Moonlight Flyers

Some squirrels do more than passively glide.

Story and photographs by Alexander Badyaev

After listening all day to relentless warnings of severe winter weather and poring over equipment manuals to determine the lowest operating temperature for various pieces of photographic gear, I decided to stick with the plan. A few hours and several miles of snowshoeing later, I was hard at work in the diminishing February twilight, setting up lines of strobes and high-speed cameras along gaps in the tree canopy that framed a forest lake at the edge of Montana's Bob Marshall Wilderness. I knew this lakeshore to be a primary movement corridor for a resident female northern flying squirrel (Glaucomys sabrinus), and based on observations from previous nights, I expected my nocturnal subject to launch herself across the lake sometime between 2:20 and 2:50 A.M.

By that time, the temperature was expected to be in the neighborhood of minus thirty degrees Fahrenheit, greatly increasing the chances of camera failure. But it was a risk I was willing to take, since I knew how spectacular that night's acrobatics were likely to be. February marks the start of the northern flying squirrel's mating season in Montana. On a typical night during this period, each female will be escorted through the forest by a squabbling squadron of ardent males. It was those energetic males and their dizzying aerial mating chases that I sought to film.

Until recently, flying squirrels were assumed to be passive gliders, using their expansive patagium—the furry wing membrane that spans from the squirrel's neck to its forelimbs and back to its hind limbs—to simply prolong jumps across canopy gaps, and to lessen impacts upon landing. During passive gliding, travel occurs along a declining linear path. This is what paper airplanes do, trading height for horizontal distance. Although gliding like this is the cheapest form of locomotion, it is also the least stable, because any change in posture, wing symmetry, or weight distribution has the potential to disrupt the glide and result in an uncontrollable fall. Imagine a paper airplane with the sudden addition of a heavy weight on one side, or with one wing that suddenly changes size or shape.

Once we began studying flying squirrels in the lab, it didn't take long to discover that there is nothing passive or constant about the species' flight. We documented a wider variety of aerodynamic modifications and flight types in flying squirrels than had been described in any other species of animal glider. In a single flight episode, a flying squirre

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may use a dozen separate flight-control techniques and—frustrating to graduate students and research assistants documenting the patterns—different squirrels will use different combinations of these techniques. Ironically, the one type of flight that we never observed in this species is passive gliding.

As more and more squirrels flew through wind tunnels and along blocked-off biology department corridors, it became clear that flying squirrels have a marked disregard for basic aerodynamic constraints. For example, squirrels were frequently recorded moving through the air with extraordinarily high "angles of attack," which is the angle between the wing—in this case the patagium—and the direction of oncoming airflow. Aircraft typically stall when their angle of attack reaches fifteen to twenty degrees. Flying squirrels routinely reach sixty degrees, far exceeding values that would result in the stall and crash of even the most advanced military jets. Stalling is caused by a loss of lift. This occurs when the main source of lift, air vortices—the swirls of air that form at the leading edge of a wing as a result of differences in the pressure below and above the wing—essentially slide down the wing surface at high angles. Except, evidently, when the wing belongs to a flying squirrel.

Another lab research finding that challenged the basic aerodynamics of gliding was the flying squirrel's ability to carry heavy objects in flight without compromising height or trajectory. In the lab, squirrels were routinely observed generating lift forces up to six times their body weight, a feat that makes it possible for them to take flight with such things as stolen peanut-butter sandwiches—or, under more natural conditions, enormous pine cones. Indeed, even advanced stages of pregnancy seem to have little impact on a squirrel's flying capabilities.

Laboratory studies also found that the squirrels fly at remarkably high speeds and have a puzzling ability to control their acceleration throughout the flight. The benefits of this are clear: Increased speed enhances maneuverability, which is critical for an animal that flies through an obstacle-strewn forest at night. However, the recorded speeds vastly exceed those that could be generated by a glide itself. Somewhere in the flying squirrel's body resides a mechanism that, without the power of flapping or internal combustion, generates exceptional lift, comparable to that of powered flight.

With each of these discoveries, it became increasingly obvious that flying squirrels are so overbuilt for flight that simple laboratory challenges of gliding from perch to perch, or up and down flights of stairs at the prodding of research assistants, were not enough to reveal their complete flight repertoire. I needed to take my study to the wild, where flight performance is a question of life and death, or at least of mating success. And that is what brought me to this forest in northwestern Montana in the middle of a frigid February night.

On the lakeshore that night, shortly after 2:30 A.M. under a nearly full Moon, I was treated to an unforgettable air show. It started with a cloud of snow dust kicked up by two males chasing each other on the upper branches of a spruce tree high overhead. One of the males lost his grip and dove into a glide over the lake, to be followed immediately by the rapidly accelerating glide of the second male. Both landed and resumed their squabble in the upper canopy on the other side of the lake, seemingly without much loss of elevation despite a glide of at least fifty meters.

Soon after, I spotted the female sitting quietly above me on a snow-covered branch. She was perched up against the tree's trunk in mid-canopy, inspecting a large cone likely left by a red squirrel earlier in the day. A few seconds later, a third male parachuted down from a nearby tree, somehow steering at the end of his near vertical descent to land on the trunk just below the female. A moment later, the female crouched, and in a powerful forty-degree jump, with body fully extended and limbs outstretched, she launched herself high into the air.

For a second or so, her patagium remained completely folded, with her flattened tail held vertically, giving additional lift. When she reached the peak of her jump, with the high-speed strobes illuminating her every move, she spread the patagium wide, completely flattened the silvery fur on her body and tail and seemed to freeze in midair for a couple of moments before gracefully gliding out of view across the snow-covered lake. For several minutes, I could see the occasional puff of snow dust and could hear the muted squabbles drifting over the frozen expanse. Then, just like that, the group disappeared into the darkness and the night's silence was restored.

I spent the next several weeks analyzing frame-by-frame the footage I captured from this performance, deciphering the array of solutions the squirrels employed to solve major aerodynamic problems—some previously unknown, others suggested by laboratory research. Foremost among the latter was the squirrels' extensive deployment of a "wing tip"—a protruding cartilaginous rod outside the wrist—sort of a long sixth finger. This trait was first described twenty years ago by mammalogist Richard Thorington at the Smithsonian Institution, who speculated that the wing tips were used in the same way as the winglets of modern jets. These vertical metal plates added to the ends of wings revolutionized air travel after NASA began installing them in the 1970s. Flying squirrels evolved wing tips about 20 million years earlier and have been perfecting their use ever since.

In both the squirrels and the aircraft, the wing tips deflect and retain large air vortices that form along the leading edge of wings and thus generate substantial lift. But in a crucial difference compared to the aircraft, flying squirrels can independently and dynamically control their wing tips on the left and right, folding and extending them as needed to modify the speed and trajectory of glides in mid-flight. This enables them, for example, to make sharp turns in mid-air to avoid obstacles or evade attacking owls.

Preparing for takeoff

Natural selection has continued to refine flying squirrel aerodynamics. While air vortices tend to form naturally during a glide, flying squirrels take this a step further. They actively generate additional vortices, and increase lift, using an ingenious adaptation that human engineers copied in the design of the world's first supersonic jet in 1969. Unlike most gliding mammals, flying squirrels have an additional fur-covered membrane between their necks and wrists that directs air flow to the main portion of the patagium just behind. This flap can be curved down, guiding airflow and generating significant forward acceleration and lift during take-off, then can be retracted during high-speed chases, or flattened and merged with the main patagium in long-distance glides. In the course of a single flight, the flying squirrel integrates precursors of some of the best inventions of human aircraft engineering over the last century, morphing flawlessly from a canard supersonic airplane design to an agile jet to a blended wing body aircraft.

And then there is the squirrel's ultimate secret weapon: the patagium itself. It appears early in each squirrel's development as a massive outgrowth of skin between hind and forelegs—making a brood of baby flying squirrels in a nesting cavity look remarkably like a stack of pancakes. As the young squirrels grow into their oversized skin, diverse muscle and nerve groups fill the patagium. The result is distributed control of the membrane, with some muscles controlled locally and others by distant nerve centers.

The importance of such distributed control is that the squirrel can adjust the membrane's billowing and stiffness independently across the patagium, and between the left and right sides. Part of the wing can be rigid while the other part is pliable, all in response to nerve signals from local stretch receptors that detect minute changes in airflow. Combined with a wide range of limb movements during flight, such local control allows squirrels to actively modify wing size, shape, and stiffness during an aerial chase—from a thin, fully extended membrane in the middle of long-distance glides to fully inflated, furry parachutes for slowing down at the end of steep descents. Designing a wing that can instantly change in stiffness and configuration in response to minute changes in local air pressure and flow remains a dream for human aircraft engineers.

Muscles in the patagium also control the orientation of specialized hairs at the membrane's edges. For example, unusually long, stiff hairs on the leading edge of the patagium are often held at variable angles during take-off and landing, generating multiple mini-vortices that are then trapped on the wing's surface, providing lift. A band of these hairs along the sides of patagium also generates substantial local turbulence during flight and—together with a pliable wing surface—seems to create a traveling corridor for air vortices along the edge of the gliding membrane.

It's now clear from our field observations that mid-flight changes in lift and acceleration are closely associated with a change in billowing of the gliding membrane and, in particular, with the formation of waves on the patagium surface. Squirrels appear to actively direct trapped air vortices across the membrane surface. The closest analogy from human engineering would be tiltrotors—aircraft, such as the V-22 Osprey, with variably tilted rotors attached to fixed wings that combine the high speed and range of a conventional plane with the lift capacity and take-off versatility of a helicopter. The crucial difference is that flying squirrels can instantly modify the size, number, and location of their "rotors" in response to minute changes in airflow and pressure—an achievement that is well beyond modern aircraft engineering.

Two males, in pursuit of a female, glide over a moonlit lake, with the second male rapidly accelerating to overtake the first.

At the end of a long field season, while waiting in the Great Falls International Airport for my flight back to the University of Arizona, I walked through a display of one of the largest private collections of aircraft models. Most inventions in aerodynamic design are represented—from the delta-wing and wing-body airplanes of the familiar Concorde and B-2 stealth bomber to the lesser-known variable-sweep wing design that converts a fighter jet into a long-range cruiser in mid-flight to bizarre-looking canard airplanes with two pairs of wings.

As I browsed, I tried to imagine what a collection of nature's innovations for animal flight would look like. Nature has had about a billion years longer to experiment with various ways to get animals as diverse as insects, frogs, reptiles, and mammals airborne, so one would think such a collection would be enormous. Surprisingly, this is not the case. Over the course of evolution, a typical animal flier may accumulate dozens of redundant aerodynamic solutions—some nearly perfect, some half-working, but all contributing to getting an animal airborne, while at the same time preserving uninterrupted paths for future adaptations. The end result is a prized combination of functional versatility and exceptional robustness of nature's flying solutions—something we have yet to achieve in human engineering. The flying squirrel is a premier example of this, easily encompassing in one small furry package the content of several of the display cases that were in front of me: the aerodynamic features of heavy transport planes, agile military jets, movable-rotor helicopters, flexible-wing parachute gliders, and many innovations we've yet to achieve.

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