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Letter to the Editor

Generation of magnetic fields in a positive–negative dusty plasma

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Abstract. It is shown that purely growing magnetic fields in a two-component dusty plasma can be generated due to the equilibrium drift of positive and negative dust grains. For this purpose, a linear dispersion relation has been derived by using the hydrodynamic equations for the charged dust fluids, the Maxwell equation and Faraday's law. The dispersion relation admits a purely growing instability, the growth rate of which is proportional to the equilibrium streaming speeds of positive and negative dust grains. A possible physical explanation for the instability is offered. Applications of our investigation to magnetic fields in the thin Martian environments, interplanetary spaces and dense molecular clouds are mentioned.

Multi-component plasmas and charged dust grains are ubiquitous in our universe and planetary ring systems [1–4], as well as in low-temperature laboratory settings [5] and in industry [6]. Specifically, they appear in protoplanetary nebulae, in interplanetary space and interstellar media, in and around cluster of galaxies, cometary tails and comae, in the asteroid Gaspra, in Saturn's rings, in the Martian environments, as well as in the near-Earth atmospheres. Both in cosmic environments and astrophysical settings, there is conclusive evidence of magnetic fields.

For example, recent observations [7] indicate signatures of electric and magnetic fields in a Nevada Playa located outside of Boulder and on Mars, where dust grains in the swirling dust devils may become electrically charged via triboelectric effects [8, 9].

Multi-component dusty plasmas are an admixture of electrons, ions and mesoscopic (sub-micrometer to micrometer and sub-millimeter sized) dust particles. The latter are charged both positively and negatively owing to a variety of processes [1, 3, 10]. Positively and negatively charged dust particles can coexist in the polar mesosphere [11–15], and in the Martian atmosphere [16, 17]. Field experiments on terrestrial dust devils show evidence of electric and magnetic field signatures that are thought to be related to the presence of positively and negatively charged dust grains in different regions of the dust devil [7]. It is plausible that positive and negative dust clouds may stream through each other, and there is thus a free energy source which can be coupled to fluctuations [17] in dusty plasmas.

In this letter, we demonstrate the possibility of a novel purely growing electromagnetic instability due to the equilibrium drift of dust grains of opposite polarity in a dusty plasma. The latter is composed of positive and negative dust grains of uniform sizes. There are no electrons and ions in our two-component dusty plasma system.

Let us suppose that the positively and negatively charged dust grains are streaming with the equilibrium drift velocities $\hat{\mathbf{z}}u_{0\pm}$, where $\hat{\mathbf{z}}$ is the unit vector along the z-axis in a Cartesian coordinate system and the subscript $+(-)$ stands for the positive (negative) dust grain. The dynamics of one-dimensional mixed-mode electromagnetic perturbations in our dusty plasma is governed by the continuity equation

$$\frac{\partial n_\pm}{\partial t} + n_{0\pm}\frac{\partial v_{x\pm}}{\partial x} = 0, \tag{1}$$

the x-component of the momentum equation

$$\frac{\partial v_{x\pm}}{\partial t} = \mp\frac{Z_\pm e}{m_\pm c}u_{0\pm}B_y, \tag{2}$$

and the z-component of the Maxwell equation

$$\frac{\partial B_y}{\partial x} = \frac{4\pi e}{c}(Z_+ n_{0+}v_{z+} - Z_- n_{0-}v_{z-}) + \frac{4\pi e}{c}(Z_+ n_+ u_{0+} - Z_- n_- u_{0-}) + \frac{1}{c}\frac{\partial E_z}{\partial t}, \tag{3}$$

where the z-component of the dust fluid velocity $u_{z\pm}$ is determined from

$$\frac{\partial v_{z\pm}}{\partial t} = \pm\frac{Z_\pm e}{m_\pm}E_z. \tag{4}$$

Here the z-component of the wave electric field E_z is related to the wave magnetic field B_y by Faraday's law,

$$\frac{\partial E_z}{\partial x} = \frac{1}{c}\frac{\partial B_y}{\partial t}. \tag{5}$$

In (1) and (3) $n_\pm$ (which is much less than the equilibrium dust particle number density $n_{0\pm}$) is a small density perturbation caused by the non-vanishing of the divergence of the dust particle flux $n_{0\pm}v_{x\pm}$ in the presence of the equilibrium dust flows. The latter produce the dust velocity perturbation $v_{x\pm}$ due to the Lorentz force involving the cross-coupling between the equilibrium dust flows and the perturbed magnetic field B_y. Furthermore, Z_+ and Z_- are the number of positive and negative

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charges residing on dust grains, respectively, $m_\pm$ is the dust mass, e is the magnitude of the electron charge and c is the speed of light in vacuum.

Combining (1) and (2), we obtain

$$\frac{\partial^2 n_\pm}{\partial t^2} = \pm \frac{Z_\pm n_{0\pm} u_{0\pm} e}{m_\pm c} \frac{\partial B_y}{\partial x}, \tag{6}$$

which shows that finite density perturbations exist only if $u_{0\pm}$ is present.

Taking the time derivative on both sides of (3), and using (4) we obtain

$$\frac{\partial^2 B_y}{\partial x \partial t} = \frac{1}{c}\left(\omega_{\mathrm{p}}^2 + \frac{\partial^2}{\partial t^2}\right) E_z + \frac{4\pi e}{c}\left(Z_+ u_{0+} \frac{\partial n_+}{\partial t} - Z_- u_{0-} \frac{\partial n_-}{\partial t}\right), \tag{7}$$

where $\omega_{\mathrm{p}} = (\sum_{+,-} \omega_{\mathrm{p}\pm}^2)^{1/2}$ and $\omega_{\mathrm{p}\pm} = (4\pi Z_\pm^2 e^2 n_{0\pm}/m_\pm)^{1/2}$ is the dust plasma frequency. Furthermore, from (6) and (7) we have

$$\left(\frac{\partial^2}{\partial t^2} - \sum_{+,-} \frac{\omega_{\mathrm{p}\pm}^2 u_{0\pm}^2}{c^2}\right) \frac{\partial^2 B_y}{\partial x^2} = \frac{1}{c}\left(\omega_{\mathrm{p}}^2 + \frac{\partial^2}{\partial t^2}\right) \frac{\partial^2 E_z}{\partial x \partial t}. \tag{8}$$

By using (5) we can now eliminate E_z from (8), obtaining the wave equation

$$\frac{\partial^4 B_y}{\partial t^4} + \left(\omega_{\mathrm{p}}^2 - c^2 \frac{\partial^2}{\partial x^2}\right) \frac{\partial^2 B_y}{\partial t^2} + \left(\sum_{+,-} \omega_{\mathrm{p}\pm}^2 u_{0\pm}^2\right) \frac{\partial^2 B_y}{\partial x^2} = 0. \tag{9}$$

We now Fourier transform (9) by supposing that B_y is proportional to $\exp(-i\omega t + ikx)$, where ω and k are the frequency and wavenumber, respectively. The result is the dispersion relation

$$\omega^4 - (k^2 c^2 + \omega_{\mathrm{p}}^2)\omega^2 - k^2 \sum_{+,-} \omega_{\mathrm{p}\pm}^2 u_{0\pm}^2 = 0, \tag{10}$$

which has the solutions

$$\omega^2 = \frac{1}{2}\Omega_{\mathrm{em}}^2 \pm \frac{1}{2}\left(\Omega_{\mathrm{em}}^4 + 4k^2 \sum_{+,-} \omega_{\mathrm{p}\pm}^2 u_{0\pm}^2\right)^{1/2}, \tag{11}$$

where $\Omega_{\mathrm{em}} = (k^2 c^2 + \omega_{\mathrm{p}}^2)^{1/2}$ is the frequency of the electromagnetic wave in a positive–negative dust plasma. Equation (11) admits a purely growing instability ($\omega = i\gamma$). The growth rate is

$$\gamma = \left[-\frac{1}{2}\Omega_{\mathrm{em}}^2 + \frac{1}{2}\left(\Omega_{\mathrm{em}}^4 + 4k^2 \sum_{+,-} \omega_{\mathrm{p}\pm}^2 u_{0\pm}^2\right)^{1/2}\right]^{1/2}. \tag{12}$$

Finally, we note that for $|\omega| \ll \Omega_{\mathrm{em}}$, we have from (10)

$$\omega^2 = -\frac{k^2}{\Omega_{\mathrm{em}}^2} \sum_{+,-} \omega_{\mathrm{p}\pm}^2 u_{0\pm}^2, \tag{13}$$

which also admits a purely growing instability, whose growth rate is

$$\gamma = \frac{k}{\Omega_{\mathrm{em}}} \left(\sum_{+,-} \omega_{\mathrm{p}\pm}^2 u_{0\pm}^2\right)^{1/2}. \tag{14}$$

To summarize, we have discussed the possibility of spontaneous magnetic field generation in a positive–negative dusty plasma in the presence of the equilibrium dust particle flow. Physically, the Lorentz force arising from the coupling between the dust flow and an infinitely small magnetic field perturbation can move positive

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and negative dust fluids in opposite directions to each other. As a result, a space-charge electric field and dust density perturbations appear. Since the latter cannot keep in phase with the magnetic field perturbation, one encounters a purely growing instability due to which magnetic fields are spontaneously created in dusty plasmas. The present results are important for understanding the origin of magnetic fields in the Martian dusty atmosphere, as well as in interplanetary spaces and in dense dusty molecular clouds.

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