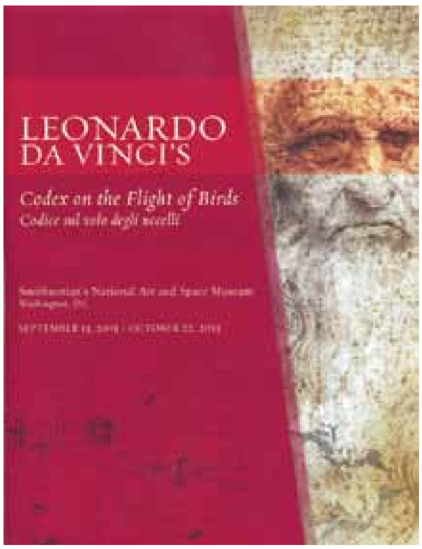
Review

The Man Who Lived in the Future

by Susan Welsh

Exhibition of "Leonardo da Vinci's Codex on 'the Flight of Birds'"
National Air and Space Museum,
Washington, D.C., Sept. 13 through Oct. 22, 2013.[1]

Everyone knows that Leonardo da Vinci (1452-1519) sketched, studied, and experimented with virtually every subject that could be investigated by man's unaided senses, ranging from wave motion in water to military machines to anatomy to the bicycle. He was particularly fascinated by the flight of birds. NASA Jet Propulsion Lab director Charles Elachi was so excited to be holding the Codex on the Flight of Birds in his hands, that he described it (a bit hyperbolically), as "probably the most important document about flight," in the delightful short video that accompanies the exhibit.



Leonardo's study of bird flight and his search for a mechanism that would allow humans to fly demonstrate perhaps more vividly than anything else, the extent to which the artist-scientist-inventor lived, thought, and dreamed in the future.

What exactly did he do?

Peter L. Jakab, the Chief Curator of the National Air and Space Museum, wrote in the exhibit brochure that in this 18-page notebook, or Codex, Leonardo "discusses the crucial concept of the relationship between the center of gravity and the center of lifting pressure on a bird's wing. He explains the behavior of birds as they ascend against the wind, foreshadowing the modern concept of a stall. He demonstrates a rudimentary understanding of the relationship between a curved wing section and lift. He grasps the concept of air as a fluid, a foundation of the science of aerodynamics. Leonardo makes insightful observations of gliding flight by birds and the way in which they balance themselves with their wings and tail, just as the Wright brothers would do as they evolved their first aeronautical designs. . . ."

The exhibit only displays two pages of the actual Codex, which are of course in the Italian idiom of the 16th Century and written in Leonardo's peculiar right-to-left mirror handwriting. Nothing that Leonardo wrote on this subject was intended to be read by anyone except himself. In fact, his mirror-writing, "back-to-front" pagination, and cryptic formulations (he uses the word "bird" for both the animal and his machine) would have doubtless confused contemporary snoops trying to steal the Master's secrets, just as they confuse the modern reader. At the museum, digitized images of all the pages can be viewed, with an English translation, on monitors that allow you to digitally turn the pages.

But the exhibit could have done so much more. What it does not provide, unfortunately, is adequate pedagogy for the visitor: how to connect Jakab's very brief generalizations to these drawings and jottings, the better to grasp their significance for the history of science in general and the development of flight in particular. I challenge the reader to choose any random page of the Codex and explain its importance (if any).

What does it all mean?

In order to rigorously answer such questions, one

1. As of this writing, it does not seem that the exhibition will be extended in view of the U.S. government shutdown, which closed the museum for two weeks.

would have to be an expert in the history of aerodynamics, which I am not. I therefore rely here on a few specialists' work, to suggest ways that visitors (or those viewing the Codex in a print edition) could think and study more deeply about what they're seeing; I also suggest ways that an exhibition like this could be improved.[2]

An Historical Note

The tiny exhibit at the Smithsonian is in a foyer adjoining the museum's large exhibit on the Wright brothers, which includes the original Wright Flyer, the first successful powered aircraft (1903). Maybe the juxtaposition of the two was supposed to make an obvious point about pioneers in flight, but the point to be made goes beyond the obvious.

In fact, the Wright brothers, by a coincidence of timing, had access to the Codex on the Flight of Birds and other notebooks by Leonardo, as they worked to invent a flying machine. The Codex, written in 1505, was first published in 1893 after having been stolen (by Napoleon), lost, and scattered for a hundred years; the American *Aeronautical Journal* in 1895 ran an article on Leonardo that included some of his drawings; and Octave Chanute's *Progress in Flying Machines* (1894) described some of Leonardo's work. The Wright brothers acquired all this material.[3] Wilbur Wright wrote to the Smithsonian Institution on May 30, 1899, asking for its papers on human flight, and received relevant works of Leonardo, along with those of much more recent flight pioneers. Orville Wright listed these sources in a 1920 deposition in a patent suit, describing Leonardo as "the greatest universal genius the world has ever known." Of course, many important breakthroughs were made after Leonardo's time, and the internal combustion engine, which powered the world's first (non-glider) flying machine nearly 400 years after his death, was unknown to him.

What insight and inspiration the Wrights may have drawn from Leonardo is not documented, to my knowledge, but I should think the museum would have wanted to point out this fascinating connection.

Powers of Observation

One of the first things that strikes one who looks at Leonardo's work on flight is his phenomenal power of observation. An example is Folio 15 verso (**Figure 1**), where he minutely describes the actions of the moving bird. At the top is a simple experimental device for determining the "bird's" center of gravity (in this case he is talking about the flying machine that he hopes to build). Elsewhere he is at pains to note the role of the wing tips in maneuvering and maintaining equilibrium, as well as the action of the tail and the *alula* (also called the "bastard wing" or the "thumb"—*dito grosso*—see **Figure 2**). (The concern with keeping the "bird" from being flipped over by the wind pervades the Codex—obviously a crucial issue for any future pilot of a mechanical "bird.") He observed the separate movement of the feathers of the bird's wing-tips, writing in another location: "What difference is there between the tips of the wings of birds which bend and those which do not ... since one sees that however slightly these tips are cut the bird's power of flight is almost stopped."[4] Elsewhere he described the action of dragonflies' two pairs of wings, whereby the front pair sometimes moves in the opposite direction from the back pair.

It is amazing, given the rapidity of birds' flight and dragonflies' wing movements, that Leonardo could see such details.[5] It makes me wonder whether he possessed something like what neurologists today call *hypervision* or visual *hyperacuity.*

The observations set down in this Codex are but a small part of his vast effort to observe, sketch, and analyze the flight of birds over a span of 25 years. Many of Leonardo's thousands of pages of other notebooks deal

2. The exhibition of Leonardo's "Codex Leicester" at the American Museum of Natural History in New York in 1996 was pedagogically excellent. The curators partnered with the Eli Whitney Museum in Hamden, Conn., to construct fine hands-on exhibits to demonstrate the principles of Leonardo's investigation of water and astronomy. See my review, "Leonardo's Leaps: Metaphor and the Process of Creative Discovery," *EIR*, Nov. 29, 1996. More recently, the Leonardo3 group in Italy (www.Leonardo3.net) has constructed amazing exhibits about Leonardo's art and science which have toured internationally, including to the Franklin Museum in Philadelphia. See Figure 1.

3. Thanks to curator Peter Jakab, who is an expert on the Wright brothers, for this information.

4. Manuscript K, 10 recto, cited by Kenneth D. Keele, *Leonardo da Vinci's Elements of the Science of Man* (New York: Academic Press, 1983), p. 192.

5. This website provides beautiful slow-motion videos of birds in flight, which the reader can compare to Leonardo's sketches. Such material would be useful in an exhibition on Leonardo's Codex, along with other photos and videos in this article.

FIGURE 1

Finding the Bird's Center of Gravity

Folio 15 verso from the Codex on the Flight of Birds *draws the distinction between the bird's center of gravity and the center of lifting pressure on the wing. The simple device at the top could easily be constructed for an exhibit (see photo below). This full translation is from the museum's digitized image (the leaf is irrelevant; Leonardo was re-using an old sheet of paper).*

"This is done to find the bird's center of gravity; without this equipment the bird as built would be of little use.

"When the bird descends, then its center of gravity is different from its center of resistance; as if the center of gravity corresponded with the line AB [right vertical line on the second image] and the center of resistance were near line CD [left vertical line].

"When the bird wants to rise, its center of gravity remains behind its center of resistance. As if the center of gravity just cited was situated at FG [left vertical line on the third image] and the center of resistance at EH [right line].

"The bird [referring to the fourth image] can stay in the air without necessarily keeping its wings balanced, because as its center of gravity does not always correspond to its midpoint, as the scales do, it is not necessarily forced to keep its wings at the same height, unlike scales. But if these wings are positioned beyond the stable position, then the bird will descend along the angle of the wings; and if the angle is complex, that is if the parts of the body point in two different directions, for example the wings pointing south and the head and tail east, then the bird will descend toward the southeast. If the angle of the bird is double that of the wings alone, the bird will descend halfway between the southeast and east, and the angle of its flight will be along the two angles."

©Leonardo3, www.leonardo3.net

An example of effective pedagogy for the Codex on the Flight of Birds is this exhibit by the innovative Italian group Leonardo3, in Brazil in 2008: a model of Leonardo's bird shown in the accompanying drawing. The visitor pulls the wires to tip the bird one way or another.

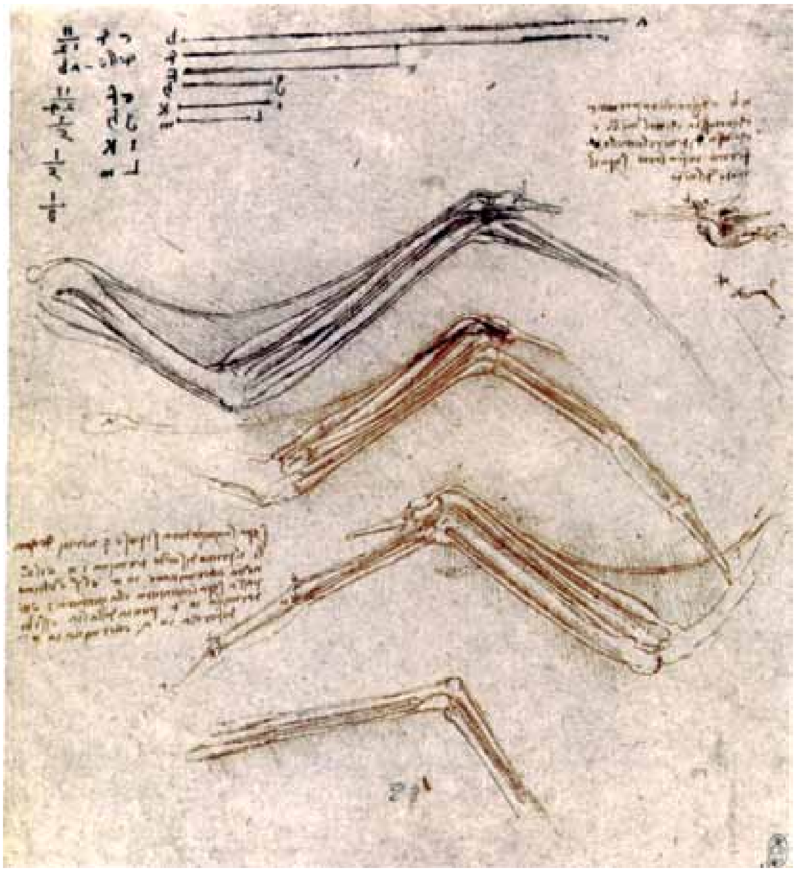
©Leonardo3, www.leonardo3.net

Children experiment with a digital display of a drawing by Leonardo, at a Leonardo3 exhibition at the Franklin Museum in Philadelphia in 2011. (Models of machines are in the rear of the photo.) Drawing children into the mind of the artist/inventor is a crucial component of any such museum exhibit.

FIGURE 2

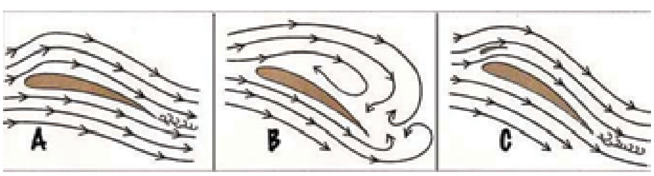
Close Observation of the Bird in Flight

The detail on the right from the Codex on the Flight of Birds (Folio 8 recto) is one of many sketches of birds in flight. Here Leonardo is considering the ways that the bird adjusts its wings according to the direction of the wind, so that it does not flip over—a great concern in the design of a machine for human flight.



The photo on the right shows the skeleton and some wing feathers of a gull in flight, with the arrow pointing to the alula, or "bastard wing." The same structure is shown in Leonardo's drawing above (Windsor 12656). The alula is essential to a bird's aerodynamics, to prevent the animal from flipping over or "stalling." The website where this photo appears describes it as an "anatomic turbulence-buster."

FiddlersGreen.net



FiddlersGreen.net

The diagram shows airflow around the bird's wing, and the effect of the alula. **A** *is a condition of smooth flight, with the wing tilted upward into the airstream, maintaining lift. In* **B**, *it is tilted up too much, and turbulence sets in, destroying lift and threatening the bird with a crash landing. In* **C**, *the alula has popped up to smooth out the turbulent airflow so that lift is maintained.*

in whole or in part with the subject of flight,[6] not to mention the estimated two-fifths of his opus which has been lost.

Metaphor and the Imagination

But acute observation alone does not account for Leonardo's seemingly miraculous discoveries. Even more important was his power of metaphor: the mental "flight" by means of which he apprehended relationships that others had never imagined.

Thus he writes, in one of his last notes on flight, "In order to give the true science of the movement of birds in the air it is necessary first to give the science of winds, and this we shall prove by means of the movements of water. This science in itself is capable of being received by the senses. It will serve as a ladder to arrive at the perception of things flying in the air and wind."[7]

It was this same capacity for metaphor that had earlier led him to investigate wave motion in water, and to be the first person to draw air as a fluid. His observations of various flow patterns (**Figure 3**), according to historian of aerodynamics and aerospace engineer John D. Anderson, Jr.,[8] "were the first qualitative contribution to experimental dynamics." Indeed, Leonardo's studies of flow patterns in air and water were at the heart of most of his discoveries about flight. As always, the conceptual approach was initially based on a metaphorical insight. He wrote in the Codex on the Flight of Birds, for example, "The bird makes the same use of his wings and tail in the air that a swimmer makes of his arms and legs in the water" (Folio 11v).

Achievements and Limitations

Leonardo's studies produced the following contributions to the science of aerodynamics,[9] according to Anderson:

- The first quantitative statement in history of **the law of continuity**, which means that the velocity of flow (V) varies inversely with the cross-sectional area (A) of a stream at any given point, such that AV = a constant. Leonardo observed this with regard to a river: "Each movement of water of equal surface width will run the swifter the smaller the depth. . . . I say that at *mn* the water has more rapid movement than at *ab*, and as many times more as *mn* enters into *ab*; [if] it enters 4 times, the motion will therefore be 4 times as rapid at *mn* as at *ab*."[10]
- The first statement of **the wind-tunnel principle**, which of course the Wright brothers used to test their flying machines. Leonardo wrote, "As it is to move the object against the motionless air, so it is to move the air against the motionless object," and "The same force as is made by the thing against air, is made by air against the thing" (Codex Atlanticus). This is known today as the "principle of aerodynamic reciprocity."[11] The principle identified by Leonardo in his private notebooks was slow to develop historically, and the first wind-tunnel simulations of flight were built in the 18th Century.

A short film, "Fundamental Nature of Air Flow and Separation," made by the National Advisory Committee for Aeronautics (NACA) at Langley Memorial Aeronautical Laboratory (date unknown), uses mainly smoke-flow tunnels to give excellent images of fluid flow, and is the kind of graphic material that would be very useful in an exhibition on the Codex on the Flight of Birds.

- The statement that **air resistance** is *directly proportional to the area* of the body.
- Introduction of the concept of **streamlining** a body to reduce drag. Leonardo sketched fishes, hull shapes for ships, projectiles from cannons, as well as bird wings, to show this effect.

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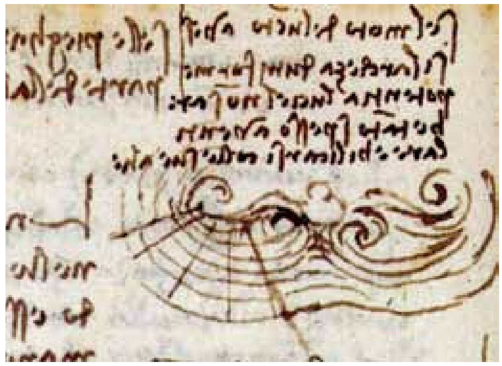
6. Many specialists in Leonardo's work for some reason find this sort of thing peculiar, like Kenneth D. Keele, who refers to Leonardo's "almost obsessional analysis of the variations of the movements of flight" (Keele, op cit., p. 188). Dominico Laurenza, in *Leonardo on Flight* (Florence-Milan: Giunti Editore S.p.A., 2004), posits, without a shred of evidence, that Leonardo plunged into "despair," "disillusion," and "a real crisis," when he concluded, at the end of his life, that a machine for human flight could not imitate a bird's flight (with flapping wings, etc.). And then there's Sigmund Freud, whose famous *Leonardo da Vinci and a Memory of His Childhood* concluded from Leonardo's account of a childhood dream about being attacked by a large bird of prey, that the artist was a homosexual—because he had been neglected by Piero da Vinci, of whom he was the illegitimate son.
7. Manuscript E, 54 recto, cited by Keele, op. cit., p. 191, who feels compelled to comment, "Obviously, he still felt as if he were just beginning his researches into flight, not coming to the end of his life." Silly Leonardo!
8. *A History of Aerodynamics and Its Impact on Flying Machines* (Cambridge University Press, 1997), p. 12.
9. In The NASA History Series, the volume *The Wind and Beyond: A Documentary Journey into the History of Aerodynamics in America* writes effusively: "Certainly no one before da Vinci, or for three centuries after him, offered anything close to his astonishing vision of flying machines or considered so many of the principles affecting flight." James R. Hansen, ed., with D. Bryan Taylor, Jeremy Kinney, and J. Lawrence Lee (NASA History Office: Washington, D.C., 2003), p. 4.
10. Hunter Rouse and Simon Ince, *History of Hydraulics* (Iowa City: Institute of Hydraulic Research, 1957).
11. Francesco Cutry, "The Flight of Birds," in *Leonardo da Vinci* (New York: Reynal and Co., Artabras book, n.d.), p. 344.

FIGURE 3
The Flow of Water and Air

Leonardo's observations of water and air reinforced his understanding of both; he was the first person to draw air as a fluid (detail from Windsor RL 12579 recto). He shows here how the placement of an obstacle in the way of a flowing stream, at different angles, affects vortex formation.



Leonardo's drawing of vortex formation around the bird's wing is from Manuscript E 47 verso. The curvature of the wing, especially at the tips, is directly connected to the curvature of the air underneath it. The straight lines drawn across the airflow represent the centripetal force that presses the wing to curve. (Domenico Laurenza, "Leonardo on Flight," 2004).

This photo of a model of the Concorde jet in a wind tunnel shows the vortices forming over the wings, as in the sketch by Leonardo (above right).

NASA

From a study of wake vortex formation at Wallops Island NASA Langley Research Center, 1990 (false color).

Subsuming several of these specific contributions is the broader concept of **lift**, which is of course crucial to getting a bird (or a plane) into the air. Anderson writes that there is no evidence of any scientific thinking about lift before Leonardo, although his conclusions about it were flawed in certain respects. Leonardo wrote: "When the force generates more velocity than the escape of the resisting air, the same air is compressed in the same way as bed feathers when compressed and crushed by a sleeper. And that object by which air was compressed, meeting resistance on it, rebounds in the same way as a ball striking against a wall" (Codex Trivultinanus). In other words, he believed that high-pressure, high-density air is formed under a lifting surface, which pushes the surface up. This is actually not the case. Anderson writes, "Today we know that lift is achieved primarily because of the low pressure (suction) over the top of a wing and that the pressure on the bottom of the wing, albeit higher than that on the top, is not much higher than the free-stream static pressure."

Nevertheless, by 1513, Leonardo was coming much closer to identifying the actual source of lift. In Codex E, he wrote:

"The air surrounding birds is above thinner than the usual thinness of the other air, as below it, it is thicker than the same, and it is thinner behind than above in proportion to the velocity of the bird in its motion forwards, in comparison with the motion of its wings toward the ground; and in the same way the thickness of the air is thicker in front of the bird than below, in proportion to the said thickness of the two said airs." [I told you it was hard to read these notebooks!—SW]

Anderson suggests replacing the words "lower pressure" for "thinness" and "higher pressure" for "thickness," concluding that the result is a clear explanation of the pressure distribution over an airfoil, and hence of the source of lift and pressure drag. "Thus," he writes, "Leonardo was three centuries ahead of his time, because George Cayley, in 1809, was the next person to appreciate the actual source of lift."

Most of Leonardo's sketches and discussions of flying machines (including in the Codex on the Flight of Birds) are based on attempts to mimic the flapping motion of birds' wings (see **Figure 4**). This was an obstacle to conceptual progress throughout most of his work on human flight, but his endless investigations finally led him to the conclusion that the flapping of the wings was not, in fact, an important source of lift, but rather was the means by which the tip feathers produced a forward thrust for propulsion. As the air flowed over the wings because of the bird's forward motion, lift was produced. Leonardo wrote: "Therefore if air moves against motionless wings the same air supports the heaviness of the bird through air" (1505, Codex Atlanticus).

Still Puzzling

Five centuries after Leonardo's Codex on the Flight of Birds was written, there is much that remains unknown about the subject. Three biology researchers introduced their article, "Bird Flight: Insights and Complications: New techniques show that more than the wing participates in flying," with a discussion of Leonardo. G.E. Goslow, Jr., K.P. Dial, and F.A. Jenkins, Jr. (*BioScience*, Vol. 40, No. 2, February 1990), wrote that much has been learned in recent decades about the performance of the wing, including the subtleties of wing movement during upstroke and downstroke as revealed by slow-motion photography. "Nevertheless, due to the complexity of its design and the movement of patterns during a wingbeat cycle, knowledge of the bird wing remains sketchy and incomplete."

They initiated a series of studies on neural control of the wing, biomechanics of the wing and shoulder, and evolution of flapping flight. But, "as was the case for Leonardo da Vinci, . . . we were confronted with unexpected results that required further investigation." The particular problem in understanding the control of the wing, they reported, has been "the inability to document the precise movements of its skeletal elements during flight. They built a wind tunnel for testing small European starlings, using a technique called the cineradiograph to observe the movements of the wing skeleton. To their surprise, they found that the bones of the shoulder and thorax move rhythmically with the wingbeat. Why? They hypothesized that the bird's wishbone (furcula) spreads and collapses with the wingbeat, acting as a secondary pumping system to meet the increased metabolic demands of flight, moving air between the air sacs and lungs.

Like Leonardo in his pursuit of artificial flight, the scientists wrote, they planned to continue their studies along these lines, thereby to understand "the evolution of this most amazing and successful form of locomotion." (More recent work by the authors can be found through the usual online search engines.)

—*Susan Welsh*

FIGURE 4
The Flapping Wing Approach to the Design of Flying Machines

This model of one o f Leonardo's ornithopter flying machine designs, displayed at the National Air and Space Museum exhibition, is based on a drawing in Manuscript B, folio 74. It is the only model in the exhibit, and is attached to the high ceiling over the exit from the exhibit area. Many viewers will not notice it (I didn't at first), and it is not close enough for children to touch it or at least inspect it. Its placement (as if in flight) implies that the flapping wing model works, which it does not.

Model built by Opera Laboratori Fiorentini Civita Group, 2006. Lent by Finmeccanica North America.

Smithsonian Libraries, from the original at the Biblioteca Reale, Turin, Italy

Folio 7 recto from the Codex on the Flight of Birds *displays a draftsman-like drawing of the (mechanical) "bird's" wing. The text shows that Leonardo is trying to figure out how to build a machine on the "flapping wing" model.*

"The bird [machine] mentioned must, with the help of the wind, rise to a great height, and this will be a safety factor because, in the case of being overturned, it would have time to return to a stable position, provided the framework were very strong, its joints constructed with strong alum-tanned leather and its ribs of very strong raw silk, so that they can withstand the stresses and the speed of descent, with the actions already mentioned; and let no piece of metal be used in its construction, because this material breaks or wears away under stress, so they should not be used.

"The cord A [in the image to the right of and just below the arching wing], used to spread the wing, must be made with a thick alum-tanned leather, so that if the bird should be turned upside down, it can overcome the fury of the wind striking the wing and trying to close it, which would be a disaster for the bird. But to be even safer, you will use the same framework of ribs both above and below, so you will be free from any danger.

"ABC are the points where the ribs are attached of the three joints of the fingers of the wing. D [at the very bottom right] is the point where the lever AD moves across the wing."

Here again, he was three centuries ahead of his time: George Cayley formulated the idea of the separation of lift and propulsion in a fixed-wing aircraft in 1799.[12]

The Codex on Mars

We return now to where we began: NASA JPL director Elachi's interview on the video that accompanies the exhibit. RAI-TV deputy editor-in-chief for science news Silvia Rosa-Brusin asks him, as he's paging through the Codex in Turin's Biblioteca Reale: "Why don't we send it to Mars?" He grins, agrees, and arranges to have NASA scan the Codex onto a chip and place aboard the Curiosity rover, which lands on Mars a few months later, on Aug. 6, 2012. Rosa-Brusin aptly concludes: "What a fitting journey for the genius whose whole life was driven by curiosity!"

12. Anderson, op cit., footnote 8, pp. 24-25.