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ON THE NATURE OF THE INTERPLANETARY GAS

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SUMMARY

The flow of compressible gas in the gravitation field of a point body, whose gravitation potential exceeds substantially the potential of the gas itself is investigated here. It is found in the adiabatic approximation that the gas enthalpy i is approximately equal to the gravitational potential of the body ϕ in the region where $\phi >> i_0$ (here i_0 is the enthalpy of the unperturbed gas). Accordingly, the gas density increases in the adiabatic correlation.

The problem is solved applicably to the Sun and to the interstellar gas. The obtained results are compared with the existing theory on the solar wind. Conclusions are derived on the nature and properties of the interplanetary gas.

* * *

The ideas developed by E. Parker [1,2] about the hydrodynamic expansion of the solar corona proved to be very fruitful during the investigation of solar corpuscular streams, of quiet solar wind, etc., However, it seems to us that in these works the interlinking region of the solar wind with the interstellar gas is chosen incorrectly. This interlinking region is determined by the equality of solar wind's dynamic pressure and the pressure of the interstellar medium. Therefore, here one must take into account the variation of the state of interstellar gas under the influence of solar gravitation. This was actually not done in the above mentioned Parker works. As will be shown later, the accounting of solar gravitatation changes radically the pattern of solar wind interlinking with interstellar gas and confirms the existence along side with the solar wind, of a relatively stable interplanetary gas.

With regard to the nearest stars, the Sun moves with a speed of ~ 20 km/sec. It is possible to assume, that the speed of Sun's motions relative to interstellar gas, is about the same as in the Sun's neighborhood. In connection with this fact, let us examine what sort of variations the gas undergoes while flowing in the region of high gravitational potential. We shall investigate the flow at distances from the Sun, exceeding its dimensions substantially. Let us write the standard equations of motion and continuity in the case of adiabatic flow:

$$\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\nabla)\mathbf{v}+\nabla(i-\varphi)=0, \qquad (1)$$
$$\frac{\partial \rho}{\partial t}+\operatorname{div}(\rho\mathbf{v})=0.$$

Here $\vec{v}$ is the gas' velocity, ϕ is the Sun's gravitational potential, i is the gas enthalpy. We disregard the mass of the gas. Apparently the problem has an axial symmetry and is characterized by the coordinates z along the axis of symmetry, and r in the perpendicular direction. It is convenient to examine here the variations of parameters along the current line. In this case Eqs. (1) are written in the form

$$\frac{\partial v_r}{\partial t}+(v_l\nabla)v_r+\frac{\partial}{\partial r}(i-\varphi)=0,$$
$$\frac{\partial v_z}{\partial t}+(v_l\nabla)v_z+\frac{\partial}{\partial z}(i-\varphi)=0, \qquad (2)$$
$$\frac{\partial \rho}{\partial t}+(v_l\nabla)\rho+\rho\left(\frac{\partial v_l}{\partial l}+v_l\frac{\partial \ln r^2}{\partial l}\right)=0.$$

Here v_l is the velocity of the gas along the current line, v_r u v_z are the velocity components in the cylindrical system of coordinates. The values entering into Eqs.(2), are also linked by the relations

$$\varphi=\frac{GM}{\sqrt{r^2+z^2}}, \quad i=i_0\left(\frac{\rho}{\rho_0}\right)^{\gamma-1}, \quad v_z^2+v_r^2=v_l^2. \qquad (3)$$

Here γ is the adiabatic exponent, i_0 and ρ_0 are respectively the enthalpy and the density of the umperturbed gas. In sc far as we investigate the variation of values along the current line, the coordinates r and z are not independent. They are linked by means of the relation

$$\frac{\partial r}{\partial z} = \frac{v_r}{v_z}. \tag{4}$$

Henceforth we shall assume the z-coordinate as independent. Here we are examining a stationary problem: namely, we assume the Sun to be quiescent while interstellar gas is moving so that at infinity the gas velocity relative to the Sun is v_*. Let us write Eqs.(2) for the stationary flow

$$\begin{aligned} v_l \frac{\partial v_r}{\partial l} + \frac{\partial}{\partial r}(i - \varphi) = 0, \\ v_l \frac{\partial v_z}{\partial l} + \frac{\partial}{\partial z}(i - \varphi) = 0, \\ v_l \frac{\partial \rho}{\partial l} + \rho \frac{\partial v_l}{\partial l} + \rho v_l \frac{\partial \ln r^2}{\partial l} = 0. \end{aligned} \tag{5}$$

Hence we shall obtain

$$\begin{aligned} \frac{v_l^2}{2} + i - \varphi = \frac{v_*^2}{2} + i_0, \\ \rho v_l r^2 = \rho_0 v_* r_0^2. \end{aligned} \tag{6}$$

Here r_0 is the sighting distance for the given current line. Moreover, from the first two Eqs. (5) we have

$$v_z^2 - v_r^2 = v_*^2. \tag{7}$$

This latter relation describes the simple fact that at velocity variation under the influence of solar gravitation the z-component of velocity always exceeds the r-component by the value of the initial velocity v_*. In particular, at $v_* = 0$ the flow will be spherically symmetrical and $v_z = v_r$.

The obtained equations form a closed system relative to all parameters of flow and state of gas of interest to us. Let us write the system completely

$$\frac{v_l^2}{2}+i-\varphi=\frac{v_*^2}{2}+i_0,\quad v_r^2+v_z^2=v_l^2,\quad i=i_0\left(\frac{\rho}{\rho_0}\right)^{\gamma-1},$$
$$\rho v_l r^2=\rho_0 v_* r_0^2,\quad v_z^2-v_r^2=v_*^2,\quad \varphi=\frac{GM}{\sqrt{r^2+z^2}},$$
$$\frac{\partial r}{\partial z}=\frac{v_r}{v_z} \tag{8}$$

Hence we shall easily obtain

$$\frac{\partial r}{\partial z}=\left(\frac{i_0-i+\varphi}{v_*^2+i_0-i+\varphi}\right)^{1/2}. \tag{9}$$

The enthalpy i is determined from the equation

$$i=i_0\left[\left(\frac{r_0}{r}\right)^2\frac{v_*}{\sqrt{v_*^2+2(i_0-i+\varphi)}}\right]^{\gamma-1}. \tag{10}$$

Hence we must express i and, substituting it into (9), we shall find $r = r(z)$. However, with an arbitrary γ a precise solution of these equations is impossible. Instead we shall utilize the approximation, based on the following considerations. Eq. (9) contains z only in the z^2 power. This means, that current lines are symmetrical relative to a plane, perpendicular to the axis z and passing through the point $z = 0$. On the strength of the continuity of motion this means that at the point $z = 0$ the derivative $dr/dz = 0$. Moreover, it is natural that $dr/dz = 0$ also as $z \to \infty$. In this last case $\phi \to 0$, $i \to i_0$ and $dr/dz = 0$. As to the point $z = 0$, we have at it $i - i_0 + \phi = 0$. Let us examine the current line in the neighbourhood of the point $z = 0$, so that $i_0 - i + \phi \ll v_*^2$. Then Eqs. (9) and (10) will be written in the form

$$\frac{\partial r}{\partial z}=\frac{1}{v_*}(i_0-i+\varphi)^{1/2} \tag{11}$$

and

$$i=i_0\left(\frac{r_0}{r}\right)^{2(\gamma-1)}\left[1-(\gamma-1)\frac{i_0-i+\varphi}{v_*^2}\right]. \tag{12}$$

Hence

$$i = \frac{\varphi \frac{i_0}{v_*^2}(\gamma-1) + i_0\left[(\gamma-1)\frac{i_0}{v_*^2} - 1\right]}{(\gamma-1)\frac{i_0}{v_*^2}\left(\frac{r_0}{r}\right)^{2(\gamma-1)} - 1}\left(\frac{r_0}{r}\right)^{2(\gamma-1)}. \qquad (13)$$

As to Eq. (11), it will take the form

$$\frac{\partial r}{\partial z} = \frac{1}{v_*}\left\{\frac{i_0\left[\left(\frac{r_0}{r}\right)^{2(\gamma-1)} - 1\right] - \varphi}{(\gamma-1)\frac{i_0}{v_*^2}\left(\frac{r_0}{r}\right)^{2(\gamma-1)} - 1}\right\}^{1/2}. \qquad (14)$$

Let us recall, that the obtained expression describes with sufficient precision the behavior of the current line with $i_0 - i + \phi << v_*^2$. From (14) it is apparent, that for $GM/i_0 r_0 >> 1$ the requirement $dr/dz = 0$ at the point $z = 0$ yields for the given current line the r_{min} value

$$\frac{r_{min}}{r_0} = \left(\frac{r_0 i_0}{GM}\right)^{\frac{1}{2\gamma-3}}. \qquad (15)$$

Utilizing this expression, we shall obtain from (13)

$$\frac{i_{max}}{i_0} = \left(\frac{GM}{i_0 r_0}\right)^{\frac{2(\gamma-1)}{2\gamma-3}}. \qquad (16)$$

It is to be remembered that the values of the adiabatic exponent could be different depending upon the physical conditions. Thus, at motion of gas masses with a highly intense magnetic field $\gamma = 2$ at motion of matter with radiation $\gamma = 4/3$, while at motion of a standard monoatomic gas $\gamma = 5/3$.

The results (15) and (16) imply that the values of r_{min} and i_{max} do not depend on the motion velocity of gas relative to the Sun, but depend solely on the initial gas temperature and on the sighting distance of the given current line. This is the corollary of the hydrodynamic consideration. The monoparticle approximation can in no case lead to such a result. Expression (16) indicates that in the Sun's neighborhood $i \approx \phi$ and consequently, high temperatures and densities are attained. At normal conditions of the interstellar medium (particle concentration $n_0 = 1$ cm^{-3}, $T_0 = 100$°K) and at Sun's mass $M = 2 \cdot 10^{33}$ g at the distance of 1 a.m. from the Sun we have respectively $n \approx 3 \cdot 10^4$ cm^{-3}; $T \approx 10^5$ °K. It is to remember that the gas then remains neutral. Only ions of easily-ionized elements, such as C, Na, Mg and others are present. The ionization of these elements results in an electron concentration in the interstellar medium of the order 10^{-3} cm^{-3} in neutral hydrogen [3]. In the Earth's vicinity we shall correspondingly obtain $n_e \approx 30$ cm^{-3}.

Before considering the physical significance of the obtained results (15) and (16), it is necessary to discuss the applicability of the hydrodynamic method to the given problem. Obviously, the hydrodynamic apparatus could be used so long as the distance from the Sun exceeds the length of the free path in the gas. From (16) it follows, that the concentration of particles in the Sun's neighborhood varies according to the law

$$n = n_0 \left(\frac{GM}{Ri_0}\right)^{\frac{1}{\gamma-1}}. \tag{17}$$

Here R is the distance from the Sun, $R = \sqrt{x^2 + z^2}$. The requirement that the length of the free path $l = 1/n\sigma$ (σ is the effective cross-section) must be greater than the distance from the Sun, yields the inequality

$$\frac{1}{n_0\sigma}\left(\frac{Ri_0}{GM}\right)^{\frac{1}{\gamma-1}} < R, \tag{18}$$

from which we obtain

$$R < (n_0\sigma)^{\frac{\gamma-1}{2-\gamma}}\left(\frac{GM}{i_0}\right)^{\frac{1}{2-\gamma}}. \tag{19}$$

At $n_0 = 1$ cm^{-3}, $\sigma = 10^{16}$ cm^2, $\gamma = {}^5/_3$, we obtain $R < 10^{16}$ cm. It is interesting that the performed estimates give the upper and not the lower limit of distances. This is connected with the fact that the expressions utilized are valid only near the Sun. It is necessary to take into account, however, that in the direct vicinity of the Sun, the gas is ionized and the length of the free path inside it constitutes 10^{12} - 10^{13} cm. Thus, the results obtained for distances of one astronomical unit are apparently correct. Let us discuss in the final resort the physical significance of the results obtained. From the zero value of the derivative dr/dz at the point z = 0, it follows that at that point $v_r = 0$. As may be seen from expressions (8), we have at the same time $v_z = v_l = v_*$. Thus, we see that near the Sun, the flow velocity of gas is the same as at infinity. Consequently, the potential energy of the gas in the field of solar gravitation is fully transferred into thermal energy. This phenomenon may be illustrated by the example of spherically symmetrical stationary gas flow in the field of a gravitating body. In this case we have

$$\begin{aligned} &\frac{v^2}{2}+i-\varphi=\frac{v_1^2}{2}+i_1-\varphi_1, \\ &\rho v r^2=\rho_1 v_1 r_1^2, \\ &i=i_1\left(\frac{\rho}{\rho_1}\right)^{\gamma-1}. \end{aligned} \tag{20}$$

Here, the quantities fixed at the distance r_1 from the center, are provided with subscript 1. Hence we find

$$\frac{v^2}{2}+i_1\left(\frac{v_1 r_1^2}{v r^2}\right)^{\gamma-1}-\varphi=\frac{v_1^2}{2}+i_1-\varphi_1. \tag{21}$$

From the form of the obtained expression it follows, that with the decrease of r and increase of ϕ, the flow velocity first increases and then decreases. In particular, at a certain distance from the center r^2, the flow velocity again becomes equal to v_1. Let us find this distance. Assuming in (21) $v = v_1$, we have two solutions

$$\begin{aligned} &r_2=r_1 \\ &\left(\frac{r_1}{r_2}\right)^{2(\gamma-1)}=1+\frac{\varphi_2-\varphi_1}{i_1}. \end{aligned} \tag{22}$$

With $i_1 << \phi_2 >> \phi_1$, i.e. if the initial thermal and potential gas energy is much lower than the potential energy at the point r_2, we shall obtain from the last equality

$$\frac{r_2}{r_1} = \left(\frac{i_1 r_1}{CM}\right)^{\frac{1}{2\gamma-3}}, \tag{23}$$

which in our problem is analogous to expression (15). The case of a total gas stop in a spherically symmetrical flow cannot be investigated due to the singularity of Eqs. (20).

Let us examine these data from the point of view of the solar wind theory and the nature of interplanetary gas. The solar wind intensity was measured by Bridge et al [4]. According to these data, the velocity of the quiet solar wind constitutes 250 - 400 km/sec., and its density is 7 - 20 cm^{-3} on the Earth's orbit. It can be easily seen that the dynamic pressure produced by such a flow of ions is smaller than the gas pressure on the Earth's orbit obtained from [16]. This means that the accounting of the influence of gravitation on the interstellar gas leads to the fact that the interlinking region of a spherically symmetrical solar wind with interstellar gas is found somewhere between the Sun and the Earth's orbit, and not beyond the limits of Solar system, as was found in the works [1,2]. Since we still observe the quiet solar wind flows, according to the observations [5-7], this suggests that is not spherically symmetrical, but has a jet or sectorial character. Moreover, according to the results of the present work, the presence of a pressure gradient in the interplanetary gas should have a definite influence on the dynamics of corpuscular streams.

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