Chapter 3 Magnetic Field Model of Milky Way Galaxy

3.1 The Recent Model

In Chapter 1, the galactic magnetic field can be investigated from several methods, but there are only two considerable models were developed. The first, Synchrotron emission model is investigated from the observed brightness temperature of synchrotron emission of cosmic ray electron. And the other, Bisymmetric Spiral model is investigated from the observed rotation measures of pulsars.

3.1.1 Synchrotron Emission Model

According to density wave theory this would correspond to the region within the inner Lindblad resonance, the magnitude of the magnetic field on the position R in the galaxy in a modified version of the Thielheim & Langhoff (1968) model.

$$H(R)\,\alpha\left[\exp\left(-R^2/R_0{}^2\right)\left(1-\exp\left(-R^2/R_1{}^2\right)\right)\right]\cdot\left[1+k^2\cos^2(\pi a/A)\right] \tag{3.1}$$

The term involving R_l ensures that the field falls to zero at the galactic center as would be expected from dynamo theory of field generation. The field curve increases sharply in the first step, near galactic center and then decreases as exponential function in spiral region (Figure 3.1). This way, in the central region consists of stars and interstellar gas which abundance with charge particles or sources of magnetic field and these are tenuous in the disk region vary as the galactic distances.

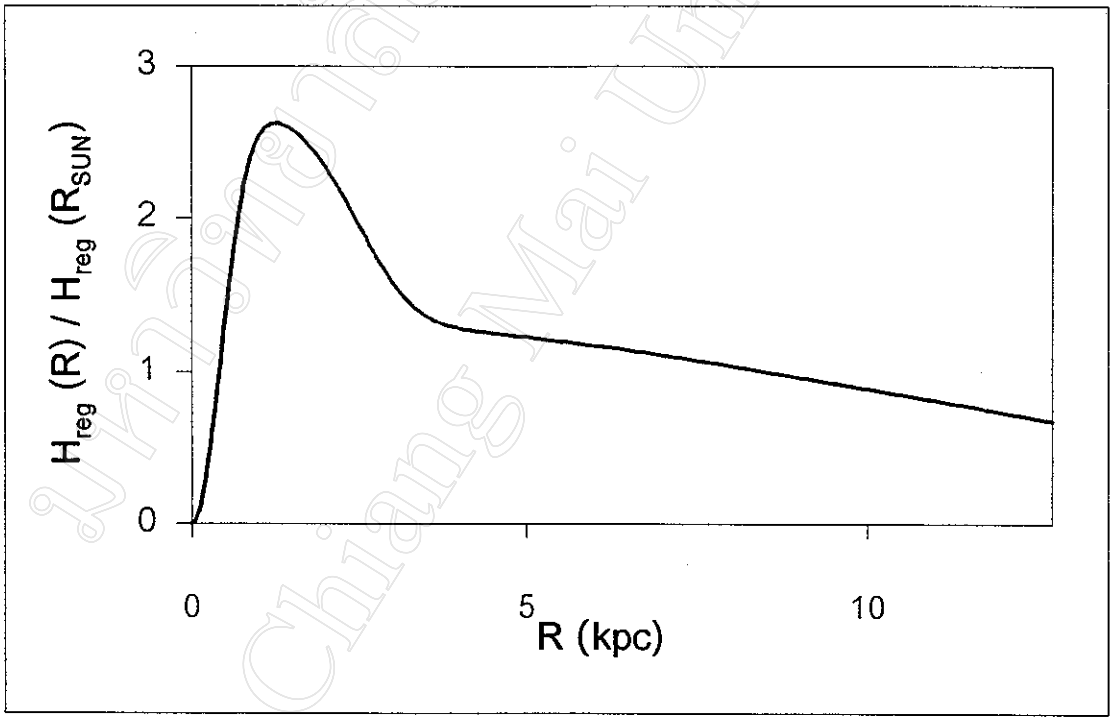

Figure 3.1 Radial variation of the magnitude of the regular component of magnetic field, $H_{reg}(R)/H_{reg}(R_{SUN})$ *used by Kearsey (1983) but scaled the position of the Sun of 8.5 kpc.*

Brindle, French & Osborne developed the galactic plane model follow as

$$H(R)\ \alpha\ \left[1-\exp\left(-\frac{R^2}{R_1^2}\right)\right]\left[\exp\left(-\frac{R^2}{R_0^2}\right)\right] \qquad (3.2)$$

They choose the parameter R_1 = 1.7 kpc (for the position of the Sun is 8.5 kpc). The second term is included to force the field to zero at the galactic center as expected from dynamo theory, but it is not important out side the expected field maximum at the galactic distance 3 kpc.

Sanguansak added term $exp(-(R/R_1)^4)$ into the model to make the field fall off more rapidly than the earlier one.

$$H(R) = \left[1-\exp\left(-2.768R^2\right)\right]\left[\exp\left(-\left(\frac{R}{R_0}\right)^2\right)+\exp\left(-\left(\frac{R}{R_1}\right)^4\right)\right] \qquad (3.3)$$

The field curve of term $exp(-(R/R_1)^4)$ is more sloping and narrow than the curve of term $exp(-(R/R_0)^2)$. Therefore, adjustment of the parameter R_1 and R_0 has effect to change the slope of the galactic central and galactic disk region respectively. She obtained the parameters R_1 = 1.91 kpc and R_0 = 11.0 kpc.

However, Synchrotron Emission Model is only fitted in the perpendicular field component (to the line of sight) with the observed brightness temperatures. But the parallel field component fitted model; Bisymmetric Spiral model is considerable too.

3.1.2 Bisymmetric Spiral Model

This field model has been found through several analysis of Faraday rotation of the linearly polarized radio emission.

$$RM = 0.81\int_{0}^{s} N_e \vec{H} \cdot \vec{ds} \tag{3.4}$$

Where *RM* is rotation measures of radio sources, N_e is the electron density in cm^{-3} and s is the distance of radio sources from the sun.

Due to the spin of the galaxy, the spiral arms move around the galactic center, stars and the interstellar matter in the spiral arms (has being fluid state) will flow about the core of arms to conserve the arm structure. This fluid in the next arm will flow in the opposite direction for equilibrium in the disk. This interstellar gas is consisted of a huge of charged particles, which are magnetic field sources. Therefore the field direction is opposite with the next arm.

The Bisymmetric Spiral Model indices a magnetic field lines along the spiral pattern and field reversals. The field varies the galactic distances, R as sinusoidal function for 3.4 kpc $< R <$ 12.75 kpc. Figure 3.2 shown that the field in term of magnitude and normalized by the field at the Sun.

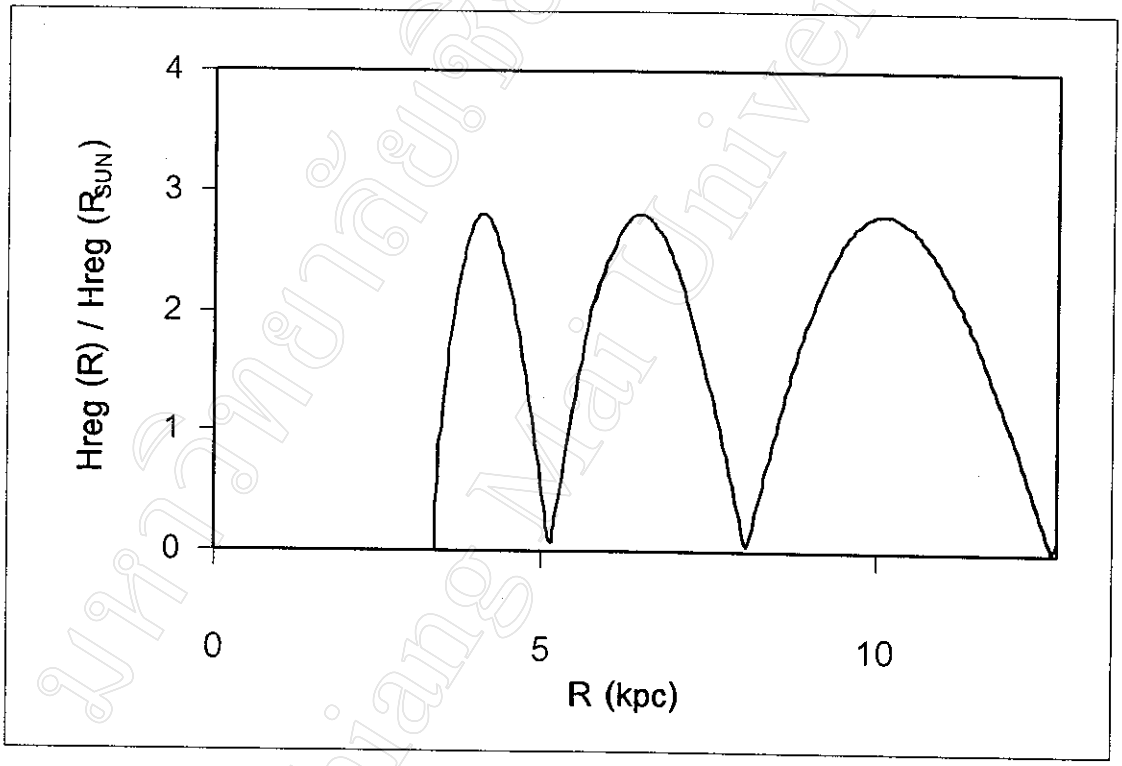

Figure 3.2 Radial variation of the magnitude of the regular component of magnetic field, $H_{reg}(R)/H_{reg}(R_{SUN})$ *adapted from Han and Qiao. A change of sign of the field strength indicates that the field has reversed its direction by 180° (for* $\theta = 0°$*).*

Simard-Normandin & Kronberg assumed that the filed is completely uniform and that the field lines follow the spiral pattern.

They showed that the Bisymmetric 4-armed Spiral Model had pitch angle of -14° and reversals.

$$H_{//}(l,s)=\frac{H(l,s)}{(k^2+1)^{\frac{1}{2}}(y)^{\frac{1}{2}}}\left[\sin l+k\left(\cos l-\frac{s}{R_0}\right)\right] \tag{3.5}$$

From the distribution of rotation measures, Fujimoto and Tosa (1980) modeled the radial and azimuth components of a magnetic field in a Bisymmetric logarithmic spiral configuration with $\beta >> 1$.

$$\begin{aligned} H_R &= -\frac{f(R)}{R}\cos\left(\theta+\beta\ln\frac{R}{R_2}\right) \\ H_\theta &= \frac{f(R)}{R}\beta\cos\left(\theta+\beta\ln\frac{R}{R_2}\right) \end{aligned} \tag{3.6}$$

$$\beta=\frac{1}{\tan p} \tag{3.7}$$

Here R and θ are respectively the galactic distance and azimuth angle around the galactic center, β is a constant with p, the pitch angle of spiral, the angle between the field and the circle around the galactic center. The symbol R_2 is a constant and $f(R)$ is a smooth function of R (Figure 3.3).

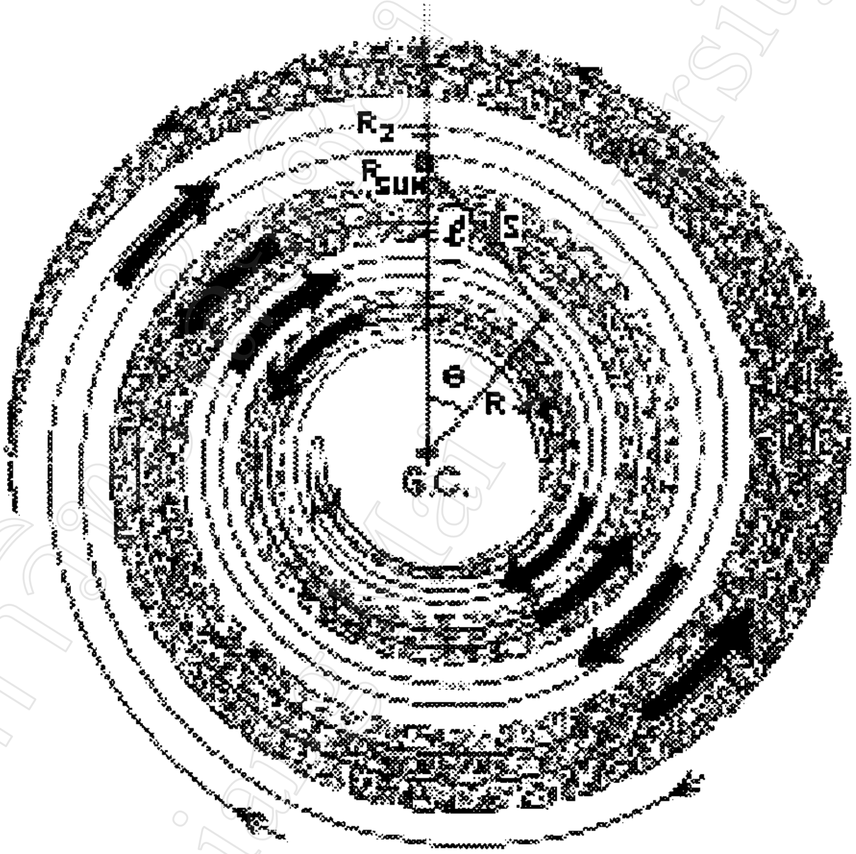

Figure 3.3 Bisymmetric Spiral magnetic fields used for our model computations of RM. The field directions are indicated with the arrows. The geometrical meanings of R_2*, p and the position of the Sun,* R_{SUN} *can be read from this figure.*

Sofue and Fujimoto adopt the early model to fit by 2-armed logarithmic spiral configuration for the distance of the Sun from the galactic center (Figure 3.4).

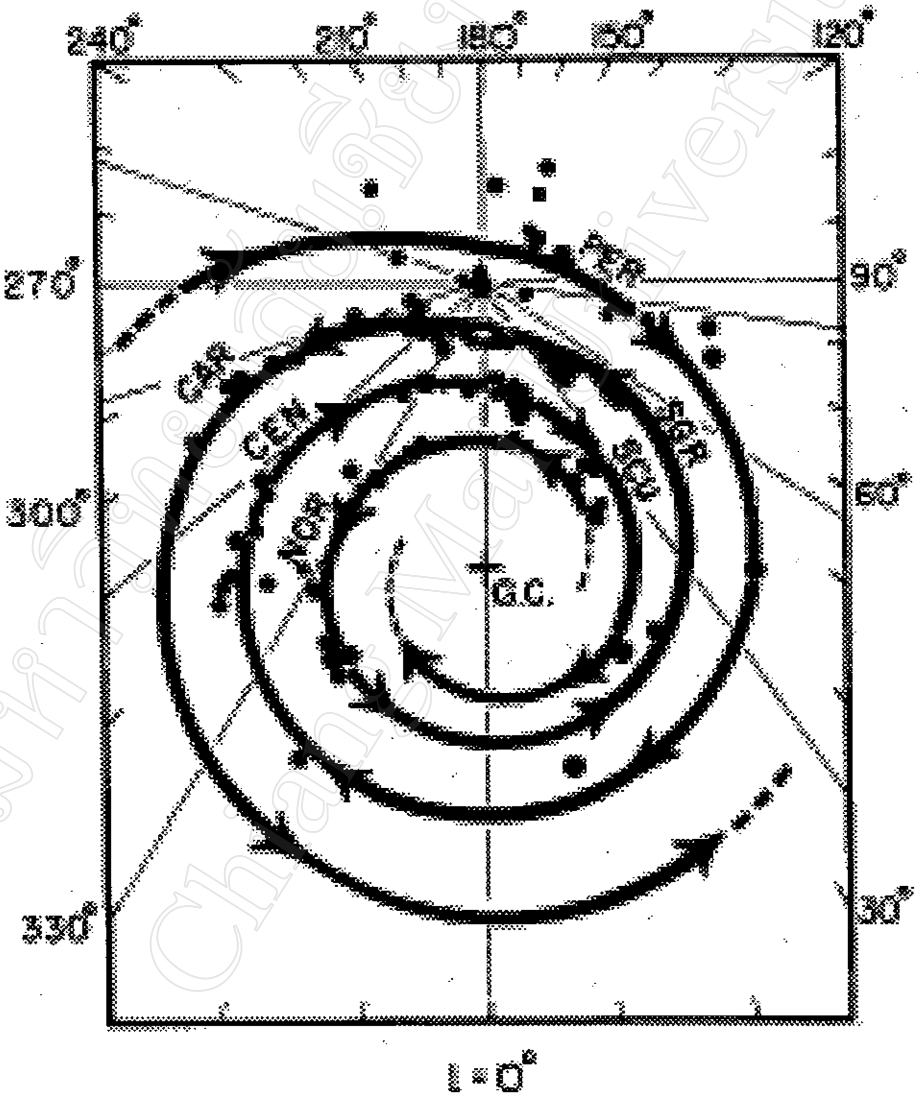

Figure 3.4 Possible, two-armed, Bisymmetric Spirals (thick lines) fitted to the distribution of HII regions (filled circles) given by Georgelin and Georgelin (1976). The arrows indicate the direction of magnetic field.

The model with such a sinusoidal variation is certainly more plausible than one with abrupt reversals. They assumed that the field is zero within 3.4 kpc of the galactic center, since the field structure in this region is poorly understood and since this region should not have a significant effect on the results given the paucity of distant pulsars (radio sources) in the inner galaxy. They also assumed that the field vanishes at the galactic distance more than 12.75 kpc. They chose pitch angle in their modeling based on fits of spirals to the distribution of HII regions in the galaxy and used the pitch angle of –5°.

It is interesting to note that the Bisymmetric Spiral field in the galaxy and those found in nearby spiral galaxies are consistent with the hypothesis of a primordial origin of the galactic magnetic fields which would predict that the magnetic line of force have been wound up from intergalactic disk.

Han and Qiao used the field model of Sofue and Fujimoto to yield the best fitting parameter R_2 and p with the smallest residual. They adjusted the parameter R_2 to match the suitable frequency of sinusoidal curve which depend on the spiral arm structure by fitting with the observed rotation measures, because of distribution of the rotation measures are indicate that the contrasting of field direction with the next arm relative to spiral pattern. And the adjustment of R_2 is effects to change phase shift of sinusoidal curve. So there must be adjust the pitch angle p to match suitable phase shift too. They obtained R_2 =10.115 ± 0.15 kpc and pitch angle, p = -8.2° ± 0.5°.

3.2 The Adapted Model

Each of the recent models has different dominant properties. The Synchrotron Emission Model shows that the magnetic field in the galactic disk region declines as exponential function relative to the galactic distance while the Bisymmetric Spiral Model demonstrates that the field direction in this region reverse to next arm as sinusoidal function. Furthermore, the first model indicates that the field in the galactic center region has a higher and more sloping than the galactic disk region.

But the both of models are used to describe the magnetic field of Milky Way Galaxy, so there should be only one model that includes all significant properties for use to describe the field. This work proposes the field model as equation (3.8).

In the galactic center region, the galactic distance less than 3.4 kpc, the model use the same of Synchrotron Emission Model. But in the galactic disk region, the galactic distance in the range of 3.4 kpc to 12.75 kpc, the field is reversal as sinusoidal curve and convergent approach to zero. But we are not believe that the field is zero at the interarm region. We put at least offset constant, C for the term $\cos\left(\theta+\beta\ln\frac{R}{R_2}\right)$.

for $R \leq 3.4$ kpc ;

$$H(R) = \left[1 - \exp\left(-2.768R^2\right)\right]\left[\exp\left(-\left(\frac{R}{R_0}\right)^2\right) + \exp\left(-\left(\frac{R}{R_1}\right)^4\right)\right]$$

for $3.4 \text{ kpc} \leq R \leq 12.75 \text{ kpc}$ and $\left|\cos\left(\theta + \beta \ln \frac{R}{R_2}\right)\right| \leq C$

$$H(R) = \left[1 - \exp\left(-2.768R^2\right)\right]\left[\exp\left(-\left(\frac{R}{R_0}\right)^2\right) + \exp\left(-\left(\frac{R}{R_1}\right)^4\right)\right] \cdot C$$

for $3.4 \text{ kpc} \leq R \leq 12.75 \text{ kpc}$ and $\left|\cos\left(\theta + \beta \ln \frac{R}{R_2}\right)\right| > C$

$$H(R) = \left[1 - \exp\left(-2.768R^2\right)\right]\left[\exp\left(-\left(\frac{R}{R_0}\right)^2\right) + \exp\left(-\left(\frac{R}{R_1}\right)^4\right)\right] \cdot \cos\left(\theta + \beta \ln \frac{R}{R_2}\right) \tag{3.8}$$

where

$$\beta = \frac{1}{\tan p}$$

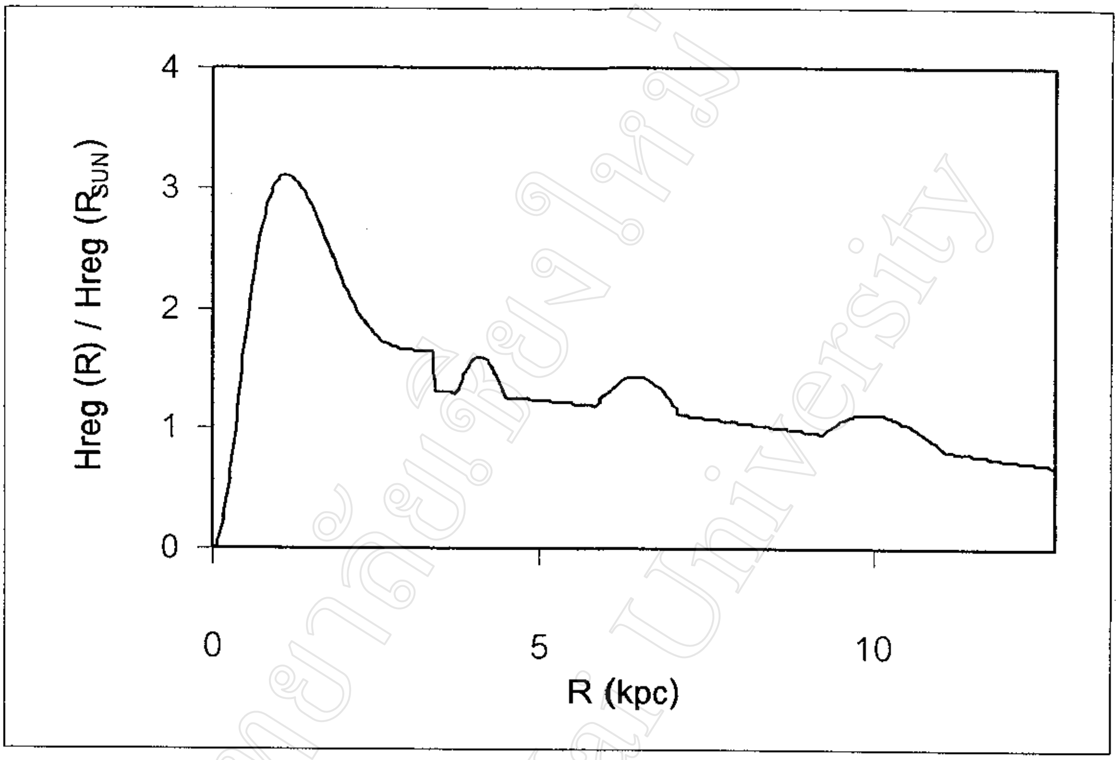

Figure 3.5 The adapted model: the magnetic field at distance less than 3.4 kpc is the same of Synchrotron Emission Model. But it mixed from exponential and sinusoidal pattern with at least the offset constant at the galactic distance in the range of 3.4 kpc to 12.75 kpc (for $\theta = 0^{o}$).