High Energy Particles in the Solar Corona

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Collective Ampere law interactions producing magnetic flux tubes piercing through sunspots into and then out of the solar corona allow for low energy nuclear reactions in a steady state and high energy particle reactions if a magnetic flux tube explodes in a violent event such as a solar flare. Filamentous flux tubes themselves are vortices of Ampere currents circulating around in a tornado fashion in a roughly cylindrical geometry. The magnetic field lines are parallel to and largely confined within the core of the vortex. The vortices may thereby be viewed as long current carrying coils surrounding magnetic flux and subject to inductive Faraday and Ampere laws. These laws set the energy scales of (i) low energy solar nuclear reactions which may regularly occur and (ii) high energy electro-weak interactions which occur when magnetic flux coils explode into violent episodic events such as solar flares or coronal mass ejections.

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I. INTRODUCTION

For physical reasons which are presently not entirely clear, dark sunspots exist on the optical solar surface. These have long been observed ever since Galileo saw sunspots with his optical telescope. It was later found that magnetic flux tubes exit out of some solar sunspots and enter back into others[1, 2]. Employing modern X-ray telescopes, spectacular pictures have been taken of magnetic flux tubes[3] which arch into and out of the solar corona, well above the optical solar surface. The situation is schematically shown in FIG.1. The closed magnetic flux tubes are pictured in both the solar photosphere and the solar corona. The closed flux tube magnetic field lines enter into the solar corona through one sunspot and exit out of the solar corona through another sunspot. The floating flux tubes in the solar corona are held up by a magnetic buoyancy[4]. The outer walls of the magnetic flux tube consist of large circulating electric currents forming a turbulent vortex with a darker comparatively quiet magnetic core. When the magnetic flux tubes explode[5] into a solar flare, with or without a coronal mass ejection[6], charged particles with very high energy are produced[7, 8, 9, 10, 11, 12], say up to $\sim 10^2$ GeV. These relativistic particles can escape the sun and be observed on earth as ground level cosmic ray enhancements[13, 14, 15] induced by solar flares.

Our purpose is to discuss how such energetic particles arise in the solar corona and how these particles induce nuclear reactions well above the solar photosphere. The central feature of our explanation, which centers around Faraday's law, is the notion of a solar accelerator closely analogous to the betatron[16, 17]. Conceptually, the betatron is a step up transformer whose secondary coil is a toroidal ring of accelerating charged particles circulating about a Faraday law (time varying) magnetic flux tube.

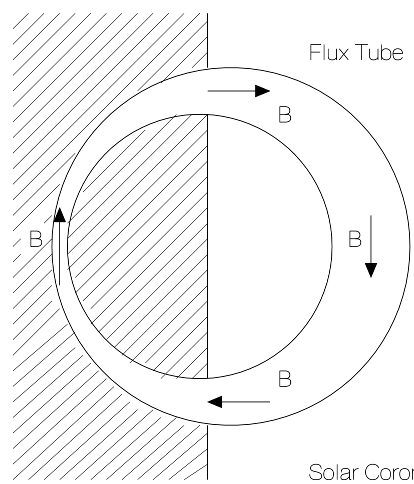

FIG. 1: Shown schematically is a magnetic flux tube which exits the solar photosphere (shaded region) and enters the solar corona (clear region) through a sunspot on the chromosphere boundary. The magnetic flux tube then exits the solar corona and enters back into the photosphere through a second sunspot on the chromosphere boundary. The walls of magnetic flux tube are a vortex of circulating electric currents.

Acting as a step up transformer, it is possible for a solar magnetic flux tube to transfer circulating charged particle kinetic energy upward from the photosphere to circulating charged particles located in the corona. Circulating currents located deep in the photosphere can be viewed conceptually as a net current $I_{\mathcal{P}}$ circulating around a primary coil. Circulating currents found high in the corona can be viewed as a net current $I_{\mathcal{S}}$ circulating around a secondary coil. If $K_{\mathcal{P}}$ and $K_{\mathcal{S}}$ represent, respectively, the charged particle kinetic energies in the primary and secondary coils, then one finds the step up transformer power equation $\dot{K}_{\mathcal{P}} = V_{\mathcal{P}} I_{\mathcal{P}} = V_{\mathcal{S}} I_{\mathcal{S}} = \dot{K}_{\mathcal{S}}$, wherein $V_{\mathcal{P}}$ and $V_{\mathcal{S}}$ represent, respectively, the voltages across the primary and secondary coils. The total kinetic energy transfer $\Delta K_{\mathcal{P}} = \int V_{\mathcal{P}} I_{\mathcal{P}} dt = \int V_{\mathcal{S}} I_{\mathcal{S}} dt = \Delta K_{\mathcal{S}}$. The essence of the step up transformer mechanism is that the kinetic energy distributed among a very large number of charged particles in the photosphere can be transferred via the magnetic flux tube to a distributed kinetic energy shared among a distant much smaller number of charged particles located in the corona, i.e. a small accelerating voltage in the primary coil produces a large accelerating voltage in the secondary coil. The resulting transfer of kinetic energy is *collective* from a large group of charged particles to a smaller group of charged particles. The kinetic energy per charged particle of the dilute gas in the corona may then become much higher than the kinetic energy per charged particle of the more dense fluid in the photosphere. In terms of the connection between temperature and kinetic energy, the temperature of the dilute gas in corona will be much higher than the temperature of the more dense fluid photosphere.

If the kinetic energy of the circulating currents in that part of flux tubes floating in the corona becomes sufficiently high, then the flux tubes can explode violently into a solar flare which may be accompanied by a coronal mass ejection. The loss of magnetic energy during the flux tube explosion is rapidly converted into charged particle kinetic energy. The relativistic high energy products of the explosion yield both nuclear and elementary particle interactions. These processes are discussed in Sec.II. For magnetic flux tubes of smaller diameter which do not explode into a flare and/or a coronal mass ejection, one may still have low energy nuclear reactions that occur in a roughly steady state by continual conversion of magnetic field energy into charged particle energy. Such processes can account for the fact that the solar corona remains continually much hotter than the photosphere. Steady state low energy nuclear processes are discussed in Sec.III. In the concluding Sec.IV we further discuss the notion that not all nuclear processes necessarily take place near within the solar core.

II. SOLAR FLARES

The magnetic flux through a cylindrical tube of inner cross sectional area ΔS and mean magnetic field B, is

$$\Delta\Phi = B\Delta S. \tag{1}$$

If a tube explodes in a time period Δt, then the resulting loss of magnetic flux yields a mean Faraday law accelerator voltage around the tornado walls as given by

$$\overline{\mathrm{V}} = \frac{\Delta\Phi}{\Delta t}, \tag{2}$$

i.e.

$$e\overline{\mathrm{V}} = ecB\left(\frac{\Delta S}{\Lambda}\right) \quad \text{wherein} \quad \Lambda = c\Delta t. \tag{3}$$

A useful identity for numerical estimates is

$$ecB \equiv 29.9792458 \left[\frac{\text{GeV}}{\text{kilometer}}\right]\left[\frac{B}{\text{kiloGauss}}\right]. \tag{4}$$

For a coronal mass ejection exploding coil with a Faraday flux loss time $\Delta t \sim 10^2$ second and with substantial sun spots at the ends of the magnetic flux coil, one may estimate[18, 19, 20]

$$\begin{aligned} \Delta S &\approx \pi R^2, \\ R &\sim 10^4 \text{ kilometer}, \\ B &\sim 1 \text{ kiloGauss}, \\ \Lambda &\sim 3\times 10^7 \text{ kilometer}, \\ e\overline{\mathrm{V}} &\sim 300 \text{ GeV}. \end{aligned} \tag{5}$$

The uncharged walls of the circulating vortex are represented roughly by an electron beam circulating in one direction and proton beam circulating in the other direction. These two colliding beams are hit with a flare or coronal mass ejecting Faraday law voltage pulse, as in Eq.(5), setting an electron proton collision energy scale of $E \sim 300$ GeV. At such a high energy scale, electron-proton scattering[21] is ruled by electro-weak exchange interactions all of the same order of magnitude in probability. Shown in FIG.2 is the electro-weak boson exchange Feynman diagram for electron-proton scattering

$$e^- + p^+ \to l + X. \tag{6}$$

The final state lepton is an electron for the case of photon γ or Z exchange and the final state lepton is neutrino for the case of W^- exchange.

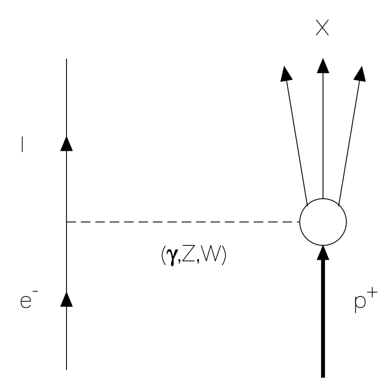

FIG. 2: Boson exchange diagrams for electron-proton scattering into a lepton plus "anything" $\{\, e^- + p^+ \to l + X \,\}$ include photon γ and Z exchange wherein the final lepton is an electron, as well as charged W^- exchange wherein the final state lepton is a neutrino. On an energy scale of ~ 300 GeV, all of these exchange processes have amplitudes of similar orders of magnitude.

A solar flare or coronal mass ejecting event is thereby accompanied by an increased emission of solar neutrinos over a broad energy scale as well as relativistic protons[12], neutrons[22, 23, 24, 25, 26] and electrons[6]. The full plethora[27, 28] of final X states including electron, muon and pion particle anti-particle pairs should also be present in such events. The conversion of magnetic field energy into relativistic particle kinetic energy via the Faraday law voltage pulse is collective in that the magnetic flux in the core of the vortex depends on the rotational currents of *all* of the initial protons and electrons.

III. LOW ENERGY NUCLEAR REACTIONS

Even without spectacular solar flare explosions ejecting mass through the solar corona, there exists (within flux tubes) collective magnetic energy which allows for a significant occurrence of low energy nuclear reactions at many different locations in and around the sun. In particular, let us consider the inverse beta decay reaction

$$W_{\rm magnetic} + e^- + p^+ \to \nu_e + n \tag{7}$$

wherein the final state lepton is a neutrino, the final state "X" is a neutron n and $W_{\rm magnetic}$ is magnetic field energy fed into the reaction.

In a steady state flux tube (which does *not* explode) entering into the solar corona from one sunspot and exiting out of the solar corona through another sunspot, there is a substantial amount of stored magnetic energy. If there is a small change δI in the current going around the vortex circumference, then the small change in the magnetic field energy $\delta\mathcal{E}$ obeys

$$\delta\mathcal{E} = \Phi\delta I. \tag{8}$$

If L denotes the length of the vortex circumference of the magnetic flux tube, then the change in current due to the weak interaction reaction Eq.(7) is given by

$$\delta I = -\frac{ev}{L}\ , \tag{9}$$

wherein v is the relative velocity component (tangent to the circumference) between the proton and electron. Putting $\Phi = B\Delta S$ and $\delta\mathcal{E} = -W_{\rm magnetic}$ yields

$$W_{\rm magnetic} = ec\left(\frac{\Phi}{L}\right)\frac{v}{c} = ecB\left(\frac{\Delta S}{L}\right)\frac{v}{c}\ . \tag{10}$$

The product (ecB) is given in Eq.(4). For the case of a cylindrical flux tube,

$$\frac{\Delta S}{L} = \left(\frac{\pi R^2}{2\pi R}\right) = \frac{R}{2}\ . \tag{11}$$

yielding

$$W_{\rm magnetic} \approx 15\ {\rm GeV}\left[\frac{R}{\rm kilometer}\right]\left[\frac{B}{\rm kiloGauss}\right]\frac{v}{c}\ . \tag{12}$$

Employing the estimates

$$\begin{aligned} R &\sim 10^2\ {\rm kilometer}, \\ B &\sim 1\ {\rm kiloGauss}, \\ \frac{v}{c} &\sim 10^{-2}, \\ W_{\rm magnetic} &\sim 15\ {\rm GeV}. \end{aligned} \tag{13}$$

On the energy scale $W_{\rm magnetic} \ll 300$ GeV of Eq.(13), the weak interaction p^+e^- processes Eq.(7) that produce neutrons proceed more slowly than the purely electromagnetic p^+e^- processes. Nevertheless one finds appreciable neutron production in the solar corona. The production of neutrons among the protons allows for the creation of nuclei with higher mass numbers via neutron-capture nuclear reactions and subsequent beta decays.

IV. CONCLUSION

Magnetic flux tubes arise[18, 19] out of the turbulent magneto-fluid mechanics of a solar fluid plasma with high electrical conductivity. Turbulent magneto-fluid flows yield a full spectrum of magnetic field values[20] expected to vary randomly over many different length scales. The estimates of the magnetic field discussed in this work are merely order of magnitude. They are based on observations of the magnetic flux tubes entering into and exiting out of sunspots and also into and out of smaller crevices and holes that are commonly observed on the sun's optical surface.

For many years, the source of relativistic particle fluxes[29, 30] often observed to emanate from the solar corona has been theoretically obscure. Our explanation for these fluxes is simply derived from Faraday's law

$$-\frac{\partial\mathbf{B}}{\partial t} = curl\mathbf{E} \tag{14}$$

as it appears in well understood transformer and inductor circuits. Circulating currents around the walls of a flux tube can transfer energy into some parts of the magnetic field configuration while removing equal amounts of energy from other distant parts of the magnetic field configuration. This transformer action is very well understood.

The resulting energy balance allows a large number of low energy charged particles to collectively transfer their kinetic energy to a significantly smaller number of charged particles whose energy per particle then becomes very high. When the charged particle energy of low density solar corona particles is made sufficiently high, reactions of the form in Eqs.(6) and (7) clearly can take place, leading to neutron production. Once neutrons are created and added to the electron-proton plasma, a variety of nuclear synthesis reactions become possible[31]. If that is the case, then Coulomb barrier-penetrating fusion reactions in the sun's core are not necessarily the sun's *only* significant source of solar nuclear energy. Relativistic particle fluxes have been clearly observed emanating from regions located well above the sun's surface and very far away from the solar core. Finally, it has not escaped our notice that the energetic particle production via the collective mechanisms discussed in this work may shed some light on the origin of the anomalous short-lived isotopes observed on other astronomical objects[32].

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