CHAPTER 6

PSR 1854+00: A PULSAR NEAR THE SNR W44

The Ooty pulsar-search observations described in Section 5.4 detected a pulsar, PSR1854+00, in angular proximity to the SNR W44. As the initial estimate of the DM of the pulsar was consistent with the estimated distance of the SNR, it became a priority to improve the measured accuracy of the dispersion measure and the pulsar position, and also to get an estimate of its age. In this Chapter, the observations performed to achieve these and the results obtained will be described. Although a radio shell, W44 has an unusual X-ray morphology with bright central emission and an absence of shell structure. The close agreement between the distances derived for the SNR and the pulsar will be highlighted and the mass estimated for the SNR from X-ray observations discussed. The presence of an expanding HI shell around the SNR, and its possible relationship with the objects in this region, will also be considered.

6.1 THE TIMING OF PSR 1854+00

The period of a pulsar, its time derivative and the position of the object can all be obtained from observations of the arrival times of its pulses. The pulse arrival times have two components. The first, collectively called the secular term, can be predicted using a mathematical model, while the second is erratic and has been described as the random walk of pulsar phases (Manchester & Taylor 1977). The second term manifests itself as a wandering of pulsar phases with excursion for various time scales having a range of amplitudes. The dominant component of this wandering is too small to be noticed in our data and will be neglected in the following discussion.

For a given pulsar, the arrival-time phases of the pulse at the solar-system barycentre are given by

$$\phi(t)=\phi(0)+\Omega(t-t_o)+(\tfrac{1}{2})\dot{\Omega}(t-t_o)^2 \qquad (6.1)$$

In this expression, $\phi(0)$ refers to the phase value measured at the reference time, t_o and $\Omega(0)$ is the angular frequency of the pulsar at time t_o. However, for a terrestial observer, the arrival-time phase of a pulse is modulated by both the rotation of the Earth and the orbital motion of the Earth around the Sun. The modulation of the arrival time due to terrestial rotation can have an amplitude of about 20 msec, while the modulation caused by the orbital motion of the Earth is expected to be about 500.cosλ sec, λ being the ecliptic latitude of the pulsar. The effect of the above modulations are easily removed from the data. Assuming that the Earth moves around the Sun in a circular orbit, an error in the coordinates of the pulsar will modulate the pulse-arrival time by

$$\delta t_c = A\cdot\delta\lambda\ \mathrm{Cos}(\omega t-\beta)\sin\lambda + A.\delta\beta.\sin(\omega t-\beta)\ \cos\lambda \qquad (6.2)$$

where λ and β are respectively the ecliptic longitude and latitude of the pulsar, A is the light travel time from the Sun to the Earth and ω is the orbital angular velocity of the Earth (Smith, 1977). Thus an inaccuracy of one arcmin in the coordinates of the pulsar could produce an annual modulation in the arrival time with an amplitude of a few pulse periods. The frequency of observing sessions required to determine the position and other parameters of a pulsar is dependent on the initial accuracy of the coordinates. For this reason, we decided to obtain an updated position for PSR1854+00 before analysing timing measurements taken to determine the period (P), period derivative ($\dot{P}$) and celestial coordinates.

Although the tracking capability of the ORT is well suited to timing measurements of pulsar, the logistics of scheduling frequent observing sessions on a given weak pulsar made it difficult to determine the parameters of PSR1854+00 from Ooty data alone. In addition, the ORT system did not have the narrow-band filters needed to obtain an accurate estimate of the pulsar dispersion measure. Hence, observations were requested with the Effelsberg 100-m telescope to obtain improved parameters for PSR1854+00. These were made in 1983 at a frequency of 1420 MHz by D.A.Graham and J.H. Seiradakis.

The Effelsberg observations gave a position for the pulsar of RA=$18^h54^m28^s\pm15^s$,DEC=$00^o53'50''\pm60''$, DM=90±5 cm^{-3} pc. The flux density at 1420MHz was measured to be

0.5 mJy, compared with the Ooty value of 15 mJy at 327 MHz, yielding a spectral index α of 2.2 ($S \propto \nu^{-\alpha}$). Such a value is typical for a pulsar (Hewish, 1982).

6.1.1 Observations with the Ooty Radio Telescope

Timing data were obtained at Ooty over a period of one year. The intitial observing sessions indicated a period derivative ($\dot{P}$) of $10^{-15}ss^{-1}$ (Mohanty 1983) and the accumulated residuals between two observing sessions due to the slowing down of the pulsar were expected to be small. Following the arrival of improved parameters from Effelsberg, a simple procedure was used to derive improved pulsar coordinates from the pulse arrival times obtained over a limited number of observing sessions. Firstly, the Effelsberg position was adopted for the pulsar and the corresponding arrival times at the barycentre were computed. A least-squares fit was made to obtain P, $\dot{P}$ and the chi-squared value of the fit. The coordinates were optimised to minimise chi-square and give an improved position. This position was then used as the new initial value to analyse data spread over a longer time interval. This procedure was followed to estimate P and $\dot{P}$ using all the available data. The residuals, the differences between the arrival times of the pulses and those expected from the least-squares fit, are plotted against observing date in Fig.6.1. Residuals obtained for the calibration pulsar PSR2045-16 were also plotted along with those for PSR1854+00. The only systematics which can be seen in the residuals had values of

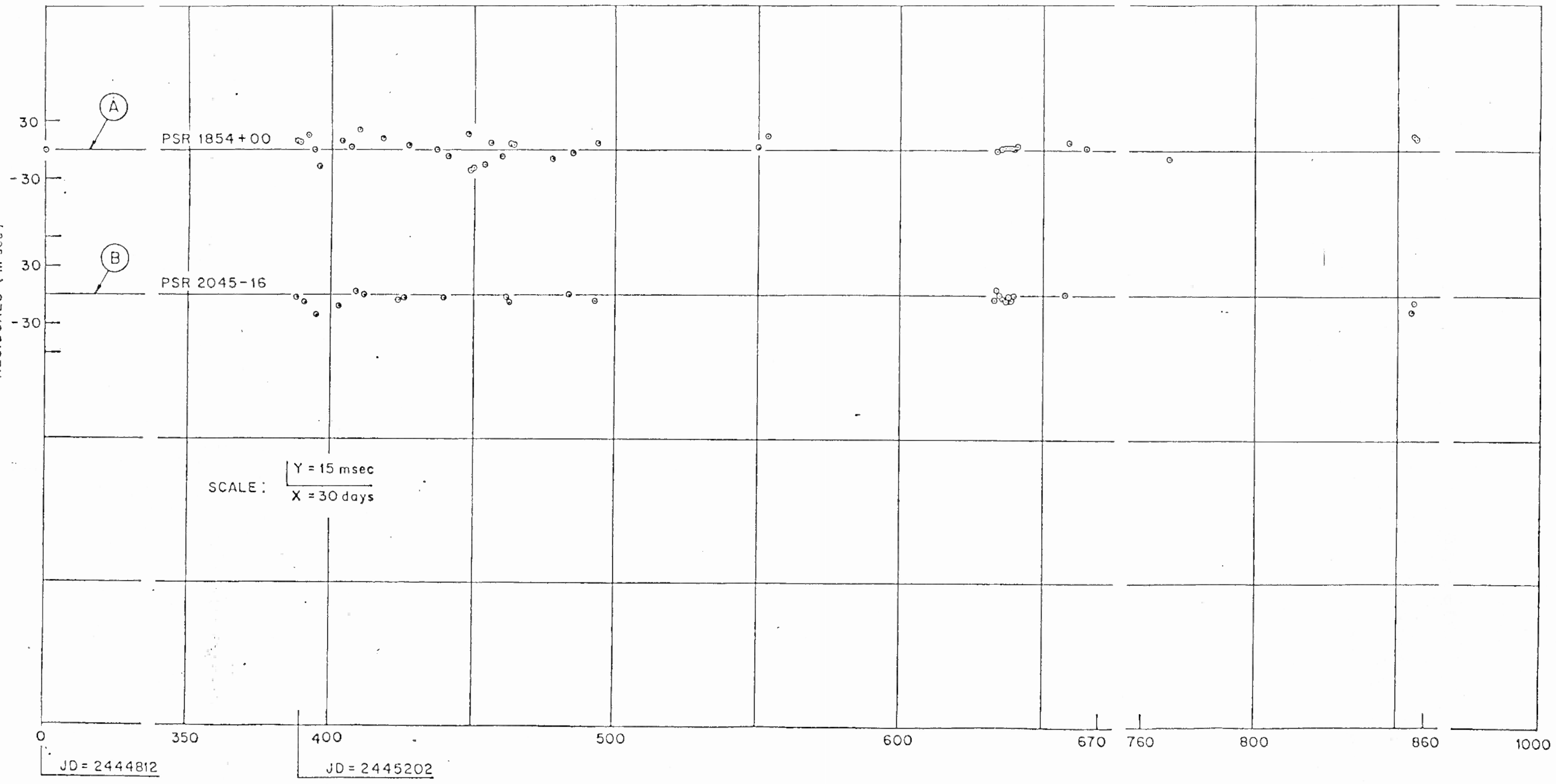

FIG. 6·1 - DAYS FROM JD = 2444812

Fig. 6.1. The plots (A) and (B) are the timing residuals for PSRs 1854+00 and 2045-16 computed from observations with ORT. Observations were not done during the intervals indicated by discontinuities in these lines.

less than 10 msec, these are likely to be uncertainties in the clock calibration. The parameters obtained for PSR 2045-16 (Table 6.1) were checked against the tabulated values (Manchester and Taylor, 1981) and found to be in excellent agreement with these. The coordinates, the period and its time derivative, and the dispersion measure of PSR1854+00 are presented in Table 6.2. We note that the derived magnetic field for PSR1854+00 is 9.6×10^{10}G compared to a median of 1.2×10^{12}G for all pulsars (Manchester and Taylor, 1981).

6.2 THE DISTANCE TO PSR1854+00

The distance to a pulsar is estimated by dividing its dispersion measure by the most probable value of the average electron density along the line of sight to the pulsar. Two approaches are in use for estimating the average electron densities to a pulsar. The first, a global electron density of 0.03 cm^{-3}, has been derived using the distances to about two dozen pulsars obtained from HI-absorption measurements, together with their dispersion measures (Manchester and Taylor, 1977). The expression used to derive the second value of the electron density depends on the z-height and includes both a constant term and a term derived from a model for the distribution of HII regions within 1 kpc of the Sun (Lyne, Manchester and Taylor, 1985). However,

Table 6.1

Parameters of PSR2045-16

RA (1950.0)	$20^h\ 45^m\ 46^s.9 \pm 4$
Dec (1950.0)	$-16^{\circ}\ 27'\ 50'' \pm 20''$
$P_{(JD\ 2445200)}^{(sec)}$	$1^s.961571143 \pm 5$
$\dot{P}(ss^{-1})$	$11.2 \times 10^{-15} ss^{-1}$

Table 6.2

Parameters of PSR1854+00

RA (1950.0)	18 h 54^{m} 27^{s}.8 ±. 2
Dec (1950.0)	0 o 53' 21" ± 2
$\dot{P}$ (JD 2444812.5)	0.356 928 976 87 ± 8
P	2.5 ± 2 x 10^{-17} ss^{-1}
DM	90 ± 5 $cm^{-3}pc$
W_{50}	17 ms
S_{327}	15 mJy
S_{1420}	0.45 mJy
B	9.6 x 10^{10} G

Note : W_{50} is the half width and B the derived magnetic field.

evidence has been accumulating that these methods can often be poor indicators of distance. For example, the measured DM for PSR0833-45 of 69 cm^{-3} pc is not consistent with the expected distance of 500 pc, assuming the pulsar to be associated with the Vela SNR. Further, the scattering broadening suffered by pulses from a pulsar at any radio frequency is expected to be a function of the distance to the pulsar, indicated by its DM (Manchester and Taylor, 1977). Although the measured scatter broadening for most pulsars indicates a dependence on DM, there are pulsars which do not follow the trend. For example, the pulses from PSR1758-23 with DM=1140 cm^{-3} pc show large scattering broadening even at 1420 MHz, while those from PSR1338-62, with a DM of 880 cm^{-3}pc show little broadening at this frequency (Manchestor, D'Amico, and Tuohy, 1985). This points to large variations in the electron distribution for different directions in the Galaxy. It has also been shown (Krishnamohan, 1986) that there are regions in the galactic plane with dimensions of hundreds of parsec that have low electron densities.

Thus, while the assumed electron density can give the statistical distribution of the pulsars in the Galaxy, the distances estimated in individual cases should be considered with due reservation. With this in mind, the distance to PSR1854+00 estimated using an average electron density of 0.03 cm^{-3} is 3 kpc, while a value of 2.3 kpc is obtained from the more rigorous model of Lyne, Manchester and

Taylor (1985).

6.3 AN HI SHELL AROUND THE SNR W44

Observations of the 21-cm hyperfine line of HI have shown that the SNR W44 coincides with a cold HI shell expanding at a velocity of about 4 kms^{-1} (Knapp & Kerr, 1974). For the kinematic distance of 3 kpc, a diameter of 80 pc for the shell puts its age at $6x10^6$ yr.

There is also an infra-red source, W44-IRS1, situated about 6’ beyond the edge of W44 (Fig.6.2) (Wootten, 1978; Wynn-Williams, Biechman and Downes, 1981). Although outside the SNR, this source is within the expanding HI shell. Wootten (1978) suggested that W44-IRS1 might be a case of SN-induced star formation, triggered by the SN of W44. Wynn-Williams, Biechman and Downes (1981) considered this to be unlikely because of its physical separation from the SNR and the well-developed stage of the HII region. However, if the expanding HI shell were considered to be the signature of an earlier SN explosion close to the site of SNR W44 about 10^7 yr ago, the question of whether the formation of W44-IRS1 was influenced by this earlier SN explosion needs due consideration.

6.4 THE AGE OF PSR 1854+00

In terms of a possible connection between PSR1854+00 and W44, it is important to estimate an age for the pulsar. The age of a pulsar can be estimated from its P and $\dot{P}$, under

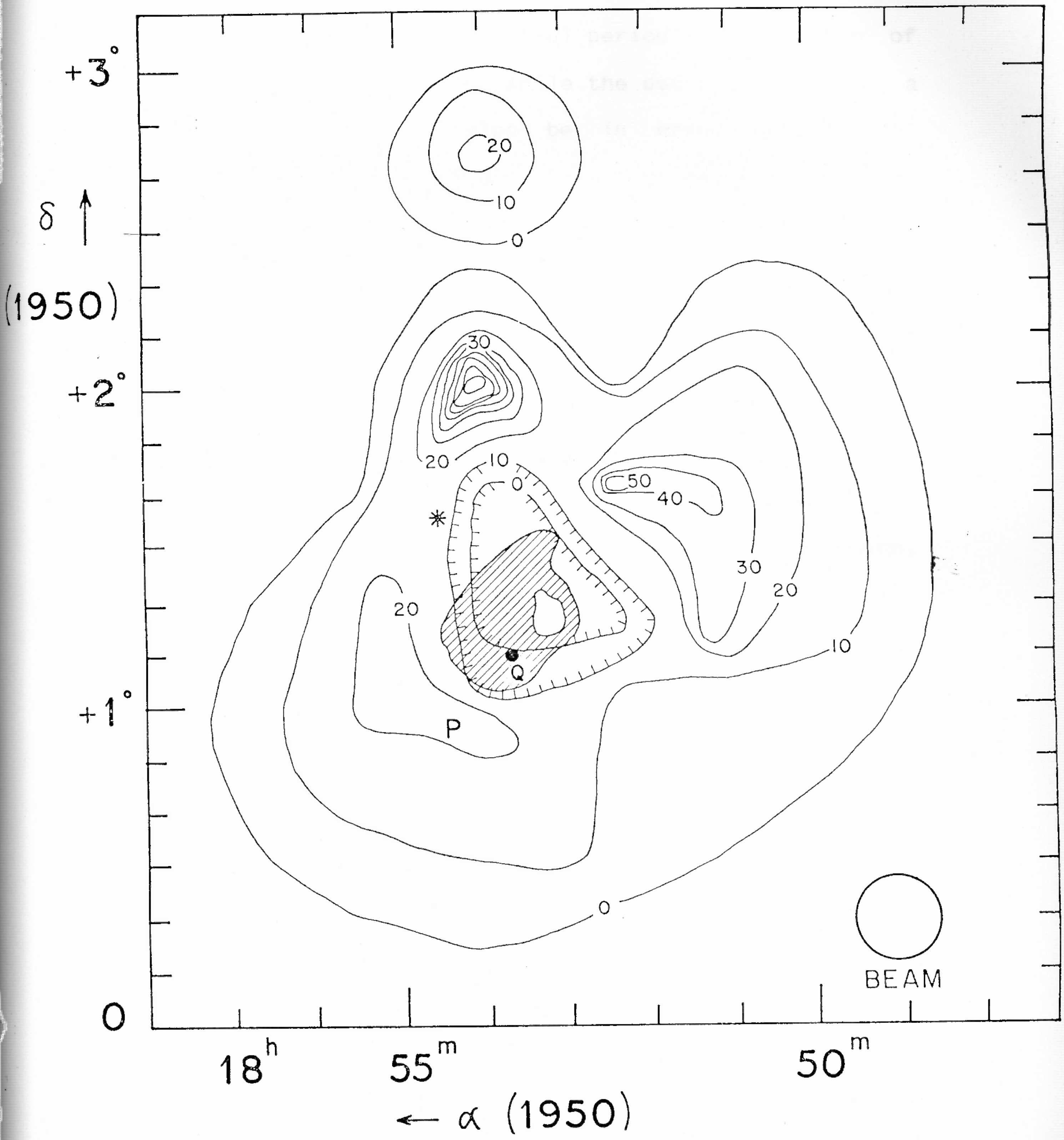

Fig. 6.2. The W44 region.
Distribution of objects in the W44 region. Solid contours show the HI shell (Knapp and Kerr, 1974). SNR W44 is shown hatched, the positions of PSRs 1854+00 and 1853+01 are indicated by P and Q respectively, * denotes the infrared source IRS1.

assumptions regarding its initial period and the form of decay of its magnetic field. While the estimated age of a short-period pulsar could also be in error due to the cumulative contribution of glitches, the major source of error for a long-period pulsar originates in the assumed time scale of decay of its magnetic field. Pulsars are generally believed to be born with periods shorter than a few tens of msec. However, the age estimate could be in serious error for a long-period pulsar such as PSR1854+00 if it were born with a period close to its present value. Pulsars, in principle, slow down because of gravitational and magnetic braking (Ostriker and Gunn, 1969). For pulsars of period >100 msec., the braking produced by the radiation from the rotating magnetic dipole plays the dominant role. This braking torque is such that the resultant slowing down is proportional to a power of the rotation frequency, i.e., $\dot{\Omega}=K.\Omega^n$ For dipole braking, n=3 and the constant K is proportional to the ratio of the square of the magnetic moment and the moment of inertia of the neutron star. Integrating the above expression, the frequency of pulsation Ω and the age t are related by the expression (Manchester and Taylor, 1977).

$$t = \frac{\Omega}{(n-1)\dot{\Omega}} \left[1 - \left(\frac{\Omega}{\Omega_i}\right)^{n-1}\right] \tag{6.3}$$

where Ω_i is the pulsation frequency at t=0 and the term K has been assumed to be constant with time. For $\Omega \ll \Omega_i$ the characteristic age τ is given by

$$\tau = \frac{\Omega}{(n-1)\dot{\Omega}} = \frac{P}{(n-1)\dot{P}} \quad ..(n\neq1) \qquad (6.4)$$

For radiation from a rotating magnetic dipole,

$$n = 3 \quad \text{and} \quad \tau = P/2\dot{P}.$$

The above expression represents the age of the pulsar assuming that $\Omega \ll \Omega_i$ and that the pulsar magnetic field has remained constant. The conclusion that pulsar magnetic fields decay as the object ages has been arrived at from several considerations. For example, it is invoked to explain the pulsar period distribution and the deficit of pulsars with high values of z. The time scale for the decay of pulsar magnetic fields has been estimated to be in the range of 2 to 20×10^6 yr (Radhakrishnan, 1982; Krishnamohan, 1987). Assuming an exponentially-decaying magnetic field, the age of a pulsar, t, is given by (Gunn & Ostriker, 1970):

$$t = \frac{t_d}{2} \ln\,(1+\tau/t_d) \qquad (6.3)$$

where t_d is the time scale of decay and τ is the characterstic age.

Although the time scale for magnetic-field decay is debatable, the age of PSR1854+00 turns out to be 10×10^6 yr, assuming a time scale for magnetic field decay of 9×10^6 yr (Lyne, Manchester and Taylor, 1985). This estimate is not affected by the mode of injection of the pulsar, provided that the underlying assumptions that a neutron star is born with a short period, and that the decay of the magnetic field can be described by a single time scale during most of its life, are valid.

6.5 THE SNR W44

6.5.1 The Radio Remnant

The SNR W44 has been classified as being of shell type in the radio region. Its age has been estimated to be about 3900 yr using the Σ-t relation for SNRs of Clark and Caswell (1976). It is one of the few SNRs for which distance estimates are available from HI and OH-absorption studies. The estimated distance of 3.0±1 kpc is considered to be sound (Green 1989). The SNR has a pear-shaped shell with contours indicating the likely interaction of the SNR with a neighbouring molecular cloud (Wootten, 1977).

6.5.2 The X-ray Remnant and its Mass

W44 has been studied using the Imaging Proportional Counter (IPC) aboard the Einstein Observatory (Watson etal., 1983). Unlike most SNRs, the X-rays originate from the central volume of the remnant and no emission is seen from the surrounding shell. This makes W44 a member of a separate class of SNRs which will be dealt with in some detail in Chapter 7.

The mass of the X-ray emitting material within this SNR has been calculated to be 60 $M_{\odot}$ (Watson etal., 1983). In order to compute this mass, it was assumed that the radiation is entirely of thermal origin and that the filling factor is unity. However, if most of the observed X-ray radiation originates from non-thermal emission, then the above mass could be a considerable overestimate. The only method of resolving this question is to obtain high resolution X-ray spectroscopy of the SNR. In the absence of this, we will assume that the mass of the X-ray emitting material is several tens of solar mass.

We can consider possible origins for such a large mass within the central volume of the SNR. For example, considering that W44 is in the neighbourhood of a dense molecular cloud (Wootten, 1977), it is likely that most of the X-ray emitting material originated in the dense interstellar medium expected in the neighbourhoods of such a cloud. In this case, the differential rate of cooling would be responsible for the peculiar X-ray morphology of the SNR. Although this is plausible, it is intriguing that a well-formed radio shell is present. The formation of a radio shell would involve the compression of the interstellar magnetic field originally situated within the present volume of the SNR into its shell. The freezing of the ionised cloud material to this field would also have resulted in its incorporation into the shell. It is more probable that the X-ray emitting material originated in the progenitor star of the supernova. We will return to the question of the mass of the progenitor in Chapter 7.

6.6 A POSSIBLE ASSOCIATION BETWEEN PSR 1854+00 AND SNR W44

PSR1854+00 lies just outside the shell of W44 (Fig.6.2). The projected separation from the centre of the remnant is 30 pc for a distance of 3 kpc. Were it to have the age of the SNR ($4x10^3$ yr, Clark and Caswell, 1976) it would need to have a transverse velocity of $10^4 kms^{-1}$ to account for the present separation.

Pulsars with such high velocities are not known and even the case of PSR2224+65, which has a reported velocity of 1750 kms^{-1}, could be due to poor sensitivity (Cordes, 1986) or possibly indicate that the distance used to compute its space velocity is an over estimate. However, it can not be ruled out that pulsars with such high-velocity do exist, but are scarce in the local volume of the Galaxy because pulsars are born close to the plane and high-velocity pulsars are expected to have moved away from the local neighbourhood. As high-velocity pulsars would represent only a tiny fraction of the total pulsar population, it would not be surprising if they are not represented in the local neighbourhood. Theoretically, such high velocities are not impossible. According to the model of Harrison and Tademaru (1977), pulsars are accelerated to high velocity during the early part of their life. The force of radiation reaction which they suggest imparts the space velocity to a pulsar, is proportional to $\Omega^5.B^2$,Ω being the pulsar angular velocity and B its magnetic field. However, if the of PSR1854+00 age were to be 10^4 yr, the low measured $\dot{P}$ would imply that the initial period would have been close to the present period and the initial magnetic field would have been low. In this case, the force of radiation reaction would have been insufficient to impart such a high velocity.

A pulsar can also get a high velocity at the epoch of its birth from an asymmetric supernova explosion. This is believed to be a plausible mechanism for imparting high velocities to pulsars (Shklovskii, 1970a). In addition, a pulsar formed by a SN explosion in a binary system could acquire high velocity (Gott, Gunn and Ostriker, 1970; Radhakrishnan and Shukre, 1985), where the sling-shot effect (Blaauw, 1961) is invoked. However, it would be difficult to employ this mechanism to account for the high velocity needed if PSR1854+00 and W44 were to be associated as it would imply that the pulsar has a similar velocity now to its orbital velocity in the presupernova binary system (Blaauw, 1961). In addition, a transverse velocity of 10^4 kms^{-1} would imply a $\dot{P}$ of $1.5x10^{-16}ss^{-1}$ due to the train-whistle effect (Shklovskii, 1970b), which is larger than our measured value of $\dot{P}$. On the other hand, if the hypothetical binary system containing the progenitors of PSR1854+00 and SNR W44 was disrupted during an earlier SN explosion associated with the formation of the former, PSR1854+00 would be expected to have a projected velocity of 2 kms^{-1} to account for its present separation from the centroid of the SNR. The probability of such a low velocity after disruption of a binary system is small. We conclude that it is unlikely that PSR1854+00 could be associated with SNR W44.

Very recently, a pulsar PSR1853+01 has been discovered within the radio contours of W44 (Wolszczan etal., 1988). It has a period of 0.2674 sec. and a DM of 98±8 $cm^{-3}pc$. Its distance as estimated from its DM is 3.3 kpc using a global value for the mean electron density of 0.03 cm^{-3} and 2.5 kpc using an electron density based on the more rigorous model of Lyne, Manchester & Taylor (1985). It is possible that this pulsar is associated with W44 and an estimate of its age is needed to investigate this further.

6.7 A POSSIBLE ASSOCIATION BETWEEN PSR 1854+00 AND THE HI SHELL NEAR W44

The distance derived for PSR1854+00 from its DM is also consistent with that suggested for the HI shell. A connection between an HI shell and the pulsar PSR0740-28 has been suggested by Stacy and Jackson (1982). It is of interest consider whether the HI shell in the direction of W44 might be associated with PSR1854+00.

Knapp and Kerr (1974) suggest an age of 10^7 yr for the expanding HI shell near W44. This age agrees with that derived for PSR1854+00 in Section 6.4. The angular separation of the pulsar from the likely centroid of the HI shell is 30 arcmin. If the pulsar is associated with the HI shell, it would need a transverse velocity of only 3

kms^{-1} to have attained the present separation of 30 pc from the centroid of the HI shell in 10^7 yr, assuming a distance of 3 kpc (Knapp and Kerr, 1974).

It has been suggested that the velocities of pulsars are correlated with their magnetic fields (Helfand and Tademaru, 1977), implying that a low-magnetic-field pulsar such as PSR1854+00 could have a low space velocity. In this case, it would not be too surprising if even an old pulsar were to be found close to the site of its birth. It is thus plausible that PSR1854+00 is associated with the HI shell. We will return to the question of a low velocity for this pulsar in Chapter 7.