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A Simple Model for Plasma Evolution in Solar Coronal Loops

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Abstract: *We propose a theoretical inhomogeneous hydrodynamic evolutionary model to investigate the full equilibrium spatiotemporal evolution of gravitationally stratified loop plasma in presence of the Lorentz force. The quasi-neutral plasma composed of the thermal electrons (Boltzmannian) and inertial ions (fluid) is assumed to be weakly confined (plasma $\beta \leq 1$) along the loop. A numerical calculation scheme is developed by applying the conservation laws of flux, force and energy of the loop plasma constituents in a closed form. It reveals an interesting complex structure showing apposite plasma-parameter variation with the loop-geometry scale length. The relevant plasma parameters show sharp transitions near the middle (central peaks) relative to both the footpoint and summit. Their temporal variation is found to be very slow on the loop scales of space and time. We show that the cross-transportation of the plasma particles and the Lorentz force have significant effect on the bulk evolutionary process of the loop parameters. The loop geometry also has the substantial contributiton towards the observed plasma dynamics. We further confirm that gravity-induced ambipolar polarization is the main source for weak but finite deviation from global quasi-neutrality. The roles of the mentioned factors on the evolution of the loop parameters are discussed in detail.*

Keywords: *Coronal loop, Corona, Magnetic field, Gravitational stratification*

1. Introduction

The solar corona is the Sun's outer atmosphere having low-density hot plasma that extends deep into the space. It is very faint and visible only during the solar eclipse. It is a magnetic field rich zone with morphology mostly determined by the magnetic field. Since its beginning, the corona remains one of the most attractive field of study for astrophysicists. It shows a rich collection of magnetic phenomena which are still not fully understood [1]. Some of the phenomena taking place in the corona, such as evolution of different kinds of coronal loops, their modeling and contribution to the coronal heating [1], global structural evolution of the corona, the supersonic solar wind acceleration, etc. [2] are still not fully demystified.

A variety of loop structures outlining the solar magnetic field is well-known to exist in the entire solar corona. They are strongly emitting solar atmospheric structures composed of ionized plasma constrained by closed magnetic field arch. These are current-carrying structures under the action of possible sub-photospheric dynamo mechanisms yet to be well understood. One of the remedial roots to understand these phenomena is to understand the evolution of different kinds of coronal loops and the dynamics of the involved plasma in the loop.

The coronal loops are the arch-like magnetic flux fixed at both ends threading through the solar structure, protruding into the solar atmosphere. They are primarily the phenomena of active region and form the basic structure of the lower corona. They are visible in the far UV and X-ray region [3]. The coronal loops are clearly visible in the bright corona when observed at X-ray band. They occur during the time of high activity and last from 1 hour up to 1 day [1]. There may be a large number of loops evolving at a time. The number of loops is directly linked to the solar cycle; it is for this reason that the coronal loops are often found with sunspots at their footpoint. They generally start at the end of photosphere, known as the footpoint, and end at the corona, called the summit. They are the consequences of twisted magnetic field of active region. The plasma beta parameter (β) becomes less than one and the transverse transportation of the plasma becomes zero leading to the confinement of plasma. Because of the confinement, the density becomes high and various kind of damping take place thereby heating the plasma to such high degree.

As known to us, the first evidence about the existence of coronal loops came in 1960s. The proper image of a loop came in 1968 from rocket mission [4]. Based on the loop size, physical condition of the confined plasma and so on, Vaiana classified the morphology of the corona as consisting of arch-like structures connecting regions of opposite magnetic poles of photosphere. There was no mean for the direct measurement of the twisted magnetic field and one has to trace using the Zeeman-effect on spectral lines. The field structure was derived by extrapolating the magnetic field in a volume under the assumption of negligible current in the corona.

A large number of theoretical studies has been made to investigate the physical mechanism of the observed phenomena in the loop. Details of the loop morphoplogy along with their plasma properties, such as distribution of the plasma temperature, population density, flow speed, etc. along the loop has been studied in the past [1-5]. Several numerical codes are also available for the loop modeling. But, almost all the models have assumed the one-dimensional force-free approach ($j \text{ x } B = 0$). This is valid for the strongly confined plasma with very low plasma beta ($\beta \ll 1$). However, this approximation becomes inadequate in the photospheric region [2]. Moreover, in a loop with high population density and temperature, the plasma beta acquires value close to unity ($\beta \leq 1$) and the concept of perfect confinement becomes inefficient. Therefore, a time-dependent hydrodynamic model with the Lorentz force incorporated is required to analyze these types of loops.

2. PHYSICALMODEL

A magnetized hydrodynamic model of the inhomogeneous coronal loop plasma is considered to be composed of two species, i.e., the electrons (screening, thermal) and the ions (massive, inertial).Thus, the electron dynamics is governed by the ideal Maxwell-Boltzmann distribution, while the ions are considered as an inertial fluid. For simplicity, we ignore the transverse variation of the plasma properties and consider the variation only along the loop length.

The coronal loops lie outside the solar surface and loop radius is very small in comparison with the solar radius ($r_L \ll R_{\odot}$). Therefore, we consider the solar gravity to be external and uniform (Lenz et al. 1998). Due to the confinement, the plasma density increases inside the loop and collision occurs. As a result, the collisional energy transfer occurs between the species and thermal equilibrium is set up ($T_e \approx T_i \approx T$). In addition, the collision results in the viscosity of the loop plasma. Due to constant strong gravity and large mass difference of the species, a gravitational stratification occurs between the two types of the species, which causes a small charge separation thereby developing electrostatic polarization effects.

The inclusion of the Lorentz force in the model formulation can be justified as follows. For a typical loop with density, $n_0 \approx 10^{16}$ m^{-3} [5], temperature, $T_0 \approx 2\times10^6$ K [1], and the magnetic field, $B_0 \approx 10$ G [5], the plasma beta parameter ($\beta = 2\mu_0 n_0 k_B T_0 / B_0^2$) comes out as $\beta = 0.7$. In such cases, plasma will not be fully confined to the loop magnetically and the effect of the Lorentz force becomes important.

3. MATHEMATICAL ANALYSIS

The coronal loop is geometrically considered as a thin semicircular tube whose length is much larger than its diameter. The local mass conservation of the plasma in the loop is described by the continuity equation with all usual notations [6] as follows,

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial s}(n_i v_i) = 0, \tag{1}$$

where, n_i is the ion population density, v_i the ion flow velocity, s the loop position and t the time.The momentum conservation [8] is described by,

$$n_i m \frac{\partial v_i}{\partial t} + n_i m v_i \frac{\partial v_i}{ds} = -\frac{\partial p}{ds} + n_i m g + \frac{\partial}{\partial s}\left(\mu \frac{\partial v_i}{\partial s}\right) + n_i e\left(E + \left(v_i \times B\right)_s\right). \tag{2}$$

Here, m stands for the ion mass, p for the thermal pressure ($p = n_i k_B T$), e for the electronic charge and g for the solar gravitational acceleration which is assumed to be external and constant under the justifications as given above. Further, $\mu = 0.96 n_i \tau_c k_B T$ stands for the coefficient of viscosity, taken from the well-known Braginskii's equation [7]. Here, τ_c stands for the collision time, given by $\tau_c = 12\pi^{3/4}\varepsilon_0^2\sqrt{m}k_B^{3/4}T^{3/4}/n_i e^4 \ln\Lambda$, where, $\ln\Lambda\,(=22)$ is the Coulomb logarithm [8]. The viscosity here arises as a result of the Coulomb collisions between the plasma particles. Also, E and B, respectively, represent the electric and magnetic fields. The magnetic field in the loop depends upon its density distribution and temperature. The explicit form of the magnetic field for the coronal loop is given by the following expression [9],

$$B = \left(\frac{n_i}{C_1}\right)^{1/2}\left(\frac{P^2}{4L^2} - \frac{1}{C_2 T}\right)^{-1/2}, \tag{3}$$

where, $P\ (= 2L/c_t)$ is the fundamental slow mode period with $c_t = \left(1/c_S^2 + 1/c_A^2\right)^{-1/2}$, where c_S is the sound phase velocity. Moreover, $C_1 = 4.8\times10^3$ and $C_2 = 2.3\times10^4$ are the numerical constants. Expanding c_t binomially, we get $c_t \approx c_A$. The energy conservation [1] is written as,

$$\frac{n_i k_B}{\gamma-1}\frac{\partial T}{\partial t} + \frac{n_i v_i k_B}{\gamma-1}\frac{\partial T}{\partial s} + p\frac{\partial v_i}{\partial s} = E_H - E_R - \frac{\partial F_C}{\partial s}. \tag{4}$$

Here, $\gamma = c_P/c_V = 5/3$ denotes the polytropic index for the coronal loop plasma.The significances of the various terms on the right hand side are as the following. The 1st term, E_H, denotes the heating function [10]. There are several processes by which the deposition of energy in the plasma loop take place. Three most important mechanisms based on the dependence of heating function upon the loop pressure, temperature and geometry are the (i) acoustic mode damping, (ii) Alfven mode damping, and (iii) direct dissipation of the coronal current. For simplicity, we consider only the Alfvenic mode damping. The model heating function for this mechanism is $E_H = 9.8\times10^4 p^{7/6}L^{-5/6}$ [10]. The 2nd term, E_R, denotes the radiative loss which accounts for the energy flux due to irradiation from the loop. The radiative loss function can be written as $E_R = -(p^2/4k_B^2T^2)P(T)$ [10], where $P(T)$ denotes the function which is approximated as a sequence of power laws joined simultaneously. For a hot loop, $T \geq 1\times10^6\,K$, the heating function, therefore, is approximated as $P(T) \approx 10^{-22}$ [10]. The 3rd term symbolizes the conductive flux which is the plasma thermal conduction, written as $F_c = \kappa T^{5/2}\partial T/\partial s$, with κ as the thermal conductivity given by $\kappa = \kappa_0 T^{5/2}$ [11]. The closing electrostatic Poisson equation [6] to describe the evolution of the electrostatic potential due to space charge polarization caused by the gravitational stratification is given by,

$$\varepsilon_0\nabla^2\phi = e(n_e - n_i) \tag{5}$$

where, ϵ_0 is the permittivity of free space and n_e the electron population density.

The above coupled set of equations (1)-(5) is normalized to make all the parameters dimensionless and scale-invariant. Normalizations are done by standard loop parameters, which are assumed to be constant for the spatiotemporal scales of our interest. The time and loop position are normalized by the Alfvenic period and loop scale-length as $\tau = t/\tau_A$ and $\xi = s/L$, respectively. The coupled set of normalized equations thus obtained are respectively enlisted as,

$$\frac{\partial N_i}{\partial \tau} + N_i \frac{\partial M_i}{\partial \xi} + M_i \frac{\partial N_i}{\partial \xi} = 0, \tag{6}$$

where, N_i is the normalized ion density ($N_i = n_i / n_0$) and M_i the ion Mach number ($M_i = v_i / c_A$). Also, n_0 is the equilibrium plasma population density and c_A the Alfven mode velocity.

$$N_i \frac{\partial M_i}{\partial \tau} + N_i M_i \frac{\partial M_i}{\partial \xi} = -\left[N_i \frac{\partial T_N}{\partial \xi} + T_N \frac{\partial N_i}{\partial \xi} \right] + \frac{g\tau_A}{c_A} N_i + \frac{\mu_0 \tau_A}{mL^2}\left[\frac{5}{2} T_N^{3/2} \frac{\partial T_N}{\partial \xi}\frac{\partial M_i}{\partial \xi} + T_N^{5/2} \frac{\partial^2 M_i}{\partial \xi^2} \right] - N_i \frac{\partial \Phi}{\partial \xi}$$
$$+ \sqrt{\frac{n_0}{c_1}} \frac{e\tau_A}{mc_A} N_i^{3/2} \left(1 + \frac{A}{T_N} \right). \tag{7}$$

The plasma temperature and plasma potential are normalized relative to the base-point temperature of the loop ($T_N = T/T_0$) and thermal potential ($\Phi = e\phi / k_B T_0$), respectively.

$$\frac{N_i}{\gamma - 1}\frac{\partial T_N}{\partial \tau} + \frac{N_i M_i}{\gamma - 1}\frac{\partial T_N}{\partial \xi} + N_i T_N \frac{\partial M_i}{\partial \xi} = Z N_i^{7/6} T_N^{7/6} - C N_i^2 - D\left\{ 5 T_N^4 \left(\frac{\partial T_N}{\partial \xi} \right)^2 + T_N^5 \frac{\partial^2 T_N}{\partial \xi^2} \right\}, \tag{8}$$

where the constants appearing in the above equation are given as, $Z = 3p_0^{1/6} L^{-5/6} \tau_A$, $C = -2.5 \times 10^{-23} \tau_A n_0 / k_B T_0$ and $D = \kappa_0 T_0^5 \tau_A / n_0 k_B L^2$.

$$\frac{\partial^2 \Phi}{\partial \xi^2} = \left(\frac{L^2}{\lambda_D^2} \right) \left[e^{\Phi} - N_i \right], \tag{9}$$

where, λ_D is the plasma Debye length. Equations (6)-(9) constitute the basic coupled set of governing loop-structure equations in normalized form, which will be used to investigate the loop plasma dynamical evolution on the relevant astrophysical scales of space and time. Thus, existence of various spatiotemporal gradients in the above equations shows that the loop plasma considered is indeed inhomogeneous in nature being handled with a developed numerical calculation scheme.

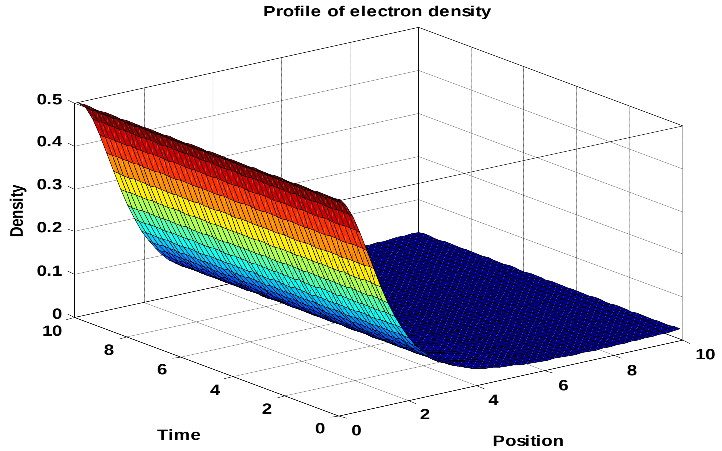
4. RESULTS AND DISCUSSION

A simplified theoretical model to study the evolutionary dynamics of the coronal loop plasma in the Sun is proposed. The basic coupled set of normalized structure equations is solved numerically using the finite difference method [12]. Initial values for the characteristic loop parameters and their evolutionary gradients are obtained by approximately fitting the earlier observational data [1-2, 4-5, 13] numerically. The boundary values used in the numerical analysis are also similarly obtained from the same observational data. Various boundary values thus used in our analysis are tabulated in Table 1. The results obtained by numerical analysis are graphically represented in figures 1-2.

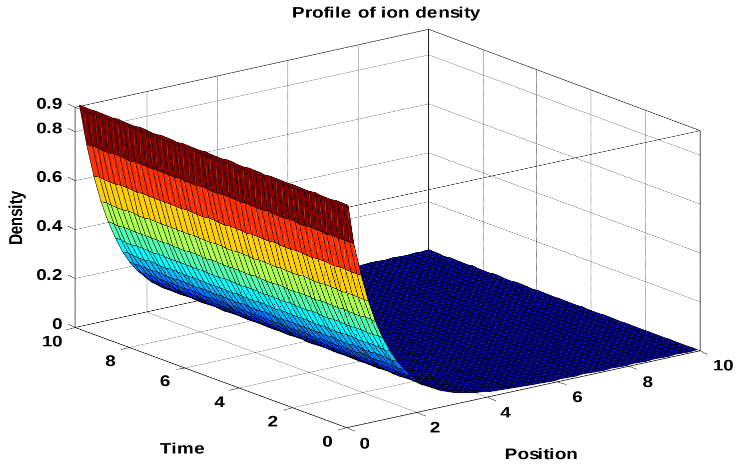
Table1. *Boundary values of relevant loop plasma parameters*

Parameters	Density (N)	Velocity (M_i)	Temperature (T_N)	Potential (Φ)
$\xi = 0$	1 ($= 10^{16}$ m^{-3})	0.07 (≈ 10 km s^{-1})	0.01 ($\approx 10^4$ K)	0 (0 V)
$\xi = L$	0.01 ($= 10^{14}$ m^{-3})	1 (≈ 150 km s^{-1})	5 ($= 5 \times 10^6$ K)	340 ($= 3 \times 10^4$ V)

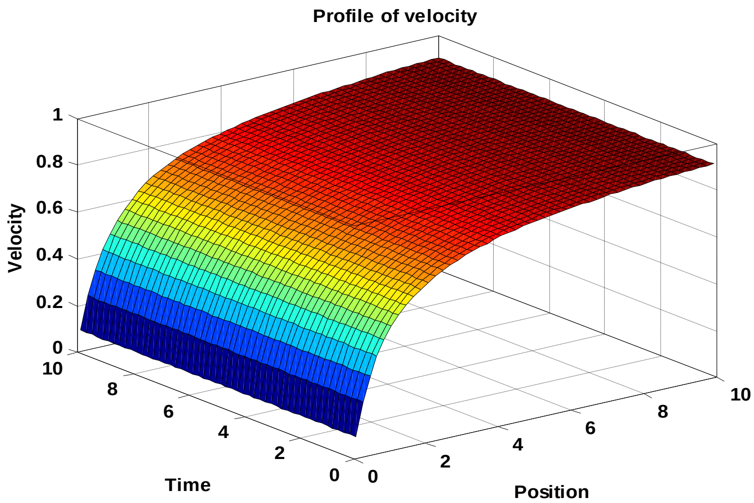
Figure 1 shows the profile structures of the hydrodynamic properties (density, velocity and temperature) of the loop plasma with variation in loop-length and time.The plasma population densities, as shown in figures 1(a)-1(b) for the electrons and ions, respectively, show similar evolutionary behavior. They show a rapid decrease up to the peak of the loop ($\xi \approx 4 - 6$) and then attain a saturated value. This is the direct consequence of the cross-field diffusion of the plasma in the loop. Quantitatively, the ion density exceeds its electronic counterpart up to the peak, while, the electron density overcomes afterwards. The effect of the density variation is reflected in the electrodynamic properties of the plasma as being seen later as well. The flow speed, as depicted in figure 1(c), shows rapid increase upto the defined peak and thereby attains stable value. On the other hand, the plasma temperature, as presented in figure 1(d), shows gradual increase up to the peak before attaining saturation. The damping of the Alfven wave cause the dissipation of the magnetic energy which in turns leads to the increased temperature. As the temperature increases, the plasma gain high velocity. In contrast to the earlier force-free models [14-16], it is seen that the variations of the hydrodynamic properties of the loop plasma are significant only upto the peak of the loop.



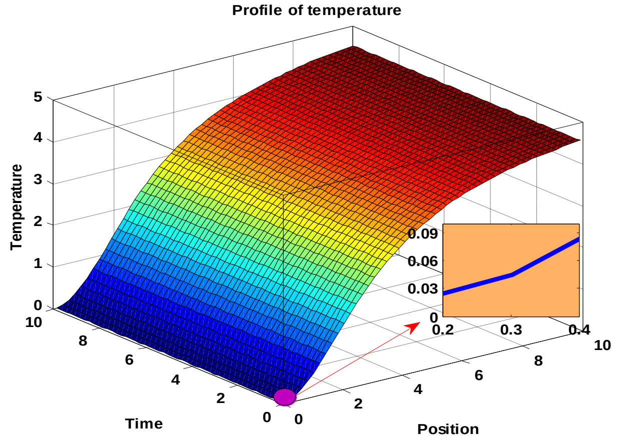
1(a)



1(b)



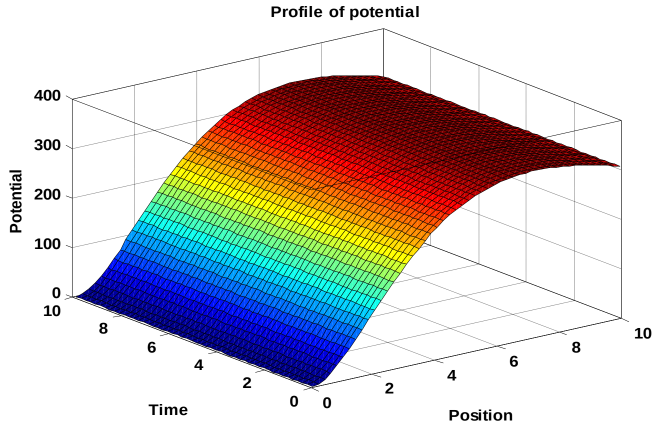
1(c)



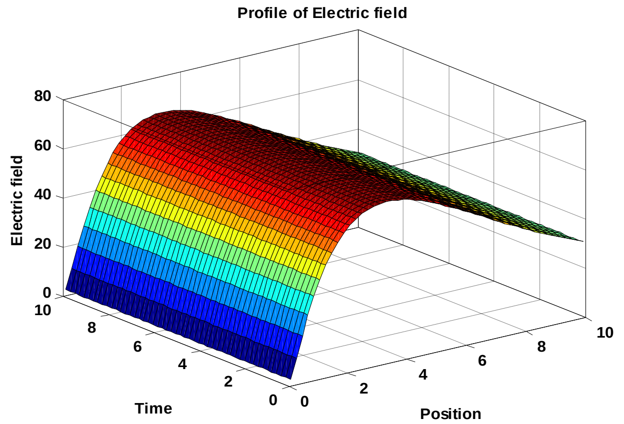
1(d)

Fig1. *Profile of the normalized (a) Electron number density, (b) Ion number density, (c) Ion flow velocity and (d) Temperature associated with the solar coronal loops with variation in loop-length and time. Various initial and boundary values used are described in the text.*

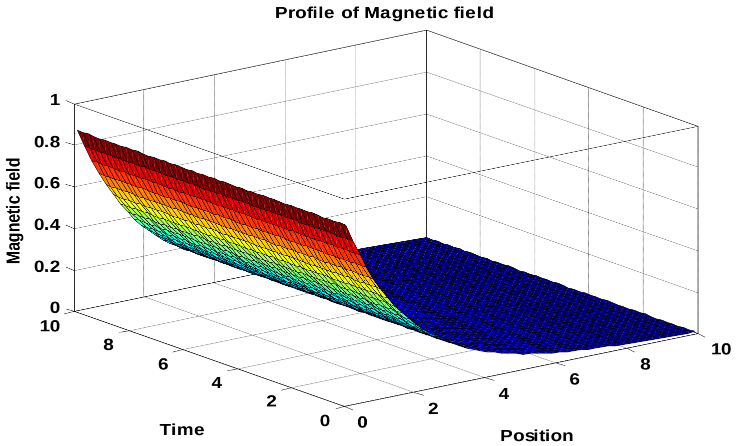
Figure 2 shows the profile structures of the electrodynamic properties (potential, electric field and magnetic field) of the loop plasma with variation in loop-length and time. The electrostatic potential and the field strength, as evident from figures 2(a)-2(b), increase up to the peak and start decreasing. Both potential and electric field are found to be positive in nature. This is a direct consequence of higher value of ion density as found above. It is seen that the electrostatic polarization is not so prominent beyond the peak, which in turn causes a decrease of the electrostatic field parameters. It shows that the effect of gravity is significant only upto the peak of the loop causing higher stratification. The magnetic field, as shown in figure 2(c), also shows similar behavior of attaining saturation after the peak. This indicates that the profile variation of the magnetic field has direct effects on the hydrodynamic properties of the plasma in the loop.



2(a)



2(b)



2(c)

Fig2. *Profile of the normalized (a) Potential, (b) Electric field and (c) Magnetic field associated with the solar coronal loops with variation in loop-length and time. Various initial and boundary values used are described in the text.*

An interesting observation resulting from this analysis is that almost all the parameters show no temporal variation on the characteristic Alfvenic time scale. This indicates that the heating function remains almost in steady-state condition for a long duration in comparison with the Alfvenic period [10].

The physical values of various plasma field parameters are in a good correspondence with earlier model predictions as well as the observed values obtained by TRACE, EIT, SoHO and Yohkoh [5, 17-19]. Details of the physical value of the loop parameters at various position are presented in the Table 2 as below.

Table2. *Physical value at different position*

Sl. No	Item	At footpoint	At critical point	At summit
1.	Electron density (n_e)	5×10^{15} m^{-3}	7.2×10^{14} m^{-3}	1×10^{14} m^{-3}
2.	Ion density (n_i)	9×10^{15} m^{-3}	6×10^{14} m^{-3}	1×10^{14} m^{-3}
3.	Velocity (v_i)	10 km s^{-1}	120 km s^{-1}	135 km s^{-1}
4.	Temperature (T)	3×10^{4} T	4×10^{6} T	4.5×10^{6} T
5.	Potential (ϕ)	0 V	3×10^{4} V	2.6×10^{4} V
6	Electric field (E)	0 V m^{-1}	5.6×10^{-2} V m^{-1}	2.6×10^{-2} V m^{-1}
7.	Magnetic field (B)	850 G	100 G	10 G

A comparison of our value (V) with the LCR circuit model [20] value (V_{LCR}) of all the relevant loop plasma parameters is made.Their percentage of deviation relative to the LCR model can be obtained using the generalized error formula, $\Delta V = [(V_{LCR} - V) \,/\, V_{LCR}]\, X\, 100\%$. Thus, the deviations are presented in Table 3 as follows.

Table3. *Comparison of our results with LCR model*

Sl. No	Parameters	Our model	LCR model	% deviation
1.	Density (n_e)	7.5×10^{14} m^{-3}	8.6×10^{14} m^{-3}	$+13\%$
2.	Velocity (v_i)	1.2×10^{4} ms^{-1}	1×10^{4} ms^{-1}	-20%
3.	Temperature (T)	4.0×10^{6} K	5×10^{6} K	$+20\%$
4.	Potential (ϕ)	3.4×10^{4} V	3.6×10^{4} V	$+5.5\%$
5.	Electric field (E)	3.3×10^{-2} Vm^{-1}	3.0×10^{-2} Vm^{-1}	-10%
6	Magnetic field (B)	100 G	113 G	$+11\%$
7.	Current density (J)	1.4 Am^{-2}	1.05 Am^{-2}	-27%

From the above comparison, it can be seen that the values of the relevant loop parameters deviate from that of the observed values in the LCR circuit model [20]. Although the deviations are small on the astrophysical scales, proper refinements in the model can increase the accuracy of the predicted results.

5. Conclusions

A simple methodological analysis of the solar coronal loops and associated plasma dynamics is carried out in the light of modified hydrodynamic model in presence of the magnetic field. It is seen numerically that a critical zone (at few loop-leghth scales) exists on the loop scales showing abrupt changes in plasma parameter values. All the variations in relevant plasma parameters are rapid up to the critical zone, and after that, almost all of them saturate. The cross-field transportation of the plasma particles is the possible cause of this type of behavior. Moreover, the magnetic field plays an important role on the dynamics of the plasma parameters. We further show that loop geometry has active influence in causing the observed saturation behavior via the critical limit. The peak of the loops behaves as a critical point between two-scale transition of strong and weak magnetic field.The loop summits behave as hot source developed due to the plasma interaction with the footpoint.The critical zone behavior of the loop plasma parameters on the standard scales of space and time may be a new addition to observations made within the framework of magnetized hydrodynamic model in the coronal loop dynamics.

The effect of space charge polarization is found to be more dominant at the central regions of the loop than anywhere else. It seems that plasma quasi-neutrality in such regions is slightly deviated due to the global heating mechanism of the loops. The gravity as well is found to have substantial effect on the electrodynamic properties through induced polarization effect. The stratification is strong only upto the critical zone that leads to higher space charge polarization.

The heating mechanisms do not depend on the characteristic time scale on the order of the Alfvenic wave period.The heating time is much longer than the characteristic Alfvenic time period such that the heating functions can be considered as steady state. The findings obtained by our simplified analysis, amid some merits and demerits, go in correspondence with the earlier reports.

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