Ballooning Spiders: The Case for Electrostatic Flight

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We consider general aspects of the physics underlying the flight of Gossamer spiders, also known as ballooning spiders. We show that existing observations and the physics of spider silk in the presence of the Earth’s static atmospheric electric field indicate a potentially important role for electrostatic forces in the flight of Gossamer spiders. A compelling example is analyzed in detail, motivated by the observed “unaccountable rapidity” in the launching of such spiders from H.M.S. Beagle, recorded by Charles Darwin during his famous voyage.

Observations of the wide aerial dispersal of Gossamer spiders by kiting or ballooning on silken threads have been described since the mid-19th century [1–4]. Remarkably, there are still aspects of this behavior which remain in tension with aerodynamic theories [5, 6] in which the silk develops buoyancy through wind and convective turbulence. Several observed aspects of spider ballooning are difficult to explain in this manner: the fan shaped structures that multi-thread launches employ [3], the capacity to launch at surprisingly high initial (and even non-vertical) acceleration in conditions where air movement is imperceptible [3, 7]; the ability of some relatively heavy adult spiders to initiate ballooning [7]; and the surprising altitudes – up to at least several km – that are achieved by some ballooning groups [9, 10].

It is curious that, given the large magnitude of the Earth’s vertical atmospheric electrostatic field, there appears to be no prior quantitative assessment of the possible action of electrostatic buoyancy to provide a lift component separate from purely aerodynamic effects. This field exists globally in the atmosphere with an average surface magnitude of 120 V m$^{-1}$ pointing downward [11]; the global charges required to sustain it originate in charge separation in clouds and electrically active storms [12].

The role of this electrostatic field in ballooning spider behavior remains unknown, despite several fascinating observations by no less a naturalist than Charles Darwin in his voyage aboard H.M.S. Beagle from 1831-1836. Darwin writes in detail of one particular period in the voyage, 60 miles off the coast of Argentina, where the ship was inundated by ballooning spiders on a relatively calm, clear day [3].

Darwin observed distinct launching behaviors in two separate species, including likely juveniles with sizes in the range of 2-3 mm, and larger spiders of sizes around 7 mm. Of the former, he reported that “I repeatedly observed the same kind of small spider, either when placed or having crawled on some little eminence, elevate its abdomen, send forth a thread, and then sail away horizontally, but with a rapidity which was quite unaccountable.” Of the latter spider, Darwin writes that it, “while standing on the summit of a post, darted forth four or five threads from its spinners. These, glittering in the sunshine, might be compared to diverging rays of light; they were not, however, straight, but in undulations like films of silk blown by the wind. They were more than a yard in length, and diverged in an ascending direction from the orifices. The spider then suddenly let go of its hold on the post, and was quickly borne out of sight. The day was hot and apparently quite calm...”

Darwin conjectured that imperceptible thermal convection of the air might account for the rising of the web, but noted that the divergence of the threads in the latter case was likely to be due to some electrostatic repulsion, a theory supported by observations of Murray published in 1830 [2], but earlier rejected by his contemporary Blackwall [1]. The center of the controversy appears to be whether thermal convection can account for the initial buoyancy of the threads as they are emitted; recent detailed observations [13] have not yet settled the question of how the lines are spontaneously initiated under very calm conditions.

Observations similar to those of Darwin and Murray may be
found in a surprising recent account by Schneider et al. of the multi-thread launching of adult individuals of the relatively large spider *Stegodyphus* [1], with masses of order 100 mg, well above the limit for such behavior based on parameters estimated from aerodynamic theory [14][15]. Schneider et al. note the apparent electrostatic repulsion of the multiple threads, forming as a result a triangular fan shape, with “tens to hundred of threads.” Scheider et al. also observed rapid vertical acceleration of the spiders in calm conditions, up to altitudes of 30 m, where they could no longer be visually tracked.

We study here the hypothesis that such spiders are able to emit threads that are either pre-loaded with a static electric charge, or rapidly gain it during or just after the strand-spinning and thread-weaving process. In either case, the presence of this charge will lead both to mutual repulsion among the emitted threads, and an additional overall induced electrostatic force on the spider, providing a component of lift that is independent of convection or aerodynamic effects.

The complex protein structure of spider silk includes a high percentage, 7-9% each of the charge-bearing amino acids glutamic acid and arginine [16], which may be generated in a charged state as part of the spinning process, or may be utilized to facilitate attachment of charge drawn up from the local launching surface as the strands are spun from the sharp nozzles of the spinneret. A generic example (from *Gasteracantha cancriformis*) showing typical nozzle geometry – with tip diameters of order 10 microns – is shown in Fig. [1].

The average negative surface charge density of the earth is about 6 nC m$^{-2}$, and may be much higher on the prominences which ballooning spiders choose to launch from. Local surface charge may thus provide a source for the thread charge. However, this may not be the only source; a triboelectric mechanism that may be important in charging of the strands during the initial strand emission and thread weaving at the spinneret is the process known as flow electrification [17][18], in which the silk protein could undergo frictional charging as it passes through the spinneret nozzle.

A lower limit on the initial charge state of the silk arises if we assume Murray was correct in his hypothesis that the silk in multi-thread observations carried enough charge to spread and buoy the threads away from each other through electrostatic repulsion. We assume that the negative charge in each thread is concentrated at the end of the silk, and that the silk mass is negligible, so that simple electrostatic equilibrium in the atmospheric electric field obtains. The upward-directed fan structure then forms as a result of the force balance of the mutual thread repulsion opposing the electrostatic buoyancy which tries to straighten the threads to a common direction.

Using this simple model, a 5-thread solution for 1 m length threads fanning to about 1 radian gives $Q_{\text{min}} \simeq 1$ nC total, or 200 pC per thread [23]. As spider silk is known to have high resistivity, this estimate is conservative; a more complete model would use a distributed charge along the threads. This quantity of charge appears well within the range of triboelectric mechanisms; for example, observations of triboelectrification of housesflies shows that they quickly charge up to levels of order 50 pC within a short time by merely walking across a synthetic dielectric surface [22], and honeybees are well known to achieve charges of 45 pC from movement on beeswax [20].

![Figure 2: Total charge (over all threads) required to reach the equilibrium float altitudes indicated for spiders of various masses shown in the labeled curves.](image)

Unaided electrostatic flight will evidently require a much higher charge. To assess the charge state required for this, we use an approximate analytic model for the atmospheric electric field, with an exponential fit to measured values at several altitudes [8]: a good approximation is given by

$$E(h) = E_0 e^{-\alpha h} \text{ V m}^{-1}$$

with $\alpha = 3.0 \times 10^{-4}$ m$^{-1}$ and $E_0 = -120$ V/m; the integrated potential difference to an altitude of 50-60 km is about 350KV. Ballooning spiders have been observed up to altitudes of order 4000 m [9]; an estimate of the total charge $Q$ of the thread can be obtained by assuming that the float altitude represented the equilibrium height $H_{eq}$ at which the weight of the spider was balanced by the Coulomb lift force, that is $Q E(H_{eq}) = mg$ where $m$ is the spider mass, and $g = 9.81$ m s$^{-2}$ is the surface gravitational acceleration of the Earth.

We assume here that only a single thread is involved; this appears to be the most common launch configuration. Combining these equations,

$$Q = \frac{mg}{E_0} e^{\alpha H_{eq}}.$$  \hspace{1cm} (2)

For spiders of mass in the range of 0.1-0.3 mg, typical of ballooners [24], the resulting $Q \simeq 10 - 30$nC (here we neglect the
mass of the silk lines, which amount to about 3 \( \mu g/m \).

Fig. 2 shows a family of solutions for various masses as a function of \( H_{eq} \). These values are a factor of 50 or more above the minimum per thread required for developing the multi-thread fan. They provide an upper limit for the charge rate at launch; since it is likely that both electrostatic and convective buoyancy will combine to create the lift needed for flight, the initial charge state will be lower in proportion to the aerodynamic contribution.

Given the much higher charge states required for electrostatic flight as compared to buoyancy for a thread fan, the question of the source of the charge becomes more acute. The charge may be intrinsic to the silk as it emerges from the spinneret, through its complex protein chemistry and perhaps aided by the spinning process itself.

Electrification of various fluids and polymers through capillary flow has been extensively studied, but the details of the mechanism and its application to a complex material such as spider silk, where internal pressure and external tension both play a role in extruding the silk from the spinneret, has not yet been quantified. Recent measurements of de-ionized water flow through capillaries of several tens of microns diameter \cite{19} give net streaming currents of several femtoamperes per Pascal of nozzle pressure. Simple scaling of these data for somewhat smaller diameter of typical spinneret nozzles, and an estimated extrusion pressure of order 10 kPa, the implied lower limit of the streaming current is of order 1 pA/strand for the same deionized water parameters. Since the charged boundary layer in flow electrification depends on the Debye length in the extruding silk, which is a function of the dielectric constant \( \varepsilon_r \approx 10 \) and conductivity \( \sigma \approx 4\mu S/m \) \cite{21}, we can further scale these results for the electrical properties of silk. Our scaling results indicate a possible streaming charge rate of order 3 nA per strand. Since a complete silk thread may consist of 30 strands or more, and the thread may be spun out for several seconds at least, a total charge per thread of tens of nC appears possible by this process.

This is however not the only plausible charging mechanism; charge may also be drawn up from the local surface charge in the vicinity of the spider. When launching, spiders appear to strongly prefer prominences above ground level; this behavior would be beneficial for both aerodynamic or electrostatic accelerations. In the latter case, local charge distributions become concentrated at convex prominences in the surface topography, and the electrostatic field will also become enhanced at such locations.

Assuming there was an adequate reservoir of surface charge available at a spider’s launch site, we must determine whether there is sufficient time for the current flow necessary to charge by this mechanism, given that the observed launch preparation requires typically no more than several seconds. While still highly resistive, spider silk threads have a conductivity six orders of magnitude higher than synthetic fibers such as nylon. The threads also behave as a normal ohmic material except at very low potentials\cite{21}. Based on these measurements, a +250V potential across a meter of silk (a factor of two above typical ambient vertical potentials) would provide enough current to charge at a rate of 10 nC/second, consistent with observed timescales for ballooning spider launches.

Regarding the initial acceleration experienced by the spiders, and assuming a constant magnitude of acceleration, we may conclude that for both the Darwin and Schneider et al. observations, initial net accelerations in the range of \( a_{net} \geq 3 \text{ m s}^{-2} \) are required. The implied charge is given by

\[
Q_{\text{accel}} = m(a_{net} + g) / E_0 \approx 100 \text{nC} \left( \frac{m}{1 \text{ mg}} \right),
\]

This result is of the same order as the values required for equilibrium float altitudes of order 100 m or so.

The quantities of charge estimated here, in the tens of nC for even small spiders, are significant, and the question arises, is there enough capacitance in spider silk to support charges at this level? For example, such charge values would imply voltages of 1 kV per nC per pF: 100 nC stored on a conductive wire could lead to a 100 kV relative potential just due to the stored charge. In this case, the measured dielectric properties of spider silk are quite important. Combining these with the cylindrical thread geometry we estimate a capacitance of order 30 pF per meter. For such values, the implied surface potential, even for 100 nC per thread, is no more than several kV, far less than (for example) \( \sim 10 \text{ kV} \) potentials that are typical of dry-air charging of macroscopic objects through contact in motion.

One puzzling question remains, however: the statement that the initial acceleration of the spiders as they left the Beagle was horizontal as described by Darwin. This seems in sharp tension with the vertical acceleration expected from the atmospheric potential gradient. To understand this observation, we used a three-dimensional electrostatic solver to determine the atmospheric electric field distortion in the vicinity of a computer-generated model of Darwin’s ship. The ship is assumed to be at an equipotential with the surface of the ocean. This is appropriate for the following reasons: (a) the Beagle carried William Snow Harris’ lightning protection apparatus \cite{25}, including conductors along the mainmast, and these were grounded to seawater; (b) while oven-dried wood can have very low conductivity, the wood in a ship at sea will contain a significant amount of moist salt, and under these conditions, conductivity is many orders of magnitude higher. We estimate that a typical conductivity for the wood surfaces would be in the range of \( 10^{-4} - 10^{-3} \text{ S m}^{-1} \). Thus while the ship’s surface would not be a good conductor for dynamic currents, under electrostatic conditions we can expect it to be at equilibrium.

With these assumptions, the results of the field solver \cite{27} are shown in Fig. 3. We find two important details: the field develops a significant horizontal component near the ships rail over most of its length, and the field strengths close to the rail are factors of 2-4 higher than the ambient field, reaching several hundred V/m within a half-meter or so of the ship’s surface. Given these results, it appears that the near-horizontal launches observed by Darwin are consistent with expectations.
if the charge state of the silk is relatively high at the time of initial spinning or shortly afterward. Such launches are very difficult to explain by thermal convection given the calm conditions noted by Darwin.

Regardless of whether the mechanism for the charging of the silk is intrinsic or extrinsic, this remarkable behavior – if it can be confirmed from direct observations of the silk charge state – will place the Gossamer spider’s electrification ability among the most striking evolutionary adaptations that Darwin encountered on his voyage. This analysis also highlights Darwin’s skill and care as an observer: his style of disinterested observation, accompanied by his detailed notes and narrative, stand nearly two centuries later as rich examples for all exploration and research.

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FIG. 3: Left: overview of three-dimensional electrostatic field simulation for a computer model of HMS Beagle. Vector color is scaled by dB(V/m), and values are set at an absolute scale similar to the undisturbed Earth’s field of 120 V/m. Right: a zoomed view showing a slice of the electric field vectors in the after-deck region, indicating the large horizontal component that develops in the vicinity of the ship’s rail. Field strengths are also a factor of 2-3 higher near the rail than in the ambient field.