POSSIBLE NONEQULIBRIUM STRUCTURES ON MAGNETIC STARS

A. Z. Dolginov
Ioffe Physical- Technical Institute
194021, Politekhnicheskaya, 26, Leningrad
USSR

ABSTRACT. The origin of the chemical abundance patches on Ap stars is considered. The possible connection of the patches with long lived hydrodynamical structures, such as zonal streams and solitary vortexes, is pointed out. The mechanism of the chemical separation due to the nonequilibrium atomic levels population in the hydrodynamical structures is discussed.

1. INTRODUCTION

The most amazing feature of Ap stars is that the observed anomalies of the chemical composition are distributed over the surface not homogeneously, but in the form of large abundance patches. It seems, at first sight, that any local inhomogeneity must rapidly sink or go upward and smear out in the surrounding matter. Even a small-scale turbulence and, to a great extent, a large-scale flow enhance this tendency. The Ap are very quiet stars. They, apparently, have no chromospheres, coronas, stellar winds, flares or eruptions. The space probe observations of Ap stars gave no evidences on X - ray, UV br visual spectral range emissions, typical for these phenomena. A few exceptions are, apparently, related to binary systems, where the emissions are due to the Ap star partner. However, some spectral characteristics of the Ap stars may be explained by the assumption that there exist small scale. ($\sim$ 10 km) turbulent actions with the characteristic velocity $\sim$ 1 km/ s on their surface (Ebbets, 1980). Such a turbulence is able to mix the matter on the surface, so that the observed long lifetime of the abundance patches seems to be very surprising, unless the patches are dynamically stabilized because of some nonlinear effects or are maintained by some an external source. The number of magnetic Ap stars among normal stars of A type is of the order of 10 - 15%. More than a few ten-years-long observations of Ap stars show no noticeable change of the surface abundance distribution. This means that the lifetime of the abundance patches exceeds 10 - 10 years and may be much longer.

Theoretical investigations show that longlived local chemical inhomogeneities in a thermodynamically open systems are possible (Haken, 1978). Mestel (196S), Mestel and Moss (1986) have considered the notion, temperature and molecular weight distribution into rotating stars. Hydrostatic equilibrium in this case requires that any horizontal variations of molecular weight μ must have associated with corresponding variations in temperature. The plasma motion, induced by the μ - nonuniformity and by the rotation of the star (meridional circulation) leads to the horizontal variation of the radiative flux divergence, so yelding a molecular weight current. The current tends to choke the actions and stabilizes the μ - nonuniformity (Mestel, 1963, Mestel and Moss, 1986). This important result demonstrates the principal possibility of the equilibrium nonuniform μ - distribution.

2. BRIEF CRITICAL REVIEW OF THE CURRENT THEORIES

The origin of Ap star chemical anomalies has been intensively discussed in the literature (Khokhlova, 1983). The most popular is the hypothesis that chemical elements are separated by the diffusion process driven by the gravity and radiations (Vauclair and Vauclair, 1982). According to the hypothesis chemical abundance patches are created owing to the different diffusion rate along and across the magnetic field. The diffusion across the field is by a factor $(1 + \omega_B^2 t_c^2)$ slower than along the field ($\omega_B = e B/mc$ being the gyrofrequency and $1/t_c$ - the collision frequency of the ions). It may lead to the increase of the number dencity of heavy ions in regions occupied by magnetic traps.
However,such explanation meets some difficulties:

a). The condition $(\omega_B t_c)^2 > 1$ holds for most of ion species only in the region where the optical depth τ is less than 10^{-2} if the field B exceeds 10^5 Gs. Observations give no unambiguous evidences on the depth of regions occupied by the chemical anomalies. However, the data about spectral lines, belonging to various elements and located in both sides relative to Balmer peaks, suggest that the anomalies are extended to the optical depth more than 10^{-2} (Khokhlova, 1983);

b). The observed surface dipole field has a magnitude 10^3 - 10^4 Gs and does not form magnetic traps corresponding to the observed large-scale chemical spots which have a very complicated configuration;

c). Magnetic traps are always imperfect. The chemical separation process in the field is assumed to be due to the diffusion which needs a long time 10^6 - 10^8 years (Vauclair and Vauclair, 1982).

However, ions are able to escape from the trap together with the surrounding hydrogen plasma because of various plasma instabilities which take much shorter time. Observations of the ions diffusion across the field and the theory of this process (Krommes et al., 1983) show that the diffusion coefficient $D_\perp \approx D_{tur} b_1^2 B_0^{-2}$, where B_0 is the basic large scale field and b_1 is the fluctuating part of the field. The fluctuating part is usually in the laboratory conditions not less than 10^{-2} from the basic field. Conditions on Ap star surface are hardly more quiet than in the laboratory.

There are also other unjustified assumptions. The dependence of the opacity on the chemical composition is often ignored, when hydro-dynamical processes are investigated, though in regions with chemical anomalies, " blanketing ", due to the absorption of radiation by heavy elements (Mihalas, 1978), can essentially change the heat transport and the hydrodynamical motions. Thus, the common treatment of heavy atoms and ions as test particles may lead to errors.

Some attempts have been made to explain the observed anomalies by the assumption that they are created due to the accretion of matter from the circumstellar medium (Havenes, 1975). This matter, accreting on the hot stars, is exposed to ionizing radiation and falls on the different surface areas owing to the separation by the stellar magnetic field in dependence on the mass and the charge. However, there are some elements, and first of all helium, whose anomalies are very difficult to explain by accretion without any additional assumption about the presence of some diffusion inward or outward the surface.

Let us consider some alternative possibilities.

3. POSSIBLE L0NGLIVED HYDRODYNAMICAL STRUCTURES ON Ap STARS

Besides the chemical spots on Ap stars we know solar spots (and their analogs on the convective stars) and spots in the planetary atmospheres (the great Jovanian red spot, for example). Solar spots are created because the local magnetic field suppresses the convective motion. There are various ordered structures in planetary atmospheres:

1). The great red spot and other spots on the Jupiter are, apparently, the solitary vortexes created by Rosby waves (Nezlin, 1986);

2). Terrestrial typhoones are solitary vortexes, formed by gyrotropic turbulence (Moiseev et al., 1983);

3). The quasistationary zonal streams in the planet atmospheres are large-scale structures, generated by the small- scale turbulence (Hasagawa, 1985) etc..

Such structures have not been yet observed on stars, because the star surface is not resolved by telescopes. However, the largest structures could be investigated by the analysis of spectral line contour variations during the star rotation period.

What conditions tingle out the chemical spot regions on Ap stars? Could the spots be related to solitonlike objects?

Regions in between opposite directed zonal streams are most suitable for the solitary vortex creation. The great Jovanian red spot vortex is stabilized by compensation of the wave dispersion by nonlinear effects. However, this stabilization does not prevent the destroying because of viscous losses. Meanwhile, the lifetime of the spot is very long. It is because the viscous losses are compensated by the energy of surrounding zonal streams. The experimental simulation (Nezlin, 1986, Read, 1986) approves this explanation. The typhoonlike vortexes are feeded by the ascending streams in the gyrotropic turbulent medium (Moiseev et al., 1983) these vortexes are characterized by intensive horizontal circulation accompanied with the comparatively weak vertical one.

The zonal stream creation needs the rotation and turbulence, but not necessarily very intensive. Such conditions may be realized in various stellar objects - from stars with developed convection to stars, which possess only small-scale turbulence in upper layers.

Can the vortex, zonal stream or some other similar structure provide the chemical separation? The observed colour and opacity of the Jupiter vortexes show that their chemical compositions are slightly different from those of the surrounding medium. Experimental simulations and the theory (Nezlin, 1986) show that the mixing of the matter inside the vortex with the matter outside is very slow. However, there is a noticeable redistribution of the matter inside the vortex. This redistribution is similar (but not identical) to the process of the tea grain concentration in the centre of the vortex which can be created in a teaglass by a spoon. However, the mechanical separation of the multicomponent matter, because of the difference in the molecular weight of the components, is not so effective in the vortex as it is necessary to explain the chemical anomalies on Ap stars. Thus, one must look about for some other mechanism which can act in the regions singled out by such structure as vortexes, zonal streams etc..

4. CHEMICAL SEPARATION IN A SYSTEM WITH A NONEQUILIBRIUM ATONIC LEVEL POPULATION

Very effective mechanism of the chemical elements separation by the directed flux of radiation has been investigated both theoretically and experimentally by Gel'mukhanov and Shalagin (1979, 1980). This process has nothing to do with the well known separation by the pressure of radiation. The essence of this process is as follows. It is well known that the thermal scattering of atom velocities leads to the Doppler broadening of spectral lines. If the atoms are irradiated by some outer source in a narrow spectral band inside the Doppler line wing (by laser beam, for example), then some of them, which travel in some definite direction, relative to the incident beam of radiation, and have an appropriate velocity value, fall in resonance with the radiation frequency, become excited and change their scattering abbility, whereas atoms, which travel in opposite direction, remain in the ground state and hold their equlibrium distribution. The drift velocity of the excited atoms differs from that in the ground state. If some source provides a stationary excess of such excited atoms, then there appears a stationary flow of the considered atoms in a definite direction. The requirements of continuity for the medium density provide the opposite directed flow of other elements, presented in the medium, which distribution remains equilibrium. Thus, the chemical separation occurs. The selective excitation of atoms, with definite velocity directions and change of the cross section, because of excitation, are the main points of the considered mechanism. The rate of the chemical separation according to the laboratory experiments and theoretical consideration may be by many orders of magnitude larger than that due to the radiation pressure (Gel'mukhanov and Shalagin, 1979, 1980).

The separation occurs along the direction of incident radiation. However, the excited atoms may travel predominantly either along or opposite this direction, depending on the decreasing or increasing of the scattering cross section for the excited state.

Is this process possible on stars? The main problem - what is the source of the inverse population of atomic levels. Of course, the total intensity of the stellar continuous spectra, even in optically thin layers, is larger than that of spectral lines, except some narrow peaks (or gaps).

Very complicated spectra of stellar atmospheres often show blending and overlapping of spectral lines, belonging to different chemical elements. It may happen that a narrow line of some element falls into spectral interval inside doppler contour of some other.

Let us consider, for example, a stream of the matter moving relative to the rest medium which emits complex spectra and irradiates the stream. The resonance levels of atoms in the stream are shifted and broadened because of the doppler effect. In this case the probability of excitation is selective with respect to the atom individual velocity direction. The excitation changes the atom scattering ability which leads in turn to the change of the drift velocities. It provides the local change of the excited atom number density and thus the chemical separation. The suggested mechanism needs special conditions. It may be, for example, the longlived hydrodynamical structure, such as zonal streams, and the appropriate distribution of the spectral intensity of radiation. We will not present here quantitative estimations (referring to the similarity with the laboratory experiment (Nezlin, 1986)) for lack of data about the real conditions on stars. However, if the conditions are favourable, then the separation rate may be of orders of magnitude larger than that due to the radiative force. Thus, many questions remain unanswered but a new statement of the problem seems valuable.

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