DENSE PLASMAS, NUCLEAR REACTIONS AND ASTROPHYSICS
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1. Introduction.- The solution of a large number of astrophysical problems depend on the understanding of the physical properties of dense matter. However, the expression dense matter does not refer to a simple domain in the plane of the state variables \((T, p)\). (1) Dense matter can be defined as a highly correlated plasma. If we call \(a\) the radius of the ionic sphere,

\[
\frac{4}{3} \pi a^3 N_a = 1
\]

a highly correlated plasma is defined by the condition

\[
\Gamma = \frac{Z^2 e^2}{4 \pi \varepsilon_0 k T} \gg 1
\]

The classical domain of the solid state is defined by \(\Gamma = 160\). The recent extension by Hansen and Mochkovitch (1979) to a lattice of Fermions and Bosons gives for the density of melting at \(T = 0\), \(R_0 = 100\) for Bosons and \(R_S = 65\) for Fermions, with \(R_S \approx a/a_0\) where \(a_0 = \left(\frac{\hbar^2}{m_e e^2}\right)\) is the ionic Bohr radius and \(a\) is the ion sphere radius. This corresponds to densities

\[
\rho = \frac{3}{4 \pi} \left(\frac{Z}{2}\right)^6 10^6 \frac{e^6}{h^3 R_S} m_H^4
\]

For oxygen \(^{16}\text{O}\), this gives \(\log 10^\rho = 15.38\); for \(^{12}\text{C}\), this gives \(\log 10^\rho = 14-16\); and for \(^{16}\text{C}\), \(\log 10^\rho = 14.67\). It should be noticed that these densities are far beyond the threshold densities for inverse Beta reactions (Beta captures), and lay in the region of nuclear densities and beyond.

\[(\text{Fig.1})\] The \((\log T, \log \rho)\) plane. The curves \(^1\text{H}, ^{12}\text{C}, ^{16}\text{C}, ^{16}\text{O}\) represent the melting curves for a one component plasma (OCP), according to the last results of Hansen and Mochkovitch (1979). The boundary between the degenerate region (D) and the non degenerate region (ND) is plotted for \((A/Z) = 2\). The level of electron capture for Carbon and Oxygen is indicated by \(^{12}\text{C}^\nu\) and \(^{16}\text{O}^\nu\). The nuclear density is \(\rho_n\). The region beyond \(4\rho_0\), where the difficulties begin is indicated by the dotted area. The line \((1/9)\rho_0\) corresponds to the at which the baryon interactions are not negligible.

(2) Dense matter can be defined as matter at sub-nuclear and nuclear density and beyond. The transition region begins somewhere below nuclear density, in the domain where nuclear forces become important. The nuclear density, which is in number density \(0.17 \text{ fm}^{-3}\) corresponds to \(\rho_{\text{nucl}} = 10^{14.43} \text{ g cm}^{-3}\). Nuclear forces are already

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DENSE PLASMAS, NUCLEAR REACTIONS AND ASTROPHYSICS

Evry Schatzman
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Résumé .- Un certain nombre de questions sont posées aux physiciens et astrophysiciens concernant : (1) les conditions dans lesquelles la matière stellaire vient constituer un plasma fortement corrélé ; (2) le rôle de la perte de masse dans la formation de la matière dense ; (3) l'évolution des naines blanches sous l'effet de l'accrétion (avec ses implications pour la formation des sources X compactes et des pulsars).

Abstract .- A certain number of questions are raised to physicists and astrophysicists concerning : (1) the conditions under which stellar matter becomes a highly correlated plasma ; (2) the role of mass loss in the formation of dense matter ; (3) the evolution of white dwarfs accreting matter (with its consequences for the formation of compact X ray sources and pulsars).

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important at a number density of 0.02 \((\text{fm})^{-3}\)
which corresponds to \(\rho = 10^{13.48} \text{ g cm}^{-3}\).
It seems that our understanding of physics of neutron star matter at \(\rho \approx 4 \rho_{\text{nucl}} = 10^{15} \text{ g cm}^{-3}\) is not satisfactory yet.
Matter at these densities can be studied in thermodynamic equilibrium. However, it is quite important to understand how these high density regions are reached. The kinematics and the thermodynamics of the transformation are important, and depend very much of the starting point in the \((T, \rho)\) diagram. These properties of dense matter are relevant to the structure of neutron stars, the formation of neutron stars, and the exploding process leading to supernovae.

2. Astrophysical considerations: stellar evolution at constant mass. – We shall consider, in the following, the conditions under which ordinary matter becomes dense matter. The starting point of the discussion is given by the conventional stellar evolution at constant mass.

We shall be interested here by the evolutionary tracks of the stellar center, for different values of the stellar mass. Such tracks have been plotted by Iben (1973a, 1974) and Shaviv (1967), Barkat (1975).

(Fig.2) : The \((\log T, \log \rho)\) plane. Evolution at constant mass. Evolutionary tracks of the center of a star for different stellar mass as given by Iben (1973a); the boundary between degenerate \((D)\) and non-degenerate \((ND)\) regions has been plotted for \((A/Z) = 2\). The ignition lines for \(H\), \(He\) and \(C\) have been plotted. The Carbon ignition line is the ignition line of Paczynski.

The numbers 1, 2, 3, 7, 9 and 15 are the stellar masses in solar units.

We have reproduced on figure 2 the evolutionary tracks of Iben (1973a). Except for very low mass stars, hydrogen ignition takes place in the region where the electron gas is non-degenerate. It is quite well known that the evolution of the star depends very much whether the star reaches the helium ignition line in the degenerate region, or in the non degenerate region. In the degenerate region, the equation of state is known as depending very little on the temperature. This has been recognized since Heisel (1952) as giving the possibility of a thermal runaway.

The mass in the hydrogen-exhausted core at the start of the thermal runaway appears to be relatively independent of the abundance of elements heavier than helium and also relatively independent of the total mass outside the degenerate core. For values of initial hydrogen content \(X \approx 0.6 - 0.7\), the helium core mass is about \(0.4 \, M_\odot\). The thermal runaway produces a major change in the star. Core temperature rises until degeneracy is lifted. The star moves, in the Hertzsprung-Russell diagram, to the horizontal branch, where it starts evolving from the ZAHB (zero age horizontal branch). Stars of mass smaller than about 2.25 \(M_\odot\) reach the He ignition line in the degenerate region, whereas stars of mass larger than about 2.25 \(M_\odot\) reach the He ignition line in the non-degenerate region. Helium burning begins and core temperature continues to increase, so that electron degeneracy never becomes appreciable in the core. Helium burning in the core leads to the production of carbon and oxygen. The stellar core moves towards the carbon ignition line, which is defined as the line where the rate of energy production by carbon burning is not balanced any more by the neutrino losses. The situation again is quite different, depending on whether the stellar core is degenerate or not. If the stellar core is degenerate, a thermal runaway can take place. If the stellar core is not degenerate, the temperature rise in the core prevents it of ever becoming strongly degenerate. The stellar core in which a thermal runaway due to carbon burning can take place, has a mass of the order of 1.4 \(M_\odot\) (the so-called Chandrasekhar limit), and this cor-
responds to an initial stellar mass of about 7 \( M_\odot \). At the end of the helium burning phase, the chemical composition of the core is a mixture of carbon and oxygen, and it depends on the stellar mass. The exact place in the \( \log \rho, \log T \) plane at which the thermal runaway takes place depends mainly on the enhancement factor of thermonuclear reactions (Schatzman, 1978; Alesuey and Jancovici, 1978; Salpeter, 1954; Salpeter and Van Horn, 1969; De Witt, Graboske and Cooper, 1973; Mitler, 1977; Itoh, Totsuji and Ichimura, 1977; Jancovici, 1977).

3. Problems of mass loss. - There are several ways of approaching the problem of mass loss: (1) the direct observational evidence; (2) the determination of the mass of the parent stars of white dwarfs in galactic clusters; (3) the abundance of iron in the Galaxy and the critical mass; (4) the theoretical estimates of the rate of mass loss; (5) consequences of mass loss on stellar evolutions. We shall limit here ourselves to the empirical evidence, the theoretical ones being presently not sufficiently sure to give any reliable estimate of the rate of mass loss and we comment the consequences for stellar evolution. At most, the theoretical models of the rate of mass loss show the compatibility of the empirical evidence and of the theory. However, stellar evolution models with empirical rates of mass loss give interesting indications on the changes of stellar structure due to mass loss.

(i) Direct observational evidence. All studied red giants and supergiants appear to have an expanding circumstellar envelope. The analysis of the line profiles and thermodynamics of the envelope have been carried several times (for example, Sanner, 1976; Barnat, 1977).

It should be noticed that the interpretation of the spectra is not easy and that the mass loss estimates vary greatly from one author to another. The rate of mass loss can be very large (\( 10^5 M_\odot \) year\(^{-1} \)), and there is some evidence that it increases with the luminosity and decreases with the kinetic energy of escape. A possible parameter describing the rate of mass loss is the quantity \( LR/M \) (Reimers, 1975a, b). Theoretical estimates by Renzini et al. (1977b), Ullmschneider et al. (1977a, b) based on the old idea of Biermann (1946), Schwarzschild (1948), Schatzman (1949) of acoustic heating of the solar chromosphere and corona, adjusted to the rate of mass loss of the Sun are compatible with the mass loss rate of Reimers. We shall use, in the following, the notation of Renzini (1977),

\[
\frac{dM}{dt} = -4 \times 10^{-13} \eta_R \frac{L}{R} \frac{M}{M_\odot} \text{ (} M_\odot \text{ year}^{-1} \text{)}
\]

where \( L, R \) and \( M \) are in solar units, and \( \eta_R \) is an adjustable factor.

Mass loss in large mass stars takes place also at a considerable rate. Results obtained with Copernicus, according to Snow and Morton (1976) show that for hot stars mass loss is a quite general phenomenon: stars brighter than \( M_{\text{Bol}} = -6.0 \) are losing mass. Estimates of mass loss, using infrared photometric results, have been given by Barlow and Cohen (1977). With a correction suggested by Lamers and Castor (1978) concerning the velocity law, the rates of mass loss of Barlow and Cohen should be doubled, with the following laws:

\[
\frac{dM}{dt} = -13.6 \times 10^{-13} (L/L_\odot)^{1.10} M_\odot \text{ yr}^{-1} \quad \text{for O stars,} \tag{5}
\]

\[
\frac{dM}{dt} = -10 \times 10^{-13} (L/L_\odot)^{1.2} M_\odot \text{ yr}^{-1} \quad \text{for B and A supergiants,} \tag{6}
\]

(ii) White dwarfs. Different methods of analysis, as described by Sweeney (1976), and by Romanishin and Angel (1979) give estimates of the mass of parent stars of white dwarfs in globular clusters. Results can be summarized in table I.
Table I

Mass of parents of white dwarfs.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>$n_{WD}$</th>
<th>$M_{WD\ min}$</th>
<th>$M_{WD\ max}$</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyades</td>
<td>13</td>
<td>2.7</td>
<td>4.5</td>
<td>a</td>
</tr>
<tr>
<td>Pleiades</td>
<td>1</td>
<td>5.25</td>
<td>8</td>
<td>a</td>
</tr>
<tr>
<td>Sirius groupe</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>a</td>
</tr>
<tr>
<td>61 Cyg</td>
<td>3</td>
<td>1</td>
<td>1.1</td>
<td>a</td>
</tr>
<tr>
<td>γ Leo</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>a</td>
</tr>
<tr>
<td>NGC 2168</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>b</td>
</tr>
<tr>
<td>2287</td>
<td>8±5</td>
<td>4</td>
<td>7</td>
<td>b</td>
</tr>
<tr>
<td>2422</td>
<td>1</td>
<td>6</td>
<td>-</td>
<td>b</td>
</tr>
<tr>
<td>6633</td>
<td>10±5</td>
<td>(\approx 4)</td>
<td>5</td>
<td>b</td>
</tr>
</tbody>
</table>

$n_{WD}$ : number of white dwarfs in the cluster ;

$M_{WD\ min}, M_{WD\ max}$ minimum and maximum mass of the parent stars of white dwarfs in the cluster

(a) Sweeney ; (b) Romanishin and Angel.

It seems then that for an isolated star, the mass of the parent star can be as large as 7 $M_\odot$ ; see also Weidemann (1977).

(iii) The critical mass. The concept of critical mass has been introduced in connection with the problem of supernovae ; the critical mass is the mass above which a star, at a late stage of evolution, becomes a supernova.

Considering a given frequency of supernovae it is tempting to relate this frequency to the rate of stellar death. Tamman (1974) suggests, in our Galaxy, a birth rate of supernovae of 0.04 yr\(^{-1}\) (if it is an Sb galaxy), or perhaps of 0.1 yr\(^{-1}\) (if it is an Sc galaxy). From the estimates of Ostriker et al. (1974), it is possible to give the total death rate for stars having a mass larger than $M$ (table II).

<table>
<thead>
<tr>
<th>((M/M_\odot)) larger than</th>
<th>(\tau) (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>6</td>
</tr>
<tr>
<td>2.9</td>
<td>10</td>
</tr>
<tr>
<td>5.1</td>
<td>25</td>
</tr>
<tr>
<td>7.4</td>
<td>50</td>
</tr>
<tr>
<td>9.1</td>
<td>100</td>
</tr>
</tbody>
</table>

The estimates of $\tau$ for our Galaxy are quite uncertain. The discussion is carried in the following way :

(a) Assume stellar evolution without mass loss. With a high birth rate of supernovae, it is necessary to assume that all stars having a mass larger than 3 to 4 $M_\odot$ explode. For moderate mass stars, with $4 M_\odot \lesssim M \lesssim 8 M_\odot$, the stellar core reaches the carbon ignition line in the degenerate region. The mass of the degenerate core is about $1.4 M_\odot$. Ostriker et al. (1974), consi-
der the possibility that all moderate mass stars explode entirely, each ejecting a 1.4 $M_\odot$ of iron-peak element at death. This, however, spreads in the Galaxy a larger amount of iron, too large by a factor of the order of 60.

b) A way out of this difficulty, which has been discussed for example by Renzini (1977), by Schramm (1977) is the following. Assume that mass loss is a very efficient process, such that all stars with a mass smaller than $M_{\text{crit}} \approx 8 M_\odot$ become white dwarfs. Then, the problem of the iron excess is solved. This however implies (1) that the supernovae birth rate is of the order of $50^{-1} \text{ yr}^{-1}$; (2) that the efficiency of the mass loss is very high, increasing with the stellar mass, up to $n_R \approx 4$. (defined in equ. 4). Renzini (1977) notices that such a high efficiency cannot apply to lower mass stars.

(c) On the other hand, consider the energy available during explosive carbon burning. For a degenerate core of 1.4 $M_\odot$, close to the instability limit, the energy available, of the order of 0.54 Mev per nucleon, can be much larger than the binding energy of the star. Disruption of the star takes place only in the case of a detonation wave, where a large fraction of the available energy is transformed into kinetic energy. If, instead of a detonation, there is a deflagration, the energy available is transformed into thermal energy, producing a pressure excess which is a small fraction of the degenerate pressure. Mazurek et al. (1977) have suggested that the pressure excess due to carbon burning is so small, for densities larger the $5 \times 10^7 \text{ g cm}^{-3}$ that no detonation wave can be produced.

(iv) Theoretical estimates. We shall not insist on this aspect of the problem, as the theoretical models are yet quite unsatisfactory, whether considering the mass loss due to radiation pressure or the mass loss due to the existence of a heating mechanism related to the presence of a deep hydrogen convective zone. In this connection, it is worth mentioning the results obtained with the satellite HEAO I, showing the presence of a corona in A stars, the difficulties met with the balance between the radiative emission of the chromosphere and the divergence of the mechanical flux, as estimated by Athay and White (1978). (See also Durrant, 1978). We can only say that the mass fluxes which can be derived from theoretical arguments are compatible with the observations, but that this cannot yet be considered as a full theory of the mechanism of mass loss.

(v) Stellar evolution with mass loss. A large number of papers have been devoted recently to stellar evolution with mass loss; for moderate-mass stars by Fusi-Pecchi and Renzini (1975a, b; 1976; 1978), Renzini (1977, 1978), for a 5 $M_\odot$ star by Forbes (1968), for large mass stars by a number of authors, Chiosi and Nasi (1974), Dearborn, Blake, Rainebach and Schramm (1978), Sreenivasan and Wilson (1978a, b), Chiosi, Nasi and Sreenivasan (1978), Stothers and Chin (1978), Chiosi, Nasi and Bertelli (1979), de Loore, de Greve and Lamers (1977), Dearborn and Eggleton (1977) see also the review paper by Conti (1978). We are concerned here with the changes in central density and temperature which are produced by mass loss. As an example, consider the evolution of a 5 $M_\odot$ star calculated by Forbes (1968). The mass loss is considerable, leading to a final mass of 0.928 $M_\odot$. However, during the helium burning phase, the differences in central temperature and central density for the star evolving at constant mass, or with an heavy mass loss, are very small. Nevertheless, the core of the star evolving at constant mass will move towards the carbon ignition line, whereas the small mass remnant will end as a white dwarf with log $\rho_0 = 7.32$ and a low temperature ($= 10^7 \text{ K}$) (Fig.3).
Consider now the events which take place during cooling. If \( X < X_E \), we first deposit oxygen. The density of solid oxygen, at \( T_0 = 1.615 \ T_C \) (\( T_C \) is the freezing point of pure carbon) is larger than the density of the remaining mixture of carbon and oxygen. We actually have, from Pollock and Hansen (1973)

\[
\frac{\rho(\text{solid O}) - \rho(\text{liquid O})}{\rho} \approx 3 \times 10^{-4}
\]

Whereas we have

\[
\frac{\rho(\text{solid C}) - \rho(\text{liquid mixture})}{\rho} = \frac{0.00480 - 0.00508 \ X}{0.00312}.
\]

Oxygen then solidifies near the center, and finally, when the eutectic solidifies, a mixture of carbon and oxygen crystals solidifies at \( T = 0.628 \ T_C \).

If \( X > X_E \), we first deposit carbon. We actually have

\[
\frac{\rho(\text{solid C}) - \rho(\text{liquid mixture})}{\rho} = \frac{0.000618 - 0.000318 \ X}{0.000300}.
\]

Carbon solidifies near the center and finally when the eutectic solidifies a mixture of carbon and oxygen crystals solidifies at \( T = 0.628 \ T_C \).

Assume now that accretion on a white dwarf takes place, the mass growing with time. In the first case, \( X < X_E \), electron capture takes place in the center before reaching the gravitational instability limit. The star contracts and enter dynamical collapse. It should be noticed that the heating which is associated with the electron capture has very little influence on the equation of state.

The energy available per electron can be determined in the following way. At constant pressure, the energy gained is

\[-Pdv + \varepsilon(16O,16O).\]
1.1 Per free electron, this is \( \frac{1}{16} \epsilon_M + \frac{1}{12} \epsilon(16^016^0) \), where \( \epsilon_M = 10.4 \text{ MeV} \) is the threshold energy for the capture of one electron on \( 16^0 \). \( \epsilon(16^016^0) = 16.541 \text{ MeV} \), so that the energy available, per free electron, is 2.028 MeV. The excess pressure due to non-degeneracy is only 0.0775, and can hardly have any influence on the collapse. If oxygen did not have time to ignite, the excess pressure would be only 0.0229. In the second case, \( X > X_E \), gravitational collapse takes place first. The energy at threshold is \( \epsilon_M = 13.37 \text{ MeV} \). The electron capture and the energy of the \( ^{12}\text{C} \rightarrow ^{12}\text{C} \) reaction \( \epsilon_N = 13.93 \text{ MeV} \) gives \( \epsilon = 2.275 \text{ MeV} \) per free electron. The final contribution to the pressure is 0.0646; if carbon did not have time to ignite, the excess would be only 0.0295.

In both cases, the temperature which is obtained in the center is very high, of the order of \( 10^{10} \), and the thermonuclear reaction rate at such temperatures is extremely high. Assuming however that the condition of Mazurek et al. (1977) for the formation of a detonation wave has to be fulfilled, we find that the detonation can take place in a larger mass fraction (1.3 % of the mass of the star) for the solid oxygen core, than for the solid carbon core (0.94 % of the mass of the star). Anyhow, it is impossible to give a correct estimate of the difference in behaviour of the two kinds of stars without a complete analysis of the collapse and bounce. It is nevertheless tempting to relate the possibly different exchange of momentum taking place in a binary star to a difference in chemical composition of the accreting white dwarf. The binary nature of the star might be conserved (leading to a compact X ray source), or the neutron star can be launched in the galaxy, producing a high velocity pulsar.

5. Conclusion.— A large number of physical problems, of a great importance for astrophysicists, await a solution, or a greater precision in the solution, especially in the field of thermodynamics of dense matter (transport processes, equation of state above nuclear density, properties of highly correlated two components plasmas, enhancement factor of nuclear reactions in mixtures, neutrino losses etc.,...); or astrophysicists still have to carry the computations, using the date provided by the physicists, to the point where it is actually possible to compare the theory with the observations.

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