Large scale magnetic field generation by accelerated particles in galactic medium

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2.Reason explonations

The main sourses of accelerated particles are SN remnants, stellar winds of OB stars and especially OB-associations; pulsars; probably, accretion discs etc.

Relativistic particles may propagate distances of order of

galactic size (ten kpc) and leave the Galaxy. They generate

the large-scale electric current and large-scale magnetic field. The estimation of magnetic field may give the information about the origin of large-scale magnetic inhomogeneities in Galaxy.

In previous works the main

attention was given to MHD modes with scales of order of

giroradius or transport path energetic particles (Wentzel 1969; Skilling 1975; Bell 2004; Ptuskin and Zirakashvili 2005 et al.

3. Notations

- r,i,e – accelerated ions, thermal ions, thermal electrons;

$n^r, n^i, n^e -$ Nonequilibrium particle number densities.

$(n^r, n^i, n^e << n_0)$

$j^r, j^i, j^e -$ electric currents;

$j^{ext} = j^r + j^i + j^e -$ total electric current

$Q(t_0) -$ Total accelerated particle number, emitted in moment t_0 (power of source).

e – elementary charge.

4. Principal approximations

1. Diffusion motion of accelerated end background particles in galactic medium.
2. Homogeneity of galactic medium (primary magnetic field and statistical properties of turbulence).
3. Point source of accelerated particles.
4. Linear approximation of MHD equations (secondary magnetic field is small compare to primary one).

5. Basic equations for currents

Diffusion coefficients: $D^{r}{}_{\alpha\beta}, D^{i}{}_{\alpha\beta}, D^{e}{}_{\alpha\beta}.$

Electroconductivities: $\sigma^{r}{}_{\alpha\beta}, \sigma^{i}{}_{\alpha\beta}, \sigma^{e}{}_{\alpha\beta}.$

$\sigma^{e,i}{}_{\alpha\beta} = \frac{D^{e,i}{}_{\alpha\beta}}{4\pi r_D}, \Leftrightarrow r_D = \sqrt{\frac{T}{4\pi n_0 e^2}}$ – Debye radius

$$j^{k}{}_{\alpha} = \mp e D^{k}{}_{\alpha\beta} \frac{\partial n^{k}}{\partial x_{\beta}} + \sigma^{k}{}_{\alpha\beta} E_{\beta}, \Leftrightarrow k = r, i, e.$$

$$\sigma^{r} << \sigma^{e}, \sigma^{i}.$$

j

6. Self-consistent equations for accelerated and thermal particles

Four equations for three particle densities $(n^k, k = r, i, e)$
and electric field **E**

$$\frac{\partial e n^r}{\partial t} + \nabla \square j^r = eQ\delta(r)\delta(t - t_0),$$

$$\frac{\partial e n^i}{\partial t} + \nabla \square j^i = -eQ\delta(r)\delta(t - t_0)$$

$$\frac{\partial e n^e}{\partial t} - \nabla \square j^e = 0.$$

$$\nabla \square E = 4\pi e(n^r + n^i - n^e).$$

7. Solutions of transport equations

We use Laplace (s) and Fourier (k) transforms and approximations

$$\frac{{r_D}^2}{{R_D}^2} << 1, \Leftrightarrow (kr_D)^2 << \frac{{r_D}^2}{{\Lambda_\parallel}^2} << 1, \Leftrightarrow \tilde{D}^r >> \tilde{D}^i >> \tilde{D}^e.$$

Here $\tilde{D} = k_\alpha D_{\alpha\beta} k_\beta, \Lambda^r, R_D -$ transport path and

Debye radius of accelerated particles.

Diffusion of accelerated particles is free. Diffusion of thermal particles is ambipolar with double ion diffusion coefficient:

$$2D^i{}_{\alpha\beta}.$$

8. Screening effects

1. Isotropic steady diffusion. Absolute electroneutrality: $n^r(r)+n^i(r)-n^e(r)=0.$

Complete screening of electric current: $j^{ext}=0.$

2. Anisotropic steady diffusion. Not complete, but very strong electroneutrality:

$$n^r{}_k+n^i{}_k-n^e{}_k=(kr_D)^2\,n^e{}_k\approx 0.$$

Electric current is partly screened:

$$j_k{}^{ext}\approx -ieQ\left(\frac{D^r{}_{\alpha\beta}k_\beta}{\tilde{D}^r}-\frac{D^i{}_{\alpha\beta}k_\beta}{\tilde{D}^i}\right)\neq 0.$$

9. Non-steady solutions

Laplace-Fourier transforms:

$$j_\alpha{}^{ext} = -ieQe^{-st_0}\left[\frac{D^r{}_{\alpha\beta}k_\beta}{s+\tilde{D}^r} - \frac{2D_{\alpha\beta}{}^i k_\beta}{s+2\tilde{D}^i}\right],$$

Currents of accelerated and thermal particles have opposite signs. Electric current is partly screened.

$$P^r = (pv)_{mean} Q\frac{e^{-st_0}}{3(s+\tilde{D}^r)}.$$

The last value is the pressure of accelerated particles.

10. Space-time solution for current and pressure

Diffusion Green function:

$$G(r,t)=\frac{\Theta(t)}{D_\perp D_\parallel^{1/2}(4\pi t)^{3/2}}\exp\left[-\frac{r_\perp{}^2}{4D_\perp t}-\frac{z^2}{4D_\parallel t}\right].$$

Electric current:

$$j_\alpha{}^{ext}(r,t)=-eQ\nabla_\beta[D_{\alpha\beta}{}^r G^r(r,t-t_0)-$$

$$-D_{\alpha\beta}{}^i G^i(r,t-t_0)].$$

In given point at first arise the current of accelerated particles. Then increase compensated background current. But complete compensation is not probably owing to different particle diffusion coefficients.

Pressure:

$$P^r(r,t)=\frac{1}{3}(pv)_{mean}QG^r(r,t-t_0).$$

11. Magnetic field calculation (particular cases)

We use MHD equations with external current, taken into account the motion of medium.

Steady solution:

$$b_{\parallel} = \frac{(pv)_{mean} Q}{3B_0 (D_{\parallel}{}^{r} - D_{\perp}{}^{r})} \left[\frac{1}{\sqrt{r_{\perp}{}^{2} + z^{2}}} - \frac{D_{\parallel}}{\sqrt{D_{\perp}(D_{\parallel} r_{\perp}{}^{2} + D_{\perp} z^{2})}} \right].$$

Non-static solution:

$$b_{\alpha} = \frac{eQv r_{\perp}}{c v_A} \int_0^t \frac{d\tau}{\tau} \left[G_{\perp}{}^{r}(r_{\perp}, t-\tau) G_{\parallel}{}^{r}(z,t,\tau) \right]$$

$$- \frac{eQv r_{\perp}}{c v_A} \int_0^t \frac{d\tau}{\tau} \left[G_{\perp}{}^{i}(r_{\perp}, t-\tau) G_{\parallel}{}^{i}(z,t,\tau) \right].$$

12. Estimations of secondary magnetic field

Main sources of accelerated particles:

1. OB stellar winds $(\dot{M} \approx 10^{-6} - 10^{-7} M_{\oplus}, u_w \approx 3\times 10^8 cm/s, \eta \approx 0.1)$

Secondary magnetic field is of order of primary field:

$b \approx B_0 \approx 3\times 10^{-6} G$ at distance 10 pc.

2. SN explosions and their remnants

$$(E \sim 10^{51} erg, u \approx 10^9 \div 3\times 10^8 cm/s, \eta \geq 0.1).$$

Probably, SN remnants produce magnetic fields not smaller then stellar winds.

13. Conclusions

- Separate sources of accelerated particles may cause the significant magnetic spots in Galaxy with sizes of tens parsec.
- Accounting of complete production of relativistic particles in Galaxy $(Q \sim 10^{43}$ relativistic particles per second) give the magnetic field estimation of order several microgauss (see Dolginov and Toptygin, 2004).

Thank you very much!