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The Effect of Gaseous Discharge on Star Formation

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Abstract: This paper examines how gaseous discharge affects molecular clouds and how that affects star formation. In the magnetic field of the star, electrons, positrons, and ions interact to form the majority of the plasma's chemical makeup. The ZK equations are used for the study of gaseous discharge effects in the presence of shocks and solitons. According to the study, shockwaves produced by gaseous discharge are crucial in creating molecular clouds, which in turn affect the evolution of stars. Within molecular clouds, denser regions develop as a result of the compression of the interstellar medium caused by shockwaves. The gravitational collapse of these squeezed regions promotes the creation of protostellar cores and starts the star-formation process as a result. Shockwaves also affect the motion and turbulence of molecular clouds and improve the amplification of magnetic fields. Clarifying the basic principles regulating star formation and the ensuing creation of stellar populations inside galaxies requires an understanding of the complex interplay between shockwaves and molecular clouds.

Keywords: Collapse, Molecular clouds, Protostellar, Shockwaves

1. Introduction

Astronomers and physicists have been enthralled by the study of the early cosmos for centuries because it provides a path to comprehending the unfathomable beginnings of our cosmic environment. The complicated interplay of plasma, shockwaves, accretion, and stellar birth sits at the center of this astonishing drama. The early cosmos was a plasma soup that was incredibly hot, thick, and full of energetic particles and radiation when it was first created. The fundamental forces of nature controlled the interactions between particles at this time, which was crucial in creating the universe as we know it today. The plasma experienced a change as the universe cooled and expanded. Plasma streams, lengthy filaments that span immense cosmic distances, finally emerged as a result of subtle variations in its density and temperature [1]. A crucial stage in the cosmic symphony of birth and expansion, these cosmic highways of plasma served as the gravitational foundation upon which galaxies and galaxy clusters would eventually come together. These plasma streams gave birth to shockwaves. These massive perturbations moulded the structure of the universe on a vast scale, driven by a variety of cosmic occurrences like supernovae and galaxy collisions [2, 3]. Shockwaves caused gravitational collapse as they moved through the plasma, which prompted the formation of matter in denser areas [4, 5]. The accretion process served as the incubator for protostar formation. Gravity brought enormous amounts of matter together during the cosmic dance of accretion, moulding it into dense cores within the plasma streams. Future stars' embryonic forms emerged within these cores, propelled by the gravitational potential energy released during the collapse. Early on, the protostar developed into a source of radiant energy, illuminating its surrounds with a comforting glow. The interaction of gravity, matter, and energy created the conditions for the star formation [6, 7]. In this paper we delve deeper into the evolutionary processes involved, examining the mechanisms driving the formation of plasma streams, the impact of shockwaves on accretion, and the transformative journey from protostar to fully fledged star. Through comprehensive analysis of theoretical models, observational data and computational simulation, we aim to shed light on the remarkable phenomenon of stellar birth and it's implications for understanding our universe

In section II, shock waves and their characteristics are described followed by the role of Shock Waves in section III. Section IV contains Mathematical Derivation & Numerical Simulation. Results and Discussion are in section V. The section VI mentions the Future Direction and conclusion is in section VII.

2. Shockwaves and Their Characteristics

A shockwave is a discontinuity that moves across a medium and causes a quick alteration in its physical characteristics. Based on their features, shockwaves can be divided into a number of categories, including regular shocks, oblique shocks, and bow shocks. Shockwaves of different types behave differently and have different effects on their surroundings [8]. Several astronomical phenomena, including supernova explosions, stellar winds from huge stars, and interactions between galaxies, can produce shockwaves. Extreme energy is released during these occurrences, which causes shockwaves to form and travel through the interstellar medium. The density, temperature, and composition of the medium are all factors that affect how shockwaves spread [9, 10].

The gas and dust in the immediate area are compressed and heated as shockwaves hit the interstellar medium. The birthplace of stars, molecular clouds, may collapse as a result of this compression. Furthermore, shockwaves cause turbulence in the interstellar medium, which improves the disintegration of molecular clouds and encourages the creation of many protostellar centres [11]. The rate and effectiveness of star formation are greatly influenced by the interaction of shockwaves with the interstellar medium.

3. Role of Shockwaves in Star Formation

3.1 Triggering of Star Formation by Shockwaves

By compressing the surrounding interstellar medium, shockwaves play a critical part in starting the birth of new stars. The gas and dust are compressed and get denser as a shockwave moves across the interstellar medium [12]. The compression causes the gravitational instability in the medium to increase, which causes the star forming molecular clouds to collapse. The creation of protostellar cores can begin when shock wave induced compression overcomes the thermal and magnetic support that usually prevents collapse [13]. Through the accretion of surrounding material, these cores then develop into protostars.

3.2 Shockwave Compression and the Collapse of Molecular Clouds

Compressing molecular clouds, which are the locations where stars develop, is one of shock waves' primary effects on star formation. The material of the cloud is more likely to collapse gravitationally due to the compression brought on by shockwaves, which also increases the density and pressure inside the cloud [14]. The stronger self-gravity produced by the higher density allows the cloud to defeat the thermal and magnetic pressure support. As a result, the cloud disintegrates more quickly, giving rise to protostellar centres and denser clumps. Smaller structures develop inside larger ones as the collapse proceeds hierarchically, eventually leading to the birth of individual stars.

3.3 Shockwave-Induced Turbulence and Fragmentation

The interstellar medium becomes turbulent as a result of shockwaves, and this turbulence significantly contributes to the breakup of molecular clouds [15]. Shockwaves cause velocity changes as they travel through the cloud, which causes the gas to move in tumultuous fashion. The molecular cloud begins to form clumps, filaments, and other structures as a result of the density changes caused by this turbulence. As a result of gravitational collapse, these compact formations are prone to shatter into protostellar cores [16, 17]. As a result, shockwave-induced turbulence encourages star fragmentation, leading to a clustered phase of star formation in which numerous stars develop near to one another.

3.4 *Shockwaves as Stellar Feedback Mechanisms*

The energy that stars produce is eventually released in the form of stellar winds, radiation, and supernova explosions. Shockwaves produced by these energetic processes may radiate outward from newly generated stars [18]. The rate and effectiveness of ongoing star formation are impacted by interactions between these feedback-driven shockwaves and the interstellar medium around them. On the one hand, these shockwaves have the potential to compress neighbouring molecular clouds, leading to the birth of brand-new stars [19]. However, they can also scatter and disturb already-existing molecular clouds, preventing or impeding the birth of new stars. The interaction between shockwaves and stellar feedback mechanisms influences the distribution and population of stars in galaxies as well as the dynamics of star-forming areas as a whole.

Understanding how shockwaves affect star formation helps us better grasp the systems and procedures that control how stars are created and evolve [20]. Shockwaves play a major role in the intricate and dynamic nature of star formation, from causing molecular clouds to collapse to fostering turbulence and fragmentation. Additionally, the interaction between shockwaves and stellar feedback has effects on both the general evolution of galaxies as well as specific star formation events [21]. We can understand the complex connection between shockwaves and star formation by investigating these interactions through observational investigations and numerical simulations, giving information on the fundamental processes that create our universe.

4. Mathematical Model

In plasma physics, the hydrodynamic model is a fundamental approach used to study the behaviour of plasmas on macroscopic scales. This model treats the plasma as a fluid with properties such as density, velocity, pressure, and temperature, allowing researchers to analyse its collective behaviour. The hydrodynamic equations, known as the fluid equations, are derived from the conservation laws of mass, momentum, and energy, along with Maxwell's equations governing the electromagnetic fields within the plasma. These equations form a set of coupled partial differential equations that describe the evolution of plasma parameters over time and space.

One of the key assumptions of the hydrodynamic model is that the characteristic length and time scales of the plasma phenomena of interest are much larger than the mean free path and collision time of individual particles. This allows for the description of plasma dynamics in terms of smooth fluid quantities rather than individual particle trajectories. The hydrodynamic model has been successfully applied to study various plasma phenomena, including the propagation of shock waves, instabilities, turbulence, and magnetic reconnection. It provides insights into the behaviour of plasmas in laboratory experiments, astrophysical environments, and fusion research. However, it's essential to note that the hydrodynamic model has its limitations, particularly when dealing with strongly collisional or non-equilibrium plasmas where kinetic effects become significant. In such cases, more sophisticated kinetic models are required for accurate description and prediction of plasma behaviour.

4.1 Governing Equations

The propagation of dust acoustic waves in a collisionless, unmagnetized warm dusty plasma made up of electrons, two-temperature ions, and highly negatively charged dust grains is investigated [22]. At equilibrium, total charge neutrality necessitates that

$$n_{0e} + n_{0d}Z_{0d} = n_{0ic} + n_{0ih} \tag{1}$$

where n_{0e}, n_{0d}, n_{0il} and n_{0ih} are the equilibrium values of electrons, dust, lower temperature ions and higher temperature ion number densities respectively. Z_{0d} is the unperturbed number of charges on the dust particles. The following set of normalized two-dimensional equations of

$$n_{0e} + n_{0d}Z_{0d} = n_{0ic} + n_{0ih} \tag{2}$$

$$\frac{\partial u_d}{\partial t} + u_d\frac{\partial u_d}{\partial x} + v_d\frac{\partial u_d}{\partial y} + w_d\frac{\partial u_d}{\partial z} = Z_d\frac{\partial \phi}{\partial x} - \frac{\sigma_d}{n_d}\frac{\partial P_d}{\partial x} \tag{3}$$

$$\frac{\partial v_d}{\partial t} + u_d\frac{\partial v_d}{\partial x} + v_d\frac{\partial v_d}{\partial y} + w_d\frac{\partial v_d}{\partial z} = Z_d\frac{\partial \phi}{\partial y} - \frac{\sigma_d}{n_d}\frac{\partial P_d}{\partial y} \tag{4}$$

$$\frac{\partial w_d}{\partial t} + u_d\frac{\partial w_d}{\partial x} + v_d\frac{\partial w_d}{\partial y} + w_d\frac{\partial w_d}{\partial z} = Z_d\frac{\partial \phi}{\partial y} - \frac{\sigma_d}{n_d}\frac{\partial P_d}{\partial y} \tag{5}$$

$$\frac{\partial p_d}{\partial t} + u_d\frac{\partial p_d}{\partial x} + v_d\frac{\partial P_d}{\partial y} + w_d\frac{\partial P_d}{\partial z} = -3P_d\left(\frac{\partial u_d}{\partial x} + \frac{\partial v_d}{\partial y} + \frac{\partial w_d}{\partial z}\right) \tag{6}$$

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = Z_d n_d + n_e - n_{ic} - n_{ih} \tag{7}$$

u_d, v_d and w_d are velocity components of the dust particles in x, y and z-directions and are normalized by the effective dust acoustic speed $C_d = \sqrt{Z_{0d}T_{eff} / m_d}$. P_d and ϕ are the pressure of the dust particles and electrostatic potential respectively and they are normalized by $Z_d n_{0d} T_d$ and T_{eff} / e, respectively. Here, $\frac{T_{eff}}{Z_{0d}n_{0d}} = \left[\frac{n_{0e}}{T_e} + \frac{n_{0ic}}{T_{il}} + \frac{n_{0ih}}{T_{ih}}\right]^{-1}$ is the effective temperature where T_d, T_e, T_{i1}, T_{ih} are the temperature of dust, electron and low-temperature and high-temperature ions. n_d and Z_d are the dust number density and the variable charge number of dust grains and they are normalized by n_{0d} and Z_{0d}, respectively. The time and space variables are normalized by the dust plasma period $\omega_{pd}^{-1} = \sqrt{m_d / 4\pi n_{0d} Z_{0d}^2 e^2}$ and the Debye length $U_D = \sqrt{T_{eff} / 4\pi Z_{0d} n_{0d} e^2}$, respectively. Electrons and ions are assumed to be distributed with nonthermal and Maxwell-

Boltzmann distribution functions, respectively. So the related dimensionless number densities for electrons (n_e), low-temperature ions (n_{il}) and high-temperature ions (n_{ih}) are

$$n_{\mathrm{e}} = \Delta_e \left[1 - C_1\phi + C_2\phi^2\right] \exp\left(\beta_1 s\phi\right) \tag{8}$$

$$n_{\mathrm{ic}} = \Delta_{ie} \exp(-s\phi) \tag{9}$$

$$n_{\mathrm{ih}} = \Delta_{ih} \exp(-\beta s\phi) \tag{10}$$

where, $\Delta_e = \dfrac{1}{\delta_1 + \delta_2 - 1}$ (11)

$$\Delta_{ie} = \frac{\delta_1}{\delta_1 + \delta_2 - 1} \quad \Delta_{ih} = \frac{\delta_2}{\delta_1 + \delta_2 - 1} \quad C_1 = \frac{4\alpha}{1+3\alpha}\beta_1 s \quad C_2 = \frac{4\alpha}{1+3\alpha}(\beta_1 s)^2,$$

$$\beta_1 = \frac{T_{\mathrm{ic}}}{T_{\mathrm{e}}}, \quad \beta_2 = \frac{T_{\mathrm{ih}}}{T_{\mathrm{e}}}, \quad \beta = \frac{\beta_1}{\beta_2} = \frac{T_{\mathrm{ic}}}{T_{\mathrm{ih}}}, \quad s = \frac{T_{\mathrm{eff}}}{T_{\mathrm{ic}}} = \frac{\delta_1 + \delta_2 - 1}{\delta_1 + \delta_2\beta + \beta_1}, \quad \delta_1 = \frac{n_{0\mathrm{ic}}}{n_{0\mathrm{e}}}, \quad \delta_2 = \frac{n_{0\mathrm{ih}}}{n_{0\mathrm{e}}}, \quad \sigma = \frac{T_{\mathrm{d}}}{T_{\mathrm{eff}}},$$

where the non-thermal parameter α determines the number of non-thermal fast electrons.

4.2 Derivation of ZK equation

In order to derive the evolutionary equation in this case which becomes as a Zakharov-Kuznetsov (ZK) equation we use the standard reductive perturbation technique (RPT). The reductive perturbation technique is a powerful mathematical method used to simplify and analyse nonlinear wave equations. It involves assuming a small parameter, typically representing the ratio of wave amplitude to wavelength, which allows for the expansion of equations into series. Through this approach, the complicated nonlinear equations can be approximated by simpler, linear ones, focusing on the dominant effects. This technique is widely applied in various fields, including plasma physics, fluid dynamics, and nonlinear optics, providing valuable insights into the behaviour of waves in complex systems and facilitating the understanding of phenomena such as solitons and wave interactions. For this we employ stretching of variables and perturbation expansion as given below.

a) Stretching Variables

$$\xi = \epsilon\left(\int_0^x \frac{dx}{U(x)} - t\right), \quad \eta = \epsilon^2 y, \zeta = \epsilon^2 z, \quad \tau = \epsilon^3 t$$

(11)

b) Perturbation series

$$
\begin{aligned}
n_d &= 1+\varepsilon^2 n_{1d}+\varepsilon^4 n_{2d}+\cdots\\
u_d &= \varepsilon^2 u_{1d}+\varepsilon^4 u_{2d}+\cdots\\
v_d &= \varepsilon^3 v_{1d}+\varepsilon^5 v_{2d}+\cdots\\
w_d &= \varepsilon^3 w_{1d}+\varepsilon^5 w_{2d}+\cdots\\
\phi &= \varepsilon^2 \phi_1+\varepsilon^4 \phi_2+\cdots\\
P_d &= 1+\varepsilon^2 P_{1d}+\varepsilon^4 P_{2d}+\cdots\\
Z_d &= 1+\varepsilon^2 Z_{1d}+\varepsilon^4 Z_{2d}+\cdots
\end{aligned}
\tag{12}
$$

c) The Zakharov-Kuznetsov (ZK) equation

With proper algebraic manipulation and employing boundary conditions we obtained the ZK equation given as

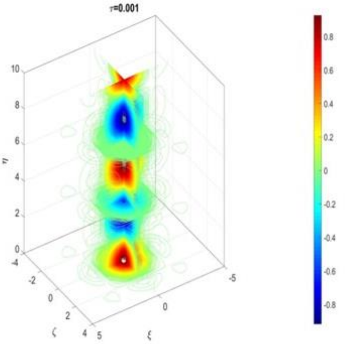
$$
\left[\frac{\partial\phi_1}{\partial\tau}+A\phi_1\frac{\partial\phi_1}{\partial\xi}+B\frac{\partial^3\phi_1}{\partial\xi^3}\right]+C\frac{\partial}{\partial\xi}\left[\frac{\partial^2\phi_1}{\partial\eta^2}+\frac{\partial^2\phi_1}{\partial\zeta^2}\right]=0 \tag{13}
$$

Here $A=\frac{1}{2U}\left[-2+\left(U^2-3\sigma\right)^2\left(\delta_1+\delta_2\beta^2-\beta_1^2\right)\frac{\left(\delta_1+\delta_2-1\right)}{\left(\delta_1+\delta_2\beta+\beta_1\right)^2}-2\gamma_2+3\gamma_1\left(U^2-3\sigma\right)-\frac{U^2+9\sigma}{U^2-3\sigma}\right]$, $B=\frac{1}{2U}\left(U^2-3\sigma\right)^2$, And $C=\frac{U}{2}$

The Zakharov-Kuznetsov equation is a nonlinear partial differential equation that describes the evolution of weakly nonlinear ion-acoustic waves in a plasma with non-uniformity in both space and time. It incorporates effects such as dispersion, nonlinearity, and dissipation, making it relevant in plasma physics and nonlinear optics. Formulated by Zakharov and Kuznetsov, this equation provides insights into wave dynamics, including soliton formation and propagation, in non-uniform plasma environments. Its study aids in understanding complex plasma behaviours and has practical applications in diverse fields such as controlled fusion, plasma diagnostics, and the development of advanced communication systems. For a better understanding of the subject the readers can refer to the following works on linerar and nonlinear phenomena in space plasma physics [23-57].

5. Results and Discussions

Figure 1 & 2 represents the Electric Field Potential of the plasma. The electric field plasma follows a continuous pattern of lower and higher potential in the beginning stage (Figure. 1) which is being distorted later (Figure. 2) as perturbations are introduced. In figures 3 & 4, the brown surface shows an isosurface of higher Electric field whereas the blue surface is a representation of lower Electric field. However, the perturbation distorts the isosurface which can also be seen in figures 5 & 6, as the Electric Field lines mess up their path with the passage of time because of introduction of perturbations. This distortion in electric field affects the magnetic field which further plays role in star formation in two ways [23].



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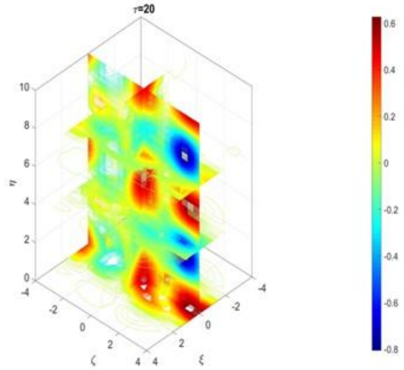

Figure 2. Electric field potential at time t=20

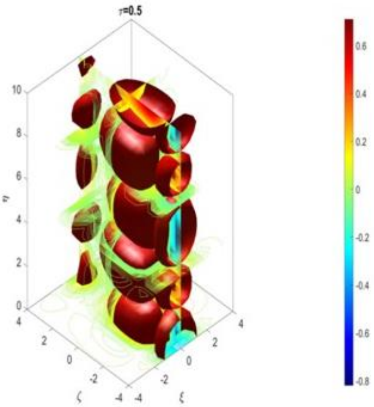

Figure 3. Isosurface of Electric Field at time=5

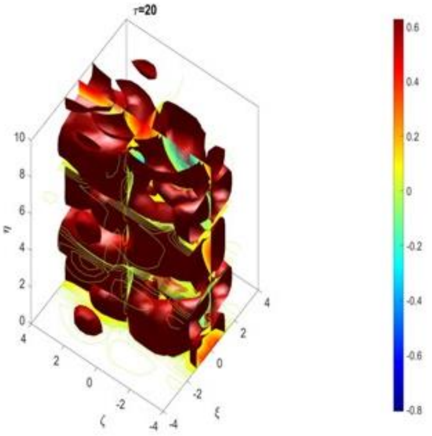

Figure 4. Isosurface of Electric Field at time=20

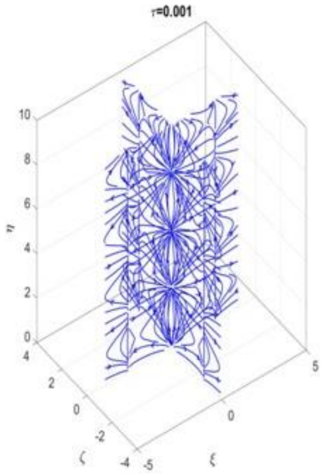

Figure 5 Representation of Electric Field Lines before

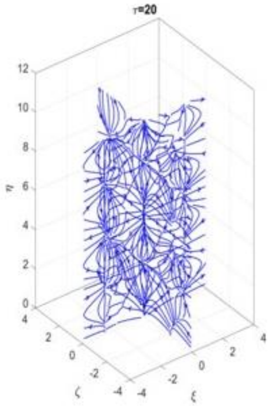

Figure 6 Representation of Electric Field Lines after perturbation

a) Magnetic fields immediately inhibit turbulence's capacity to collect gas into gravitationally unstable clumps by preventing turbulent compression and pressure that defies gravity. This lowers the star formation rate.
b) Magnetic fields also play a critical indirect role by providing the means for forming stars to launch jets and outflows. By ejecting gas that would otherwise accrete onto stars and by promoting fragmentation, outflows reduce the mean stellar mass on tiny scales.

6. Conclusion

This paper has examined the impact of shockwaves on the star-forming process. We have obtained important insights into the intricate processes involved by examining shockwave features, their interactions with the interstellar medium, and their function in initiating and directing star formation. The enormous impact of shockwaves on star formation and their broader implications for galaxy evolution are supported by computational models. Our knowledge of star formation and its position within the broader context of astrophysics will increase as a result of additional research in this area.

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