Nuclear reactions in Ap stars

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Fiz. Elem. Chastits At. Yadra 8, 1134–1154 (September–October 1977)

Data derived from astronomical observations of Ap stars are presented. The theory of the anomalous chemical composition of Ap stars is briefly presented: diffusion theory, magnetic accretion, nuclear reactions on the surface and within the star. The isotopic abundance of mercury and the discovery of promethium in the atmospheres of Ap stars are considered. The attempts at theoretical explanation of these observations are reviewed. It is impossible to explain all features of the chemical composition of the atmospheres of Ap stars by just one of the mechanisms discussed in the paper. The features of Ap stars emphasize the importance of further observations and also calculations of the abundance of promethium and the transuranium elements in the atmospheres of these stars.

PACS numbers: 97.10.Cv, 95.30.Cq, 97.30.Fi

INTRODUCTION

During the last decade, the investigation of Ap stars has been one of the most rapidly developing branches of astrophysics. If the criterion for the development of a new branch of knowledge is taken to be the posing of every new questions, there is no doubt that it would be hard to find any other branch of astrophysics that competes in this respect. The explanation of the astronomical observations on Ap stars prompts questions for which answers can be given on the basis of completely different and even contradictory conceptions. There is no completely satisfactory theory of these stars. The abundance of elementary and simple questions which cannot be readily answered is a challenge to investigators and, if you please, an indication of the importance of the problem.

1. BASIC DATA ON Ap STARS

When stellar spectra were first studied, it was assumed that the differences in the spectra are due primarily to differences in the chemical composition. Stars were divided into spectral classes; stars with lines of the same elements were put into one spectral class. It then transpired that what had previously been regarded as a classification according to chemical composition was in reality a classification according to surface temperature. In order of decreasing surface temperature, the classes are now designated as follows: *O*, *B*, *A*, *F*, *G*, *K*, *M*, *R*, *N*, *S*. In each spectral class, there are ten subclasses. For example, the hottest stars of class *A* are designated *A*0; the coldest *A*9. The surface temperature of *O* stars is approximately $5 \cdot 10^4$ °K; of *S* stars, $3 \cdot 10^3$ °K. The Sun belongs to the class *G*2.

The Ap stars make up 10%, and according to some estimates 25%, of all stars of classes from *B*4 to *F*0. The spectra of these stars are peculiar (hence the *p* in the nomenclature) for two reasons. Besides the unusual strength of certain spectral lines, variations in the line intensities are also observed. The spectra of these stars exhibit lines of short-lived elements that do not exist on the Earth.

Other elements, for example the lanthanides, gold, and mercury, are present in the Earth's crust in small amounts, whereas in the atmospheres of Ap stars their abundance is much higher, in some by 10^5 times!

The basic observable characteristics of stars are the luminosity and surface temperature. The luminosity, i. e., the total energy emitted by the star in 1 sec, can be calculated from the energy received at the Earth if the distance to the star is known. The surface temperature of the star can be deduced from the distribution of its radiation with respect to frequencies. If the luminosities of stars with known distances are plotted on a graph against their temperatures, we obtain the well known Hertzsprung–Russel diagram.

Astronomers know the position of the Ap stars on the Hertzsprung–Russell diagram, their chemical composition, the frequency of occurrence of binary systems, the magnetic field strengths, the rotational velocity, the morphological age, and other physical parameters. What remains obscure is the origin of the "peculiarity". Before we consider the theories that attempt to explain the peculiarity of the Ap stars by nuclear processes, let us briefly give the physical characteristics and the data of astronomical observations.

Position in the Hertzsprung–Russell diagram. Age of Ap *stars.* In the Hertzsprung–Russell diagram, the Ap stars are situated among the young stars. However, some features of their composition recall the composition of red giants. There are three possible ways of explaining the evolutionary stage of Ap stars; namely, Ap stars are:

1) very young objects that have just joined the main sequence;

2) stars that will shortly leave the main sequence;

3) stars that have passed through the red giant stage and intersect the main sequence a second time.

The ages of the stars for these three possibilities are 10^6, 10^8, and $2 \cdot 10^9$ years. The young stars in our Galaxy are concentrated near the Milky Way. However, among the Ap stars only the stars of the silicon group (Si stars) are found to be concentrated near the Milky Way.[61] Later, we shall consider the existing groups in the class of Ap stars. The remaining stars are dispersed much more strongly. The average distance

TABLE I. Degree of enrichment of elements in Ap stars.

elements	α^2CVn	*HD*133029	*HD*151199	βCrB	γEqu	3CenA	73Dra	53Tau	αCnc
He	—	—	—	—	—	−0.8	—	—	−1.2
Be	+1.2	—	—	—	—	+0.4	—	—	+2.0
C	—	—	—	—	—	0.0	—	+0.4	—
N	—	—	—	—	—	+0.7	—	—	—
O	−1.0	—	—	<−1.8	<−1.7	−0.8	—	—	+0.3
Ne	—	—	—	—	—	0.0	—	—	—
Na	—	—	—	—	0.0	—	—	—	—
Mg	−0.4	+0.1	+0.1	+0.2	+1.2	−0.6	+2.7	−0.3	−0.8
Al	0.0	+0.3	—	—	—	−0.2	—	—	—
Si	+1.0	+1.4	+0.1	—	+0.5	+0.3	+0.7	+0.1	—
P	—	—	—	—	—	—	—	—	+2.0
S	—	—	—	—	—	−1.0	—	—	—
Ar	—	—	—	—	—	+0.1	—	—	—
Ca	−1.7	−1.3	+0.4	+0.1	+0.7	−0.4	−2.0	−1.5	—
Sc	−0.2	—	—	+0.4	+0.7	<+0.6	—	—	—
Ti	+0.4	+0.4	—	+0.9	+0.2	<+0.2	+0.3	+0.6	−0.2
V	+0.1	+0.5	—	+0.4	+0.8	<+0.7	—	—	—
Cr	+0.7	+1.0	+0.3	+1.5	+1.3	<−1.0	+1.6	−0.9	+0.1
Mn	+1.2	+1.2	+1.0	+1.6	+1.8	+0.6	+1.5	+1.8	+1.5
Fe	+0.5	+0.6	+0.0	+0.8	+0.6	+0.6	+0.6	−0.3	−0.3
Co	—	—	—	+1.0	+1.7	—	—	—	—
Ni	+0.5	+0.4	—	+0.3	+1.6	−0.2	—	—	—
Ga	—	—	—	—	—	+3.8	—	−2.4	—
Kr	—	—	—	—	—	3.1	—	—	—
Sr	+1.1	+1.2	+1.8	+1.6	+2.6	<+1.7	+0.9	+1.5	—
Y	+1.3	—	—	—	+0.6	—	—	—	—
Zr	+1.5	+1.6	—	+2.0	+0.8	—	—	—	—
Ba	⩽0.0	—	−0.2	+0.7	+1.2	—	—	—	—
La	+3.0	+2.3	—	+2.8	+2.3	—	—	—	—
Ce	+2.6	+2.4	—	+2.9	+2.0	—	+1.3	—	—
Pr	+3.0	+2.8	—	+2.7	+2.4	—	—	—	—
Nd	+2.4	+2.1	—	+2.2	+2.3	—	—	—	—
Sm	+2.6	+2.4	—	+2.3	+1.7	—	—	—	—
Eu	+3.3	+2.9	+2.1	+3.2	+2.6	—	+3.3	—	—
Gd	+2.9	+2.5	—	+2.9	+2.2	—	+2.8	—	—
Dy	+2.9	+2.7	—	+3.6	+2.5	—	—	—	—
Pb	—	+3.2	—	—	—	—	—	—	—

from the galactic plane is more than 60 pc, so that Ap and Am stars (the m denotes metallic) are not very young.

On the other hand, Ap stars have also been found in very young clusters: three Si, four Sr, and two Mn stars have been found in the Scorpius–Centaurus association, whose age is $5 \cdot 10^6$ years. In addition, five Ap stars have been found in the Orion association, whose age reaches $3 \cdot 10^6$ years. The majority of astronomers assume that there is no connection between peculiarity of a star and its evolutionary stage.

Physical characteristics of Ap *stars*. The average magnetic field induction of a typical Ap star is 10^3–10^4 G. Periodicity is observed in the variations of the magnetic field strength. The shortest periods of variation of the field are a few days.[1] These variations can be explained by means of a model of an inclined rotator in which the magnetic axis of the star is inclined relative to the rotation axis, and both axes are inclined relative to the line of sight.

A typical Ap star has a surface temperature of order 10^4 °K and atmospheric density of about 10^{15} atoms/cm^3. The convective envelope of such a star is very thin, and the strong magnetic fields must slow down convection appreciably. The Ap stars have masses 2–5 times greater than the Sun.

Chemical composition of Ap *stars*. As we have already said, the Ap stars stand out above all because of their chemical composition, which is very different from the solar. The data given in Table I indicate the deviations of the chemical composition of Ap stars from the composition of the majority of other stars of class *A*. We give the main features of the chemical composition of Ap stars. It should be emphasized that in each star the concentrations of the elements are different.

When speaking of the age of Ap stars, we have already mentioned various groups that exist among these types of stars. The name of the group (for example, Si) indicates a feature of the spectrum or an element (silicon) for which the anomalous excess abundance is the most pronounced. Among the peculiar stars, there are two main groups: the metallic-line stars Am, in which an excess of metals is observed, and the Ap stars.

In the Am stars, the deviations in the element abundances are less than in Ap stars. The Am stars do not have a magnetic field. The physical characteristics given in Table I refer basically to Ap stars. The anomalies in the element abundances and the differences between the Ap and Am stars can be clearly seen in Fig. 1.

Let us comment briefly on the data in Table I and Fig. 1. The abundance of the lightest elements He and O is reduced by a factor of ten. The Si abundance is increased by ten times in the hottest Ap stars and by slightly less in the others. The Ga abundance is frequently reduced by 10–100 times. The abundances of the elements in the region of the iron peak—Ti, V, Cr, and Mn—are frequently enhanced, especially for Mn in hot stars and Cr in cold stars. For iron, the increase is not so pronounced. The abundance of Ga and Kr in the star 3 Cen A is up by 100 times, and the Sr, Y, and Zr excess in the majority of Ap stars is characterized by a factor 10–100. The greatest deviations from the norm are observed for the abundances of the rare earth elements. In normal A stars the elements La, Ce, Pr, Nd, Sm, Eu, Gd, and Dy are not observed at all, whereas their abundance in Ap stars is enhanced by 500 times compared with the universal abundance. The abundance of Ba is normal or slightly above it.

For stars in which a variable magnetic field is observed, the spectra are also variable. The intensity

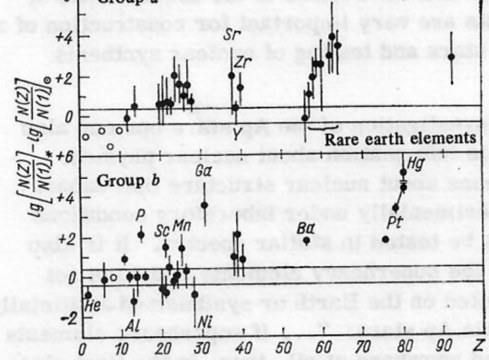

FIG. 1. Logarithm of relative abundance of elements in Ap stars (group *a*) and Am stars (group *b*). The thin horizontal lines (±0.4 on the ordinate) determine the limits for the deviations in the abundances of the elements in ordinary stars of class *A*. The figure is taken from Ref. 3.

TABLE II. Observations of heavy elements in Ap stars.

Element	Star
W	HD25354 [27], 73Dra [28], HR8911 [29]
Re	HD35354 [27], 73Dra [28], HR8911 [29]
Os	73Dra [30, 31], HR8911 [29], HD25354 [27], 5 Ap stars [32], HR465 [33], βCrB [34], HD5797 [35]
Ir	73Dra [28], HR8911 [29]
Pt	HR4072 [36], Φ Phe [36], 46Dra [36], HD173650 [36], HR465 [33, 37], 73Dra [28, 31, 34], HD25354 [27], 78 Vir [34], HR8911 [29], 5 Ap stars [32], HD 5797 [35]
Au	HD25354 [32], HD71866 [32], 73Dra [31], HR4072 [38], χ Lup [38]
Hg	α Anol [39], χ Lup [38—40], τ CrB [40, 41], Φ Phy [36], 46Dra [36], HD173650 [36], HR4072 [38], 73Dra [28], HR465 [33, 37], 10 Ap stars [42], 20 Mn stars [43]
Pb	73Dra [28], HR4072 [28], HR8911 [29], α^2 CVn[13,29]
Bi	73Dra [28]
U	73Dra [30, 31. 34], β CrB [32, 34, 44, 45], HD25354 [27, 46], HR465 [25, 46], HD224801 [25], 17ComA [25], HR8911 [29], 4 Ap stars [32], 25 cold Ap stars [4[, 25 Ap stars [47]
Th	73Dra [28], HD25354 [27], HR465]37]
Pu, Am, Cm	HD25354 [27, 48]

of some lines in the spectrum is constant, whereas for others it varies with the same period as the magnetic field. There are stars in which there are no correlations between the variations of the magnetic field and those of the spectral-line intensities. As a rule, if the line intensities of certain elements increase, then those for others decrease. For example, in the stars α^2CVn and HD 125248 the intensities of the lines Eu II and Cr II vary in antiphase. The maximal intensity of the Eu II line in the star HD 125248 is observed when the magnetic field is positive, but for α^2CVn the maximal intensity of the Eu II line is reached at negative polarity of the magnetic field.

Anticipating, let us say here that the peculiarities of the spectra are due to different enhancements with heavy elements in the surface of the stars and by different physical conditions in the layers in which the lines are formed. Each star requires individual investigation, and this considerably complicates the determination of general rules.

In Table II, we give data on observations of heavy elements not contained in Table I and Fig. 1. These elements have been observed only in individual stars, and it is as yet difficult to speak of regularities. We shall see later that the results of the observations of these elements are very important for construction of a theory of Ap stars and testing of nuclear synthesis models.

From the investigation of the Ap stars one can also obtain valuable information about nuclear physics. Some hypotheses about nuclear structure that cannot be tested experimentally under laboratory conditions could perhaps be tested in stellar spectra. It is also probable that the superheavy elements that have not yet been detected on the Earth or synthesized artificially exist on certain Ap stars: "... if superheavy elements are to be found anywhere at all, then, in the first place, they must be found in Ap stars" (Ref. 8).

In their turn, the astrophysicists investigating Ap stars must have precise data on the spectra of rare earth and transuranium elements. Preston[3] has listed in more detail the requirements of the astrophysicists addressed to the physicists. The astronomical problems in the investigation of Ap stars have been reviewed in Refs. 17 and 62.

2. EXISTING THEORIES OF THE ANOMALOUS CHEMICAL COMPOSITION OF Ap STARS

The observed anomalies can be explained on the basis of two different approaches. One of them is to look for a mechanism that could explain the enhancement of certain spectral lines and the disappearance of others. According to this view, the anomalies in the element abundances are therefore only apparent. Certain elements for example, Cr, Mn, and Eu, have large magnetic moments, and therefore they could migrate in magnetic fields with large gradients.[9,10] However, one cannot explain all the observed features; in addition, this mechanism requires the magnetic field gradient to be too large. The explanation of the observed abundance of heavy elements in the surface layers by diffusion transport of elements of the surface of the Ap stars is better founded. According to this hypothesis, the element abundances in the star do not differ from the universal; but because of diffusion certain elements accumulate on the surface.

In the second approach, it is assumed that the anomalies of the chemical composition are real and due to nuclear reactions either within the star or on its surface.

In 1965, Fowler, the Burbidges, and Hoyle attempted to explain the production of heavy elements in Ap stars by the process of rapid capture of neutrons (r process) occurring during the time of a supernova explosion. They therefore assumed that these stars have already passed through a fairly long period of their evolutionary path and that they return once more to the main sequence after the red giant stage.

The isotope ^{12}C is formed as a result of the helium flash, and ^{13}C by proton capture: $^{12}C(p,\gamma)\,^{13}N(\beta^+)^{13}C$. The $^{13}C(\alpha,n)$ reaction is the principal source of the neutrons needed for the production of heavy elements. Violent mixing of the layers in the star carries the reaction products to the surface. Fowler *et al.* explained the shortfall of light elements by surface spallation reactions. However, this theory presupposes a considerable age of the Ap stars, which, as follows from the observations, is not justified.

Formation of anomalous composition in the atmospheres of Ap *stars by nuclear reactions on the surface of the star.* Brancazio and Cameron[2] have analyzed the suggestion that nuclear reactions on the surface can make an important contribution to the mechanism responsible for the anomalous composition of Ap stars. The suggestion was made by the Burbidges[13] in 1955.

In accordance with the observed cosmic-ray spectrum, it was assumed that the spectrum of protons and α particles that bombard the surface of a star is given by $N(E) \sim E^{-n}$ with exponent $n = 2.5$. For the production part (about 1%) of the surface of a star is irradiated with an intense α-particle flux. An estimate of the energy expended by the magnetic field on accelerating the α particles confirms the probability of this process. It is harder to account for the selectivity of the acceleration mechanism in accelerating only α particles.

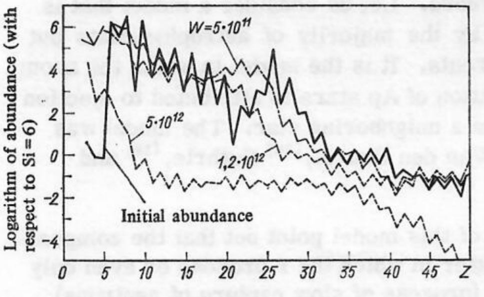

FIG. 2. Dependence of the resulting abundances of the elements on the integrated proton flux (Ref. 2) (W in erg·sec·cm^{-3}).

of heavy elements, the flux of particles corresponding to the section 1–50 MeV of the energy spectrum was considered. Particles with lower energy lose it by ionization, and those with higher energy in spallation reactions. About 300 nuclei in the network of reactions were considered. The final numbers of nuclei were calculated as a function of the integrated flux of protons and α particles. Since the method of calculating the capture cross section was based on a statistical model,[14] the results obtained for light nuclei occasion certain doubts. It was assumed that the original element abundances are the same as the solar.

It was found that the flux of bombarding protons transforms the original matter into a mixture of hydrogen and helium. The change in the initial element abundances as a function of the total proton flux is given in Fig. 2. For small integrated fluxes, one notes a reduction in the Fe, Co, and Ni abundances and the enrichment with elements from Ca to Fe. High fluxes lead to the destruction of all heavy elements, and a flux of α particles increases the abundances of heavy elements through (α, n), (α, p), $(\alpha, 2n)$, (α, pn), $(\alpha, 3n)$ reactions. The results of the calculations are given in Fig. 3. But if one considers the simultaneous effect of protons and α particles, then if the fluxes are equal the destructive effect of the protons ultimately predominates.

Applying their calculations in an attempt to explain the element abundances on the surface of Ap stars, Brancazio and Cameron concluded that only a small

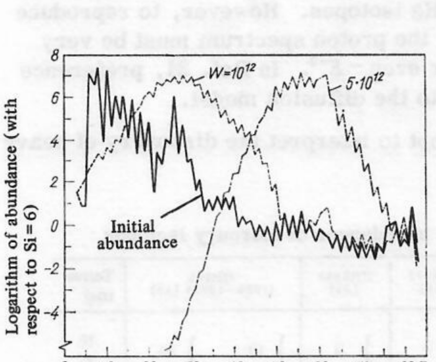

FIG. 3. Dependence of the resulting abundances of the elements on the integrated flux of α particles (Ref. 2) (W in erg·sec·cm^{-3}).

There are other shortcomings of the model. The calculated Fe and Si abundances do not correspond to their observed excess. According to the calculations, the Sr and Y abundances must increase together, which is not observed experimentally. Contrary to the observations, Fe and Si cannot simultaneously attain their maximal abundance since the Fe excess is produced by capture of α particles by Si nuclei and neighboring elements.

The large ratio $^3He/^4He$ (for example, $^3He/^4He \sim 10$ in 3 Centauri A) can be explained by nuclear reactions on the surface of the star. There are two ways in which ^3He can be produced:

1) the isotope ^3He can be produced in thermonuclear reactions on deuterium, but to obtain the observed ^3He abundance one requires a too high deuterium density;

2) ^3He is formed in the reactions $^4He(p, d)^3He$ and $^4He(p, pn)^3He$, whose threshold is 20.6 MeV. Note that protons with energy greater than 7.7 MeV are also capable of causing spallation of the nucleus ^3He in the reactions $^3He(p, d)2p$ and $^3He(p, pn)2p$. Thus, the ^3He excess in the atmospheres of Ap stars depends on the ratio of the rates of spallation of the ^4He and ^3He nuclei by protons. If the spallation rate is greater for ^4He than ^3He, the ratio $^3He/^4He$ increases. But if the rate for ^4He is slightly less than for ^3He, the ratio $^3He/^4He$ is constant. To obtain the measured ratio $^3He/^4He \sim 10$, the cross sections of the two reactions must satisfy the condition $\sigma(^4He)/\sigma(^3He) = 0.9$.

According to the measurements,[63] the ratio $\sigma(^4He)/\sigma(^3He)$ increases from zero at proton energy 18 MeV to 0.9 at 38 MeV and then remains constant right up to 50 MeV. This good agreement is an argument in favor of the suggestion that nuclear reactions on the surface of Ap stars are very important for the formation of the composition of their atmosphere.

Model of magnetic accretion. This model was put forward by Havnes and Conti[15] in 1971 and its gist is as follows. The magnetic field of an Ap star captures ions from the surrounding interstellar space. Since the charge-to-mass ratio for heavy elements is smaller than for light elements, the heavy ions approach closer to the star, which facilitates their further ionization. Ions with enhanced degree of ionization are captured by the magnetic field and spiral toward the magnetic poles of the star. The magnetic field, which becomes stronger as the star is approached, can deflect the ions, but the heaviest of them diffuse to the surface of the star and, thus, change the abundances of the elements in the atmosphere. Since the composition of only the uppermost layers of the star's atmosphere is enriched, even under the most conservative assumptions about the density of the interstallar medium and the capture range one can obtain an appreciable enrichment with heavy elements, comparable with the one observed, in a short period (~ 10^7 years). The time scale of 10^7 years for an enrichment of order 10^3 was obtained under the assumption that the velocity of the star is ~ 10 km/sec, the matter density in interstellar space is ~ 1 atom/cm^3, and the capture radius is ~ 2 AU, i.e., more than 200 times greater than the geometrical radius of the star. With regard to this model, we may point out that if it is complemented by physical processes not taken into account in Ref. 15 it may lead to a different chemical composition of the surface of the star from the one obtained in Ref. 15. In addition, this mechanism cannot explain the observed isotopic details in the composition of the stars, for example, the $^3He/^4He$ ratio or the ratio of the various isotopes of mercury.

Diffusion model. The strong magnetic field of Ap stars prevents the development of convective motions, in other words, it stabilizes their atmospheres. Radiative pressure gives rise to a diffusion displacement of the atoms. In the radiation field, only those atoms whose ionization potential lies in a definite range are subject to the radiation pressure. According to the calculations of Michaud,[16] the elements for which the ionization potential lies in the range 10.5 to 13.6 eV will be expelled by the radiative force to the surface of the star. The elements C, P, Cl, Ca, Sc, As, Br, Sr, Y, Zr, Xe, Rn, and the rare earths come in this group. Elements for which the ionization potential is less than 10 eV or greater than 18 eV do not absorb a sufficient amount of energy to overcome the force of gravity. The atoms He, Li, Be, B, Ne, Na, Al, K, Ni, Cu, Ga, Se, Rb, In, Sb, Te, and Cs come in this group. The ions of Mg, Mn, Fe, and Cr, whose ionization potential lies in the range from 13.6 to 18 eV, may be subject to a radiation pressure capable of carrying them to the surface of the star. The diffusion velocity is of the order 10^{-3} cm/sec, which can ensure a change in the composition of a star's atmosphere in 10^4 years. On the other hand, it is hard to explain the absence in the star's atmosphere of convective flows whose velocity does not exceed 10^{-3} cm/sec. Let us now list the observed facts that are hard to explain in the framework of this model:

According to the model, Y must exhibit excess, but a normal abundance of this element is observed in cold Ap stars[4];

there must be a deficiency of magnesium, but in cold Ap stars its abundance does not deviate from the norm[4];

in the framework of the model it is hard to reproduce the observed superabundance of the elements neighboring iron;

the model predicts an enhanced abundance of rare earth elements, but not to the extent actually observed;

it is hard to explain the observed $^3He/^4He$ ratio.

Despite these difficulties, the diffusion model is supported by many astrophysicists.

The hypothesis that the anomalies of the chemical composition in Ap stars are due to the ejection of matter by a supernova. Let us consider a model that is now rejected by the majority of astrophysicists but still has adherents. It is the model in which the anomalous composition of Ap stars is attributed to ejection of matter from a neighboring star. The model was developed by Van den Heuvel,[18] Guthrie,[19] and Renson.[20]

The critics of this model point out that the composition of the matter in which the r process or even only the s process (process of slow capture of neutrons) takes place differs from the composition of Ap stars. Besides this argument, there is another: The matter ejected by a supernova in a binary system would more probably strip off the atmosphere of the Ap star rather than enrich it. The star could, however, be formed from matter ejected in supernova explosions. The asymmetric fission of nuclei—the products of the r process—considered by Ohnishi[60] gives the peak in the region of Nd and Sm observed in the star HR 465.

To confirm this model, it is necessary to determine the abundances in this star of the elements Rh, Ag, Cd, and In, i.e., the elements corresponding to the light fission fragments. We shall not dwell on these questions in detail since the observations of recent years lead to the conclusion that one must invoke more complicated models that take into account at least two of the mechanisms listed above. Among the essentially new observations that could be important for testing the theory of Ap stars there is the discovery of the isotopic shift of the Hg and Pt lines and also the report of the discovery of lines of Pm, U, and transuranium elements.

3. OBSERVATIONS AND EXPLANATION OF THE ISOTOPIC SHIFT OF THE MERCURY LINES

The results of observations in the spectra of Ap stars of the lines of various mercury isotopes are given in Table III. In Ref. 21, Michaud *et al.* attribute the appearance of the heavy mercury isotopes to the diffusion process; they also consider a mechanism in which the matter is first displaced to the surface of the star and is then bombarded by the proton flux. They also considered numerous spallation reactions in lead due to protons with an energy of a few MeV. Large energy expenditures are not required to reproduce the observed abundances of the Hg isotopes. However, to reproduce the observed data, the proton spectrum must be very steep: about E^{-8} or even ~ E^{-9}. In Ref. 21, preference is therefore given to the diffusion model.

A different attempt to interpret the discovery of heavy

TABLE III. Relative abundances of mercury isotopes.

<table>
<tr><th>Isotope</th><th>Iota CrB [41]</th><th>HR4072 [38]</th><th>HR5883 [38]</th><th colspan="2">HR465 (1964–1969) [49]</th><th>Terrestrial</th></tr>
<tr><td>198</td><td rowspan="2">6</td><td rowspan="2">0</td><td rowspan="2">0</td><td rowspan="2">10</td><td rowspan="2">10</td><td>10</td></tr>
<tr><td>199</td><td>17</td></tr>
<tr><td>200</td><td rowspan="2">16</td><td rowspan="2">4</td><td rowspan="2">0</td><td rowspan="2">45</td><td rowspan="2">60</td><td>23</td></tr>
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<tr><td>204</td><td>33</td><td>59</td><td>97</td><td>7</td></tr>
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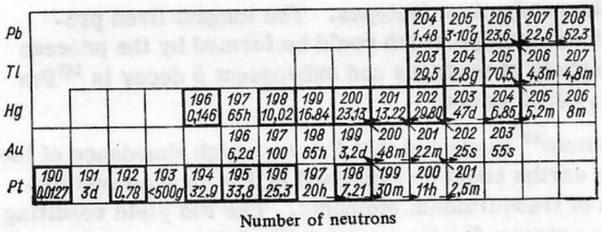

FIG. 4. Section of the table of isotopes in the region of mercury. The arrows indicate the path of successive neutron captures and β decays in the intermediate time scale.[22]

Hg isotopes has been made by Cameron[22]. Since the "ordinary" γ or s process does not lead to heavy Hg isotopes, these could be formed by capture of neutrons over a medium time scale.

A section of the isotope charge is shown in Fig. 4. Here, the squares surrounded by a heavy line are stable isotopes. The upper number is the atomic mass; the lower, their relative terrestrial abundance. In the squares surrounded by thin lines are the isotopes which are unstable against β decay. The upper number gives the atomic mass; the lower, the half life. The arrows indicate the sequence of neutron captures and β decays under the assumption that the average time between two successive neutron captures is about 1 hour.

Under these conditions, the isotope ^{200}Hg is formed in a reduced amount since the majority of the ^{200}Au can capture a neutron before they undergo β decay. For a characteristic time of the order of 1 hour, the chain of neutron captures terminates at ^{205}Hg. The isotope ^{204}Hg has 124 neutrons—only two fewer than the closed shell $N=126$. Since the neutron capture cross section decreases in the neighborhood of a closed shell, it is to be expected that the cross section of neutron capture for ^{204}Hg is less than for ^{202}Hg. Thus, the process of neutron capture can result in a large yield of ^{204}Hg. Cameron[22] assumes that this process takes place on the star after the helium flash, during which time the necessary neutron flux can be generated. As a result of the helium flash, the temperature of the outer layers of the core of the star is raised to $6\cdot10^{8}$ °K, and the process of carbon burning, which is accompanied by numerous nuclear reactions, commences. The carbon burning must proceed nonexplosively, and the energy released must ensure complete mixing of the layers of the matter of the star. It should be noted that the assumption made by Cameron: $\sigma_{n,\gamma}(^{204}\text{Hg}) \ll \sigma_{n,\gamma}(^{202}\text{Hg})$ contradicts the conclusions of the experimental studies,[64,65] according to which $\sigma_{n\gamma}(^{204}\text{Hg}) = 190 \pm 50$ mb, and $\sigma_{n,\gamma}(^{202}\text{Hg}) = 50 \pm 15$ mb.

4. DISCOVERY OF PROMETHIUM LINES IN THE SPECTRA OF Ap STARS

Promethium does not have stable isotopes; its longest lived isotopes are ^{145}Pm ($T_{1/2}=17.7$ years) and ^{146}Pm ($T_{1/2}=5.53$ years). Promethium was observed for the first time by Aller and Cowley[23] in 1970 in the star HD 9996 (HR 465). The star HD 9996 is a magnetically variable star with an exceptionally long period of variation of all characteristics—about 22 years. A number of lines of heavy elements, in particular U, have been observed on this star. Aller and Cowley identified more than 40 lines of Pm II on HR 465. However, Wolff and Morrison,[24] who analyzed the spectrograms at their disposal, did not find lines of Pm II.

TABLE IV. Identification of U II and Pm II lines in the star HR 465.

λ_{lab}	I_{lab}	λ_*	I_*	Commentary
		U II		
3793.10	42	93.17	2	Clearly visible
3826.51	55	26.47	3	Blended
3854.66	180	54.60	1	The same
3859.58	360	59.62	2	Clearly visible
3863.92	140	65.98	3	Blended
3881.46	75	81.47	1	Clearly visible
3895.80	85	95.98	1	The same
3932.03	450	32.00	2–3	" "
3954.66	40	54.66	2–3	" "
4050.04	120	50.09	1	Blended
4062.55	65	62.52		The same
4116.10	60	16.16	1	Clearly visible
4171.59	100	71.57	1	Blended
4472.34	44	72.44	0–1	Clearly visible
4241.67	75	41.66	1	The same
4515.28	23	15.29	1	" "
4538.19	23	38.20	1	" "
		Pm II		
3877.63	80	77.64	2	Clearly visible
3892.16	100	92.27	1	Blended
3910.26	100	10.23	1	Clearly visible
4417.98	100	17.82	1	The same
4473.23	30	73.19	1	" "

Aller and Cowley's report of the discovery of Pm II on HR 465 gave rise to a lively discussion in the literature on Ap stars and nucleosynthesis. The majority of authors denied the discovery of Pm II lines in the spectrum of this star. The problem is that the spectra of Ap stars are very complicated; many lines in them have not yet been identified and the spectra of all rare earth elements are not sufficiently well known. There is a real probability that the lines ascribed by Aller and Cowley to Pm II belong to a different element.

Since the question of the presence of promethium, uranium, and transuranium elements is very important

TABLE V. Variations in the intensities of the U II and Pm II lines and the radial velocity in HR 465.

Number of plate	JD (2442300+)	W_λ, mÅ			V_{rad}, km/sec, from $\lambda=3933$	φ ($P=0^d27847$)
		U II $\lambda=3932$	U II $\lambda=3859$	Pm II $\lambda=3877$		
2532	38.40901	25.4	23.4	12.9	−1.5	0.00
2533	38.45554	21.7	21.6	12.1	+1.5	0.14
2534	38.50207	14.2	14.8	4.3	+0.8	0.29
2544	43.37151	15.7	17.3	6.3	−3.0	0.50
2545	43.47221	21.6	24.2	6.3	−3.0	0.82
2546	43.56249	23.0	27.7	15.1	−0.5	0.10
2547	44.44096	17.7	20.8	9.4	−2.1	0.85
2548	44.55068	17.6	14.3	10.0	+1.0	0.19
2552	45.39235	23.3	18.0	14.2	−3.0	0.81
2553	45.50000	21.7	21.4	13.2	−1.5	0.15

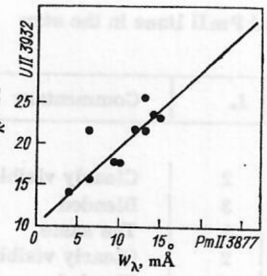

FIG. 5. Correlation between intensities of the U II and Pm II lines in the star HR 465 (Ref. 25).

for theories of the origin of heavy elements and the theory of nucleosynthesis, it would be worthwhile looking for possible correlations between the intensities of these lines and also others of elements not listed here that could be parent elements of promethium. In Ref. 25, Aslanov *et al.* attempted to solve the problem. In the spectrograms of the star HR 465 they identified 17 lines of U II and five lines of Pm II. These lines are listed in Table IV. They measured the equivalent widths of the most pronounced lines of U II ($\lambda = 3859$, $\lambda = 3932$) and Pm II ($\lambda = 3877$). In Table V, we give the results of the measurements of the equivalent widths for these lines. The results of the measurements fit well onto a curve with period 6^h41^m (Fig. 5). The chromium lines, which have approximately the same intensity as the investigated lines, do not change their intensity. The dependence of the equivalent width of the line $\lambda = 3877$ on the equivalent width of the U II line $\lambda = 3932$ (Fig. 6) may confirm not only a probable genetic connection between promethium and uranium but also the presence of promethium lines in the spectrum of HR 465 and indicate a common origin of the variations of these lines.

5. NUCLEAR REACTIONS LEADING TO THE PRODUCTION OF PROMETHIUM

The longest lived Pm isotopes cannot be produced in the chain of neutron capture and successive β decays. The majority of heavy elements are produced in such a chain in the *s* or *r* process. However, the long lived Pm isotopes are shielded from sequences of this type

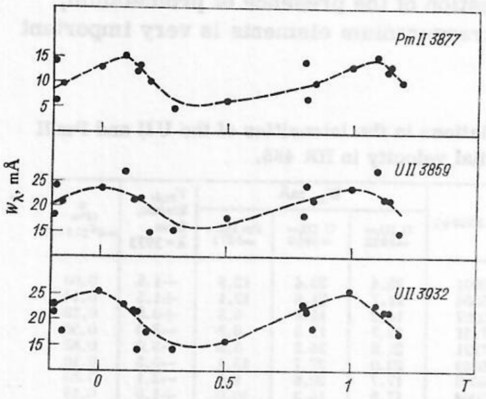

FIG. 6. Correlation between periodicity in the variations of the U II and Pm II line intensities in the star HR 465 (Ref. 25).

by the neodymium isotopes. The longest lived promethium isotope which could be formed by the process of capture of neutrons and subsequent β decay is ^{147}Pm ($T_{1/2} = 2.62$ years).

Selinov[50] suggested that the very high abundance of the rare earths could be explained by the spontaneous fission of transuranium elements. The Pm yield resulting from uranium fission is about 2% of the total of the fission products. With increasing mass number of the fissioning transuranium nucleus, the position of the heavy-fragment peak in the mass distribution curve remains practically unchanged, but the light-fragment peak is steadily displaced and approaches the heavy-fragment peak. It could be that the two peaks coincide for superheavy nuclei. The Pm yield resulting from the fission of a superheavy nucleus is estimated at 5%. The superheavy elements could also be formed as a result of the *r* process during a supernova explosion.

The heavy-element production mechanism proposed in Ref. 51 could produce many of the other elements. In Ref. 51, which is not devoted to Ap stars, a model is described for the production of heavy elements when matter is ejected from a neutron star. This mechanism is not so catastrophic for a star as a supernova explosion, and the star can periodically replenish interstellar space with heavy elements. However, it is hard to accept that there is a neutron star in the neighborhood of every Ap star, and therefore we shall not consider this model further.

In Ref. 52, the possibility is analyzed that promethium could be produced in the reactions Nd(p, n)Pm, ^{148}Nd (γ, n) ^{147}Nd (β^-) ^{147}Pm, and Sm(n, p)Pm. The cross sections of these reactions at a proton energy around 7 MeV were calculated by means of the optical model using parameters extrapolated by means of Perey's formula.[53] The minimal proton flux needed to obtain the observed Pm/Nd ratio is 10^{15} protons $\cdot$ cm^{-2} $\cdot$ sec^{-1}; estimates show that if Pm lines are observed in an Ap star, the ratio Pm/Nd must be not less than a few percent.

Photonuclear mechanism of promethium production. Edwards and Harrison[55] proposed a photonuclear reaction for the production of promethium and technetium in the atmospheres of stars. The source of γ rays is one of the reactions in the CNO cycle, namely

$$^{15}\mathrm{N} + p \rightarrow {}^{16}\mathrm{O} + \gamma \quad (E_\gamma > 12\ \mathrm{MeV}).$$

Some investigators assume[55] that promethium is not present in conjunction with technetium. Let us say right away that such predictions have little basis.

A reaction in which ^{147}Pm is produced but not ^{99}Tc simultaneously was proposed by Harrison.[56] Promethium can be produced in the reaction ^{148}Nd (γ, n) ^{147}Pm. The threshold energy of the γ rays for this reaction is 7.3 MeV. The source of the γ rays is a different reaction in the CNO cycle: $^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} + \gamma$ ($E_\gamma = 7.5$ MeV). The energy of these γ rays is insufficient for production of technetium in the reaction ^{100}Mo (γ, n) ^{99}Mo (β^-) ^{99}Tc since the threshold of this reaction is 8.3 MeV. There is no experimental value of the cross section of the reaction $^{148}Nd(\gamma, n)^{147}Nd$.

In the calculations made in Ref. 56, Harrison obtained the deviation for the ratio $^{147}Pm/^{148}Nd$, varying the reaction cross section and the integrated γ flux. He took into account the time needed for convective transport of the promethium to the surface of the star, the convection velocity being taken equal to 0.5 km/sec. With regard to the plausibility of the suggestion that Pm and Tc are not contained together in the atmospheres of Ap stars let us say the following. Irrespective of their origin, γ rays lose some of their energy in scattering processes before being absorbed by the nucleus ^{148}Nd or the nucleus ^{100}Mo. It is therefore hard to support selectivity of the γ absorption reaction under stellar conditions.

CONCLUSIONS

If the reader now has the opinion that at the present time there is no consistent theory capable of explaining the peculiarity in the spectra of Ap stars, this should be attributed, not so much to my inability to expound the subject clearly, as to the reality of the situation. It has not changed much since 1971, when Sargent and Burbidge expressed the following opinion: "There is high probability that diffusion to the surface of the star and accretion of matter synthesized within a neighboring star played a role in the creation of these remarkable objects."

We may find that stars that are now in different subgroups were also different in the past. There is also no doubt that for later theoretical investigations it is important to obtain as much information as possible about the abundances in Ap stars of heavy elements, in particular, the transuranium elements. From the relative abundance of the transuranium elements and the methods developed in nuclear chronology, one can with great accuracy determine the time when the last nucleosynthesis event took place. Let us, for example, consider the pair U–Th. During the first 10^7 years after the ending of the r process, the U abundance exceeds the Th abundance by 5–10 times, and it is only after 10^9 years that the abundances of these elements become equal. Determination of the Pm abundance and also the isotopic composition of other elements may be a good tool for any theory but it is difficult for the following reasons: The identification of the lines in the stellar spectra is complicated, the experimental spectra of these elements and their ions are not known completely, nor are the oscillator strengths, and there are considerable uncertainties in the models of the atmosphere. As a summary, I invite the reader to consider Fig. 7, which illustrates possible explanations for the unusual composition of Ap stars.

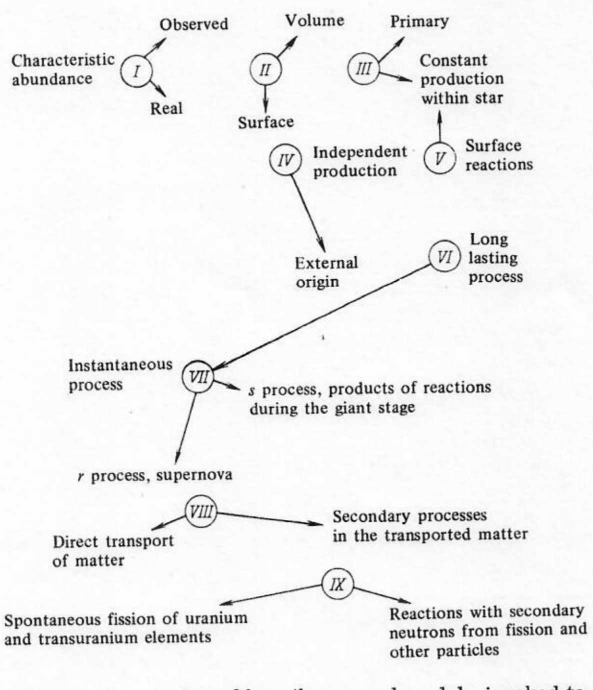

FIG. 7. Succession of hypotheses and models invoked to explain the anomalous abundances of the chemical elements in Ap stars.[59]

[1]H. W. Babcock, Astrophys. J. 137, 690 (1963).
[2]P. J. Brancazio and A. G. W. Cameron, Can. J. Phys. 45, 3297 (1967).
[3]G. W. Preston, Nucl. Instrum. Methods 110, 405 (1973).
[4]S. J. Adelman, Astrophys. J. 183, 95 (1973).
[5]W. L. W. Sargent and L. Searle, Astrophys. J. 136, 408 (1962).
[6]L. Searle and W. L. W. Sargent, Astrophys. J. 139, 793 (1964).
[7]A. I. Sargent, J. L. Greenstein, and W. L. W. Sargent, Astrophys. J. 157, 757 (1969).
[8]B. Kuchowicz, in: Proc. Intern. Conf. on Heavy Iron Physics, Dubna, Febr. (1971), JINR Dubna (1971), p. 31.
[9]E. Jensen, Nature 194, 668 (1962).
[10]H. W. Babcock, Astrophys. J. 137, 690 (1963).
[11]W. A. Fowler *et al.*, Astrophys. J. 142, 423 (1965).
[12]J. R. Percy, Astron. J. 80, 698 (1975).
[13]G. R. Burbidge and E. M. Burbidge, Astrophys. J. Suppl. 1, 431 (1955).
[14]P. J. Brancazio, A. Gilbert, and A. G. W. Cameron, Can. J. Phys. 45, 3275 (1967).
[15]O. Havnes and P. S. Conti, Astron. Astrophys. 14, 1 (1971).
[16]G. Michaud, Astrophys. J. 160, 641 (1970).
[17]S. B. Pikel'ner and V. L. Khokhlova, Comm. Astrophys. Space Sci. 3, 190 (1971).
[18]E. P. J. Van den Heuvel, Bull. Astron. Inst. Neth. 19, 11 (1967).
[19]B. N. G. Guthrie, Publ. R. Obs. Edinburgh 6, No. 6, 145 (1966).
[20]P. Renson, Ciel et Terre 79, 68 (1963).
[21]G. Michaud, H. Reeves, and Y. Charland, Astron. Astrophys. 37, 313 (1974).
[22]A. G. W. Cameron, Publ. Astron. Soc. Pac. 83, 585 (1971).
[23]M. F. Aller, and C. R. Cowley, Astrophys. J. 162, L145 (1970).
[24]S. C. Wolff and N. D. Morrison, Astrophys. J. 175, 473 (1972).
[25]I. A. Aslanov, M. Kowalski, and Yu. S. Rustamov, IAU Colloquium No. 32 (Ed. W. W. Weiss), Vienna (1976).
[26]W. L. W. Sargent, Ann. Rev. Astron. Astrophys. 2, 297 (1964).
[27]M. Jaschek and E. Brandi, Astron. Astrophys. 20, 233

(1972).
[28]B. N. G. Guthrie, Astrophys. Space Sci. 15, 214 (1972).
[29]P. Galeotti, Astrophys. Space Sci. 31, 193 (1974).
[30]B. N. G. Guthrie, Observatory 89, 224 (1969).
[31]M. Jaschek and S. Malaroda, Nature 225, 246 (1970).
[32]E. Brandi and M. Jaschek, Publ. Astron. Soc. Pac. 82, 847 (1970).
[33]C. R. Cowley, M. R. Hartoog, M. F. Aller, and A. P. Cowley, 183, 127 (1973).
[34]C. R. Cowley *et al.*, Astrophys. J. 194, 343 (1974).
[35]S. J. Adelman, Astrophys. J. Suppl. 26, 1 (1973).
[36]M. M. Dworetsky, Astrophys. J. 156, L101 (1969).
[37]M. F. Aller, Astron. Astrophys. 19, 248 (1972).
[38]M. M. Dworetsky, J. E. Ross, and L. H. Aller, Bull. Am. Astron. Inst. Soc. 2, 311 (1970).
[39]W. P. Bidelman, Astrophys. J. 135, 651 (1962).
[40]W. P. Bidelman, in: Abundance Determination in Stellar Spectra (IAU Symposium No. 26) (Ed. H. Hubenet), Academic Press, New York (1966), p. 229.
[41]G. Preston, Astrophys. J. 164, L41 (1971).
[42]B. N. G. Guthrie, Astrophys. Space Sci., 10, 156 (1971).
[43]S. C. Wolff and R. J. Wolff, Astrophys. J. 194, 65 (1974).
[44]S. J. Adelman and S. S. Shore, Astrophys. J. 183, 121 (1973).
[45]J. Hardorp and S. S. Shore, Publ. Astron. Soc. Pac. 83, 605 (1971).
[46]C. R. Cowley and M. R. Hartoog, Astrophys. J. 178, L9 (1972).
[47]C. R. Cowley and S. J. Adelman, Astrophys. Lett. 16, 5 (1975).
[48]S. J. Adelman, Astron. Astrophys. 24, 325 (1973).
[49]C. R. Cowley and M. F. Aller, Astrophys. Lett. 9, 159 (1971).
[50]I. P. Selinov, Proc. Second UN Intern. Conf. on the Peaceful Uses of Atomic Energy. Vol. 30, Unit. Nations, Geneva (1958), p. 307.
[51]V. M. Chechotkin and M. Kowalski, Nature 259, 643 (1976).
[52]H. R. E. Tjin *et al.*, Astrophys. Lett. 13, 215 (1973).
[53]F. G. Perey, Phys. Rev. 131, 745 (1963).
[54]J. B. Blake and D. N. Schramm, Astrophys. Space Sci. 30, 275 (1974).
[55]T. W. Edwards and T. G. Harrison, Astrophys. J. 187, 313 (1974).
[56]T. G. Harrison, Astrophys. Lett. 16, 87 (1975).
[57]R. C. Cowley, Not. from Observ. 93, 195 (1973).
[58]R. C. Cowley, M. S. Allen, and C. G. L. Aikman, Nature, 258, 311 (1975).
[59]B. Kuchowicz, IAU Colloquium No. 32 (Ed. W. W. Weiss), Vienna (1976).
[60]T. Ohnishi, Nature 249, 532 (1974).
[61]M. Hack, Sky and Telescope 36, No. 2, 92 (1968).
[62]S. B. Pikel'ner and V. L. Khokhlova, Usp. Fiz. Nauk 107, 389 (1972). [Sov. Phys. Usp. 15, 395 (1973)].
[63]A. M. Sourkes *et al.*, Phys. Lett. B 51, 232 (1974).
[64]B. J. Allen *et al.*, in: Advances in Nuclear Physics, Vol. 4 (Ed. M. Baranger and E. Vogt), Plenum Press, New York (1971), p. 205.
[65]A. K. Chaubey and M. L. Sehgal, Phys. Rev. 152, 1055 (1966).

Translated by Julian B. Barbour