Pulsars : Problems & Progress
ASP Conference Series, Vol. 105, 1996
S. Johnston, M. A. Walker and M. Bailes, eds.

Debate : The Origin and Evolution of Millisecond Pulsars

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1. Part One

Dick Manchester We now have what I hope will be a vigourous debate and discussion on the 'Origin and Evolution of Millisecond Pulsars'. To being this I would like to welcome Ed van den Heuvel who just arrived off the 'plane an hour or so ago.

Ed van den Heuvel Thank you. I am very happy to be here. Dipankar already mentioned this point of the birth rate problem and of the progenitor problem of the low-mass binary pulsar systems. In my opinion there is no need at all that should be a one to one relationship between the low-mass X-ray binaries which we see - the long-lived ones which we see - and the low-mass binary pulsars. I mean, a low-mass X-ray binary may produce a low mass binary pulsar but it is not said that all low-mass binary pulsars come from the low-mass X-ray binaries that we observe because that is a very pre-selected group.

This problem looks a little bit like that of this man who walks along the street and he comes to a lamppost and near the lamp post there was another man on his hands and knees crawling around and the first man asked 'What is your problem?', and the man on his hands and knees turned out to be drunk and he said 'I am looking for my key. The man said, 'did you find it?' and the drunk man said 'No'. 'Did you lose it here?' 'No. I lost it over there but there it is dark and so I can't find it there.... [Laughter]

This is the problem with the low-mass binary pulsars. It's very well possible that there is a group of progenitors which are short-lived as an X-ray source and therefore that we don't see. Dipankar already pointed that out quite nicely. Actually if you look, the low-mass binary pulsars are characterised by the fact that the companion is a helium white dwarf with a mass below 0.45 $M_\odot$. Such a degenerate helium core forms in any star of mass below 2.3 $M_\odot$ - it depends a little bit on chemical composition. But all these ones have produced giants which have a degenerate helium core and finally if it is a single star it evolves through the helium flash. Now if you put it in a binary you take away the envelope by mass transfer and you are just left with this degenerate helium core. So you can go up to companions of about 2.3 $M_\odot$. Now we also know that there is a core mass-radius relation for these degenerate helium cores. This relation is independent of the mass of the envelope so it doesn't matter whether you put the 0.1 $M_\odot$ hydrogen envelope around it or a 2 $M_\odot$ hydrogen envelope around it. Once the degenerate helium core mass is fixed the radius of the star is fixed. So in a binary system with a radius when its transferring mass equal to the Roche lobe radius. So too the star of 2 $M_\odot$ - if you put it into binary with a neutron star companion it will of course go through. That is the important point because if it is 2 $M_\odot$ it is more massive than the neutron star and you will get that the mass transfer rate, in the beginning, runs out of hand, because if you transfer mass from a higher mass star to a lower mass star the orbital period shrinks while the star is wanting to expand and then you get mass transfer on the thermal time scale of the donor. There is a simple formula for that - it goes inversely proportional to the mass of the star squared, so that the mass transfer rate then is just the envelope mass which is about the same mass as the mass of the star divided by the thermal time scale and very roughly this goes as $M^{1/3}$ / 3×10^7 in $M_\odot$/yr If you just plug in numbers you get then mass transfer rates which are very high. If the companion is 1.2 $M_\odot$ (and assuming the neutron star to be a little less massive of course) you have mass transfer rates which are 5 times or more higher than the Eddington limit and so this thing will not show up as an X-ray source because it has too much matter around it. It will be some funny shrouded object which you won't see as an X-ray binary.

Still the duration of this phase is pretty long - of the order of 10^7 yr. You are bound to get a lot of mass loss from system when you have mass transfer higher than the Eddington limit; the surplus will be blown out of the system. The phase until it gets to this thermal time scale is very short - a few hundred thousand years only. Her X-1 is an example of this because you have a 2 $M_\odot$ companion to a neutron star. So Her X-1 you see only very short now and maybe after it has lost a lot of mass, its envelope mass has become smaller, the total mass of the star has become smaller than the neutron star mass then it can stabilise and get a relatively short lasting phase as an observable X-ray binary. This mass loss will of course affect the orbital period very much and so all these things can happen and you are not bound to see these systems for a very long time. It is true what Dipankar said at the end of this presentation. It is rather unfortunate that there could be many systems of types which we don't see for a long time but still they could have a high birthrate. Actually I came to the conclusion that Her X-1 lives for only 2×10^5 yr. Suppose that you compare it to the standard low-mass X-ray binaries where the donors have masses below 1 $M_\odot$. These systems are long-lived like 10^8 yr. The fact that we see one Her X-1 out of say 100 low mass X-ray binaries, implies that the birthrate of the Hercules systems is higher than the birthrate of the 100 low mass X-ray binaries that we see because they live 100 million years and this guy lives only for 2×10^5 yr. So it could very well be that this Her X-1 population has a much higher birthrate than the standard low mass X-ray binary.

Matthew Bailes It's only one object Ed!!

Ed van den Heuvel It is one object but a very important object!! [Laughter]

Ralph Wijers What I want to say is that Her X-1 will go back to a phase of stable mass accretion after the mass ratio has reversed. Then there should be a hundred times more of those stable descendents of Her X-1 than there are Her X-1.

Frank Verbunt They will be 3 kpc from the Galactic Plane!

Ed van den Heuvel They will be hidden amongst the low mass X-ray binaries.

Frank Verbunt At 3 kpc distance from the Galactic Plane?

Ed van den Heuvel Yes, what's the problem?

Frank Verbunt You require a lot of low mass X-ray binaries out there!!

Ed van den Heuvel Why?

Ralph Wijers Well because Her X-1 itself is that far from the Galactic Plane!!

[At this point things become very confusing with a lot of people speaking simultaneously. Some discussion cut.]

Jon Arons Will it also lose its space velocity if it accretes?

Ed van den Heuvel Her X-1 does not need much more velocity to get where it is than 100 km/s.

Jon Arons That's not what I'm asking. Where are all the descendents? If Her X-1 has a space velocity of 100 km/s and it is at 3 kpc then wouldn't it's descendents, if they were also like that, be at that height?

Ed van den Heuvel That's what you would expect. I don't know how far the low-mass binary pulsars get from the Galactic Plane. Could you comment on this?

Frank Verbunt I think the main problem there is that the velocity effect that you observe for the X-ray binaries is of the order of 100 km/s but because they are much closer to the Galactic Centre they can still have velocities of 100 km/s and not get too far from the Galactic Plane. I think that must be the answer.

Ed van den Heuvel But do you see low mass binary pulsars going out to 2 kpc or 3 kpc?

[Again a plethora of voices. Most people seem to be saying no but there are rumblings about selection effects including ...]

Matthew Bailes The problem is that once a pulsar gets outside the electron layer it becomes difficult to determine its true z-height.

Roger Romani The observed velocities are quite consistent with 100 km/s.

[More general confusion ... then ...]

Dick Manchester I think it would help the recording if only one person spoke at a time!!

[An excellent comment in retrospect!]

Ed van den Heuvel I won't talk for much longer than this but I think we should start the debate.

Dick Manchester I think the debate has already started!!

Ed van den Heuvel What I wanted to say is that there is no reason why nature would only produce companion stars of masses preferably below a solar mass or so to the standard low mass X-ray binaries. Actually it is rather unlikely that nature would do that because in the supernova explosion it is easier to keep (with these kicks) a 2 $M_\odot$ companion bound than a 1 $M_\odot$ companion. So everything in the range from 1 to 5 $M_\odot$ of course is easily kept bound. The only ones which really show up as a long-lived low-mass X-ray binary are the ones which have low mass donor stars and that does not mean that they should be the real reservoir of progenitors of low mass binaries.

Fred Rasio I have a few questions. The low mass binary pulsars that seem to be missing progenitors - the very long orbital period ones...

Matthew Bailes No, there is an over-supply of short-period ones [binary pulsars], not long period ones.

Ed van den Heuvel No, there is a shortness of supply of the short period ones [X-ray binaries].

[This seems rather confusing. The point being made is that there are too many short orbital period millisecond pulsars compared to the low-mass X-ray binaries]

Fred Rasio So does your scenario give you a preferred dynamical orbital period?

Ed van den Heuvel Her X-1 is going to go to a mode of a lot of mass and angular momentum loss. At the moment it has a 1.7 day orbit but it could easily wind up shorter. But that depends very much on how much angular momentum is being lost by the system during this phase.

Roger Romani I'd like to comment briefly on Ed's population of intermediate mass objects. There is a natural laboratory for testing much of this and that is the black hole binaries. There of course at these intermediate masses you have stable transfer. We've done a population synthesis and indeed you will find that there are a number of systems expected in this to 2 to 5 $M_\odot$ range of the donor object. And interestingly, in the black hole population as limited as it is today there are several objects with companions in this mass range. So one can check the birthrates of high mass progenitors with intermediate mass companions and thereby extrapolate towards the shortlived Her X-1 sort of system that we would expect for neutrons stars. We have indeed done that sort of population synthesis and presented it at IAU Symposium 165.

Ralph Wijers But how many are there in that gap. I thought that ...

Roger Romani It's not a gap for the blackhole systems that's the whole point. Here you expect them to be stable transfer objects.

Ralph Wijers Sure. But I mean I thought that the highest mass of the low mass black hole systems was 1.3 $M_\odot$ and then the next one up is 6 $M_\odot$.

Roger Romani Oh not at all. In LMC X-3 you have a 4 $M_\odot$ object.

Paul Ray Yeah, I was just wondering. How many of the currently living super-Eddington accreting systems do you need to account for the birthrate and if there are a bunch of them how do we expect to see them? We should at least accelerate relativistic radio jets or something if we don't see them as radio sources.

Ed van den Heuvel I don't know whether you really need to see them as relativistic jets. Do you think that is a requirement if you are going super-Eddington?

Paul Ray Somehow you have to get rid of this [excess mass]. You can't accrete that much matter so it's got to get rid of it somehow. I would expect that there would be a lot of particle acceleration.

Ed van den Heuvel On the time scale that the high mass transfer rate states lasts, you would expect that you would have an order of magnitude or more of these systems than of the observed Her X-1 systems.

Paul Ray Ten or so currently observable in the Galaxy?

Ed van den Heuvel More even.

Matthew Bailes I have a question for Roger Romani. How many assumptions are in your population synthesis code and how many radio pulsar black hole binaries did you predict?

Roger Romani As in all these codes there are of course many assumptions and you have to try to follow the binary evolution as best as you can. The number of radio pulsar black hole binaries predicted in the current population was of order of 0.3 or 0.5, just as similar calculation by Narayan has illustrated. But of course as you point out, all these population synthesis calculations are sensitive to the many details of binary evolution. In particular the common envelope phase is of course very poorly understood at present and integral to all these evolutions.

Ed van den Heuvel But I think the only way to really get to the problem is to do these simulations even though all kinds of assumptions are maybe difficult. Matthew points out that there is only one Her X-1. So if you really want to know something about what birthrate you expect, I think the only way would be to do population synthesis because there you can produce many of them with your computer program.

Dick Manchester I think we might move on to the next semi-formal presentation. I believe Ene Ergma is going to address the first point on Dipankar's list. The orbital period companion mass relation.

Ene Ergma Ed has already told you about this relation. And recently Rappaport and others re-examined the evolution of binaries which started out as neutron stars and low mass X-ray giants and ended up with millisecond pulsars and white dwarfs. This idea has been put before the audience ten years ago and it was a really nice possibility to look at how the stellar evolution works and to compare results with the observations of millisecond binary pulsars. There exists a very good relation between the core mass (or the white dwarf mass) and the red giant radius and if you accept Roche lobe filling then you can find the initial orbital period and it is connected with the radius and mass of the red giant. As Ed told you from this influence of mass loss we can find the final orbital period which is connected also to the red giant radius and thus with the mass of the white dwarf. If you know this relation you can get a very interesting empirical formula with only two parameters, the white dwarf mass and the final orbital period. They claim that this dependence is good for an orbital period between 1 and 100 days. But if we compare the real population with the calculations we can see that especially for orbital periods of less than 10 days we can get a very large discrepancy between the calculation and the simple formula. The problem arises if the secondary fills its Roche lobe.

Near a 1 day orbital period the evolution is extremely complicated since the Roche lobe filling star is not a giant, it does not have a well-developed core inside and the core is increasing during the evolution when the star is losing mass. For this case the evolution is completely different. It depends very strongly on mass and angular momentum losses from the system. It depends very strongly on the structure of the star during the Roche lobe filling.

[Viewgraphs were shown here which unfortunately the editors to not possess ...]

For example you can see. For two cases. There is an extremely small change of the initial period and you can get completely different values of the final period and also very different values for the masses of the white dwarf. But we know that we have a lot of systems with an orbital period of less than 10 days - the majority of systems - so please be careful when you use this empirical relation.

Another point which is much more worrying to me is that we have several systems which have an orbital period of more than 100 days and the masses of the white dwarfs are very very very small compared to this simple relation. Please also look at the Tauris posters [later in this volume]. So, I think that there are two things to do to find this white dwarf orbital period relation especially for orbital periods of less than 10 days. We need a homogeneous set of binary evolution calculations. We cannot use this simple formula. The second thing is of course that we need independent white dwarf mass determinations.

Dick Manchester Ene Ergma has questioned this relation and I know we have some champions for it and some people who would also may want to question it. We'll have a few points if anybody wants to comment.

Frank Verbunt I would just like to make this point that there is no argument that between 1 and 10 days - where most of the low mass binary pulsars are - you cannot apply ordinary giant evolution, as I and Rappaport and others have shown. There is no way you can end up with a period of less than 10 days, starting with the giant unless you go through common-envelope [?? Editor's guess] evolution as we pointed out. On that aspect there can be no debate.

Fernando Camilo But what about the long orbital period ones that are predominantely to the left of the line.

Marten van Kerkwijk Maybe I should just put up a viewgraph so that you know more of what the statistics are.

[This is a graph of companion mass verus orbital period which can be seen in Figure 2 of Bhattacharya]

Marten van Kerkwijk Basically this is a logarithmic scale so all the error bars are the same size. You can see that the top six or so fall a bit too much to the left. Actually I think that a straight vertical line is consistent with the data!! [Laughter]

Fernando Camilo Anyway Frank says you can't use this relation for periods less than 10 days or so, right?

Frank Verbunt Let me give an off-hand explanation. We know that most of these binaries will probably also lose mass. For example a single star becomes a white dwarf by losing a lot of mass. Now mass loss will widen the binary. This is not taken into account in any of these calculations.

Matthew Bailes Then why did they publish them! If they had fallen on the line you would say it was perfect confirmation of the model but they don't so they say the model is wrong.

Frank Verbunt You will find actually I think in all these papers (in the bits people don't tend to read) the very careful statement that the model is only valid for conservative mass transfer. And if the mass transfer doesn't happen to be conservative the problem becomes very complicated and you get twenty papers instead of a few.

Ed van den Heuvel No I do not agree with that because the star always has to keep to its Roche lobe. If this core mass radius relationship holds, whether you lose mass by a wind or whatever it should always keep to its Roche lobe. So you would always expect to wind up with a core mass-Roche lobe radius relation and this core mass-orbital period relation.

Frank Verbunt There is a timescale argument in there because this is only valid if the timescale of the mass transfer and mass loss is less than the thermal timescale.

Ed van den Heuvel O.K. but then you have to go very fast.

Frank Verbunt Yes. Which at the end of their evolution they do.

Ralph Wijers You should realise that all these very wide period systems have had a phase in their evolution where the nominally computed accretion rate onto the neutron star would be super-Eddington.

Fred Rasio Could somebody show the orbital period eccentricity relation because that has always impressed me as being much more convincing with basically the same ideas, the same theory.

Ed van den Heuvel If this orbital period eccentricity relation holds then this one [ie the orbital period versus companion mass relationship - see Figure 2 of Bhattacharya] should also hold. I cannot see why that shouldn't be the case.

Fred Rasio All you can say here is that it is not incompatible.

[Confusing voices, different people saying yes and no ...]

Frank Verbunt So there is some sort of prediction in this diagram that the ones that are really far from the line should have a different type of white dwarf. They do!! [Laughter] No they really do!

Marten van Kerkwijk I am going to talk about that tomorrow. [See his contribution in this volume]. We know that in one case it is not a helium white dwarf. The very clear prediction is true.

Frank Verbunt I think we basically have to wait for independent measurements for determining the masses of these white dwarfs. Then we can ask a question whether this is compatible or not. I am perfectly happy with this diagram [Figure 2 - Bhattacharya].

Dick Manchester The ones that are furthest off, this group up here at the top. What are the prospects for getting independent mass estimates?

Marten van Kerkwijk It is in principle very simple for a white dwarf with hydrogen line. You can fit the line profiles to get a surface gravity and with a mass-radius relation you get the mass of the white dwarf. At the moment the range in mass that I get from the fit is about as big as that error bar and it will become smaller.

Sterl Phinney I will discuss cooling models tomorrow. I think cooling models almost require it to be way over to the right, a CO white dwarf.

Dick Manchester We're still talking about these up here at the top [of Figure 2 of Bhattacharya] are we? So you're saying they all should be over to the right.

Sterl Phinney At least two of them should be over on the right and the others I don't know yet.

Frank Verbunt May I ask you a question Sterl? If Ed was right and most of the progenitors of these actually were starting with rather more massive companions originally and go through an Algol stage. Do you still then predict the same eccentricity period relationship?

Sterl Phinney The eccentricity-period relationship is determined in the final phase of mass transfer as the last thousandth of a solar mass is transferred. So what determines the eccentricity-period relationship is whether the star is just inside its Roche lobe at that point and whether the luminosity is consistent with the core mass-luminousity relationship. So it's just the last thousandth of a solar mass that matters. Whatever happened to the previous solar masses is irrelevant - forgotten.

Frank Verbunt Do you expect the luminosity of the systems to be higher? Because you start off with a more massive star and therefore the minimum luminousity on the giant branch is higher than for a low mass star.

Ed van den Heuvel No - because of the core mass luminousity relationship.

Frank Verbunt A 2 $M_{\odot}$ star has to be at least eight times brighter than a 1.5 $M_{\odot}$ star once it gets to the vertical part of the giant branch. That's unavoidable isn't it?

Sterl Phinney But when it's got down to the same core mass then it is only the difference in the Hyashi track between the two masses [that matters].

Frank Verbunt So I'm wondering if [?? Ed: unclear] can make these lower ones.

Ed van den Heuvel Yes because you have a phase of orbital shrinking and stuff like that. No, no, no. This cannot make the lowest ones.

Frank Verbunt What is the mass of the white dwarf when the 2 $M_{\odot}$ star leaves the main sequence?

Ed van den Heuvel 0.2 $M_{\odot}$.

Frank Verbunt Fine.

Paul Ray I want to ask a question to Marten. Looking at a fit to a line with large error bars [Figure 2 of Bhattacharya]. How are those error bars drawn and what assumptions do you make? Are you assuming the neutron stars are 1.4 $M_\odot$?

Marten van Kerkwijk These error bars are sort of the usual thing. It is a 1.4 $M_\odot$ neutron star. I will come to that in a moment. 95% confidence limits. Actually you should realise that 95% confidence means that 1 of those will actually be out of the error bar. Very likely. Perhaps PSR 1831–00 but that would be too good!! [Laughter!]

Frank Verbunt There is actually another way of attacking the problem. A prediction of all these pregenitor models is also that the neutron star has accreted at least 0.1 $M_\odot$ and quite possibly rather more.

Marten van Kerkwijk From an observers point of view, what possible relations does one have? We already talked about this long orbital period one and the other one is the one Frank mentioned - that the neutron star should accrete up to 0.6 $M_\odot$. There is a very simple prediction which I would actually almost be inclined to use as a relation that if you could ever determine the angle between the rotation axis of the neutron star and the line of sight from polarisation studies (and we've heard how difficult that is unfortunately), then you should have the inclination of the orbit too. I listed the number of systems from which we know the inclination and I will come back to it tomorrow. The other prediction is that the neutron star should be more massive and so there are a number of systems for which you could determine the neutron star mass. PSR B1855+09 is the only one from which it has been done from the Shapiro Delay but it's very uncertain. For PSR J1812 [?? Ed: Probably means J1012+5307 here] it is also very uncertain and for PSR B1957+20 I know Roger's working on it and I don't know what the current status is. Do you get 1.8 $M_\odot$?

Roger Romani No it's more like 1.5 $M_\odot$ but the errors are still fairly large.

Marten van Kerwijk Anyway, that is another thing which is very interesting for the equation of state of neutron stars. The tendency at the moment tends to go for soft equations of states for which the neutron star cannot be more than 1.55 $M_\odot$. There is evidence for that especially from heavy ion experiments. That means that if you accrete so much mass and if you really think that our evolution is right we should have accretion induced collapse (AIC) of the neutron star into a low mass black hole. I think that is very hard to avoid. So it would be very interesting to test this and before this I wondered that for the Z sources we have some evidence of a low magnetic field neutron star. Maybe that some of the other low mass X-ray binaries have a low mass black hole can be tested. Coming back to Jon Aron's comments about magnetic fields. Is there any field reduction or should we actually invert this whole question about AIC. Instead of trying to have it solve just one or two systems we just say now all systems are AIC. That is the reason the magnetic fields are so different, and only the few which have a high magnetic field are from supernovae.

Dick Manchester Marten has raised this issue of AIC which has of course been a point of controversy. It's a bit down on Dipankar's list. We've skipped over a few points but because of time I'm tempted to start on the AIC issue. Does anyone have anything they would like to ....

Marten van Kerkwijk Dipankar said there is no reason for an X-ray phase after AIC and I don't understand that.

Dipankar Bhattacharya I said that if AIC is to be an real alternative route then there should not be an X-ray phase.

Marten van Kerkwijk Why not? If you form the magnetic field at the right level then the X-ray period is fine. You spin it up and then you have the right magnetic field. No need for field reduction.

Dipankar Bhattacharya You get the same birthrate problem.

Marten van Kerkwijk Oh. O.K. I still think that the magnetic field problem is bigger than the birthrate problem.

Matthew Bailes In Aspen, Shri Kulkarni pointed out that there are actually four models of AIC not one. The four models basically have an accreting white dwarf and a donor star, that is common to all models. What happens next is the important thing and during the collapse to a neutron star (if it can happen at all) you either get a high magnetic field star or a low magnetic field neutron star, and you can either get a kick of the neutron star or not a kick So you actually have this little box and there are four different possibilities. I you get a kick then your runaway system has a higher velocity. If it has a high magnetic field then it is not a millisecond pulsar and so the only way that yo can transform it into a millisecond pulsar is to have an LMXB phase later on. I it has no kick then you get a low velocity binary system and if it has a high fielc it is not a millisecond pulsar still so you have to decay it by some mechanism and you can't get a millisecond pulsar without an LMXB phase. On the othe hand if you have argued (like Bailyn & Grindlay have) you can collapse directl to a lower magnetic field neutron star which is already a millisecond pulsar anc if you have a kick as well then you have a high velocity system which already ha a millisecond pulsar which can do something like evaporate its companion anc you don't have an LMXB phase at all. The other possibility is that you don' have a kick but you go straight to a millisecond pulsar and then you get a lov velocity millisecond pulsar and no LMXB phase. So if you want to have reall high velocity millisecond pulsars you just invoke one combination and you ge it. Or if you want low velocity millisecond pulsars then you invoke a differen set of combinations. So in globular clusters for instance where you want pulsar to be retained and you don't want the birthrate problem then you go for thi combination. In the disk where you want high velocity millisecond pulsars yo go for a different combination. So if there is a range of magnetic fields and range of kicks going off in AIC, then they can explain everything. It is not reall what you would call Occam's favourite model but it is worth pointing this out

Dick Manchester But can't we, on the basis of these velocity kicks, prett well rule out your no kick option altogether?

Matthew Bailes You can't explain things in globular clusters then.

Dick Manchester You can if there are a lot more there to start off with

Matthew Bailes So you have a kick distribution.

Frank Verbunt Yes. A kick distribution and a field distribution. [Laughter]

Matthew Bailes Now something we've done to try and address this n kick/high kick/anywhere you go kick type model is to look at kinematics c millisecond pulsars. So, like Roger, following in his footsteps, we have a mode with a thousand assumptions and we did a Monte Carlo simulation of what sort of velocities you would expect and luckily our model predicts that you can get virtually any velocity and any orbital period and that's good because then you can just tweak assumptions one way or the other . Now we'll go to the cutting edge. This is the velocity distribution we expect for millisecond pulsars if they are born from type II supernovae and if you have Lyne-Lorimer type kick velocity distributions (and what you use depends on where you were brought up I guess). Basically millisecond pulsars are all going pretty fast and if you have a much lower kick velocity distribution they've got more like the velocities we see. So the problem is if you use AIC and you have a kick, you can work out what sort of velocities you might be able to get and this is the diagram you need to look at and this is recoil velocity along here. If you have a large kick you can get an AIC system going up to 500 km/s if you want. If you have no kick, the real velocity is more like tens of km/s. So if you want them in globular clusters, you look at this figure. If you want to explain a really high velocity object like Alex's planet pulsar [PSR B1257+12] which is going about 300 km/s you just go down to this figure and say AIC's consistent. So it's pretty hard to distinguish on the basis of kinematics between the models. That was my point.

Dick Manchester Any comments on what Matthew's just said?

Dipankar Bhattacharya What was the kick velocity distribution that you assumed?

Thomas Tauris For the box on the right corner we used the average kick magnitude of 450 km/s using a spread of 200 km/s, and that yields an average recoil velocity of 161 km/s.

Roger Romani A quick question to Dipankar on your presentation during your original talk. There you displayed population synthesis based on different kick distributions and argued that for Gaussian-type kicks at low velocity were consistent but also that Lyne-Lorimer and Phinney-Pacynski was consistent with high velocities. However they surely predict very different numbers in the population. Very different birthrates.

Dipankar Bhatttacharya I think if you take 100 km/s Maxwellian that has 5 times more birthrate in low-mass velocity X-ray binaries than the Lyne-Lorimer distribution.

Roger Romani So that may be a discriminant at the end of the day.

Dipankar Bhattacharya Well I think that the problem is that we really don't know the mass-ratio distribution at this low level and that is a real hurdle there.

Roger Romani And observationally that is extraordinarily difficult to probe. Yes.

Thomas Tauris Just a quick comment here. We find that if we use the large Lyne-Lorimer kicks we have a 1 in 7 systems will survive compared to using symmetric kicks. So the probability of the binaries surviving is only 1/7th as high.

Frank Verbunt Do you assume circular orbit right from start. Or do you allow eccentric orbits?

Thomas Tauris Yes. We assume circular orbits prior to the explosion.

Frank Verbunt That makes a very big difference but not for very high kicks.

[There is some further discussion here, mainly between Rathna Sree and Frank Verbunt which unfortunately is not very clear on the tape and which is not included here.]

[Part 1 of the debate ended here with a well earned coffee break for all the conference participants. Well refreshed, Part 2 begins ...]

2. Part Two

Ed van den Heuvel With AIC there are two questions. First of all will it occur in nature and the second one is it relevant for the systems which we are looking at here - for the binary pulsar systems. Now about will it occur in nature I think you can apply this well-known rule which Jerry Ostriker pointed out some time ago. Anything which the physical laws allow will occur somewhere in the universe, so we have all kinds of crazy objects like neutron stars, even double neutron stars, physically allowed so they exist and all kinds of other things. Now, AIC is not so strange because we have the Chandrasekar limit and so if we have a rather massive white dwarf you dump some matter on it it should collapse to a neutron star in some cases. It must occur in nature certainly, with 10^{11} stars in the Galaxy it certainly will occur.

The best candidates are the O-Ne-Mg white dwarfs. If you increase the mass, the central density grows and then you get electron-capture onto this massive nuclei which makes the core unstable and then it will collapse. Basically this is what happens in the type II supernova in a single star in the mass range 8-12 $M_\odot$. A growing degenerate O-Ne-Mg core forms; when this core grows at a certain point the density is so high that you get this electron capture collapse producing a type II supernova and a neutron star. Now how do you make an O-Ne-Mg white dwarf? You make it from a star in this mass range by mass transfer losing the envelope to another star in the binary. Then you can be left with a star which just did not collapse yet but is an O-Ne-Mg white dwarf. If you transfer matter back to the white dwarf in a later stage in the binary, it could just be a delayed collapse. You would expect just the same type of object to come out, which in my opinion is a strong magnetic field neutron star because the physics of the collapse is no different from that in a single star. So I never understood why people could get low magnetic field rapidly spinning millisecond pulsars out of this collapse. That's a point which always has escaped me why they would do it.

The other question is, can you make the mass of the white dwarf in the binary grow and indeed is this possible? If you have massive white dwarfs, around 1 $M_\odot$ or more, there are certain mass transfer ranges of the order of $1 - 4 \times 10^{-7}$ $M_\odot$/year, in that case you get steady nuclear burning without the star getting big. If you transfer more it begins to form a red giant envelope and you still get steady burning but the star will get larger than the whole binary system. If you transfer mass in this range you can keep the white dwarf small and it burns the hydrogen steady on the surface. If you are below this range you may get flashes - nova-like flashes and you can lose the mass, the matter which you have transferred. So in this mass range you can get stable mass transfer, that's already a long-known thing, and also we know that systems which are doing these things are the super soft ROSAT sources of which there are about

30 known now in our Galaxy, the LMC, M31 and M33. These tend to be binary systems where you have the steady mass transfer but apparently you just have the right mass transfer rate. The total number of these systems in the Galaxy is estimated to be of the order of 1000 although you see only a few of them because of the interstellar extinction which implies you can see them only out to a rather small distance. Observationally there are two types and also theory shows that you can get this $\dot{M}$ value in this range in two ways. If the donor is in this mass range , more massive than the white dwarf, you get thermal timescale mass transfer and the right mass transfer rate of this order of $10^{-7} M_\odot$/year and you get stable burning and the white dwarf can grow and possibly also collapse. An alternative is that you have a symbiotic system which has a donor star which is less massive than the white dwarf and becomes a low-mass giant like in the progenitors of the wide low-mass binary pulsars. You get the nuclear time scale mass transfer which for the right initial orbital period (more than about 30 days), so that you can make the white dwarf collapse if it is the right type of white dwarf. Now the question is of course, is this relevant for the low mass binary pulsar systems? We will look at that. I have my favourite object for that. I think that there is one for which one can make a strong case although it's a pity that Shri Kulkarni is not here because he will certainly tell me that I am wrong.

Ralph Wijers Someone else will instead!

Ed van den Heuvel Thank you Ralph. [Laughter]. Anyhow I want to now produce this picture which you may believe or not believe but if you plot the orbital period against the pulse period of low mass binary pulsars, the ones with helium white dwarf companions. It seems to me that there is a relationship but there are two guys which deviate from it. One is in a globular cluster, PSR 1718–19 but this one is in the Galactic disc, PSR 1831–00. You can make a similar plot of magnetic field strength against orbital period and of course these guys also deviate there. So this one has a strong magnetic field but still a short orbital period. Now if you try to make these systems with evolution in a binary like Ene Ergma showed and we have also made similar calculations, you can calculate assuming that the neutron star was in the system from the beginning of the mass transfer (so it was not formed during the mass transfer by AIC) if the companion was a 1 $M_\odot$ star (it could not have been much smaller to begin with because you need more than the age of the Galaxy to evolve such a star), more than 1 $M_\odot$ to overflow its Roche lobe and transfer matter. Assuming that the companion started out as 1 $M_\odot$, or maybe even more, you can calculate how much mass was captured by the neutron star assuming conservative [?? Ed: guess] mass transfer. This is the amount which I have put here at the top.

The assumptions going in are that if the mass transfer rate was below the Eddington limit and all the material captured by the neutron star was accreted. If the mass transfer rate was above the Eddington limit then only the Eddington limited amount was accreted and the rest was expelled from the system. That is in these wide systems the mass transfer rate is very fast so the majority of the mass was expelled and only the other small amount was accreted. This is the maximum possible amount of accretion that you can have which we calculated here because it is always possible that during this mass transfer and accretion there is a wind and that is blown off so it is possible that it is less efficient than indicated here. But now we look at this PSR 1831–00 system and if you assume that the amount of matter accreted is the cause of the decay of the field and it seems from this relation that it seems to fit in some way of another. This one does not fit at all. Now, how could you make it fit? The only way in my opinion is that PSR 1831–00 started out as a white dwarf, it accreted a lot of matter, and only near the end of the mass transfer phase it collapsed to a neutron star so there was little accretion and this is the reason why it deviates so much from this general relation. This is the point that I would like to make here. I look at many other different ways in which you could get this high magnetic field case. With a lot of accretion I have seen no way in which you could explain its very deviating position other than by AIC.

Dick Manchester That raises a few issues.

Ene Ergma You can happily have the hydrogen burning stable, like in super-soft sources but you forget about the helium flashes.

Ed van den Heuvel Of course that may occur, but in the O-Ne-Mg white dwarfs it may not be so much of a problem. If the white dwarf itself is already pretty massive to begin with say 1.3 $M_\odot$ or so, then you accrete a little - 0.1 $M_\odot$ is probably enough.

Ene Ermga No I think for this accretion rate that you may have a helium flash and lose the mass.

Ed van den Heuvel I thought this was more the case for the lower mass white dwarfs.

Ene Ermga No. Because the conditions are favourable then it may be a possibility.

Ed van den Heuvel The idea is that the hydrogen goes to helium and you form a helium layer. If you detonate the bottom of the helium layer of course you also have something which may compress the whole thing and then collapse it.

Ralph Wijers I don't quite follow your reasoning. Let me take PSR 1831–00 back in time. In order for PSR 1831–00 to have come from here [a long orbital period] ...

Ed van den Heuvel No no no. Not from a long orbital period.

Ralph Wijers If you want PSR 1831–00 after it has AIC'd and then it cannot have accreted much more mass, otherwise the fields would become low. Is that your argument? How much mass should it have accreted? Maybe 0.1 $M_\odot$. But the total mass transfered is almost 0.8 $M_\odot$ so there is 0.7 $M_\odot$ that is transferred before it became a neutron star. So the initial mass of the white dwarf is 0.7 $M_\odot$. That's a CO white dwarf you have but that thing doesn't accrete.

Ed van den Heuvel No, but if you assume that this was a purely conservative type of thing, you could have say a few tenths of a $M_\odot$ transferred and then an explosion.

Ralph Wijers No no no. Wait a second. There is in your scenario a rigorous prohibition on accreting more than about 0.1 $M_\odot$ onto the star.

Marten van Kerkwijk But anyway, if you form a neutron star with a large magnetic field you can no longer accrete any matter and it all escapes from the system. You just have the propeller effect. The system is already transferring rapidly. In the event of mass transfer rate it is like 10^{-7} $M_\odot$/yr. At some point you form this pulsar and then the mass transfer rate still goes on, but the pulsar easily manages to kick that amount out of the system for say a million years. That gets rid of the rest of the mass.

Ed van den Heuvel I would like to say these are really the maximum amounts. This is for purely conservative transfer. If you have wind or something like that, but mass transfer in general in these systems is not very efficient so you could have to multiply by 0.5 or something like that.

Marten van Kerkwijk Why is it not a normal star or the remainder of a normal star? This neutron star has just formed in a normal supernova explosion. Why does it have to have that much evolution at all with any mass transfer? How do you even know it has a white dwarf companion?

Ed van den Heuvel and Frank Verbunt It's in a circular orbit.

[All the debaters arguing about PSR 1831–00. Not easy to understand]

Ed van den Heuvel No no, suppose there was a main sequence star in there. You have to presume some scenario in which you shot the neutron star into [the envelope of the main sequence star] [?? Ed: guess]. It would have gone straight into the centre I think. If you do not have a compact core there is no way why it would stop in the spiral in phase and go straight to the centre.

Sterl Phinney PSR 1831–00 is unique not only by sticking out in this diagram but if you look at the core-mass period relationship it is the only one which is sitting way off the left at the short period end.

Ed van den Heuvel It has a small core yeah.

[Sterl Phinney and Ed van den Heuvel argue quite a bit, but the words are not very clear on the tape]

Marten van Kerkwijk What you need is an optical identification!!

Ed van den Heuvel You get low masses when the donor star is very close to the main sequence when it begins to transfer mass. You can get cores which are rather small, 0.1 $M_\odot$ or so.

Sterl Phinney Does that agree with the requirement that it has a high accretion rate?

Dick Manchester We'll have to move on now to the question of magnetic field evolution. This is an important issue which is poorly understood. First, Ralph.

Ralph Wijers The point that I want to look at briefly is recycling and spin down of massive binaries. The reason I think it's interesting is that we now have a number of high mass binary pulsars like PSR 1913+16 and family of which at least one that has a field that could be as low as 10^9 G. At least right now there is an upper limit 2×10^9 G in David Nice's system [PSR J1518+4904] so this whole business of recycling and reducing magnetic fields and increasing periods if it has any validity should operate here as well.

The problem with field decay is very severe if you realise that even the initial conditions are unknown, because somehow you want to recycle pulsars by having some change of a field by mass flows, but is it the amount of accreted mass that does the decaying, or the heating? That would work if the field was in the crust. Or is it perhaps something to do with spin down as Dipankar and colleagues have proposed which only makes sense if the field is in the core? So question 1 - Is the field of the neutron star in the crust or in the core? Well you tell me, I don't know. So what I will try to do is look at it a bit empirically and see whether you can say something about these scenarios from whether these systems fit in. Intimately related to it is slow down of pulsars because that is always needed, even if you don't want to do the decreasing of the field by slowing the pulsar down. At least initially you will have to slow the pulsar down before it can accrete material because if you imagine this time in a massive system you have a neutron star with an OB star accreting from the wind, there is a certain accretion radius which for high velocities is rather small and if the pure electromagnetic radiation from the neutron star is able to the stop material from flowing in you will do nothing to it. One way in which you can look at that is to look at what sort of mass transfer rate you would need at what spin period to have a system accrete or not accrete in such systems.

So if you look at the spin periods of neutron stars and you look at the mass that is being dumped onto the neutron star then there are sort of a few regimes. If you have very high accretion rates and long periods, then you actually accrete material onto the neutron star. If you have somewhat lower accretion rates than you get into a regime where material can penetrate down to the Alfvén radius, but at the Alfvén radius the magnetosphere is rotating more rapidly than the material that is coming in, so you don't accrete again, and you have what is called a propellor and you can spin a pulsar down. If you have even lower accretion rates you can't even make the material get to the neutron star, you do nothing to it. Most X-ray binaries comfortably fall in the region where they are supposed to accrete. There are a few systems that may not. For example, this Be star A0538 would appear to have to have a much greater mass inflow rate in order to be able to accrete. It's not that the luminosity is above the Eddington luminousity so maybe it's true accretion rate is indeed much higher than the Eddington accretion rate. If you try to do this spin-down there is a bottle neck at the period of about 1 second and that's an important thing. At very short periods you spin-down by simple pulsar electromagnetic spin-down and the spin-down time scale for that increases as B^2. If you have very long period and you have a reasonable amount of mass accretion you can decrease the period further by a propellor and you can see that both are very inefficient around 1 second. The embarrassing question is always - at this transition the spin-down time-scale is on the order of the life-time of a massive star. So it is not always clear that in massive X-ray binaries or X-ray pulsars you have enough time during the lifetime of the massive companion to get the pulsar from 10 - 100 ms where it was probably born to 100 sec or so where you see it. The most difficult one is X Persei, which has a very low mass inflow rate now and probably was only smaller in the past and still it managed to get to a spin period of 800 sec. It's very hard to get it there but it's not impossible, especially if you allow yourself to assume that X Per has a highish magnetic field maybe 10^{13} G instead of $10^{12.5}$ G. That makes a lot of difference.

So what is the bottom line? What sort of times and mass overflow amounts could you have if you try to recycle pulsars in massive binaries? Well first of all you have wind accretion during the main sequence which may last 3 - 10 Myr at an accretion rate observed up to the Eddington rate, but mostly much lower. The amount of mass you can accrete can be up to one percent of a $M_\odot$. But that is very very hard to get. Typically it will be 10^{-6} to 10^{-4} $M_\odot$. The ratio of final to initial periods can be anything and X Per is a 1000 sec so you can make it very slow. Once the star evolves off the main sequence you have another phase where you have Roche lobe mass transfer. Contrary to what is often assumed that is stable for a while. The reason that you have a wind mass loss rate which tends to expand the orbit, and it turns out that you can show that the mass transfer rate across the Roche lobe has to grow to about the wind mass loss rate from the star before you get unstable mass transfer and spiral in and because the wind mass loss rate of such a massive star can easily be 10^{-6} $M_{\odot}$/yr, you can have a very high Roche lobe mass transfer rate before the system becomes unstable. But still since this phase lasts for only a short time, the amount of mass you can transfer this way is only on the order of 10^{-4} $M_{\odot}$.

I think that there is a real problem, and the real problem is the following. If I try to make a score card of how I might recycle the fields in massive binaries, there are these 2 things. Can I recycle the field by having just some recycling proportional to the amount of accreted material or does it depend on the ratio of the final periods? But if you try to do it by pure ΔM, if you fit the normalisation to low mass X-ray binaries which have accreted about 0.1 $M_{\odot}$, you conclude that to get this 10^9 G pulsar in David Nice's relativistic binary pulsar [PSR J1518+4904], you need to accrete a percent of a solar mass, and as I have just showed you that is very difficult to do. But for the period ratio argument, then you need to get a maximum period in that pulsar in a previous phase of about 100 sec, which is very easy. 100 sec is quite a typical period for X-ray binaries. Then, the other problem is for many of these models where you have field decay proportional to mass accretion or heating, the field decay is immediate. That means that as soon as you start accreting mass you start decreasing the field. My question is then, why is it that in all massive X-ray binaries you still see an X-ray pulsar which indicates that you have a fairly high field. There is only one possible exception which is 1700–37. Whereas for most of these things where you expel fields from the core, you have to then wait for the field to decay in the crust which may take 10^8 years or so which is much greater than the lifetime of the X-ray binaries. There is then no problem why you see all massive X-ray binaries having high periods.

Another point that I would like to make is regarding whether low-field pulsars have very different formation periods than high-field ones. Among the old systems, the white dwarf + neutron star binaries, we now have the full range of magnetic fields available and among the neutron star + neutron star binaries you have almost a full range of field available. So why should you have different mechanisms of getting those ranges and fields is not quite clear to me. Another point regarding PSR 1831–00. An easy way in which you could or at least a possible way in which you could have a high field in that system is if the decay is proportional to the maximum period you get, then you could make a system like this in an old binary with a high field by having a fairly sudden onset of mass transfer so that you never have a propellor spin down, you never get to a very low period and still you have a lot of mass transfer but since you've never had a long period you don't get a low field. So my bottom line of this is that this sort of period ratio changing of the magnetic field seems to me to be more consistent with the binary pulsars and I don't see why there should be special mechanism to make the white dwarf + neutron star ones.

Dick Manchester O.K. Thank you Ralph.

Roger Romani I'd like to first dispel one misconception about accretion-induced field decay. Except for models where you are doing it via inverse battery effects or thermal effects, it is not necessary for the field to be in the crust, in fact the screening sort of models that I and Ed have advocated, it's quite the same if it's in the core or in the crust so you should not distinguish between crustal and core field as a means of determining which of these two mechanisms is applicable. The second point is that immediate accretion is really not an issue because the first 10^{-5} $M_\odot$ or so there is virtually no effect on the field in these scenarios. You really must accrete of order 10^{-3} or so before you decay the field even by a factor of 10. The final point that I would like to make, I think that in all these scenarios for field reduction (this point was made earlier I think in Dipankar's review) it is essential in my view that there is some floor to the mechanism. You really do not wish to have it automatic when you have say 0.3 $M_\odot$ accreted on the star that you would drive the field below perhaps 5×10^7 G. If we could drive too many pulsars below the detectable floor for magnetic field, I think that we would have an even worse birthrate problem than we do. Such sort of floors are in fact very natural in accretion-induced field decay scenarios they probably can occur in rotation-induced field decay scenarios as well.

Ed van den Heuvel You said it would be difficult in a high mass binary to accrete 10^{-2} $M_\odot$ and I thought that is indeed the case. However there is a recent paper by Jerry Brown where he shows how to make say double neutron stars like PSR 1913+16. If you assume that the companion of the pulsar is something like a Wolf-Rayet star, because the wind of the Wolf-Rayet star lasts for 0.5 Myr you can accrete something like that 10^{-2} $M_\odot$.

Dick Manchester O.K. Marten. Would you like to make your 1 minute contribution.

Marten van Kerkwijk This is the figure that I showed you before [Figure 2 of Bhattacharya]. My devil's advocate position is that everything is AIC and it just depends on what the field of the white dwarf was when it collapsed. Actually I was just talking over coffee and of course you could also have AIC of neutron stars not into low mass black holes but into quark stars. Anyway, the real question is is there a limit to the magnetic field? I personally don't worry about the birthrate problem as much I still think that the magnetic field is really a much larger problem. I think Ed gave a very good suggestion of how to get rid of the birthrate problem. So are there any predictions for the B field configuration? The only model that I know that actually makes predictions is the Ruderman model. I don't know if Roger or Dipankar can make any predictions of what the configuration of the field is after the recycling, if there are any predictions. What do you predict for alignment and for how close is the field to a dipole? We heard from Jose Navarro [see his contribution in this volume] that at least for PSR J0437–4715 he says it is almost impossible to understand if it is just a dipolar magnetic field. One point which the same as Ralph's - where are the high-mass X-ray binaries with in-between fields? I would say for accretion induced field decay you would expect some systems with 10^{10} G which should be pulsars. A0538 is an example of an intermediate field which gets rid of Ralph's problem.

Dick Manchester There are a couple of questions in that.

Nobu Kawai I would just like to make a comment about [?? system name, not clear] There are recent observations of transient X-ray binaries with low luminosity of the order of 10^{32} erg/s. If we interpret it by accretion due to the [companion's stellar wind - Ed's guess] you have to demand a very low magnetic field.

Ralph Wijers What is the spin period of that system? Because X Per of course has a very low X-ray luminosity, it's only a few times 10^{33} erg/s and that is not prohibited at all by a high magnetic field. If you look at where the propellor accreter boundary line is at 800 seconds, you could easily get 10^{33} erg/s accretion rate with a very high magnetic field.

Dick Manchester O.K. I think perhaps we'd better move along, otherwise even our invited speakers won't get a change to say their piece. We'll move on to the question of isolated recycled pulsars.

Frank Verbunt The problem is that there is a problem of notation. Most people talk about millisecond pulsars whereas I think it is in fact better to talk about recycled pulsars, because not all of the so-called millisecond pulsars have a millisecond period. So I will in fact not be talking not about the ones with very short period but the ones with larger periods. This is a diagram that Dipankar showed [Figure 1 of Bhattacharya] and you will notice that in the diagram there is a binary pulsar there, so if it is recycled it is just hiding amongst the ordinary pulsars. I personally think that that particular one [unclear as to which pulsar he means, perhaps PSR B1820–11] is not recycled, but it is possible that amongst the ordinary pulsars there are pulsars which have actually been in a binary and whose properties have changed due to the binary evolution and that is the topic that I will address.

[There are viewgraphs used here not available to the editors] Anyway this is briefly what I wanted to do although I feel that it seems to be outside the range of the questions I will actually discuss evolution scenario models and I think that is quite appropriate for many of the other topics. So how can you get a recycled pulsar amongst a single pulsar population? Well basically you have a binary, the neutron star stays in the binary after the first supernova explosion where it is formed and then it leaves the binary when its companion explodes in its turn. So there have been arguments that looking at those pulsars you can find these things. For example people have argued that there are too many pulsars at high periods. If you compare with evolutionary scenarios, some of those have pulsars with rather small periods. Other people have investigated it and have argued the opposite and the same is true for the question of whether you need injection in order to explain these low field pulsars. Some people say yes, some people say no.

So I want to start from the other end and just say lets start with the binary, look at the binary evolution and see whether this occurs often, or not often. Now one then has to assume a model and we call it a standard model, not because we think it is better but because it is the one with which we compare all our other models. This is work which was done mainly with Portegies Zwart and others. We assume some mass loss in the stellar winds, some mass transfer loss in the binary. We allow for originally eccentric orbits and this has an effect on its survival probability at the first supernova event and for the moment in this explanation I assume no kicks. And the reason why I will not talk about kicks is because they are random and because they are low kicks. Once you know the initial situation, you can work your way through final situation without branching. So take for example a 16 $M_\odot$ and a 9.6 $M_\odot$ star in a 2 day binary period. These two stars will merge and only form one neutron star in the end so these cannot lead to the kind of things you want. If you have 20 days you'll have mass transfer that leaves the core of the first star which explodes as a supernova, so now you leave a neutron star main sequence binary. But then you have a spiral-in process and in this case these two stars merge so the helium star doesn't get a chance to explode. It merges onto the neutron star before it gets there, so this will not work either. At longer orbital periods, however, the helium star can explode but due to the spiral-in process, the orbital period after spiral-in is so small that it cannot escape if there is no kick. So you have a bound system of two neutron stars which does not contribute to a single neutron star population. If your orbital period is 800 days there is never any mass transfer at all and the binary is disrupted at the first supernova explosion. I indicated with these inverted brackets that the binary is disrupted. Now for another example, take a 12 and a 10 $M_\odot$ star, for short orbital periods you would get mergers in this case after the helium star has formed, and the interesting case now is that it really it depends on the period whether you form a bound system, more or less along these lines: for a 25 day and an 800 day initial period. There is an intermediate period range where in fact the binary is disrupted. So this one will contribute to this population of recycled pulsars amongst the single ones.

Now why is this so complicated? The reason is that when at these periods, the mass transfer is more or less conservative and in the intermediate range it is not, there is a tricky thing there which I don't have time to go into. At very long periods again, the binary is disrupted, because these don't interact because the binary is eccentric, it depends on where in the binary the supernova explodes, whether you have a bound or an unbound system. In all these scenarios only this one will actually contribute to this single pulsar recycled population. Then we go to the population synthesis. We now take a lot of binaries, you select original masses, mass ratios, distances between the stars, in other words, orbital periods and eccentricities, you use your set of prescriptions that you like to evolve all these binaries and now I include kicks because I think that these stars do have kicks. So you evolve one binary and you repeat until you have enough systems that you can do statistics. For this particular case we find that if we use our favourite model, less than 1% of all type II supernovae are actually systems in a binary where the binary is disrupted after the explosion. So out of every hundred single neutron stars made only one was made in a binary. That's the claim here. I think that is too few for a significant population. Now there is a loophole which you might argue. In this particular case this neutron star accretes a lot of matter during this merging process, or at least this could happen. So that's the Thorne-Zytkow type object that might form and so if this neutron star accretes a lot of mass you could also call it a recycled single pulsar. Now for those my numbers are not quite as accurate but I think they are still less than 1% of the total number. So the first half of my talk is that I told you that this probably doesn't work. The second half of my talk which will only be a minute, I will explain to you why you should not be believe this statement!! [Laughter]

The reason for that is that there are uncertainties involved. We don't know the initial conditions. Especially not of the type of binaries that could produce neutron stars. There are very bad statistics on O star binaries. We don't know the period distribution or the eccentricity distribution. We don't know the evolution prescriptions. We do not know what the kick velocities are. We don't know how much mass is lost and how it affects the binary period. We do not understand the details of spiral-in sufficiently well to give the effects on the binary period, and we do not understand at all I think how Thorne-Zytkow objects work. In order to illustrate this I just want to compare two evolutionary scenarios published in the literature, one is in press, where people compare the same initial binary. According to Tutokov & Yugelson the binary shrinks during the first mass transfer according to us it expands by a factor of 100!! [Laughter] According to these people such a short-period binary cannot spiral in and still survive, according to our prescriptions this would be totally impossible. Now you'll be gratified to know that although the roots are very different, both of these scenarios actually lead to the same final result!!! [Laughter] O.K. So the population synthesis seems to indicate that there is no significant single population of recycled pulsars, but on the other hand I think one should really be very careful in believing these results. This does not include only our own population synthesis calculations but also the ones by you Roger and the ones by Dipankar I think.

Dick Manchester People who do these sorts of things are evidently masochists.

Frank Verbunt ..... if you can live with uncertainties.

Dick Manchester O.K. We'll have a short discussion on this topic but we might have to move on to the final topic.

Paul Ray I'd just like to point out that there is one pulsar that I want to look at as an example of this class that we found in a survey a little while ago that was a 96 ms pulsar we initially noted that it was near the Cygnus Loop and had a very short period and every pulsar with a shorter period was in a supernova remnant, so we thought maybe that was associated. It made Vicky's list as a poor supernova remnant association, but when we started to time it we found a very low period of derivative, which gives it only a $\sim 2 \times 10^{11}$ G field. But it is a single pulsar so it may well in a class of something that had accreted some matter during its lifetime and that's why the period is so short.

Frank Verbunt I think it will occur ... but the question is especially at the low magnetic field end, I believe this could happen. I did not even split my final population into those that have accreted a lot of mass during their evolution and those that have accreted almost nothing.

Roger Romani I'd just like to add to the previous example. PSR 1951+32 is another possible case of a disrupted binary where you have a low field single neutron star.

Matthew Bailes .... it's also another possible example of just a neutron star which is born with a weak magnetic field.

Roger Romani Quite.

Dick Manchester O.K. I'll suggest that we move on then to the final topic. Fred Rasio's been pointing out at frequent intervals that globular clusters are being somewhat short-changed in this meeting and he'd like to redress that a little. So Fred you'll have the floor for 10 minutes.

Fred Rasio I'm just feeling a little bit overwhelmed because I told Dick that I would say something about globular cluster pulsars not imagining for a moment that I would be practically the only person at this conference to even mention them. So now I feel a little bit compelled to start with a few general comments to sort of make sure that everybody remembers that globular clusters are interesting.

I think one main reason... [tape ends here, but only about one sentence is missing] .... from a theoretical point of view mainly from the realisation that primordial binaries exist in dynamically significant numbers in global clusters and that dynamical interactions involving primordial binaries play an absolutely crucial role in both determining the long term dynamic evolution of the clusters and in producing all these wonderful exotic systems like millisecond pulsars.

Computationally there has been enormous progress just to mention one thing. The Japanese have now built a computer, this is a special purpose hardware that they are using to do direct n-body simulations of systems with n of order 10^5, that is you can now do direct n-body simulations of systems where the number of stars is comparable to the real number of stars in the cluster. Observationally of course there has been enormous progress with things like HST images of cluster cores, x-ray observations etc. So this is a particularly good time to work on globular clusters I think. Pulsars of course have made lots of contributions to this and hopefully it will continue.

Just quickly to mention some of the interesting applications. I think that the simple realisation that there are large numbers of low mass binary millisecond pulsars in clusters has played a rather crucial role in sort of forcing us to accept the idea that dynamical interaction of primordial binaries are really important, and especially for the long orbital period systems. I think there is really no other way of forming that, other than an exchange interaction involving a neutron star with a binary in the cluster. If you measure $\dot{P}$s for cluster pulsars, they are often affected if not entirely determined by acceleration in the cluster, if you also have good positions you can then start constraining the mass distribution in the cluster, perhaps the relaxation rate and Sterl Phinney has done the this exercise very nicely for M15. You can also use the binary orbit as a probe of globular clusters, especially the wide systems, they are wide so they have a big cross-section to interact with other things. You know that the eccentricity when they are born is extremely small, so that even a fairly mild distant interaction with something else in the cluster is going to perturb the eccentricity and leave a permanent memory of this interaction in the orbital perameters. This is something that you can then detect and hopefully learn something, for example constraining the age of the system, and there are a couple of posters outside on this with Douglas Heggie. From specific systems you can learn a lot. When M15C, the double neutron star system in M15, was discovered, Phinney & Sigurdsson pointed out that this was absolutely clear evidence for an exchange interaction with a cluster core. In fact, it was the first direct evidence for an exchange interaction ever taking place in the core of a globular cluster. A somewhat similar situation is the binary in NGC 6539 although it is less clear what the mechanism is, but it has a very large eccentricity, way too large to have been to be explained by just a distant fly-by type interaction with a passing star. Here again there is evidence that the companion that you see today is not the remnant of what used to be the companion that transferred mass onto the neutron star which recycled it.

So now I come to the triple system in M4 and I'd like to use the next few minutes of my talk to say a few words about this because there are actually some new results. There are two posters outside, one by Thorsett and Arzoumanian on the latest data and one by Joshi and myself on theoretical interpretation. [These are combined into one presentation by Arzoumanian in this volume] This is a wonderful system. It is a binary millisecond pulsar - it was realised a few years ago, I think first by Don Backer, that the pulsar has very large, completely anomalous second derivative of the pulsar period, almost certainly not just timing noise, it was interpreted and I think well accepted that this is due to the acceleration of a second companion of the system. That is, this pulsar is in the heirarchical triple configuration. Now this is one of those very rare cases where theorists had actually predicted something before it was observed. If you look at the latest n-body simulations of clusters including primordal binaries work by Piet Hut, Steve McMillan and collaborators, the clear prediction is that there should be a small population of heirarchial triple systems in the cluster cores. The way you form a triple is through binary-binary interaction and typically looks something like this. If you have two binaries with fairly different separations you can think of the tighter one as just one object. Then it is just basically an exchange interaction again. You exchange this object into the binary, the other star gets kicked out and you are left with the binary at the centre with another star and the wide orbit around it. I wrote a little paper last year with Steve McMillan and Piet Hut showing that for this particular system in this particular cluster you can make it positive and it works and it produces something of order one system of this star observable at any one time.

From the early timing data we knew that the mass of this second companion was anywhere in the range 10^{-3} to basically 1 $M_{\odot}$. This was very exciting, particularly right around the time of the pulsar planet meeting at Caltech and so this 10^{-3} seemed particularly exciting because that is a Jupiter. There was at the time also some indication it might actually be more likely a star. One piece of evidence comes from the large eccentricity of the inner binary which you can explain in terms of secular purterbations in the system only if the second companion is a stellar mass. Then it was Bailyn who actually looked for an optical counterpart which you obviously expect if it is a star and found a reasonably good candidate with the mass of somewhere around 0.5 $M_{\odot}$ which I certainly liked. Unfortunately we have more data now [Laughter!!] and if we look at the poster by Thorsett & Arzoumanian outside you will see that they have now measured period derivatives up to the fourth. So you have basically four quantities Pdot to P4dot that are known in the system. If you had five you would have a complete solution as there are basically four orbital parameters and a mass. With four you now have a one parameter family of solutions. I was rather surprised to find that if you look at all those solutions they give you masses for the second companion which appear to be all in the range of 10^{-3} to 10^{-2} $M_{\odot}$. That's in the Jupiter to brown dwarf range. I think that it is most likely now that this object is in fact of low mass something like a Jupiter. It doesn't matter of course in the end. No matter what this turns out to be, this is obviously an extremely interesting, fascinating system. It is the first millisecond pulsar found in a triple system. The first triple system found in a globular cluster. It might be the first Jupiter or brown dwarf found in orbit around millisecond pulsar or globular clusters. The message here is there are extremely interesting systems like that in globular clusters, you expect them to form because of all these interaction processes. There are probably many more to be found. Please look for them. Thank you.

Ralph Wijers One point Fred - since you described the formation of this triple system as being so like an exchange interaction. That doesn't make it any easier, does it. You have that planetary mass, because normally in the exchange interaction the lighter one is the most easiest to get kicked out.

Fred Rasio I didn't get into that. Stan Siggurdsson wrote a very long paper last year in ApJ discussing in great detail four various scenarios that could actually put a planet in there so you should refer to that paper. It is of course somewhat different from the simplier binary binary interaction that I described.

Dick Manchester First we'll have our final sort of semi-formal presentation then by Andrew Lyne, and then we'll have a bit more discussion and then we'll wrap it up.

Andrew Lyne I'm going to talk about very simple systems in globular clusters. In the first discoveries of pulsars in globular clusters, 34 pulsars were found of which most were millisecond pulsars but there were a bunch, a very small number, of long-period objects discovered of which we've recently, in the last couple of years, measured period derivatives and they've got properties more akin to those of normal galactic pulsars. There is no doubt about the association of PSR 1745–20 and PSR 1820–30B with their clusters because of their very close proximity to the cluster and in the case of PSR 1820–30B there is a millisecond pulsar with the same dispersion measure. There is some debate about PSR 1718–19 whether it is associated with the cluster - observationally the probability is high, the chance of coincidence up at 10° latitude of a binary field pulsar being within a few arc minutes of a cluster core are very small, but if it is bound, it is only very lightly bound. These seem to be part of a continuum of pulsars in the BP diagram. [Figure 1 of Bhattacharya] The big dots here represent pulsars in globular clusters which have got measured period derivatives. There are about a similar number of pulsars which are not on here either because the period derivatives have been corrupted by acceleration effects or because they have just not been measured yet and in fact there are several more binary pulsars down here. These pulsars that I was talking about are these two up here, the spin-up line runs up to just about through there. The strange thing about them is that of these three, the two certain ones are both solitary, they've got no binary companions. Although there are only this small number because of their small ages, the formation rates are very similar. Whatever processes form these things, the rates are very similar to those which form the millisecond pulsar systems. The high luminosities of these of a few hundred mJy kpc^2 suggests that there are in fact a much larger population in the galactic system.

It seems to me that there are two possible ways in which these can be formed. Either AIC or spin-up of some form. The main problem is getting rid of the companion. If it's AIC you need to have a kick which is large enough to disrupt the binary, of course if there is a bigger kick, then the pulsar will disappear from the cluster and you won't see it anyway, so these may be just the ones which are left. Of course the questions of the frequency and likelihood of the AIC process and it's not clear whether you get fields which are large enough. The other possibility is of course a spun-up following collision in the cluster. There has been a period of mild spin-up within the last 10^7 or 10^8 yr and in that period of time, although these pulsars are actually in rather massive clusters, I think it is unlikely that collisional ionisation will have occurred. It seems if they have been spun-up due to accretion then it is most likely to have been a direct hit with a brief common envelope phase after becoming tidally bound and eventually tidal disruption of the planet [?? Ed - not clear]. But in order to do this you need a large pool of primordial neutron stars so that you have a suitable rate of formation of these things. Of course if these really are primordial neutron stars which have been rejuvenated, the implication is that there has been very little magnetic field decay occuring over the lifetime of the clusters. So which of these two possibilities is the case depends on the details of your calculations and assumptions which go into the calculations.

Dick Manchester I suggest that we go on for a few more minutes. Are there any issues that anybody would like to raise with anybody in the panel? Or the panel amongst themselves. We could address those or if not we can go onto the next thing.

Ralph Wijers Yes. If I could just make a comment which is that Andrew has raised a rather pressing issue which was first raised by Julian Krolik. What happens if there is tidal capture or [other] capture processes in globular clusters? Then quite a sensible fraction, even most, are going to be these disrupted cases, cases in which you more or less have a direct hit or an instability soon after the hit in which you form something like a neutron star with a massive disc around it. I think theoretically that this is a very pressing problem, what does that give? Does that give a very strongly recycled pulsar, so directly a millisecond pulsar? Does that give these mildly recycled things or almost not recycled things that have just been spun up that you have now been finding - doesn't it do anything? I think that right now the answer is not that clear.

Fred Rasio Unfortunately the calculation is hopeless, but it is even more pressing now that we know about the presence of primordial binaries. The presence of primordial binaries makes the rates of these direct hits and collisions considerably higher and it would be nice if we could calculate that if this did produce anything good at all then they would be considerably over-produced. In that case you could then probably conclude that it gives you nothing. [Ed Note : This is somewhat confusing. The point is that if direct collisions give you anything, they will give you too many of them for comfort]. Various people will give you a range of answers that vary from marginally recycled to millisecond pulsars, low mass black holes, Thorne-Zytkow objects ... we've really no idea.

Dipankar Bhattacharya Is this just a hydrodynamics problem?

Fred Rasio This is not a hydrodynamics problem at all. You learn nothing about what happens later on on the long time scales. It is a question of the usual problem of energy transfer and angular momentum transfer in something that's rapidly and differentially rotating and you basically can't do it.

Dick Manchester O.K. Anyone want to have the last word?

Frank Verbunt I just want to make one remark on the globular clusters. If the velocity distribution of neutron stars peaks at high velocities at birth then obviously only a small fraction of neutron stars can be retained in a globular clusters, and so you may have to find a solution for it in binary evolution. However if, for example, as Sterl Phinney has argued, the pulsar velocity distribution peaks at smaller velocities which is compatible as we have heard several times today, with many of the observations, then in fact you can still retain a sizeable fraction of neutron stars in globular clusters and then the pool that you require Andrew is available.

Matthew Bailes I think there is another way of retaining clusters pulsars even if you do have large kicks and that is that many of these things might be born in binaries and when they get kicked they still get a kick of a few hundred km/s and the runaway velocity of the binary is only 30 or 40 km/s and then they can spiral into the core as Ed and Dipankar suggested and you have a low velocity pulsar, even though you had a big kick.

Dick Manchester Fernando, you had a point you wanted ....

Fernando Camilo Well actually Ralph made most of my point which is that in the old days as Shri always pointed out he liked a magnetic field gap between the high-mass binary pulsars and the low-mass binary pulsars, and now for the four possible high-mass binary systems, well actually only three are in binaries, but for those systems the details are all over the place - just presuming that we don't find many of those, if we did they would be all over the place. But the small point that I wanted to make is that we usually assume that the upper limit on the spin-down age, on the age since the millisecond pulsars were last spun up, is of course at most, the age of the Galaxy, or 10 or so billion years, the age of the Galactic disc. But in fact we should just start being a little more restricted because the main sequence lifetime of the progenitors of the white dwarfs that we see today could have been of the order of several billions of years, up to five or even more billions of years. So in fact most of those pulsars since they were last spun-up should only be on average, let us say, five billion years or maybe less. So when we find cooling ages - we'll be talking about that tomorrow. You should keep that in mind. We shouldn't be finding too many cooling ages of 10 billion years.

Dick Manchester I think that these topics that have been discussed today are obviously very complicated and we can't hope to solve them in a debate like this, but I feel we've been quite successful on airing the issues at the very least. So I'd like you all to thank our panel and also yourselves.

[Tape recordings made by **Bryan Gaensler** and **Simon Johnston**.
Transcription by **Fiona Gately** and **Simon Johnston**.]