ATOMS IN MAGNETIC FIELDS: POSSIBLE ORIGIN OF CHEMICAL ANOMALIES IN MAGNETIC STARS

G.S. Bisnovatyi-Kogan

Space Research Institute, Russian Academy of Sciences
Profsoyuznaya 84/32, Moscow 117810 Russia, *gkogan@mx.iki.rssi.ru*

ABSTRACT. The interaction of atomic magnetic moments with non-uniform magnetic fields may be important for the diffusion in the matter near the surface of neutron and magnetic stars. Formation of the anomalous abundance of some elements in magnetic stars is considered as an extension of the old model of Babcock (1963) and Jensen (1962). Phase transition of the second order is shown to be held in helium as a transition from diamagnetic to paramagnetic stare with increasing of magnetic field (Bisnovatyi-Kogan and Höflich, 1990), efficiency.

Key words: Stars: atomic magnetic moments; magnetic stars.

1. Introduction

Chemical anomalies are observed in Ap stars, having masses $M \leq 2\,M_\odot$ and strong magnetic fields up to 10^4 Gs. The existence of such anomalies may be connected with the following exceptional properties of these stars.

They have a small convective core $< 0.3\,M_\odot$, and very thin convective envelope. Absence of strong convective zones make it ineffective an action of dynamo processes. The magnetic field of such stars is formed from the compression of the contracting magnetized cloud, and dynamo action on the short convective stage during star evolution to the main sequence, lasting about $5 \cdot 10^5$ years (Bisnovatyi-Kogan, 2001). These property may imply a large variety of magnetic field strength and topology in Ap stars. Slow rotation observed in these stars may be connected with a large rate of a loss of stellar angular momentum due to magnetic stellar winds. Slow rotation implies negligible meredional circulation and consequently negligible mixing. It also decrease even more the action of the dynamo processes. Strong magnetic field suppresses completely the residual convection in the outer envelope. That create conditions of accumulation of slow diffusive changes of the composition in stellar layers near the photosphere.

Three types of a diffusion are considered in the literature for creation of chemical anomalies.

1. Radiative diffusion (Mishaud, 1970).
2. Accumulation of anomalies during accretion (Havnes and Conti, 1971).
3. Diffusion of paramagnetic atoms in the non-uniform stellar fields (Babcock, 1963; Jensen, 1962).

The last mechanism was considered because of a striking correlation between the anomalous abundance and magnetic moment of the corresponding atoms: the largest anomaly ($\sim 10^7$ times over the solar abundance) has the element Eu, which has the largest atomic magnetic momentum in S state, $J = 7/2$. The first models could not quantitatively explain the observed anomalies. The improvement of this model by Bisnovatyi-Kogan and Höflich (1990) (see also Bisnovatyi-Kogan, 1992) permitted to obtain much better quantitative agreement with observations.

2. Observational correlations.

The largest chemical anomalies correspond to elements with large atomic magnetic momentum, among which the most distinguished are, see Table 1.

Another intriguing correlation exist between the spectral class of a star where maximum anomalies for given element are observed, and the ionization potential of the corresponding atom (Ledoux and Renson, 1966), see Table 2.

The model, explaining these anomalies by motion of paramagnetic atoms in non-uniform magnetic fields, was proposed by Babcock (1963) and Jensen (1962). The "optical pumping" was used for increasing the relative population of atoms with a given orientation of their spins. The "equilibrium" abundance gradient established in the non-uniform magnetic field, which balances the diffusion under the action of a field gradient, is determined by formula

$$\frac{\nabla n}{n} \approx \frac{\mu_B \nabla B}{kT}, \tag{1}$$

where μ_B is the atomic magnetic momentum. It was noted by Babcock (1963) and Ledoux and Renson (1966), that for large observed $\nabla n/n$ very large field gradients $\nabla B > 10^{-3}$ Gs/cm are needed, which at least 100 times exceed observed field gradients in solar spots.

Table 1: Properties of elements showing strong chemical anomalies

Element	Eu	Cr	Mn
Atomic shell structure	$4f^7 6s^2$	$3d^5 4s$	$3d^5 4s^2$
Atomic state	$^8S_{7/2}$	$^7S_3$	$^6S_{5/2}$

Table 2: Elements showing strongest chemical anomalies versus spectral class of a star

Element	Eu	Sr	Cr	Mn
Spectral class corresponding to maximum overabundance	A8 - A3	A8 - A5	A2	B8
T_{eff} (K)	7580 - 8720	7580 - 8200	8790	11900
I_{ion} (eV)	5.67	5.695	6.766	7.44

2. The model

The modification of the Babcock-Jensen model suggested by Bisnovatyi-Kogan and Höflich (1990) is based on the fact, that atoms moving in the magnetic field towards magnetic poles enter a region with greater densities and temperatures, where they are inevitably ionized. It means that concentration gradient of neutral atoms preventing farther diffusion will, not be installed and the real gradient of element concentration (including atoms and ions) may be much greater than follows from (1). Due to ionization there is a continuous flux of paramagnetic atoms to the regions of the magnetic poles, see Fig.1.

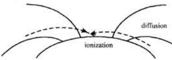

Figure 1: Schematic picture of the magnetic diffusion into polar region.

2.1. Neutral atoms in Ap stars.

Let us investigate Eu anomalies, and find first the concentration of Eu atoms in the surface layers of Ap stars with the effective temperature $T_{eff} = 7600$ K, characteristic for (A7-A8) type stars. In LTE equilibrium the concentration is determined by Saha formula for ground states (Mihalas, 1978)

$$\frac{n_a}{n_i} \approx 2.07 \cdot 10^{-16} n_e \frac{g_a}{g_i} e^{I_{\mathrm{Eu}}/kT} T^{-3/2} = 2 \cdot 10^{-17} n_e \quad (2)$$

for $I_{\mathrm{Eu}} = 5.67$ eV, g_a=8, g_i=9, and $T = 6000$, which can be regarded as a representative value above the photosphere of A8 - A3 stars (Kurutz, 1979). Taking corresponding $n_e = 5 \cdot 10^9 - 5 \cdot 10^{13}$, we obtain $\frac{n_a}{n_i} = 10^{-7}\ 10^{-4}$. This value is too small to produce the observed anomalies due to diffusion of atoms. But the condition of LTE is violated in the regions above the photosphere, so the degree of ionization may be less in reality.

2.2. Non LTE treatment of upper layers.

Non-LTE model of the atmosphere of the star with $T_{eff} = 7600$ K, $\log g = 4$ was constructed by Bisnovatyi-Kogan and Höflich (1990), using a method of Höflich and Wehrse (1987). The properties of the star were close to those of the star βCrB, which element abundances (Ledoux and Renson, 1966) have used in calculations (see Table 3). Other abundances were presumed to be solar. The non-LTE atmosphere was constructed for optical depths $\log\tau$ between -15 and 1.2. Up to 20 lower levels were allowed to deviate from LTE for H, He, C, N, O, Na, Mg, K, Ca and Eu. All radiative and collisional bound-bound and bound-free transitions were included in the statistical equations. Having in mind a suppression of the convection by the strong magnetic field, only radiative energy transport was taken into account in the atmosphere. Farther details of physical conditions used in calculations are given by Bisnovatyi-Kogan and Höflich (1990).

2.3. Structure of non-LTE atmosphere.

The density and temperature profiles in non-LTE atmosphere shown in Fig.2 from Bisnovatyi-Kogan and Höflich (1990) resembles closely at the photosphere to the corresponding LTE model of Kurutz (1979) in all layers except the very inner regions, because in normal atmospheres convection results in slightly less steep temperature gradient. The minimum temperature is somewhat lower because of the stronger cooling due to metal lines. In the very outer regions the relative abundance of EuI is higher by more than an order of magnitude than the LTE value due to reduction of the radiation field. The fraction $\chi_{\rm EuI}$ of the neutral EuI is of the order of 10^{-4} - 10^{-3} over a large fraction of the atmosphere (see Fig.3 from Bisnovatyi-Kogan and Höflich, 1990), and is sufficient to explain our effect. The concentration of EuI may increase due to increase of a local electron density n_e which in the layers $\log \tau_{5000} = -8 - 10$ is determined mainly by ionization of abundant elements with low ionization potential like Na (I=5.138 eV, $X_{\rho,{\rm Na},\odot} = 4.4 \cdot 10^{-5}$), K (I=4.339 eV, $X_{\rho,{\rm K},\odot} = 4.4 \cdot 10^{-6}$), for solar abundances.

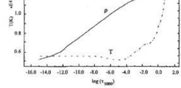

Figure 2: Temperature and density profile as a function of τ(5000 Angström) for an atmosphere with $T_{\rm eff}$=7600 K, and $\log g = 4$. Element abundances are taken which can be regarded as typical for Ap stars (see text).

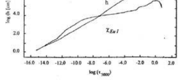

Figure 3: $\chi_{\rm EuI}$ and atmosphere height h as a function of τ(5000 Angström).

EuI lines have not been observed in the spectra of Ap stars, probably, because they are strongly blended by other lines. Lines of atomic CaI with I=6.11 eV, close to EuI with I=5.67 eV, have been observed in the spectrum of A2.6 star TX Leo (Leushin and Topil'skaya, 1988).

3. Diffusion flux of Eu atoms into the polar regions.

Consider diffusion of Eu atoms under the action of the magnetic field gradient, taking into account collisions with the H atoms. Collisional cross-section and the cross-section of a spin overturn during collision are written as

$$\sigma_{coll} \approx 10^{-16}{\rm cm}^2, \tag{3}$$

$$\sigma_{\uparrow\downarrow} \simeq 10^{-3}\alpha^2\sigma_{coll} \simeq 10^{-23}{\rm cm}^2$$

Eu atoms in S state with a spin projection $\sigma = \frac{7}{2}$ is drifting in the direction of increasing of the magnetic field to the magnetic poles. The diffusive flux of Eu atoms is equal to (Lifshits and Pitaevski, 1979)

$$\vec{l}_{\rm EuI} = D\left(\frac{n_{\rm EuI}\vec{F}}{kT} - \nabla n_{\rm EuI}\right)\ {\rm cm}^{-2}{\rm s}^{-1}. \tag{4}$$

Here $n_{\rm EuI}$is the concentration of Eu atoms, $F = \frac{7}{2}\hbar\nabla\omega_B$ is the force acting on the paramagnetic Eu atom in a non-uniform magnetic field, $\omega_B = \frac{|e|B}{m_e c}$ is a cyclotron frequency, $D \approx \frac{v_H}{n\sigma_{coll}}$ is a diffusion coefficient for Eu atoms, $n = n_{\rm H} + n_{\rm He}$, $v_{\rm H}$ is the thermal velocity of hydrogen. Without ionization the concentration gradient balances the magnetic forse and in equilibrium, when brackets in (4) are equal to zero we have the Babcock -Jensen result (1). If Eu atoms are ionized during the move along the magnetic field lines, when they enter the hot regions near the magnetic poles, the term $\nabla n_{\rm EuI}$ does not prevent continuous diffusion. The total flux of Eu atoms in this case is equal to

$$\vec{L}_{\rm EuI} = 2\pi R_s \bar{n}_{\rm EuI}\frac{7}{2}\hbar\frac{\nabla\omega_B}{kT}\frac{v_H}{n\sigma_{coll}}({\rm s}^{-1}), \tag{5}$$

where $\bar{n}_{\rm EuI}$ (cm^{-2}) is the surface density of the Eu atoms of the star reverse layer, R_s is a radius of the star.

Let θ be the angle size of the polar spot (or of the surface of a spherical layer) with anomalous composition. The surface area of the spot is

$$S \simeq 2\pi R_s^2(1-\cos\theta) \approx \pi R_s^2\theta^2. \tag{6}$$

The total mass of the spot over the reverse layer, corresponding to the mass over the layer where EuII lines are formed, is equal to

$$m_t = \bar{\rho}S \approx \bar{\rho}\pi R_s^2\theta^2. \tag{7}$$

Table 3: Elements abundances in the star βCrB, according to Ledoux and Renson (1966).

Element	Mg	Si	Ca	Sc	Ti	V	Cr	Mn
Abundance of elements relative to solar $\frac{[X]}{[X_\odot]}$	1.6	3.4	1.4	2.5	7.7	2.5	30	40
Element	Fe	Co	Ni	Sr	Zr	Ba	La	
Abundance of elements relative to solar $\frac{[X]}{[X_\odot]}$	7	10.5	1.8	40	90	4.5	620	
Element	Ce	Pr	Nd	Sm	Eu	Gd	Dy	
Abundance of elements relative to solar $\frac{[X]}{[X_\odot]}$	880	535	150	192	1440	890	3800	

Let us suppose for simplicity that outside the spot the composition is normal $X^{(0)}_{\rho,\mathrm{Eu}} \approx 7.9 \cdot 10^{-10}$ by mass, and $X^{(0)}_{n,\mathrm{Eu}} \approx 4.4 \cdot 10^{-12}$ by number of atoms, $A_{\mathrm{Eu}} = 152$. The concentration of Eu in the spot increases in time due to diffusion and according to (5-7), is equal to

$$\begin{aligned} X_{\rho,\mathrm{Eu}} &\approx X^{(0)}_{\rho,\mathrm{Eu}} + \frac{m_{\mathrm{Eu}} L_{\mathrm{Eu}}}{m_t} \\ &\simeq X^{(0)}_{\rho,\mathrm{Eu}} \left[1 + 7 \frac{\hbar}{kT} \frac{|e|B}{m_e c} \frac{v_H \chi \mathrm{EuI}}{n \sigma_{coll} R_s^2 \theta^2} \left(\frac{R_s \nabla B}{B}\right) t\right] \\ &\approx X^{(0)}_{\rho,\mathrm{Eu}} \left[1 + 3 \cdot 10^{-14} \frac{B \chi \mathrm{EuI}}{T^{1/2}} \left(\frac{\nabla_{300}}{n_{13} \theta_{0.1}^2}\right) t\right], \end{aligned} \qquad (8)$$

where $n_{13} = n/10^{13}$ cm^{-3}, $\theta_{0.1} = \theta/0.1$ rad, $\nabla_{300} = R_s \nabla B / 300\, B$. $\nabla_{300} = 1$ at $B = 10^4$ corresponds to the magnetic field gradient in solar spot (Babcock, 1963). When $B = 10^4$ Gs, $T = 5000$ K, $\chi\mathrm{EuI} = 0.001$, and $t = 3 \cdot 10^{16}$ s $\simeq 10^9$ years we have from (8) in the spot

$$\frac{X_{\rho,\mathrm{Eu}}}{X^{(0)}_{\rho,\mathrm{Eu}}} \simeq 130 \qquad \text{for} \qquad n_{13} = \nabla_{300} = \theta_{0.1} = 1. \qquad (9)$$

Note that the main contribution to the diffusion flux comes from layers with $n < 10^9$ cm^{-3}. Smaller spots, larger field gradients may give even larger Eu concentrations. The value from (9) is about 10^3 times larger than Babcock (1963) estimated for the same ∇B.

If an atom of Eu changes its spin direction during its motion to the poles, it does not reach the magnetic poles, and starts to move in opposite direction. But this motion does not lead to hot region, atoms are not ionized, and the equilibrium concentration gradient is formed which prevents the motion from the poles (see Fig.1). At $n < 3 \cdot 10^8$ cm^{-3} the spin does not change its direction due to small overturn cross-section (3), and EuI flux goes directly to the poles.

4. He atoms in a very high magnetic fields: second order phase transition.

The magnetic field has a large influence on the atomic structure when the energy level of the electron in the magnetic field E_B exceeds the binding energy E_b of the electron in the atom. For hydrogen we have (Landau and Lifshits, 1963)

$$E_b = \frac{m_e e^2}{2\hbar^2}, \quad E_B = \hbar \frac{|e|B}{2 m_e c}, \qquad (10)$$

and these energies are equal at characteristic magnetic field

$$B_* = \frac{m_e^2 |e|^3 c}{\hbar^3} = 2.35 \cdot 10^9 \ \mathrm{Gs}. \qquad (11)$$

When the atomic $J \neq 0$ the atom is paramagnetic with a positive susceptibility, like H or Eu. The ground energy level of this atom deepens and its binding energy increases with increase of B. The ground state of He atom has $J = S = L = 0$, and in it is diamagnetic with a negative susceptibility. The ground energy level of this atom goes up with B, making it less bound. The first excited state of *He* with excitation energy $E_{\mathrm{ex}} = 19.82$ eV, $S = J = 1$ and with atomic structure $^2S_1$, has paramagnetic properties. With increasing of B the binding energy of the diamagnetic ground level decrease, and the binding energy of the first excited state (paramagnetic) increases. As was obtained by Gadiyak et al. (1982) the binding energies of the ground and the first excited state become equal at $B_c = 0.7 B_* = 1.7 \cdot 10^9$ Gs (see Fig.4). At $B > B_c$ the ground state of the atom is already paramagnetic with nonzero spin. It was noted by Bisnovatyi-Kogan and Höflich (1990), that the phase transition of the second order happens at $B = B_c$, when the neutral helium change its property from diamagnetic to paramagnetic ground state.

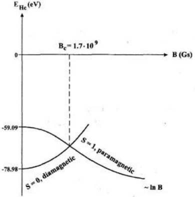

Figure 4: Semi-quantitative behaviour of energy of the He atomic levels (ground and first excited states) in a magnetic field. The point $B = B_c$ corresponds to the second order phase transition.

The motion of He atoms in the non-uniform magnetic field may create an inverse population of He atomic states, leading to laser-like radiation. It may happen during accretion of He atoms onto a neutron star, having $B >> B_c$, or in the more exotic situation with an ejection of atomic He from the neutron star surface. Matter velocities at accretion and ejection are very large (sub-relativistic), so the He atoms become excited in both cases, giving finally the strongly collimated pulse of ultraviolet radiation.

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