Orbital Motion of Electrically Charged Spheres in Microgravity

Shubho Banerjee, Kevin Andring, Desmond Campbell, John Janeski, Daniel Keedy, Sean Quinn, and Brent Hoffmeister, Rhodes College, Memphis, TN

The similar mathematical forms of Coulomb's law and Newton's law of gravitation suggest that two uniformly charged spheres should be able to orbit each other just as two uniform spheres of mass are known to do. In this paper we describe an experiment that we performed to demonstrate such an orbit. This is the first published account of a successful orbit using electrostatic forces.

The goal of the experiment was to orbit a graphite-coated Styrofoam® sphere (radius = 1.6 cm, mass = 1.4 g) around a fixed aluminum sphere (radius = 6.5 cm) with an orbital radius somewhere in the range of 10-30 cm. The spheres were oppositely charged with a bipolar high-voltage power supply capable of 30 kV. To achieve such an orbit, we needed to minimize the effects of Earth's gravity on the orbital motion of the sphere because even for a Styrofoam® sphere, Earth's force of gravity on the orbiting sphere greatly exceeds the electrostatic force in our experiment.

Our experiment was performed aboard a specialized NASA aircraft dubbed “The Weightless Wonder,” which simulates conditions of weightlessness. The aircraft does this by flying in a special parabolic trajectory so that the plane (and everything in the plane) is in free fall. In a typical flight, the aircraft flies 30 parabolas that each produce weightless conditions lasting approximately 20 seconds. Our experiment was performed during two flights that took place on Aug. 17 and 18, 2006.

Microgravity

The aircraft used by NASA for microgravity missions is a modified McDonnell Douglas C-9B. The aircraft and NASA’s reduced gravity flight program are based at Ellington Air Force Base near Houston, TX. We were awarded flight time aboard the aircraft through a NASA program for undergraduate students called Microgravity University. The program is very similar to a program for high school students that was described in a recent article in *The Physics Teacher.* Microgravity conditions are produced by flying the aircraft in a parabolic trajectory. Interestingly, the parabolas are hand flown by the pilots and not by an automated flight system. Each flight consists of 28 (nearly) zero-g parabolas, a 1/3-g parabola to simulate Mars gravity, and a 1/6-g parabola to simulate lunar gravity. The
symbol \( g \) refers to the gravitational acceleration near Earth’s surface: 9.8 m/s\(^2\).

**Experimental Apparatus**

Figure 1 shows photographs of the experimental apparatus as used in flight. The apparatus was designed to orbit a charged graphite-coated Styrofoam® sphere in a vertical (relative to the floor of the aircraft) plane about an oppositely charged fixed aluminum sphere. The other main elements of the apparatus included a high-voltage power supply, launching mechanism for the orbiting sphere, and video cameras. These were mounted to a 2-x-5-x-5-ft wooden frame that was bolted to the floor of the aircraft. Foam pipe insulation was wrapped around the frame members for safety padding, and plastic mesh was wrapped around the bottom of the frame to help contain the orbiting sphere when microgravity periods ended.

The high-voltage power supply (CPS Model 2596) was a bipolar supply capable of providing up to \( \pm 30 \) kV to two electrodes, current limited to 200 \( \mu \)A. The power supply can be seen in Fig. 1(c). The high-voltage power supply was connected to the fixed aluminum sphere and the launching mechanism for the orbiting sphere by RG-8 coaxial cables. Specifically, the central conductors of the coaxial cables were connected to the sphere and the launching mechanism, and the outer ground braid was stripped back approximately 10 cm from the end of the cable.

The fixed aluminum sphere was fabricated from a 6.5-cm radius hollow aluminum sphere purchased from an ornamental metal company (King Architectural Metals). The surface was machined smooth and hand polished, and two holes were drilled across the diameter of the sphere to accommodate a rectangular cross section polyethylene rod that rigidly connected the sphere to the wooden frame. The orbiting sphere was a 1.6-cm radius graphite-coated Styrofoam® sphere purchased from a science education company (Boreal Laboratories).

The launching mechanism for the orbiting sphere consisted of a Teflon® cup on a polyethylene platform attached to drawer slides that allowed the cup to be easily positioned at varying distances from the fixed aluminum sphere. The Teflon® cup held the orbiting sphere, and a hollow polyethylene rod passing through a hole in the bottom of the cup was used to eject the sphere. One of the high-voltage cables was threaded through the hollow rod, and a polished aluminum electrode was connected to the end to make electrical contact with the orbiting sphere when it was ejected from the cup. The launching mechanism was manually operated by pushing up on the ejection rod by hand. The ejection rod and electrode are seen protruding from the launching cup in Fig. 1(b). To prevent the orbiting sphere from accidentally drifting out of the cup before launch, two small strips of black vinyl tape were attached to the cup extending slightly over the opening. The launch mechanism was oriented so that the orbiting sphere would be launched upward relative to the floor of the aircraft in a direction perpendicular to the radial line joining the fixed and orbiting spheres.

Video data of the orbits were acquired using three digital camcorders (Canon model ZR500). Two of the video cameras were mounted to the upper corners of the frame as seen in Fig. 1(a). The third video camera (not shown) was mounted to a pole across the cabin from the apparatus. An accelerometer was mounted to the frame of the apparatus near the high-voltage power supply to record accelerations experienced during the flight.

**Experimental Procedure**

The voltage on the fixed aluminum sphere was adjusted to the maximum voltage that could be achieved without sparking or corona discharge. This voltage ranged from 20-25 kV. The orbiting sphere was charged to a predetermined voltage from 15-27 kV, beyond which corona discharge would occur. The sliding launch mechanism was moved to position the orbiting sphere at some predetermined center-to-center distance ranging from 14-20 cm from the fixed sphere. Distances less than approximately 14 cm resulted in sparking between the launch mechanism and the orbiting sphere.

The orbiting sphere was launched by gently pushing the ball up out of the launcher cup with the charging electrode. The launch mechanism was then quickly retracted on the slides, and the voltage to the launch electrode was turned off. All three video cameras continuously recorded the resulting orbits. The launch electrode voltage and the launcher position were adjusted to achieve as many successful orbits as possible.
possible. If a particular launch resulted in an open orbit (an “overshoot”), then the launch electrode voltage was increased, or the launcher was positioned closer to the fixed aluminum sphere. Adjustments were made in an opposite fashion if the orbiting sphere collided with the aluminum sphere (an “undershoot”).

Technical Challenges

One of the challenges of performing a high-voltage experiment is to avoid electrical discharge by dielectric breakdown of air. Interestingly, this problem is exacerbated in an aircraft flying at altitude. From Paschen’s law, it is known that the dielectric breakdown voltage of air decreases with decreasing air pressure down to approximately $10^{-3}$ atmospheres. This occurs because the mean free path between collisions of ions with air molecules increases, allowing the ions to gain more energy between collisions and enhancing ionization. The NASA aircraft is pressurized to an equivalent altitude of 8000 feet or approximately 0.74 atmospheres. Compared to ground-based testing, we noticed about a 10-20% reduction in the dielectric breakdown voltage of air in the pressurized aircraft.

Another challenge involved the rotation of the aircraft itself during a parabola. During a microgravity parabola the aircraft starts at an approximately 45° nose-up attitude and then rotates to a 45° nose-down attitude at the end of the parabola. This means that free-floating objects in the aircraft appear to rotate by approximately 90°. For this reason we designed our apparatus to produce orbits that were coplanar with the parabolic trajectory of the aircraft during microgravity. In other words, we oriented the orbital plane vertically relative to the floor of the aircraft, with the normal of the orbital plane oriented perpendicular to the long axis of the aircraft fuselage. This prevented our orbital plane from tilting (actually appearing to tilt) relative to the rest of the apparatus.

A key aspect of the success of the experiment involved finding a way to electrically isolate the fixed sphere. Initially we tried mounting the sphere to the frame using a PVC pipe that passed snugly through holes drilled in the center of the sphere. Although PVC is a good insulator, it did not provide sufficient electrical isolation for the voltages we were using. Charge leaked off of the sphere faster than our high-voltage power supply could provide it. We found that we could significantly improve the electrical isolation by reducing the contact area with the sphere and the rod with the frame by replacing the PVC pipe with a rectangular polyethylene rod.

Another challenge involved the stability of orbits in an attractive central force field. Central force fields are fields that depend on the radial position of an object. If the central force $F(r)$ has the form of a power law, $F(r) = c r^n$, a circular orbit is stable if $n < 3$. For $n > 3$, orbits are not stable, meaning that only perfectly possible.

<table>
<thead>
<tr>
<th>Successful orbit number</th>
<th>Fixed sphere voltage (kV)</th>
<th>Launch electrode voltage (kV)</th>
<th>Launch distance (cm)</th>
<th>Exponent values for $c/r^n$ fit</th>
<th>Orbital revolution (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.5</td>
<td>17.8</td>
<td>16</td>
<td>2.6</td>
<td>270</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
<td>18.8</td>
<td>14</td>
<td>3.6</td>
<td>315</td>
</tr>
<tr>
<td>3</td>
<td>21.0</td>
<td>22.0</td>
<td>16</td>
<td>1.9</td>
<td>450</td>
</tr>
<tr>
<td>4</td>
<td>21.0</td>
<td>20.0</td>
<td>17</td>
<td>1.9</td>
<td>360</td>
</tr>
<tr>
<td>5</td>
<td>21.0</td>
<td>22.0</td>
<td>16</td>
<td>1.9</td>
<td>360</td>
</tr>
<tr>
<td>6</td>
<td>25.0</td>
<td>22.0</td>
<td>18</td>
<td>1.4</td>
<td>360</td>
</tr>
</tbody>
</table>

Table I. Experimental parameters that yielded the six best orbits. The resulting orbital revolution and the measured value of $n$ from a $c/r^n$ fit to the data are also shown. Note that $n$ is not always close to two as one would expect from Coulomb’s Law.
circular (unstable) orbits are possible. In practice, this means that it is impossible to achieve such an orbit. Our goal was to create stable orbits; therefore, it was important that the force law exponent $n$ be less than 3. This was generally the case as can be seen in Table I.

Data Analysis

Video data were transferred to a computer and converted to “.avi” (Audio Video Interleaved) type files. Orbits that achieved more than three-quarters of a complete revolution were analyzed. Analysis was performed in VideoPoint® by measuring the orbiting sphere’s position as a function of time, as shown in Fig. 2. Acceleration as a function of radial distance $a(r)$ was then determined, and from this the force $F(r)$ acting on the orbiting sphere was plotted in Microsoft Excel®. An example of one such graph is shown in Fig. 3. An inverse power-law fit of the form $c/r^n$ was performed on the data to obtain the exponent $n$ for comparison to the expected value of $n = 2$ from Coulomb’s law.

Results

A total of 43 launches were performed. Seven of those achieved three-quarters of a revolution or greater, and six yielded video data that could be analyzed. These are listed in Table I, which provides the voltages and launch distances that produced successful orbits, the total orbital revolution in degrees, and the resulting measured values of $n$. The list is presented in (chronological) order in which these orbits were experimentally achieved. Video footage of these orbits is available online.3

Why Not $1/r^2$ Behavior?

As seen in Table I, our measured values of $n$ sometimes yield a value that is quite different from the expected value of 2 from the inverse-square nature of Coulomb’s law. We believe this is due to two main factors: 1) electric polarization of the spheres, and 2) fluctuations in microgravity.

Polarization of the conducting spheres occurs when the electrical interaction between them causes the charges to redistribute on each sphere. Polarization effects lower the overall electrostatic energy of the system and hence produce an additional attractive force. The force between two spheres of arbitrary charge and radii was calculated by Maxwell using zonal harmonics.4 Slisko et al. demonstrated that the force could be understood through a method of images approach.5 The method of images approach is very similar to the way two shiny spheres create images of each other in themselves, which in turn creates more images, creating an infinite number of images. The net force is found by summing up all the interactions between the charges on one sphere (real and all the images) with the charges on the other sphere.

Fluctuations in microgravity also cause the force...
to deviate from perfect Coulombic behavior. Our aluminum sphere was fixed to the frame of the aircraft whereas the orbiting sphere was “freely” floating. Any acceleration of the aircraft away from zero-g causes a pseudoforce on the orbiting sphere. These deviations are typically less than 0.5 m/s² (see Fig. 4), and they tend to oscillate as the pilots make fine adjustments to the trajectory of the aircraft during the parabola. As shown in Fig. 3, the electrostatic force can be as little as 1 mN for large radial separations. The corresponding acceleration of the orbiting sphere (force divided by orbiting sphere mass) is 0.7 m/s². Thus, fluctuations in microgravity can produce pseudoforces that significantly affect the measured 1/rⁿ behavior at large radial separations.

**Summary**

This is the first published report of an orbit created purely by an electrostatic force. Although such an orbit is predicted by Coulomb’s law, we find that the force law can deviate significantly from the expected 1/r² behavior due to electrical polarization effects between the charged conducting spheres and fluctuations in microgravity.

**Acknowledgments**

The authors would like to express their appreciation to NASA’s Reduced Gravity Student Flight Opportunities Program for the opportunity to perform this experiment. In addition, we thank Eva Owens for her administrative support, Glen Davis for his technical support, and Ann Viano for her support of our team in Houston. We also would like to thank Spence Wilson, Chair of the Rhodes College Board of Trustees, for his enthusiasm and encouragement. Finally, we thank Rhodes College for financially supporting this exciting adventure.

**References**


PACS codes: 01.55.+b, 45.00.00