Forces That May Explain Ball Lightning's Motion

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Abstract: The motion of ball lightning is one of its least understood characteristics. It is observed to move horizontally as well as vertically, and at relatively slow speeds of 1 m/s down to zero. Most theories of ball lightning are not well suited to account for this type of motion. If one assumes that ball lightning is incompressible (e. g. shows liquid-like behavior), this assumption leads to a restoring force that causes it to hover at a constant height that is stable against perturbations.

1. Introduction

Ball lightning has been observed by thousands of eyewitnesses [1, 2]. One reason that many observers can recall details of the phenomenon long afterward is that the behavior of ball lightning—in particular, the way it moves—is unlike anything else in most peoples' experience. Many ball lightning objects move horizontally as well as vertically, at speeds ranging from a few meters per second down to zero. Any theory that gives a full account of ball lightning must explain the peculiar ability of such objects to float in the air and move slowly a few meters above the ground.

Ball lightning theories fall into two grand classes: external-energy theories and internal-energy theories. Most external-energy theories such as that proposed by Kapitsa [3], followed later by Handel [4] and Lowke [5], claim that the visible manifestation of ball lightning depends on the configuration of electromagnetic fields. Observational evidence for the existence of such fields is tenuous at best, and so external-energy theories will not be considered further in this paper.

Internal-energy theories generally assert that the visible light radiation from ball lightning comes from energy stored in the ball by chemical, electrical, or other means. Turner [6] and Abrahamson and Dinniss [7] propose that this energy is provided by nitrogen compounds or oxidizing silicon nanoparticles, respectively, and cite various reaction-slowing mechanisms in order to account for the relatively long lifetime of some ball lightning objects, which can last a minute or more. They attribute the motion of ball lightning to a combination of forces, including possibly an electrostatic force due to a net charge on the object. As we have shown elsewhere [8], there are charge limits beyond which a net electrostatic charge on an object such as ball lightning will attract it promptly to the nearest grounded surface. This is in contrast to what many ball-lightning objects are observed to do: to hover or drift slowly at a distance of a meter or two above the ground for a substantial fraction of the total observed lifetime. This behavior is especially characteristic of the reports of ten professionally trained observers who witnessed independent ball lightning events as recorded in Stenhoff [2, pp. 168-174].

The observational evidence concerning ball-lightning motion favors internal-energy theories which are consistent with an average mass density for ball lightning that is close to the density of the ambient atmosphere. This is because ball lightning is not always observed to make the rapid, violent, and unidirectional motions that would probably occur if its density were much greater or less than about 1.2 kg m^{-3}, which is typical of atmospheric air at sea level.

2. Assumption of Constant-Density Liquid

In the remainder of this paper, we will develop the consequences for ball-lightning motion that arise naturally from making two assumptions: (1) that ball lightning of the type to be described has a density equal to that of air at a particular reference height $z = z_0$, and (2) the object's mass density remains approximately constant during its lifetime, independent of the object's altitude z. These assumptions amount to proposing that at least one type of ball lightning behaves like a liquid with the density of air, in that its compressibility is much less than that of a normal gas.

Currently, justification for such an assumption is lacking, but a number of possible physical processes might bring about such a condition. For matter having such a low mass density to exhibit incompressibility comparable to that of a liquid, its constituent particles must form a structure more ordered than that of the randomly colliding molecules of a gas, so that long-range forces (possibly electrostatic) between particles or groups of particles dominate over the collision-force regime that prevails in gases or ordinary plasmas.

Charged nanoparticles (larger than air molecules) may be involved in the formation of ball lightning. Some experimental evidence that such particles can form ordered structures was reported in 2004 by Arp, Block, and Piel [9], who formed a "Coulomb ball" of 3.4-μm melamine-plastic particles in a low-pressure RF discharge in argon. Despite the fact that the average spacing between charged particles was about 0.7 mm, which is 200 times the particle diameter, the particles spontaneously formed an orderly spherical structure with identifiable shells. Larger systems of particles exhibited a "melting" phase transition to a liquid-like state. This experiment shows that it is possible for charged particles separated by many times their own diameter to form structures with solid- or liquid-like order and behavior.

In this paper, our purpose is not to develop a detailed theory of how ball lightning could form a liquid having the density of air, but to show the consequences of such a property. Remarkably, these consequences include motions that strongly resemble those reported by many ball lightning observers, as we will show.

3. Fluid Dynamics of a Constant-Density Sphere in Air

Consider a sphere of radius r_0 (m) whose mass density ρ_0 (kg m^{-3}) equals that of air at a reference altitude z_0 (m), measured from sea level. Both the pressure and density of air vary with altitude z. The exponential variation of air density with altitude can be approximated within 1% over a range of about 87 m from z_0 by the following linear expression:

$$\rho(z) \simeq \rho_0(z_0)\left[1 - \frac{gM}{RT}(z - z_0)\right] \tag{1}$$

where g = acceleration of gravity (9.807 m s^{-2} at sea level), M = molar mass of air (28.79 kg/kmol), R = gas constant (8514 J kmol^{-1} K^{-1}), and T = temperature (K). In this analysis, we assume that the reference altitude is sea level and the ambient temperature is 300 K, although the results will change very little for other realistic ground-level altitudes and temperatures.

Suppose that the mass m_S of material inside the sphere is the same as that of an equal volume of air at the reference altitude z_0. At that altitude, the sphere will have neutral buoyancy. That is, its mass exactly equals the mass of the volume of air which it displaces, and it will experience no net upward or downward force due to buoyancy or gravitational effects.

Next, assume that an unspecified external force moves the sphere as a unit to a higher altitude above z_0. Because it is assumed to be incompressible, the sphere's volume will not change in response to the lower air pressure at the higher altitude. According to Equation (1), the sphere will now be surrounded by air which is less dense than the sphere's average density, which remains at ρ_0 under the assumption that the material inside the sphere behaves like an incompressible liquid. The sphere now has a negative buoyancy; that is, it is now heavier than an equal volume of the air around it. It will therefore tend to fall until it reaches the reference altitude z_0. Conversely, if the sphere is moved downward to a lower altitude than z_0, it will experience positive buoyancy that will make it rise to z_0. If one assumes a constant volume for the sphere whose mass density is that of air at the reference altitude, one therefore obtains a restoring force F_R whose sign depends on whether the sphere is above or below the reference altitude, and whose magnitude is linearly related to displacement from that altitude, at least for displacements less than 87 m.

A sphere of fluid which moves in a fluid medium experiences a drag force F_D which is a generalization of the drag force experienced by solid objects moving in a fluid. Saboni and Alexandrovna [10] have shown that the drag force is a function of the dimensionless Reynolds number *Rey* and the dimensionless ratio κ of absolute (dynamic, not kinematic) viscosities of the two media. Let μ_S be the dynamic viscosity (kg m^{-1} s^{-1}) of the fluid in the sphere and μ_M be that of the medium. Then if $\kappa = \mu_S / \mu_M$, Saboni and Alexandrovna show that the following analytical expression for the drag coefficient C_D approximates their numerically derived value for Reynolds numbers between 1 and 400:

$$C_D(Rey,\kappa) = \frac{\left[\kappa\left(\frac{24}{Rey} + \frac{14.9}{Rey^{0.78}}\right)\right] Rey^2 + 40\frac{3\kappa + 2}{Rey} + 15\kappa + 10}{(1+\kappa)(5+Rey^2)} \qquad (2)$$

The Reynolds number for a sphere moving at a velocity v relative to a fluid medium is

$$Rey = \frac{2r_0\rho_M}{\mu_M}|v| \qquad (3)$$

where the fluid medium has density ρ_M and dynamic viscosity μ_M.

The viscosity of the assumed fluid inside ball lightning is not known, but two limiting cases can be identified. Solid objects have an effective viscosity approaching infinity, so setting κ to a large value (e. g. 1000) in Equation (2) will have the same effect as substituting a "solid" sphere for the liquid sphere, as far as viscosity effects are concerned. Because the boundary condition at the surface of a solid is that the fluid medium's velocity relative to the solid is zero, the assumption of a solid sphere produces maximum drag. At the other extreme, we can assume the viscosity of the sphere to be zero ($\kappa = 0$). Even a sphere consisting of zero-viscosity fluid encounters some drag, although the drag force is smaller than that encountered by a solid object. Gaiˇdukov [11] has shown that assuming a viscosity of zero for ball lightning leads directly to fluid-dynamic behavior that can explain such actions as passing through narrow cracks in walls or windows, which have been repeatedly noted in ball-lightning reports. In modeling ball-lightning motion, if we examine the results from values for κ between 0 and 1000, we can be reasonably certain that we have bracketed the effective viscosity of the actual object, which must lie somewhere between these extremes.

Assuming for this analysis that the only forces on the sphere are the buoyancy-gravitational restoring force F_R described above and the drag force F_D, the overall one-dimensional equation of motion for the sphere in a viscous medium is

$$F_R(z) + F_D(z') = m_S z'' \quad (4)$$

where the primes denote differentiation with respect to time, and $m_S = (4\pi r_0^3 \rho_0)/3$ is the sphere's (constant) mass. Using Equation (1), we can show that the restoring force is

$$F_R(z) = -(z - z_0)\frac{g^2 m_s M}{RT} \quad (5)$$

and the drag force is

$$F_D(z') = -z'|z'|\frac{\pi r_0^2 \rho_0}{2} C_D(Rey, \kappa) \quad (6)$$

Note that the multiplication of velocity $v = z'$ by its absolute value in Equation (6) ensures that the sign of the drag force always opposes the direction of motion, and also means that the drag force is nonlinear for all but the lowest velocities (below 1 mm s^{-1}) [12].

4. Numerical Results

We solved the second-order differential equation (4) numerically using a fixed-point Runge-Kutta algorithm [13]. For initial conditions, we chose to begin the integration with the sphere's velocity $z' = 0$ and displacements z-z_0 beginning at 0.5 or 50 meters above the equilibrium altitude z_0. We assumed a radius for the sphere of $r_0 = 15$ cm, which is near the median reported radius for many ball-lightning reports. Because of the nonlinearity of the drag force, the results from a large displacement z-z_0 of 50 m differ materially from the results from a small displacement of 0.5 m.

Fig. 1 shows the theoretical results of our numerical solution for a small initial displacement of 0.5 m above the equilibrium altitude. At $t = 0$, the object accelerates due to the net downward force F_R only. By the time it passes the equilibrium point ($z = z_0$) , its accumulated momentum carries it past that point to a displacement of -0.38 m (for the zero-viscosity sphere) or -0.18 m (for the "solid" sphere). After that, the object executes a damped oscillation similar to a classical mass-and-spring system, except that the damping force in this case is nonlinear.

For a larger initial displacement of 50 m, the results are different. The greater initial velocity of the sphere leads to disproportionally greater damping force, with the result shown in Fig. 2. Although the zero-viscosity sphere still exhibits oscillatory behavior with a period of about 150 s, the high-viscosity (solid-like) sphere's greater drag produces a quasi-exponential motion that asymptotically approaches the equilibrium point without oscillation.

This simplified model neglects other forces such as independent electrostatic fields (e. g. from thunderclouds), polarization-induced attraction, wind currents, and non-isotropic exchange of air with the environment. Nevertheless, this model provides a simple and easily calculated mechanism that directly

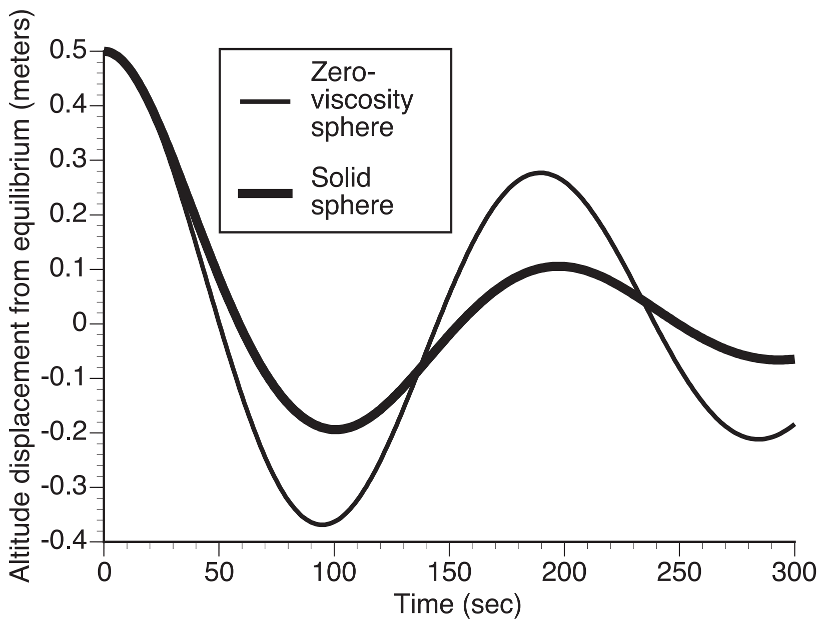

Fig. 1. Theoretical altitude displacement from equilibrium altitude z_0 versus time for a sphere with radius $r_0 = 0.15$ m initially displaced 0.5 m from equilibrium, with viscosity ratios $\kappa = 0$ (zero-viscosity sphere) and 1000 (solid sphere) as parameter.

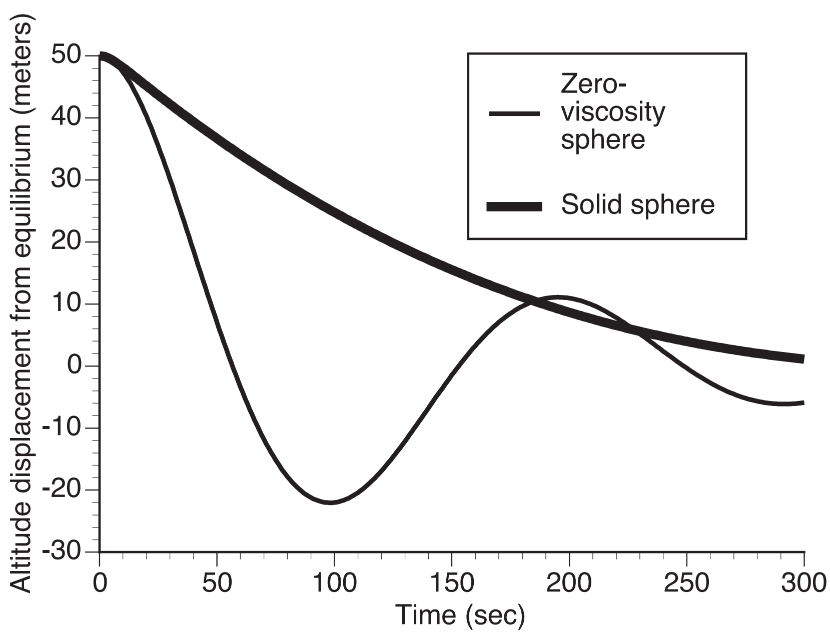

Fig. 2. Theoretical altitude displacement from equilibrium altitude z_0 versus time for a sphere with radius $r_0 = 0.15$ m initially displaced 50 m from equilibrium, with viscosity ratios $\kappa = 0$ (zero-viscosity sphere) and 1000 (solid sphere) as parameter.

produces a restoring force to maintain the altitude of a ball lightning object at a constant level, in conformance with many observations.

Conclusions

We have shown how assuming a constant density for the volume of material inside a ball lightning structure whose mass density approximates that of air, naturally leads to a restoring force that tends to maintain the object at a constant height despite other transient forces such as wind currents. Such behavior is in agreement with many eyewitness observations of certain types of ball lightning which describe the object as moving horizontally a meter or two above the ground or hovering stationary in space. Since laboratory experiments involving dusty plasmas have exhibited quasi-liquid-like behavior to a limited extent, future theoretical studies of ball lightning should consider structures that would exhibit an approximately constant average mass density close to that of ambient air, and would maintain this density despite pressure variations in the manner of a liquid.

Acknowledgments

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