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Some elements for the discussion about a modernized definition Of karman Line

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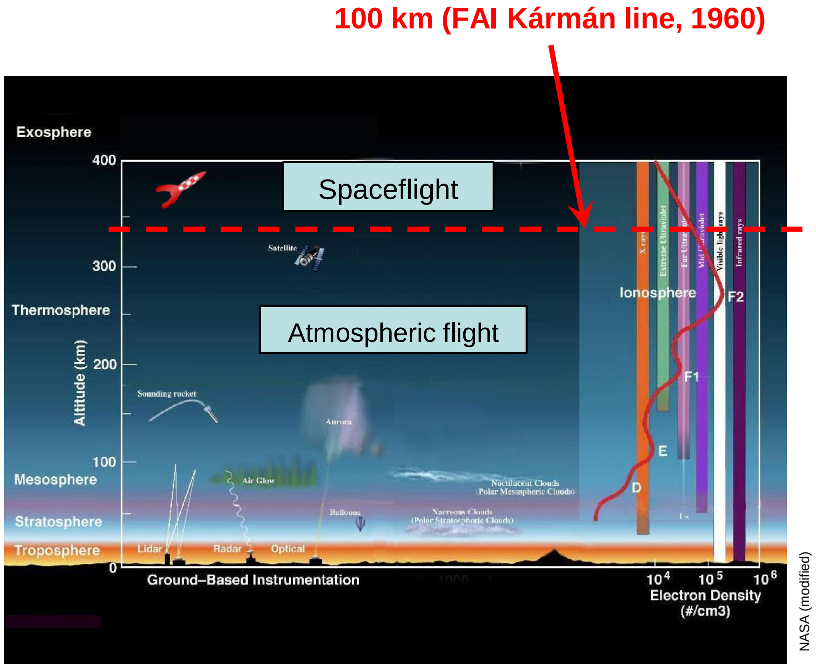
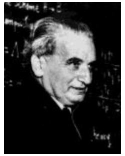
Introduction about the Kármán line



NASA (modified)



NASA

Theodore von Kármán
(1881-1963)

- Kármán line = one convention for defining a “boundary of space” (other exist, e.g. USAF astronaut wings: 50 miles [80.47 km]).

- This concept emerged in space law discussions in the 1950’s (name “Kármán line” coined by Andrew G. Haley in a 1957 IAC paper, following discussions with Kármán)

- Set at 100 km by FAI in 1960 (with a group of scientists, including Kármán) for separating aeronautics and astronautics records

FAI website article about the Kármán line definition

- From "100km Altitude Boundary for Astronautics" (S. Sanz Fernández de Córdoba, FAI website, 2004):

In Aeronautics, level flying higher and higher meant to deal with less and less dense atmosphere, thus to the **need of greater and greater speeds to have the flying machine controllable by aerodynamic forces**. A speed so big in fact, that, above a certain altitude, could be close or even bigger than the circular orbital speed at that altitude (i.e. lift was no longer needed, since **centrifugal force took over; and consequently aerodynamic flight was meaningless**).
Conversely**, in Astronautics, lower and lower orbital flying led to encounter more and more dense atmosphere, so much that it would be impossible to keep the orbit for a number of turns around Earth** without a significant forward thrust (thus making the free fall, or orbiting, concept meaningless). A lot of calculations were made, and finally it was reached the conclusion, accepted by all scientist involved, that around an altitude of 100 Km. the boundary could be set.(...)
It was apparently Von Kármán himself who realized, and proposed to the rest, the very round number of 100 Km (very close to the calculated number).

- This article provides some insights about the physics of the Kármán line:
  - It does not contains a precise definition
  - Information are sometimes ambiguous or contradictory (different concepts are mixed: aerodynamic controllability, centrifugal force "taking over", orbit stability and atmospheric drag).

What Kármán himself wrote

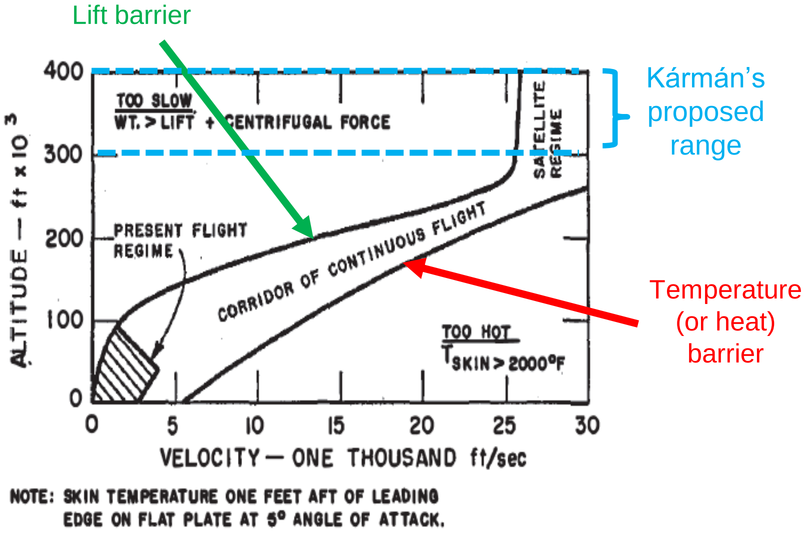
Source: "From Low Speed Aerodynamics to Astronautics", Pergamon Press, 1963 (conferences by Th. Kármán at University of Maryland, 28-29 April 1961)

"In considering the re-entry problem, we must first ask where is the limit between atmosphere and outer space. **It is a judiciary rather that a scientific problem** (…)
I propose to adopt as a conclusion the graphics on altitude and velocity study for real flight proposed by M. Gazley from "Rand Corporation". He considered that permanent flight is limited by two extremal conditions:

1/ either the vehicle is to slow to fly because its weight is greater than the sum of lift due to air and centrifugal force ["lift barrier"]

2/ or the vehicle is too hot to fly because the coating's temperature is greater than the critical temperature of the material. Gazley estimated this critical temperature to 2000° F. He found that permanent flight was limited to a narrow strip on the graphics (…). **["Heat barrier"]**

It is evident that when centrifugal force becomes dominant, the vehicle turns into a satellite. That condition can be considered as the beginning of space. **Hence I propose that space starts from 300 or 400,000 ft [91.44 or 121.92 km]**"



Gazley (or "Masson & Gazley") graphics

(from "Surface Protection And Cooling Systems For High-Speed Flight, IAS National Summer Meeting, Los Angeles, June 18-21, 1956)

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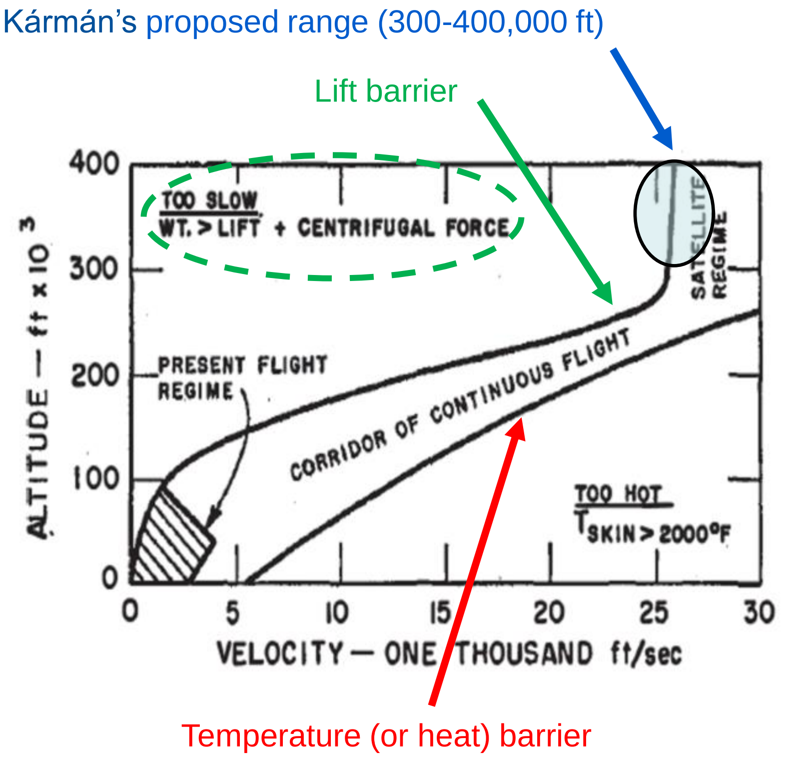
Role of the "lift barrier curve" in the Kármán line theory

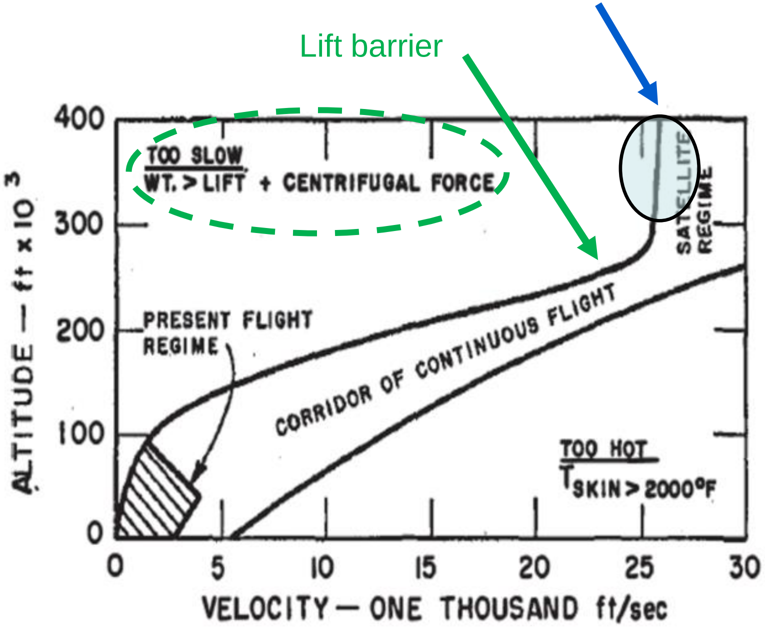


- Kármán apparently never **calculated** precisely an altitude for the boundary of space. He only proposed the approximate range where the "**lift barrier**" curve becomes very steep ([300-400,000 ft] or ~[91-122 km]).
- The (rounded) 100 km altitude eventually set by FAI is definitely consistent with this range.
- **Warning:** the 275,000 ft (83.82 km) is often presented as the "original altitude calculated by Kármán". It is actually an "**illustrative**" figure provided by Haley in his 1957 IAC paper (a figure that "**may be significantly changed**"). This altitude is actually **outside** Kármán's proposed range.

Understanding the "lift barrier" curve

Kármán's proposed range (300-400,000 ft)

Lift barrier



- Correspond to (altitude, velocity) conditions for **sustained horizontal flight** (where: **Weight = Lift +Centrifugal force**) for a vehicle characterized by a given lift parameter (M/(S.C$_L$)):

$$\frac{\mu_E}{(r_E+h)^2} = \frac{\frac{1}{2}\rho(h)V^2}{\left(\frac{M}{S\cdot C_L}\right)} + \left(\frac{V^2}{r_E+h}\right)$$

$\rho(h)$	atmos. density (kg/m^3
M	mass (kg).
C_L	lift coefficient (-)
S	aerodyn. surface (m^2)
$\frac{1}{2}\rho(h)V^2$	dyn. pressure (Pa)
M/(S.C$_L$)	lift parameter

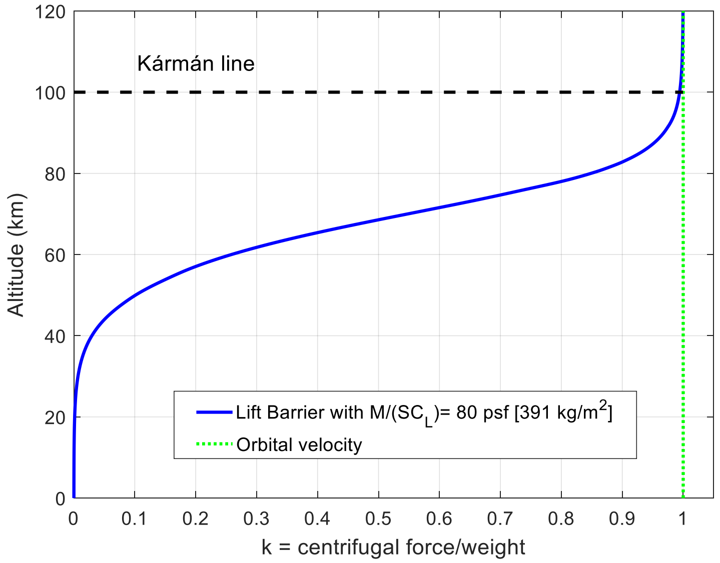
$$\text{Lift parameter} = \frac{\text{Wing loading}}{\text{Lift coefficient}} = \frac{\text{Ballistic coefficient}}{\text{Lift to Drag ratio}}$$

$$\frac{M}{S\cdot C_L} = \frac{\left(\frac{M}{S}\right)}{C_L} = \frac{\left(\frac{M}{S\cdot C_D}\right)}{(C_L/C_D)}$$

- In Masson & Gazley's curve: M/(S.C$_L$) ~400 kg/m2 [80 psf] , representing the technological limit of a future, **hypothetical** vehicle which would be able of **sustained horizontal flight** at the (high) altitude considered.

- The 80 psf figure was originally set by Heinz Haber in a previous paper. Masson & Gazley and Kármán kept it.

Physical phenomena represented by the “lift barrier” curve



- Moving up along the curve:
  - Increases the “velocity to orbital velocity” ratio.
  - Increases also the “centrifugal force/weight ratio”, which is related:

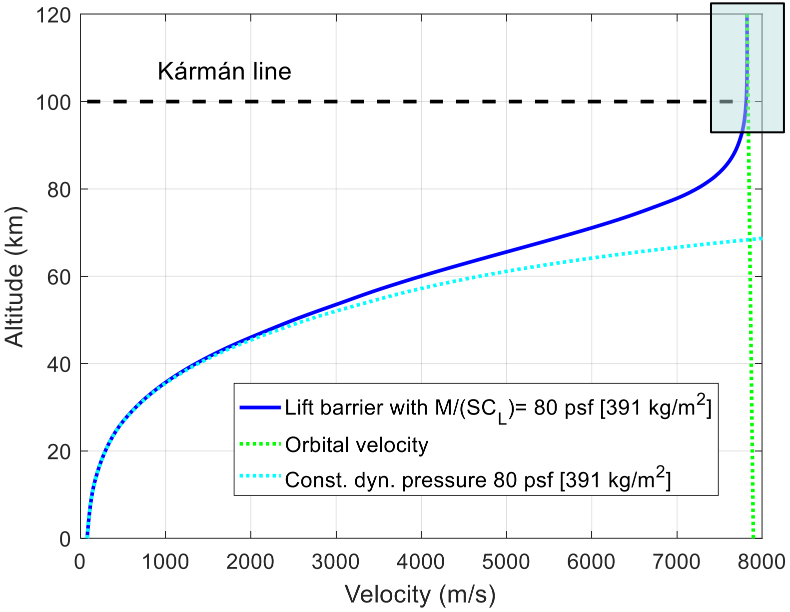
$$\boldsymbol{k} = \frac{\left(\frac{V^2}{r_E + h}\right)}{\left(\frac{\mu_E}{(r_E + h)^2}\right)} = \frac{(r_E + h) \cdot V^2}{\mu_E} = \left[\frac{V}{\sqrt{\frac{\mu_E}{r_{E+h}}}}\right]^{\mathbf{2}}$$

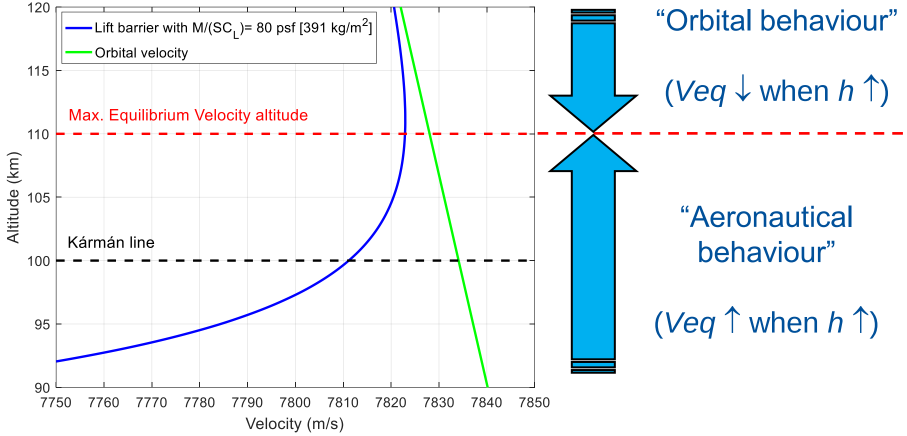
$$k = \frac{\text{Centrifugal force}}{\text{Weight}} = \left[\frac{\text{Velocity}}{\text{Orbital velocity}}\right]^{\mathbf{2}}$$

- Defining a precise boundary based on a threshold on k (or $\sqrt{k}$) would be a possibility … but it would be an arbitrary choice (like the rounding to 100 km).

~87 km for k= 95 %
~97 km for k= 99 %

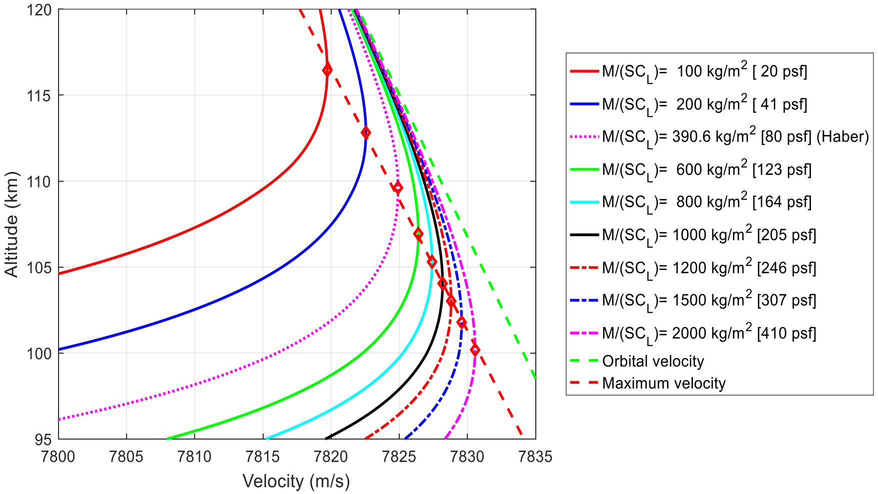
A proposal to define a *precise* altitude using physics
(IAC-22-C1.IP.8)





- There exists a Maximum Equilibrium Velocity (MEV) altitude which separates two domains:
  - **At lower altitudes:** the equilibrium velocity increases with altitude, like in the constant dynamic pressure curve ("**aeronautical behaviour**” prevails).
  - **At higher altitudes:** the equilibrium velocity decreases with altitude, like in the orbital velocity curve ("**orbital behaviour**” prevails)

A new proposal to define a *precise* altitude using physics



- The Maximum Equilibrium Velocity (MEV) altitude is **~110 km** for $M/(S.C_L)$~400 kg/m2 (original hypothesis in Masson & Gazley's curve).

- It is relatively stable wrt. $M/(S.C_L)$:
  - For half the hypothesis (~200 kg/m^2) ~112 km
  - For twice the hypothesis (~800 kg/m^2) ~105 km

- "Backward compatibility" with the original 100 km value obtained with $M/(S.C_L)$ ~ 2000 kg/m^2

With simplifying assumptions:

$$h_{MEV} \cong \mathrm{L} \cdot \ln\left(\frac{\rho_0 \cdot {r_E}^2}{2L\left(\frac{M}{S \cdot C_L}\right)}\right)$$

For fun (?):
- Mars: h_{MEV} = 113 km
- Venus: h_{MEV} = 303 km

$$\rho(h) = \rho_0 \cdot e^{-\frac{h}{L}}$$

Conclusion

- The Maximum Equilibrium Velocity (MEV) definition identifies more precisely the physical phenomenon that occurs in the altitude range designated by Kármán. It is definitely compatible with Kármán's guidelines and altitude range (and relatively close to FAI's rounded value: 110 km vs. 100 km current value).

- Unlike the 100 km altitude, it does not rely on an arbitrary rounding, but only on physics

- However, it still depends on the choice of the lift parameter, which is (relatively) arbitrary as it corresponds to an **hypothetical** vehicle capable of horizontal lifting flight at the (high) altitude considered.

- The Kármán line theory **is not the only possible definition** relying on aerodynamic forces:
  - Kármán line theory → based on **lift**
  - USAF limit → based on **aerodynamic controllability** (cf. Jenkins, 2005)
  - McDowell's proposal (2018) → based on **drag** ("satellite" point of view)

- The question of the boundary of space is, in any case, **a matter of convention.**