Ib. ROTATION-POWERED PULSARS

Pulsars and Supernova Remnants

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THE GALACTIC PULSAR POPULATION AND NEUTRON STAR BIRTH

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ABSTRACT. The radio pulsars in the Galaxy are found predominantly in the disk, with a scale height of several hundred parsecs. After allowing for pulsar velocities, the data are consistent with the hypothesis that single pulsars form from massive stellar progenitors. The number of active single pulsars in the Galaxy is $\sim 1.5 \times 10^5$, and their birthrate is 1 per ~ 60 yrs. There is some evidence that many single pulsars, particularly those with high magnetic fields, are born spinning slowly, with initial periods $\sim 0.5 - 1s$. This could imply an origin through binary "recycling" followed by orbit disruption, or might suggest that the pre-supernova stellar core efficiently loses angular momentum to the envelope through magnetic coupling. The birthrate of binary radio pulsars, particularly of the millisecond variety, seems to be much larger than previous estimates, and might suggest that these systems do not originate in low mass X-ray binary systems.

1. INTRODUCTION

More than 400 radio pulsars, including 7 binaries, have by now been discovered in the Galaxy, most by standardized surveys. The selection effects of these surveys are understood quite well. Therefore, a meaningful statistical analysis of the pulsar data should be possible, and may provide valuable information on basic questions concerning the origin and birth of neutron stars. Some recent results are discussed here. A more comprehensive review can be found in Taylor and Stinebring (1986).

Pulsar surveys measure the following basic parameters for each pulsar they detect: the galactic coordinates ℓ, b, the pulse period P, the time derivative of the period $\dot{P}$ (this requires follow-up timing observations and is not available for very recently discovered pulsars), the dispersion measure DM, and the radio flux S. Using a suitable model of the free electron density in the Galaxy (e.g. Lyne, Manchester and Taylor 1985, henceforth LMT), the observed DM of a pulsar can be used to infer its distance d, and thus its luminosity L, defined by

$$L = Sd^2 \ (\mathrm{mJy} \cdot \mathrm{kpc}^2) \tag{1}$$

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If the slow-down of the pulsar is primarily due to magnetic dipole braking, then the surface magnetic field B can be estimated by

$$B \sim (10^{15} P\dot{P})^{1/2} 10^{12} \text{ G} \tag{2}$$

assuming standard values for the radius and moment of inertia of the neutron star. Another useful number is the "characteristic age" of a pulsar,

$$\tau = P/2\dot{P} \tag{3}$$

This represents the true age, if the pulsar is born with with an initial period $P_i \ll P$, if it slows down primarily by magnetic dipole braking, and if its magnetic field has remained essentially constant during its life.

2. GALACTIC DISTRIBUTION OF SINGLE PULSARS

Let us for simplicity assume that the distribution function of single pulsars can be factorized in the form

$$\rho(R, z, L) dR dz d\ln L = \rho_R(R) dR \rho_z(z) dz \Phi(L) d\ln L \tag{4}$$

where R, z are galactocentric cylindrical coordinates. This particular decomposition was first introduced by Large (1971) to analyze the early data from the First Molonglo survey. LMT have redone the analysis and fitted more recent data using an iterative self-consistent scheme that allows for selection effects. Their estimates for $\rho_R(R)$ and $\rho_z(z)$ are shown by the histograms in Figs. 1 and 2, where the Sun has been assumed to be located at $R = 10$ kpc. Note that the radial gradient of the pulsar number density is strongly negative in the solar vicinity, implying that most of the active pulsars in the Galaxy lie within the solar circle. The apparent deficit of pulsars at $R \lesssim$ 5kpc may not be real since the selection effects (particularly scatter-broadening) of the surveys on which LMT based their analysis are such that pulsars in this part of the Galaxy would be extremely hard to detect. A recent high frequency (1400 MHz) survey by Clifton and Lyne (1986) detected many new high DM pulsars towards the galactic center region, suggesting that the true number density there could be greater than Fig. 1 might suggest. A least squares fit of a Gaussian to LMT's results for $R \geq 5$ kpc gives

$$\rho_R(R) \propto \exp[-(R/8)^2] \tag{5}$$

The distribution as a function of z (Fig. 2) shows that pulsars are definitely a disk population, but with a rather large scale height. A least squares fit gives

$$\rho_z(z) \propto \exp[-(z/0.61)^2] \tag{6}$$

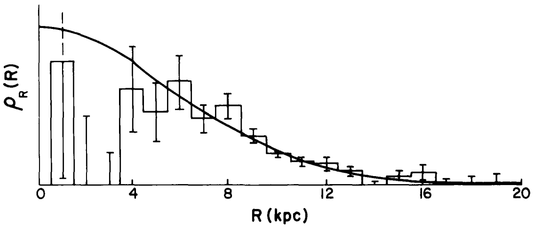

Fig. 1–Histogram of $\rho_R(R)$ estimated by LMT. The solid curve corresponds to eq. (5)

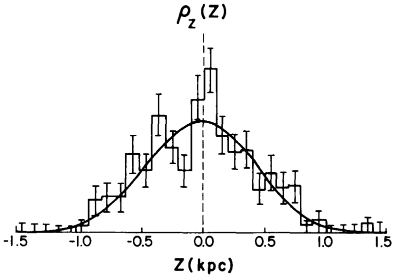

Fig. 2–Histogram of $\rho_z(z)$ estimated by LMT. The solid curve corresponds to eq. (6)

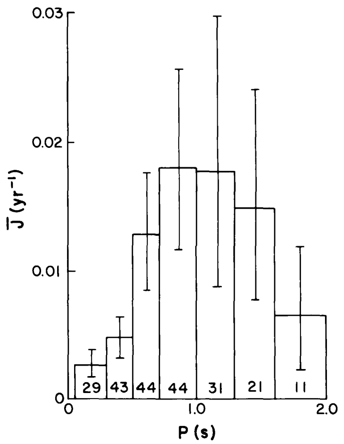

Fig. 3–Histogram of the mean pulsar current $\bar{J}(P_1, P_2)$, calculated using the scale factors $S(P, \dot{P})$.

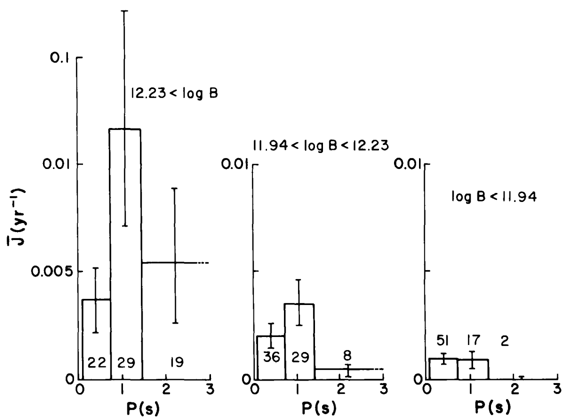

Fig. 4–Histograms of the mean pulsar current $\bar{J}(P_1, P_2)$ for pulsars corresponding to three ranges of magnetic field B, calculated using the scale factors $S(P, \dot{P})$.

which corresponds to an rms z height of 430 pc. The large scale height is believed to be almost entirely due to the large space velocities of pulsars (e.g., see the articles by Lyne and Cordes in this volume), and it is likely that pulsars originate with a scale height $< 100 - 200$ pc (LMT, Chevalier and Emmering 1986).

The above results are consistent with the hypothesis that single radio pulsars, and hence single neutron stars, are produced when young massive stars die. An additional piece of supporting evidence is due to del Romero and Gomez-Gonzalez (1981), who showed that radio pulsars are well correlated with HII regions, which are good tracers of young, hot stars in the Galaxy.

The solution for $\Phi(L)$ obtained by LMT shows that it varies as L^{-1} for $L \gtrsim 10$ mJy kpc^2. Unfortunately, since all surveys are flux-limited, very few pulsars with $L < 1$ mJy kpc^2 have been discovered, and so the luminosity function is poorly determined at the faint end. An important recent advance is the work of Dewey *et al.* (1985), who claim on the basis of more sensitive observations that the luminosity function definitely rolls over at $L < 1$ mJy kpc^2. Thus, we can now state with some confidence that there is unlikely to be a dominant class of single pulsars in the Galaxy that is completely unrepresented in the observed sample. Still, since the most numerous pulsars in the Galaxy are the faintest, and hence most poorly represented in the observed sample, therefore statistical studies of the galactic population are generally plagued by poor signal-to-noise. For instance, if Δp is the error in some estimated parameter p, then $(p/\Delta p)^2$ will not be ~ 400 as one might naively expect for a sample of 400 pulsars, but may be < 10 in many cases. One frequently needs to introduce extra assumptions, usually in the form of a model of the time evolution of a pulsar, or a model of its radio luminosity, in order to improve the signal-to-noise ratio.

3. NUMBER OF ACTIVE SINGLE PULSARS IN THE GALAXY

A quantity of some interest is the number of active single pulsars N_{psr} in the Galaxy. A straightforward way to obtain this is to normalize $\rho_R(R), \rho_z(z), \Phi(L)$ suitably so as to fit the observations, and then to integrate over these functions. (One would still need to allow for the beaming factor, discussed below.) However, we introduce here another approach (Narayan and Vivekanand 1981; Vivekanand and Narayan 1981, henceforth VN), which is equivalent as far as this discussion is concerned, but is of considerable value in the analysis of section 4.

Let us describe the present true population of pulsars in the Galaxy by the continuous function $\rho_t(P, \dot{P}, L)dPd\dot{P}dL$. The observed distribution $\rho_o(P, \dot{P}, L)$

differs from ρ_t because of the selection effects of the surveys. Let us define the scale factor $S(P, L)$ as follows

$$S(P,L) = \frac{\int\int \rho_R(R)\rho_z(z)dRdz}{\int\int' \rho_R(R)\rho_z(z)dRdz} \tag{7}$$

where $\int\int'$ means that the integration is over only that part of the Galaxy where a pulsar with period P and luminosity L could have been detected by at least one of the surveys included in the calculation. A crucial requirement for the computation of $S(P, L)$ is a knowledge of all the selection effects of the surveys, including P-dependent effects arising from dispersion (Vivekanand *et al.* 1982), sampling (Dewey *et al.* 1984), and scatter-broadening (Manchester *et al.* 1985). The author has recently computed $S(P, L)$, including all known and suggested selection effects, for the following four surveys: Jodrell Bank Survey (Davies *et al.* 1972), U Mass-Arecibo Survey (Hulse and Taylor 1974), Second Molonglo Survey (Manchester *et al.* 1978), and U Mass-NRAO Survey (Damashek *et al.* 1978).

The meaning of $S(P, L)$ is that for every one pulsar of given P and L detected by the surveys considered, there are on average $S(P, L)$ similar ones in the whole Galaxy, which could be detected with sufficiently sensitive telescopes. The total number of potentially visible single pulsars N_v in the Galaxy can thus be estimated to be

$$N_v = \sum_i S(P_i, L_i) \tag{8}$$

where the summation is over all single pulsars detected by the particular surveys with radio flux above the modeled minimum sensitivity limits of the surveys.

To obtain N_{psr}, we need to allow for one more factor *viz.*, the beaming fraction f_i, which represents the fraction of solid angle swept by the pulsar beam. If it is assumed that the conical beams that emerge from the two magnetic poles of a pulsar have circular cross-section, then one estimates $f \sim 0.2$ for all pulsars. However, there seems to be evidence that the beams are elongated in the meridional direction, with an elongation that is P-dependent (see Narayan, 1984, for a summary of earlier work). If we define R to be the ratio of the NS to EW dimensions of the beam (where the directions are defined with respect to the rotation axis), polarization data suggest (Narayan and Vivekanand 1983) that

$$R \sim 1.8P^{-0.6} \tag{9}$$

Consequently, f also has a P-dependence, with $f(P) \to 1$ at short periods $\lesssim 0.1s$, and decreasing to $f(P) \sim 0.2$ at long periods $\gtrsim 2s$. Including the beaming fraction, we thus estimate the total number of active single pulsars in the Galaxy to be

$$N_{psr} = \sum_i S(P_i, L_i)/f(P_i) = (1.5 \pm 0.5) \times 10^5 \tag{10}$$

The number of active single pulsars per kpc^2 in the solar vicinity is 150 ± 50. The errors quoted here and elsewhere in the article correspond to 95% confidence limits, and refer purely to the random statistical error. There could be additional systematic errors in the adopted distance scale and in the estimation of $f(P)$. The form of eq. (10) is obvious when one notes that the true and observed pulsar distributions are related by $\rho_t = \rho_o S(P,L)/f(P)$.

4. BIRTHRATE OF SINGLE RADIO PULSARS, AND "INJECTION"

If we take the pulsar population in the Galaxy to be in steady state, then we can follow VN and define the steady current of pulsars, $J(P)$, crossing from periods shorter than P to larger then P by

$$J(P) = \int\int \dot{P}\rho_t(P,\dot{P},L)d\dot{P}dL \tag{11}$$

The mean current in the period-interval between P_1 and P_2 is then

$$\overline{J}(P_1,P_2) = \frac{1}{(P_2 - P_1)}\int_{P_1}^{P_2} J(P)dP \tag{12}$$

If all pulsars are born with periods $< P_{min}$ and die with periods $> P_{max}$, and if $P_{max} > P_{min}$, then the birthrate BR of pulsars is given by $\overline{J}(P_{min}, P_{max})$ (see VN for a discussion). We have already seen that the factor $S(P,L)/f(P)$ relates the observed pulsar distribution ρ_o to ρ_t. Thus, we can estimate BR from the observed sample of pulsars as follows

$$BR \simeq \frac{1}{(P_{max} - P_{min})}\sum_i{}' \dot{P}_i S(P_i,L_i)/f(P_i) \tag{13}$$

where the summation $\sum'$ is over those pulsars detected by the various surveys with periods within the range P_{min} to P_{max}. Arbitrarily selecting $P_{min} = 0.05s$, $P_{max} = 2s$, and using the current data, we find

$$BR \sim 1 \text{ psr in } 50^{+240}_{-30} \text{ yrs} \tag{14}$$

It should be noted that this method of estimating the birthrate is quite model-independent, in contrast to most other approaches, which assume some model regarding pulsar spindown (e.g. magnetic dipole braking), as well as a model for the variation of L with P and $\dot{P}$. The price we pay for the model-independence is that the statistical errors are extremely large.

To improve the signal-to-noise ratio, we now introduce the following model for pulsar radio luminosity

$$L \propto \dot{P}^{1/3}P^{-1} \tag{15}$$

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Several previous studies have shown that L increases with increasing $\dot{P}$ and decreases with increasing P, with exponents similar to those in (15) (Lyne *et al.* 1975; VN; Proszynski and Przybicien 1984). The particular form chosen here is somewhat natural since (i) $\dot{P}/P^3 \propto \Omega\dot{\Omega}$ is the total energy loss rate of a pulsar, and (ii) pulsars seem to switch off in the radio when they fall below a particular value of $\dot{P}/P^3$ (Taylor and Stinebring 1986).

The model (15) only gives the *mean* luminosity of a pulsar observed with period P and period derivative $\dot{P}$. There is a great dispersion around this mean, which should also be included in the model. This can be done (the details will be reported elsewhere), and one can calculate a scale factor $S(P, \dot{P})$, which is defined in a manner similar to $S(P, L)$. Thus, the quantity $S(P, \dot{P})/f(P)$ represents, for every pulsar detected with a given $P, \dot{P}$, the expected mean number of similar pulsars in the whole Galaxy. Using these scale factors, we can again calculate the mean current $\overline{J}(P_1, P_2)$ between periods P_1 and P_2 as follows

$$\overline{J}(P_1, P_2) = \frac{1}{(P_2 - P_1)} \sum_i{}' \dot{P}_i S(P_i, \dot{P}_i)/f(P_i) \tag{16}$$

Fig. 3 shows the estimated $\overline{J}$ for the same four surveys considered earlier, binned suitably in P in order to have a reasonable signal-to-noise ratio within each bin. The current appears to have a flat top between $P \sim 0.7s$ and $\sim 1.4s$. Using these values as P_{min} and P_{max}, we then estimate

$$BR \sim 1 \text{ psr in } 60 \pm 20 \text{ yrs} \tag{17}$$

This is in reasonable accord with other recent determinations of pulsar birthrate (e.g., Vivekanand 1984; LMT), and is consistent with the rate of occurrence of supernovae, rate of formation of supernova remnants, and the rate of death of massive stars in the Galaxy (e.g. see LMT for a discussion). As recently as 5 years ago, estimates of BR were embarrassingly high, typically 1 psr in $\sim$7 yrs (e.g., Lyne 1981, Phinney and Blandford 1981). The key advances that have led to the present reduced estimates are (i) the realization by J. H. Taylor (see VN) that the variation of L with P and $\dot{P}$ is important and should be allowed for (this reduces BR by a factor $\sim 2 - 3$), (ii) the introduction of non-circular beams (reduction factor ~ 2), and (iii) a modification of the distance scale (LMT). The pulsar birthrate per kpc^2 in the solar vicinity is estimated to be 1 per $\sim 7 \times 10^4$ yrs.

A surprising feature of Fig. 3 is that the pulsar current does not reach its maximum value until $P \sim 0.7s$. It is difficult to reconcile this result with the standard assumption that all new pulsars are, like the Crab pulsar, born spinning rapidly with $P \lesssim 20$ ms. VN noted this effect and termed the phenomenon as "injection", since new pulsars are being "injected" into the pulsar "stream" at intermediate points. It is unlikely that "injection" is due to a selection effect, since all suggested P-dependent effects have been included in the present calculation. Neither is it due to the assumed luminosity model (eq. 15), since a similar result is obtained even with a model-free calculation using $S(P, L)$, except with a much poorer signal-to-noise ratio. Also, the effect is present even if we eliminate the variable beaming fraction $f(P)$ and use a constant $f = 0.2$. We note that "injection" has been confirmed in an independent analysis by Chevalier and Emmering (1986). Also, Stokes *et al.* (1985) found fewer fast pulsars than expected in a new survey and concluded that many pulsars may be born spinning slowly. Srinivasan *et al.* (1984) studied the rate of formation of Crab Nebula-like plerions and again concluded that very few pulsars could be born spinning as rapidly as the Crab pulsar.

A further indication that "injection" is not the result of a statistical fluctuation, but possibly due to a real physical effect, is provided by Figure 4. Here the pulsars have been ordered according to the strength of their magnetic field (eq. 2), and divided into three equal groups. We see that "injection" is very strong for the high B pulsars, not so prominent for the intermediate B pulsars, and absent for the low B pulsars. Using this as a clue, one could suggest three possible explanations for "injection". i) Many single pulsars may be "recycled" in massive binary systems before being released (e.g. articles by Srinivasan and van den Heuvel in this volume). High B pulsars would be naturally "recycled" to longer periods. ii) Neutron stars with strong fields may be born slower because of magnetic braking during the red giant phase. Although the magnetic energy of a neutron star is negligibly small compared to the rotation energy, the two energies could be comparable *before* collapse, because they scale differently with radius, and so a magnetic coupling between the stellar core and its envelope is not unlikely. iii) Neutron stars may be born fast, but could turn on as radio pulsars only after slowing down (VN; Phinney and Blandford 1981), perhaps because magnetic fields build up after birth (Blandford, Applegate and Hernquist 1983). The results of Fig. 4 would require that high magnetic fields take longer to build up than low fields.

5. BIRTHRATE OF BINARY PULSARS

Of the 7 known binary radio pulsars, 6 were discovered in major surveys. It is therefore possible to roughly estimate the rate of formation of these systems. Van den Heuvel (e.g., this volume) divides the binary pulsars into two classes. The pulsars 0655+64, 1913+16, and 2303+46, have companions with masses $\gtrsim 1\ M_\odot$, and are believed to be produced from massive X-ray binaries (MXRB). The approximate birthrate of this class of binary radio pulsars in the Galaxy is 1 in $\sim 10^4 - 10^5$ yrs. The MXRB's in the Galaxy form at a much larger rate and can comfortably maintain this rate. The second group, consisting of 0820+02, 1831-00, 1855+09, and 1953+29, have companions with masses $\lesssim 0.4\ M_\odot$, and are believed to originate in low mass X-ray binaries (LMXB). Here there may be a problem with the birthrate (Kulkarni and Narayan, in preparation).

Consider the millisecond binary pulsar 1855+09, with $P = 5.362$ ms, $B \sim 10^9$ G, discovered by Segelstein *et al.* (1986) in their recent Princeton-Arecibo survey. Allowing for the volume of the Galaxy surveyed so far for such objects, we estimate $S(P, L)$ for this pulsar to be $\sim 10^5$. This somewhat astonishing result implies that there may be as many active binary millisecond pulsars in the Galaxy as ordinary single pulsars.

To estimate the birthrate of these objects, we need to know the age of 1855 +09. If the magnetic field is still decaying, then its age is $\tau \lesssim 10^8$ yrs, assuming a decay timescale of 10^7 yrs. However, Kulkarni (1986) (see also Srinivasan, this volume) suggests that fields stop decaying after they reach a low value $\sim 10^8 - 10^{10}$ G. If this has happened to 1855+09, then it is slowing down by magnetic braking, and its age is $\sim 10^9$ yrs. Using this latter estimate, we find that the birthrate of 1855+09-like objects in the Galaxy is 1 in $\sim 10^4$ yrs. Although this is much smaller than the rate of formation of single pulsars, it is still much larger than the rate that can be maintained by LMXBs. The number of known LMXBs in the Galaxy is ~ 30, and they are presumed to live $\sim 3 \times 10^8$ yrs, which suggests that they can support a birthrate of only 1 in $\sim 10^7$ yrs. Unless we say that Segelstein *et al.* (1986) were extremely lucky to have found 1855+09 (which is unlikely since 1953+29, a similar system, was also discovered while searching a very small volume of the Galaxy, J. H. Taylor, private communication), we may be forced to conclude that either the galactic LMXBs are not the progenitors of 1855+09-like binary radio pulsars, or that the observed sample of LMXBs in the Galaxy is much more incomplete than we think.

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DISCUSSION

J. Taylor: I like your suggestion that coupling to outer layers may explain the slow initial rotation rates of "injected" pulsars, but wouldn't coupling to an ejected supernova shell be as good as coupling to the outer layers of a red giant?

R. Narayan: Yes, it would, and the same coupling might also explain the orign of pulsar velocities and the correlation of velocity with magnetic field (Lyne, this volume). However, once the neutron star is formed, its rotation energy is so much larger than its magnetic energy that it is hard to visualize the field doing anything important. It is for this reason that I feel the extraction of angular momentum should take place before collapse, possibly over a long time in the red giant phase.

S. Kulkarni: I object to your extrapolation to small galactocentric radius (R) because pulsars are primarily young objects and hence their distribution should follow the molecular gas distribution. It is well known that, apart from some molecular gas at the Galactic center, there is a great deficiency of H_2 inwards of the "5-kpc ring".

R. Narayan: If we assume the galactic electron density model of LMT, then the results of the 1400 MHz survey of Clifton and Lyne (1986) suggest that there is little or no deficit of pulsars at small R. However, the electron density model was determined from previous data which did not probe the inner Galaxy. A self-consistent analysis of the new data to simultaneously solve for the electon density as well as the pulsar number density at small R might well show a concentration of pulsars in the 5-kpc ring. However, I believe that the functional form of $\rho_R(R)$ in eq. (5) is quite adequate for the limited purpose of estimating N_{psr} and BR.

F. Verbunt: The X-ray sources in M31 are distributed in a central group (probably Pop II) and a ring (probably pulsars) around the center. The X-ray pulsars in our galaxy are also absent in the direction of the galactic center; in fact almost all X-ray pulsars are in the Carina arm. If there really are many radio pulsars in the galactic center area, doesn't this cause problems for the idea that radio and X-ray pulsars originate from the same O-star progenitors? What do we know about the O-star distribution near the galactic center?

R. Narayan: I believe the distribution of O stars in our Galaxy is traced by the giant HII regions, which are known to peak in the 5 kpc ring. Therefore, there would indeed be a problem if the pulsar distribution did not decrease in the galactic center region. The situation will become clearer after the data from the Clifton and Lyne (1986) survey are analyzed.

J. Arons: The argument that beams are elongated because of the lack of polarization sweep assumes the polarization-limiting radius is always deep in the dipole field region, independent of the rotation period and light cylinder distance. However, if the plasma density in the magnetosphere is sufficient to lead to collective emission, as in the case for the pair creation models, the polarization-limiting radius in the shorter period objects is well into the region where toroidal fields reduce the polarization sweep just as well as the elongated beam models. Therefore, the elongated beam model is <u>not</u> model independent, and is, in my opinion, less likely than the toroidal field model worked out by Barnard.

R. Narayan: I agree that Barnard's work nicely explains the polarization data without invoking an elongated beam. However, as reviewed in Narayan (1984), there are other arguments that support the elongated beam hypothesis. I would mention in particular the fact that interpulses occur very often in short period pulsars, and hardly at all in slower pulsars. This finds a natural explanation with period-dependent beam elongation, but would need additional hypotheses with a circular beam.

W. Sieber: The computation of pulsar luminosities assumes pulsar beam shapes which are box-like, i.e. there is either emission or no emission. Real pulsar beams are much smoother. Should one take this "smoothing" into account.

R. Narayan: You have raised an important problem for which I have so far found no simple solution. The hope is that the box-like beam can replace the true beam (which has a smooth fall-off of intensity) in some average sense, so that estimates of beam elongation, luminosity model, birthrate, etc. are not affected very much. It is important to make a more careful analysis of this effect.

A. Blaauw: Where would you suggest lies the dividing line in mass between the larger and the smaller mass groups in the binary pulsars?

R. Narayan: The division of the binary pulsars into two groups has been suggested by van den Huevel (this volume). In the smaller mass group, the companion white dwarf has a mass $\lesssim 0.4\ M_{\odot}$. These systems are believed to have evolved from binary stars with masses $\lesssim$ 8-10 $M_{\odot}$. In the larger mass group, the companion is either a neutron star with mass $\sim 1.4\ M_{\odot}$, or a heavy white dwarf with mass $\gtrsim 1\ M_{\odot}$. These systems are believed to originate from binary systems with masses $\gtrsim 10\ M_{\odot}$.

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