THE PROGENITORS OF PULSARS

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ABSTRACT. The progenitors of single as well as binary pulsars are discussed with special emphasis on binary pulsars with low mass companions. Several predictions are made concerning millisecond pulsars.

1. INTRODUCTION

Till quite recently it was believed that formation of all neutron stars was associated with type II supernovae: in sufficiently massive stars the mass of the degenerate core will eventually reach the Chandrasekhar limit and become dynamically unstable, resulting in the formation of a neutron star and accompanied by a supernova explosion. For a variety of reasons, one has now been forced to entertain additional scenarios for the formation of neutron stars. It may be worth listing these before proceeding further.

The second route for the formation of neutron stars is through white dwarfs. There are three possibilities.

(1) A white dwarf more massive than the Chandrasekhar limit could in principle be stabilized by thermal energy or rotation. Eventually due to cooling or magnetic braking it will become unstable (Shklovsky 1978; Ostriker 1971). But this scenario must be so rare that we shall not discuss it further.

(2) An extremely tight binary consisting of two white dwarfs will eventually coalesce, perhaps resulting in the formation of a neutron star. Since this mechanism is likely to be discussed in detail later in this conference, we shall not discuss it here.

(3) The third possibility is accretion induced collapse of a white dwarf in a binary (Miyaji et al 1980). Very few people dared to speak about it in public a few years ago, and yet this seems to be popular now and, indeed, taken for granted !

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2. THE OBSERVED POPULATION OF PULSARS

Keeping these theoretical scenarios at the back of our mind, let us turn to the observed population of pulsars.

The B-P plot: Figure 1 shows approximately 300 pulsars with their measured periods and derived surface magnetic fields. Pulsars in binaries are indicated by dots inside open circles. There are seven binary pulsars known so far (J.H. Taylor, this volume). The first thing that strikes one is that the single pulsars have fairly high magnetic fields and predominantly in the range 10^{12} - 10^{13} gauss. The binary pulsars, however, have a wide spread in their fields, ranging from 10^{12} to 4×10^{8} g a u s s. There may be other differences between the single pulsars and the binary pulsars, such as their space velocities and scale heights, but we shall not pursue them further at the moment. But it *is* worth noting that the seven binary pulsars may be further subdivided into two classes - one in which the companion has mass comparable to that of the neutron star itself and the other group having very low mass companions. The companion of PSR 1913+16 is almost certainly another neutron star; this is probably the case for PSR 2303+46 also. The mass of the white dwarf companion of PSR 0655+64 is again probably $\sim 1\ M_{\odot}$. On the other hand, the two *millisecond* pulsars in binaries, as well as PSR 0820+02 and PSR 1831-00 have rather low mass companions.

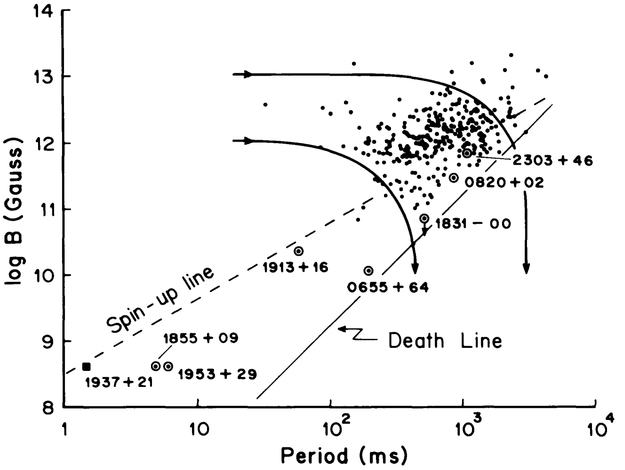


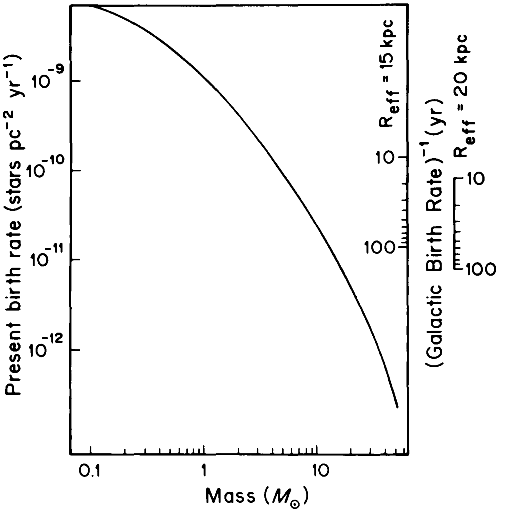
Fig. 1: The periods and derived magnetic fields for about 300 pulsars are shown. The dots with open circles are pulsars in binaries.

Given this grouping of pulsars into several familities, it is natural to ask if they can be traced back to the different progenitor systems outlined before.

3. THE ORIGIN AND EVOLUTION OF SINGLE PULSARS

Let us first turn to a discussion of the progenitors of single pulsars and their evolution as pulsars. The standard picture is that they were formed by the collapse of degenerate cores of massive stars. The progenitors could have been single stars or members of binary systems. From the statistics of pulsars one can deduce their birthrate (see e.g. Lyne et al 1985; R. Narayan, this volume). Although there is some uncertainty in this number, for the purpose of definiteness I shall assume a birthrate of 1 in 40 years.

The question to be asked now is the following: Are there enough massive stars to give a pulsar birthrate of 1 in 40 years and what is the mass range which makes the dominant contribution to the pulsar population? To answer this question one takes recourse to some initial mass function (IMF), and a smoothed lifetime of stars as a function of their mass. For example, figure 2a shows the integrated deathrate of stars using the IMF



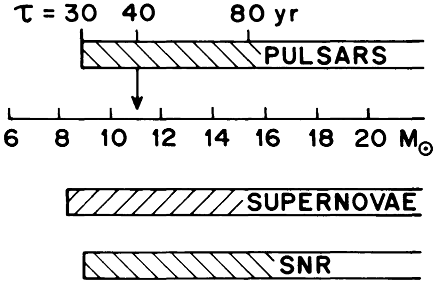


Fig. 2(b)

←*Fig. 2(a)*

Fig. 2: (a) The integrated birth rate of stars derived by Miller and Scalo (1979). This can be used to derive the limiting mass of progenitors of pulsars given their galactic birthrate and an effective radius for the galaxy. This is indicated on the right.

(b) The lower limit for the mass of the progenitors implied by the pulsar birthrate, the frequency of supernovae and the birthrate of supernova remnants is shown. The uncertainties in these rates are indicated by hatched regions. (R_{eff} = 20 kpc has been assumed)

of Miller and Scalo (1979). In order to use this deathrate function, which is derived from a study of stars in the local neighbourhood, one has to convert the *galactic* birthrate of pulsars to a *local* rate. For this one needs to assume a value for the effective radius of the galaxy. If the distribution of pulsars were uniform in the galaxy, then one would simply take a standard number like 15 kpc for the radius. However, it is believed that the radial distribution of pulsars is not uniform; there are more pulsars around $\sim$ 5 kpc from the centre of the galaxy than in the solar neighbourhood. Therefore, in going from a galactic rate to a local rate one must assume a larger effective radius for the galaxy than its actual dimensions. Figure 2b summarizes the conclusions assuming an effective radius of 20 kpc. We see that a pulsar birthrate of 1 in 40 years implies that all stars above $\sim$ 11 $M_\odot$ should produce neutron stars. The hatched region represents the uncertainty in the pulsar birthrate. Also shown in the figure are the birthrate of supernova remnants and the frequency of supernovae. Although there is considerable uncertainty in each of these rates, it is interesting to note that there is significant overlap between them.

Recently Blaauw (1985) has looked into this question from a different point of view, and has arrived at some important conclusions. His approach may be summed up as follows. He restricts himself to the observed sample of pulsars whose distances projected on to the galactic plane are within 0.5 kpc. From the information about the scale height of pulsars, and their measured proper motions, he concludes that the *local* population of pulsars must be replenished every 5 million years by *local* progenitors. After examining the deathrate of stars in the nearby OB associations he arrives at the conclusion that the local pulsar population *cannot* be replenished by OB associations alone. The field stars must therefore make an important contribution. Blaauw's conclusion is that the progenitors of the overwhelming majority of the local pulsar population must be the relatively old population of field stars with masses in the range 6-10 $M_\odot$. There simply aren't enough stars more massive than 10 $M_\odot$ to replenish the local population of pulsars every 5 million years or so. If one accepts this, then an equally important corollary is that 'Pulsars are, on a galactic scale, tracers of regions of past spiral structure (20-50 Myr) rather than of active spiral structure' (Blaauw 1985).

It should be remembered that all these conclusions regarding progenitors are based on star counts and there are considerable uncertainties involved in going from that to an integrated deathrate function, as has been repeatedly emphasized in the literature. However, if one accepts these conclusions for the moment, the next logical question to ask is whether stars in these mass ranges are likely to produce neutron stars. I shall leave this question to later speakers. Assuming that the answer is positive, let us ask if the observed characteristics of the single pulsars is consistent with what one expects from such progenitors.

As already mentioned one of the most significant characteristics of the population of single pulsars is that they have high field. Indeed, even before neutron stars were discovered it was surmised that flux conservation during core collapse will result in fields $\gtrsim 10^{12}$ gauss (e.g. Woltjer 1964). Therefore there may not be much mystery in that. It was also conjectured that the newly born neutron star will be spinning very rapidly, perhaps close to the limiting period $\sim$ 1 millisecond. The discovery of a fast pulsar in the Crab Nebula seemed to confirm this expectation. However, both the statistics of pulsars and the absence of a large number of bright plerions in the galaxy strongly suggest that the majority of pulsars must be born spinning rather slowly with periods $\gtrsim$ 100 ms (Vivekanand and Narayan 1981; Srinivasan, Bhattacharya and Dwarakanath 1984; Chevalier and Emmering 1986). As the pulsars age their periods will lengthen; thus their evolutionary tracks will be horizontal in the B-P plane (see fig. 1). After a few million years the magnetic field will begin to decay and the trajectory will become vertical. Although it is generally agreed that magnetic fields of neutron stars do decay, there is no consensus on either the mechanism or the time scale over which the field decays significantly. Observations suggest a timescale $\sim$ 4-8 million years (Chevalier and Emmering 1986; Lyne, Manchester and Taylor 1985). If we admit field decay in this sort of time scale then the *distribution of fields at birth will be narrower than the observed spread.*

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As the period lengthens, and the field weakens, the pulsar will eventually die. Even though the details of the emission mechanism are poorly understood, there is strong observational evidence and theoretical justification for the existence of a 'death line' (Ruderman and Sutherland 1975; Rawley, Taylor and Davis 1986).

4. PULSARS FROM MASSIVE BINARIES

We now turn to the progenitors of pulsars like 1913+16 and 2303+46 which have massive companions. In sufficiently massive binaries two neutron stars will be born. In very rare cases the system will remain bound after the second supernova explosion which signals the birth of the second neutron star. The first born beutron star will be *recycled* during the X-ray phase. The rotational history of a neutron star in a mass transfer binary has been reviewed in several places (see. e.g. van den Heuvel 1984) and therefore I shall summarize it rather briefly (fig. 3a). Initially the

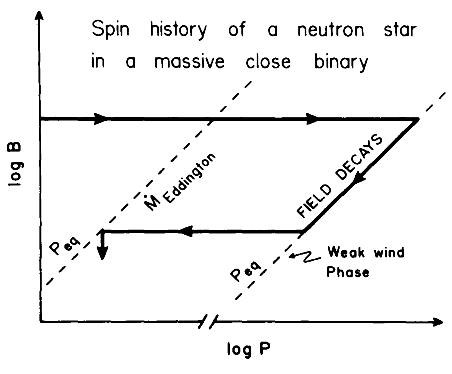

Fig. 3(a)

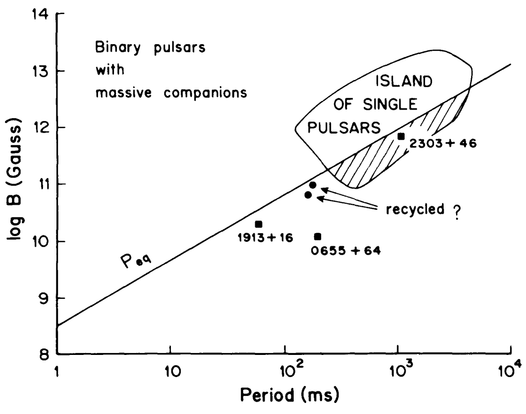

Fig. 3(b)

neutron star will experience a braking due to its pulsar activity. During the weak stellar wind phase, the braking will be much more rapid, and soon it will cease to function as a pulsar. Eventually the period of rotation will settle down to an equilibrium value determined by its magnetic field and accretion rate. Before the secondary evolves and fills its roche lobe, the magnetic field of the neutron star can decay significantly, and it will move down along this line. When the neutron star becomes a power X-ray source, it will be spun-up to its *critical equilibrium period*. The period after such a recycling will depend upon the time between the first and the second explosion, which will determine the extent of field decay. The anomalous combination of small B and small P of 1913+16 clearly indicates that we are seeing such a recycled pulsar (fig. 3b). PSR 2303+46 is probably the second born pulsar, but it could also be the recycled one if the field had not significantly decayed.

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In the majority of cases, however, the system will disrupt during the second supernova. The second born pulsar can end up anywhere in the pulsar island (fig. 3b). The only definite thing we can say about its partner, the recycled member, is that it will be *below* the critical equilibrium period line. If its field had decayed significantly before the onset of accretion then it will stand out from the population of single pulsars, as does PSR 1913+16. PSR 1804-08 and PSR 1541-52, which are just outside the island, may also be recycled pulsars.

What is the formation rate of such recycled pulsars? The only thing certain about the answer is that it is uncertain!

The statistics of the standard massive X-ray binaries gives a birthrate of only one in $\sim$ 1000 years (see van den Heuvel and Habets 1985). Thus they will make only 3-5% contribution to the population of pulsars. van den Heuvel and Habets (1985) have suggested that B-emission X-ray binaries may make substantial contribution, but this is controversial.

The picture is not much clearer if we try to estimate the frequency of occurrence of binaries while both the stars are unevolved. The typical statement one finds in the literature is that $\sim$ 30% of massive stars are in binaries (see e.g. Boland and van Woerden 1985). Blaauw (1985) has also addressed this question. From a study of 135 stars of spectral types B2, B2.5, B3 in the nearby associations he concludes that only 18% are well established binaries, and there is no reason to think that the frequency of binaries among the B stars of the field population will be very different.

This question is of considerable importance. As we have heard, pulsars have a typical velocity $\sim$ 100 kms^{-1}. The prevalent opinion about the origin of this velocity is that the neutron star receives a kick at birth due to a small asymmetry in the supernova explosion. However, Radhakrishnan and Shukre (1985) have argued that both the observed velocities, as well as their correlation with magnetic field of the pulsars, will find a natural explanation if most, if not all, pulsars came from binary systems. The idea is that pulsars acquire their velocities from the disruption of the binary during the second supernova. In fact, pursuing this idea further they have been able to put fairly stringent constraints on the parameters of the progenitor binary systems. It should be emphasized that this mechanism is particularly attractive since there is, as yet, no logical basis for believing in an asymmetric explosion. Blaauw (1985) on the other hand, has argued that the high velocities of pulsars cannot be due to their binary origin since only a very small fraction of binaries are *close enough* to be of interest in this connection. Clearly this important question deserves further study.

5. PULSARS WITH LOW MASS COMPANIONS

Let us finally turn to a discussion of the progenitors of the binary pulsars with low mass companions, and their formation rates. Since this question will be discussed in detail by others, here we shall confine ourselves to one or two intriguing aspects.

It has been aruged by several people, in particular by Joss and Rappaport (1983), that the progenitor of the 6 ms pulsar must have been a Low Mass X-ray Binary (LMXB). In such systems, given the right parameters, there is no difficulty in maintaining mass transfer at close to the Eddington rate for as long as 10^8 years or more. Turning to the recently discovered 5 ms pulsar, this must have also evolved from an LMXB. An initial orbital period $\sim$ 1 day would lead to the presently observed period of 12.3 days. Although the absence of a companion for the 1.5 ms pulsar complicates matters this, too, may have come from a LMXB.

The real puzzle concerning the millisecond pulsars is not regarding their progenitors, but their *location*. It is an extraordinary fact that all three of them are very close to the galactic plane. Normal pulsars have a scale height $\sim$ 350 pc, which is much larger than the scale height of their progenitors, which is $\sim$ 60 pc. This is easily understood if the neutron stars acquire substantial velocities at birth. Even if millisecond pulsars are not created with such velocities, one would expect them to have a scale height at least comparable to that of their progenitors. The scale height of LMXBs is $\sim$ 300 pc, consistent with their belonging to old disk population. It is, therefore, extraordinary that all three millisecond pulsars discovered are within 25 pc of the galactic plane!

This remarkable 'coincidence' could in principle be rationalized under two exotic circumstances:

(i) It may be that the scale height of the very old neutron stars associated with LMXBs is indeed large, but for some reason they do not function as pulsars unless they are in an environment that obtains only close to the galactic plane!

(ii) For some unknown reason the velocity dispersion of these old pulsars *decreases* with time, and they 'settle down' near the plane. In other words, the population of millisecond pulsars 'cools' with time.

Since we have no suggestions at present for either of these two exotic possiblities, we shall offer a more modest alternative, viz, the proximity of the millisecond pulsars to the galactic plane is possibly due to selection effects. If so, an immediate implication of this is that there must be many more potentially observable millisecond pulsars.

If the scale height of these pulsars is $\sim$ 300 pc, like that of the LMXBs from which they have come, then one expects only $\lesssim$ 10% of them to be within $\sim$ 30 pc from the galactic plane. A simple scaling which takes into account this factor, beaming and the fact that all the three millisecond pulsars have been discovered in a small sector of the galaxy, suggests that there should be >300 binary pulsars with low mass companions within $\sim$ 4 kpc, implying a total number in the galaxy greater than two thousand.

Unfortunately, this number is much larger than the number of LMXBs in the galaxy. Presently about 30 LMXBs are known, and it is very unlikely that there are more than 100 of them (McClintock and Rappaport 1985). If our basic premise, namely that millisecond pulsars evolve from LMXBs, is correct then the lifetimes of these pulsars must be 20-30 times longer than the X-ray phase of these systems, which are believed to last for $\sim 10^8$ years. We thus conclude that millisecond pulsars must live for $\gtrsim 10^9$ years.

An immediate conclusion one can draw from this is that the magnetic field of a neutron star, after an initial decay in the timescale of a few million years settles down to an asymptotic value. This conclusion has also been arrived at, for essentially the same reason, by van den Heuvel et al (1986). Motivated by the very large apparent age of the white dwarf companion of the binary pulsar 0655+64 Kulkarni (1986) has also concluded this.

Till now the intriguing thing was why the field decays at all. Now we have to understand why the decay stops! Perhaps the correct picture is that the field decay is not a simple exponential process, but a power law. The next question is what is the limiting value of the field, and is this the same for all neutron stars?

Even before the latest millisecond pulsar 1855+09 was discovered, we noticed that the 1.5 ms pulsar and the 6 ms pulsar have almost identical fields. Considering that the 6 ms pulsar is far from the spin up line in the vertical direction (see fig. 1), we felt that this could not be an accident. This led us to speculate that the magnetic fields of very old neutron stars will probably be $\sim 5\times10^8$ gauss. Soon after the discovery of the latest millisecond pulsar 1855+09 we predicted (Bhattacharya and Srinivasan 1986) that its field will be very close to this value. Since then the $\dot{P}$ of this pulsar has been measured (J.H. Taylor, this volume) and its magnetic field is almost exactly the same as that of the other two millisecond pulsars, confirming our conjecture.

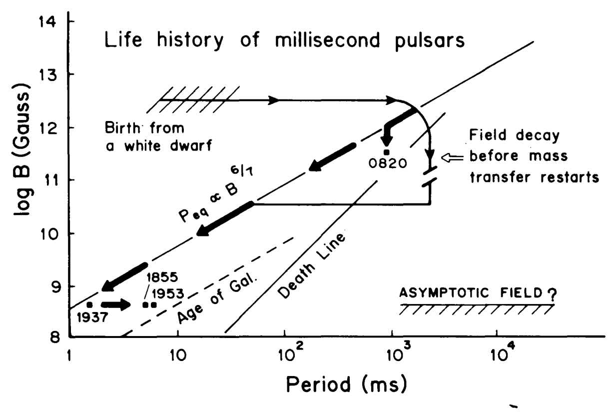

Fig. 4

If one accepts all this, then one can summarize the evolution of pulsars born and processed in LMXBs as follows (see fig. 4). Let us begin with the birth of the neutron star due to accretion-induced collapse of the white dwarf. Presumably it had a high field $\sim 10^{12}$ gauss. One cannot be so certain about its initial

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period, but most likely it would have been spinning rather rapidly and functioning as a pulsar (we are grateful to W.H.G. Lewin for pointing out that accretion on to the newly born neutron star may not commence till several million years have elapsed since its birth and its magnetic field can decay somehwat during this interval). With the onset of accretion it will be spun up to its equilibrium period. It will then dribble down along the equilibrium period line till the mass transfer phase is over. If the initial orbital period is rather large, for example, a couple of 100 days, then the mass transfer will last for less than 10 million years and the field would not have decayed significantly. Then the pulsar will 'peel off' from the 'spin-up' line. The evolutionary history of PSR 0820+02 was probably this; the present orbital period of $\sim$ 1200 days is fully consistent with this picture. But if the mass transfer lasts longer the neutron star will continue to dribble down the 'spin-up' line till the field reaches its asymptotic value of $\sim 5\times10^8$ gauss. After the debris clear away the recycled pulsar will move along a horizontal trajectory. An important implication of this constant-field evolution is that since $\dot{P} \propto P^{-1}$, more pulsars will be found at longer periods. However, given the age of the galaxy, the maximum spin period reached will be only $\sim$ 10 ms. One will, therefore, expect a concentration of millisecond pulsars near $P \lesssim 10$ ms. The periods of the observed millisecond pulsars is consistent with this expectation.

Summary:

1. The fact that all three known millisecond pulsars are so close to the galactic plane can only be a 'selection' effect. Millisecond pulsars must have a scale height comparable to that of LMXBs from which they probably evolve and we predict that there should be $\gtrsim 100$ potentially observable millisecond pulsars within $\sim$ 4 kpc.

2. Such a large number of millisecond pulsars is consistent with the birthrate of LMXBs only if the lifetime of these pulsars is more than $\sim 10^9$ years. This, in turn, would require that their magnetic fields do not decay indefinitely.

3. The fact that all three known millisecond pulsars have fields very close to each other indicates that the limiting field is around $\sim 5\times10^8$ gauss.

4. The corollary of this is that the majority of ultrafast pulsars will be in binaries and will have periods in the interval 6-10 ms.

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DISCUSSION

J. Shaham: First a comment: In a forthcoming Phys. Rev. D paper, Harvey, Ruderman and myself calculate the lifetime of neutron star core fields (due to superfluid proton vortices) and find them to be $\gtrsim 10^9$ years. Core fields may, thus, be the slowly relaxing component. Now a question: Do the ages of the 3 millisecond pulsars, measured via their deviation from the zero-age curve for spun-up pulsars, conform statistically to your assumed age of $> 10^9$ years?

G. Srinivasan: Yes.

W. Lewin: When a white dwarf is pushed over the Chandrasekhar limit (due to accretion), its binding energy increases by ~ 0.2 $M_\odot$. As a result the system will detach (mass transfer will stop). Mass transfer will resume when the Roche geometry again exists. This, according to Ed van den Huevel can take between a few 10^6 to a few 10^7 years. Therefore the magnetic field decay could be substantial before the neutron star begins to accrete and is spun up due to the accretion torques.

J. Taylor: First a comment: The period derivative of PSR 1855+09 has now been more accurately measured. The new value corresponds to a magnetic field almost exactly the same as those of PSRs 1937+21 and 1953+29, $B = 5\times10^8$ G. Now a question: Is it not true that the numbers you quoted for the frequency of binaries among massive stars should be viewed as lower limits?

G. Srinivasan: Thank you. I am pleased to hear that the magnetic field of PSR 1855+09 is exactly what we had predicted. Turning to your question concerning the frequency of massive stars in binaries, let me say this. Perhaps it is best if I first quoted Blaauw's remarks pertaining to this question (Blaauw 1985). ". . . 18% are well established (single-line) spectroscopic binaries with determined orbits. The semi-amplitudes of the velocity variations of their primaries range from 14 to 131 km/sec with a median value of 50 km/sec. For the remaining 82%, we are certain that the semi-amplitude of the primary is below 30 km/sec for 13%, below 20 km/sec for 38%, and below 10 km/sec for 31%. These numbers do not leave more than a few percent room for objects of which the explosion of either of the two components could result in a runaway star with a velocity of at least 100 km/sec and a mass of at least the mass of a neutron star." There is of course a possibility that many of the low-velocity binaries may contain a neutron star in which case they would be of interest in this context. However such a postulate is not consistent with the statistics of B-emission X-ray binaries or that of their progenitors.

D. Eichler: If the decaying magnetic field "settles down" to a value of $\sim 10^9$ gauss, as you have suggested, in dipolar form, why do accreting X-ray bulge sources not display spin periodicity? A 10^9 gauss field is enough to funnel the flow needed to produce a typical luminosity.

G. Srinivasan: This will be discussed Thursday.