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We are entering a new phase of the space age. The era of superpower rivalry has been replaced by intense commercial activity in orbit and by new types of vehicles operating at the margins of space. Virgin Galactic and Blue Origin are about to start flying tourists in those margins, while militaries are experimenting with hypersonic flight in the upper atmosphere and hucksters are advertising high-altitude stratospheric balloon flights at the edge of space. As a result, the six-decade-old delimitation question has gained renewed relevance: Where does outer space begin? How high do you have to fly to be a space traveler?

Of course, Earth's atmosphere has no sharp edge. Its density decreases exponentially with altitude, and it slowly becomes largely ionized but still detectable even 1000 km above Earth. Interplanetary space itself is not a perfect vacuum, and one could argue that the boundary of our atmosphere is the magnetosphere bow shock, where the flow of the solar wind around our planet interacts with the gas that is loosely bound to Earth. But in practice everyone agrees that you are in outer space well before you reach the tens of thousands of kilometers to which the magnetosphere extends.

At the other extreme, some have argued for the so-called Armstrong limit at an altitude of only about 19 km, where water can boil at normal body temperature and an unprotected human cannot survive even with an oxygen supply. (The limit is named after Harry Armstrong, a major general in the US Air Force and unrelated to astronaut Neil.) But the ability of airplanes and balloons to fly well above that limit makes it implausible to assert that 20 km is in outer space.

The Kármán line

Aerospace pioneer Theodore von Kármán argued that the point where orbital dynamics forces exceed aerodynamic forces is a sensible place to set the limit—now known as the Kármán line (see figure 1, in which $k = 0$ defines the Kármán line height). His proposal is the most widely accepted definition of outer space and was originally popularized in 1963 by space lawyer Andrew Haley. (At the time, space law dealt mostly with international treaties; now it's also about licensing commercial satellites.)

Modern commentators often assume that the order-of-magnitude estimate of 100 km for the Kármán line's altitude is actually its definition. But that assumption is not historically correct. In a 2018 paper in *Acta Astronautica*, I showed that von Kármán's argument places the line close to 80 km, largely independent of atmospheric variations and satellite properties.

Von Kármán's original point was that an altitude exists where generating lift with a wing is impossible. That's because you would have to fly so fast in the thin atmosphere that you'd exceed the Keplerian velocity, the speed at which a satellite flies in a circular orbit at that height. But a basically identical calculation shows that drag dominates gravitational forces on an orbiting satellite at a similar height. The result depends a little on the mass-to-area ratio of the spacecraft—whether it's a balloon, say, buffeted by the thin wind or a dense object plowing through the exosphere. The effect is captured by a quantity known as the satellite's ballistic coefficient, essentially its drag per unit mass, which varies from 0.005 m^2/km to 0.05 m^2/km for the majority of spacecraft.

Nevertheless, the atmospheric density falls off so rapidly in the 70–100 km region that the location of the effective Kármán line doesn't actually change much for the different cases. At higher altitudes, the atmospheric density is highly sensitive to solar activity; below 100 km it's much less sensitive. The upshot is that using von Kármán's criterion, the theoretically cal-

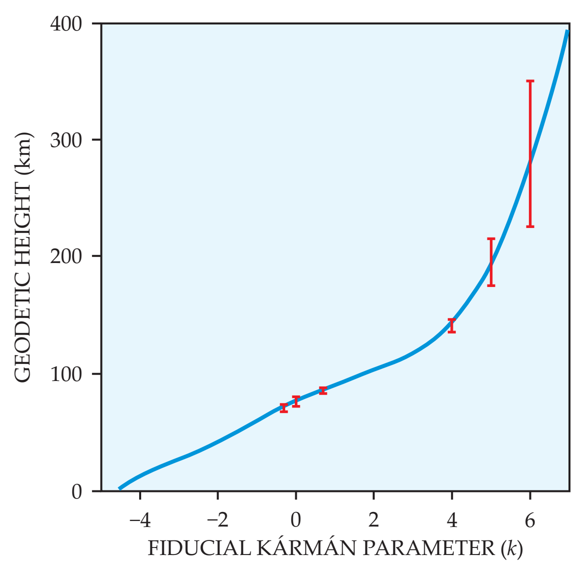

FIGURE 1. THE FIDUCIAL KÁRMÁN PARAMETER *k* is the logarithm of gravitational force divided by aerodynamic force. The plot illustrates how that ratio rapidly changes with altitude for a typical satellite and for a density profile defined by the 1976 US standard atmosphere. The point $k = 0$ corresponds to the effective Kármán line at about 80 km, where gravity and aerodynamics balance. Error bars indicate variations due to realistic atmospheric conditions. (Adapted from J. C. McDowell, *Acta Astron.* **151**, 668, 2018.)

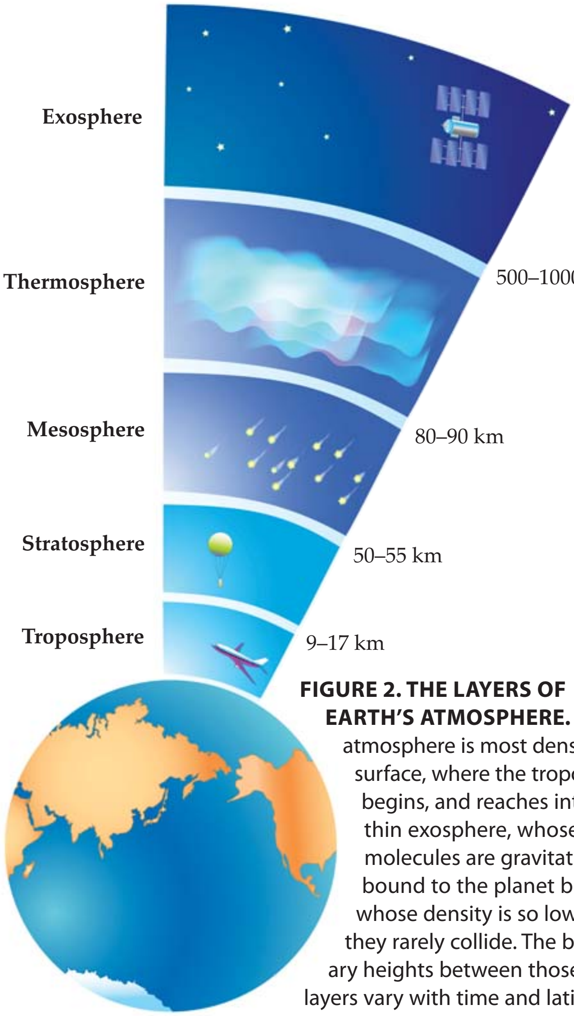

FIGURE 2. THE LAYERS OF EARTH'S ATMOSPHERE. The atmosphere is most dense at the surface, where the troposphere begins, and reaches into the thin exosphere, whose air molecules are gravitationally bound to the planet but whose density is so low that they rarely collide. The boundary heights between those end layers vary with time and latitude. See the Quick Study by John Emmert, PHYSICS TODAY, December 2008, page 70. (Adapted from the Center for Educational Technologies.)

culated boundary is always between 70 km and 90 km, with 80 km being a reasonable representative value. Because drag is proportional to atmospheric density and to the square of the satellite's velocity, the large density causes rapid deceleration below that height and makes the satellite fall out of orbit. The strong braking also generates extreme heating, and in the absence of a heat shield, the satellite quickly breaks apart and melts.

Practical, historical, physical

Practical evidence suggests that the 80 km line is a reasonable boundary. An analysis of 60 years of archival satellite orbital data shows that elliptical-orbit satellites can survive for days or weeks with a perigee (low point of the orbit) between 80 km and 90 km. At each perigee, the braking effect of the upper atmosphere reduces the satellite's velocity and causes the height of the next apogee (orbital high point) to be somewhat lower. Once the perigee drops below 80 km, however, the satellite does not survive more than one orbit.

Satellites with perigees in the 80–90 km range drop below 100 km every few hours. If you regard 100 km as part of outer space, keep in mind that the satellites would leave space, briefly pass through some country's airspace, and then return quickly to outer space. That implication is inconvenient and impractical. When objects are in orbit traveling at more than 400 km/min and crossing national boundaries every few minutes, we must conclude they are in outer space.

The 80 km boundary also has historical resonance: It is closely equal to 50 statute miles, the boundary used since 1961 to award "astronaut wings" to US military pilots, including several who flew the X-15 suborbital space plane. Pilots have made 8 suborbital flights above 100 km and another 14 above 80 km, most recently the flights by *SpaceShipTwo* and the emergency abort of the *Soyuz MS-10* launch.

The 80 km boundary corresponds reasonably well with the typical altitude of the mesopause, which is the highest well-defined boundary in the atmosphere and thus provides a physical reason for the choice. Most of us live in the troposphere, below about 12 km, although academics like me tend to spend too much time at the upper edge of that region, where commercial jets fly. (See figure 2.) All vehicles that need aerodynamic lift to remain aloft are restricted to the stratosphere, whose ceiling, the stratopause, is at about 50 km. The jet altitude record remains a mere 38 km.

Above the stratopause is the mesosphere region between 50 km and 80 km. That is a forbidden zone, where neither aircraft nor satellites can fly. It is visited for only a few minutes at a time by sounding rockets, reentry vehicles, and rocket stages, which complete a partial orbit. Starting with work by international space lawyer Bess Reijnen in the 1970s, various authors have suggested that the mesosphere could be regulated as an intermediate region—neither airspace nor outer space—but no consensus has been reached to date.

At the United Nations and in other international forums, Russia and other spacefaring countries have repeatedly suggested adopting the 100 km boundary, or something near it. The US government, though, has long resisted any official legal definition of space. Instead, US officials argue for a functional definition, in which different rules would apply to different kinds of vehicles, but they ignore the issue of what happens when vehicles interact.

As traffic in the liminal region increases, I believe that some legal rule will eventually be necessary to specify where a national airspace becomes a global, international space. In the meantime, those of us who make lists of astronauts or of suborbital space launches have to adopt some choice for what to include or exclude. I advocate using 80 km as that boundary.

Additional resources

▶ J. C. McDowell, "The edge of space: Revisiting the Karman line," *Acta Astron.* **151**, 668 (2018).
▶ R. F. A. Goedhart, *The Never Ending Dispute: Delimitation of Air Space and Outer Space*, Editions Frontières (1996).
▶ Committee on the Peaceful Uses of Outer Space, *Historical Summary on the Consideration of the Question on the Definition and Delimitation of Outer Space*, report A/AC.105/769, United Nations (2002).
▶ J. M. Picone et al., "NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues," *J. Geophys. Res. Space Phys.* **107**, 1468 (2002).
▶ T. Gangale, "The non Kármán line: An urban legend of the space age," *J. Space Law* **41**, 151 (2017). PT