A METHOD OF HEATING MATTER OF LOW DENSITY TO TEMPERATURES IN THE RANGE 10^5 TO 10^6 °K*

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Introduction

If gas of controlled composition could be held steadily at temperatures greatly exceeding 10^4 °K an interesting field for experimental research would be open. In particular it should be possible to duplicate some conditions existing in stellar atmospheres. Current research into the feasibility of constructing fusion reactors adds further interest (Thirring 1955).

At the temperatures and densities considered here, namely, 10^5–10^6 °K and 10^{17}–10^{18} atom/m^3, the gas would be almost fully ionized, and its temperature

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could be maintained by electromagnetic induction. In order to avoid excessive heat loss it is necessary to hold most of the heated gas away from all solid material, and this might also be achieved by electromagnetic means.

Description of the Method

It is proposed that the configuration of conductors and fields take the form of a spherical, copper shell with a core of ionized gas at its centre, as indicated in Figure 1. In the cavity between shell and core standing electromagnetic waves are maintained. Pressure on the core is due to the radiation pressure of the standing waves.

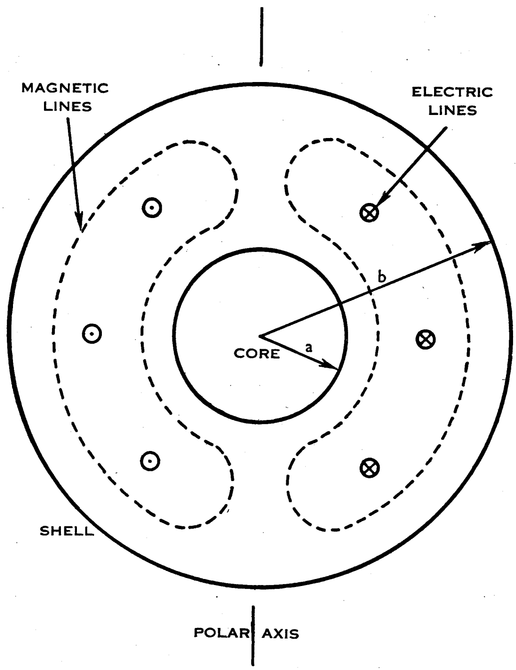

Fig. 1.—Form of the H_{101} mode.

The standing waves must exert a pressure that is uniform over the whole surface of the spherical core. This can be achieved by establishing three standing wave systems at different frequencies. Figure 1 illustrates the form of the simplest system the H_{101} mode (Lamont 1942). It consists of electric lines which are circles centred on the polar axis and lying in planes normal to it, and magnetic lines which lie in planes through the axis, run close to each surface of the cavity, and loop over near the axis. It can be shown that the resulting time-averaged pressure exerted by the H_{101} mode on the surface of the core varies as $\sin^2 \theta$, where θ is the angle between the polar axis and the radius vector.

The other two systems are the H_{102} and H_{103} modes. In diagrams similar to Figure 1 they would show respectively two and three bean-shaped magnetic circuits instead of the single circuit of the H_{101} mode. In each case, however, the pressure over the core surface varies as $\sin^2\theta$.

If the three wave systems were established with their polar axes mutually perpendicular, and if the field intensities were adjusted to give equal maximum time-averaged pressures P_0 on the core, the total time-averaged pressure over the core surface would be constant and equal to $2P_0$. For, under the condition that no appreciable fluctuation of the core volume occurs, the total time-averaged pressure is simply the sum of the time-averaged pressures of the modes acting separately. The pressure on the core surface at a point θ_1, θ_2, θ_3 is

$$P=P_0\,(\sin^2\theta_1+\sin^2\theta_2+\sin^2\theta_3)=2P_0,$$

since $\cos\theta_1$, $\cos\theta_2$, $\cos\theta_3$ are the direction cosines of the point with respect to three rectangular axes.

It is inherent in this method that the pressure exerted on the core surface by any one standing wave varies between zero and a maximum value with a frequency twice that of the wave. In addition, beating between waves of different frequencies could give rise to further fluctuation of pressure. Therefore, both the frequencies and differences in frequencies of the standing waves must be sufficiently great that there is negligible fluctuation of the core volume. For a 1 m diameter core of hydrogen at 10^5 °K, if the linear dimensions are not to fluctuate more than a few centimetres, the minimum frequency is of the order of 10^6 c/s. In the system to be described the relevant frequencies are of the order of 10^8 c/s.

Stability

So far it has been shown that, if the radiation pressure equalled the gas pressure, a spherical core would be in hydrostatic equilibrium. The stability of this equilibrium must be considered. The configuration of the field is affected by the form of the core, and a deformation in the core might alter the wave in such a way as to assist the deformation to increase.

For a change in core size, any instability that might arise would be countered if the modes are forced to oscillate at frequencies slightly higher than the resonant frequencies. For, if the core size increases, the cavity size decreases and brings the resonant frequencies nearer the forced frequencies. The field intensities therefore increase and the core tends to be forced back to its equilibrium size.

The change in pressure distribution over the core surface during a change in core shape has been examined in detail only for the case of the simplest deformation associated with a single H_{101} mode. In this deformation the core becomes slightly oblate or prolate about the polar axis. It was found that, for a core diameter less than $0 \cdot 44$ times the shell diameter, the radiation pressure increases at points where the core surface moves outwards, and decreases where it moves inwards. This suggests that small cores would be stable against change of shape, and if this is the case it implies stability against change of core position, which can be looked on as a special case of change of shape. It may therefore be possible to support a core of finite weight.

Power Dissipation

A major power loss is due to eddy currents in the shell. It is estimated that for a shell of diameter 3 m and a core of diameter 1 m the resonant frequency for the H_{101} mode is $1 \cdot 66 \times 10^8$ c/s. If this field is sufficiently intense to exert a mean time-averaged pressure over the core surface equal to the pressure of a gas at a temperature of 10^5 °K and a density of 2×10^{18} particles/m^3, it will dissipate 6×10^4 W in a copper shell. For the frequency given, this power is large but not unattainable. Dissipation rates of the same order of magnitude would occur for the other two modes.

The power transferred to the core as heat has been estimated using an expression given by Spitzer (1956). A core of hydrogen at a temperature of 4×10^5 °K and a density of $0 \cdot 25 \times 10^{18}$ atom/m^3 under the conditions described in the preceding paragraph would absorb energy at a rate of the order of 4×10^3 W. This is much more than the gas could be expected to dissipate by radiation. Some means must therefore be provided for removing heat from the core at just the rate required to keep the temperature constant at a given value. Otherwise the temperature (and pressure) will increase until the field can no longer hold the core away from the shell.

One way of increasing the heat flow from the core is by placing a small metal surface (of the order of 1 per cent. of the core surface) in contact with the core. Under steady conditions protons collide with the surface and pick up electrons from it, becoming neutral hydrogen atoms. Electrons flow into the surface at an equal rate, maintaining its charge constant. Unless the neutral hydrogen atoms have kinetic energy negligible compared with the mean thermal energy of the protons, they will escape from the core. In any case, for each proton arriving at the metal surface an amount of energy equal to the sum of the mean thermal energies of a proton and an electron, and the ionization energy of the hydrogen atom is, on the average, lost by the core. Cooling of the metal surface does not appear to present any great problem.

Neutral hydrogen atoms produced by recombination would escape from the core and give rise to an atmosphere of neutral hydrogen in the space between shell and core. The density of this neutral hydrogen gas is estimated to be of the same order as the density of ionized hydrogen in the core. Its re-ionization in and near the core surface makes up for the loss of ionized atoms from the core due to recombination.

Forming the Core

It is expected that a small quantity of molecular hydrogen at room temperature, filling the shell in the absence of the core, would be ionized by the electromagnetic field. The ionized material would divide into two zones. In the inner zone electrons would be driven toward the centre and, together with the positive ions attracted there by the space charge field of the electrons, would form a core. In the outer zone, electrons and positive ions would be driven outward, recombine at the inner surface of the shell, and ultimately (often after a number of ionizations and recombinations) be driven to the centre.

Conclusions

It appears practicable to provide sufficiently strong radio fields of a suitable form to contain by radiation pressure a fully ionized gas of density in the range 10^{17}–10^{18} atom/m^3 at a temperature in the range 10^5–10^6 °K. The equilibrium has not been completely investigated but indications so far are that it would be stable. Eddy current losses in, are more than sufficient to balance heat radiation from fully ionized hydrogen.

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References

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