

# Cosmic Electron Spectra by the Voyager Instruments and the Galactic Electrostatic Field

Antonio Codino

Department of Physics, University of Perugia, Perugia, Italy  
Email: antonio.codino@pg.infn.it

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## Abstract

The Voyager spacecrafts have been measuring since 2012 the rates of electron and nuclei of the cosmic radiation beyond the solar cavity at a distance of more than  $10^{13}$  meters from the Earth. A record of unique and notable findings has been reported and among them, the electron-to-proton flux ratio of 50 to 100 below energies of 50 MeV. This ratio is thoroughly opposite to that of 0.01 measured at higher energies in the range 10 GeV to 10 TeV. The difference amounts to four orders of magnitude. Arguments and calculations to show how this surprising and fundamental ratio lends support to the empirical evidence of the ubiquitous electrostatic field in the Milky Way Galaxy are presented. In other respects, this paper examines and calculates, for the first time, the electric charge balance in the solar system delimited by the *termination shock* of the solar wind.

## Keywords

High Energy Astrophysics, Particle Astrophysics, Solar Magnetic Fields, Solar Physics, Galactic Cosmic Rays

## 1. Introduction

A recent work provides empirical evidence of the Galactic electrostatic field [1]. A very short account of this work has been presented at the 37th ICRC 2021, Berlin, Germany [2]. The Galactic electric field, designated by  $\vec{E}_g$  ( $g$  for galactic), is permanent and ubiquitous except in regions where electrostatic shielding of structured ionized materials occurs. The solar system is one of these shielded regions and, in spite of the electric shielding, highly specific effects with unmistakable signatures manifest themselves, attesting the existence of the Galactic electric field  $\vec{E}_g$ . This paper deals with one of these effects, that is, the energy spectrum of cosmic electrons at low energies below 80 MeV and above 3 MeV measured by the Voyager

spacecraft.

In essential terms and in other contexts, the negative electric charge of the electron spectrum, 3 - 80 MeV, is just the electric charge needed to continuously neutralize the positive electric charge deposited by cosmic rays in the solar cavity. Hence, this paper examines, calculates and reports, for the first time, the electric charge balance in the solar system within the *termination shock* of the solar wind.

A stuffy introduction is avoided here by relegating in **Appendix A** (The new scientific context) where the present paper properly shines.

All the stars in the *Galaxy* retain a notable amount of positive electric charge deposited by the Galactic cosmic-ray nuclei. Charge deposition occurs in two different ways in two separate regions: the first way is the stopping of low-energy cosmic rays in the solar wind and the second way is the stopping of all cosmic rays of low and high energies in the *Solar* body by ionization and nuclear interactions. By solar body is meant all the high-density material residing within photosphere of radius  $R_s$  (*s* for *Sun*). The electric charge per second deposited in the *Sun* will be designated by  $I_{sw}$  (*s* for solar *w* for wind) and  $I_{ds}$  (*d* for dense and *s* for *Sun*), respectively. In the following, the photospheric radius  $R_s$  of the *Sun* is  $6.98 \times 10^5$  km and the mass inside  $1.989 \times 10^{33}$  g, so that the average density is  $1.4 \text{ g/cm}^3$ . Anticipating successive results, above 5 GeV,  $I_{ds} = 1.1 \times 10^3$  Coulomb/s (hereafter C/s) and  $I_{sw} = 1.96 \times 10^{12}$  C/s in the range 3 MeV - 20 GeV of the cosmic-ray spectrum, where data are available. According to the research book [3] published at the end of 2022, *How Electrostatic Fields Generated by Cosmic Rays Cause the Expansion of the Nearby Universe*, the positive electric charge retained by stars concurs to resolve the Dark Matter problem.

The region occupied by the solar wind is approximated by a sphere of radius  $R_{sc}$  (*sc* for solar cavity). Its volume  $V_{sc} \equiv (4/3)\pi R_{sc}^3$  is a surrogate of the non-spherical volume delimited by the termination shock of nominal radius  $R_{sc}$  of  $1.331 \times 10^{13}$  m observed by the Voyager Probes in two different positions of the nearby circumstellar space [4] [5]. The two positions in heliocentric system are 37.5 degrees North at 94 AU [3] (Astronomical Unit,  $1.49597870 \times 10^8$  m) and -116.5 degrees South at 83.7 AU [4]. Crudely and nominally,

$$R_{sc} \equiv (94 + 84)/2 = 89 \text{ AU} = 1.331 \times 10^{13} \text{ m} \quad \text{and} \quad V_{sc} = (4/3)\pi R_{sc}^3 = 9.8769 \times 10^{39} \text{ m}^3.$$

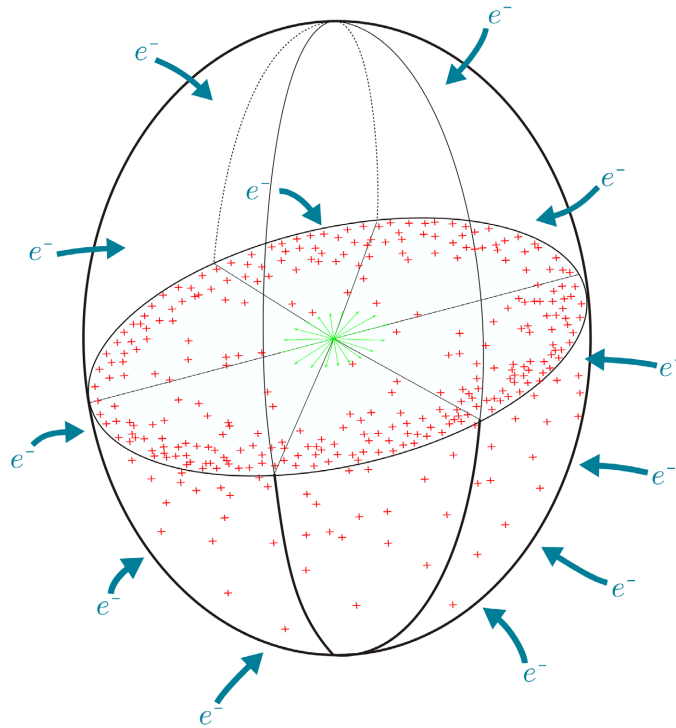
In this work, solar cavity is synonymous with solar electrostatic cavern.

The electric charge deposition in the *Sun* by cosmic nuclei mentioned above also applies to any stars, as stellar winds are universal (see, for example, [6]).

## 2. Charge Deposition in the Solar Wind Region

Nuclei and electrons of the Galactic cosmic radiation intercepting the solar wind, in *Classical Mechanics*, a sort of continuous fluid moving outwards, loose energy and a conspicuous fraction of the cosmic-ray flux with energies below 1 - 10 GeV/u is thoroughly arrested and dispersed in the environment.

An artistic portrait of the electric charge deposited by cosmic rays in the solar wind is shown in **Figure 1** by red crosses.



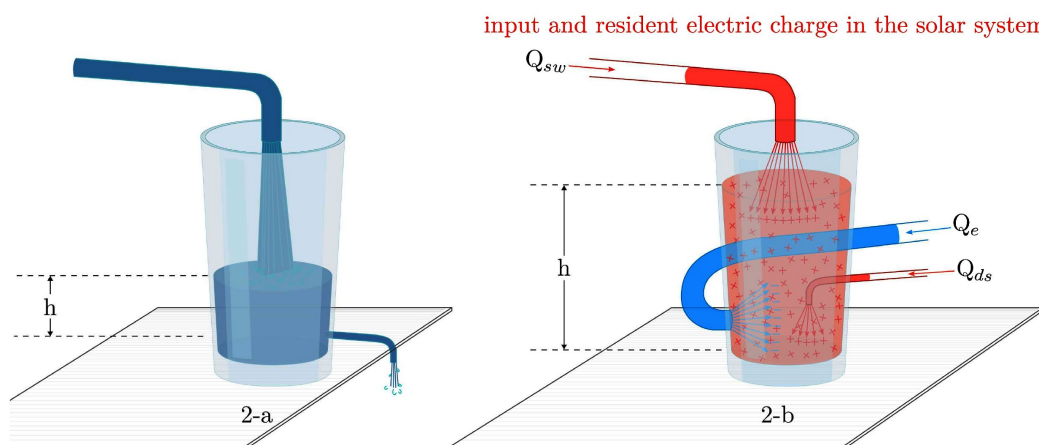
**Figure 1.** Artistic portrait of low-energy cosmic rays extinguished in the solar wind. The positive electric charge deposited by cosmic rays extinguished in the solar wind is marked by red crosses. Solar wind stems from the corona and is propelled in the corona. Quiescent electron currents (represented by thick blue arrows) coming from the nearby circumstellar space migrate toward the region occupied by the solar wind where cosmic-ray extinction takes place. Green vectors of fanlike shape represent the electrostatic field  $\vec{E}_{ds}$  at the base of the *Solar* photosphere projected in an arbitrary plane, for simplicity. The ovoidal volume of the figure is arbitrary.

Let  $J_T$  ( $T$  for terrestrial flux) denote the flux of cosmic rays measured at *Earth* at the top of the atmosphere (zero atmospheric depth) and  $J_{de}$  ( $de$  for demodulated) the unperturbed flux in the nearby interstellar space usually called demodulated flux. Solar modulation cyclically affects cosmic-ray intensity below 10 - 20 GeV within the solar wind volume (see, for example, ref. [7]). The total amount of electric charge,  $Q_{sw}$  deposited by cosmic rays in the volume  $V_{sc}$  occupied by the solar wind  $Q_{sw}$  is given by:

$$I_{sw} = \bar{q}_{cr}(E) A_{sc} \int_{E_1}^{E_2} J_{de} dE \tag{1}$$

where  $A_{sc} = 4\pi R_{sc}^2 = 2.2262 \times 10^{27} \text{ m}^2$  is the area intercepted by the demodulated flux of cosmic rays in the energy band  $E_1$  and  $E_2$  being  $E_2 \geq E_1$ . For protons  $\bar{q}_{cr} = 1.0 \times 10^{-19} \text{ C}$  and for all cosmic nuclei at low energy  $\bar{q}_{cr} = 1.2 \times 10^{-19} \text{ C}$  (see **Figure 2** in ref. [8]). Of course, the electric charge deposited between the *Earth* radius and the *Sun* photosphere is missing in Equation (1) and it has to be summed up. Here only notice that measurements of the cosmic-ray flux at 0.1 - 1 AU performed by recent and past space missions (Parker Solar Probe, Helios, Ulysses) are available.

The demodulated spectrum besides nuclei include electrons  $J_e$ , positrons  $J_{pos}$  and antiprotons  $J_{\bar{p}}$ , so that the global positively charged cosmic-ray flux is,  $J_{de} - J_e + J_{pos} - J_{\bar{p}}$ . Traditionally, in the literature, the demodulated spectrum is also termed *Local Interstellar Spectrum* (LIS), but this is an interpretation of the demodulated spectrum, and not pure data, like energy spectra resulting from measurements are.



**Figure 2.** Illustration of electric charge flows in the solar cavity by a simple hydraulic analogy. (a) The gap  $h$ , in the liquid levels in the bucket is not zero (an empty bucket corresponds to  $h = 0$ ) but it has some finite value governed by gravity pressure, input and output calibers and input velocity of the liquid. (b) Red pipelines entering the bucket from top and side in the arbitrary time interval  $\delta t$  represent the positive charge  $Q_{sw} + Q_{ds}$  which equals the negative charge  $Q_{ne}^-$  represented by the blue pipeline. Here the bucket denotes the nominal volume of the solar cavity  $V_{sc} = 9.8769 \times 10^{39} \text{ m}^3$ . The stationary condition in the charge balance within  $V_{sc}$  is referred to as equilibrium or quasi steady condition. Equilibrium implies that some residual positive charge,  $R(\delta t)$  defined by Equation (2), permanently remains in the bucket in a regime where positive and negative currents  $Q_{sw} + Q_{ds} + Q_{ne}^-$  balance. From this charge, namely  $R(\delta t)$ , originates the permanent electrostatic fields  $E_{sw}$  and  $\vec{E}_{ds}$ .

### 3. Charge Balance around Stars and Multiple Star Systems

According to Potassium abundance in terrestrial meteorites [9], the cosmic-ray intensity in the last 2 billion years has maintained approximately constant. This datum is regarded as solid input here to state, or posit, the quasi-stationary state in the flows of the electric charge in the volume  $V_{sc}$ .

At the arbitrary time interval  $\delta t$ , the positive electric charge deposited in the volume  $V_{sc}$  amounts to:  $(I_{sw} + I_{ds})\delta t$ .

The neutralization of the positive charge excess during the time span  $\delta t$ ,  $I_{sw}\delta t + I_{ds}\delta t$  in the volume  $V_{sc}$  promotes a quiescent electron current designated by  $I_e$  and called *migration current*. The electric current  $I_e$  is qualitatively represented by the thick blue arrows in Figure 1. The current  $I_e$  entering the solar cavity coming from the nearby interstellar space, beyond the radius  $R_{sc}$ , transports the negative electric charge  $Q_e = I_e\delta t$  in the arbitrary time interval  $\delta t$ . For an ideal, continuous isotropic current and a spherical solar cavity it would be:

$Q_e(\delta t) = 4\pi R_{sc}^2 I_e \delta t$ . The total electric charge contained in the solar cavity of volume  $V_{sc}$  in the time interval  $\delta t$  is given by:

$$(I_e + I_{sw} + I_{ds})\delta t + q_{sc}(0) = R(\delta t) \quad (2)$$

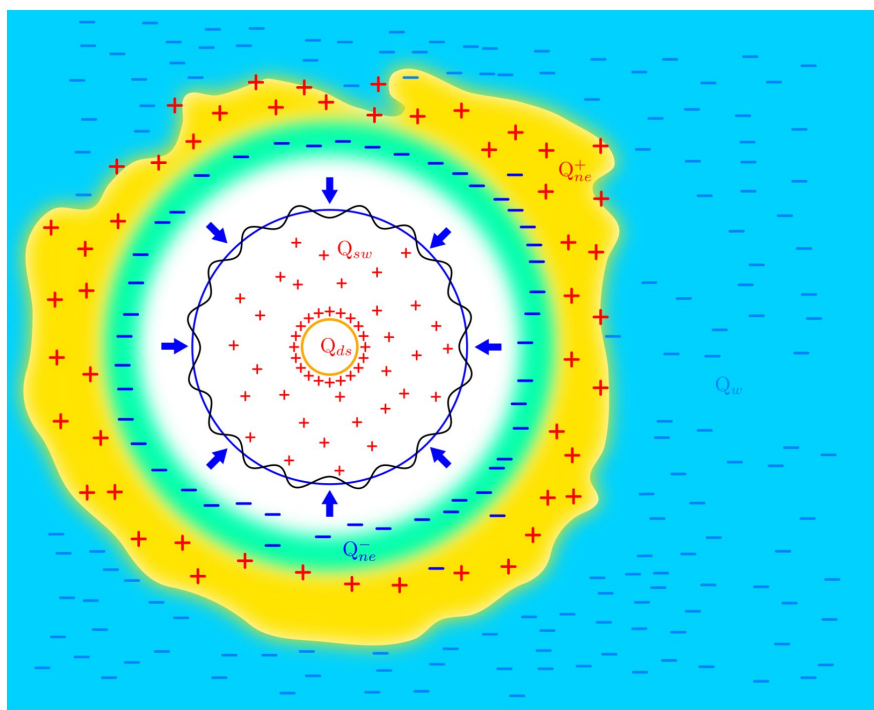
where  $q_{sc}(0)$  is the total electric charge in the volume  $V_{sc}$  at initial time  $t = 0$ . Any arbitrary time may be chosen as initial time or zero time taking into account the *Sun* age of about 4.5673 Ga. The charge within the volume  $V_{sc} = 9.8769 \times 10^{39} \text{ m}^3$  at time  $\delta t$  is denoted by  $R(\delta t)$ .

The stationary state during the time interval  $\delta t$  posits,  $I_e + I_{sw} + I_{ds} = 0$  and, therefore,  $q_{sc}(0) = R(\delta t)$  where  $R(\delta t)$  designates the residual electric charge at the time  $\delta t$ . For instance, during the temporal span surveyed by Potassium data [9] of  $\approx 2$  Ga, the residual charge  $R(2 \text{ Ga})$  remained constant and the time  $t = 0$ , *i.e.*, the initial time of the present calculation is 2 Ga back in time from the present epoch.

If the average displacement velocity of the migration current  $I_e$  was very high, ultimately, comparable to  $c$ , the light speed, a rapid neutralization of the positive electric charge  $(Q_{sw} + Q_{ds}) = (I_{sw} + I_{ds})\delta t$  within the volume  $V_{sc}$  at any arbitrary time spans  $\delta t$  would take place. In this imaginary and unphysical condition the residual charge  $R(\delta t)$  in Equation (2) would turn out to be  $q_{sc}(0)$ . The neutralization of the positive electric charge,  $I_{sw}\delta t + I_{ds}\delta t$  requires a characteristic time interval  $T_{ne}$  ( $ne$  per neutralization) regulated by the conductivity of the circumstellar medium, the distance of the cosmic-ray sources, the convective motion of local materials, moving charged plasma parcels, moving neutral plasma pockets in the environment, the local magnetic fields, local electrostatic fields, the electrostatic field of the star surfaces  $\vec{E}_s$  and in the solar wind region  $\vec{E}_{sw}$  and other parameters. During the time span  $T_{ne}$ , the negative charge  $Q_{ne}^-$  transported by quiescent electrons surrounding nearby stars and nearby clouds (see **Figure 3**) uncovers the positive quiescent charge  $Q_{ne}^+$  in a larger circumstellar ambient so that:  $Q_{ne}^- + Q_{ne}^+ = 0$ , based on charge conservation in a finite volume of the adjacent larger ambient surrounding the tiny solar cavity.

How much electric charge did the nascent *Sun* store before emanating solar wind? If the time  $t = 0$  is set at 4.567 Ga back in time (nominal *Sun* age), then the term  $q_{sc}(0)$  in Equation (2) would represent the pristine, presolar electric charge at the *Sun* birth.

Due to the finite neutralization times  $T_{ne}(\delta t)$ , the positive electric charge  $q_{sc}(t)$  accumulates implying  $q_{sc}(t) > q_{sc}(0)$ . Ultimately,  $q_{sc}(t)$  will be neutralized by a fraction of the negative electric charge  $Q_w = 2.58 \times 10^{31} \text{ C}$  dispersed in the cosmic-ray sources in the whole Galactic disk. This negative charge is that orbital electrons lost by the accelerated cosmic nuclei in all Galactic cosmic-ray sources. These particular orbital electrons are designated in the twin works [1] [3] by the new term, *widow electrons*. The term is useful whenever charge balance of various particle populations including cosmic rays has to be examined and calculated. This point is debated in *Chapter 12* of ref. [1].



**Figure 3.** Qualitative, unempirical chart of spherical regions around the Sun where positive and negative charges are expected to prevail. The wavy black curve designates the termination shock of the solar wind observed by the Voyager Probes V1 and V2 encircling the positive electric charge of volume  $V_{sw}$ . The charge  $Q_{ne}^-$  of the migration current occupies the spherical green region with negative charge prevalence around the solar cavity where low energy electrons are expected to dominate. The yellow region with positive charge (plus signs) surrounding the green negative charge region (minus signs) is depleted of low energy electrons migrated in the inner adjacent green region surrounding the termination shock (wavy black region). The vast blue region with negative charge  $Q_w$  (blue minus signs) designates the *widow electron* region. Widow electrons are defined as orbital electrons abandoned in the environment by cosmic nuclei during the acceleration stage at the cosmic-ray sources.

Taking into account the total negative charge of widow electrons  $Q_w$  and the positive charge of cosmic-ray nuclei  $Q_{cr}$  being  $Q_{cr} = -Q_w = 2.58 \times 10^{31}$  C, a more rigorous expression of Equation (2) may be written in this way:

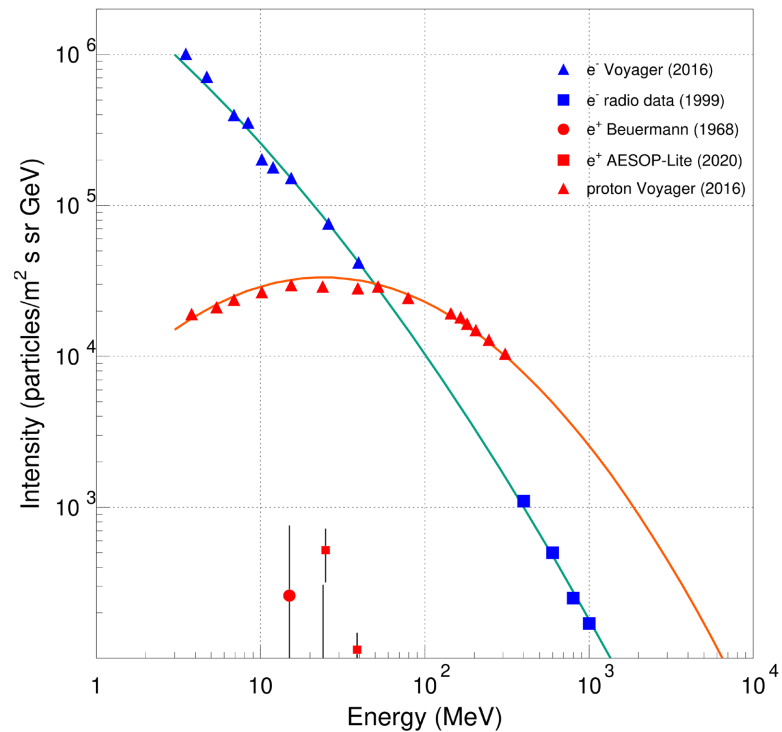
$$(I_e + I_{sw} + I_{ds})\delta t + Q_w(V_{sc}) + Q_{cr}(V_{sc}) + q_{sc}(0) = R(\delta t) \quad (3)$$

where  $Q_w(V_{sc})$  is the nominal negative charge of widow electrons in the volume  $V_{sc}$  and  $Q_{cr}(V_{sc})$ , the nominal positive charge of cosmic-ray nuclei in the same volume  $V_{sc}$ . Therefore, *a priori* the nominal negative charge of *widow electrons* would be  $Q_w(V_{sc}) = -4.6 \times 10^{11}$  C and  $+Q_{cr}(V_{sc})$  less than this value because the positive charge is dispersed in a volume larger than that of the disk (see next Section 4).

Notice that sources of electric charge within the solar cavity do not alter the stationary state envisaged above. For example, Jupiter planet releases electrons [10] [11] observed at 1AU by *ISEE3* at a rate of some  $4.6 \pm 0.19 \times 10^4$  electron/GeV $\cdot$ m $^2$ ·s·sr

in the range 1 - 30 MeV [11]. Charge conservation requires a corresponding positive electric charge *in situ* in the Jupiter planet. Other known sources of negative charge within  $V_{sc}$  are sporadic emission of energetic electrons during solar flares.

#### 4. The Equilibrium of the Electric Currents in the Heliosphere



**Figure 4.** Cosmic-ray electron spectrum measured by Voyager in the range 2 MeV to 100 MeV along with cosmic-ray proton in the range 3 MeV to 600 MeV measured by the *Voyager Probes* [12]. The continuous blue line is the extrapolated solar modulation curve. The continuous red line is the proton solar modulation curve. Positron data at these low energies are scarce; positron intensity is more than an order of magnitude below the proton curve.

The electric charges  $I_{ds}\delta t$  and  $I_{sw}\delta t$  stored in the *Sun* and solar wind, respectively, during the time span  $\delta t$  produce distinctive physical effects. For example, as the charge  $Q_{ds}$  rotates with the *Sun*, it has to generate a magnetic field. This effect is presented in Section 6.

The basic condition of the charge balance expressed by Equation (2) is the stationary state or steady condition or equilibrium. In this condition, in the volume  $V_{sc} = 9.87 \times 10^{45} \text{ cm}^3$ , electric currents equilibrate, e.g.  $I_e + I_{ds} + I_{sw} = 0$  and the baseline charge,  $R(\delta t) = Q_w(V_{sc}) + Q_{cr}(V_{sc}) + q_{sc}(0)$  is not zero but it assumes some finite value as depicted in **Figure 2(a)** by an hydraulic analogy. In the steady-state condition at the arbitrary time span  $\delta t$ , regardless of the complexity of the environment, the neutralization charge  $Q_{ne}^- \equiv I_e\delta t$  entering the solar cavity from the adjacent interstellar space (see **Figure 3**) has to equalize the positive electric

charge  $(I_{sw} + I_{ds})\delta t$  deposited by cosmic nuclei in the same volume and same time span  $\delta t$ . This neutralization is certainly influenced by the permanent charge  $R(\delta t)$ . The equilibrium implies that the number of quiescent electrons of extremely low energy entering the solar cavity has to swamp that of quiescent protons and quiescent nuclei in the same energy band because of the overwhelming positive charge entering the solar cavity via cosmic nuclei of higher energies, above 60 MeV as attested in **Figure 4**. Notice that the nominal charge of widow electrons in the solar cavity,  $Q_w(V_{sc})$ , is thoroughly negligible compared to the charge  $I_{sw}\delta t + I_{ds}\delta t$  deposited by cosmic nuclei. As the average charge density of widow electrons in the Galactic disk of volume  $V_d$  is,

$Q_w/V_d = -2.58 \times 10^{31} \text{ C} / 5.19 \times 10^{66} \text{ cm}^3 = -0.498 \times 10^{-35} \text{ C/cm}^3$  [1] and the volume of the spherical solar cavity is  $V_{sc} = 9.87 \times 10^{45} \text{ cm}^3$ , nominally, the total negative charge  $Q_w(V_{sc}/V_d)$  is about  $4.9 \times 10^{10} \text{ C}$ , thoroughly negligible relative to any plausible estimate of  $I_{ds}\delta t$  and  $I_{sw}\delta t$ . For example, by setting the lifetime of cosmic rays in the Galaxy,  $\delta t = 15 \times 10^6 \text{ years} = 4.73 \times 10^{14} \text{ s}$ , it results

$$Q_{ds} = I_{ds}\delta t = 1.1 \times 10^3 \times 4.73 \times 10^{14} = 5.20 \times 10^{17} \text{ C} \quad \text{and}$$

$$Q_{sw} = I_{sw}\delta t = 1.96 \times 10^{12} \times 4.73 \times 10^{14} = 9.27 \times 10^{26} \text{ C}, \text{ respectively, which outnumber } Q_w(V_{sc}) \text{ limited to } 4.9 \times 10^{10} \text{ C}.$$

As local electric fields exist in interstellar clouds as also pointed out by others and the solar system is embedded in the nearby clouds<sup>1</sup>, quiescent electrons of the indifferenced interstellar medium are accelerated and decelerated with multiple gains and losses of kinetic energies in a wide range of values. For example, a local electric field of  $10^{-6} \text{ V/m}$  acting in an unshielded milliparsec region ( $3 \times 10^{13} \text{ m}$ ) imparts 100 MeV of kinetic energies to charged particles. This implies that the neutralization charge of quiescent electrons most likely occurs not at thermal or suprathermal energies ( $>70 \text{ eV}$ ), in the keV band, but at higher energies due to the ubiquitous presence of local electrostatic fields.

## 5. The Positive Electric Charge Stored in the Solar Cavity

The intensity of cosmic nuclei versus time during the magnetic solar cycle of 22 years enables to infer the intensity of cosmic nuclei in the outer space surrounding the solar cavity. The energy spectra of the cosmic radiation are called *LIS* (*Local Interstellar Spectra*) or demodulated spectra, or, eventually, energy spectra of the very local interstellar medium (*VLIS*) as hinted earlier.

The most recent advance on the measurements of the electric currents  $I_{sw}$  and

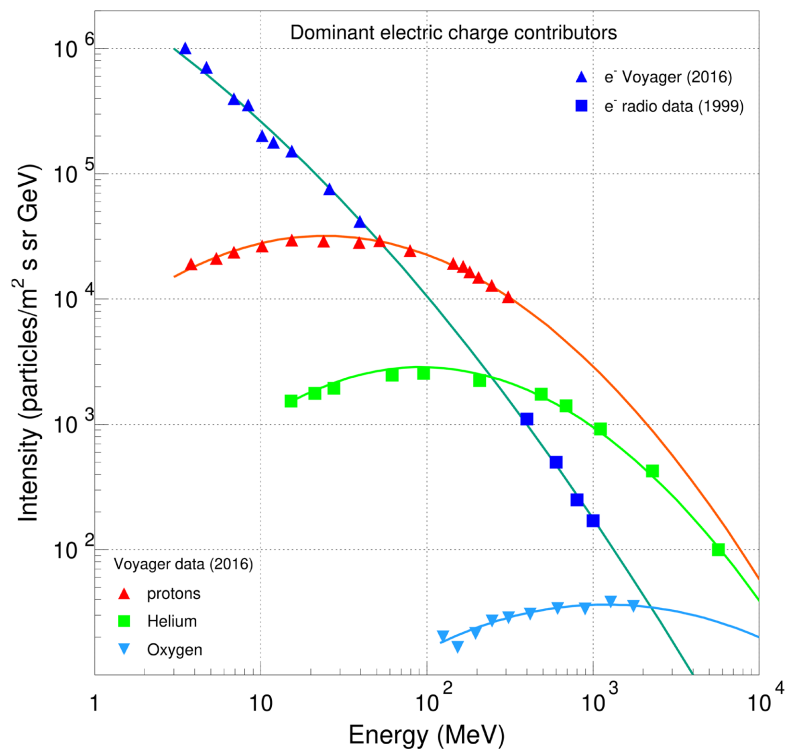
<sup>1</sup>The volume of the space adjacent to the solar cavity is insignificant relative to that of the Galaxy of some  $2.55 \times 10^{66} \text{ cm}^3$ . The Local Bubble surrounding the Sun has a size of about 10pc, gas density  $0.05 \text{ atoms/cm}^3$  and temperature of about 10,000 degrees. The Local Interstellar Cloud embraces the Local Bubble in a wider ambient, about 300 pc in size, and other bubbles called Loop 1, Loop 2 and Loop 3 lie in the vicinity. The precious, unique and historical results of the Voyager Probes on magnetic fields, gas density, pressure, solar wind features and others are expected to vary in these larger regions because the static and dynamic conditions of matter and radiation are different. Thus, measurements of the Voyager Probes refer indeed to the very skinny region around a G star, the Sun, and extrapolations of these measurements to the huge and variegated interstellar space might be insecure.

$I_{ds}$  have been made by the *V1* and *V2* Voyager detectors which directly determine cosmic-ray fluxes in the very local interstellar medium. The energy spectra of cosmic proton and electron are shown in **Figure 4**. The electron spectrum from radio data [13] in the interval 400 MeV to 1 GeV (blue squares) shown in **Figure 4** intrinsically constitutes the demodulated spectrum and, in this particular case, appropriately termed *LIS* spectrum.

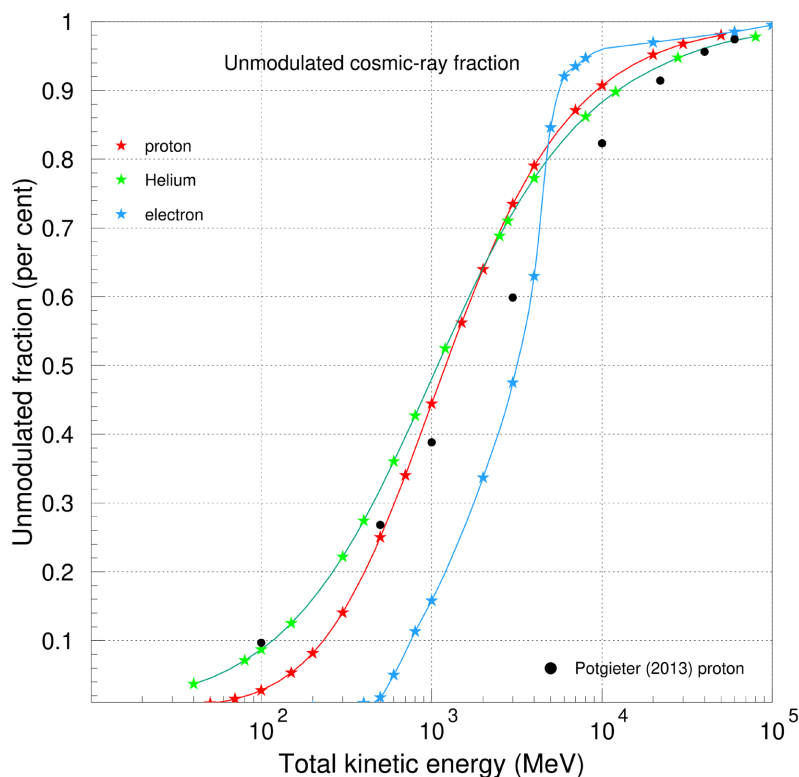
Cosmic protons in the range 3 MeV - 10 GeV entering the solar cavity have a flux of 15,037 part/m<sup>2</sup>·s *sr* according to the observed spectrum shown in **Figure 4** and **Figure 5**. Due to the solar modulation only a fraction  $F_p$  of these protons contributes to the current  $I_{sw}$ . The fraction  $F_p$  depends on the energy and it is intended to be the average value in many solar cycles of 22 years. The fraction  $F_p$  is shown in **Figure 6** according to observations collected in the last 70 years. The proton fraction  $F_p$  is called unmodulated proton fraction. The positive charge lost by cosmic protons in the volume  $V_{sc}$  due to the flux  $J_p$  is:

$$qA_{sc} \int_{E_1}^{E_2} J_p F_p dE = 3.92 \times 10^{12} \text{ C/s} \quad \text{where} \quad q = 1.602 \times 10^{-19}, \quad A_{sc} = 2.2262 \times 10^{27},$$

$$E_1 = 3 \text{ MeV} \quad \text{and} \quad E_2 = 20 \text{ GeV. Details of the calculation are given in Appendix B.}$$



**Figure 5.** The total electric charge permanently entering the solar cavity comes from four dominant particles: electrons, protons, Helium and Oxygen. The four spectra shown in the figure are the local interstellar energy spectra or demodulated spectra, namely, those purified by the solar modulation effect. These spectra have been measured by the Voyager Probes *V1* and *V2* during many years of observation. At low energies, below 100 MeV, solar modulation at Earth can decrease the demodulated intensity by more than an order of magnitude.



**Figure 6.** Fractions of unmodulated intensities versus total kinetic energy for electron, proton and Helium in the solar cavity. Black dots are just an example of estimates of unmodulated proton fractions [14] that might serve for illustrative comparison.

Cosmic electrons in the same energy range 3 MeV - 20 GeV have a flux of 9219 part/m<sup>2</sup>·s sr according to the observed spectrum shown in **Figure 4** and **Figure 5**. The unmodulated electron fraction,  $F_e$ , versus energy is given in **Figure 6**. The negative charge entering the volume  $V_{sc}$  corresponding to this flux is  $3.28 \times 10^{12}$  C/s. Therefore, the global electric charge balance of proton and electron in the range 3 MeV - 10 GeV is  $+0.64 \times 10^{12}$  C/s.

Proton and electron spectra shown in **Figure 4** and **Figure 5** intercross around 60 MeV. This energy represents a critical divide: above 60 MeV the total electric charge entering the solar cavity via cosmic rays is always positive while below 60 MeV is always negative. In the range 3 - 60 MeV the global input charge of proton and electron is negative,  $-5230$  C/s while that above 60 MeV is positive, being  $+10,741$  C/s.

In the global charge balance across the solar cavity positrons and antiprotons at low energies have to be included. In the critical range 1 MeV to 200 MeV no measurements of these antiparticles in the interstellar medium are available. Thus, only tentative extrapolations of the modulated spectra observed at Earth might be used.

The antiproton flux in the energy range 1 MeV to 200 MeV remains unmeasured. Just above 200 MeV the  $\bar{p}/p$  flux ratio is about  $10^{-5}$  [15] reaching a stable plateau of about  $2 \times 10^{-4}$  above 2 GeV. Loose upper limits of about  $10^{-1}$  at the maximum explored energies of 1 - 10 TeV have been reported [16] using the standard Moon

shadowing technique. As antiprotons are secondary particles generated by interactions of cosmic nuclei in the *Galaxy* and no obvious sources are known, the negative charge from antiprotons entering the solar cavity is negligible compared to that of low-energy cosmic electrons.

Cosmic positrons are secondary particles generated by interactions of cosmic nuclei in the *Galaxy*, but unlike antiprotons, Galactic quiescent positron sources do exist located in stars and supernovae remnants. These sources are the radioactive nuclides  $^{44}\text{Ti}$ ,  $^{56}\text{Ni}$  and  $^{26}\text{Al}$  which yield positrons in the MeV range while decaying.

Important measurements of positron flux below 100 MeV at Earth were performed in 1968 by the *IMP-8* detector [17] and in 2018 during the positive magnetic polarity of the *Sun* cycle by the AESOP-Lite detector in the energy band 20 MeV to 1 GeV [18]. Data points of the highest rates of these two experiments are shown in **Figure 4**. Positron electric charge, in principle, might challenge the dominance of negative electric charge carried by electrons in the range 1 MeV - 100 MeV (see **Figure 4**).

Similarly to Equation (1) the charge of the positive positron current,  $Q_{pos}$ , is computed by:  $I_{pos} \equiv qA_{sc} \int J_{pos} dE$ .

In principle low energy positrons from radioactive decays of  $^{44}\text{Ti}$ ,  $^{56}\text{Ni}$  and  $^{26}\text{Al}$  might be trapped in local electric fields debouching in flux spikes at very low energies in the band 1 MeV to 50 MeV thereby affecting the neutralization of the positive charge  $Q_{sw}$ . Should the positron current  $J_{pos}$  be comparable to the migration current  $I_e$ , the postulated neutralization around the *Sun* becomes questionable.

## 6. Electric Charges Stored by Stars Are Consistent with the Observed Stellar Magnetic Fields

From the previous analysis follows that a current of negative charges of quiescent electrons  $I_e$  called *migration current* in the work [1] and depicted in **Figure 1** has to enter stellar cavities of any stars to neutralize the positively charged currents,  $I_{sw} + I_{ds}$  certainly deposited by cosmic rays.

Moving charges generate magnetic fields of definite strengths and shapes. As stars retain positive electric charge and move at high velocities, both rotating and translating, smooth magnetic fields sprout everywhere. Here, the focus is on the fact that measurements of magnetic field strengths of various stellar categories and *Sun* are consistent with rotating electric charges in the range  $10^{19}$  -  $10^{20}$  C with typical rotational periods 0.1 - 50 days [19].

The *Sun* surface receives from the cosmic radiation the positive charge per second  $I_{ds} = 1.14 \times 10^3$  C/s computed by  $J = a/E^\gamma$  with  $a = 28656$  part/m<sup>2</sup>·s sr GeV<sup>1.67</sup> [1],  $\gamma = 2.67$  [1], a threshold energy  $E_1 = 5$  GeV,  $E_2$  arbitrarily large being not influential,  $\bar{q} = 1.2 \times 10^{-19}$  C [8] and  $4\pi R_s^2 = 6.2262 \times 10^{18}$  m<sup>2</sup> the *Sun* collecting area. The threshold energy of 5 GeV seems in the correct range taking into account solar modulation. For example, a threshold of 10 GeV would result

in  $I_{ds} = 3.6 \times 10^3 \text{ C/s}$ .

As particle density in the *Sun* is close to  $8.3 \times 10^{23}$  particles/cm<sup>3</sup> from  $1.4 \text{ g/cm}^3 / 1.67 \times 10^{-24} \text{ g}$ , being exceedingly high relative to the electron density of the migration current, the neutralization of the charge  $Q_{ds}$  occurs *in situ*, i.e., cosmic nuclei extinguished within solar photosphere absorb quiescent electrons from local solar materials. If no charge neutralization from external sources takes place, the requirement of charge conservation within the *Sun* radius  $R_s$  would yield an unlimited accumulation of positive charge as electrons from the *migration current* from the local interstellar medium are thoroughly absorbed by the ionized atoms of the solar wind and cannot reach the *Sun* main body which resides within the tiny radius of  $R_s = 6.98 \times 10^5 \text{ km}$  face to  $R_{sc}$  of  $1.331 \times 10^{13} \text{ km}$ .

For example, in one billion years ( $\delta t = 3.155 \times 10^{16} \text{ s}$ ) assuming no charge neutralization from the migration current  $I_e$ , the accumulated charge in the *Sun* would amount to  $I_{ds} \delta t = 3.61 \times 10^{19} \text{ C}$ . Notice further that prestellar materials do certainly store positive electric charges deposited by cosmic rays as argued elsewhere (see *Segments* 11.2 and 12.4 of ref. [1]). This pristine charge deposition occurring in the nascent *Sun* certainly adds to the charge  $I_{ds} \delta t$  computed above. With no charge neutralization, ineluctably, magnetic field intensities in stars have to augment with time until charge densities saturate the hosting and absorbing structures eventually enabling new electric discharge channels.

Global magnetic fields resulting from spinning charges can be estimated by assuming a simple loop of current  $i$  of radius  $R$ . The order of magnitude of the field strength is,  $B = \mu_0 i / (2\pi R)$  where  $R$  is the radius of the star. Measured star rotation periods range from 0.1 to 200 days (see data of stellar rotational periods in Table 3 of ref. [19]). For example, the *Sun* rotation period is 27.5 days,  $2.376 \times 10^6 \text{ s}$  so that, after one billion years,  $i = Q_{ds} / T = 1.519 \times 10^{13} \text{ A}$ . The magnetic field strength of the rotating charge  $I_{ds} \delta t$  from the formula above is:  $B = 2.0 \times 10^{-7} \times 1.519 \times 10^{13} \text{ A} / 6.98 \times 10^8 \text{ m} = 42 \times 10^{-4} \text{ T} = 42 \text{ G}$ . In the quiet *Sun*, the overall magnetic field strength is in this range [20] and, similarly, in other stellar categories [21].

Perhaps the best measurements of magnetic field intensities in stars are those in binary systems. Magnetic flux conservation is invoked during stellar explosions in binary systems. Such explosions yield neutron stars. The typical radius of collapsed stars is about  $10^6 \text{ km}$  while that of a neutron star about  $10 \text{ km}$ . In a spherical geometry the ratio of the areas is  $10^{10}$  which is the enhancement factor of the magnetic field. Magnetic field strengths measured in neutron stars are in the range  $10^{11} - 10^{12} \text{ G}$  and, consequently, with a reduction factor of  $10^{10}$ , those in collapsing parent stars in binary systems are in the range  $10 - 100 \text{ G}$ .

These magnetic field strengths are also measured, order of magnitude, in the quiet *Sun* [20], in *F*, *G*, *K* and *M* stars [21] and *O* and *B* stars [22]. A sample of magnetic field strengths measured in *O* and *B* stars conform to a lognormal distribution with an average value of  $338 \text{ G}$ . It is worth recalling that magnetic field strengths measured in the spots, flares and energetic outbursts from the *Sun* surface and other star

surfaces are approximately 1000 - 5000 G, some 2 to 3 orders of magnitude higher than 10 - 100 G. As magnetic field intensities in stars in quiet conditions unambiguously differ from those measured in magnetic spots, the nexus between rotating charges and magnetic field intensities is highly suggested or tentatively demonstrated.

In order to explain magnetic fields in stars, aside from spinning positive charges  $Q_{ds}$ , other mechanisms have been proposed such as the dynamo theory quite recurrent in the literature.

Neutron stars result from the explosion of massive stars, which have magnetic field strengths of some  $\mu\text{G}$  believed to be originated by the classical dynamo mechanism. As magnetic flux during explosion conserves, field strengths in neutron stars have enhanced magnetic fields by a rough factor of  $10^{10}$ , as previously noted. Do magnetic fields in neutron stars also originate via dynamo mechanism? This mechanism seems inapplicable to neutron stars, which hardly might host the large convective cells of normal stars due to the small sizes of about 10 km. Conceivably, rotating positive charges appear to be a more natural explanation of both magnetic fields in progenitor star and neutron star.

## 7. Compendium and Conclusions

It is an assessed fact that cosmic rays arriving at Earth are arrested in the solar wind, thereby depositing a positive electric charge at all the energies above 60 MeV (see **Figure 4**) according to the Voyager data. The positive electric charge per second  $I_{sw}$  deposited by cosmic-ray nuclei (proton and Helium) in the solar cavity of nominal radius  $R_{sc} = 1.331 \times 10^{13} \text{ m}$  [4] [12] has been calculated in Section 5 and **Appendix B** of this work and it amounts to  $I_{sw} = 3.83 \times 10^{12} \text{ C/s}$ . The estimated current  $I_{sw}$  is likely to be correct within a factor of 2.

This charge has to be neutralized in order to avoid electric fields of very high intensity within the solar wind volume<sup>2</sup> and its environment. Sources of electric charge within the solar cavity in a finite, specified volume, for example, Jovian electrons [10] [11], conserve electric charge and, accordingly, cannot neutralize  $I_{sw}$  over adequate, long-time intervals. It follows that the electric charge has to come from the exterior of the solar cavity as qualitatively depicted in **Figure 1** by blue arrows pointing inward, representing entrant negative charge (electrons). The motion of these low-energy electrons and their inherent electric currents in the

<sup>2</sup>The electric field  $E_{sw}$  generated by the permanent electric charge residing in the solar cavity is immersed in a bath of moving ions, namely, the solar wind, which tends to shield and, consequently to obscure any electrostatic effects. In spite of that, during transient phenomena within the solar wind itself or perturbations originated outside the solar wind volume, shielding may be inefficient or absent. In this case electron acceleration and nucleus acceleration within the solar wind have to manifest. Indeed, proton and Helium acceleration in the range 0.1 - 10 MeV in the interplanetary medium has been observed long time ago [23]; it was unpredicted and erroneously attributed to non electric acceleration processes. A population of energetic electrons in the solar wind in the interval 2 - 100 keV during quiet time conditions has been also reported and its acceleration is not in the Sun [24] but in the interplanetary space. It is worth noting that quiet time conditions indicate absence of CIR compressions, absence of shocks in the medium and no sudden ambient alterations.

whole Galaxy gives rise to the *migration current* denoted by  $I_e$  as asserted in this work and motivated elsewhere [1] [2]. The pristine spatial origin of the *migration current*  $I_e$  is in all cosmic-ray sources in the Galaxy, as amply debated in ref. [1].

The neutralization of the positive charge in the arbitrary time interval  $\delta t$  within the solar cavity of nominal radius of 89 AU [3] [4]  $Q_{sw} = I_{sw} \delta t$  requires an equal amount of negative charge designated here by  $Q_{ne}^- = I_{ne}^- \delta t$  to be established by measurements. Ideally, in steady state flows  $Q_{ne}^- \delta t = I_e \delta t$ , where  $I_e$  is the migration current based on a logical inference amply debated in the work [1], as mentioned earlier. The notion of  $Q_{ne}^-$  derives from the necessity to neutralize the electric charge deposited by cosmic nuclei extinguished in the Galaxy. The Sun offers a unique opportunity to measure the electric charge balance of cosmic rays around one star and, hence, to observe one *migration current* around a single  $G$  star and not the *global migration current* of the  $10^{11}$  Galactic stars, which concur to generate the Galactic magnetic field (see ref. [1], Chapters 14 and 15).

It is an impressive and notable fact that the negative current  $I_{ne}^-$  has been detected by the Voyager instruments V1 and V2 by measuring huge rates of energetic electrons in the range 3 to 60 MeV (see Figure 4) while exiting the solar cavity beyond the shell region denoted *Heliosheath* [25].

The negative electric charge per second in the range 3 - 60 MeV entering the solar cavity  $I_{ne}^-$  is  $-1.86 \times 10^{12}$  C/s, derived in Section 5 and Appendix B from the cosmic-ray electron spectra measured by the Voyager detectors. This negative charge surprisingly counterbalances the positive electric charge per second deposited by cosmic rays in the solar cavity,  $I_{sw} + I_{ds}$ , of  $3.83 \times 10^{12}$  C/s in the range 60 MeV - 20 GeV. Within the accuracy of the calculation, the missing negative charge labeled here  $N_-$  is necessary for a perfect charge neutrality, namely,  $-1.86 \times 10^{12} + N_- + 3.83 \times 10^{12} = 0$  is  $-1.97 \times 10^{12}$  C/s. This charge amount is not incompatible with the electron spectra in the range 100 keV - 3 MeV constrained by the Pioneer data [26] and low frequency radio data [13] as speculated by others in the solar modulation arena (see, for example, ref. [27] for a plausible electron spectrum in this unexplored energy range).

In some respects, the postulated dominance of cosmic electrons over nuclei below 60 MeV is both impressive and surprising<sup>3</sup> because cosmic rays above solar modulation energies, *i.e.*, 10 GeV - 40 TeV, exhibit the opposite trend, namely, fluxes of protons and heavier nuclei dominate those of cosmic-ray electrons. The energy of 40 TeV above is the maximum measured cosmic-ray electron energy to date (2025).

In the census of electric charges within the finite volume  $V_{sc}$  and arbitrary time span  $\delta t$ , the charge absorbed inside the *Sun* photosphere within  $R_s$ , namely

<sup>3</sup>The surprise has been vented by those who made the measurements like William R. Webber of the Las Cruces University, New Mexico, a colleague of balloon experiments of bygone days (see for example ref. [28] [29]). In fact, he asserts [30]: “the LIS ratio of the electron to H nuclei intensities in MeV,  $e/H(E)$ , measured up to 60MeV by V1 outside the heliosphere... At 2 MeV this  $e/H(E)$  ratio is 100 (yes 100!) decreasing to 1.10 at 60 MeV”.

$I_{ds} \delta t$ , is negligible, but it appears quite adequate to generate stellar magnetic fields as loomed out in Section 6.

Along the same logical framework of this calculation it emerges that rotating electric charges stored by stars due to the charge deposition of cosmic rays generate magnetic field strengths in the range 10 - 100 G with dipolar geometry which are in accord, order of magnitude, with spectropolarimetric Zeeman data of *O* stars and radio observations of magnetic fields of neutron star progenitors as debated in Section 6. The agreement of computed and observed magnetic field intensities of about 10 - 100 G further supports the context of this work.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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## Appendix

### A. The Novel Scientific Context in Cosmic Ray Physics

According to the works [1] [2], the *Milky Way Galaxy* has a pervasive and stable electrostatic field designated by  $\vec{E}_g$  (*g* for galactic) generated by the motion of positively and negatively charged particles of the cosmic radiation. Cosmic rays are accelerated by the electrostatic field, which performs the acceleration from quiescent energies up to the maximum energies of  $2.48 \times 10^{21}$  eV of cosmic Uranium nuclei [31]. In restricted regions of the *Galaxy*, the field  $\vec{E}_g$  is shielded by ionized materials, for instance, the region occupied by the solar wind in the solar system.

Facts supporting the existence of the *Galactic* electrostatic field discussed in [1] are: 1) the constant spectral index of the overall cosmic-ray energy spectrum comprised between 2.64 - 2.68 up to energies of  $2.8 \times 10^{19}$  eV; 2) the maximum energies of Galactic protons of  $2.8 \times 10^{19}$  eV; 3) the chemical composition of the cosmic radiation above the energy of  $2.8 \times 10^{19}$  eV which has to consist only of heavy nuclei; 4) the intensity, orientation and direction of the Galactic magnetic field; 5) the absence of correlation of the arrival directions of ultra-high-energy cosmic rays in the interval  $10^{18}$  -  $10^{20}$  eV with powerful radio galaxies in the nearby universe. As cosmic rays are Galactic up to  $2.48 \times 10^{21}$  eV, the absence of correlation is a natural, obvious in the context of the novel picture of the cosmic radiation reported in the works [1]-[3].

The calculated features 1) - 5) impressively agree with the experimental data as debated and highlighted in the aforementioned research book [1]. By contrast, results and predictions recurrent in the past and present literature of the traditional theories of the cosmic radiation are severely inconsistent with the facts 1) - 5). For example, the bulk motion of cosmic rays in the traditional theories is thoroughly disconnected from the geometrical pattern of the Galactic magnetic field.

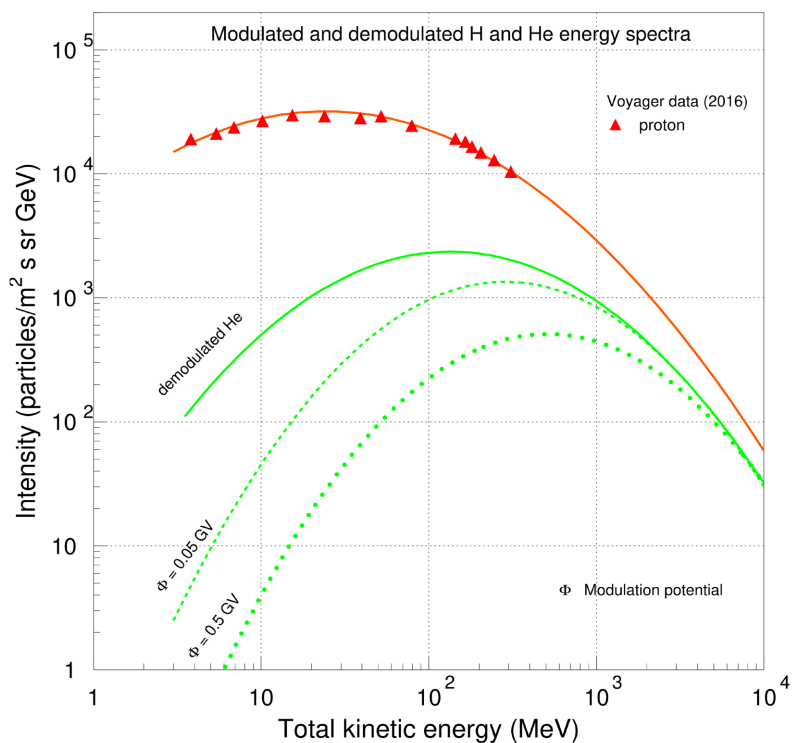
Probably, the most outstanding result in terms of accord between data and calculation reported in [1], designated fact (4) above, is the exact account of the regular magnetic field of the *Milky Way Galaxy* with its intensity of 1 - 5  $\mu$ G and its variegated and unique geometrical pattern in all the Galactic volume and beyond. The remarkable accordance with the optical and mostly radio data is described in *Chapters* 14 and 15 of ref. [1].

Presently, a conspicuous fraction of scientific community believes that cosmic rays are accelerated in supernova remnants up to  $10^{15}$  -  $10^{16}$  eV by a mechanism called diffusive shock acceleration. Numerous and variegated experimental data disagree with this credence. These inconsistencies are presented and debated in **Appendix C** of ref. [1] and in the research book [32]: *Progress and Prejudice in Cosmic Ray Physics until 2006*.

## B. The Modulated Spectra of Electron, Proton and Helium

In Section 4, to preserve a simple calculation scheme of the electric charge balance in the solar cavity, namely,  $I_{sw} + I_{ds}$ , only electrons and protons have been considered. Here are two necessary extensions of the calculation: 1) the effect of the solar modulation on the energy spectra; 2) the inclusion of Helium in the charge budget, the third major charge source in the solar cavern. The next contributing heavier nucleus is Oxygen. Its charge input, according to the data shown in **Figure 5**, is less than 8 per cent of the charge input of proton and Helium and therefore negligible for the aim of this work.

The analytical representation of the demodulated spectrum,  $J_{de}$ , anchored to the observational data of Voyager Probes [17] and radio data [13], allows a reliable evaluation of the *modulation factors*. These factors quantify the amount of the observed flux of energy  $T$  (total kinetic energy) arrested in the solar cavity, namely,  $F = J_{de}/J$  where  $J$  is the measured terrestrial flux or that in another location within  $1.331 \times 10^{13}$  m. The modulation region goes from the Sun photosphere up to 112 AU [4] [5].



**Figure A1.** Examples of solar modulation for cosmic-ray Helium with two arbitrary values of the modulation potential,  $\phi = 0.05$  and  $0.5$  GV. The interstellar Helium spectrum in the range  $3$  MeV -  $10$  GeV is also shown, called, more appropriately, demodulated Helium. Analytical expressions for the He spectra are from ref. [34]. To preserve simplicity demodulated Helium data are not shown; they are in **Figure 5**.

Since half a century, it is known that the intensity variations of proton and Helium registered on Earth in the range of  $50$  -  $500$  MeV, between minimum and

maximum modulating conditions, span a factor of about 5-6. This basic fact remains true to day after exploring 4 solar cycles. The spectra displayed in **Figure A1** are an example of computed modulation of Helium according to a classical parametrization [33] adopted in this work.

Electron and proton charge flows are given in Section 5. Here are those of Helium.

Helium in the range 12 MeV - 20 GeV entering the solar cavity has a flux of 3668.7 part/m<sup>2</sup>·s sr according to the observed spectrum shown in **Figure 5**. Due to the solar modulation, only a fraction of Helium nuclei,  $F_{He}$ , contributes to the current  $I_{sw}$ . The fraction  $F_{He}$  depends on the energy and it is intended to be the average value in many solar cycles of 22 years. The fraction  $F_{He}$  is shown in **Figure 6** according to observations collected in the last 70 years. The positive charge lost by Helium in the volume  $V_{sc}$  due to the flux  $J_{He}$  is:

$2qA_{sc} \int_{E_1}^{E_2} J_{He} F_{He} dE = 2.61 \times 10^{12}$  C/s, where  $q = 1.602 \times 10^{-19}$ ,  $A_{sc} = 2.2262 \times 10^{27}$ ,  $E_1 = 12$  MeV and  $E_2 = 20$  GeV. Thus, the He charge input is 39 percent of that of the proton.

For comparison with proton and electron, in the range 12 - 60 MeV, the global He input charge is  $0.0735 \times 10^{12}$  C/s while that in the range 60 MeV - 20 GeV is  $1.26 \times 10^{12}$  C/s.

The modulation factors shown in **Figure A1** are obtained by the demodulated spectra (often called *LIS* for Local Interstellar Spectra) and measured spectra at Earth, or close to it. As the Earth is located at 1 AU, additional electric charge deposition occurs between the *Sun* and the Earth. As the spherical volume enclosed by the Earth radius to the *Sun* is only a fraction of  $9.5 \times 10^{-5}$  of that of the solar cavern, this charge deposition is neglected in this work. Notice also that a severe conflict between measured and computed radial cosmic-ray gradients emerged in the inner heliosphere, making uncertain plain extrapolations of charge deposition based on the outer heliosphere data.

The dominant error source in the evaluation of charge  $I_{sw} + I_{ds}$  comes from the electron spectrum below 3 MeV, which is unmeasured but highly constrained by radio data [13] and Pioneer 10 observations [26] made at 70 AU for electron energies of 2 - 20 MeV. The limit of 3 MeV above is an intrinsic limitation at low energy of the V1 and V2 Voyager instruments.

### C. Failures of Diffusion Equation Applied to Cosmic Rays

In principle, the omission of the Galactic electrostatic field in any calculation of the properties of Galactic cosmic rays has to conduct severe inconsistencies with observational data. Here, some conflicts between computed and observed cosmic-ray features are mentioned. The computed features are obtained by the *Diffusion Equation of Galactic cosmic rays* used for more than 70 years. These conflicts are commonly registered in the literature.

1) The Boron-to-Carbon flux ratio in the range 10 - 25 MeV is inconsistent with standard calculations (see Figure 9 of ref. [12]).

2) According to the *V1* Voyager Team [12], the  $^2\text{H}$  and  $^3\text{He}$  isotope spectra in the range 5 - 50 MeV/u severely disagree with those computed by the *GALPROP* simulation code of Galactic cosmic rays in spite of the fine-tuning of simulation parameters. In the energy band 10 - 100 MeV/u, the observed intensity of  $^3\text{He}$  is higher than that computed by *GALPROP* code by more than an order of magnitude. The *GALPROP* code adopts the diffusion equation tuned, in this case, at low energies around 0.005 - 20 GeV/u.

3) The ionization rate of Hydrogen, termed  $\zeta_{cr}$  (*cr* for cosmic rays), computed with the reconstructed cosmic-ray energy spectrum in Galactic environment via *Diffusion Equation* amounts to  $(1.51 - 1.64) \times 10^{-17} \text{sec}^{-1}$  [12]. It differs by more than an order of magnitude from the ionization rate extracted from chemical reactions in the interstellar medium, namely,  $\zeta_c$  (*c* for chemical) =  $1.78 \times 10^{-16} \text{sec}^{-1}$  [26]. The reconstructed energy spectrum of cosmic rays in Galactic environment is derived from the diffusion equation with its highly abstract and unrealistic scheme.

4) The diffusion equation of cosmic rays in the *Galaxy* predicts a decreasing ratio of the antiproton-to-proton flux ratio ( $\bar{p}/p$ ) above the energy of 2.6 GeV. On the contrary, recent and past data in the intervals of 3 - 400 GeV show a flat  $\bar{p}/p$  ratio incompatible with calculations.

Additional evidence of the inadequacy of current ideas to describe low-energy cosmic rays, solar energetic particles and other solar phenomena is elsewhere [34].