THE KINEMATICS OF PULSARS

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ABSTRACT. Pulsars have a galactic radial distribution similar to that of many galactic populations such as HII regions, massive stars and supernova remnants. However they are generally much further from the plane of the Galaxy than these objects. Proper motion measurements sho that this is because they are typically moving with high velocities. The measurements also indicate that most pulsars were formed a few million years ago close to the plane, within the normal Population I regions. Some pulsars will escape from the Galaxy, although the majority will end up in a halo population. The origin of the high velocities is not clear at present but may be due either to some asymme try in the formation event or to the disruption of a close binary system.

1. INTRODUCTION

The galactocentric radial distribution of pulsars (Lyne, Manchester and Taylor 1985) shows a falling surface density beyond the Sun's position and an increasing density towards the inner regions of the Galaxy. This is qualitatively similar to the distribution of many galactic Population I species of objects, notably massive stars, HII regions where massive stars are likely to be formed and supernova remnants, the likely birthplaces of pulsars.

These objects all have quite narrow galactic z-distributions, typically falling to half density at 50-100 pc from the plane. Pulsars on the other hand (Figure 1) have a half-density height of about 400 pc Gunn and Ostriker (1970) suggested that this might be due to a general migration from the galactic plane because of high velocities imparted to pulsars at birth. It remained for direct observation of the velocities to confirm this explanation.

This paper describes how we measure the motions of pulsars and what we can infer about their evolution, about their progenitor population and the origin of the high velocities.

2. METHODS OF MEASUREMENT

The three main methods of determining the velocities of pulsars involve pulse timing measurements, direct radio interferometry and

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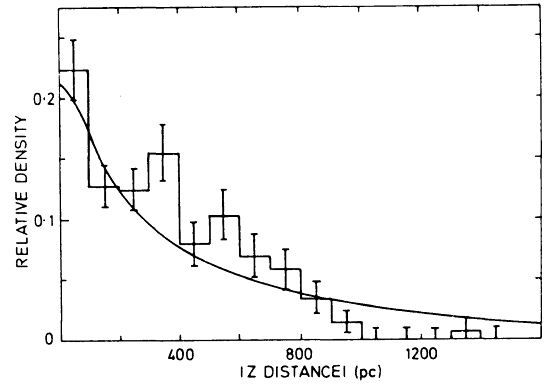

Figure 1. The | z |—distribution of pulsars.

measurements of interstellar scintillation. The first two methods determine proper motions which, combined with distance estimates, yield pulsar velocity vectors and it is these two which this paper will address. In the third method the motion of the scintillation pattern across the Earth is inferred and hence an estimate of the pulsar transverse speed obtained. This method is reviewed by Cordes (this volume).

2.1 Pulse Timing Measurements

The residuals of the observed times of arrival of pulses from a simple model of pulsar spin-down are very sensitive to the assumed position of the pulsar because of the annual barycentric correction term of about 500 seconds. The sensitivity is such that a 1 arcsec position error gives rise to an annual sinusoid in the residuals of up to 2.5 milliseconds. By fitting such sinusoids to the data, positions accurate to a small fraction of an arcsec can be obtained. From observations over several years, proper motions can be derived.

The first measurement of proper motion was carried out in this manner by Manchester, Taylor and Van (1974) and this illustrates the technique very nicely. Figure 2 shows an annual sinusoid increasing linearly with time as the pulsar moves away from the assumed position.

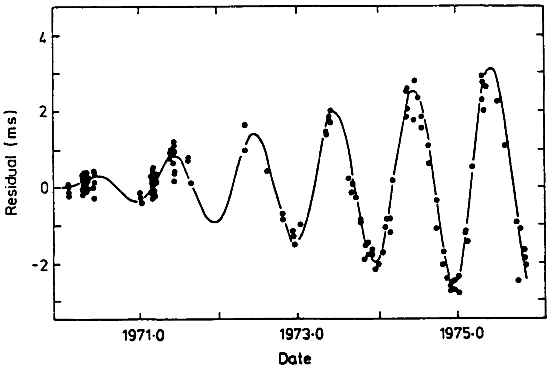

Figure 2. The timing residuals for PSR 1133+16 for an assumed constant pulsar position (Manchester, Taylor and Van 1974).

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Such measurements have been carried out on a total of about 16 pulsars by Gullahorn and Rankin (1978) and by Helfand, Taylor, Backus and Cordes (1980), providing measurements with typical errors of 50 milliarcsec/year.

2.2 Radio interferometry

This method is akin to the conventional optical determination of proper motion which involves the measurement of motion relative to stationary background objects. In fact optical techniques have already been applied to the determination of the proper motion of the Crab pulsar (Wyckoff and Murray 1977).

In the radio case the measurement is relative to one or more nearby small diameter radio sources, usually lying within the primary beam of the instrument. At radio frequencies around 400 MHz, the ionosphere causes the image of the pulsar to move by up to several arc-seconds on timescales of a few minutes. However the reference source moves in a very similar way and relative positions can be measured with great accuracy. Figure 3 illustrates the motions of two pulsars

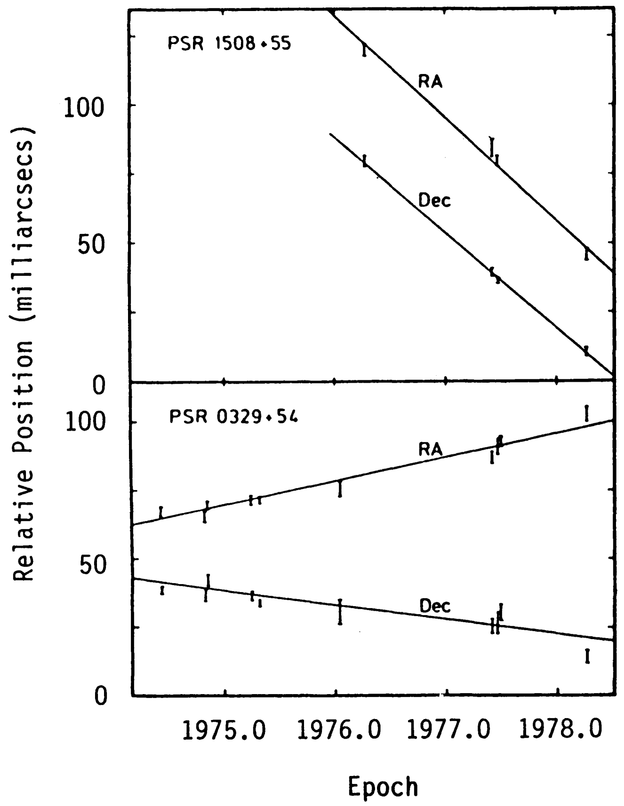

Figure 3. The positions of PSR 0329+54 and PSR 1508+55 relative to their reference sources as a function of epoch.

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relative to nearby reference sources over periods of several years and shows that errors in position of only a few milliarcsec can be achieved (Lyne, Anderson and Salter 1982).

Two main experiments of this kind have been carried out to date: one at Jodrell Bank at 408 MHz (Lyne et al. 1982) on a total of 26 sources and one at Green Bank at 2700 MHz (Sramek and Backer 1981) on 5 sources, all of which were included in the Jodrell Bank list.

2.3 Comparison of measurements

The interferometric results from the Jodrell Bank and Green Bank experiments were in satisfactory agreement for all 5 sources in common. However, while some of the timing results also agreed with these results, for others the agreement was very poor indeed. In view of the consistency of the interferometric measurements we have to conclude that the timing measurements are prone to an unrecognized source of error. It seems that this error comes from the timing noise which arises in the irregularities in the rotation rates of pulsars. This timing noise may have significant spectral components with period of a year and these can masquerade as an apparent shift in the position of the pulsar. Although there are doubts about the general reliability of timing determinations of proper motion, for very stable pulsars such as the millisecond pulsar 1937+21, it seems that very precise measurements can be made (Davis et al. 1985).

The observations discussed here are therefore confined to the 26 pulsars contained in the list of Lyne et al. (1982) which encompass all the pulsars in the other experiments and also had rather smaller errors.

3. THE VELOCITIES

As suggested by Gunn and Ostriker (1970), the velocities are indeed high. The root mean square transverse velocity for the sample of 26 pulsars is 170 km/s implying that the mean space velocity is somewhat over 200 km/s. This velocity is an order of magnitude greater than the random velocities of most normal stellar populations. I will discuss the possible origin of these high velocities later.

4. THE MIGRATION FROM THE GALACTIC PLANE

The directions of the high velocities as seen on the sky are not random. Figure 4 shows how the directions of the velocity vectors are disposed relative to the galactic plane. For most of those objects which lie more than 50 or 100 pc away from the plane the motion is directed away from the plane confirming the picture of Gunn and Ostriker. The mean migration velocity from the plane is about 124 km/sec. The two pulsars which appear to be moving toward the galactic plane are both situated at high latitude so that their apparent motion on the sky is dominated by the component of velocity parallel to the plane. They may indeed have a velocity component directed away from the plane but this is mostly hidden in the unknown radial component of velocity. Most of the sources lie at low galactic latitudes where this effect is not important. Those pulsars which we see close to the galactic plane are mostly either young ones or those which have velocities parallel to the plane.

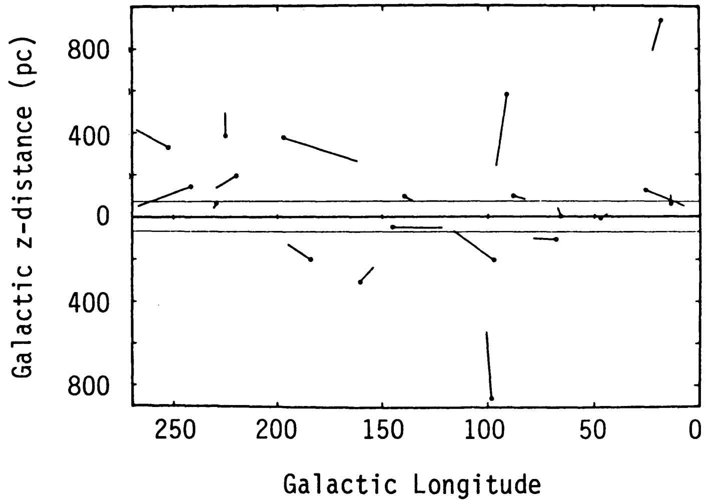

Figure 4. The positions and velocities of 20 pulsars relative to the galactic plane. The filled circles represent the observed positions of the pulsars as a function of galactic z-distance and longitude and the tails represent the distances travelled in the last million years.

5. KINETIC AGES

Accepting the model of pulsars being born on the galactic plane within a narrow Population I type of distribution and then given a high velocity at birth, extrapolation of their motions back to the time when they would have left the plane provides an estimate of the age of the pulsar, known as the kinetic age of the pulsar. There are some uncertainties in this estimate because the precise position of birth within the progenitor layer is not known and also because the radial component of velocity is not known. The latter means that the precise form of the trajectory may be poorly determined, although this effect is not important for the majority of pulsars in the sample as they lie at low latitudes.

Figure 5 shows the comparison of these kinetic ages with the characteristic ages $T=P/2\dot{P}$ which are determined from the spin-down rates of the pulsars. The characteristic age equals the true age if the pulsar is born with a very short period and the effective magnetic dipole moment of the neutron star remains constant. For pulsars with ages of less than a few million years the agreement is reasonably satisfactory. However for older objects, it is clear that the characteristic ages are substantial over-estimates of the 'true' ages as revealed by the kinetic ages. This discrepancy is most satisfactorily explained in terms of a decay in the effective braking torque of the pulsar, which may be due to decay of the magnetic field or alignment of the magnetic and rotation axes. The lines in Figure 5 indicate how a pulsar will evolve for various time-scales of exponential decay of braking torque. The data in this diagram suggests that the decay occurs on a time-scale of a few million years. This is in reasonable agreement with the

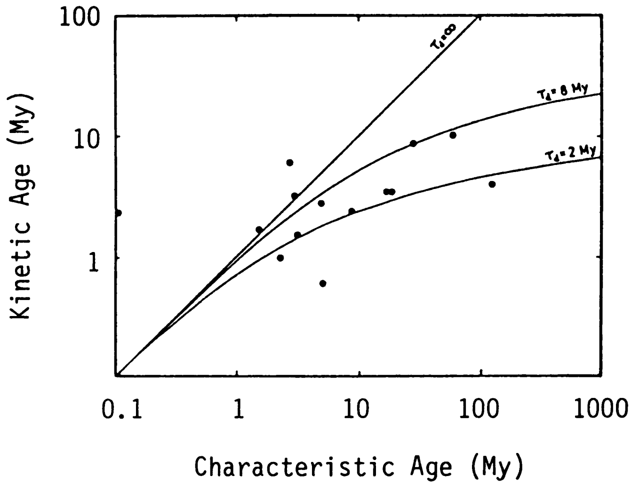

Figure 5. The kinetic and characteristic ages for 14 pulsars. The three lines show the paths expected for pulsars whose effective magnetic fields decay on the time-scales indicated.

time-scale of 9 million years obtained by Lyne, Manchester and Taylor (1985) using independent arguments.

6. THE PULSAR z-DISTRIBUTION AND LUMINOSITY DECAY

Lyne, Manchester and Taylor (1985) also provide evidence that the decay of effective magnetic field is accompanied by an exponential fall in luminosity on a timescale of about 4.5 million years. This assertion can now be checked by considering a model in which pulsars are born on the galactic plane with the observed velocity distribution and then suffer luminosity decay. This model provides a prediction of the steady-state z-distribution of pulsars exceeding a given radio luminosity. This distribution is compared with the experimentally determined one in Figure 1 which shows a satisfactory agreement between the two, indicating that the luminosity does indeed decay on that sort of timescale.

7. THE GALACTIC DISTRIBUTION OF DEAD PULSARS

The escape velocity from the Galaxy is about 300 km/s at the position of the Sun so that only about 10-20% of pulsars will leave the gravitational well of the Galaxy completely. The majority will continue their motion away from the plane long after they cease being radio pulsars and will reach maximum heights of several kpc above the plane after 30-60 million years. They will thus form a halo population containing between about 3×10^8 and 3×10^9 'dead' neutron stars, the number depending upon rate of formation of neutron stars in the earlier life of the Galaxy.

8. THE ORIGIN OF THE HIGH VELOCITIES

Although a number of mechanisms have been proposed for the acceleration of pulsars to the high velocities we observe, it is not clear which one or ones are responsible, since no single explanation by itself is entirely satisfactory (see for example Anderson and Lyne 1983). In this review I consider the three most likely possibilities.

The first mechanism is that first proposed by Blaauw (1961) to explain the high velocities of the runaway stars, involving the disruption of a binary system by a symmetrical supernova explosion of the more massive component. If more than half of the mass of the system is lost in a time interval short compared with the orbital period, then the system will be disrupted. Any stellar remnant of the supernova will have a velocity whose magnitude is the same as its pre-supernova orbital velocity (Radhakrishnan and Shukre 1985). It seems that velocities comparable with those observed for pulsars could be produced by the disruption of appropriately close binary systems. Although many stars are formed in binaries, a substantial fraction are born as solitary stars. If these undergo symmetrical supernova explosions in the formation of pulsars, then there should be a class of low-velocity pulsars still lying within their progenitor population, presumably at small z-distances. There is no evidence (Figure 1) for such a population, any which does exist containing no more than about 20% of the known pulsars, despite the fact that a greater proportion of massive stars than this are probably solitary. Similarly there is no evidence of a bimodal distribution of transverse velocities as one might expect, although here the statistics are rather poor.

I think we must accept nevertheless that at least some high pulsar velocities are likely to be derived from this mechanism. For instance, the Crab pulsar has a transverse velocity of 100 km/s and is moving away from the galactic plane. However it is only 1000 years old and hence lies very close to its birthplace in the Crab Nebula at a z-distance of about 200 pc, well outside the proposed progenitor Population I region. It could well have resulted from the supernova of a runaway star which was originally in a binary system which was disrupted by the supernova of a more massive companion (Gott, Gunn and Ostriker 1970).

There is one rather puzzling piece of evidence first noted by Helfand and Tademaru (1977) which cannot be easily explained by a binary formation scenario, namely the apparent correlation of the measured transverse velocities with the pulsar magnetic field shown in Figure 6 (Anderson and Lyne 1983). One possibility (Helfand and Tademaru 1977 and Radhakrishnan 1984) is that there is no causal relationship here, but that there are two classes of pulsars, a high magnetic field, high velocity one and a low magnetic field, low velocity one. Perhaps there is some systematic difference in the magnetic moments of solitary and binary stars, so that the binary stars have much larger magnetic fields, leading to the observed correlation.

Another possible mechanism, proposed by Harrison and Tademaru (1975), involves asymmetric dipole radiation due to an off-axis magnetic moment. The resulting acceleration occurs during the first few months of the existence of the pulsar while the rotation rate is high, initial periods of a few milliseconds being required. It turns out that one would not expect any dependence of the final velocity upon the magnitude of the pulsar dipole moment, contrary to what is observed. A prediction of this model for the acceleration is that the proper motion will be

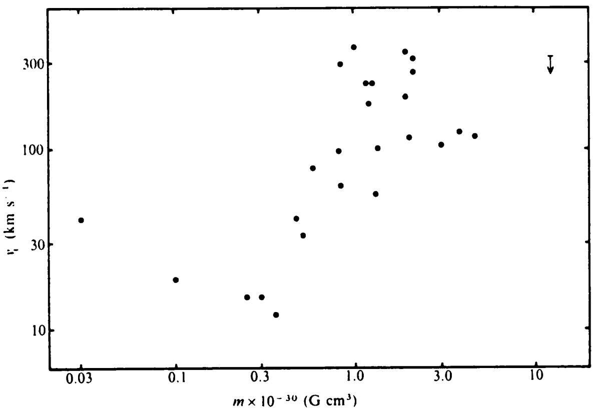

Figure 6. The transverse velocities of 26 pulsars as a function of the effective magnetic dipole moment (Anderson and Lyne 1983).

parallel to the rotation axis, whose direction should be revealed by the position angle of the linear polarization near to the centre of the radio pulse (Morris, Radhakrishnan and Shukre 1976). No clear relationship is observed. A further argument against this mechanism is that, although it may be able to explain the velocities of pulsars born in single stars, by itself it would be unable to disrupt most close binary systems, the main result being that the whole system would probably be dragged along. The small number of binary systems containing radio pulsars compared with the large number of stars in such systems suggests that the acceleration mechanism must also disrupt most systems.

The third mechanism is that the supernova explosion itself is asymmetric, giving a velocity impulse of the order of 200 km/s to the neutron star remnant (Shklovskii 1970). As far as I am aware there is no real theoretical basis for believing that this might or might not happen. Such an impulse would certainly disrupt most binary systems and explain why only about one percent of known pulsars are in binaries. Possible sources of asymmetry include the magnetic field configuration and gravitational distortion of the pre-supernova star by a binary companion. I think we are in need of more theoretical work on the possibilities for such asymmetrical events.

9. FUTURE OBSERVATIONS

Observations of the proper motions of pulsars can give much information on their physics and history. However, the presently available data are rather sparse and some are on local high latitude objects for which the kinetic age errors are likely to be large due to the unknown radial velocity component. A number of new programs are under way and these should provide 60 or 70 new proper motion determinations within the next three years or so. The main instruments being used for this work are MERLIN, the VLA and the Parkes-Tidbinbilla interferometer in Australia. These results should provide a more precise study of the magnetic field decay in neutron stars and also allow investigation of the nature of the magnetic field, velocity relationship.

REFERENCES

Anderson, B. and Lyne, A.G., 1983. Nature, 303, 597.
Blaauw, A., 1961. Bull. Astron. Inst. Netherlands, 15, 265.
Davis, M.M., Taylor, J.H., Weisberg, J.M. and Backer, D.C., 1984. Proceedings of Green Bank Workshop on Millisecond Pulsars.
Gott, J.R., Gunn, J.E. and Ostriker, J.P., 1970. Astrophys. J., 160, L91.
Gullahorn, G.E. and Rankin, J.M., 1978. Astrophys. J., 225, 963.
Gunn, J.E. and Ostriker, J.P., 1970. Astrophys. J., 160, 9.
Harrison, E.R. and Tademaru, E.P., 1975. Astrophys. J., 201, 447
Helfand, D.J. and Tademaru, E.P., 1977, Astrophys. J., 216, 842.
Helfand, D.J. Taylor, J.H., Backus, P.R. and Cordes, J.M., 1980. Astrophys. J., 237, 206.
Lyne, A.G., Anderson, B. and Salter, M.J., 1982. Mon. Not. R. astr. Soc., 201, 503.
Lyne, A.G., Manchester, R.N. and Taylor, J.H., 1985. Mon. Not. R. astr. Soc., 213, 613.
Manchester, R.N. and Taylor, J.H., 1977. Pulsars. (Freeman, San Francisco).
Manchester, R.N., Taylor, J.H. and Van, Y.Y., 1974. Astrophys. J., 189, L119.
Morris, D., Radhakrishnan, V. and Shukre, C.S., 1976. Nature, 260, 124.
Radhakrishnan, V., 1984. Proceedings of Green Bank Workshop on Millisecond Pulsars.
Radhakrishnan, V. and Shukre, C.S., 1985. Proc. of Workshop on Supernovae, their Progenitors and Remnants (Indian Acad. Sci., Bangalore, India), 155.
Shklovskii, I.S., 1970. Astr. Zh. 46, 715.
Sramek, R.A. and Backer, D.C., 1981. IAU Symp. No. 95, Pulsars, Reidel, Dordrecht, Holland, p.205.
Wyckoff, S. and Murray, C.A., 1977. Mon. Not. R. astr. Soc., 180, 717.

DISCUSSION

G. Bisnovatyi-Kogan: How many old pulsars do exist within 100 parsec of the Sun? I mean the low-velocity pulsars accumulated in the galactic plane.

A. Lyne: Assuming that the formation of massive stars and hence pulsars has occurred at a constant rate for the life of the Galaxy, then about 5000 pulsars will have been formed within about 100 pc of the Sun. However, these are now spread over a scale height of a few kpc, so that I estimate that there are only about 200 dead pulsars within 100 pc of the Sun.

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S. Kulkarni: In addition to the three methods for determining proper motion which you mentioned (interestellar scintillation, timing and radio interferometry) I would like to add another technique which works in the fortunate case where the pulsar system is identified at optical wavelengths. From optical data we hope to obtain proper motion of 1855+09, 0655+64, 0820+02 and Vela by next year. (In the first 3 cases, the optical candidate is the secondary white dwarf and in the last case the optical emission comes from the pulsar itself).

A. Lyne: Indeed. However, I think you are optimistic about the timescale!

R. Manchester: Could you comment on the importance of selection effects for the main conclusions you have drawn from the proper motion measurements?

A. Lyne: On the whole, selection effects do not seriously affect the main conclusions I have described. The most obvious one is that which reduces the observed number of low magnetic moment and hence low luminosity pulsar which have high velocities in the (m, υ_t) diagram (Anderson and Lyne 1983).

J. Arons: First a comment: A discrepancy between the $P/\dot{P}$ age and the kinematic age reflects a decay of the torque; such torque decay might or might not involve decay of the light cylinder field. I know of no model of surface field decay (or growth) which I find acceptable. It would be nice if the language more accurately reflected the observations, and one referred to torque decay, rather than biasing one's thoughts by referrring to field decay. Question: Does the luminosity decay smoothly, or is there a sharp cutoff?

A. Lyne: There is no evidence for anything other than a smooth decay of luminosity except in the small minority of pulsars which display nulling. In this group there may be a more sudden decrease in luminosity towards the end of their radio lives.

R. Becker: You should be careful in assuming that pulsars are born within 70 pc of the galactic plane. Half of the Crab-like SNR, which are indicators of where pulsars are born, are more than 75 pc from the plane.

A. Lyne: The proper motion measurements provide evidence that the acceleration to high velocity occurs within about 100 pc of the Galactic plane. This is the main justification in the subsequent discussion for assuming a Population I progenitor distribution.

R. Becker: Well, then, perhaps pulsars which form Crab-like SNR are a different population from most pulsars.

A. Lyne: I would not argue with that comment, although maybe the acceleration to high velocity still occurred at low z-distance in the disruption of a binary system by a supernova event. The pulsar was then formed some time after this from the supernova of the runaway star.

A. Blaauw: In the selection of pulsars for future proper motion programs, may I suggest that due attention be given to the nearby pulsars, say within 1 kpc, for these reasons:

- The direction of the (larger) proper motion is better determined thus narrowing down the choice of possible domains of the progenitor population.
- Only within these distances may we hope to obtain a reasonably complete inventory of the masses and evolutionary stages of the (B star) progenitor population.