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Thermonuclear Plasma Conditions in Stellar Interiors [and Discussion]

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Thermonuclear plasma conditions in stellar interiors

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Thermonuclear reactions provide the main source of radiated energy for stars and they are also believed to be responsible for the production of most of the heavy elements in the Universe. The thermonuclear plasma is confined by the force of gravitation and for most of a star's history the reactions occur slowly and steadily. In some circumstances, the properties of a star change very rapidly and explosive nuclear reactions occur. In very dense stellar interiors the energy states available to electrons may be limited by the Pauli exclusion principle. When thermonuclear reactions start in such a degenerate gas, a rise in temperature is not accompanied by a significant rise in pressure and as a result there may be a runaway increase in reaction rate. In contrast, when reactions start in a non-degenerate gas, there is normally an effective thermostat. A star is usually opaque to reaction products, so that there is no problem in maintaining the reaction temperature, but at late stages of stellar evolution nuclear or elementary particle reactions may produce large numbers of neutrinos and antineutrinos that do escape.

1. Introduction

Thermonuclear reactions supply most of the energy that is radiated by stars during their life history. Before the stellar central temperature is high enough for nuclear reactions, the radiated energy is provided by gravitational contraction, and in some cases the final stage of gravitational collapse to a neutron star or a black hole may provide an energy release higher than the thermonuclear energy throughout the star's life. However, although the most violent astronomical events are probably powered by gravitational energy, thermonuclear reactions are the most uniformly important process. In addition to their role in providing the radiated energy of stars, they result in a conversion of light elements into heavy elements. If, as seems likely, the original chemical composition of the Universe was essentially a mixture of hydrogen and helium, the heavy elements which we observe today were probably mainly produced by fusion reactions in previous generations of stars and subsequently expelled into the interstellar medium, where they could be incorporated in later generations of stars.

Since it became clear that nuclear fusion reactions were almost certainly the major source of stellar radiation, a very good qualitative understanding of stellar evolution and of the place of different types of star in the evolutionary pattern has been obtained; see for example any standard text on stellar evolution such as Clayton (1968). In general one is attempting to explain the observed surface properties of stars in terms of unseen processes in their deep interiors. Only one way of studying the interior of a star is known. If neutrinos are produced in nuclear reactions, they can escape from a normal star and can in principle be detected. Neutrinos escape freely from stars because they interact so weakly with matter, but this in turn means that a very high flux is needed for them to be detected. This should be possible for the Sun and possibly from a much more distant catastrophic event.

The main nuclear reactions in stars involve the conversion of hydrogen into helium; because two neutrons are produced from protons, two neutrinos are emitted. An experiment to detect solar neutrinos has been under way for many years (see, for example, Kuchowicz 1976) and the number detected has always been lower than the number predicted by theory, but the discrepancy is smaller now than it was a few years ago (see, for example, Davis *et al.* 1978). Although it is generally believed that the main outlines of the theory of stellar evolution are secure, a satisfactory explanation of the solar neutrino result is certainly required.

A stellar thermonuclear reaction has some substantial advantages over a possible terrestrial thermonuclear reaction in terms of confinement mechanism, heating, energy losses and timescale, apart of course from the absence of external walls and other ancillary equipment.

Stars are held together by gravitation, and most of their life is spent in a quasi-static state in which

$$\mathrm{d}P/\mathrm{d}r = -GM\rho/r^2, \tag{1.1}$$

where P and ρ are the pressure and density at radius r, and M is the mass contained within radius r. If equation (1.1) holds, it can be shown that

$$\Omega + 3\int \frac{P}{\rho}\,\mathrm{d}M = 0, \tag{1.2}$$

where Ω is the total (negative) gravitational energy of the star. If the star loses energy and as a result contracts, Ω becomes more negative and the average value of P/ρ increases. For most of its active life a star is composed of an ideal Boyle's law gas and, therefore, gravitational energy release leads in an increase in the internal temperature of the star. In a stellar thermonuclear reactor, confinement usually implies heating.

The first contraction under gravity produces conditions in which hydrogen is converted to helium and, once any nuclear fuel is exhausted, further heating occurs and the next fuel becomes usable. This only ceases to be true if the gas becomes degenerate. Its pressure is then essentially a function of density alone, and a rise in density can be accompanied by a fall in temperature. We return to this point in §2.

Stars are usually opaque to the products of nuclear fusion reactions. The surface temperature is much lower than the central temperature so that energy losses are low. In fact, the energy release from nuclear reactions usually just equals the surface energy losses, and the central temperature adjusts itself so that this is just possible. The energy losses are low in the sense that the timescale for complete release of nuclear energy is very long. The conversion of hydrogen into helium can take from 10^6 years to at least 10^{11} years depending on the star's mass, the least massive stars living longest. Another consequence of stellar opacity is that the central temperatures of most stars can be much lower than that in a terrestrial reactor.

There are exceptions to the general rule stated in the last paragraph. When neutrinos are produced by nuclear reactions, they usually escape freely and the loss of energy can become important. If the material is still a Boyle's law gas, the energy loss does not lead to cooling but rather to accelerated evolution because it produces contraction and a further rise in temperature. In contrast, neutrino losses may cool a degenerate gas.

In some cases nuclear reactions are not quasi-static but are instead explosive; this question of stellar reactor safety will be considered in §3.

2. Quasi-static thermonuclear reactions

The basic principles governing thermonuclear reactions are the same whether they occur in a laboratory or in a star, but the star has no choice of nuclear fuel. In return for that potential disadvantage, a star usually has a lifetime and a stability that enable it to use whatever fuel is available. In addition, as we have already seen, the central temperature at which fusion energy can compensate for surface losses can be very much lower than in a hypothetical terrestrial reactor. Stars are mainly composed of hydrogen and helium, with only a very small admixture of heavy elements. Because the Coulomb barrier increases rapidly with nuclear charge, nuclear reactions involving light nuclei generally occur at lower temperatures than those involving heavy nuclei. As a result the abundant nuclear fuel can be used early in a star's evolution.

The main nuclear fuel possessed by a star is, in fact very unpromising, as both hydrogen 'burning' and helium 'burning' (burning being used in its astrophysical sense of nuclear fusion) have complications associated with them. If a star contained no heavy elements (i.e. elements other than H and He), the conversion of H to He,

$$4\,{}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_{\mathrm{e}}, \tag{2.1}$$

would have to proceed through the proton–proton chain:

$$\begin{aligned} &{}^{1}\mathrm{H}({}^{1}\mathrm{H},\, \mathrm{e}^{+}+\nu_{\mathrm{e}})\,{}^{2}\mathrm{H}({}^{1}\mathrm{H},\, \gamma)\,{}^{3}\mathrm{He}({}^{3}\mathrm{He},\, 2\,{}^{1}\mathrm{H})\,{}^{4}\mathrm{He} \\ &\qquad\qquad\qquad ({}^{4}\mathrm{He},\, \gamma)\,{}^{7}\mathrm{Be}(\mathrm{e}^{-},\, \nu_{\mathrm{e}})\,{}^{7}\mathrm{Li}({}^{1}\mathrm{H},\, {}^{4}\mathrm{He})\,{}^{4}\mathrm{He} \\ &\qquad\qquad\qquad\qquad\qquad ({}^{1}\mathrm{H},\, \gamma)\,{}^{8}\mathrm{B}(,\, \mathrm{e}^{+}+\nu_{\mathrm{e}})\,2\,{}^{4}\mathrm{He}. \end{aligned} \tag{2.2}$$

The first reaction of this chain is highly improbable, involving in effect the β-decay of the highly unstable nucleus ^{2}He. At one time it was not believed to be an allowed reaction and, therefore, hydrogen was believed to burn through the carbon–nitrogen cycle:

$${}^{12}\mathrm{C}({}^{1}\mathrm{H},\, \gamma)\,{}^{13}\mathrm{N}(,\, \mathrm{e}^{+}+\nu_{\mathrm{e}})\,{}^{13}\mathrm{C}({}^{1}\mathrm{H},\, \gamma)\,{}^{14}\mathrm{N}({}^{1}\mathrm{H},\, \gamma)\,{}^{15}\mathrm{O}(,\, \mathrm{e}^{+}+\nu_{\mathrm{e}})\,{}^{15}\mathrm{N}({}^{1}\mathrm{H},\, {}^{4}\mathrm{He})\,{}^{12}\mathrm{C}. \tag{2.3}$$

The C–N cycle involves heavier nuclei and a higher Coulomb barrier but it has no such difficult individual reaction.

Although its fuel is much less promising than D–D or D–T, a self-balancing reaction can occur in a typical star with a temperature between 10^{7} K and 2×10^{7} K, the C–N cycle being more important at higher temperature. In the Sun the average current power output is only 2×10^{-4} W kg^{-1} which implies a very long lifetime. In terms of the much-used Lawson criterion, 'nt' for the sun is *ca.* 10^{44}. The neutrinos emitted in hydrogen burning typically carry away a small percentage of the energy released. The highest energy neutrinos are those from the decay of ^{8}B and are those most readily detected. The proportion of reactions passing through ^{8}B is a function of temperature, so the solar neutrino experiment should measure the solar central temperature. The observed value is lower than the theoretical value. When stars are formed they may contain some D, Li, Be and B but these are burnt much more rapidly than H and at lower temperatures.

Helium burning is also unusual because of the absence of a stable nucleus with an atomic mass number of 8. Beryllium 8 is highly unstable, being liable to break-up into two helium nuclei, and helium burning is essentially a three-body reaction in which three helium nuclei form ^{12}C. The reaction proceeds through an excited state of ^{12}C which takes up most of the energy release before decaying to the ground state. Hoyle (1954) predicted the existence of the excited state, as without it helium burning would have been too slow. Helium burning typically occurs at temperatures of order 10^8 K and it is highly temperature dependent.

The products of helium burning are ^{12}C and ^{16}O. A further rise in temperature leads to reactions initially converting ^{12}C and ^{16}O into nuclei in the neighbourhood of Si and finally producing nuclei in the so-called iron peak, Cr, Mn, Fe, Co, Ni, which are the most strongly bound nuclei. There is a local maximum in the observed element abundances around iron. Nuclear fusion reactions cannot produce more massive nuclei with a net release of energy. The heavier elements are believed to have been produced by neutron capture reactions (see, for example, Clayton 1968), but that is not the concern of this paper.

We have not discussed whether all of the nuclear reactions occur in a given star. In fact the degree of nuclear evolution depends on a star's mass; the lower the mass, the less nuclear evolution occurs. As has been explained, the central temperature of a star initially rises but this rise may cease if the electron gas becomes degenerate. Low mass stars have higher central densities at a given temperature than high mass stars and they suffer degeneracy first. In sufficiently low mass stars (less than about $0.1\ M_\odot$, $M_\odot$ = solar mass = 2×10^{30} kg), the maximum temperature is too low for hydrogen burning, and the star dies without any nuclear evolution. At higher masses some nuclear evolution may be possible but the temperature may then fall, and the star may die before iron peak elements have been produced. In the high mass range there is a further complication. Only two types of dead star of finite radius exist and there is a maximum mass in each case (*ca.* $1.2\ M_\odot$, black dwarf; *ca.* $2.5\ M_\odot$, neutron star). We discuss what may happen to more massive stars in §3.

Degeneracy has another important effect. If the stellar centre becomes degenerate just before it is ready to ignite a further nuclear fuel, the temperature may continue to rise so that the fuel is ignited. At that stage, the sudden release of energy causes the central temperature to rise, with no corresponding rise in pressure. Whereas in a non-degenerate gas there is pressure increase, which leads to expansion and cooling and which usually acts as a thermostat, there is no such control in a degenerate gas, and the nuclear reactions may run away and become explosive. This point will be mentioned again in §3.

In the later stages of nuclear evolution, it is possible that the nuclear reactions will be accompanied by reactions that release neutrinos in much larger numbers than in hydrogen burning. To do this the reactions must emit neutrino–antineutrino pairs whose energy is obtained from the thermal energy of the plasma. The first process suggested was the U.R.C.A. process of Gamow (Gamow & Schönberg 1941):

$$\left.\begin{aligned}(Z, A) + e^- &\rightarrow (Z{-}1, A) + \nu_e,\\ (Z{-}1, A) &\rightarrow (Z, A) + e^- + \bar{\nu}_e.\end{aligned}\right\} \qquad (2.4)$$

In this process, a nucleus of charge Z and a mass number A captures an electron to produce an unstable nucleus which subsequently decays.

There are now known to be many other very effective neutrino-emitting reactions (see, for example, Fowler & Hoyle 1964) such as

$$e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e, \qquad (2.5)$$

where e^-e^+ pairs have themselves been produced from the radiation field. Recent developments in elementary particle physics indicate that $\nu_\mu\bar{\nu}_\mu$ pairs and $\nu_\tau\bar{\nu}_\tau$ pairs (if the ν_τ exists) can also be produced in stellar interiors (see Tayler 1980). In very dense matter an important reaction is

$$\Gamma \rightarrow \nu_e + \bar{\nu}_e, \tag{2.6}$$

where Γ is a plasmon which, unlike a massless photon, can decay into a neutrino–antineutrino pair. In general these neutrinos escape freely from a star, which suffers a very enhanced energy loss. In §3 we discuss what may happen if the neutrino escape is not free.

The effect of neutrino emission can be very different according to whether it occurs in a degenerate gas or in a non-degenerate gas. In the latter case, as has already been mentioned, cooling of the stellar interior only leads to a drop of pressure, further collapse and heating, so that the net effect of neutrino emission is to speed up the evolution of the star. In the former case, cooling has essentially no effect on the pressure and in some cases the cooling may be effective, cutting off nuclear evolution or at least moving the temperature maximum and further nuclear evolution away from the centre of the star.

Departures from thermodynamic equilibrium are usually unimportant. In particular, particles have Maxwellian or Fermi–Dirac distribution functions, and the tail of the nuclear Maxwellian distribution is probably populated correctly. There is also a Planck distribution or a modified Planck distribution of photons in dense stars when the plasma frequency ω_p satisfies

$$\omega_p \gtrsim kT/\hbar, \tag{2.7}$$

where T is the temperature. In calculating nuclear reaction rates in dense stars, it may be necessary to allow for the presence of other particles near those which are reacting. Thus, for example, the effective charge on a nucleus may be reduced because of the screening effect of electrons, and β-decay rates are modified in the presence of a degenerate electron gas.

Many stars in quasi-static nuclear evolution are stable controlled fusion reactors, whose energy output is steady for a long time; but at any time a minority are suffering from instabilities which lead to a fluctuating light output and possibly to mass loss. In most cases these instabilities are not caused by a property of the nuclear reactions but instead are related to the equation of state of the outer layers of the star or to the mechanism of energy transport. To continue an analogy with terrestrial reactors, we are observing oscillations of the pressure vessel rather than of the reactor core; we discuss the latter in §3. The calculation of the ultimate effects of instabilities, including mass loss from stars and the mixing of material inside stars, is one of the most difficult problems in stellar evolution theory.

3. EXPLOSIVE NUCLEAR REACTIONS

Some stellar thermonuclear reactors suffer catastrophic instabilities. It is not yet entirely clear whether the nuclear reactions themselves are commonly responsible for the catastrophe. It has been known for a long time that some stars explode as supernovae and that much of their mass is thrown back into the interstellar medium. It is believed that this is the main mechanism whereby elements produced in stars are released and can then be included in stars formed later. For a long time it was assumed that what was thrown into space had been synthesized in a star before the explosion, but it was later realized that nuclear reactions would occur at the time of the explosion itself.

There is an important difference between quasi-static nuclear reactions and explosive nuclear reactions. In slow stages of stellar evolution, any unstable isotopes produced can decay before undergoing a further reaction. When reactions are explosive, this need not be so. Although any unstable isotopes which survive the explosion will ultimately decay, the final mixture of isotopes will be different from that resulting from quasi-static burning. In addition there are some isotopes, such as the heavy radioactive ones, which can only be produced by an explosive process.

As soon as the importance of explosive reactions was recognized, it was realized that the observed isotopic abundances of solar system material could to a large extent be understood better in terms of explosive reactions than in terms of quasi-static reactions. Of course, the matter that undergoes the explosive reactions has had its composition determined by quasi-static reactions.

We now turn to the cause of explosive nuclear reactions and we differentiate between three types of cause, without necessarily excluding other possibilities. The first has already been mentioned in §2; it is related to the onset of nuclear reactions in a degenerate gas. The second is concerned with massive stars whose nuclear evolution has proceeded all the way to iron and to the final stages of their evolution. The third involves nuclear reactions in a non-degenerate gas, when the usual thermostat mechanism is not effective, and it may also involve the presence of a close stellar companion. The first two processes are believed to be associated with the explosions of supernovae and the third may be related to less violent events known as novae.

The onset of helium burning in stars of mass less than about 2.25 $M_{\odot}$ is potentially explosive. At the time of helium ignition the electron gas is degenerate and the rate of energy release from helium burning is typically proportional to the thirtieth or fortieth power of the temperature. It is agreed that a runaway release of energy occurs in the helium flash. It is extremely difficult to follow the evolution of the star through the period of peak energy release when the characteristic time for change in the central properties of the star is a fraction of a second and when for a very short time the rate of nuclear energy release can be greater than that of an entire galaxy of ordinary stars. Current indications are that this intense activity is largely contained within the star. There are certainly very significant readjustments of internal structure as a result of the helium flash but the star probably does not explode. The stellar pressure vessel can withstand an intense central explosion, but only because it is made of a fluid.

In stars of a wider range of masses, the onset of carbon burning occurs in a degenerate gas. This is again a highly temperature-sensitive reaction and the resulting explosion is generally believed to be effective in stars of mass around $5M_{\odot}$. This is the carbon detonation model of a supernova explosion (Arnett 1969). The calculation of what actually happens at the peak of the explosion is again very difficult and it is unclear what type of remnant is left behind. Some calculations have even suggested that the entire star could disperse leaving no stellar remnant. It is believed that explosive carbon burning is responsible for the production of some isotopes with atomic mass number between 20 and 30, which are not produced by quasi-static carbon burning.

Explosive nuclear reactions are probably the cause of the carbon detonation supernovae. They were once believed to be responsible for very high mass supernovae, but it now seems that they accompany the supernova explosion rather than causing it. In a sufficiently massive star, the central regions are processed to iron and neighbouring nuclei when the stellar gas is still non-degenerate. There is no longer any energy release from fusion reactions but the star is still radiating photons from its surface and, particularly, neutrinos from its interior. The central regions therefore contract, heat up and suffer even greater neutrino losses. Eventually (and at this stage in stellar evolution this means almost immediately) the temperature is so high that an iron–helium phase change occurs:

$$^{56}\mathrm{Fe} \rightarrow 13\,^{4}\mathrm{He} + 4\mathrm{n}; \tag{3.1}$$

a similar change occuring for other isotopes. The energy to effect this phase change must come from the thermal energy, and this induces catastrophic core collapse.

Fowler & Hoyle (1964) suggested that as material above the phase change region fell inwards it would be raised rapidly to a high temperature at which thermonuclear reactions would occur explosively; if the normal quasi-static stellar reactor has some relation to a magnetically confined terrestrial reactor, these explosive reactions are more reminiscent of inertial confinement. Hoyle and Fowler further suggested that the star would be blown apart and become a supernova. Although there is certainly enough nuclear energy to disrupt the star, subsequent calculations have suggested that thermonuclear reactions alone do not produce a supernova. Colgate & White (1966) pointed out that the core of such a star is so dense that it might become opaque to neutrinos. In this case neutrinos emitted from the stellar centre might be absorbed or scattered further out and the deposition of neutrino energy or momentum might remove the outside of the star.

References to more recent work on this subject can be found in Tayler (1980). Currently it appears that neutrinos alone also do not produce a supernova. An additional factor is that, when the stellar centre reaches neutron star density, there is a core bounce which produces a strong outward-going shock wave. This may be more important than either explosive nuclear reactions or neutrino scattering in determining the final state of a massive star. Whether or not the explosive nuclear reactions are significant in the supernova event, they are believed to produce many of the heavy elements in the Universe.

It has been stated earlier that nuclear reactions in a non-degenerate gas are usually peaceful but Schwarzschild & Härm (1965) pointed out that this is not always true. If nuclear reactions start in a sufficiently thin shell, the cooling produced by expansion of the shell may be minimal and it may be insufficient to prevent a further rise in temperature and energy release. As a result there may be a shell flash, which is a sudden peak in energy release. Such shell flashes can occur at several stages in stellar evolution but they normally result in internal readjustment of the star and a brief increase in surface luminosity rather than a long-term dramatic change in stellar properties.

A special case can arise in close binary systems when one of the components is a compact star, a white dwarf or a neutron star. If the other star is at an evolutionary stage in which its radius is increasing, mass may be transferred from it to its compact companion, with a large release of gravitational energy. If matter is dumped sufficiently rapidly, the surface layers of the compact star may become sufficiently hot for explosive nuclear reactions to result. The eruption of novae (Gallagher & Starrfield 1978) and X-ray burst sources (Joss 1979) may be produced by this mechanism.

It should be clear that there are very severe computational problems in trying to follow the evolution of an exploding star. This must be particularly true if any significant departures from spherical symmetry occur. For that reason it is not yet possible to decide whether a star will end its life as a black dwarf, a neutron star, or a black hole, or perhaps be dispersed completely. There are also problems in determining the mixture of chemical elements produced by explosive nuclear reactions. Some intermediate isotopes produced are so far from the region of β-stability that it is difficult to know what their properties are. In fact observed isotopic abundances may be used to predict nuclear properties.

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Discussion

J. G. Morgan (*U.K.A.E.A. Culham Laboratory, Abingdon, Oxfordshire OX*14 3*DB, U.K.*). I should like to make two comments concerning the solar neutrino problem.

First, although many unconventional models of the Sun have been proposed to reduce the theoretically predicted neutrino flux, the resolution of the problem may lie in the physical input to solar modelling.

The neutrino flux depends sensitively on the cross section of the proton–proton reaction, which is very small and has not been measured experimentally at the energies relevant to the solar centre. Newman and Fowler have found that an increase in the accepted value of this cross section by as little as 50 % would resolve the problem.

Secondly, the detection of solar neutrinos is an extremely difficult experiment. Professor Davis's ^{37}Cl experiment (Davis *et al.* 1978) is sensitive only to high-energy neutrinos from a side reaction in the chain of nuclear reactions which power the Sun. Professor Davis has proposed experiments with other detector materials, which would permit the measurement of the entire neutrino energy spectrum. The absence of the expected low-energy neutrinos from the proton–proton reaction itself would be a much more fundamental problem than the discrepancy in the flux of high energy neutrinos described in this paper.