

ELECTRIC FIELDS, ACCRETION, AND STELLAR WINDS IN HELIUM-RICH ATMOSPHERES*

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ABSTRACT

We suggest that the electric fields of stellar atmospheres play an essential role in the accretion and mass ejection processes, especially of He-rich stars. The static configuration implies an electric field that is strong enough to push protons outward, but sufficiently weak to enable as many electrons as protons to escape. This process can stop hydrogen accretion on white dwarfs and may thus explain the existence of He-rich white-dwarf atmospheres in an H-rich environment. However, a hot corona must be postulated. It also gives the driving force needed for the stellar wind which is probably necessary to explain the He-rich main-sequence stars. At the same time, a pure helium white dwarf need not be created with no hydrogen. Any remaining hydrogen will be expelled.

It is found that the behavior of the electric field close to the star requires further study.

Subject headings: stars: accretion — stars: hydrogen-deficient — stars: white dwarfs

I. INTRODUCTION

The importance of electric fields in stellar atmospheres has recently been discussed by Montmerle and Michaud (1976, hereafter MM), who suggested that, in He-rich atmospheres, the electric forces may succeed in overcoming the gravitational pull on protons, eventually leading to mass loss. However, they did not suggest a model in which both electrons and protons could simultaneously diffuse outward. Even though they were not very explicit about it, it appeared to them that some other force would have had to take over as protons were leaving the star, so that the neutral combination of protons and electrons could leave simultaneously. We show here, however, that when a hydrostatic solution applies, the star adjusts its electric field so that an equal number of protons and electrons may leave simultaneously. This has important consequences both for the stellar winds of He-rich main-sequence stars and for accretion onto He-rich white dwarfs. We suggest that the electric field can effectively halt simultaneously the accretion of protons and electrons if a hot corona exists.

Vauclair (1975) suggested that He-rich main-sequence stars could be explained if they had an appropriately tuned wind that would leave behind the rapidly diffusing neutral helium. However, she suggested no model to accelerate this wind. For these objects, there exists an alternative possibility in which the radiative force on He I pushes it upward (Michaud, Martel, and Ratel 1978), but the radiative force appears to be somewhat too small (Michaud *et al.* 1979).

Another astrophysical situation in which He-rich atmospheres are encountered is when one is dealing

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with non-DA white dwarfs. These stars roughly constitute some 30% of the known white dwarfs and are characterized by exceedingly pure helium atmospheres with helium-to-hydrogen number ratios of the order of $\sim 10^4$ (Weidemann 1975). Accretion of H-rich interstellar matter would rapidly contaminate these atmospheres even at the minimal rate obtained from the gravitational cross section of a star (Strittmatter and Wickramasinghe 1971; Sion 1973). We show here that the existence of electric fields in the atmospheres of white dwarfs may effectively halt the accretion process.

We will start (§ II) by deriving the strength of the electric field in an He-rich region, and then show that such an electric field can lead, in the atmosphere, to an outward flux of *both* protons and electrons. We then show (§ III) that, above the atmosphere where the hydrostatic solution is no longer valid, the outward electron flux can be maintained if the existence of a corona around a helium-rich star is postulated. We next compare the outward mass flux with accretion rates expected in white dwarfs and determine the maximum density an interstellar cloud can have and still be pushed back (§ IV). Finally, we discuss the implications of our model for white dwarfs and He-rich main-sequence stars (§ V). Throughout the paper we will sometimes, for explicitness, discuss the accretion case and sometimes the mass-loss case. The discussion is fundamentally the same for both.

II. THE ELECTRIC FIELD

It has been realized (Milne 1924; Eddington 1930) for a long time that, whenever there is a partially ionized plasma, an electric field had to develop to keep electrons and protons or helium from separating.

It is simplest to obtain the electric field for a two-component plasma, e.g., He II and electrons, for which we have, in hydrostatic equilibrium,

$$\frac{\partial \ln p_e}{\partial r} = -\frac{m_e g}{kT} - \frac{eE}{kT} \quad (1)$$

and

$$\frac{\partial \ln p_{\text{He II}}}{\partial r} = -\frac{m_{\text{He}} g}{kT} + \frac{eE}{kT}, \quad (2)$$

where the p 's and m 's are the partial pressures and masses, respectively, g is the local gravity, and E is the electric field.

In order to keep electrons and helium from separating, we need

$$\frac{\partial \ln p_e}{\partial r} = \frac{\partial \ln p_{\text{He II}}}{\partial r},$$

or

$$\begin{aligned} eE &= (m_{\text{He}} - m_e)g/2 \\ &\approx 2m_p g, \end{aligned} \quad (3)$$

where m_p is the proton mass.

Half of the weight of helium is supported by the electric field. If helium were only slightly ionized, the electric field would be twice as large, and it if were completely ionized the electric field would be equal to

$$\frac{4}{3} \frac{m_p g}{e}.$$

The electric field will always adjust itself to keep electrons and the main, or rather, average, donor of electrons from separating (see MM and Montmerle 1975 for a more complete discussion). From equation (3) it follows that the electric force on protons in a helium environment is twice as large as the gravitational force on them and directed in the opposite direction. Protons are thrown away from the star.

The electric field lines must start and end on electric charges. The charge separation implied by equation (3) is, however, very small (Milne 1924; Montmerle 1975; MM), of the order of 10^{-37} , essentially because of the ratio of the electric to gravitational coupling constant. This is also the charge-to-mass ratio (Z/A) of stars. Because of the small separation needed, the diffusion time is small, of the order of 10^{-25} s, and the separation is established rapidly even in convection zones (see Michaud 1977).

Do electric field lines end close to the surface of the star or not? Do stars appear charged to an incoming proton, or do they appear neutral? A definitive answer would require a detailed description of the space surrounding the white dwarf. One needs to know the density profile in order to determine where electric field lines end. First Milne (1924), then MM and Bally and Harrison (1978), obtained that, in the hydrostatic case, the electric field lines should end only when $n < 10^{-6} \text{ cm}^{-3}$, much smaller than the

average particle density of the interstellar matter. This led Bally and Harrison (1978) to conclude that stellar electric field lines end only in intergalactic space. However, the hydrostatic solution is not expected to be valid above the atmosphere where a hydrodynamic solution will make the junction of the interstellar matter and the gas linked to the star. In the absence of an electron transport mechanism, protons would encounter local concentrations of electrons in this region, and electric field lines would probably end close to the stellar surface, as was suggested by MM. We suggest below (§ III), however, that the existence of coronae around He-rich atmospheres may provide the required mechanism by furnishing a hot enough temperature for electrons to evaporate. Further, in the atmosphere where the hydrostatic solution applies, we show that a macroscopically neutral flux of protons and electrons can be maintained.

When a non-DA white dwarf accretes, a gas formed of protons and electrons approaches a star with a He II-dominated atmosphere. If the gas is not ionized, the electric field will obviously have no influence and there will be accretion. On the other hand, if the gas is ionized, we may ask whether both electrons and protons can indeed be pushed back by the star. We first assume that the incoming gas is tenuous enough not to interact with itself. (Compression is indeed negligible in most cases of interstellar matter accretion, and free-fall conditions are then appropriate.) Now, even though both mechanisms are similar, it is a little easier to formulate the problem precisely in the case of a stellar wind of protons and electrons in a He II atmosphere. Is it possible to have simultaneously an outward steady-state proton and electron flux with

$$\phi_e = \phi_p? \quad (4)$$

One has

$$\begin{aligned} \phi_e &= n_e w_{e \text{ He}} \\ &= n_e D_{e \text{ He}} \left(\left. \frac{\partial \ln c_e}{\partial r} \right|_{\text{eq}} - \left. \frac{\partial \ln c_e}{\partial r} \right|_{\text{act}} \right) \\ &= n_e D_{e \text{ He}} \left(-\frac{2eE}{kT} + \frac{4m_p g}{kT} \right) \end{aligned} \quad (5)$$

and

$$\begin{aligned} \phi_p &= n_p w_{p \text{ He}} \\ &= n_p D_{p \text{ He}} \left(\frac{3m_p g}{kT} \right), \end{aligned} \quad (6)$$

where the diffusion velocities were obtained by an argument similar to that developed by Michaud (1977), with the assumption that

$$\left. \frac{\partial \ln c_p}{\partial r} \right|_{\text{act}} = 0.$$

In these equations, D stands for the diffusion coefficient, and the subscripts "eq" and "act" for the equilibrium and actual values of the concentration gradient.

From equations (4), (5), and (6),

$$eE = \frac{1}{n_e D_{e\text{He}}} \left(\frac{n_e D_{e\text{He}} 2m_p g}{kT} - \frac{3m_p g}{2} n_p D_{p\text{He}} \right) \approx eE_{\text{no flux}} \left(1 - \frac{3}{4} \frac{n_p D_{p\text{He}}}{n_e D_{e\text{He}}} \right). \quad (7)$$

Since we are in a He II-dominated atmosphere ($n_p \ll n_e$) and since

$$D_{e\text{He}} \approx 40 D_{p\text{He}}, \quad (8)$$

the electric field need only be very slightly reduced for the electron flux to be maintained as large as the proton flux. The electric force on protons then remains larger than the gravitational force on protons and oppositely directed.

We come to the rather surprising conclusion that a He-rich star maintains a proton flux and an electron flux simultaneously. The stable configuration is one in which the outward fluxes are equal. Indeed, if more electrons than protons were to escape, this would lead to an increase of the local electric field which would tend to cancel this difference. Conversely, a larger outward proton flux leads to an excess of electrons that would decrease the electric field. This decrease then facilitates the escape of electrons in such a way that as many electrons as protons are ejected.

Similarly, matter trying to accrete onto a helium white dwarf will be pushed back. In terms of an individual proton, the forces it feels are directed outward, since the electric force is twice as large as the gravitational force (see eq. [3]) and directed outward.

III. THE ELECTRON LOSS MECHANISM

In white dwarfs, as in He-rich main-sequence stars, the hydrostatic equations that apply in the atmosphere cannot be used to describe the region in between the interstellar matter and the atmosphere. The atmosphere and the hydrostatic solution extend to densities of perhaps 10^{10} cm^{-3} or perhaps 1.0 cm^{-3} , but even this is only some 20 scale heights (or one-tenth or one-fifth of a stellar radius) above optical depth unity. Beyond that, before the interstellar matter is reached, there extends a large region up to 10 or 100 stellar radii in which no hydrostatic solution exists. Around the Sun, there are the corona and the solar wind. Around white dwarfs, it has also been suggested that there could be a corona (Böhm and Cassinelli 1971). In any case, the hydrostatic equations, used above to obtain a proton and an electron flux and used by Bally and Harrison (1978) to conclude that electric field lines are open around stars, do *not* apply. We now analyze what should happen in that region, *assuming* a corona around a white dwarf. Should the electric field lines then be open or closed, and should incoming protons be turned back?

In their paper, Bally and Harrison (1978) do not discuss how stars get rid of their electrons to become

charged. They merely allude to the greater thermal velocity of electrons that thus could easily reach the escape velocity. In the presence of an electric field, however, the escape velocity of electrons is very different from that of protons or helium. The kinetic energy must be large enough to cancel not only the gravitational but also the electric potential of electrons (Milne 1923). The number of electrons leaving the star per second per cm^2 may then be written (Milne 1923)

$$\phi_e = n_e \left(\frac{kT}{2\pi m_e} \right)^{1/2} (1 + q_0) \exp(-q_0), \quad (9)$$

where

$$q_0 = \frac{\alpha m_p g R}{kT}, \quad (10)$$

g is the local gravity, and R the stellar radius. An isothermal atmosphere has been assumed, and it has been assumed that the electric field lines are open. The ratio of the electric to the gravitational field is then a constant. If one assumes the same electric field as given by equation (3), then $\alpha = 2$. The electron evaporation flux has to be as large as the proton diffusion flux in the He-rich main-sequence stars or as large as the accretion rate in the white dwarfs, which in turn depends on the cloud density (see below). Assume in both cases that the electron flux must equal $10^{15} \text{ cm}^{-2} \text{ s}^{-1}$, which is approximately the proton diffusion flux in He-rich stars (see below). Then from equation (9) it is easy to obtain Table 1, which shows that in the absence of a corona, when the atmosphere temperature is of the order of 10^4 , electrons can escape only if the star has an electric field 10^2 or 10^4 times smaller than in the atmosphere. Only in the presence of a corona with temperatures of the order of 10^6 K for He-rich main-sequence stars and 10^8 K for white dwarfs can an appreciable electron flux be maintained. Furthermore, since the temperature appears in the denominator of an exponent which is large ($q_0 \approx 10^3$ for $T = 10^4$ K, $\alpha = 1$ for He-rich main-sequence stars), the results of Table 1, are not sensitive to the electron flux, or the

TABLE 1
VALUES OF α AND T FOR THE ELECTRON TO EQUAL THE PROTON FLUX

α	T (K)
He-Rich Stars*	
2.....	10^6
10^{-2}	2×10^4
White Dwarfs†	
2.....	10^8
10^{-4}	10^4

* $\log g = 4$, $R = 10^{11} \text{ cm}$.

† $\log g = 8$, $R = 10^9 \text{ cm}$.

electron density assumed (taken here as the density below which the collision mean free path becomes larger than the stellar radius). One may vary these parameters within reasonable limits and one obtains roughly the same values for α or T .

One can also obtain an estimate of the minimum extension the corona must have in order for the star to get rid of its protons and electrons. For the protons to leave the star, they must attain the escape velocity. Assuming the electric field of equation (3), as they leave the star protons gain the kinetic energy $E(r)$

$$E = m_p g \left(R - \frac{R^2}{r} \right) \quad (11)$$

as soon as collisions become negligible. We wish to know for what radius this equals the energy needed to leave an uncharged star,

$$m_p g \frac{R^2}{r}.$$

Equating the two, we obtain

$$r = 2R. \quad (12)$$

The electric field lines then need to extend to a radius twice the stellar radius for the protons to be sufficiently accelerated by the electric field; similarly, for the electron flux to cross this area, the corona must extend to approximately twice the stellar radius.

The conclusion of Bally and Harrison (1978) that electric field lines are open can hold only if stars have a way to get rid of electrons. If not, they will rapidly accrete them, or equivalently will lose protons and keep electrons. If there is no corona, only one in 10^4 of the electric field lines will be open in white dwarfs and one in 10^2 in main-sequence He-rich stars. Only if there are coronae can most of the electric field lines be open. Then the electric field in the corona will act as a shield throwing back protons that try to accrete.

A more complete solution of this problem would require an elaborate dynamical model of the corona. This is outside the scope of this paper. Whenever it is attempted, the electric field should be explicitly included in the model, due to its central role.

IV. MAXIMUM DENSITY OF ACCRETING CLOUDS

We now establish a limit to the maximum density of an incoming cloud that can diffuse in and out of an atmosphere without compressing it. We will require that the outward proton flux allowed by diffusion be as large or larger than the accretion rate. We estimate this loss rate near 2 stellar radii where the protons have been accelerated to the escape velocity. The proton-loss rate C is given by

$$\begin{aligned} C &= 4\pi r^2 n_p w_p \\ &= 4\pi r^2 n_p D_p \frac{3m_p g}{kT}, \end{aligned} \quad (13)$$

where use has been made of equation (6). We note that one obtains the same result by equating the diffusion velocity of protons in helium with the velocity of the infalling matter, which is given to a sufficient accuracy by the free-fall velocity. This will remain a good model so long as the main constituent of the gas is helium. As soon as the main constituent becomes protons (that is, if the accretion rate is so large that the diffusing hydrogen is more abundant than the helium in the atmosphere), then hydrogen starts to accrete.

In the corona, at $T \lesssim 10^7$ K and $n_e \gtrsim 10^{10}$ cm $^{-3}$ helium will be mainly ionized; and, using the diffusion coefficient of Aller and Chapman (1960), one obtains

$$C = 10^8 g R^2 \frac{n_p}{n_{\text{He}}}, \quad (14)$$

where R is the stellar radius. Since the electric force on a proton is larger than gravity for $n_p \lesssim n_{\text{He}}$, the proton flux can be as large as

$$C = 3.4 \times 10^{-16} M_\odot \text{ yr}^{-1}, \quad (15)$$

for typical white-dwarf values of $g = 10^8$ cm s $^{-2}$ and $R = 10^9$ cm.

This value for the proton flux must be compared with the expected accretion rate in order to determine the density below which the electric field effectively stops the accretion process. Despite the fact that interstellar matter accretion onto stars (Talbot and Newman 1977), and onto white dwarfs in particular (Sion 1973; D'Antona and Mazzitelli 1975; Koester 1976; Truran *et al.* 1977; Wesemael 1978), has been the subject of several recent publications, the question of the accretion rate is still unsettled. What emerges, however, is that the canonical Hoyle-Bondi rate (Bondi 1952) is an overestimate that can even reach several orders of magnitude in some cases. For pure hydrogen, it is given by

$$\begin{aligned} \dot{M} (M_\odot \text{ yr}^{-1}) &= 10^{-15} \left(\frac{M}{M_\odot} \right)^2 \left(\frac{n_\infty}{10 \text{ cm}^{-3}} \right) \\ &\times \left(\frac{30 \text{ km s}^{-1}}{(C_\infty^2 + V^2)^{1/2}} \right)^3, \end{aligned} \quad (16)$$

where n_∞ and C_∞ are, respectively, the hydrogen number density and the sound speed far from the star, and V is the relative velocity of the star with respect to the interstellar medium or clouds. The maximum allowed cloud density is then given by

$$n(\text{max}) = \frac{10^{16}}{(M/M_\odot)^2} \left[\frac{\sqrt{C_\infty^2 + V^2}}{30 \text{ km s}^{-1}} \right]^3 C. \quad (17)$$

At this point, it is necessary to verify that we are indeed dealing with an infalling gas of ionized hydrogen. We thus estimate the radius of the H II region around a white dwarf following the standard method given, for example, in Osterbrock (1974). (In this context, note that eq. [20] of Talbot and Newman 1977 applies only to cases in which the radius of the

Strömgren sphere is less than or equal to the accretion radius,

$$R_c = \frac{GM}{C_\infty^2 + V^2},$$

a situation which is essentially never encountered when dealing with white dwarfs.) Assuming that a helium-rich white dwarf radiates like a blackbody (an approximation which is expected to be reasonable), we estimate that the fraction f of the star's luminosity that is emitted at wavelengths smaller than 912 \AA is equal to 2.1×10^{-1} , 1.0×10^{-4} , and 1.2×10^{-8} for $T_{\text{eff}}(10^3 \text{ K}) = 30, 10,$ and 6 , respectively. Neglecting the contribution of the infalling matter to this ionizing radiation, we find that the ratio of the Strömgren sphere radius to the stellar radius in the interstellar medium ($n_\infty \approx 1.0 \text{ cm}^{-3}$) is $\bar{R}/R = 1.8 \times 10^9, 3.4 \times 10^7,$ and 8.4×10^5 , for $T_{\text{eff}}(10^3 \text{ K}) = 30, 10,$ and 6 , respectively. The ratio \bar{R}/R_c is also found to be quite large for typical values of the encounter velocity. It is also much larger than the radius of the corona. We note that, in this situation, Mestel (1954; see also Schatzman 1955) has argued that the accretion rate given by equation (16) should further be reduced by a factor $\sim 5.7 \times 10^5$. However, even without this correction, we find that $n(\text{max})$ is of the order of typical cloud densities. Indeed, in an H II region with $T \approx 10^4 \text{ K}$, $C_\infty \approx 17 \text{ km s}^{-1}$, and using a typical space velocity of He-rich white dwarfs (Eggen and Greenstein 1967; Sion and Liebert 1977) $V \approx 30 \text{ km s}^{-1}$, we find that

$$n(\text{max}) \approx 10 \text{ cm}^{-3},$$

for a white dwarf with $M = 0.6 M_\odot$ ($\log g = 8$) and $T_{\text{eff}} = 10^4 \text{ K}$.

Keeping in mind the fact that the expected accretion rate is most probably a large overestimate, we conclude that the electric fields in the atmospheres of helium-rich white dwarfs can prevent accretion, since the probability of encounters with clouds having densities much larger than say $10^{+2}n(\text{max})$ is quite small during the lifetimes of these objects (Talbot and Newman 1977).

V. DISCUSSION

A He-rich white dwarf must be able to selectively counteract hydrogen accretion throughout its lifetime, as the atmospheric contamination time scale is very short (less than a year for the Hoyle-Bondi accretion rate, according to Strittmatter and Wickramasinghe 1971). Heavier elements could accrete and still present characteristically large atmospheric underabundances, since they would rapidly diffuse below the photosphere in the presence of radiative equilibrium, or below the superficial helium convection zone (Fontaine and Michaud 1979). We have found that hydrogen accretion could possibly be halted if a corona were to extend beyond approximately 2 stellar radii. Acoustically heated coronae around white dwarfs were first discussed by Böhm and Cassinelli (1971). Significant

mechanical energy is generated in the helium convection zones of helium-rich white dwarfs, and it is believed that acoustical waves propagating outward in the atmospheres lead to the formation of hot coronae. While the acoustic flux decreases above $T_{\text{eff}} \approx 30,000 \text{ K}$ (Fontaine 1977), superficial helium convection zones remain present up to $T_{\text{eff}} \approx 60,000 \text{ K}$ for helium white dwarfs with $\log g \approx 8$. Further, white-dwarf corona temperatures of the order of 10^8 K have been discussed by Böhm and Cassinelli (1971). Somewhat lower values of the temperature (Muchmore and Böhm 1978) are found if Hearn's (1975) method is applied, but his formulation has recently been criticized by Antiochos and Underwood (1978). Future X-ray observations may help in determining the temperatures of white-dwarf coronae. The infalling matter may also contribute in heating the corona (G. Vauclair, S. Vauclair, and J. L. Greenstein, private communication).

Assuming the existence of a hot corona, a He-rich white dwarf is capable of maintaining a significant proton and electron flux. The size of the Strömgren sphere increases very rapidly with the effective temperature. Therefore the expected accretion rate should be reduced compared with the Hoyle-Bondi expression. During essentially its entire life span, a He-rich white dwarf does not accrete interstellar hydrogen, as the electric fields present in its atmosphere are strong enough to repel the hydrogen gas.

This mechanism also offers a natural explanation for the He-rich main-sequence star phenomenon. In the atmospheres of these stars, a macroscopically neutral stellar wind of protons and electrons is produced by a sufficiently strong electric field, leaving behind a He-enriched atmosphere. By arguments similar to those leading to equation (15), one arrives at a mass-loss rate

$$v_D \rho \approx 10^{-10}$$

in neutral helium (in the same units as Vauclair 1975) and

$$v_D \rho \approx 10^{-12}$$

in ionized helium, which covers the range of mass losses needed to allow the helium enrichment (see Vauclair 1975). However, it is not clear in this model how the helium enrichment is created. It can maintain itself by mass loss, but the electric field is available only when substantial helium enrichment is present. To discuss this point further we will await the results of the accurate radiation force calculations on He I alluded to earlier. Another problem that requires further study is whether the stellar wind suggested by Vauclair is large enough to eject all the protons entering through the bottom of the He-rich zone. Whatever be the details of the model, however, there should be a stellar wind powered by the electric field of He-rich stars, if they also have a corona. It is also interesting to note here that the solar wind shows a hydrogen-to-helium number ratio of 25 (Feldman et al., 1977), three times larger than the assumed surface value.

Similarly, if a white dwarf is created with a residual hydrogen abundance, it will preferentially eject it into the interstellar matter, leading to a very pure He atmosphere. White dwarfs need not be born with pure helium. This may help in explaining the coexistence of non-DA white dwarfs and nuclei of planetary nebulae, the vast majority of which show hydrogen absorption lines (Aller 1948).

Our final remark concerns the electric field. It is essential here that the electric field lines do not close near the star. The studies that have been made suggest that they do not. However, we note that Milne (1924) and Bally and Harrison (1978) consider only electro-

static solutions, to arrive at the conclusion that field lines will end only at very small densities ($n < 10^{-6} \text{ cm}^{-3}$). When a star goes through the interstellar medium, the kinetic energy density of the interstellar gas is larger than the local electrostatic field energy of the star. The electrostatic solution may then be affected. Obtaining a detailed model of the interaction of the star with the interstellar matter is, however, beyond the scope of this paper. Does a star act as an icebreaker or is it pushing the gas back? Considering its impact on accretion and mass loss, this is a very important question.

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