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Electric field and Lorentz force contribution to atmospheric vortex phenomena

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Abstract

The physics that initiate and sustain tornados and dust devils is still under investigation. Forces that operate throughout a wide range of scales and could contribute to atmospheric vortex phenomena are the Lorentz force and the force of electric fields. The Lorentz force results in a circular motion of charged particles in a magnetic field. An electric field will pull or repel a charged particle in the direction of the field. This paper will demonstrate that the Lorentz force and the force of electric fields, acting on charged particles that exist in atmospheric vortex phenomena, plausibly contribute to the set of physics that will explain tornados and other atmospheric vortex phenomena.
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1. Introduction

Tornados and dust devils have been studied for many decades, but a conclusive explanation of the complete set of physical mechanisms, which form and sustain these phenomena has not yet been developed [1]. The search for an explanation of these phenomena is growing, due to the discovery of similar phenomena on other celestial bodies such as Mars, and even the Sun [2,3]. The mere existence of these vortex structures on the Sun and two planets suggests that the existence of rapidly rotating vortex structures are possible over a very wide range of conditions of atmospheric density, pressure, and temperature. This suggests that a possible contributor to the formation and operation of these phenomena may be physical forces common to all these environments.

Two forces that operate on a wide range of scales and could possibly contribute to the vortex phenomena are the Lorentz force and the force of an electric field. The Lorentz force results in a circular motion of charged particles in a magnetic field [4]. An electric field will attract or repel a charged particle in the direction of the field, depending on the charge of the particle. The combination of the two, with electric fields and magnetic fields in the proper orientation, would create a tornado-like vortex in an atmosphere containing charged particles.

Although the relationship between tornados and electricity has been examined in the past and has generally been discounted, that early work focused on the flow of the electric current for producing Joule heating (heating by collisions of the atmospheric molecules and particles), without considering the circular motion of the charged particles themselves [5]. This paper will demonstrate that vertical electric fields and the Lorentz force, acting on charged particles that exist in these vortex phenomena, plausibly contributes to the set of physics that will explain tornados and other phenomena.

2. Lorentz force equation

The Lorentz force equation is probably much more familiar to space physicists than to meteorologists. The form of the equation is

$$F_{\mathrm{L}} = qE + qvB, \quad (1)$$

where (in SI units) F_{L} is the resulting force on the particle, called the Lorentz force; q is the charge of the particle

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(Coulombs); E is the electric field (volts per meter); v is the particle velocity (m/s); B is the magnetic field (Tesla (T)).

From this equation, where the electric field $E = 0$, it can be derived that the motion of a charged particle in magnetic field is circular. The radius of the circular path defined by the particle in a vacuum (called the gyroradius) is given by [4]

$$\text{Gyroradius} = \frac{mv\perp}{qB}, \quad (2)$$

where $v\perp$ is the velocity perpendicular to the magnetic field.

Since the atmosphere is not a vacuum, the effect of drag must also be considered; it will be considered in a later section.

3. Existence of forces and particles

All of the constituents necessary to the application of the Lorentz force equation—moving charged particles, electric fields, and magnetic fields—are found in tornados and dust devils.

The mechanism for charging particles in dust devils has been explained by triboelectric charging (commonly known as "static electricity") of the dust particles as they collide [2]. Particles moving along the ground receive an electric charge by the process called saltation [6]. Another source of charged particles is the ionization of atmospheric molecules such as oxygen; even on Earth near sea level, approximately 100–5000 free ions exist per cubic centimeter [7]. Additional ions are also created through the action of strong atmospheric electric fields, and, for example, result in the phenomena of lightning and (perhaps the less familiar) St. Elmo's fire.

The Earth's atmosphere typically contains an electric field. During storms a process within the clouds creates separation of charged particles (in a process that is still being studied, see, for example, Ref. [8]). This charge separation results in electric fields exceeding hundreds of thousands of volts per meter. These electric fields up at cloud level become strong enough to create ions and powerful flows of current—the proof of this process is the resulting lightning. At ground level, as storm clouds pass overhead, the strength of the electric field is measured at kilovolts or tens of kilovolts per meter. Rapid fluctuations in electric fields at ground level are observed during and immediately after lightning; lightning appears to be Nature's attempt to equalize the charge between the cloud and another section of the cloud, or between the cloud and the ground.

The existence of magnetic field on Earth has been known for millennia, and can be thought of (very roughly) as a bar magnet [9]. The magnetic field lines enter the Earths surface at an angle (called the dip angle), which depends on the magnetic latitude. The strength of the magnetic field varies with location and orientation, and measurement maps have been created to define both the horizontal and vertical magnetic fields. Magnetic fields also exist on the sun (several times stronger than earth) and on Mars (much weaker, at roughly 400 nT) [10].

4. Computation of the gyroradius

Since the physics which forms and sustains a tornado does not appear to be trivial, one way to start the investigation into whether the Lorentz force and atmospheric electric fields contribute to tornados is to determine if any plausible particle exists with a charge and mass which would result in the movement of typical winds in the tornado wall near the core. If the gyroradius of a set of particles with a specific charge, mass, and speed matches the radius and wind speed of the observed tornados, then the possibility of the Lorentz force contribution to vortex formation or operation deserves further consideration.

Several examples of such computations are provided below.

A useful test particle in Earth's atmosphere to carry the electric charge is a spherical water droplet. The use of water droplets seems reasonable for a terrestrial weather phenomena, since water droplets and ice crystals in clouds are thought to be charge carriers which produce the huge electric fields necessary to generate lightning. According to [11], a water droplet, which is moderately charged, will become highly charged as it evaporates to a smaller size. The maximum charge that a liquid droplet can carry is given by the Rayleigh limit (a stronger charge will cause the droplet to break apart) [11]. The equation given for the Rayleigh limiting charge (in number of elementary charges, n_L):

$$n_L = \left(\frac{(2\pi\gamma d_P^3)}{K_e e^2}\right)^{1/2}. \quad (3)$$

However, for the purpose of this paper to show plausibility, it was more convenient to read off the limiting charge from the accompanying graph in the same Ref. [11].

Table 1 shows the resulting gyroradii of four example diameters of maximally charged spherical water droplets in an magnetic field typical of Earth (50,000 nT) with the wind velocity set to 30 m/s. The example represents the wind speed of a high-end F0 tornado.

Table 1 shows that, if the Lorentz force is to have an effect on the structure of vortex on Earth, then the charged particles must be very small (from 0.1 to 0.01 μm)

Table 1
Gyroradius of test spherical water droplet at 30 m/s in Earth's magnetic field (50,000 nT)

Diameter (μm)	Maximum charge (C)	Mass (kg)	$v\perp$ (m/s)	Gyroradius
1	2.5×10^{-14}	5.2×10^{-16}	30	12.48 km
0.1	1.6×10^{-16}	5.2×10^{-19}	30	2.08 km
0.02	3.2×10^{-17}	4.12×10^{-21}	30	77.3 m
0.01	9.6×10^{-18}	5.2×10^{-22}	30	32.5 m

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