Dense matter theory: a simple classical approach

P. Savic\textsuperscript{1} and V. Celebonovic\textsuperscript{2}

\textsuperscript{1} Serbian Academy of Sciences and Arts, Knez Mihajlova 35, 11000 Beograd, Yugoslavia
\textsuperscript{2} Institute of Physics, Pregrevica 118, 11080 Zemun-Beograd, Yugoslavia.

celebonovic@exp.phy.bg.ac.yu
vcelebonovic@sezampro.yu

\textsuperscript{2} to whom all communications should be sent.
Abstract: In the sixties, the first author and R. Kasanin started developing a mean-field theory of dense matter. It is based on the Coulomb interaction, supplemented by a microscopic selection rule and a set of experimentally founded postulates. Applications of the theory range from the calculation of models of planetary internal structure to DAC experiments.
The purpose of this paper is to review briefly the main ideas and examples of applicability of a particular classical theory of the behaviour of materials under high pressure. It was developed jointly by the first author and R. Kasanin in the early sixties [2] (abbreviated as SK in the following).

The starting point for its development was a paper by Savic [1], referred to as S61, which had the aim of exploring the origin of rotation of celestial bodies. As a result of this work, there emerged the conclusion that rotation is closely related to the internal structure, and that a theory of dense matter was needed to explain it correctly.

The starting object of S61 is a low-temperature cloud of arbitrary shape containing any number of chemical elements and their compounds. Two processes influence the life of such a cloud: the mutual gravitational interaction of its constituting particles, and the loss of energy due to thermal radiation. As a combined result, the temperature of the cloud decreases, while its mean density and internal pressure increase. Increasing pressure leads to excitation and ionisation of atoms and molecules in its interior. In quantum-mechanical terms, this means that increasing pressure leads to the expansion of the radial part of the electronic wave-function of the atoms and molecules that make up the material. A quantum-mechanical treatment of this process has been given only recently [3], nearly three decades after the idea was used in SK.

Due to pressure ionization, the primeval cloud passes into the state of a two-component plasma (assuming, for simplicity, that the cloud consists of one chemical element). It consists of a randomly moving free-electron gas (which has a non-zero magnetic field [4]) and the atoms and molecules ionized under pressure. Owing to high pressure their magnetic moments become oriented in parallel, and the resulting torque starts the rotation of the whole system. Although it may seem highly qualitative, a detailed elaboration of this mechanism ([2] parts III and IV, or [5]) gives values of the strengths of the magnetic fields and the allowed intervals of the speed of rotation of the Sun and the planets, which are in good agreement with the observed values. For example, the SK theory gives for the magnetic field of Jupiter a value between 10 and 14 Gauss, while the measured value is 14 [5]. The observed value of the speed of rotation of the solar equatorial region is \(2.9 \times 10^{-6}\) rad s\(^{-1}\); the possible interval according to SK is \(1.2 \leq \omega \leq 44.7\) rad s\(^{-1}\).
Apart from the magnetic fields and the speed of rotation, SK gives the possibility of complete modelling of the internal structure of solar system bodies. One can thus determine the number of layers in the interior of the object and their thickness, the distribution of pressure, density and temperature with depth, the mean atomic mass of the chemical mixture that the object is made of. For example, it was calculated within SK that the depth of the Moho discontinuity is 39 km; the experimental value is 33 km. It was shown that the magnetic moment of the Moon is zero, which was later confirmed by in-situ measurements. More examples are given in [5]. The temperature of the Earth’s center was estimated, starting from SK, as 7000 K [9], which is close to experimental values. A word about chemistry: it has been shown that the asteroid (1) Ceres and Neptune’s satellite Triton are similar (by their mean atomic mass) to Mars and Mercury, which has cosmogonical implications.

The SK theory has also found applications in laboratory high pressure work. It provides a method for determining phase transition points and equations of state of materials exposed to high pressure by a calculational procedure that is much simpler than the usual approach in statistical mechanics. The mean interparticle distance is defined so as to correspond to the position of stable equilibrium of the “full” interparticle interaction; it is assumed in SK that the atoms and/or molecules in a specimen under pressure interact only by the bare Coulomb potential. A succession of phase transitions is presumed to occur in a specimen subdued to increasing pressure, and a selection rule, giving the possibility to “pick” only those transitions which are physically realizable in a given material, has been developed. The densities of two successive phases are assumed to differ by a factor of two. This ratio is a consequence of an empirical rule, first discussed in S61 in an astrophysical context whose validity was later extended to laboratory high pressure work [2],[8],[10].

Starting from these (and three more) postulates discussed in detail in [8], it becomes possible to determine high pressure phase transition points of materials in DAC experiments.
Metallisation of hydrogen is predicted to occur at 3 Mbar, while the corresponding value for helium is 106 Mbar [8]. A detailed comparison of the predictions of the SK theory with DAC experiments on 19 materials and a discussion of some possible causes of the existing discrepancies has recently been published [10]. For example, a phase transition occurs in CdS at 27 kbar, while the SK prediction is 26.3 kbar.

Work aimed at refining the method for deriving the EOS of a material under pressure and diminishing the causes of discrepancies discussed in [10] is at present in progress.

Note (added March 7th, 1998):


References