

NUCLEOGENESIS IN STARS

Another proposal for a non-equilibrium explanation of the iron peak is given in the paper by Dr Nemirovsky.

The formation of by-passed nuclei is easily explained by ($p, 2n$) reactions with 10 MeV-protons.

As one of the difficulties it may be noted that in some cases a single (p, γ) process followed by β -decay is sufficient, but no marked increase in abundance is observed. This requires a proton spectrum poor in protons below the (p, n) threshold.

The required protons in the energy range 2–10 MeV in non-equilibrium conditions cannot be of a thermal origin. They must be attributed to cold acceleration.

For the case of nuclear reactions, acceleration of particles in a plasma, and not in a vacuum, is required. Then effective acceleration is possible only at initial ion velocities, beginning with a value not lower than the velocities of thermal electrons. With lower velocities the energy gained is wasted through electronic friction. It follows that the mechanism of cold acceleration must consist of two stages: primary gas-dynamical injection and subsequent electromagnetic acceleration.

The preliminary gas-dynamical acceleration can be effected by shock waves on their passage into a medium of decreasing density (density cumulation as we call this mechanism). The energy attained depends critically upon the thickness of the shock front. This problem is considered in detail by Dr Sagdeyev in his paper.

We see that nuclear reactions at stellar surfaces require a combination of shock waves and electromagnetic fields.

The products of nuclear reactions can be detected spectroscopically only under the condition that they accumulate at the surface of the star. But they are very likely to be ejected by shock waves into interstellar space, or carried into the stellar interior by turbulent diffusion. The latter problem is treated by Dr Tverskoy in a paper that follows.

We have now to look for cosmic objects in which cold acceleration processes might lead to nuclear reactions. In the first place these may be the non-stationary red dwarfs, or the so-called flare-stars. We know from the theory of internal constitution that they have very deep convection zones comprising a large part of the whole volume. Large flares and polarization in the continuous spectrum are signs of gas-dynamical and magnetic activity. The second group might include the Wolf-Rayet stars and cores of planetary nebulae, since shock waves seem to provide the most effective mechanism for the ejection of matter.

On the contrary, peculiar A-stars (magnetic variables) do not show signs of gas-dynamical activity. They should be regarded as objects in which the products of a previous active stage are frozen at the surface due to the formation of a general magnetic field. The fact that they are localized near the intersection of the horizontal branch with the main sequence, seems to give support to the view stated.

It is generally accepted that D, Li, Be, B are formed by cold acceleration processes in stellar atmospheres. We have attempted to collect some evidence in favour of a wider role of these processes. It seems that they might be responsible for the iron peak and for the genesis of by-passed nuclei.

Laboratory work on controlled thermonuclear reactions has shown that it is much easier to achieve a nuclear reaction due to cold acceleration processes than a genuine thermonuclear reaction. This result may also have some significance for astrophysics.

7. ON THE MECHANISM OF PRELIMINARY PARTICLE ACCELERATION IN RAREFIED STELLAR ATMOSPHERES

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In the problem of nuclear reactions in stellar atmospheres, produced by cold accelerations, as well as in the problem of the origin of cosmic rays, the question of injection is not yet clear.

JOINT DISCUSSION

Rarefied ionized gas (plasma) in stellar atmospheres in the presence even of a weak magnetic field possesses specific 'co-operative' properties, which can be very important for injection.

Chew, Goldberger and Low [1] have pointed out that even in the absence of binary collisions the motion of a plasma in a plane perpendicular to the magnetic lines of force satisfies equations similar to the hydromagnetic ones, provided the scales of space and time are large in comparison with the radius and inverse frequency of Larmor rotation of ions (electrons). From the adiabatic invariance of $\mu = E_{\perp}/H$ for each particle it follows immediately that the adiabatic index is equal to 2. In the processes of shock-wave cumulation towards the axis, or towards the low-density region near the stellar surface [2], etc., if the ion Larmor radius takes the part of free-path length, a very significant increase in particle velocities can be attained. We can evidently consider this effect as an injection mechanism.

However, the plasma motion within the shock front does not satisfy the criterion adopted in [1], thus the question arises of the possibility of the existence of shock waves in a rarefied plasma. In [3] we have put forward a hypothesis that even in this case shock waves are possible (I was told by S. B. Pickelner that a similar hypothesis had been forwarded simultaneously by H. Petchek).

In ordinary hydrodynamics the entropy increase during the transition across the shock front is secured by the processes of viscosity and heat transfer. In a rarefied plasma, where collisions are absent, the entropy is well preserved.

It is necessary for an investigation of the structure of a steady shock wave to find a solution of the kinetic equation, depending on the combination of space and time variables $x - ut$ (u being the wave velocity). A rigorous investigation is very difficult. But some approximations are possible. Neglecting thermal motion of charges, we obtain a steady plasma motion consisting of undamped oscillations of finite amplitude. The velocity of propagation of such oscillation is higher than the Alfvén speed $H/\sqrt{4\pi\rho}$.

In these oscillations charge separation takes place. It is caused by the 'grouping' of particle phases. Collisions, which are rare in our case, or some other mechanisms not connected with collisions, are necessary for damping such oscillations inside the shock front.

It is known from the theory of linear plasma oscillations that thermal motion leads to a specific damping mechanism, which is not connected with collisions—it is the so-called 'Landau damping', but in the case of a finite amplitude this mechanism produces no real damping [4].

A specific non-linear damping mechanism is, however, possible—it is the 'randomization' of phases in a non-uniform magnetic field.

If a shock wave (without collisions) is propagating across the magnetic field, then the plasma states on both sides of the shock are connected by Hugoniot equation with $\gamma = 2$. There exists, however, a 'co-operative' mechanism securing energy transfer from the transverse to the longitudinal degree of freedom. It is connected with a specific plasma instability [5, 6] caused by the 'temperature' anisotropy: mean value of $(v_{\perp} - v_{\parallel})^2 \neq (v_{\perp} + v_{\parallel})^2$. This must lead to a decrease of γ in waves of large amplitude.

REFERENCES

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