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MAGNETIC STARS

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CONTENTS

1. THE MAGNETIC FIELDS OF THE STARS

THE magnetic field of the nearest star, the sun, was discovered by Hale. In 1908, he succeeded in measuring the Zeeman splitting of lines in the spectra of sunspots—dark, relatively cold formations that exist for several months at a time and occupy a small fraction of the sun's surface. The magnetic fields of the spots average 1–3 kG, so that it is comparatively easy to measure them, the more so since the bright light of the sun permits the use of high-dispersion spectrographs. Fields have not been observed by this method outside of the spots.

During the 1950's[1a], Babcock developed a complex photo-electric instrument, the solar magnetograph, which permits measurement of minute line splittings and, accordingly, of weak magnetic fields. The principle of the new method consists in the following. The spectrograph forms a high-dispersion image of the spectrum of a certain area of the sun. A line with a large Lande factor is selected. Slits with radiation receivers behind them are set to the right and left wings of this line. Crossed polaroids are placed in front of the slits. The longitudinal component of the field shifts the components with right- and left-hand elliptical polarization in different directions, by an amount that is small by comparison with the Doppler line width. A quarter-wave plate converts the elliptical polarizations into linear polarizations of different directions. In the magnetograph, this plate is an ADP crystal, which acquires birefringent properties under the influence of an applied electric field.

Since the applied field alternates, a component of given polarization is shifted into the right and left wings by turns. This results in antiphase modulation of the intensity of the light passing into each slit. Appropriate calibration makes it possible to convert to the intensity of the magnetic field's longitudinal component[13c]. The magnetograph detected extended areas on the sun's surface in which the fields range into the tens and hundreds of gauss and have a complex structure. On the rest of the surface, fields of several tens of gauss are concentrated in the form of peripheral networks around granulation cells (e.g.,[2,3]), but there are practically no fields within the cells. It appears that the overall dipole field of the sun does not exceed a few gauss.

The basic difficulty encountered in measuring the magnetic fields of other stars was the small amount of available light. In 1946, therefore, Babcock used a method similar to that by which Hale had detected the sunspot fields. An analyzer set up at the slit of a spectrograph consisted of a quarter-wave plate and a felspar crystal for separation of the beams with different polarizations. This method yields the weighted-average value of the radial field component over the star's disk. The weighting factor is the brightness of the disk, which diminishes toward the limb. To obtain this effect, it is necessary that one polarity predominate on the visible hemisphere. If this condition is met, a field can be detected if it is stronger than 200–1000 G, depending on the brightness of the star and the sharpness of its lines.

Using this method, Babcock succeeded in detecting magnetic fields on certain stars, ranging in some cases to 10 kG and more. The catalogue[1b] (see also[1c]) lists data on 89 magnetic stars, and more than a hundred are presently known. The spectral characteristics of most magnetic stars place them in a special group. Their spectral classes are enclosed in a certain interval around class A (from B5 to F0), corresponding to temperatures from 18 000°K to 7500°K. However, strong fields have not been observed on all stars with such temperatures, but only on those among them that have come to be known as peculiar stars in virtue of a number of spectral peculiarities. Stars of this group are therefore called A-peculiar and designated A$_p$. The present article will discuss precisely these stars, which are of particular interest owing to their anomalies of chemical composition and other features.

Among the other magnetic stars, note should be taken of a group of stars that are cooler than Ap—from A7 to F5. Their fields range up to several hundred gauss. This group differs from normal stars of the same spectral classes in having more intense metal lines, and it is designated Am. In addition, fields up to 1 kG have been observed on several red giants and on a few more stars. Use of the solar magnetograph in combination with a 2.6-meter Shaĭn reflecting telescope (2Tsh) has made it possible to measure much weaker fields—down to a few tens of gauss—on several of the brightest stars without spectral peculiarities[3b].

After the 1968 discovery of pulsars—collapsed neutron stars—it became clear that a magnetic field that must attain values of 10^{10} G and more is a decisive factor in the mechanisms of their emission[4]. This field is the collapse-compressed magnetic field of the star. The idea of compression of the magnetic field in the process of stellar evolution drew attention to the white dwarfs, which are also cores of stars that have passed through evolution and whose compression is offset by the pressure of a degenerate electron gas. Attempts to observe Zeeman splitting of the hydrogen lines in the spectra of certain white dwarfs have led to an upper-limit estimate of $B < 10^5$ G[5b].

Spectrally, white dwarfs are classified into two groups. Stars of the first group have broad hydrogen lines, while the spectra of those of the second group are practically continuous, with a few very weak unidentified bands. Circular polarization ranging up to 1—3% has been detected on one of these white dwarfs without hydrogen lines[6]. This has been interpreted as due to the presence of a magnetic field stronger than 10^7 Oe, in which the Larmor frequency is no longer too small by comparison with the frequency of the visible region of the spectrum. The absorption coefficient of the plasma depends here on the sign of the circular polarization of the wave, and the temperature gradient in the atmosphere of the dwarf results in different intensities of the different rotation signs. Similar investigations of six other white dwarfs without hydrogen lines produced a negative result: their polarizations were less than 0.1%[7].

The magnetic field is not of the same nature in all of the objects enumerated above. In stars of the sun's type with strongly developed convection in their external regions, the principal factor is generation of the field at the expense of the energy of the convective motions, which are not spherically symmetrical, owing to the rotation of the star. The strong regular fields of pulsars and white dwarfs appeared on compression of a conductive gas, and depend on the presence and on the regular character of the field in the interior of the star before collapse. As will be argued below, the fields of Ap stars apparently formed from the interstellar magnetic field during compression of the interstellar gas into the star. The field of the Am stars is perhaps of similar origin. It must be stressed that the presence of a magnetic field is highly essential for the formation of the stars themselves. If the gas is compressed with conservation of angular momentum, the rotation will prevent compression of the cloud into the star, even if it is a binary. The field binding the central and outer parts of the compressing cloud will be twisted, the magnetic forces will transfer momentum to the outer layer, and the central region will be compressed. This explains, for example, the slow rotation of the sun, which has transferred momentum to the protoplanetary cloud.

2. GENERAL REMARKS ON THE Ap STARS

Ap stars have fields ranging from 1 to 34 kG. In a few cases, with $B > 10$ kG, the π and σ components of the Zeeman splitting are observed directly in some lines; this has made it possible to determine the magnitude of the total field vector[5a]. The field of the Ap star is comparatively homogeneous on large areas of the surface and cannot be represented as a certain average of an extended weak field and the very strong fields that are concentrated in small spots of the sunspot type, since no Zeeman splitting would then be observed in the spectra of any of the stars. But the field cannot be considered homogeneous over the entire surface either; its variations suggest that it has a certain structure and is concentrated in magnetic fields that do not occupy the entire surface.

The peculiarity of the Ap stars is manifested in the fact that a number of their lines have anomalous strengths as compared with normal stars of the same classes. The intensities vary with a period from 0.5 to 10—20 days. Several stars have periods around 100 days, and a star with a period of 22 years was recently discovered. The field also varies with the same period.

The field variations may be quite complex in nature (Fig. 1a); often, not only the magnitude, but also the sign of the field intensity varies (in the figure, the dots represent observations and the line the calculation for the inclined-rotator model[8]. The luminosity and color of the stars also vary with the same period but very small amplitude (a few percent). In addition to the regular variations, fast (with periods of 1—2 hours) irregular variations of brightness with amplitude below 1% are also observed.

Peculiarity is closely related to the strong magnetic field: all Ap stars with lines that are narrow enough for investigation of the Zeeman effect exhibit a variable magnetic field and, conversely, all stars with such fields are peculiar. The group of Ap stars composes approximately 10% of all stars in the same spectral-class interval.

One of the important characteristics of stars is their rotation. There exists a statistical dependence of the velocity of rotation on spectral class, i.e., ultimately on the mass of the star—stars of earlier spectral classes rotate more rapidly. On the average, magnetic peculiar stars rotate more slowly than normal stars of the same classes. The average value of the projection of equatorial velocity onto the line of sight $\langle v \sin i \rangle$ is 177 km/sec for normal stars and 52 km/sec for peculiars. It was at first thought that this might be an effect of selection—the field can be measured provided that the lines are not excessively broadened, i.e., when the stars are seen from the pole. However, unlike the field, the intensity anomalies may be appreciable even for rapidly rotating stars, and Ap stars therefore actually rotate more slowly than normal ones. It also appears that these stars enter into binary systems less frequently: while 40% of ordinary class A stars are binaries, the figure is less than 20% for Ap stars.

Ap stars fall into the range of the Main Sequence on the Hertzsprung-Russell diagram. Analysis of the spectra indicates that their photospheres show practically no structural differences from those of normal stars of the same class. Their masses (determined for the components of binaries) and radii and, accordingly, the acceleration of gravity at their surfaces show practically no systematic differences.

The observed periodic variations of the magnetic field are difficult to explain in terms of the real intensity variations at the surface of the star. The field is frozen into the conductive gas, the force lines move together with the matter, and it is difficult to envisage a change in the sign of the regular field. Various models of the torsional-oscillation type cannot change the sign of the field in a thin surface layer. Nor are analogies with the solar cycle valid in this case, since the convection necessary for the dynamo mechanism is weak in type A stars and involves only a thin layer at the star's surface, so that a field of a few kilogauss suppresses it completely. Moreover, the period of the variations is too small for many magnetic variable stars. The radial oscillations of Ap stars are too small in amplitude to result in variation of the field. Further, the natural period of such oscillations in stars with masses ranging from 2 to 5 sun masses amounts to a few hours, while the field variations are observed to have widely varying, much longer periods. The periodic field variations are naturally explained by the rotation of a star having a quasi-constant field of nearly dipole character, with the axis of the dipole forming an angle near 90° with the rotation axis and that axis itself forming a certain angle i with the line of sight (Fig. 1a)[8]. This model, which is known as the inclined-rotator model, is supported by the fact that the line widths, which are determined by the velocity of rotation, vary in inverse relation to the period of the field variation[9]. In some cases, it is necessary to assume the presence of several magnetic poles on the surface in order to explain a more complex field-variation curve. As will be seen below, the inclined-rotator model also offers the only acceptable explanation of the spectral variability of magnetic Ap stars.

3. ANOMALIES OF CHEMICAL COMPOSITION

The anomalous intensities of the lines in the spectra of magnetic Ap stars cannot be explained in terms of anomalies in the physical conditions in their atmospheres, i.e., by differences in the conditions for ionization and excitation of atoms, such as occur in the relatively cold sunspots. Nor can splitting of the lines by the field produce any noticeable effect. There is a real variation of chemical composition in the atmospheres of these stars, with the line-intensity variability suggesting a nonuniform distribution of the elements over the surface. This is confirmed by study of the widths of the anomalous lines and by the variation of their radial velocities: if the lines are formed on part of the star's surface, they should shift periodically and not be broadened to the same degree as lines formed over the entire surface of the star. Quantitative analysis of all these factors has shown that the anomalies are for the most part local in nature, and that these regions with anomalous chemical composition occupy a significant fraction of the star's surface. The chemical-composition difference influences the coefficient of absorption in the photosphere and, consequently, the outgoing radiation. This explains subtle features in the continuous spectra of magnetic stars, and apparently also the variations of color and brightness as the star rotates.

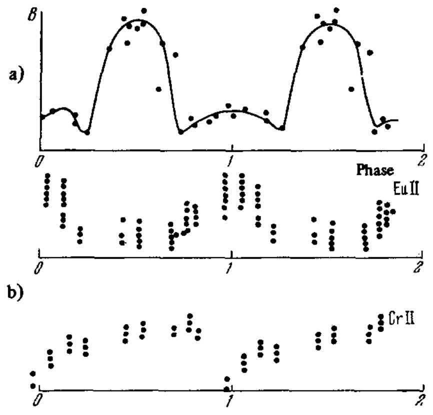

FIG. 1. Field-strength variation of the star α^2 CVn as a function of phase (a) and strength variations of the Eu II and Cr II lines of the same star (b).

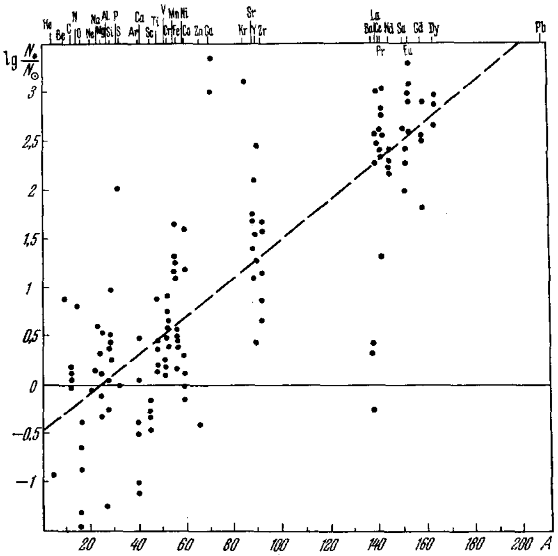

FIG. 2. Abundances of the elements (relative to the solar abundances) vs. atomic weight for Ap stars (after [4]).

The relation of spectral variability to the field variation suggests that the regions of anomalous composition generally correspond to magnetic regions. There are, however, exceptions—some lines vary in antiphase to others (Fig. 1b), i.e., the excess of these elements occurs outside of the strong-field regions. In the star α^2 CVn, for example, there is a large excess of Eu and a nearly 100-fold excess of Cr, but these elements are concentrated on different areas of the star's surface[1c].

Quantitative determinations of chemical composition are made either by the growth-curve method or by a more accurate method using a model of the atmosphere. The profiles and equivalent widths of the lines are calculated by numerical solution of the transfer equation and then compared with observations. These extremely tedious determinations have been made by various authors for approximately 30 Ap stars. As a rule, however, they have been made from single spectrograms, without account for the changes of the lines with changing phase. At the same time, the abundances determined may depend strongly on phase, as we see, for example, from the observations made for "silicon" stars[11].

Figure 2 shows the general pattern of the chemical-composition anomalies. Each point corresponds to the abundance of the particular element with respect to hydrogen in one star, expressed as a fraction of the solar abundance[12]. The wide scatter of the data reflects, for the most part, real differences between different stars. In spite of this scatter, the increase in the anomalies with increasing atomic weight is clearly evident.

It is customary in the literature to classify Ap stars by peculiarity types, i.e., in accordance with the strengthening of the lines of various elements in the spectrum of the star. The classification adopted by Sargent and Searle (see[13]) contains several groups, basic among which are the silicon, manganese, europium-chromium, and strontium stars, along with several intermediate groups; the effective temperatures of the stars diminish from 15 000°K for the first group to 7500°K for the last. However, use of such a classification does not take account of the conditions for excitation and ionization of the atoms on the basis of whose lines the classification is drawn. At the same time, the lines of ionized silicon attenuate strongly at $T_{eff} < 10\,000°$ because of the weak ionization and relatively high excitation potentials. The lines of Sr II and Eu II attenuate strongly at $T_{eff} > 10\,000°K$ owing to the secondary ionization of these elements. When use is made of quantitative determinations of chemical composition in the atmospheres of Ap stars in which the abundance is determined with consideration of excitation and ionization conditions, no systematic dependence of the excess of one or another element on the effective temperature of the star emerges.

Analysis of all available results from quantitative determination of Ap-star chemical composition brings out the following principal anomalies as compared with the composition of the solar atmosphere.

a) A scarcity of helium for most stars hotter than A0 (the lines of He I are very weak in colder stars). For some of them, for example HD 124 224, 56 Ari, and HD 193 722, in which there is an excess of Si and spectral variability, the helium content is normal on part of the surface, but 1/10 of normal on the rest of it. There is more He^3 than He^4 on one of the Ap stars, 3 Centauri A, with an over-all helium deficit.

b) A small deficit of the light elements C, O, Mg, and Si in some stars.

c) Excesses of the light elements Al, Si, P, S, and Cl in some stars, sometimes ranging up to 2—3 orders of magnitude. There is a very distinct correlation between the Mg and Si contents.

d) A 10- to 100-fold excess of elements of the iron peak (Sc, Ti, Cr, Mn, Fe, and sometimes Ni and Co) is observed in many Ap stars. There appears to be a correlation, though not a very strong one, between the contents of these elements.

e) An excess of the fifth-period elements Sr, Y, and Zr, ranging up to a factor of 1000. The contents of these elements correlate very nicely with one another, and there is also a correlation with the iron-peak elements, especially Mn.

f) An excess of the rare earths: La, Eu, Gd, Dy and sometimes other elements of this series, by factors of 300—1000 and more. It is difficult to establish correlation of these elements with others, since they are difficult to observe in stars hotter than A0. Nevertheless, there appears to be a correlation between the rare earths and elements of the iron peak (Cr, Ti, Mn).

g) An excess of Hg, Pt, U, and Au is observed in occasional stars. Reports[14] of the identification of Os and Pm have recently appeared, their most interesting aspect being that the longest-lived isotope of Pm among those that can be produced by neutron capture has a half-life of less than three years, while the period is less than 18 years for light isotopes. The isotope composition of the mercury is interesting[5C]. In three peculiar stars, neutron-rich isotopes are present in larger quantities than they are on the earth. Different stars have different excesses of these isotopes, ranging from low to extreme for the star HR 4072, where Hg^{204} composes 97% of the mercury, while the most abundant isotope on earth, Hg^{202}, represents only 3% of it.

h) Most of the stars have a Ca deficit, but it correlates neither with the light-element (Mg + Si) contents nor with the elements of the iron peak.

j) An Li II line has been observed in a number of cold Ap stars, indicating an elevated lithium content in these stars.

A number of different hypotheses have now been advanced to account for the origin of the above peculiarities of magnetic Ap stars. In principle, the observed chemical-composition anomalies can arise either as an actual change in the chemical composition of the matter as a result of nuclear reactions or as a result of some mechanism that separates elements in matter having normal chemical composition. Since the observations available to date indicate a definite connection between a strong regular magnetic field of the star and a peculiarity in the form of strong chemical-composition anomalies, the theory of magnetic Ap stars must establish the nature of this connection: is the magnetic field the cause of the anomaly, or do the field and the anomaly appear together as a result of the action of some mechanism? Below we shall examine in detail the existing hypotheses, with consideration of the arguments for and against each of them.

4. POSSIBILITY OF CREATION OF THE ANOMALIES BY NUCLEAR REACTIONS

The change in chemical composition may be associated with nuclear reactions taking place in the star (in its interior or on its surface) or with nuclear reactions in the vicinity of the star, e.g., on a component of a binary system that evolved more rapidly with subsequent transfer of matter of anomalous chemical composition into the atmosphere of the Ap star. It is quite well known that only He is synthesized in Main Sequence stars, and that the other light elements are synthesized by α capture and burning of C and O at a later stage in the evolution of red giants. Heavier elements are formed by slow neutron capture (the s process), while the very heaviest ones can be formed only by rapid capture of neutrons (the r process), conditions for which are created, for example, in supernova explosions[15].

It might be supposed that the Ap stars were at one time red giants or, more precisely, supergiants. Such stars have an extensive external convective zone, and under certain conditions, when equilibrium is maintained by degenerate-gas pressure but the synthesis of C from

He has begun in the core, an internal zone as well. If the zones become so extensive that their boundaries meet, total mixing of the star can occur; its composition again becomes homogeneous, though different from the initial composition: it contains little hydrogen and relatively large amounts of helium and certain other elements.

Now the star does not differ very greatly from normal Main Sequence stars—the helium tends to make it brighter and the heavy elements tend to make it fainter, and these effects cancel one another to a substantial degree. In the red-giant stage, the star may lose part of its mass, so that it may be found among the less massive stars after its return to the Main Sequence. This would explain why there are sometimes more massive normal Main Sequence stars in clusters in which an Ap star occurs[16]. The total-mixing process does indeed occur in some cases. It would appear to explain the presence of giants with anomalous composition, which are classified as S stars (excesses of Zr, Tc and other elements formed by the s process) and C stars with an excess of C and sometimes of N and certain elements of the s process. The isotopic composition of the carbon differs substantially from the terrestrial; the C^{13} content is slightly smaller than that of C^{12} (see[17]).

The hypothesis according to which the elements are synthesized in the red giant with subsequent mixing cannot, in this form, explain the excess of the heavier elements—those of the "iron peak" and the rare earths. The "iron-peak" elements and especially the heavier elements are formed on rapid capture of neutrons, in which there is not enough time for β decay. Attempts have been made to obtain this process in a static star[18] as a result of a so-called flareup, in which the reaction begins in the star's carbon or hydrogen core, which is confined by degenerate-gas pressure. In this case, the temperature rise does not initially cause expansion of the core, so that the temperature rises sharply and fusion reactions take place with emission of neutrons at a rate that may approach that necessary for the r process. However, it would then appear that the explosion of the star as a supernova is inevitable[19], after which the star cannot belong to the Main Sequence. The number of neutrons would also appear to be insufficient for the r process. Cameron[16] recently suggested that a new intermediate type of nuclear fusion, in which the characteristic time between two neutron captures by a heavy nucleus is of the order of 1 hour, may occur in massive stars in the red-supergiant stage. There would then be time for β decay only of short-lived isotopes. This would create a strong excess of such elements as Hg, Au, Pt, and others, with predominance of the heavy isotopes, as well as an excess of rare earths.

Among the magnetic Ap stars, the manganese stars, with their weaker fields and weaker variability, submit most readily to this mechanism, since the anomalies in the contents of mercury and its isotopes are encountered in precisely these stars.

The hypothesis of the preceding supergiant stage cannot explain such peculiarities in the chemical composition of Ap stars as the shortage of helium and the excess of lithium. The matter should be enriched in helium and lithium should be burned out in the convective phase. In addition, the local nature of the anomalies on the surface of the star and their relation to the magnetic field would not be preserved after total mixing.

Rapid capture of neutrons and the formation of heavy elements occur basically in the supernova explosion. Some of the gravitational energy released here is transferred to the outer layers of the core by the neutrino flux[20] and electromagnetic forces[21]. A powerful shock wave is formed and heats the outer layers of the core to $(2-3) \times 10^9$ °K at densities up to 10^5 g/cm^3[22]. This is accompanied by numerous reactions, whose products form, in turn, complex branched chains of other reactions until temperature and density have been lowered, after which there is only decay of unstable particles and the composition of the gas is "frozen"[23,24]. Only in recent years has it been possible to design computer programs that take account of the entire mesh of thousands of reactions with their probabilities and yield the final composition for given initial conditions and a given cooling rate. One of the characteristic features of the resulting solutions is a quasiequilibrium nature of the reactions at a certain stage, at which the composition of the core is determined not by the reaction cross sections, such as the neutron-capture cross section, but by binding energy. This would explain, among other things, the abundance of the "iron-peak" elements. In a later stage, the reactions are nonequilibrium, so that composition is determined by the cross sections for most atoms. The light elements formed previously by α and s processes survive in part, while the heavier ones are formed in the explosion in quantities that correspond approximately to those observed if appropriate initial conditions are chosen.

Since the Ap star cannot itself be a supernova, the hypothesis that the elements entered it as a result of explosion of a more massive companion has been discussed. Here the role of the magnetic field reduces to two effects. On the one hand, the field influences the motion of the ions, screening the zone of the magnetic equator and directing the flux toward the poles. Admittedly, if the envelope has enough energy, occasional bunches of gas may, undergoing compression and overcoming the diamagnetic repulsion, penetrate to the surface. On the other hand, a strong field stops convection and the general circulation, which mix the matter, thereby tending to retain the anomalies at the surface. Thus, even if the elements fell initially over the entire surface, they are retained only in strong-field regions, regardless of the direction of the field-intensity vector. If the heavy elements of Ap stars were formed as a result of a supernova explosion, the relative quantities of the elements within this group should be the same as on the sun, since supernovas are the basic Galactic source of the r-process elements. At the same time, the relative contents of the heavy elements in some Ap stars, and on the average for these stars, differ substantially from normal. This is a weighty argument against the hypothesis of supernova flareups as the cause of the chemical-composition anomalies of Ap stars.

Another variant of the hypothesis according to which the anomalies are externally caused[18] assumes that the more massive companion became a supergiant and that elements of the α- and s-processes and, if a static r process is possible, also heavier atoms were synthesized in it. In a sufficiently close pair, the radius of this supergiant may exceed the so-called Roche limit, i.e., the radius of the Roche surface, where the tidal force from the second star and the centrifugal force from rotation of the system become stronger than the attraction to the first star. Gas then begins to flow over to the second star. Matter rises from deeper layers to take the place of the departed gas. In addition, the Roche surface itself moves closer to the star whose mass has been diminished. As a result, the star can lose the greater part of its mass, becoming a dense white dwarf that consists of heavy elements and is difficult to observe owing to its low luminosity. The second star, on the other hand, increases its mass to acquire anomalous composition in its outer layers.

From the standpoint of the statistics of supernova flareups and the statistics of binary systems, no objections can be raised to hypotheses according to which the anomalies are externally caused. However, they do encounter a number of other difficulties.

The observed He deficit is a major difficulty. It is difficult to explain by burnout in nuclear reactions, since the H should be burned out earlier. In principle, this deficit could be obtained on a sharp, transitory temperature and density rise in a zone with normal composition, e.g., when a large-amplitude shock wave propagates in the layers surrounding the core. Since the rate of the hydrogen reactions is limited by β-decay and that of helium reactions is unlimited, the relative shortage of He might result from sufficiently strong transitory heating of a high-density gas. However, concrete calculations[23] indicate that H burns out more rapidly. Equilibrium processes occur in the explosion of a dense neutron core with subsequent freezing of composition, and the resulting composition depends strongly on the initial conditions and the rate of the explosion. However, calculations made to date for different variants do not support the conclusion that the relative He deficit could have formed in this manner. A general objection to the burnout of He is that its mass deficit should be offset by an excess of heavier elements. It appears that such compensation is observed only in silicon stars in virtue of the Si excess. In other Ap stars, the large relative excess of heavy elements is still insufficient to give a mass comparable to the missing mass of the second most abundant element, helium.

A helium deficit could have been created without burnout by electromagnetic focusing. Because of its high ionization potential, He can be neutral under a broad range of physical conditions under which other elements are ionized. The motion of the ions depends on the magnetic field, and He atoms can cross lines of force. In the case of a supernova explosion, the density and kinetic energy of the envelope are too large to permit separation of the elements, but it can be assumed in the case of quiet crossover that the ions flow along force lines to the magnetic poles, where they are focused, and that the He atoms move along straight paths and reach the star in insignificant amounts[12]. However, this hypothesis requires very special conditions and is rather improbable.

Another major difficulty encountered by hypotheses that assume an influx of elements to the magnetic star from the outside results from the fact that the star must have had a strong magnetic field, but normal composition prior to the explosion of its neighbor or prior to crossover of the matter. However, no such stars are observed: all magnetic stars are anomalous. It would therefore be necessary to assume that the field arrives at the star together with the matter. A field exists in the atmospheres of giants, and it could flow over together with the gas to form the field of the magnetic star[18]. However, crossflow occurs in many binary systems, and in most cases before the star has evolved to the stage of formation of elements in the s process. In addition, elements heavier than Mg, Ne, O or even He are not synthesized at all in ordinary giants of moderate mass. And the magnetic fields of the giants hardly depend so strongly on their mass and especially on the distance to the second star, so that even in this case there should be many magnetic stars without anomalies.

If heavy elements are formed in supernova explosions, the correspondence between the strong field and the anomalous composition requires that the field also be formed in the explosion. We can consider this possibility here. The explosion is preceded by compression of the core, which is set in rapid rotation. If, prior to the explosion, there was a field linking the core and the shell, it is now twisted, and the sharp increase in magnetic pressure may be the cause of ejection of the shell[21]. The shell may draw the field along with it and transfer it to the second star together with gas of anomalous composition. However, creation of a stable, near-dipole field requires that the shell penetrate to a depth greater than 0.3R into the stable zone of the star. It is easily estimated that the energy of the shell is not sufficient for this, since density rises rapidly toward the interior. In addition, entropy diminishes with depth in the stable zone, and a massive bunch of the shell would have to sink adiabatically. After a certain time, therefore, it would have to float to the surface.

One more possible external origin of the anomalies, involving accretion of interstellar gas on the magnetic star, can be considered[25]. Since convection is weak in type A stars, they evidently do not have coronas and the winds associated with them. Thus accretion is possible in principle. However, since the composition of the interstellar medium resembles closely that of the sun, it is difficult to create anomalies. In addition, the density of the medium is low and the number of incident atoms is small compared to the number of atoms in the photosphere. Hence the authors of this hypothesis assume that magnetic stars form magnetospheres that extend out 2 to 15 times farther than the distance of the earth from the sun (this distance is determined from the condition that the dipole field diminish to the intensity of the interstellar field). Capture of interstellar atoms and ions occurs when these particles are ionized in their passage through the outer parts of the magnetosphere by the radiation of the star and can no longer escape the field. They gradually diffuse along force lines and ultimately fall in at the magnetic poles. If the magnetosphere is large enough and captures efficiently, it sweeps in, during the lifetime of the star, a quantity of gas comparable to that necessary to change the composition of the uppermost layers of the photosphere.

Here, capture should, in principle, be more probable for the heavy elements. However, the centrifugal force of a rapidly rotating magnetosphere of this radius would be much larger than the force of gravity, and diffusion would actually take place not toward the star, but away from it.

In addition to the reactions that take place in the interior regions of the stars, so-called surface reactions, which arise under the action of a flux of accelerated particles, are also possible[15]. If a gas of normal composition is bombarded with protons and α particles, both captures, including β decay and ejection of nucleons, and nuclear fissions should result. The pure effect can be determined by a detailed calculation covering the mesh of reactions for 300 species of initial nuclei and their derivatives[26]. The initial spectrum is assumed to be power-law with an exponent $\gamma = 2.5$ from 1 MeV. The calculations indicate that proton bombardment produces more nuclear fissions than heavier nuclei, especially at high energies, when they dislodge two or more nucleons from the nucleus. Thus, protons cannot create an abundance of heavy nuclei, although they can increase the number of less abundant elements, such as Li or P, by disintegration of adjacent more abundant elements.

Bombardment by 10-MeV and higher-energy α particles results in capture with ejection of a nucleon, so that the average atomic weight increases if the effects of particles with very high energies, whose number is small, are taken into account. In principle, therefore, the anomalous composition can be explained if it is assumed that the matter is bombarded by a flux of α particles in certain places on the star and then scattered over a large area, mixing with unmodified matter[26]. However, like the internal reactions, surface reactions cannot explain the shortages of certain light elements in certain stars. But the main difficulty here is that of obtaining a source of α particles without accelerating protons. In principle, fast particles can be ejected from a supernova companion or be generated by the star's magnetic field in discharges of the chromospheric-flare type, but with much higher power. In either case, it is difficult to explain the numerical superiority of the α particles, since the outer layers of both the Ap star and the supernova consist predominantly of hydrogen. It has not been possible to find a plausible mechanism by which He can be accelerated selectively. The hypothesis of bombardment by particles from the supernova also encounters the general difficulty that we have already mentioned—in this case, magnetic stars without anomalies should exist. The hypothesis of powerful discharges on the star proceeds from an analogy with the sun, where the field is weak on the average but rises to several kilogauss in the sunspots. However, the spot fields are created by compression at the boundaries of deep-lying convective cells and by the pressure of the photospheric gas, which compresses the cold spot with its field as soon as this field has become strong enough to stop convection and lower the heat flux. Magnetic stars have large-scale fields of the order of several kilogauss. However, the energy of even this field exceeds the energy of the convection, which is, in general, weak on type A stars and does not extend to a great depth. Thus, convection cannot strengthen the field substantially. The gas pressure is also inadequate, the more so since the temperature of the gas on these stars depends weakly on convection and there are no cold spots like those on the sun. Finally, flares require strong fields of complex structure, and such fields can be created only by powerful convective motions. Consequently, we may not expect strong discharges on magnetic stars. The absence of strong radio outbursts from Ap stars also tends to negate such discharges[27].

Thus, both high-temperature and surface nuclear reactions are incapable of explaining most of the chemical-composition anomalies.

5. SEPARATION OF ELEMENTS BY DIFFUSION

The difficulties of the hypotheses enumerated above and the close relation between the magnetic field and the composition anomaly oblige us to seek a magnetic-field mechanism to account for the change in photosphere composition. Diffusion separation, i.e., separation of the elements in a star with normal composition under the influence of gravity and radiation pressure, is such a mechanism[28].

The radiation pressure can differ very strongly for different elements. We may expect heavy atoms with complex optical-term structure to have many spectral lines in the visible and ultraviolet, with the absorption in these lines creating a higher radiation pressure on these atoms than on He and atoms and ions of light elements which have relatively simple structure. This could explain their abundance in the photosphere. On the other hand, the deficit of He and light elements can be explained by their sinking (relative to the hydrogen) under the influence of gravity. The rate of diffusion of the atoms is very low. For neutral He at a hydrogen concentration of 10^{15} cm^{-3}, it is less than 10^{-4} cm/sec, i.e., hundreds of thousands of years would be required to cross the photosphere (2×10^{8} cm). For ions having large effective cross sections, the diffusion times are substantially longer. Thus, separation can come about only in the total absence of convection, i.e., where there is a sufficiently strong field.

The diffusion-separation mechanism is attractive for its simplicity and naturalness. In principle, if the magnetic field suppresses convection and circulation, the effect of this mechanism is inevitable. However, its influence on the observed chemical composition in Ap stars requires quantitative investigations. We can cite a number of contradictions and difficulties that arise in attempts to explain all of the observed anomalies in terms of this mechanism. To ensure a 10^{4}-fold or larger observed excess of a given element, it is necessary to collect atoms in the upper layer of the photosphere from a thicker layer. Using a model[29] of a star with $T_{eff} = 10\,080$°K and $g = 10^{4}$ cm/sec^{2}, it can be calculated that a layer only 100 times more massive than up to $\tau = 0.3$ extends to an optical depth $\tau = 24$. The temperature varies from 7900°K to 17 500°K from $\tau = 0.3$ to $\tau = 24$. There are accompanying changes in ionization and excitation conditions, as well as in the energy distribution in the spectrum, but the radiation pressure must remain high throughout the entire layer for the separation mechanism to operate.

A difficulty of the diffusion mechanism consists in the different types of peculiarities of different stars.

As we noted at the outset, the relation between the type of peculiarity and the star's effective temperature is apparently a result of failure to take excitation conditions into account. If this is the case, it is necessary to explain why different elements ascend in different stars under similar conditions.

To explain the accumulation of atoms in the upper layers of the photosphere, it is necessary that radiation pressure be effective in the photosphere and below it and disappear above the photosphere, since otherwise the atoms would fly away from the star. An obvious qualitative solution of this problem is that the condition of local thermodynamic equilibrium is not satisfied in the upper layers, and the atoms do not absorb light, converting it into heat, but scatter it. Then the intensity at the centers of strong and medium lines in the outgoing-radiation spectrum drops to 5—7% of the intensity in the continuous spectrum, and the radiation pressure becomes insignificant for these atoms. A quantitative investigation of this effect must also include a calculation of the line profiles during the accumulation of atoms in the upper layers of the atmosphere.

Another difficulty of the diffusion-separation hypothesis is the fact that not all anomalies are concentrated at the magnetic poles. For certain elements, the lines vary in antiphase with other elements and with field intensity, e.g., in α^2 CVn, which we mentioned earlier (see Fig. 1b). It might be assumed that the field is also strong in these regions, but has a small radial component. In this case, however, convection would still stop and composition would be the same as at the magnetic poles. This difficulty can be circumvented, for example as follows. Most of the atoms experiencing radiation pressure are stopped in the upper part of the photosphere, forming a scattering layer with deep lines. However the ions of certain elements are not stopped, and are ejected from the photosphere along force lines. This can occur, for example, for elements having a large number of weak unsaturated absorption lines. As a result, these ions can accumulate at the vertices of the magnetic arcs, forming something of the nature of radiation belts at a distance of several radii from the star. These belts are projected onto the surface of the star preferentially away from the magnetic poles. Needless to say, this hypothesis requires quantitative verification. The diffusion mechanism cannot, in principle, explain one of the chemical-composition features of the Ap stars—the excess of heavy mercury isotopes in certain manganese Ap stars and the high content of the isotope He^3 in the star 3 Centauri A. In the former case, the only conceivable mechanism by which these anomalies could arise is capture of neutrons with an intermediate time scale; in the second, it is the destruction of helium in surface reactions[16] (the cross section of this process for He^4 is somewhat larger than that for He^3), although both He^3 and He^4 should then nearly vanish.

6. THE ORIGIN OF THE FIELD

Investigation of magnetic stars can also yield certain information on the origin of the field—both in these stars and in ordinary stars, where the field intensities are lower. Two basic ideas are under discussion at the present time. The first proceeds from the fact that there is a field on the order of 3×10^{-6} G in the interstellar medium from which the stars are formed. Compression of gas in the star also compresses and strengthens the field. In isotopic compression, the field B varies like $\rho^{2/3}$, and measurement of the field in interstellar clouds of various densities gives a qualitative confirmation of this dependence[30]. An increase in ρ from 10^{-24} to 10 g/cm^3 should raise B to 10^{11} G. Consequently, the problem is not how to create the field of a star, but how to reduce it to an acceptable value. This decrease is evidently related to anisotropy of compression, when the magnetic forces stop condensation across force lines[31].

The conductivity is sufficiently high in the interior regions of a star for a field to have existed there for billions of years. True, turbulence contributes to the decay of the field. However, if we exclude cold stars, the major part of a star's volume is stable. It is also necessary to consider the influence of the field on the convection that arises. A strong field should stop it, at least in stars toward type A, where convection is in general weak. Although no quantitative theory has been devised for all of these processes in stars, there is as yet no serious ground for doubt that remnants of a strong initial field may persist in A to F stars throughout their lifes.

The second possible origin of the field is based on the fact that a large-scale field can increase in a turbulent medium if the turbulence is anisotropic, i.e., if there is a certain preferred direction in it[32]. Convection may play the role of anisotropic turbulence on stars. The possibility of generation of dipole, quadrupole, and more complex fields has been demonstrated on this model. The mechanism of generation in a turbulent medium is one particular case of the dynamo processes, in which the field is generated by the motion of a conductive medium. Various types of dynamo processes have been analyzed in connection with attempts to explain the solar-activity cycle and the earth's field.

In principle, the existence of the field can be explained in either of the above ways; it is therefore necessary to employ more detailed field characteristics and various corollaries, comparing them with observations. The variability of the field in the solar cycle would seem to favor dynamo processes. On the other hand, although these processes create a field in the convective zone, it should penetrate very slowly into the stable internal region. The phenomena associated with pulsars are explained by rotation of a star with a field of dipole character that was sharply intensified on the collapse of the star's core. There was, therefore, a regular field in the core of this star prior to compression. This would tend to favor the relict origin of the field, although the possibility is not excluded that the relict has been preserved only in the core and the dynamo mechanism operates in the convective shell.

The magnetic stars offer certain additional possibilities for analysis of hypotheses of the origin of the field. If the field is intensified by convection, its energy cannot exceed that of the convective motions. At the same time, the magnetic energy of Ap stars often greatly exceeds their kinetic energy, and convection is suppressed. This is also suggested by the diffusion separation of the elements and the local nature of the chemical-composition anomalies.

Magnetic stars differ from ordinary stars of the same class in that they rotate more slowly and few of them are binaries. Since Coriolis forces promote dynamo processes, it would be more natural to expect intensification of the field in rapidly rotating stars. On the other hand, an initial field will carry momentum away from the star undergoing compression, and this would naturally explain the slow rotation of stars with large fields. Slow rotation might, of course, be due to outflow of mass in a giant stage (this outflow carries momentum with it) if the Ap stars were giants. In the latter case, it could be assumed that the field was formed by convective motions in the giant stage and then intensified further during compression, stopping convection wherever it was strong enough.

A stronger argument in favor of the initial field is the fact that Ap stars are seldom binaries. Generally speaking, whether or not the star is a binary cannot be essential for generation of a field, since the tidal forces are small at the Main Sequence stage. Double stars form as a result of the large momentum of the protostar as it is compressed. If momentum is efficiently carried away by the field, the protostar does not divide but is compressed into a single star. Consequently, the small percentage of binaries may be due to the fact that Ap stars had stronger fields at the prestellar stage, at which they were still clouds several thousand solar radii in size or even larger, since the field would have to cover not only the region occupied by the binary system, but also the outlying layers to which momentum is transferred.

7. CONCLUSION

The basic problem of the magnetic Ap stars—the origin of the chemical-composition anomalies—has not yet been definitely solved. These anomalies could not have been created solely by nuclear reactions in the interior of the star, nor could they have resulted from surface reactions. They could not have been imported to the star, either from a supergiant companion or from a supernova. The hypothesis of separation by diffusion appears most natural, but it requires a quantitative investigation. In addition, this hypothesis encounters substantial difficulties in certain cases—both in the explanation of the different types of peculiarities and in explanation of the Pm, Li, and helium and mercury isotopes. Some of these peculiarities may have resulted from capture of neutrons at an intermediate velocity, others from nuclear fission reactions. Different stars have different peculiarities. It appears that a single mechanism cannot be used to explain all of them, and that it will be necessary to assume the operation of different mechanisms in different stars. Diffusion separation operates in all magnetic stars; some of them were giants and experienced mixing, while fast particles on others fragmented some of the atoms. The field is most probably of primary origin. On the whole, the problem of the magnetic Ap stars requires further investigation, both experimental and theoretical.

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[1] a) H. W. Babcock, Astrophys. J. **118**, 387 (1953); b) Astrophys. J. Suppl. **3**, No. 30 (1958); c) in: "Stellar Atmospheres" edited by J. Greenstein, U. of Chicago, 1961.

[2] S. B. Pikel'ner, Usp. Fiz. Nauk **88**, 505 (1966) [Sov. Phys.-Uspekhi **9**, 236 (1966)].

[3] A. B. Severnyĭ, a) ibid. **88**, 3 (1966) [**9**, 1 (1966)]; Astrophys. J. Lett. **159**, L73 (1970); c) N. S. Nikulin et al., Izv. Krym. Astrofiz. Obs. **19**, 3 (1958).

[4] V. L. Ginzburg, Usp. Fiz. Nauk **99**, 514 (1969) [Sov. Phys.-Uspekhi **12**, 800 (1970)].

[5] G. W. Preston, Astrophys. J. a) **157**, 247 (1969); b) **160**, L143 (1970); c) **164**, L41 (1971); M. M. Dvoretsky et al., Bull. Am. Astron. Soc. **2**, 311 (1970).

[6] J. C. Kemp et al., Astrophys. J. **161**, L77 (1970).

[7] J. R. P. Angel and J. D. Landstreet, ibid. **162**, L61 (1970).

[8] E. Bohm-Vitense, Sonderdruck aus Lehrst. Theor. Astrophys. (Univ. Heidelberg), No. 7, 19 (1967).

[9] A. Deutsch, Publ. Astron. Soc. Pacific **68**, 92 (1956).

[10] D. Pyper, Astrophys. J. Suppl. **18**, 347 (1969).

[11] V. L. Khokhlova, Astron. Zh. **48**, 939 (1971) [Sov. Astron.-AJ, **15**, 741 (1972)].

[12] P. Renson, Ann. d'Astrophys. **30**, 697 (1967).

[13] W. L. W. Sargent, Ann. Rev. Astron. Astrophys. **2**, 297 (1964).

[14] M. F. Aller, Sky and Telescope **41**, 220 (1971).

[15] E. M. Burbidge, et al., Rev. Mod. Phys. **29**, 547 (1957).

[16] A. G. W. Cameron, Publ. Astron. Soc. Pacific **83**, 585 (1971).

[17] G. A. Shaĭn and V. F. Gaze, Izv. Krym. Astrofiz. Obs. **2**, 51 (1948).

[18] E. P. J. van den Heuvel, Bull. Astron. Inst. Netherlands **19**, 326 (1968).

[19] J. W. Truran and A. G. W. Cameron, Magnetic and Related Stars, ed. by R. C. Cameron, Baltimore, Mono Book Corp., 1967, p. 273.

[20] S. A. Colgate and R. H. White, Astrophys. J. **143**, 626 (1966).

[21] N. S. Kardashev, Astron. Zh. **41**, 807 (1964); **47**, 465 (1970) [Sov. Astron.-AJ **8**, 643 (1965); **14**, 375 (1970)].

[22] W. D. Arnett, Astrophys. J. **157**, 1369 (1969).

[23] D. D. Clayton, Comm. Astrophys. Space Phys. **3**, 13 (1971).

[24] M. D. Delano and A. G. W. Cameron, Astrophys. and Space Sci. **10**, 203 (1971).

[25] O. Havnes and P. S. Conti, Astron. and Astrophys. **14**, 1 (1971).

[26] P. J. Brancasio and A. G. W. Cameron, Canad. J. Phys. **45**, 3297 (1967).

[27] K. Kodaira and E. B. Fomalout, Astrophys. J. **161**, 1169 (1970).

[28] G. Michaud, ibid. **160**, 641 (1970); M. A. Smith, Astron. and Astrophys. **11**, 325 (1971).

[29] D. Michalas, Astrophys. J., Suppl. **9**, No. 92 (1965).

[30] G. L. Verschuur, Interstellar Gas Dynamics, ed. by H. J. Habing, Dordrecht, D. Reidel, 1970, p. 170.

[31] L. Mestel and L. Spitzer, Mon. Not. Roy. Astron. Soc. **116**, 503 (1956).

[32] M. Steenbek et al., Zs. Naturforsch. **21A**, 369 (1966).

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