A Pervasive Electric Field in the Heliosphere (Part II)

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Abstract—In Part I of this paper [1] it was proposed that a static electric potential of about +800 MV is present in the heliosphere, sustained by the continual inflow of galactic cosmic ray (GCR) protons. Charge neutralization cannot occur because the solar wind and magnetic fields allow more protons than electrons to pass through the termination shock (TS) deeply into the heliosphere. The result is a quasi-static electric field, at dynamic equilibrium, inside the heliosphere. This paper adds some important details that were not included in Part I, and makes some clarifications. The presence of the heliospheric electric field opens up the possibility of accounting for the Pioneer Anomaly, and also the anomalous cosmic rays, as caused by electric fields.

I. INTRODUCTION

During the year following publication of Part I [1], I engaged a physicist who is very knowledgeable and experienced with the physics of the heliosphere, in extensive email discussions. My correspondent expressed numerous concerns, including the following major specific objections to the concept:

1. The excess free protons responsible for the electric field would be neutralized if the bulk solar wind electrons simply flow only slightly slower than the bulk solar wind ions.

2. An electric field that diminishes the kinetic energy of incoming galactic cosmic ray (GCR) protons by 800 MeV would also accelerate heliospheric thermal electrons, some of them to as high as 800 MeV, toward the center of the heliosphere, and such energetic electrons are not observed.

3. Interstellar thermal electrons have velocities comparable to that of the solar wind (SW), so can easily pass through the termination shock (TS) to neutralize the electric field.

In the course of defending the concept against these objections, the author has achieved a more complete understanding of the physics involved, which included a few surprises. This paper, Part II, documents that more complete understanding and points out some implications of the model (Sec. III).

II. DISCUSSION

A. Response to Objection 1 (SW electrons flow more slowly than SW protons)

The heliospheric electric potential results because of the diffusion-like behavior of the highly modulated GCR protons in the central portions of the heliosphere, and the time delay in the arrival of neutralizing electrons, which are accelerated to near the speed of light, from the TS. If the bulk flow of electrons in the SW were to slow relative to the bulk flow of SW protons, tending to neutralize the field, this would mean that, instead of traveling from the TS, the neutralizing electrons drop out of the SW flow along the way. However, the effect of a dropout electron on the potential would not be felt until the SW proton (with which that SW dropout electron was loosely coupled) arrives at, and passes through, the TS. Until then, the decoupled SW proton would continue to contribute its charge to the heliospheric electric potential. This means that, instead of immediately neutralizing an excess proton, the charge exchange is not felt by the potential until a time interval three orders of magnitude longer than that assumed in Part I (1) for neutralizing excess protons, i.e., at velocity near the speed of light vs. several hundreds of km/s. Since the magnitude of the potential depends on the time delay in the arrival of neutralizing electrons, this mechanism would act to increase, not decrease, the potential.

The bulk of the heliospheric plasma flows outward toward the TS at several hundreds of km/s, and is in transit for almost a year before reaching the TS. The bulk flow is neutral, for otherwise its flow would be prevented by the electric field, and its velocity is negligible compared to that of the dynamic flows associated with maintaining the field at equilibrium, so except for the analysis in this section the SW will be considered stationary, and its constituent particles treated as thermal.

B. Response to Objection 2 (acceleration of electrons to 800 MeV)

This turned out to be by far the most challenging of the three major objections, although in retrospect it should not have been nearly so difficult. As described in Part I [1], the equilibrium electric potential results because of a slight excess of free protons inside the heliosphere (some 10^{31} compared to a total of about 10^{46} each of free electrons and free protons). It was not specified how the 10^{31} excess protons are distributed inside the heliosphere, but the implicit assumption was that they are configured roughly in spherical symmetry. That being the case, an electric potential of +800 MV must exist between any point on the the TS (which is an equipotential surface) and the centroid of the heliosphere, the graphs of the field and potential being functions of the actual spatial distribution. The average magnitude of the potential, + 800 MV, was simply inferred from empirical force field parameter data [2], and for purposes of this work will be assumed constant and exact.

As can be seen from Figure 1, GCR protons with kinetic energy less than a few hundred MeV cannot penetrate more than about 20 AU into the heliosphere before giving up almost all of their energy and being swept back out of the heliosphere by the SW. Similarly, the great majority of the GCR protons with higher energy, but much less than 800 MeV, will also be deflected and turned around by the electric field and swept out of the heliosphere. Those GCR protons whose vector velocities are toward the centroid of the heliosphere and have energy close to 800 MeV, can arrive near the centroid having lost nearly all of their kinetic energy. But even if these GCR protons lose 99% of their energy they still have about two orders of magnitude greater energy than the SW protons. These protons undergo diffusion-like motions because of their short radii of gyration caused by the irregular magnetic fields they encounter, and the low magnitude of the electric field in this region.

Since the GCR protons that can reach the inner heliosphere arrive at a far smaller rate than those that can reach the outer heliosphere, one might expect that the density of excess protons would be much higher in the outer heliosphere than elsewhere. However, the residence time is longer for the lesser quantity of GCR protons which are deposited deeply inside the heliosphere, and in combination with mutual repulsion of the excess free protons they tend toward a homogeneous distribution. The actual distribution is uncertain due to the complex interactions of the dynamic processes involved, so to fix ideas the following simplifying assumptions will be made:

> <u>Assumptions</u> : The distribution of excess protons is exactly homogeneous throughout the heliosphere, on average, and the heliosphere is exactly spherical with radius 90 AU.

For this case the electric field would be E = 2kr inside the heliosphere (3), increasing linearly from 0 to 120 mV/km at r ≈ 90 AU, and the electric potential would be $V = 800 - kr^2$, decreasing from 800 MV at r = 0 to 0 MV at r ≈ 90 AU, as shown in Figure 1.

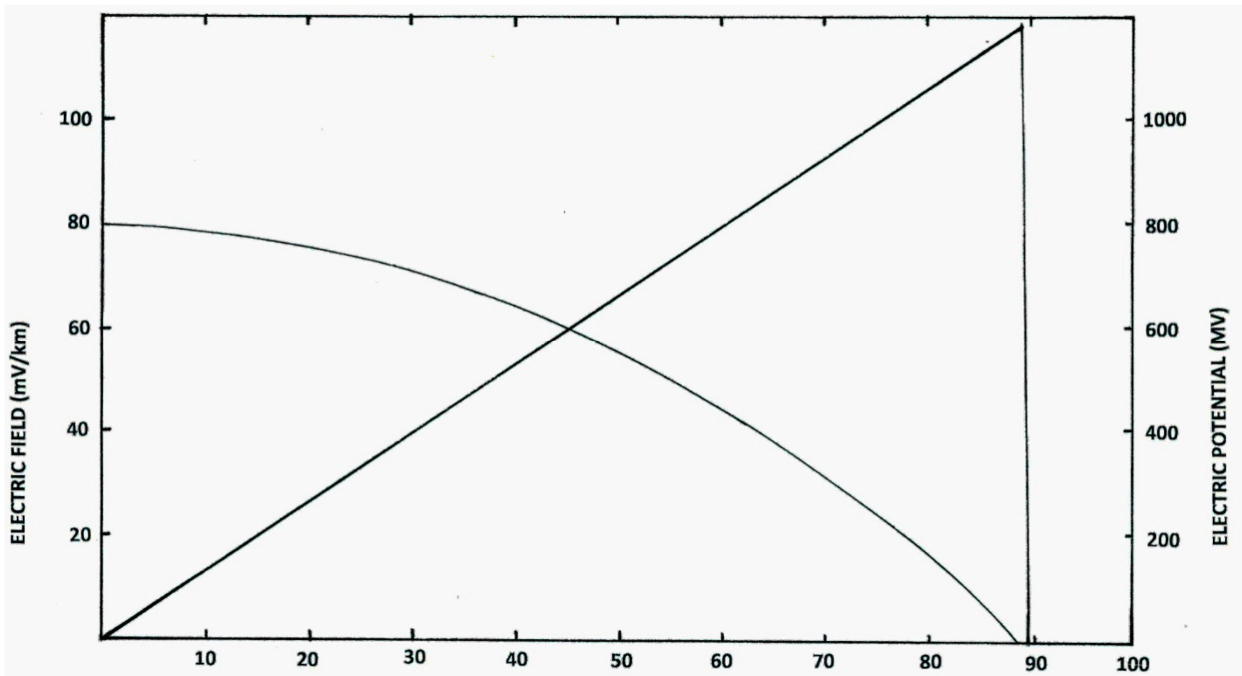

Fig. 1 Electric field E (line passing through origin) and electric potential V, vs. radius of the heliosphere. The potential decreases abruptly to – 1,000 MV (not shown) just short of the termination shock at 90 AU, then abruptly increases back to 0. The field also decreases abruptly, passing through 0 at the radius of the potential minimum, continuing to E < 0 (also not shown), and then increases back to 0. Potential and field are both 0 beyond the termination shock. See text for assumptions and explanations.

An equilibrium would be established between the flow of SW protons and electrons outward through the TS, and the flow of GCR protons and electrons inward through the TS, such that the net flow of electric charges across the TS is exactly zero on average. There are 10^{31} excess protons distributed throughout the heliosphere, and this means that their associated GCR electrons that passed through the TS remain in the outer heliosphere or were ejected. If the overall heliosphere is electrically neutral, as seems unavoidable, this means that 10^{31} excess electrons remain in or near the TS, probably in a thin spherical shell inside the TS. The average negative potential in such a thin spherical shell would be:

$$V = \frac{Q}{4\pi\varepsilon_0 R} \qquad (1)$$

which works out to – 1,000 MV. The field would also decrease rapidly to negative, reaching a minimum inside the spherical shell at the same radius as the minimum of the potential. The magnitude of the electric field in the spherical shell is not known, but it is probably 2 or even 3 orders of magnitude larger than the average main (+) field in the heliosphere. Both potential and field would then rise abruptly to zero, relative to the local interstellar medium.

Each of the thermal electrons inside the heliosphere participates in the equilibrium process which determines how the excess protons are distributed, by flowing toward any higher concentrations of protons. Since there are more free protons than free electrons inside the heliosphere (1 extra proton for every 10^{15} proton-electron pairs), a completely neutral inner heliosphere is not achievable through the rearrangement of charged particles. My correspondent pointed out that the equilibrium state that I described could not exist, because any thermal electrons would be accelerated by the field, as long as the field is present, some to energies as high as 800 MeV, and such energetic electrons are not observed in the central regions of the heliosphere.

As to the thermal electrons already present in the outer heliosphere, it was recognized at the outset that all of the 10^{46} thermal electrons would have to be accelerated by the field together, rather than just one or a few at a time. And since each electron experiences a force qE (where q is the electric charge and E is the field) the force vector on each of the electrons acts in the direction of the center of the heliosphere. The electrons cannot all compress and move together toward the central point, leaving the protons behind, so the thermal electrons are effectively confined by the heliospheric electric field. For each electron there is one very nearby proton which feels almost exactly the same force qE, except in the opposite direction. Naively, one might expect that the thermal protons, having a clear path to expand outwards through the TS and flow into the heliosheath, would respond to the qE force on them and accelerate radially outwards. But since the thermal protons are coupled by their electric fields to the thermal electrons, the protons are also confined by the field. The situation is very much the same as it would be with 10^{46} atoms of neutral hydrogen, instead of plasma, dispersed throughout the electric field. The field does not accelerate any of the thermal electrons or protons, whether in a plasma or bound state, the major difference being that the free protons and electrons move independently in a plasma instead of in bound pairs, as in neutral atoms. The electric field offers no resistance to neutral plasma flows, such as the solar wind, so the solar wind protons are not prevented from flowing freely away from the Sun, as long as they carry their loosely coupled electrons along with them. When high energy charged particles such as GCRs enter the heliosphere, they are accelerated by the electric field because the particles are not thermalized and therefore do not participate actively in the equilibrium process.

When considering this somewhat surprising outcome, it should be noted that nature abounds in examples of force fields which do not accelerate elements upon which their forces act. Common examples are gravitating solid planets, moons, and asteroids. Other examples are massive gaseous, and even hot plasma bodies such as stars, in which gravitational forces drive convection, causing mass flows away from the center of gravity as well as toward it, resulting in a net mass flow rate of zero.

It is so well known that Earth’s gravitational field causes rocks and other massive objects to accelerate downward when they are dropped from a high place, or into a hole, that it is usually given no thought. It is similarly well known that a rock does not accelerate when it is at rest on or beneath the surface. The reason, of course, is that Earth's gravity field is highly symmetric, spherically, so that it can only accelerate masses toward the center of gravity, and the pathway for acceleration is blocked for all elements of its mass, except when those masses are disturbed. Each element of mass rests atop those below it, and as a result of the gravity field each such mass at rest acquires a weight of mg, where g is the acceleration of gravity at the location where the mass m happens to be located.

The quasi-static electric field proposed in Part I [1] is also highly symmetric spherically and can only accelerate electrically charged particles in the radial direction, electrons toward the center and positive ions diametrically away from the center. Since every free electron at equilibrium in the heliosphere is prevented from accelerating toward the center of the heliosphere because of the electric fields of the electrons below it, each electron acquires an electrical "weight" of qE, where q is the electron charge and E is the electric field at the point where the electron is located. Except for edge effects near the TS, all of the free protons are similarly prevented from accelerating outward because of the electric fields of protons above it, so they each acquire a negative "weight" from the heliospheric field, also of magnitude qE. The TS is an extremely dynamic and complex region, with GCR ions and electrons entering the heliosphere and heliospheric ions and electrons exiting, all in the presence of a large negative electric field. A more detailed analysis of edge effects will not be attempted here, except to note that the bulk protons cannot flow away from the bulk electrons, because doing so would very rapidly increase the potential energy of the plasma.

C. Response to Objection 3 (neutralization by interstellar electrons)

It is proposed in Sec. IIB that the main heliospheric field decreases abruptly below zero in a thin spherical shell inside the TS, reaches a minimum, then rises abruptly to zero near the outer surface of the TS. Although the magnitude of the field is not known, the electric potential decreases to about – 1,000 MV, then rises to zero in this region, so the field may have a magnitude in the tens of V/km. This is more than sufficient to prevent the diffusion of any interstellar thermal electrons into this region. Interstellar thermal protons and ions which diffuse into this region will be accelerated inward by the field, but they will lose almost as much energy that they gain when they encounter the main (+) field, so will be turned before they penetrate more than about 10 AU into the heliosphere (see Fig. 1) and swept back out with the SW. These ions may contribute to the general + field in the heliosphere. Because of the steep gradients of the electric field in the region of the TS, this would seem to be an ideal location for the anomalous cosmic rays to achieve their high observed energies.

III. SOME IMPLICATIONS OF THE MODEL

It seems likely that the Pioneer spacecraft acquired a very large negative electric charge in their external thermal blankets during their gravity boost inside Jupiter's magnetosphere, possibly as large as 0.03 coulombs [4], and that the Pioneer Anomaly is caused by the attractive electrostatic force of the heliospheric field. The electric field derived here using the simplifying assumptions in Sec. IIC is linear in r, but the actual field could instead have a plateau over the range of measurements which characterize the Pioneer Anomaly. Alternately, the electric field may be approximately as shown in Figure 1, and the electron charge in the thermal blankets which cover the outer surface of the spacecraft may have leaked away at a rate such that the product of electric field and charge (the accelerating force on the spacecraft) remained approximately constant, as observed. The positive heliospheric electric field combined with a negative electric charge of 0.03 coulombs are more than sufficient to account for the anomalous acceleration.

The electric potential plummets from 0 to – 1,000 MV (average) inside the thin spherical shell just inside the TS, then rises as rapidly back to 0 at the outer surface of the TS. Although it will not be explored further here, such a large swing in the potential within a small region is ideally suited to account for the anomalous cosmic rays, which are believed to be neutral interstellar particles that become ionized after passing through the TS (or possibly SW ions). The anomalous cosmic rays are accelerated to energies of hundreds of MeV, in or near the TS, but the mechanism responsible for the acceleration is not presently understood [5].

Because of the electric field through which the solar wind flows, the plasma becomes polarized, so that each proton is exposed to a slightly larger field than its loosely coupled electron, resulting in a small net outward force on each proton-electron pair. Although the bulk solar wind is neutral, it is accelerated by the field because of the net outward force caused by the polarization.

Using the simplifying assumptions employed in Sec. II.C, it is found that the repulsive electric force on a free proton would dominate over the Sun's attractive gravitational force everywhere in the heliosphere except inside a central sphere having radius of 7.7 solar radii. Since the Sun is probably rarely (if ever) located within 7.7 solar radii of the centroid of the heliosphere, the electric field in effect dominates over gravity for protons everywhere in the heliosphere.

IV. CONCLUSIONS

The suggestion that the modulation of galactic cosmic rays in the heliosphere might be due to an electric field was first made in 1949 by Alfvén [6], who mentioned a potential of order 3,000 MV. Ehmert [7] first published the detailed GCR particle spectra which would result from this form of modulation, and suggested that a dynamically sustained potential of 1,000 MV was needed to explain the observations. In 1965, Freier and Waddington [8] gave their opinion that, "the major difficulty of the idea seems to be the conceptual problem of establishing and maintaining the electric field", and that difficulty has now persisted for more than 50 years.

As described in Part I [1] and modified and elaborated here, the answer to the elusive conceptual problem is the greater flow rate of GCR protons into the heliosphere, compared to GCR electrons. The electric field maintains zero net flow rates of positive and negative charges across the TS, and it accomplishes this through a feedback loop. For example, if the potential decreases, the deposition rate of GCR protons in the inner heliosphere increases significantly because of the steep power law of its spectrum, i.e. an increase in the numbers of GCR protons which have energy very near the maximum of the potential. Although many complex interactions take place inside the heliosphere, the deposition of GCR protons deeply inside the heliosphere, which have lost almost all of their energy and undergo diffusion-like motions, is the dominant interaction which maintains the heliospheric electric field.

ACKNOWLEDGMENT

I am grateful to my unnamed correspondent for forcing me to consider some important points that were not dealt with in Part I (1).

IV. REFERENCES

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