Where Does Space Begin?

Functional Concept of the Boundaries Between Atmosphere and Space

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IN SPEAKING of "space," one commonly refers to it as a topographically defined system. In this sense, the borders of space in relation to the earth are identified with those regions where the last traces of air become lost in the void, i.e., 400 to 800 km. (250 to 500 miles) above the earth's surface; or, the borders of space are occasionally interpreted as that zone where the terrestrial field of gravitation is so reduced as to be insignificant. However, "space" as a topographical concept is misleading when used in discussions related to manned rocket flight.[2] Rather, these problems must be treated on the basis of the functions which the atmosphere has for man and craft. In this regard the atmosphere fulfills three important functions:

1. The function of supplying breathing air and climate,
2. The function of supplying a filter against cosmic factors,
3. The function of supplying mechanical support for the craft.

Each of these three functions has a technical as well as a medical aspect. These functions lead us to a new concept of space which is more adequate to the peculiarities of manned rocket flight than is a topographical interpretation of space. In that which follows, this functional definition of space will be discussed briefly with special emphasis on the space medical aspects.

THE FUNCTION OF SUPPLYING BREATHING AIR AND CLIMATE

Breathing Air. — Through experiments on explosive decompression we obtain quantitative information as to the extent to which the atmosphere can maintain the oxygen supply of the body. In those experiments a subject is transposed, within fractions of a second, from a state of normal oxygen supply to a state of oxygen want such as would be found at higher altitudes. Because the stratosphere has become accessible through the rapid development of aviation in recent times, such explosive decompression experiments have been performed in great numbers. The results of the experiments which are of interest in our case may be related briefly, wherein technical and physiological details are omitted.

If a subject is brought abruptly from normal oxygen pressure to that found at 8000 meters (26,000 feet) the first psychophysiological disturbances can be observed after a period of about two minutes; after another minute the subject becomes entirely helpless, falling into a critical phase (loss of consciousness). The time span, during which he is still capable of acting is called the "time of useful consciousness,[1] or the "time reserve."[24] This characteristic time span is reduced to 80 seconds at 9 kilometers (29,500 feet), to 50 seconds at 10 kilometers (33,000 feet), and finally to between 15 and 11 seconds at about 14 kilometers (46,000 feet).[3,7,9,16,18,20,21] At this point a decisive limit is reached. At still higher altitudes the time reserve remains constant, as was proven in experiments up to 17 kilometers (56,000 feet).

Experiments have shown that this minimum time reserve of about 13 seconds is reached at 16 kilometers (52,500 feet), if oxygen, instead of air, is breathed prior to explosive decompression.[3] However, this is a mere experimental variation. The essential point is that the time reserve attains a minimum limiting value at an altitude of 14 kilometers (46,000 feet), and, in the extreme case, of 16 kilometers (52,500 feet). We have to expect the same anoxic time reserve of about 13 seconds in case of a rocket ship, cruising outside the atmosphere, being destroyed completely by the impact of a meteor. This means that, from the viewpoint of respiratory physiology, the borders of space are found at an altitude of about 16 kilometers or 10 miles. It is at this height that the atmosphere's function of supporting the oxygen supply vanishes. The constant time reserve observed at this altitude acquires the rank of a physiological time reserve of space.

The same line of thought can be applied, in principle, to other phenomena such as "survival time" and "revival time" which were studied in detail in animal experiments.[10,19,22] We are concerned primarily, however, with time reserve because it is the most obvious example.

The boiling point of body fluids in relation to ambient pressure is another significant factor which merits consideration. According to experimental investigations, the boiling point is reached at an altitude of approximately 20 kilometers (65,000 feet).[1]

Another problem related to the atmosphere's complex function for respiration will be mentioned briefly. It is the problem of "bottled air." It has been computed that, above a certain altitude, breathing air for the ship's crew can no longer be derived from the ambient air. The low air density would require large compression pumps and bulky radiators for the air which is being heated by the necessary compression. At a certain altitude, this equipment would have to be so cumbersome as to be prohibitive. There, the ship would depend as much on "bottled air" as in actual space. In addition, at an altitude of no less than 20 kilometers (12 miles) the ozone concentration in the ambient air is so high as to exceed the toxic threshold after compression. As is known, in these layers, ozone is generated photochemically.

Climate.—In discussing the atmosphere's function of providing a suitable climate, we confine ourselves to temperature as the most characteristic climatic factor. In the denser layers of the atmosphere the temperature inside an aircraft is chiefly determined by the exchange of heat between the ship's hull and the ambient air. Owing to adiabatic and friction heating the process of heat exchange between ship and air is dependent on velocity.

Above a certain altitude the heat transfer between the atmosphere and the ship becomes negligible. From then on the ship's temperature will be determined solely by the exchange of radiation between the ship's exterior on the one side, and the sun, the earth, and cosmos on the other.[4,5] Depending upon the incoming radiation and the spectral reflectivity of the hull, a certain equilibrium temperature will result.

For a body at rest in relation to the ambient air (balloon), the conditions of pure radiation climate are practically fulfilled at an altitude of about 20 kilometers (12 miles). This limit is found at even greater heights with increasing velocity of the body. The upper altitude limit, where atmospheric heating plays the major role in determining the ship's hull temperature, lies at 150 kilometers (90 miles) for average meteoric speeds. An aircraft cruising at presumable operational speeds will find itself in the state of pure radiation climate at altitudes ranging from 40 to 50 kilometers (25 to 30 miles).

THE FUNCTION OF SUPPLYING A FILTER AGAINST COSMIC FACTORS[5]

A large number of physical factors display themselves in extraterrestrial space. The most important of these factors are listed below in the order of their significance.

(a) Solar radiation (visible, heat, ultra-violet, x-rays, radio waves).

(b) Cosmic rays (protons, heavy primaries).

(c) Meteors

These factors differ considerably in their physical nature. Consequently, one must expect that, in meeting and traversing the terrestrial atmosphere, these factors will react in the most diverse fashion. Especially, we will find that the rate of conversion which these factors suffer in the atmosphere will be quite different for each factor. The extent of this conversion will depend greatly on the altitude. These considerations permit us to define functional borders of space by evaluating the filter effect of the atmosphere for each single factor.

Solar Radiation.—On a bright day the visible part of the solar spectrum is the only radiation capable of reaching the ground practically unimpaired.[12] More than 90 per cent of this radiation may occasionally pass the entire atmospheric filter. The blue of the sky that owes its appearance to the scattering of visible light through the action of air molecules. The brightness of the daylight sky decreases gradually with increasing altitudes and finally fades into the blackness of space. At an altitude of about 120 km (75 miles), the sky is as dark as that of a moonlit night at sea level. The last traces of daylight have vanished at an altitude of about 150 km (95 miles).

The infrared parts of solar radiation are affected to some extent by the absorptive action of water vapor, though the bulk of the extraterrestrial infrared radiation of the sun reaches down to the ground. So far as visible and infrared radiation from the sun are concerned, the earth's surface can be taken as the border of space.

Solar radio waves, up to a certain wave length (50 centimeters), i.e., the microwaves, pass the entire atmosphere without any appreciable loss in intensity, whereas longer electromagnetic waves ($>$ 50 centimeters) are almost entirely reflected back into space by the ionosphere. These waves could be observed at extremely high altitudes only.

The erythema-producing parts of the solar ultraviolet spectrum are almost entirely blocked by the ozone layer extending between the 15 and 30 kilometer levels (9 and 18 miles). Above this altitude erythema of the skin and eyes could be produced in one-tenth the time required to produce the same effects at sea level. From the standpoint of erythematic effects of ultraviolet radiation, the conditions to be encountered in space exist at altitudes as low as the upper border of the bulk of the atmospheric ozone.

Proceeding to still shorter wave lengths the photoelectrical and photochemical effectiveness of the radiation becomes greater. Consequently, lesser air equivalents are necessary to cut off these radiations. This means in terms of our concept that the borders of space lie higher and higher when proceeding from ultraviolet radiation to soft x-rays. No trace of such radiation can be observed even at a height of 100 km. (60 miles). Only hard x-rays could again reach farther down into the 50 kilometers (30 miles) region, but they have not yet been observed. This does not disprove their existence, since solar radiation of this kind must be expected to vary extremely as to intensity and it will most probably be confined to brief periods of time (short time solar activity of isolated areas on the sun's surface).

Cosmic Radiation.—The primary particles of cosmic radiation cause extremely complex secondary and higher order nuclear events in colliding with the nuclei of the air atoms and molecules.[15,17,23] Practically no cosmic primaries reach the ground. In view of our concept we can omit the complexities of the secondary reactions and confine the discussion to the question at what altitudes an appreciable percentage of the original primaries, as they traverse space, may be found.

The frequency distribution of the cosmic primaries in atomic species (H:He:Heavier Elements — 0.79: 0.20:0.01) can be expected to correspond roughly to the cosmic abundance ratio of the elements. Owing to the tremendous energy of the primaries ($\sim$ 2 BeV per nucleon), they are characterized by an enormous energy dissipation in passing through matter. This energy dissipation is greater, if the kinetic energy of the individual particle is greater. Consequently, the lower limits to which a certain percentage of the primaries can penetrate exhibit a certain stratification according to atomic number and energy of the particles.

About one-half of the primary protons penetrate down to an altitude of approximately 20 kilometers (12 miles). The lower limit of the heavy primaries is about 21 kilometers (13 miles). Above this altitude their number increases considerably, while the heavier ones appear in the order of their weight and energy. Concerning the biological effects[23] of the primary cosmic particles one has to expect them to act similarly to radiation of the alpha particle type: quick energy dissipation with a correspondingly high concentration of ion pairs produced along short tracks. For the practical case it has to be considered further that man will not be exposed directly to the cosmic primaries but will be protected by the ship's hull. A protective screen that would absorb the heavy primaries entirely would have to be so thick as to be prohibitive for any self-propelled ship.* A certain amount of the heavy primaries would have to be absorbed by the passengers. In addition to this, bursts of secondary particles and γ-rays originating in the walls will find their way into the interior of the ship. Experiments on the biological effect of secondaries have been made by the use of optimal shielding above the specimen. It appears that certain biological effects can be produced under these conditions.[17]

Summing up, one can state that, from the standpoint of cosmic radiation, the borders of space are reached at the altitude of about 30 kilometers (18 miles).

Meteors.—The atmosphere absorbs meteors of virtually all sizes. Only the larger ones are capable of reaching the ground. The problem of meteors is a serious one, in view of possible collisions between a ship cruising at highest altitudes and these specimens of stray cosmic matter. Because of the considerable average velocity of the meteors (20 to 60 kilometers/seconds), (12 to 36 miles/seconds), such a collision would be catastrophic if the meteor involved exceeds a certain mass. In hitting a ship a meteor would instantaneously transform the major part of its kinetic energy into heat, vaporizing the steel of the hull at the point of impact to a greater or lesser degree.

Because of their tremendous velocities most meteors are vaporized and annihilated at great altitudes. The impact of atmospheric molecules and atoms upon the surface of the meteors and, in the denser layers, adiabatic and friction heating are responsible for the fast vaporization of the meteors. The event of a vaporizing meteor displays itself as a shooting star.

The great majority of meteors ranging between fine meteoric dust and particles weighing a gram or more, are annihilated before reaching the 80 to 90 kilometer level (50 to 56 miles). Occasionally meteors become visible at more than 150 kilometers (90 miles) above the earth's surface; most commonly, however, they appear at an altitude of 110 kilometers (70 miles). Above that altitude, those meteors which are a potential danger to space craft still have the bulk of their original kinetic energy.

THE FUNCTION OF SUPPLYING MECHANICAL SUPPORT

Since a lack of weight is an outstanding factor of environment in present and future flights in the upper atmosphere and in space, it is appropriate to discuss the phenomena of weight and weightlessness in relation to our problem.[6,8,11,13,14] It can be shown that these phenomena are governed by the interplay of gravitation, inertia, and outer forces related to the atmosphere.

The kinematic and dynamic conditions of a body moving in space are

*Contrary to the case of a self-propelled ship it would be thinkable to provide shielding for the crew of an artificial satellite.

characterized by the lack of friction, since any mechanically noticeable medium is absent. These conditions permit us to treat the motion of the stars by applying the well-known Newtonian equations of celestial mechanics. The solution of these equations leads to certain trajectories which the bodies follow in their motion through space. The distribution of masses in the solar system is such that Keplerian orbits (i.e., the conical sections: circle, ellipse, parabola, hyperbola, and the straight line) result in a high degree of approximation.

In the absence of frictional and propelling force (rocket engine) the body moves under the influence of its own inertia and the resultant gravitational forces only. According to the principle of d'Alembert the forces of inertia and gravitation exactly eliminate each other. A body is without weight under these circumstances. These conditions are valid only in the emptiness of space. Since our problem concerns the border-area of space, namely, the atmosphere, we have to deal with the influence of the atmosphere upon the motion of the body.

It follows from this point of view that the weight of the body depends on the extent to which it is allowed to move along its celestial trajectory that would result from the gravitational field of forces. Any kind of support arising from lifting, frictional, or propelling forces lends weight to the body by destroying the equilibrium between the forces of gravitation and inertia. Consequently, in deriving the conditions of weight and weightlessness we have to discuss the nature of lifting and frictional forces, and the propelling forces of the rocket engine.

Let δ_a be the air's density, v the velocity of the craft, and A a suitable area of reference (for instance, cross-section of the exhaust) then any aerodynamical force F can be described by

$$F=\delta_a.v^2..A.k \qquad (1)$$

wherein Σk represents the sum of all spective force. The vectorial sum of all aerodynamical forces may be written as:

$$\Sigma F=\delta_a.v^2.A.\Sigma k \qquad (2)$$

wherein Σk represents the sum of all coefficients. It may be noted that Σk does not vanish; Σk becomes meaningless if δ_a or v becomes equal to zero. The thrust of a rocket engine can be expressed by

$$T=\delta_g.c^2.A \qquad (3)$$

wherein δ_g is the density of the exhaust gases, c the exhaust velocity and A the cross-section of the exhaust. The acceleration resulting from the lifting, frictional, and propelling forces can be written as

$$a_F+a_T=a=\frac{\Sigma F+T}{m}=[\delta_a.v^2.\Sigma k+\delta_g.c^2].\frac{A}{m} \qquad (4)$$

in which m is the mass of the rocket.

Equation 4 can be multiplied by the fraction l/l, l being a linear element, and we arrive at

$$a_F+a_T=a=\frac{\delta_a}{\delta_b}.\frac{v^2}{l}.\Sigma k+\frac{\delta_g}{\delta_b}.\frac{c^2}{l} \qquad (5)$$

in which δ_b represents $\frac{m}{A.l}$. δ_b is a measure of the specific density of the rocket.

If a in equation 5 assumes the value g (981 cm/sec²) the conditions inside the craft are those of normal gravity.

In a rocket aircraft, for instance, which flies at a constant velocity parallel to the ground, the various factors in the right side of equation 5 are such that a becomes equal to g. However, as a in equation 5 vanishes, the gravity free state will result.

A detailed analysis of the interrelation of the various factors involved shows that gravity or the lack of gravity can be realized by a number of combinations of the different variables. These combinations represent a certain functional set of conditions causing distinct values of gravity including zero.

Equation 5 consists of two summands a_T and a_F. The possible values a_T and a_F can assume, are illustrated in the following scheme:

	$a_F=0$	$a_F\neq 0$
$a_T=0$	I	II
$a_T\neq 0$	III	IV

As indicated by this scheme, there are four different combinations of a_T and a_F which represents three characteristic categories.

$a=0$; zero gravity	I
$a\neq 0$ gravity	II, III
$a\neq 0$; gravity; or, in the special case $a_T=-a_F$ $a=0$; zero gravity	IV

I. Zero gravity.

$a_T=0$
$a_F=0$

These conditions prevail if:

1. $c=0$, and $\delta_a=0$, or
2. $c=0$ and, $v=0$

1 is the case of a craft coasting outside the atmosphere.

2 is the case of a body falling freely at the very beginning of its motion. It may be noted that, simultaneously, δ_a may have any value. Obviously a parachutist jumping from a balloon belongs to this case for an infinitesimal time.

II. Gravity

$a_T=0$
$a_F\neq 0$

These conditions prevail if:

$c=0$ and, $\delta_a\neq 0; v\neq 0$

This case represents a rocket craft coasting within the atmosphere. Lifting and frictional forces provide weight.

III. Gravity

$a_T\neq 0$
$a_F\neq 0$

These conditions prevail if:

1. $c\neq 0$ and, $v=0$; $\delta_a\neq 0$
2. $c\neq 0$ and, $\delta_a=0$; $v\neq 0$

1. is the case of a rocket craft at the moment of take-off.
2. is the case of a rocket craft outside the atmosphere with operating engine cruising at any desired speed.

IV. Gravity; zero gravity.

$a_T\neq 0$
$a_F\neq 0$

1. Gravity prevails under these conditions, since we are dealing with the case of normal propelled flight within the atmosphere.
2. The condition of zero gravity can be realized under the special condition that $a_F=-a_T$. Speaking in terms of physics it means that the propelling forces balance the lifting and frictional forces. It follows automatically from these conditions that the craft is forced to describe a celestial trajectory inside the atmosphere. It may be noted that this case is the only practicable possibility of maintaining the zero-gravity state for some length of time within the atmosphere.[13]

It may be noted, that the density δ_b of the body is of some significance, if it assumes extreme values. The gravity of a body of great density will be less as compared to a body of small density under the same conditions.

From the foregoing it becomes evident that the phenomena of weight and weightlessness are not principally topographical in nature. As was shown in Case III-2, the engines of a craft can provide weight anywhere in space. On the other hand, as shown in Case I-2, and IV-2, gravity can be conditionally removed within the atmosphere of a planet. Naturally, the durations of the gravity free state as represented by Case IV-2, are limited, since the velocity of a body moving along in a celestial trajectory are such that the condition a_T—a_F cannot be maintained technically for more than 30 to 45 seconds.[13]

At high altitudes, however, the density of the air decreases. Consequently the condition of Case IV-2, can be maintained for longer periods of time and finally Case I-1 is realized if δ_a approaches zero. Owing to the decreasing support of the atmosphere with increasing altitude the borders of space from the viewpoint of weight and weightlessness are not sharply defined.

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From what has been said in the foregoing we have indeed to conclude that an appraisal of the technical and medical problems of space flight from strictly topographical viewpoints is misleading.

In contrast to this, a functional interpretation reveals that at relatively low altitudes we will encounter or can produce conditions typical of space.

In view of this concept, space flight ceases to be a premature topic. For limited periods of time, manned rocket crafts of today are capable of cruising at heights where the various attributes of space are approximated to a very high degree. Space flight, as we have it today, differs in only one point from space travel in its usual, commonly accepted, meaning: at the present time it is still limited to durations of the order of minutes.

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(Continued on page 357)

Where Does Space Begin?

(Continued from page 349)

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