_R	13.1	11.4
M_{bol}	13.3	$\leq 9.35^a$
τ_c (yr)	2×10^9	1×10^{7a}

^aAssumed values (see text).

^bDetermined from H I emission data (Heiles and Habing 1974).

better than $1''.2$ (FWHM). Sky transparency was in general excellent except for a patch of cirrus which appears to have affected observations of the 0820+02 field (see below). A software package (DAOPHOT) developed by P. Stetson of the Dominion Astrophysical Observatory was used to process the data. The typical 1σ errors in the instrumental magnitudes are ~ 0.05 mag. Flux-standard stars in a KPNO CCD standard field, NGC 7790 (Christian *et al.* 1985), were used to convert the instrumental magnitudes to R and V magnitudes. The KPNO filter system is discussed by Christian *et al.* (1985); basically, " V " refers to Johnson V and " R " to Kron-Cousins R . In order to convert the V and R magnitude to a physically meaningful unit (Jansky) we used the absolute calibration of Bessel (1979).

Special steps had to be taken to obtain the instrumental magnitudes of star H owing to its close proximity to a galaxy (see Fig. 1). For each frame, we first masked out a circle of radius $1''$ centered on the pulsar. GASP, a surface photometry package developed by M. Cawson of the Steward Observatory, was used to fit a set of elliptical annuli centered on the

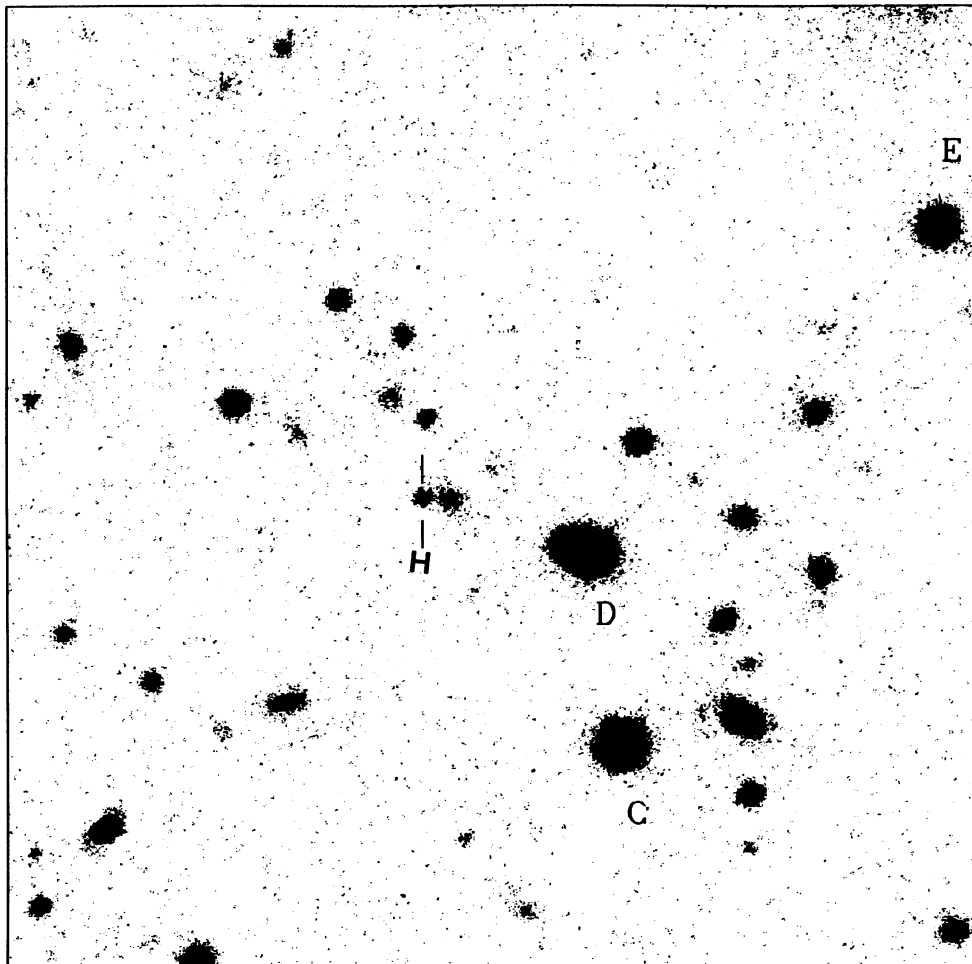


FIG. 1.—KPNO R -frame of 0655+64 field. North is up, and east is to the right. The field is a square of side $76''.4$. Star H is the proposed optical candidate of the secondary in the 0655+64 system. The fuzzy object to the west of star H with $\Delta\alpha = -2''.1$, $\Delta\delta = 0''.4$ could, in principle, be considered to be a valid optical counterpart of the pulsar system. We reject this association since a quantitative analysis of the data shows that the object is an elliptical galaxy.

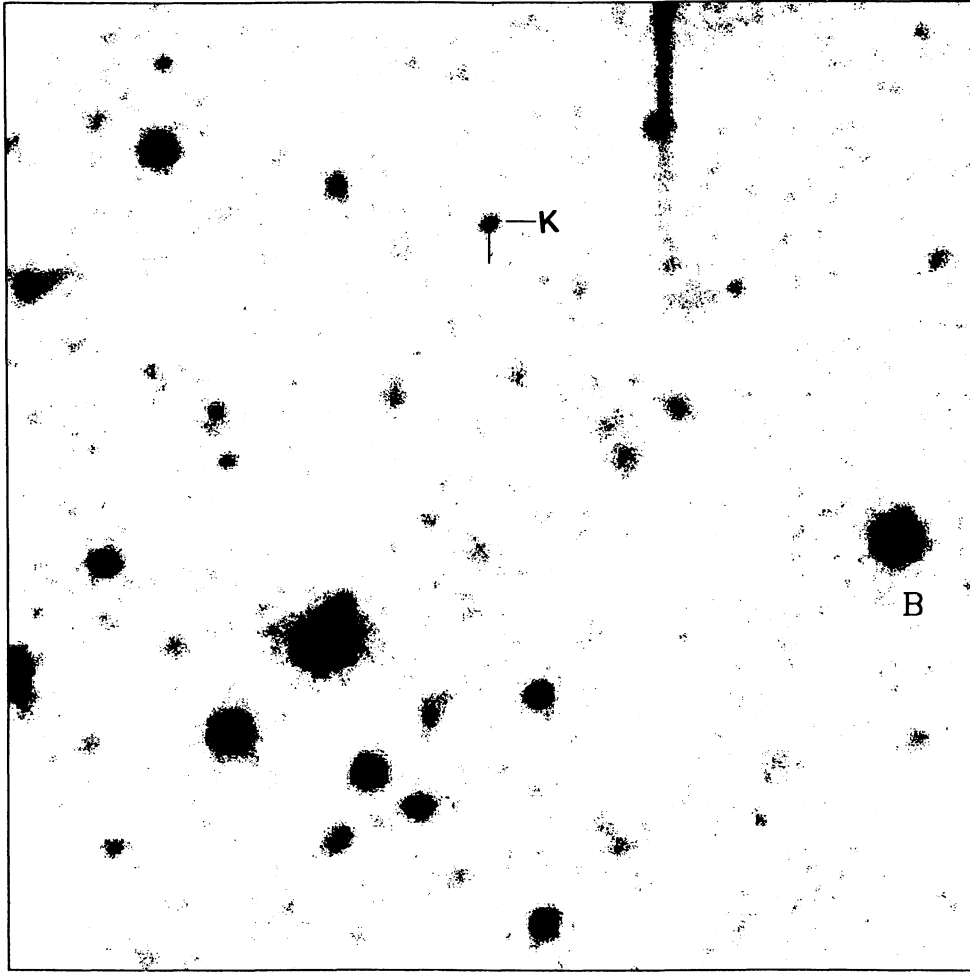


FIG. 2.—KPNO R -frame of 0820+02 field. North is up, and east is to the right. The field is a square of side $76''$. The proposed optical candidate for the secondary of the 0820+02 system is star K.

galaxy. The resulting fit was then used to estimate the increase in the sky level in the pixels centered around the pulsar. In Table 1, we present the corrected magnitude and the color index. For both the candidates we have ignored any corrections due to reddening since the estimated E_{B-V} (see Table 1) is comparable to the photometric errors.

Our data for 0820+02 appears to have suffered from temporal variations in transparency due to a cirrus patch. The mean $V-R$ of the stars in this field is ~ 0.47 mag smaller than that of the 0655+64 field. Despite this complication one point is clear: star K, unlike star H, is very blue; in particular, the $V-R$ of star K is smaller than that of the field stars in the 0820+02 frame by ~ 1 mag! Assuming that the mean $V-R$ in both the fields is the same, we find $V-R$ for star K is ~ -0.2 mag. Preliminary MMT spectroscopic observations confirm the blue nature of star K (J. Leibert and H. Spinrad, personal communication).

III. DISTANCES AND NATURE OF THE SECONDARY STARS

Estimates of distances to these systems are critical before further interpretation is possible. Distances to pulsars with no H II regions along the line of sight can be obtained by

assuming a mean electron density of 0.025 cm^{-3} (Lyne, Manchester, and Taylor 1985). From the measured DM (see Table 1) the nominal distance to PSR 0655+64 and PSR 0820+02 is 320 pc and 950 pc, respectively. Lyne, Manchester, and Taylor (1985) assert that such estimates probably have a typical error of a factor of 1.5 and a maximum error of a factor of 2. VLBI parallax measurements for two nearby pulsars (PSR 0823+26 and PSR 0950+08) which have dispersion measures comparable to our pulsars confirm this assertion (Gwinn *et al.* 1986).

For the 0655+64 system, the mass of the secondary inferred from timing and scintillation data is about $0.7 M_{\odot}$ (Lyne 1985)—closely equal to the mass of a typical field white dwarf. Given our distance estimate, star H is too faint to be a main-sequence star. A white dwarf with a standard radius of $10^{-2} R_{\odot}$ will satisfy the measured m_R and $V-R$ for $T_{\text{BB}} = 5500 \text{ K}$, $d = 320 \text{ pc}$ or $T_{\text{BB}} = 8000 \text{ K}$, $d = 640 \text{ pc}$ or $T_{\text{BB}} \approx 10^4 \text{ K}$, $d = 960 \text{ pc}$; here T_{BB} is the blackbody temperature and d is the distance. The first and last choice basically define the extreme limits allowed by the errors in photometry (i.e., the color temperature). The constraints imposed by the DM lead us to conclude $T_{\text{BB}} < 8000 \text{ K}$. Pending detailed spectro-

scopic data (now in progress) we adopt the second choice and keep in mind that the true values of T_{BB} and d are probably somewhat smaller than our adopted values.

The measured mass function of 0820+02 leads to a lower limit of $0.2 M_{\odot}$ for the mass of the secondary star (Manchester *et al.* 1983). This rules out all main-sequence stars earlier than M5. The extremely blue color of star K rules out the rest of the main sequence. The data are well fitted by a hot, white dwarf of standard radius ($10^{-2} R_{\odot}$). The measured $V - R$ is consistent with $T_{\text{BB}} \approx 2 \times 10^4$ K. A precise estimate of T_{BB} requires U and B measurements since $V - R$ is an insensitive temperature indicator for hot stars.

For stars as hot as star K, the optical flux rises only linearly with T_{BB} and hence the distance estimate is even less sensitive to the adopted T_{BB} . For $T_{\text{BB}} = 2 \times 10^4$ K, $d \approx 1890$ pc, which is consistent with the dispersion measure estimate. Incidentally, with optical measurements (in the blue) it will be possible to measure d to better than 10%. This will increase the number of pulsars with distance estimates that are independent of DM.

IV. AGES OF PULSARS AND WHITE DWARFS

Further interpretation of our data requires an understanding of the formation and evolution of binary pulsars, which we now proceed to review (see van den Heuvel 1984 for a comprehensive review). The currently accepted scenario for 0655+64 starts off with a binary system consisting of a primary with $M > 8 M_{\odot}$ and a second with $4 M_{\odot} < M < 8 M_{\odot}$. The primary quickly evolves to become a neutron star. At some later point, the secondary evolves and becomes a red giant and as a result mass and angular momentum are transferred to the primary. At the end of the accretion phase, the secondary is a hot white dwarf and the primary is a spun-up radio pulsar. The currently favored model for PSR 0820+02 starts off with a white dwarf primary and a low-mass main sequence ($M < 1.2 M_{\odot}$) secondary. Mass transfer increases the orbital separation as well as the mass of the primary. The primary is converted to a neutron star when its mass exceeds the Chandrashekar limit.

Despite the vast differences between the two scenarios the important point is that the neutron star is always older than the secondary; here the ages refer to the time since the collapse to the degenerate state. Several time scales can be inferred from observations:

a) τ_c , the "Cooling" Age of White Dwarfs

It is now an accepted fact that white dwarfs shine by radiating away their internal heat (see Shapiro and Teukolsky 1983, chap. 4). Using the cooling curve of Iben and Tutukov (1984) for a $0.6 M_{\odot}$ white dwarf, we obtain $\tau_c \approx 2 \times 10^9$ yr for star H. For star K, our estimate of τ_c is as good as our guess of T_{BB} (§ III). Our limited data is not inconsistent with a cooling time as short as 10^7 yr (note that since $\tau_c \propto M^{-2.5}$, star K cools faster than given by the cooling curve of Iben and Tutukov 1984). In Table 1 we have adopted the lowest value of T_{BB} consistent with data (§ III).

b) τ_p , the "Spin-Down" Age of Pulsars

Theoretical models for pulsars assume a rotating, magnetized neutron star. The radiated energy loss depends upon

P , the present-day rotation period, the strength of the magnetic field and possibly α , the angle between the magnetic and rotation axes. The torque is assumed to be $\propto P^{-n}$, where P is the present period and n is the "braking index." If the energy loss is by magnetic dipole radiation, then $n = 3$ —close to the observed value of 2.5. Within the framework of the dipole approximation, the present magnetic field can be evaluated from P and \dot{P} (see Manchester and Taylor 1977). If the dipole magnetic field does not decay with time then the period evolution of the pulsar is implicitly specified by the equation

$$t = \frac{P}{(n-1)\dot{P}} \left[1 - \left(\frac{P_i}{P} \right)^{n-1} \right],$$

where t is the present time and P_i is the period at $t = 0$ (i.e., birth). Thus if $P_i \ll P$ then t , the true age of the pulsar, is equal to $\tau_p \equiv P/2\dot{P}$, the spindown age of the pulsar. The value of τ_p for PSR 0655+64 is 3.6×10^9 yr and 1.1×10^8 yr for PSR 0820+02.

c) τ_m , the "Magnetic" Age of Pulsars

The progenitors of single pulsars are supposed to be massive main-sequence stars. In contrast to the progenitors, pulsars have a larger scale height. The observed z -height and velocity dispersion yield a "kinematic" age, $\tau_z \approx 10^6$ yr for pulsars (see Manchester and Taylor 1977 for further details). In contrast, the spin-down age for one-third of the pulsars exceeds 10^7 yr and $\sim 5\%$ of the pulsars have $\tau_p > 10^8$ yr. In order to resolve the inconsistency between τ_z and τ_p a hypothesis has been introduced: the surface magnetic field exponentially decays with an e -folding time scale, τ_d . Estimates of τ_d are somewhat model dependent and range from about 4.5×10^6 yr (see Manchester and Taylor 1977) to 9×10^6 yr (Lyne, Manchester, and Taylor 1985); we adopt the latter value. Binary pulsars, besides being older than single pulsars, also have lower magnetic field strengths. This fits the magnetic field decay hypothesis very nicely (Taam and van den Heuvel 1986). In the framework of the alternative, less popular hypothesis of torque decay as a result of gradual alignment of the two axes, one has to make additional ad hoc assumptions to explain binary pulsars. The rapid decay of the magnetic field results in a spuriously large τ_p . Additionally, the rapid decay of the field restricts the lifetime of the pulsar phase to $\leq 10^7$ yr since radio emission ceases when $B_{12}/P^2 \leq 0.2$; here B_{12} is the present surface field strength in units of 10^{12} G. Observationally, the inferred magnetic field of young pulsars appear to tightly cluster around 10^{12} G. Thus within the framework of the field-decay hypothesis, $\tau_m \equiv -\tau_d \ln(B_{12})$, the "magnetic age," is in fact equal to the age of the pulsar. The values of τ_m for PSR 0655+64 and PSR 0820+02 are 4.6×10^7 yr and 1.1×10^7 yr, respectively.

If we believe the evolutionary scenario reviewed above, the theories of cooling of white dwarfs, and the hypothesis of decay of neutron star surface magnetic fields then $\tau_m > \tau_c$, rigorously. For 0820+02 system, this inequality appears to be obeyed. However, the inequality fails by two orders of magnitude for 0655+64 system where our various estimates are on sure footings. Hence for at least this system, *either the white dwarf has cooled much faster than predicted by theory or the surface magnetic field of the pulsar has decayed much slower*

than our expectation. There is considerable observational work confirming that the basic understanding of the cooling of white dwarfs is correct (see Shapiro and Teukolsky 1983, chap. 4). Thus we are forced to give up the conventional hypothesis of decay of magnetic field with a single, exponential time scale τ_d as small as 10^7 yr.

V. RESOLUTION OF PARADOX AND CONCLUSIONS

From the discussion in § IV we are forced to conclude that PSR 0655 + 64 is really old and still pulsing in the radio band whereas PSR 0820 + 02 is probably young. Hence for at least one pulsar the conventional magnetic field decay hypothesis fails. At the same time there are overwhelming observational data suggesting that a majority of pulsars are indeed young objects: (a) the similarity between the radial distribution function of pulsars and tracers of massive stars, (b) $\tau_z \lesssim 10^6$ yr, (c) the association of pulsars with Type II supernovae, and finally (d) most of the few dozen pulsars with known proper motion appear to be drifting away from the Galactic plane (Lyne, Anderson, and Salter 1982).

We resolve this apparent paradox by introducing a new hypothesis: *the magnetic field decays exponentially from the birth value of $B_{12} \approx 1$ to a "residual" value of $B_{12}^c \lesssim 10^{-2}$, and thereafter the field does not decay significantly.* This is the single most important conclusion of this Letter. This simultaneously explains both systems since B_{12} for PSR 0655 + 64 is $\sim 10^{-2}$, whereas $B_{12} \approx 0.3$ for PSR 0820 + 02.

We now speculate on the origin of the "residual" field. Over the same time the crustal field is decaying, the core field, if any, will penetrate the crust and appear at the surface. The core field is assumed to decay slowly (if at all) on time scales comparable to the age of the Galaxy. The magnitude of the "residual" field, B^c , presumably is not fixed as can be seen by the great spread in the surface field strengths of the spun-up pulsars; B^c may be related to the magnetic field strength of the progenitor. The period of the pulsar at the time the core field appears at the surface critically decides the fate of the neutron star. Neutron stars with $B_{12}^c P^{-2} \geq 0.2$ will continue to be radio pulsars, and the rest will rapidly fade away from the radio sky. The total radio lifetime of spun-up pulsars is about $10^8/B_{12}^c$ yr. Thus all three millisecond pulsars (1937 + 21, 1855 + 09, 1953 + 29) will be pulsing over a Hubble time.

Recently, quasi-periodic oscillations (QPO) have been detected in about 20% of the Galactic bulge low-mass X-ray sources. Currently popular models invoke neutron stars with surface magnetic field strength of about 10^9 – 10^{10} G to ex-

plain this phenomenon. In the framework of the conventional field-decay hypothesis, the existence of such high field strengths in systems as old as these is hard to understand. For this reason, Lewin and van Paradijs (1986) suggest that the neutron stars in these systems were formed only recently ($\sim 10^7$ yr) much the same way as in the more sophisticated model discussed for PSR 0820 + 02 in § IV. In the framework of the conventional field decay hypothesis (as is assumed by Lewin and van Paradijs) there should be as many X-ray sources $B_{12} \approx 10^{-1}$ to 1 as with $B_{12} \approx 10^{-2}$ to 10^{-3} ; the former should manifest as X-ray pulsars, and the latter should show QPO. However only two bulge sources are X-ray pulsars whereas about nine sources exhibit QPO. This immediately suggests that the QPO phase is long-lived in comparison to the X-ray pulsar phase. In our model, the QPO sources are simply sources with $B_{12}^c \approx 10^{-3}$ to 10^{-2} G, and the observed ratio supports the existence of a steady, residual field. If our hypothesis is correct, we predict, from the observed statistics and the average lifetime of QPO sources, that there should be about 80 millisecond binary pulsars in the Galactic bulge. Hence a search for radio pulsars in the Galactic bulge region and the globular clusters is highly advisable.

Despite the impressive observational support for our residual field hypothesis there is one grave inconsistency, viz., if indeed all the spun-up pulsars are old systems then the tendency of fast pulsars (binary or single) to be found at low $|z|$ (except for PSR 0820 + 02) is hard to explain. We do not offer any new explanation for this well-known mystery other than to add that perhaps the various ongoing and planned intensive searches for fast pulsars may yield new pulsars at high $|z|$. If these expectations are not met, then PSR 0655 + 64 and the neutron stars in the QPO systems (perhaps) are special.

I am much indebted to Drs. M. Schmidt and D. Schneider for Hale 5 m data and my friend Dr. S. Djorgovski for superb seeing KPNO 4 m data. With great pleasure I thank Dr. A. Klemola for assistance with astrometry, Dr. G. Bothun for help with GASP, and Dr. H. Spinrad for discussions about the optical data. I am grateful to Dr. J. Greenstein for showing me my way around white dwarf literature. Finally I would like to thank Drs. D. Backer, R. Blandford, C. Heiles, E. van den Heuvel, and R. Romani for discussions which led to considerable improvement in this Letter. This work was supported in part by NSF grant AST84-16863 and a Millikan Fellowship.

REFERENCES

- Bessel, M. S. 1979, in *Problems of Calibration of Multicolor Photometric Systems*, ed. A. G. Davis Phillip, *Dudley Obs. Report No. 14*.
 Christian, C. A., Adams, M., Barnes, J. V., Butcher, H., Hayes, D. S., Mould, J. R. and Siegel, M. 1985, *Pub. A.S.P.*, **97**, 363.
 Damashke, M., Backus, P. R., Taylor, J. H., and Burkhardt, R. K. 1982, *Ap. J. (Letters)*, **253**, L57.
 Fomalont, E. B., Goss, W. M., Lyne, A. G. and Manchester, R. N. 1984, *M.N.R.A.S.*, **210**, 113.
 Gwinn, C. R., Taylor, J. H., Weisberg, J. M., and Rawley, L. A. 1986, *A.J.*, **91**, 338.
 Heiles, C., and Habing, H. J. 1974, *Astr. Ap. Suppl.*, **14**, 1.
 Iben, I., and Tutukov, A. V. 1984, *Ap. J.*, **282**, 615.
 Kulkarni, S. R. 1986, *IAU Circ.*, 4160.
 Lewin, W. H. G., and van Paradijs, J. 1986, *Comments Ap.*, in press.
 Lyne, A. G. 1985, *Nature*, **310**, 300.
 Lyne, A. G., Anderson, B., and Salter, M. J. 1982, *M.N.R.A.S.*, **201**, 503.
 Lyne, A. G., Manchester, R. N., and Taylor, J. H. 1985, *M.N.R.A.S.*, **213**, 613.
 Manchester, R. N., Newton, L. M., Cooke, D. J., Backus, P. R., Damashke, M., Taylor, J. H., and Condon, J. J. 1983, *Ap. J.*, **268**, 832.
 Manchester, R. N., and Taylor, J. H. 1977, *Pulsars* (San Francisco, Freeman).
 Shapiro, S. L., and Teukolsky, S. A. 1983 *Black Holes, White Dwarfs, and Neutron Stars* (New York: Wiley).
 Taam, R. E., and van den Heuvel, E. J. P. 1986, *Ap. J.*, **305**, 235.
 van den Heuvel, E. J. P. 1984, *J. Ap. Astr.*, **5**, 209.

S. R. KULKARNI: Palomar Observatory, California Institute of Technology, 105-24, Pasadena, CA 91125