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On the global electrostatic charge of stars

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Abstract. As was discovered in the nineteen-twenties, a significant electric field exists in the solar corona as well as in the solar interior. This field is a consequence of the tendency of light electrons to segregate from heavier protons in the solar gravitational field. Since the principle is valid for a plasma in every star, the result can be generalized. The presented paper is intended to rehighlight this significant physical property of stars. In particular, we stress that there has to be charge Q_r inside a stellar sphere with radius r, which is linearly proportional to mass M_r inside the sphere. Both quantities are related as $Q_r = 77.043 M_r$, if Q_r is given in *Coulombs* and M_r in *solar masses*. The global stellar electrostatic field is 918 times stronger than the corresponding stellar gravity and compensates for a half of the gravity, when it acts on an electron or proton, respectively. The external electric field has to cause an occurence of electric current and appropriate magnetic field in a highly conductive plasma, when, e.g., the plasma is in a turbulent motion or spirals onto a star in a hot accretion disc.

Key words. Sun: corona – Sun: fundamental parameters – Sun: particle emission – stars: atmospheres – stars: fundamental parameters

The purpose of this paper is remind of the existence of the global electrostatic field of the Sun and other stars, since it has been ignored by the authors of textbooks and review papers during the last several decades. Consequently, it has probably not been taken into account in the concerning works.

The average velocity of free electrons is higher than that of free protons in a plasma in thermodynamic equilibrium. This is a consequence of momentum conservation and the approximately three orders lower mass of the electron in comparison with the mass of the proton. Consequently, a larger number of electrons than protons on the stellar surface would move with a velocity exceeding the appropriate escape velocity, if the star were perfectly electrically neutral. (It is possible to show that the velocity of 22% of electrons, but only 10^{-1735}% of protons would exceed the escape velocity in the case of the Sun.) Because of a much more frequent escape of electrons, the neutrality would be broken and the star would achieve a positive electric charge inducing an electric field.

In the case of the Sun, the global electrostatic field was, in a theoretical manner, already deduced by astronomers in the early twenties of 20th century, within the first models of the solar corona. The first theoretician, who found this electric field compensating a half of gravitational attraction when acting on protons in the solar atmosphere, was Dutch astronomer Pannekoek in 1922. A similar conclusion was presented by Rosseland (1924) and Cowling (1929). A description of the field with some consequences, mainly on the stratification of elements in stellar atmosphere, was also given by Eddington (1926, reeditions 1930, 1959, 1988; pp. 272-276).

After the Second World War, some studies where the concept of field was included were published by Pikel'ner (1948, 1950) and Van de Hulst (1950). The possible impact of the field on the internal structure of white dwarfs was analysed by Salpeter in 1961. Disproving erroneous results by some previous authors (for instance Auluck & Kothari 1951, or see Schatzman 1958, Chap. 5), he concluded that there is no significant impact in this case. Except in reeditions of the above cited book by Eddington, the last very short note about the solar electric field was presented by Shklovsky in 1962 (the English translation of his Russian written book was published in 1965). The last review, by Van de Hulst, occurred in 1953.

More recent books and review papers on the solar corona or the Sun have generally omitted the effect of electric field (e.g. Parker 1963; Newkirk 1967; Gibson 1973; Athay 1976; Zirin 1988; Bird & Edenhofer 1990; Foukal 1990; Stix 1991; Low 1996). Since we have not found any paper mentioning a reason why the field should not exist, it seems that it was simply forgotten. This is also Van de Hulst's (1996) opinion. The fact that the field was found within a model of the solar corona, probably caused it to be regarded as an attribute of the highest part of the

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solar atmosphere and its actual nature remained unnoticed. Consequently, the field was put aside together with the obsolete corona models.

It is possible that the claim about the electrical neutrality of stars originates in a misunderstanding of net charge on a star. For example in the textbook by Glendenning (1997; p. 71), there is subsection entitled "Electrical Neutrality of Stars", in which the upper limit on the net charge is derived. The net positive charge has to be smaller than $10^{-36}\ qA$ Coulombs, where q is elementary electric charge (charge of proton) and A is number of baryons in the star. Hence, the author concludes that "the net charge per nucleon (and therefore the average charge per nucleon on any star) must be very small, essentially zero". Of course, we must agree that the charge per nucleon is negligible, even the charge of a small macroscopic volume of plasma is usually negligible. In this sense, we can speak about the neutrality. However, it is necessary to realize that the number A is very large (e.g. $A \approx 10^{57}$ for an one-solar-mass star) resulting in a significant global charge of the star as a whole. If a reader is not attentive enough, he or she can easily accept the wrong concept of global neutrality of a star evoked by the title.

It is perhaps worthy to sketch the derivation of the field. As was mentioned, the lighter electrons tend to separate from heavier protons (or ions in the general case) in plasma situated in a gravitational field. The separation is stopped by the electric field ψ (e.g. Eddington 1926, or reeditions in 1930, 1959, 1988; pp. 272–276). The potential energy of a free proton with mass $m_{\rm p}$ and charge q in gravitational, ϕ, and electric, ψ, force fields is

$$W_{\rm p} = -m_{\rm p}\phi + q\psi. \tag{1}$$

The potential energy of a free electron with mass $m_{\rm e}$ and charge $-q$ in the same force fields is

$$W_{\rm e} = -m_{\rm e}\phi - q\psi. \tag{2}$$

The densities of both kinds of particles are proportional to $\exp[W_{\rm p}/(kT)]$ or $\exp[W_{\rm e}/(kT)]$, respectively, where k is the Boltzmann constant and T is temperature of plasma. The ratio of these densities must remain essentially constant since not more than the minutest separation of the charges can occur. Hence, $W_{\rm p} = W_{\rm e}$, and

$$\psi = \frac{m_{\rm p} - m_{\rm e}}{2q}\phi. \tag{3}$$

Since the global electrostatic stellar field is function of radial distance, r, from the centre of star, a more universal quantity seems to be the charge inducing this field. For the entire star, it can be given as a single constant (which can be remembered or presented easier than a function).

Using Eq. (3), one can easily find that the global electrostatic charge Q_r inside the star-centric sphere of radius r, in general, is

$$Q_r = \frac{2\pi\varepsilon_{\rm o}\kappa(m_{\rm p} - m_{\rm e})}{q}M_r, \tag{4}$$

where $\varepsilon_{\rm o}$ is permittivity of vacuum, κ is gravitational constant, and M_r is stellar mass inside the sphere of radius r. If the mass M_r is given in solar masses and charge Q_r in Coulombs, then $Q_r = 77.043\ M_r$.

Inspecting the conditions assumed in the derivation procedure of the field (3) in more detail, it is clear that the result is valid for an ideally quiet, perfectly spherical, non-rotating star. Obviously real stars do not have physical properties completely identical to ideal stars and this causes the instantaneous global charge of a given star to differ from the value Q of an ideal star. Nevertheless, the star permanently tends to set up this charging and we can assume it as a rough approximation (rough but much better than exact neutrality).

We can demonstrate that the existence of the global charge is necessary to avoid some serious physical problems. It is difficult to describe the thermodynamic equilibrium between protons and electrons in a proton-electron plasma situated in the stellar gravitational field without the appropriate electric field. The charge also equalizes the gradients of proton and electron partial hydrostatic pressures as the functions of distance from the centre of star. If the charge were not taken into account (if we assumed its zero value), then we would obtain a partial electron pressure about three orders lower in comparison with the partial proton (ion) pressure. This would be in disagreement with the common assumption of equal electron and ion pressures in a stellar plasma.

Though the electric field generated by the charge is significant in comparison with gravitational field, when electrically charged microscopic particles are considered, it can be shown that it does not affect the fundamental concept of stellar structure, i.e. the fundamental equations describing stellar structure remain unchanged.

We can also demonstrate that the electrostatic interaction between two idealized stars charged with the electrostatic charges, derived here, is extremely weak compared to gravity. The magnitude of electrostatic force represents only about 10^{-36} of the magnitude of gravity. However, if we study the dynamics of an electrically charged elementary particle or ion, with mass m_x and charge q_x, then the electrostatic force acting between this particle and charge Q_r is $-q_x(m_{\rm p} - m_{\rm e})/(2qm_x)$ multiple of gravitational force. Thus, the magnitude of the force represents about 50% of the magnitude of gravity, if the star acts on proton, and it is about 918 times more intensive than gravity, if the star acts on electron.

The concept of the global charge or global electrostatic field is certainly important to be considered in the rotation of plasma enforced by an external force. Here, the difference of the external force per mass unit (i.e. acceleration due to the external force), acting on both protons (ions) and electrons in a highly conductive plasma, causes a difference of velocities of both kinds of charge carriers and, thus, an electric current inducing the appropriate magnetic field. Two examples of such field seem to be obvious: the magnetic fields generated by eddies in a turbulent plasma and the magnetic field of a hot accretion disc around a star.

In conclusion, it seems to be desirable to remember the global electrostatic charge as a significant physical property of every star in various stellar studies and in teaching.

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