Open Access Online Journal on Astronomy and Astrophysics

Acta Astrophysica Taurica

www.astrophysicataurica.org

Acta Astrophys. Tau. 3(3), 1–3 (2022) doi:10.34898/aat.vol3.iss3.pp1-3

Mechanisms of the regular acceleration of electrons by induced electric fields in solar flares

Yu.T. Tsap[1], Yu.G. Kopylova[2], O.A. Korolkova[2], M. Barta[3]

[1] Crimean Astrophysical Observatory, Nauchny 298409
yur_crao@mail.ru
[2] Central Astronomical Observatory at Pulkovo, Pulkovskoe shosse 65/1, St. Petersburg 196140, Russia
yulia00@mail.ru
[3] Astronomical Institute ASCR, Ondřejov 251 65, Czech Republic

Received 27 December 2021

ABSTRACT

A critical analysis of mechanisms of the regular acceleration of electrons in solar flares is carried out. The corresponding models are shown to face difficulties associated with the transverse direction of the induced electric field with respect to the magnetic one, plasma magnetization, and small efficiency. It is concluded in favor of an important role of longitudinal electrostatic electric fields in the acceleration of electrons.

Key words: Sun, flare energy release, accelerated electrons, electric field

1 Introduction

The problem of acceleration of the charged particles in solar flares is one of the most important and unsolved problems of heliophysics. From the analysis of almost two hundred flare events of X-ray class M and X observed by the RHESSI satellite (Ramaty High-Energy Solar Spectroscopic Imager) from 2002 to 2005 it follows that non-thermal energy of electrons exceeds thermal energy in 85 % of cases (Aschwanden et al., 2016). Although estimates have been made on the basis of the so-called "warm thick target" model implying serious theoretical limitations, the results convincingly indicate a crucial role of accelerated charged particles in the energy balance of solar flares.

Acceleration mechanisms can be divided into two classes: regular and irregular, or stochastic (Miller et al., 1997; Tsap, 2000; Aschwanden, 2004; Liu, Jokipii, 2021). In the first case, the particles are accelerated continuously, and in the second case, their energy increases only on average, i.e., they can gain and lose energy. It is obvious that regular mechanisms are the most effective, and particular attention will be paid to them. In the light of available observational data, they must meet the following requirements (Miller et al., 1997):

1. Electron acceleration up to relativistic energies should take place during ~ 0.1 s.
2. Electron fluxes should be 10^{35}–10^{36} s^{-1}, which roughly corresponds to the acceleration of all thermal electrons contained in flare loops.
3. Accelerated electrons should reach ultrarelativistic energies up to 10 MeV.

No strong indications in favor of the dominant acceleration mechanism during flare energy release have been known so far. In our opinion, this is due to a small number of works devoted to the critical analysis of basic physical principles, which will be the subject of the present paper.

2 Peculiarities of electron acceleration by induced electric field: single-particle and drift approximation

A description of plasma processes can be carried out on the basis of the following approximations: single-particle, drift, magnetohydrodynamic, and kinetic. Each method has its own advantages and disadvantages. In particular, the first approach is the simplest, which allows one to highlight the most important characteristics of the phenomenon under consideration. However, it becomes of little use for describing effects associated, for example, with the inhomogeneity of the magnetic and electric field in the magnetized plasma. The drift approximation following from averaging the motion of a charged particle in Larmor orbits, although devoided of this shortcoming, nevertheless does not take into account, like the one-particle approach, the plasma diamagnetism. The magnetohydrodynamic approach does not allow us to take into account the kinetic effects caused by the deviation of the distribution function of charged particles from the equilibrium one, which can lead to the development of various small-scale oscillations and waves. Although the kinetic theory assumes the most general approach, it often turns out to be too complicated and too detailed. This significantly complicates the understanding of the physical essence of the phenomenon — “you can’t see the forest for the trees”. However, if we are talking about regular mechanisms of acceleration by an induced electric field, then we can restrict ourselves to single-particle and drift approximations.

The equation of electron motion can be represented as

$$m\frac{d\mathbf{V}}{dt} = e\left(\mathbf{E} + \frac{\mathbf{V}\times\mathbf{B}}{c}\right), \tag{1}$$

where m and $\mathbf{V}$ are the mass and velocity of an electron, respectively, e is the elementary charge, c is the speed of light. Hence, a change in the kinetic energy of a nonrelativistic particle $T = mV^2/2$ is reduced to the form

$$\frac{dT}{dt} = \mathbf{V}\frac{d\mathbf{p}}{dt} = e\mathbf{V}\mathbf{E}. \tag{2}$$

According to Equations (1) and (2), only an electric field can accelerate charged particles.

Using standard notation, we have

$$\mathbf{E} = -\nabla\varphi - \frac{1}{c}\frac{\partial\mathbf{A}}{\partial t}.$$

Substituting the latter expression into Equation (2), we find

$$\frac{dT}{dt} = -e\mathbf{V}\left(\nabla\varphi - \frac{1}{c}\frac{\partial\mathbf{A}}{\partial t}\right). \tag{3}$$

Note that the second term on the right side of Equation (3) describes the so-called betatron acceleration by the vortex induced electric field.

By the induced electric field $\mathbf{E}_i$ we mean the electric field that arises as a result of changes in time of the magnetic field $\mathbf{B}$ (see, however, Liu, Jokipii, 2021). Constrained by the Cartesian coordinate system and supposing, for simplicity, the magnetic field $\mathbf{B} = (0, 0, B(t, \mathbf{r}))$, where $\mathbf{r}$ is the radius vector of the observation point directed along the $\mathbf{Z}$ axis, from Faraday’s law

$$\nabla\times\mathbf{E}_i = -\frac{1}{c}\frac{\partial B}{\partial t}\mathbf{e}_z, \tag{4}$$

where $\mathbf{e}_z$ is the unit vector, we get

$$(\nabla\times\mathbf{E}_i)_z = \left(\frac{\partial E_{iy}}{\partial x} - \frac{\partial E_{ix}}{\partial y}\right)_z = -\frac{1}{c}\frac{\partial B}{\partial t}. \tag{5}$$

Equation (5) suggests that the induced electric field $\mathbf{E}_i$ is perpendicular to the magnetic field $\mathbf{B}$. At least this can be demonstrated more for the case of the uniform magnetic field when $\mathbf{B} = (0, 0, B(t))$. In this case, it is easy to show (Lehnert, 1964) that

$$\mathbf{E}_i = -\frac{1}{2}(\mathbf{e}_z\times\mathbf{r})\frac{\partial B}{\partial t}. \tag{6}$$

We especially emphasize that Equation (6) also satisfies the condition

$$\nabla\cdot\mathbf{E}_i = 0,$$

i.e., the electric field $\mathbf{E}_i$ cannot be related to the spatial separation of electric charges. It should also be noted that $\mathbf{E}_i$, according to Equations (5) and (6), cannot be considered homogeneous, since it should depend on the coordinates.

As is known, if the period of rotation of electrons on the Larmor orbits is much shorter than the characteristic time of electric or magnetic field changes, and the space scale of the system L significantly exceeds the Larmor radius of a charged particle (both of these conditions, as a rule, are satisfied under coronal flare plasma conditions), then one can use the drift theory. In this case, the law of conservation of kinetic energy for the electron rotated with velocity $v_\perp$ and the equation of motion describing the motion of the center of its Larmor orbit (leading center approximation R) can be represented as

$$\frac{d}{dt}\left(\frac{mv_\perp^2}{2}\right) = \mu\frac{dB}{dt}, \tag{7}$$

$$m\frac{d\mathbf{v}_R}{dt} = e\left(\mathbf{E} + \frac{\mathbf{v}_R\times\mathbf{B}}{c}\right) - \mu\nabla B, \tag{8}$$

where $\mu = mv_\perp^2/2B$ is the magnetic moment. An important relation follows from Equation (7) — the so-called law of conservation of the first (transverse) adiabatic invariant

$$\frac{d}{dt}\mu = 0. \tag{9}$$

As can be seen from (9), the betatron acceleration can lead to an increase in the energy of electrons only in the case of a growth of the magnetic field B (see, however, Fleishman et al., 2020).

In turn, assuming

$$\mathbf{v}_R = v_z\mathbf{e}_z + \mathbf{v}_{R\perp},$$

according to (8) we get

$$m\mathbf{e}_z v_z - \frac{e}{c}(\mathbf{v}_{R\perp}\times\mathbf{B}) = e\mathbf{E} - \mu\nabla B - m\left(v_z\frac{d\mathbf{e}_z}{dt} + \frac{d\mathbf{v}_{R\perp}}{dt}\right). \tag{10}$$

Multiplying Equation (10) first scalarly and then vectorially by $\mathbf{e}_z$, supposing $v_z \gg v_{R\perp}$, and neglecting the mirror force $\mu\nabla B$, we obtain the equations of electron motion

$$m\frac{dv_z}{dt} = eE_z, \quad \mathbf{v}_{R\perp} = \frac{c}{B}(\mathbf{E}\times\mathbf{e}_z). \tag{11}$$

Note that the condition $v_z \gg v_{R\perp}$ for the flare coronal plasma is fulfilled with a large margin. Indeed, the Dreiser electric field (Tsap, Kopylova, 2017; Tsap et al., 2019)

$$E_D \approx 2\times 10^{-11}\frac{n}{T}\ \text{statV/cm}.$$

Hence, taking the concentration of electrons (ions) $n = 10^{10} - 10^{11}$ cm^{-3} and temperature $T = 10^6$–10^7 K, we get $E_D \approx 2\times(10^{-8} - 10^{-6})$ statV/cm. Therefore, for $B = 100$ G, according to (11), the electron drift velocity $v_{R\perp} = 10 - 10^3$ cm/s. This estimate strongly suggests that the speed of the transverse drift even in the case of superdreiser electric fields (see, for example, Fleishman et al., 2020) when $E \gg E_D$ is negligible compared to the characteristic thermal electron velocity $v_{Te} = \sqrt{2kT/m} \sim 10^8$ cm/s, where $k = 1.38\times 10^{-16}$ erg/K is the Boltzmann constant.

Thus, Equation (8) obtained in the leading center approximation suggests that only the electrostatic field E_z is capable of efficient accelerating of electrons in solar flares. This is largely due to the transverse directivity of the generated induced electric field $\mathbf{E}_i$ with respect to the magnetic field $\mathbf{B}$, which leads to the phenomenon of electromagnetic shielding, which forms the basis for the ideas about the frozen-in magnetic field.

As for the betatron acceleration mechanism, it can hardly be considered very effective under flare plasma conditions. In particular, the energy of an accelerated electron can be increased by two orders of magnitude if the magnetic field also increases by two orders of magnitude (see Equation 9), which seems unlikely. Some numerical calculations show that a noticeable acceleration is possible only for electrons already having sufficiently high energies (hundreds of keV) for which the acceleration rate is greater than the deceleration rate due to Coulomb collisions (Filatov et al., 2013). The attraction of the Fermi mechanism in the framework of the concept of a collapsing magnetic trap (Bogachev, Somov, 2005) can hardly improve the situation. In this case, $v_z L$ = const, and hence to ensure a significant acceleration of electrons, the trap must shorten along the top of a flare arch by at least three times, which does not find observational evidence. In addition, the minimum acceleration time $\tau \approx L/v_A$, where v_A is the Alfvén speed. Putting $L = 10^8$–10^9 cm and $v_A = 10^8$ cm/s into the latter formula, we get τ = 1–10 s significantly exceeding, for example, the duration of spikes observed in hard X-rays (see, e.g., Miller et al., 1997).

3 Discussion and conclusions

In the present work, using the drift approximation, we conducted an analysis of the regular mechanisms of electron acceleration, which can be realized in solar flares. We have shown that acceleration in induced electric fields confronts difficulties. In our opinion, this may indicate a limited role of betatron electron acceleration in flares and possible significant contribution of accelerating by longitudinal electrostatic electric fields. In the latter case, a separation of charges can be caused by both the motion of the plasma across the magnetic field lines (see, e.g., Tsuneta, 1995) and the decrease of the electrical conductivity due to partial ionization and nonstationarity (Zaitsev, Stepanov, 2015). We hope to consider in greater detail the possible nature of these phenomena in our forthcoming paper. However, one cannot exclude an important role of the stochastic acceleration of electrons by small-scale turbulent pulsations.

The study was partially funded by the grant of the Russian Science Foundation No. 22-12-00308, RFBR and GACR (project number 20-52-26006), and the Ministry of Science and Higher Education of the Russian Federation (project No. 1021051101548-7-1.3.8).

References

Aschwanden M.J., 2004. Physics of the Solar Corona: An Introduction, New York: Springer.

Aschwanden M.J., Holman G., O'Flannagain A., et al., 2016. Astrophys. J., vol. 832, id 27.

Bogachev S.A., Somov B.V., 2005. Astron. Lett., vol. 31, pp. 537–545.

Filatov L.V., Melnikov V.F., Gorbikov S.P., 2013. Geomag. Aeronom., vol. 53, pp. 1007–1012.

Fleishman G.D., Gary D.E., Chen B., Kuroda N., Yu S., Nita G.M., 2020. Science, vol. 367, iss. 6475, pp. 278–280.

Lehnert B. Dynamics of Charged Particles, North-Holland Publishing Company, Amsterdam, 1964, 300 pp.

Liu S., Jokipii J.R., 2021. Frontiers in Astronomy and Space Sciences, vol. 8, id. 100.

Miller J.A., Cargill P.J., Emslie A.G., et al., 1997. J. Geophys. Res., vol. 102, no. A7, pp. 14631–14660.

Tsap Yu.T., 2000. Izv. Krymsk. Astrofiz. Observ., vol. 96, pp. 165–175.

Tsap Yu.T., Kopylova Yu.G., 2017. Geomag. Aeronom., vol. 57, no. 8, pp. 996–1000.

Tsap Yu.T., Stepanov A.V., Kopylova Yu.G. 2019. Geomag. Aeronom., vol. 59, no. 8, pp.789–792.

Tsuneta S., 1995. Publ. Astron. Soc. Japan, vol. 47, pp. 691–697.

Zaitsev V.V., Stepanov A.V., 2015. Solar Phys., vol. 290, no. 12, pp. 3559–3572.