The Time it Takes to Lose a Planetary Atmosphere

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Atmospheres can leak into space. It happens very high in the atmosphere where a special condition holds: If you consider a single molecule and you give it a good thwack, it needs to (1) have enough velocity to escape the gravity of its planet, and (2) not hit any other particles on its way out, because that would slow its speed. When you get high enough, and on earth it's about 500 km above the surface, then the last condition is met. We call that the exosphere.

The exosphere is a strange place. Each atom is a separate satellite of earth on a ballistic trajectory. Note that the "edge of space" is at much lower altitude (118 km for Earth) and "low earth orbit" where most satellites are is around 300 km. The outer edge of the exosphere is where Earth gases blend with the solar wind. The inner edge is fuzzy and time variable. It heats in the day and cools at night, and also puffs up much higher during periods of high solar activity. For our approximate calculation here, we will assume a temperature of 1000 K, an altitude of 500 km (Earth) or 3000 km (moon), and a number density of 5.4×10^{11} particles per cubic meter. Also note that escaping oxygen at that altitude will be atomic, not molecular O_2 or O_3.

At the exosphere, a molecule can escape if it is fast enough. We compare with the planet's escape velocity

$$v_{esc}^2 = \frac{2GM}{R} \tag{1}$$

where M is the mass of the planet, and R is the distance from the center of the planet. If a particle is fast enough, it can escape the planet altogether, and if enough particles do that, the atmosphere will leak away. This is called the Jeans mechanism.

The spread of speeds of particles in a gas is known, and it is called the Maxwell-Boltzmann velocity distribution. Considering only the fastest molecules at the high-velocity tail end of that distribution, we arrive at an escape rate $dN/dt = \dot{N}$ particles per second of

$$\dot{N} = 4\pi R^2 \nu n \tag{2}$$

where n is the number density of particles (of one species) at the exosphere in particles per cubic meter (we assume 5.4×10^{11} m^{-3}) and the radial location R is adjusted for the height of the exosphere: $R = R_{moon} + R_{exo} = 4.7 \times 10^6$ m. The symbol ν is an atmospheric escape parameter given by

$$\nu = \frac{1}{8}\Big(\frac{m}{2\pi kT}\Big)^{1/2}\Big(v_{esc}^2 + \frac{2kT}{m}\Big)\exp(-mv_{esc}^2/2kT) \tag{3}$$

where k is the Boltzmann constant (1.38×10^{-23} J K^{-1}), m is the mass of the particle ($m = 2.6 \times 10^{-26}$ kg for atomic oxygen), v_{esc} for the moon is 1440 m s^{-1}, and we assume an exosphere temperature of $T = 1000$ K.

If the rate of escape from an atmosphere is $dN/dt = \dot{N}$ particles per second, then the timescale for atmospheric loss is written simply as

$$\tau = \frac{N}{\dot{N}} \tag{4}$$

And the number of particles N is most conveniently gotten by dividing the mass of the atmosphere by the mass of one particle (For the moon, 4.5×10^{17} kg / 2.6×10^{-26} kg $= 1.7 \times 10^{43}$ atoms of oxygen).

This all works out to an approximate time scale of 120 million years for atmosphere loss. That is, if we give the moon a breathable oxygen atmosphere, that atmosphere is essentially permanent over any conceivable human timescale.

Over geologic time, of course, it's a different story. 120 million years is very short compared to the 4.55 billion year age of the moon, so, even in the unlikely event the moon ever had a thick atmosphere, we would expect it to be gone today, lost to space.