Chapter 6

Summary of the main results obtained in the thesis

Pulsars, which are believed to be rotating neutron stars, are the end-states of massive stars in the Galaxy. That is, the massive stars, at the end of their evolution, explode violently as a supernova to give rise to a compact neutron star. Many of the statistical properties of pulsars are understood by studying the observable parameters like rotation period, its time derivative, *etc.* The kinematic properties of the population are understood by studying some of the observable parameters like the position in the Galaxy and transverse velocity, *etc.*

This thesis concentrates on some of the statistical properties of pulsar population. Let us summarise in this Chapter, the main results of the thesis.

I Chapter 2 describes an analysis of pulsar current. The main results in this Chapter are the following.

- The galactic birth rate of the pulsar population is about one in 75 ± 15 years.
- Supporting evidence has been found for the earlier hypothesis that a fraction of pulsars may be born with long initial periods —0.5 sec. Some physical interpretations have been given for the phenomenon of injection, that they are *recycled pulsars from massive and intermediate mass binaries.*
- An upper limit to the fraction of such injected pulsars in the main population of pulsars has been calculated, and it is about $10-15\%$.
- The interpretation that the injected pulsars are the recycled pulsars from binary systems seems to qualitatively explain the distribution of pulsar current as a function of the height from the galactic plane z, and the characteristic age τ_{ch}.

First of all, the usage of the new distance model (Taylor & Cordes 1993) and the new luminosity model (Narayan & Ostriker 1990) can be considered to be an improvement over the earlier works. Apart from this, this Chapter gives some physical interpretation for the phenomenon of *injection.* It is interpreted that injection is due to the recycled pulsars from massive and intermediate mass binaries in the Galaxy. This provides a way to estimate an important number – the fraction of recycled pulsars in the main population of pulsars. This fraction has been estimated to be about 10–15%. At this point it is worth recollecting that this has been estimated by measuring the magnitude of the sudden increase in pulsar current, in figure 2.2 of Chapter 2. The statistical significance of this step is only $\sim 2\sigma$. hloreover, part of this step could be due to a genuine spread in the initial periods of pulsars. Keeping this in mind, one can consider the above estimated fraction to be only an upper limit.

II If it is really true that the fraction of recycled pulsars is considerable, then it has many important implications. Therefore, we decided to test this out by an entirely different method. Chapter **3** describes a Monte Carlo simulation of massive stellar systems in the Galaxy, which **was** done essentially to estimate the fraction of recycled pulsars in the main population of pulsars. In addition to this, this simulation has given some results on the formation and the merger rate of double neutron star binaries, the number of *observable* double neutron star binaries, *etc.* These results can be summarised as follows.

- The fraction of recycled pulsars in the main population of pulsars is less than 5–8%. The fractional birth rate of these recycled pulsars in the total birth rate is less than about $\sim$ **3%.**
- The number of *observable* (where at least one neutron star is alive as pulsar) double neutron star binaries in the Galaxy may be about a few thousands.
- The formation rate of double neutron star binaries in the Galaxy is about $10^{-4}\mathrm{yr}^{-1}$. The merger rate of these binaries due to the emission of gravitational radiation is about $(2-4) \times 10^{-5}\mathrm{yr}^{-1}$. With the assumption that all galaxies are similar to ours, the merger rate upto a distance of about 200 Mpc has been estimated to be about a few events per year. This may have significant importance to the modern gravity wave detectors like LIGO etc.

Many authors have done simulations of binary systems in the Galaxy. The aims of these exercises were to study many different things, like properties of Be/X-Ray Binaries, the evolution of binaries in open clusters, properties of pulsars from binary systems, *etc.* The overall procedure which is followed in Chapter **3** to evolve binary systems is roughly the same as the procedure followed by most of the earlier works. However, significant difference comes in dealing with pulsar population. First of all, properties of pulsars are considered to be the observational constraints. This is because of tn-o reasons: (1) the intrinsic properties of a few species of binary systems like Be/X-Ray binaries are not at all clearly modeled, and (2) one knows how to satisfactorily model the observational selection effects of pulsars, in finding out the intrinsic properties. Also, the evolutionary model of pulsar population described in Chapter **3** is more satisfactory and complete than any previous work. This can be considered as a significant improvement over all the previous works.

At the end of Chapter **2** we concluded that the fraction of recycled pulsars could be as high as 15%. However, Chapter **3** seems to suggest that this fraction could be only a few percent. This needs some understanding. If one considers this discrepancy significant, then one can give many interpretations. The main reason for this is that a very good fraction of binary systems seem to get disrupted during the first explosion itself. It may be true that the currently believed kick velocity distributions bias against low velocities. **A** few recent statistical studies seem to favour this idea (Hartman 1996; Hartman et al. 1996). There could be some selection effects in the low velocity side, which we have not modeled properly. Or, it may be true that most of the injected pulsars are from solitary progenitors, and they are born rotating slowly, and there is no necessity to invoke binary scenario to explain injection. At present it is not clear, which is correct.

III Chapters 4 & 5 deal with the kinematic properties of pulsars. The third Chapter describes an exercise which studies the spatial distribution of pulsars in the Galaxy. The main conclusions of this Chapter can be summarised as follows.

- A significant correlation has been found to exist between the distribution of pulsars in the Galactic plane and the past locations of the spiral arms some 60 Myr ago.
- This gives an independent way of estimating the threshold main sequence mass for neutron star formation, and this turns out to be about $7M_{\odot}$.
- A lower limit to the average velocity of pulsar population has been determined. This comes to about $160 - 200$ km/sec.

The correlation between the spiral pattern of the Galaxy and the distribution of pulsars was conjectured by Blaauw way back in *1985*. If there really exists a correlation, it straight away tells us that the velocities of pulsars are not all that high (*i.e.,* not high enough to smear out the correlation). There is a considerable fraction of pulsars with low velocities. Also, this correlation is quite important for it gives an independent way to determine the masses of the progenitors of pulsars. This is the point that Blaauw had stressed in his seminal paper in *1985*. He came to a conclusion that the vast majority of pulsars must be produced by relatively low mass stars ($6 - 10M_{\odot}$), and this made him to conjecture that the distribution of pulsars in the Galaxy must trace out the past locations of the spiral arms, rather than the present locations.

The threshold main sequence mass derived from this analysis comes to about $7M_{\odot}$. This agrees with the recent theoretical models (like Hillebrandt *1987)* which predict that all stars with mass $\gtrsim 8M_{\odot}$ produce neutron stars.

IV Chapter 5 deals with a different problem, the kinematical properties of millisecond pulsars and their progenitors. The main conclusions of this Chapter are summarised below.

> - The kinematic properties of Low Mass X-Ray Binaries and millisecond pulsars seem to agree with each other.
> - The observed LMXB and millisecond pulsar data seem to favour initial velocity distributions with considerable fraction of low velocity pulsars.
> - The velocity distribution of millisecond pulsars in the Galaxy seems to be quite different from that of the ordinary pulsars.

If LMXBs are the progenitors of millisecond pulsars, their kinematic properties must be identical. For the first time, the kinematic properties of these two populations have been compared. Moreover, many different initial velocities and spatial distributions have been tried out for the simulated samples, while comparing them with observations. This makes this exercise more complete than any of the previous works.

The kinematic properties of LMXBs and millisecond pulsars match with each other. This is consistent with the suggestion that LMXBs are the progenitors of millisecond pulsars.

The observed LMXB and millisecond pulsar samples seem to favour an initial speed distribution which has considerable low velocity objects.

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