Generation of the Toroidal Field in the Galactic Halo

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Abstract We demonstrate that the antisymmetric toroidal magnetic field can be generated from the dipole field through velocity shear, and noticed that the effect of the radial shear is opposite to and greater than the effect of the vertical shear.

The large scale global magnetic field structure of our Galaxy has been obtained from the rotation measures(RMs) of pulsars and extragalactic radio sources. In the Galactic halo and near the Galactic Center, there are toroidal fields with opposite directions below and above the Galactic plane and poloidal fields of dipole form (Han 2002). This fields have been believed to be produced by A0 dynamo (Han et al. 1997). We investigate here whether these fields can be generated by velocity shear.

Galaxies have extended ionized diffuse layer. The velocity shear exists in our Galaxy and nearby galaxies. In NGC 891, the halo gas appears to rotate 25 to 100 km s^{-1} more slowly than the gas in the plane (Swaters et al. 1997). Exterior to R >10 kpc, a strip averaged between 2.8> z >1.4 kpc shows a rotation speed that is $\cong$ 25 km s^{-1} lower than the value in the plane. Interior to R <7 kpc, the difference gets greater, reaching 100 km s^{-1} at $R = 5$ kpc. The velocity shear has been detected in NGC 5775 (Tüllmann et al. 2000). The gas velocity strongly depend on z. It reaches the highest of 1822±8 km s^{-1} at z around 0 kpc, but decrease slowly towards larger z, finally reach to the systermic velocity of 1681 km $^{-1}$ at $z = 9$ kpc. In our Galaxy, the neutral hydrogen has a component with a scaleheight of ~500 pc (Dickey & Lockman 1990). Observations of the velocities at high z of our Galaxy are obviously difficult. Benjamin & Danly (1997) discussed the volocity stratification of high velocity clouds. On the other hand, we noticed the velocity shear exists in all gravitational potential models, such as that of Paczynski (1990) which consists of a contribution of disk, halo and bulge. The radial acceleration and the velocity of the Galaxy can be derived from the model. Fig.1 shows the rotation velocity decreases with increasing heights.

To explain the the toroidal field found in our Galaxy, we now show whether the toroidal field can be generated through velocity shear defined by the potential model of Paczynski. As we know, the magnetic lines are frozen in plasma. We suppose that the initial magnetic field in our Galaxy is of dipolar form. When there is vertical velocity shear, azimuthal stretching of vertical componet of field lines will also produce the azimuthal toroidal field, as shown in Fig. 2. The strength of toroidal fields grows with time in the form of

$$B_\varphi(R,z) = B_z(R,z)\frac{\partial v_{rot}(R,z)}{\partial z}t\,,$$

where the B_z is the vertical component of dipole field, v_{rot} is the function of rotation velocity, B_φ is the toroidal field.

On the one hand, when the Galaxy rotates differentially, so that there is radial velocity shear. The radial component of field lines will be winded up, producing the toroidal field. The toroidal field thus generated should be

$$B_\varphi(R,z) = B_R(R,z)R\frac{\partial \omega(R,z)}{\partial R}t\,,$$

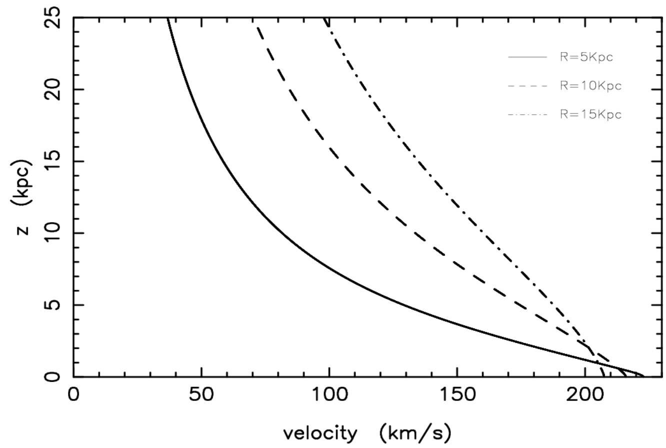

Fig. 1 The rotation velocities as a function of z and R calculated using the potential model of Paczynski (1990)

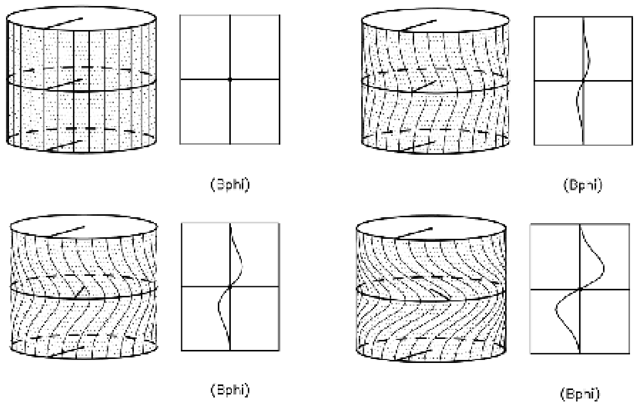

Fig. 2 The toroidal field gets stronger with time due to the vertical velocity shear

where the B_R is the radial component of dipole field, and ω is the function of angle velocity.

Both kinds of velocity shear can produce the toroidal fields. Observationally, these field can be revealed by rotation measures of radio sources. Rotation measure depends on the magnetic field and electron density, given by

$$RM = 0.820 \int_0^{\mathrm{dist}} n_e(x,y,z) \cdot \vec{B}(x,y,z) \cdot \mathrm{d}\vec{l}(x,y,z) \mathrm{rad\ m}^{-2} \,,$$

To demonstrate the RM distribution of the produced toroidal fields, we use the model for galactic electron density in a smooth and axisymmetric pattern (Comez et al. 2001)

$$n_e(R,z) = n_0 \frac{f(R/R_0)}{f(R_\odot/R_0)} f(\frac{z}{z_0}) + n_1 \frac{f(R/R_1)}{f(R_\odot/R_1)} f(\frac{z}{z_1}) \,,$$

where $f(x) = \mathrm{sech}^2\mathrm{x}$.

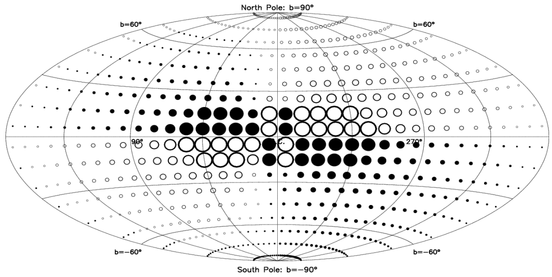

Fig. 3 The simulated RM distribution by using the toroidal fields produced by vertical velocity (t = 2000 Myr) shear plus the dipole field. The electron density model is from Comez et al. (2001)

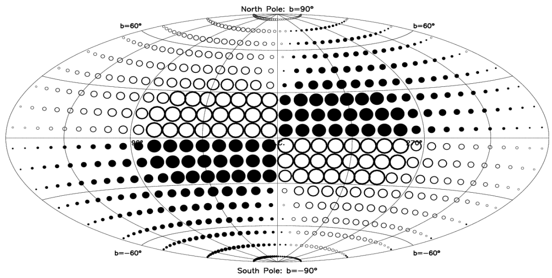

Fig. 4 The same to Fig. 3, but for the radial shear at t = 1 Myr

The simulate RM distribution are shown in Fig. 3 and Fig. 4 for the vertical and radial velocity shear, respectively. We found that both shears produce the antisymmetric rotation measure sky. However, it is interesting to notice that the directions of toroidal fields produced by the vertical and radial velocity shears are contrary to each other. As effects of both kinds of shears should exist in our Galaxy and they should cancel each other somehow finally. Although the effect of radial shear appears much stronger than that of vertical shear, the observed rotation measure sky (Fig. 5) is very similar to Fig. 3. Two possible explanations: First, the assumed dipole field should have an opposite direction comparing to the real dipole in our Galaxy, so that toroidal field directions produced by the radial shear consist with observed ones and the toroidal field produced by the vertical shear does not dominate but cancle partially the field from radial shear. Secondly, the dipole field

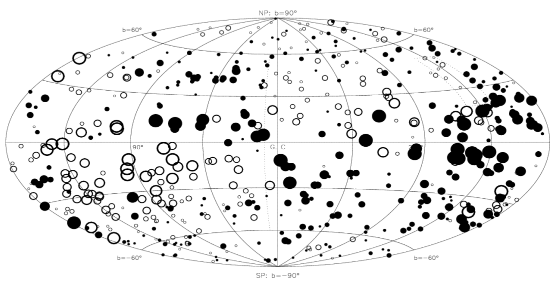

Fig. 5 The observed RM sky from Han, Manchester & Qiao (1999)

assumed is fine, and the toroidal field by vertical velocity shear dominates. The radial shear only works at very low z and so produce the field does not affect the rotation measure sky much.

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