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# A theoretical model for electromagnetic characterization of a spherical dust molecular cloud equilibrium structure

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## HIGHLIGHTS

- A spherical charged dust cloud is electromagnetically characterized.
- Weak but finite inertia of the thermal species is considered.
- Technique applies the modified Lane–Emden equation and its multi-order solutions.
- Cloud surface properties, transitional dynamics and expansions are highlighted.
- Besides, application of the model in diverse astrophysical situations is demonstrated.

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## ABSTRACT

A theoretical model is developed to study the equilibrium electromagnetic properties of a spherically symmetric dust molecular cloud (DMC) structure on the Jeans scales of space and time. It applies a new technique based on the modified Lane–Emden equation (*m*-LEE) of polytropic configuration. We consider a spatially inhomogeneous distribution of the massive dust grains in hydrodynamic equilibrium in the framework of exact gravito-electrostatic pressure balancing condition. Although weak relative to the massive grains, but non-zero finite, the efficacious inertial roles of the thermal species (electrons and ions) are included. A full portrayal of the lowest-order cloud surface boundary (CSB) and associated significant parameters is numerically presented. The multi-order extremization of the *m*-LEE solutions specifies the CSB existence at a radial point $8.58 \times 10^{12}$ m relative to the center. It is shown that the CSB gets biased negatively due to the interplay of plasma-boundary wall interaction (global) and plasma sheath–sheath coupling (local) processes. It acts as an interfacial transition layer coupling the bounded and unbounded scale-dynamics of the cloud. The geometrical patterns of the bi-scale plasma coupling are elaborately analyzed. Application of our technique to neutron stars, other observed DMCs and double layers is stressed together with possible future expansion.

## 1. Introduction

Stars and planets are born in turbulent cold self-gravitating interstellar dust molecular clouds (DMCs) (Pandey et al., 1994; Honda and Honda, 2003; Gao and Lou, 2010; Klessen et al., 2011; Falco et al., 2013). The basic mechanism of galactic structure formation in such clouds is dictated by the interplay between the self-gravity of the gas and other such as turbulence, magnetic field, radiation and thermal pressure that support such a gaseous cloud against self-gravity. The turbulent velocity field coupled with the thermal instability generates dense structure in a molecular cloud, some of which is isolated and clumpy, while many other density structures are contiguous, filament-like. The clumps that satisfy the Jeans criterion fragment further to form smaller prestellar cores that eventually spawn stars (Gao and Lou, 2010; Klessen et al., 2011; Falco et al., 2013; Anathpindika, in press). Ambipolar diffusion, the process by which ions drift along magnetic field lines, becomes important in a self-gravitating prestellar core only when it has sufficiently collapsed as to raise its gas temperature whence, molecules rupture to release ions.

As a consequence of gravity-induced electrostatic polarization effect (Bally and Harrison, 1978; Vranjes and Tanaka, 2005), ambipolar electric field is developed, which in turn is responsible for many electromagnetic phenomena sustaining on the new-born stars and their atmospheres like electromagnetic waves, inductive effects, reconnections and so forth (Hale, 1913; Rosseland, 1924;

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Gunn, 1931; Pandey et al., 1994; Pandey and Dwivedi, 1996; Verheest, 1996; Larson, 2003).

Electromagnetic states, their properties and associated field-induced effects have been discussed by many authors with *electrical stellar models* (ESMs) in past (Hale, 1913; Rosseland, 1924; Gunn, 1931; Ray et al., 2004). The separation of electrical charge inside a star within the ESM framework has been understood by modeling the star as a ball of hot ionized gas (spherical plasma ball) under the light of basic ionization and diffusion processes. Such dynamic processes allow the stellar structure to acquire a net electrical negative charge ($Q_s \sim -10^{10}$ C) on the surface (Rosseland, 1924; Gunn, 1931). Later, however, it has been hypothesized that all gravitationally bounded structures possess positive charge, whereas, in contrast, expanding intergalactic medium between clusters acquires compensating negative charge at the cost of the expelled electrons (Bally and Harrison, 1978). This implies that as if all astronomical objects like stars, galaxies and clusters of galaxies consist of positively charged clouds embedded in an intergalactic sea of negative charge. In the relativistic regime, unstable polytropic high-compact stellar objects like neutron stars can have a huge amount of charge ($Q_s \sim +10^{20}$ C) under global force-balancing condition (Ray et al., 2004). The origin mechanism and maintenance of the high electric field in such astrophysical situations still remains an open problem to be well studied. Thus, there has long been a need of a self-consistent technique-development for such electromagnetic investigation in equilibrium bounded structures in a simplified way for decades. In addition, the finite inertial character of the plasma thermal species, however small and finite it may be, has never been included in the earlier descriptions over such debatable issues.

A polytropic model defined by the Lane–Emden equation (LEE) (Honda and Honda, 2003; Mirza, 2009; Gao and Lou, 2010) is usually adopted for the description of stellar structure in both force- and mass-balanced conditions under temperature-independent configurations (Milne, 1930, 1931; Chandrasekhar, 1957; Parand and Taghavi, 2008; Bhrawy and Alofi, 2012). There indeed exist various exact solutions for diverse equilibrium configurations describable by the LEE and its various constructs (Khalique et al., 2008). The earlier investigations have ignored the plasma-boundary–wall interaction, gravito-electrostatic coupling processes, and collective scales of the plasma constituents. A full procedural description of the electromagnetic anatomy of the DMCs has been an important challenge for decades from various astrophysical perspectives. We also note, there is no model formalism developed so far which gravito-electrostatically couples the self-gravitational contraction (Newtonian dynamics) due to the weight of the massive dust grains, and electrostatic expansion (Coulombic dynamics), resulting from the complicated interaction of the electrically charged grains, to depict electromagnetic behavior in the inhomogeneous cloud. In addition, the inertial effect of the thermal species on such cloud electrodynamics is still unknown. Therefore, there has been a great need for a long period of time for designing a simple self-consistent technique for investigating the electromagnetic cloud properties of basic interest as a function of collective gravitational weight and electrical charge interaction in presence of active inertial roles of the thermal species. This might systematically be explained on a single potential variable of the cloud, its multi-order derivatives and their extreme behavior on transition.

In this report, motivated by the importance of basic electromagnetic cloud characterization and its expansion, we propose a simple strategy independent of any polytropic index. The lowest-order inertia-corrected thermal species (Deka et al., 2004; Karmakar et al., 2005, 2006; Deka and Dwivedi, 2010) with all the possible thermal effects, gravito-electrostatic coupling and plasma boundary–wall interaction processes are taken into account in a spherical geometry. We build up a modified LEE (*m*-LEE) scheme, after the self-gravitational Poisson formalism, coupling both the electromagnetic (Hale, 1913; Rosseland, 1924; Gunn, 1931) and hydrostatic (Milne, 1931; Chandrasekhar, 1957; Avinash and Shukla, 2006; Parand and Taghavi, 2008; Bhrawy and Alofi, 2012) behaviors within an integrated gravito-electrostatic framework (Avinash, 2006, 2007; Avinash and Shukla, 2006). The proposed model in this contribution presents a precise examination whether efficacious inertial contribution of the thermal species affects the existence of the cloud surface boundary (CSB), at least, on the lowest-order, by the balanced gravito-electrostatic interaction, which has earlier been found to be located at a radial point $\xi = 3.50$ on the Jeans scale in like situations (Dwivedi et al., 2007; Karmakar, 2010, 2012; Karmakar and Dwivedi, 2011). Efforts are put to see also the detailed electromagnetic aspects on the entire cloud scale, taking care of both force balancing (electromagnetic) and charge balancing (electrostatic) in the fluid form governed by continuity equation (hydrostatic). The different multi-order derivative constructs of the *m*-LEE on the normalized electrostatic pressure considering weak but finite thermal inertia are methodologically obtained. Besides, the derivatives are shown to have important roles in full electromagnetic CSB specification. The electrostatic pressure arises due to the electrostatic repulsion among the shielded dust grains and their inhomogeneous distribution (Avinash, 2006, 2007; Avinash and Shukla, 2006). It is seen that this model is justifiably successful in the cloud characterization of electromagnetic interest with a single dependent variable in the form of the electric pressure only. It offers an extension for detailed methodological characterization of neutron stars, other observed DMCs and double layers in space and astrophysical environments.

Apart from the "Introduction" part already described in Section 1 above, this paper is structurally organized in a usual simple format as follows. Section 2 describes physical model setup. Section 3 describes the mathematical formulation. Section 4 presents the results and discussions. Lastly, Section 5 depicts the main conclusions along with tentative future applicability through new vistas.

## 2. Physical model

An astrophysical environment of field-free quasi-neutral self-gravitating cloud consisting of the thermal electrons ($e$), ions ($i$) and inertial dust grains ($d$) in a spherically symmetric geometry approximation in hydroelectrostatic equilibrium is considered. The assumption of spherical symmetry simplifies the problem (to radial 1-D) mathematically, where, complications due otherwise to multi-order spherical harmonics (in 3-D) and their nonlinear coupling is avoided for now. A bulk equilibrium differential flow is assumed to pre-exist, which is justifiable due to unequal distribution of thermal energies of the heavier and lighter species (i.e., $T_d << T_e \approx T_i = T$ for $m_d >> m_i > m_e$; where $T$ stands for temperature and $m$ for mass of the superscripted species, defined in detail later). This means that the inhomogeneous distribution of the dust grains renders different parts of the cloud to move with different thermal velocities (since, the bulk normal flow is the dust thermal velocity $v_{td} = \sqrt{T_d/m_d}$ with superscript '$d$' for dust). Global electrical quasi-neutrality is supposed to subsist over the gravito-electrostatically bounded spherical enclosure containing the plasma volume. The solid matter of the assumed identical spherical grains is embedded in the inhomogeneous gaseous phase of the background plasma. We further consider that the heavier grains behave as an inertial fluid, whereas, lighter inertia-corrected electrons and ions as the inertia-modified Boltzmannian thermal particles (Deka