What Holds the Stars Together?

Gravitation, the all-pervading force

By **Alfred J. Lotka**

A HEALTHY man weighing three grains? Ridiculous! Nevertheless, it is true.

You see, it all depends. Weight is a relative thing. The earth pulls you down with a force of, say, 150 pounds weight in New York. But, at the same time, the moon in the sky is pulling you up, and so far as the moon is concerned you weigh, at New York, about three grains—about as much as a fly.

The Moon Constantly Pulls Us

The reason why you weigh so little relatively to the moon is that the moon is only about one eightieth of the earth in mass, and that it is so far away—about sixty times as far from New York as that city is from the center of the earth. Still, even so, and at that distance, the moon is constantly pulling you toward her with this weight of three grains. You do not notice it because the earth is holding you down with so much greater force. But if the earth and the sun were suddenly removed and all motion were arrested, leaving you hanging in space, you would immediately begin to fall toward the moon. It would not be a very hasty fall, it is true—at least, not at first. You would have plenty of time to think about your misfortune, for it would take you over two minutes to fall one foot! You would, in fact, be quite unconscious at first that you were falling. Still, when, after a long time, you reached the surface of the moon, you would have gained speed, and you would land there at the rate of 7,780 feet per second. (So, after all, it is well the earth does not suddenly abandon you to the attraction, gentle but firm, of the moon.)

By the time you reached the moon you would weigh twenty-five pounds; and you would astonish the natives by unheard-of acrobatic feats

As you approached the moon not only your speed but also your weight would increase. You would not regain your full earthly dignity of 150 pounds, but at least you would be saved the humiliation of those miserable three grains. By the time you reached the surface of the moon, supposing you were somehow able to break your fall, you would step about lightly in your new surroundings with a weight of 25 pounds. You would astonish the natives (if there were any) by jumping over their houses and performing other unheard-of acrobatic feats.

However, the moon is not a healthy place to stay on. Temperature conditions are very uncomfortable, and there is no air. So we are not much interested in any athletic prowess which we might develop there.

The case is a little different with the planet Mars. According to Percival Lowell, Mars is probably inhabited. Now, on Mars a 150-pound earth-man would weigh about 53 pounds, say in round numbers about one third of his earth weight. Here is a problem: How big could nature afford to build a Martian man without putting a greater load on every square inch of the soles of his feet than a 150-pound earth-man rests on his? The answer is that the Martian could be made three times as tall, say 17 feet 6 inches. For if he stood on the earth his weight would then be 3x3x3x150 = 4,050 pounds; but on Mars it will be only 1,350 pounds.

If an ordinary man touches the ground with his feet over an area of about 50 square inches, our Martian would stand on 3x3x50 = 450 square inches. If, then, we figure out the number of pounds borne by each square inch, we find for the ordinary man on earth 150 ÷ 50 = 3 pounds. For the Martian 17 feet 6 inches high we find 1,350 ÷ 450 = 3 pounds, just the same. We see, therefore, that the Martian could be built on three times the scale in height, breadth, and depth as an ordinary man; and though he would, on earth, weigh more than two tons, this would not put any greater tax on his feet on Mars than that which is normal for us on earth. Yet this Martian giant, though in no way encumbered by his own weight, would be twenty-seven times as powerful as an earth-man. In certain special operations where the work consists in overcoming gravity, such as digging canals, he could accomplish 3x27 = 81 times as much as an earth-man on earth, since Martian gravity is only one third that of the earth.*

On the moon and on Mars gravity is less than on the earth. On the planet Jupiter it is more than 2½ times as great as here. A 150-pound earth-man on Jupiter would be weighed down with a load of 390 pounds. Walking would be a very tiring process. On the sun gravity is more than 27 times that on earth. If the sun were solid and the temperature such as to permit the presence of life, an earth-man on its surface would not only be utterly unable to rise into a standing position, but even when lying flat on his back he would be crushed by his own weight of more than two tons. If there were sun-men they would not exceed 2½ inches in height.

Influences Every Phase of Life

So then the size of man, and of every living creature, is determined, among other things, by gravitation. But that is only a minor detail.

Gravitation has a fundamental influence on every phase of life. What makes a plant shoot its stem upward, its branches sideways, its roots down into the soil? Gravitation—at least, in part. What keeps the earth shrouded in the atmosphere from which you draw your life-breath? Gravitation. What keeps the earth from flying off at her speed of 18½ miles per second into the dark recesses of space, where, far from the sun's warm rays, not only would all life perish from cold, but even the air would freeze solid? And what holds

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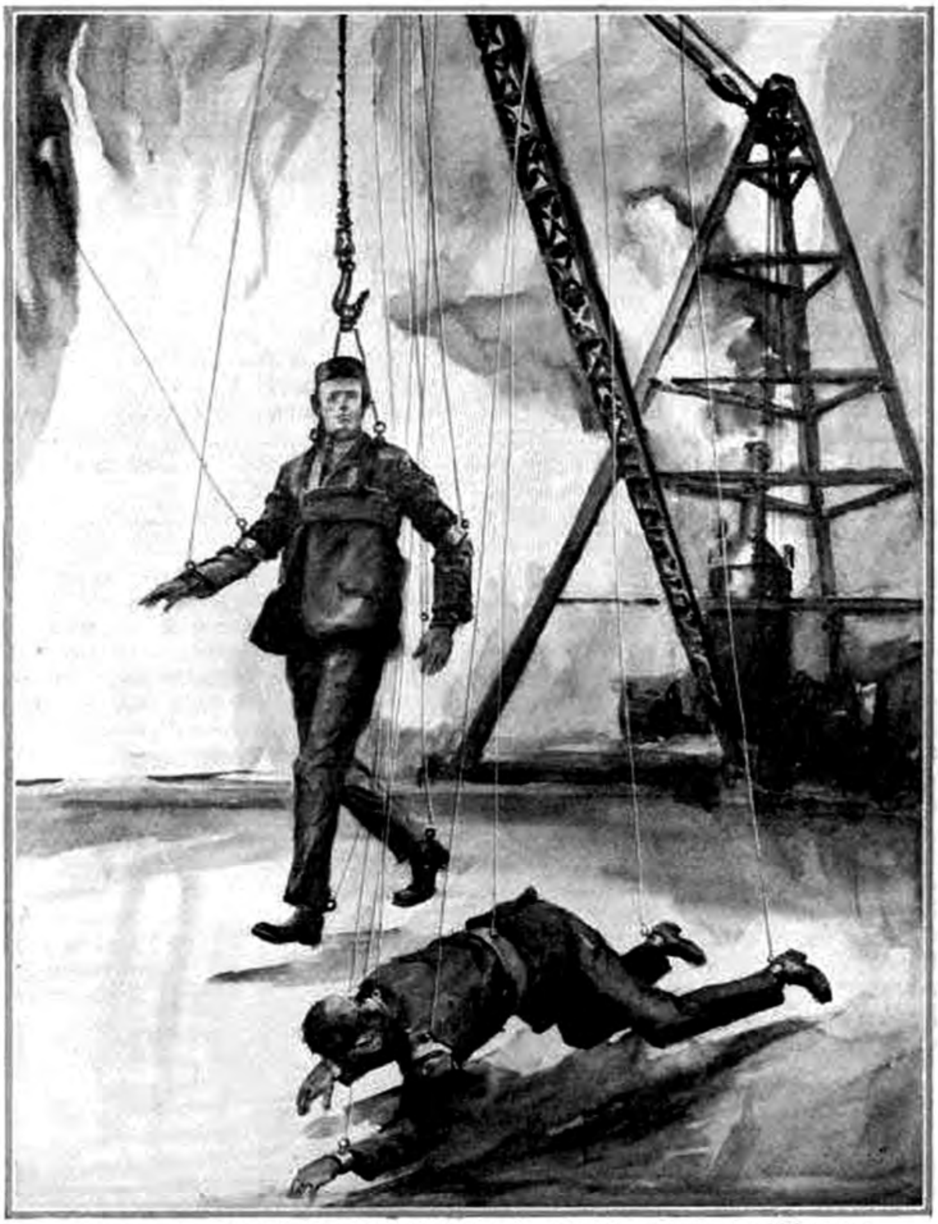
*This estimate is somewhat excessive because we have used the round figure 3 instead of the accurate 2.65; but it will serve to illustrate the principle.



A sun-man would be about 2½ inches tall. On the sun you would become an unwieldy giant, unable to rise to your feet or move in any way without the assistance of puppet-strings manipulated by high-power cranes

the moon in its course around the earth? Gravitation. And so on, indefinitely. How does it all come about? A partial answer at least can be given to some of these questions.

The response of plants to gravitation is strikingly illustrated in the life-plant, so called perhaps because of its extraordinary vitality. A single one of its leaves may be cut into thirty pieces, and from each piece, when sown on the moist ground or suspended in moist air, a new plant will grow. If a piece of the stalk of this plant is hung up horizontally in a moist atmosphere it starts to grow. But it grows all on one side, the lower face only, with the result that it acquires a curved outline. If we paint black marks or rings around the stem, it can be seen how the space between these remains unchanged at the upper face, but how the rings spread apart on the lower face in consequence of the growth. A seedling planted horizontally in a vertical surface of soil will very soon curve into an S shape, the stem growing upward, the root downward. The explanation of all these effects probably is that certain substances collect by their weight toward the bottom of certain parts of a plant, causing increased or diminished growth.

Not only plants but animals also display geotropism, as this property of being directed by the earth's gravitation is called. A certain aquatic animal known as the sea-cucumber, if placed on a flat plate, will keep on climbing vertically upward no matter how the plate is turned. The only thing that guides it is gravitation. There is no other inducement for it to seek the highest point in the plate.

Is man geotropic? He most certainly is, though in his case gravitation does not direct the course of his steps but merely regulates his erect position.

If you suppose that this does not require any special faculty, just call to mind the actions of a drunken man. How is the regulation accomplished? By means of a system of "spirit levels" carried in the head, the so-called semicircular canals of the inner ear. Injury to these canals causes more or less acute symptoms of dizziness or inability to maintain equilibrium.

Spirit Levels in Our Ears

The greatest freak in the matter of geotropism is a little crustacean known as Palæmon (the prawn). This creature has a most extraordinary method of solving the problem of keeping on an even keel. It possesses an apparatus similar to the spirit level of our inner ear, but within its liquid are little loose particles of grit, so-called otoliths or "ear-stones." It appears that these, by their pressure against the bottom or the sides of the space containing them, indicate to their owner whether he is steering an even course, or whether he is tilted this way or that. Now, the remarkable thing is this: At the time of moulting, Palæmon loses his otoliths or ear-stones. So what does he do? He coolly picks up sand from the bottom and puts it in his ears; and he goes on his way rejoicing, with the confidence of the man who has not touched a drop for a year. Even that does not exhaust Palæmon's repertoire of tricks. One ingenious biologist conceived the idea of giving Palæmon iron filings to put in his ears instead of sand. The obliging creature promptly inserted them, and lo and behold, Palæmon had developed a new sense: he responded to a magnet somewhat after the fashion of an animated compass needle! He had become magnetotropic.

To understand how the atmosphere is tied to the earth by gravitation, we must form a mental picture of a gas, such as the air. Can you call to mind the appearance of a swarm of gnats dancing in a sunbeam? How they flit to and fro and up and down with irregular motion? If your powers of sight could be increased about ten million times the air might present to you an appearance not unlike that swarm of gnats. For the air consists of innumerable particles (molecules) of diminutive size, flitting about and jostling each other, now colliding like billiard balls, now flying apart, now hitting against the solid objects of which the visible world is composed.

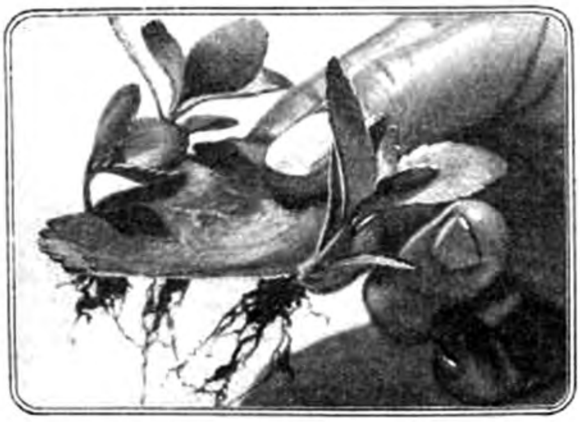
Just as would be the case with a jumble of billiard balls rolled at random on the table, the individual molecules have all kinds of different speeds. But the average speed of a large number of them is definite, and depends on the temperature. At 60° F. the average speed of the molecules of the air is about 1,500 feet, or something over ¼ mile, per second.

Now, if you read the article in the

April issue of POPULAR SCIENCE MONTHLY on "Hurling a Man to the Moon," you may remember that to shoot a body off the earth so that it will never return requires a velocity of about seven miles per second. You will therefore see that a molecule of the air, at the average speed at 60 degrees, can never leave the earth.

This is not saying that some of the more rapidly moving molecules might not do so. However, it can be shown by a complicated calculation that, if the earth loses any of its atmosphere at all, the loss is so slow that even after millions of years it would not be noticeable.

So then the inhabitants of our globe are guaranteed against an air famine for many generations to come. How about the other planets? Computation shows that they too are provided for, though Mars is losing or has lost its hydrogen and helium, both of which are much lighter than air. The moon, on the other hand, is quite unable to hold an atmosphere, and is well known to be devoid of any.



The same force that keeps the earth from flying off into space makes a plant shoot its roots down, its stem up, and its branches sideways. This response of a plant to gravitation is particularly marked in the life-plant, so called because from a single leaf thirty new plants may grow

Weight Is a Relative Thing

The earth's gravitational pull falls off as the distance increases. A stone weighing one pound at the earth's surface, four thousand miles away from the center, will weigh only one quarter of a pound if taken to a point out in space four thousand miles from the surface or eight thousand miles from the center. In other words, if the distance from the center of the earth is doubled, gravitative attraction is reduced in the proportion of 1 to the square of ½. This is the law discovered by Newton.

But if, instead of going out into space, we make a deep bore-hole in the earth, how will gravity vary as we go down?

If the earth were a uniform perfect sphere, gravity would decrease as you go down into it. But, as a matter of fact, the central portion of the earth is more than twice as dense as the crust, and for this reason the weight of a body increases as you go down; though, if you could go far enough, a point would undoubtedly be reached where gravity would begin to drease, becoming zero at the earth's center.

Weight is a relative thing. It changes not only as you burrow into the earth or fly out into space, but it even changes from point to point as you travel on the earth's surface. If your weight were 150 pounds at the North Pole, it would decrease by three quarters of a pound as you traveled to the Equator. There are two reasons for this change in weight. One is that, owing to the flattening of the earth at the poles, you are nearer its center there than at the Equator. The other is that at the Equator, owing to the earth's rotation, you are carried around in a circle with a velocity of about seventeen miles a minute, and a part of the earth's pull is spent in keeping you from flying off at a tangent. This part of the earth's attraction, about one three-hundredth of your weight, is not indicated by any kind of balance.

Supposing the earth were all alone in space, you could not tell by looking at the stars whether it was rotating or not. You would not know whether your weight was 150 pounds on a stationary earth, or 300 pounds on an earth revolving with such speed that one half your weight was taken off your feet by centrifugal action. In other words, you would have no way of distinguishing between gravitational force and the effect of inertia.

This inability to distinguish between gravitational and inertia effects is the root of the modern theory of gravitation. It is impossible to enter here into the details of a rather abstruse mathematical argument. But perhaps some indication of the nature of the theory can be given by stating that according to this theory the presence of a portion of matter, such as the earth, produces a kind of strain in space.

The theory has, so far, yielded one important concrete result. It accounts for certain observed irregularities in the motion of the planet Mercury which could not be explained in any other way.

The Moon's Grip on the Earth

Although, as we saw, the moon's gravitation is insufficient to hold the elusive molecule, it gives her a grip upon the earth, the strength of which may be illustrated as follows: If, instead of gravitation, we had to rely upon a steel bar to tie the moon to the earth, this bar, 240,000 miles long, would need to have a diameter of 225 miles to sustain the pull required to keep the

A Martian giant could be over seventeen feet high without putting any undue strain on his feet. In the way of digging he could do the work of fifty men on the earth. On the sun you would have to be shrunk to two and a half inches if you wished to retain an upright posture without strain

moon circling around the earth! If the moon is being constantly pulled with this great force, why does it not fall to the earth?

The answer may be a little surprising. The moon does fall; it falls about one nineteenth of an inch every second. This does not mean that it is approaching the earth. But, instead of traveling on in a straight line, as it would without the deviating effect of gravitation, it is as it were, drawn aside by one nineteenth of an inch every second and thereby kept circling in its path around the earth.

By the way, why should the moon complete its cycle between two full moons in 29½ days? Has the lunar month always been of this length? And where did the moon come from?

These are not idle questions. The astronomer has an answer ready for them. The clue to the mystery is found in the tides. The moon, by her gravitational pull, raises on the earth two tides, one on the near side, the other on the far side. Between these two the earth rotates as between two brake-shoes. The obvious result is a very gradual slowing down of the earth's rotation. A little less obvious is the reaction on the moon. As the moon in its revolution lags behind the faster-moving earth, the first effect would be for the earth to hasten on the moon in its travel. But, instead of giving way directly to this impulse, the moon recedes farther away from the earth, and actually slows down. The net result is a gradual lengthening of the day, and at the same time a more rapid lengthening of the month, while the moon is slowly, very slowly, getting farther and farther away from the earth.

But if the moon is moving away from the earth, then formerly it must have been nearer to it; and if we go back far enough in time, what then?

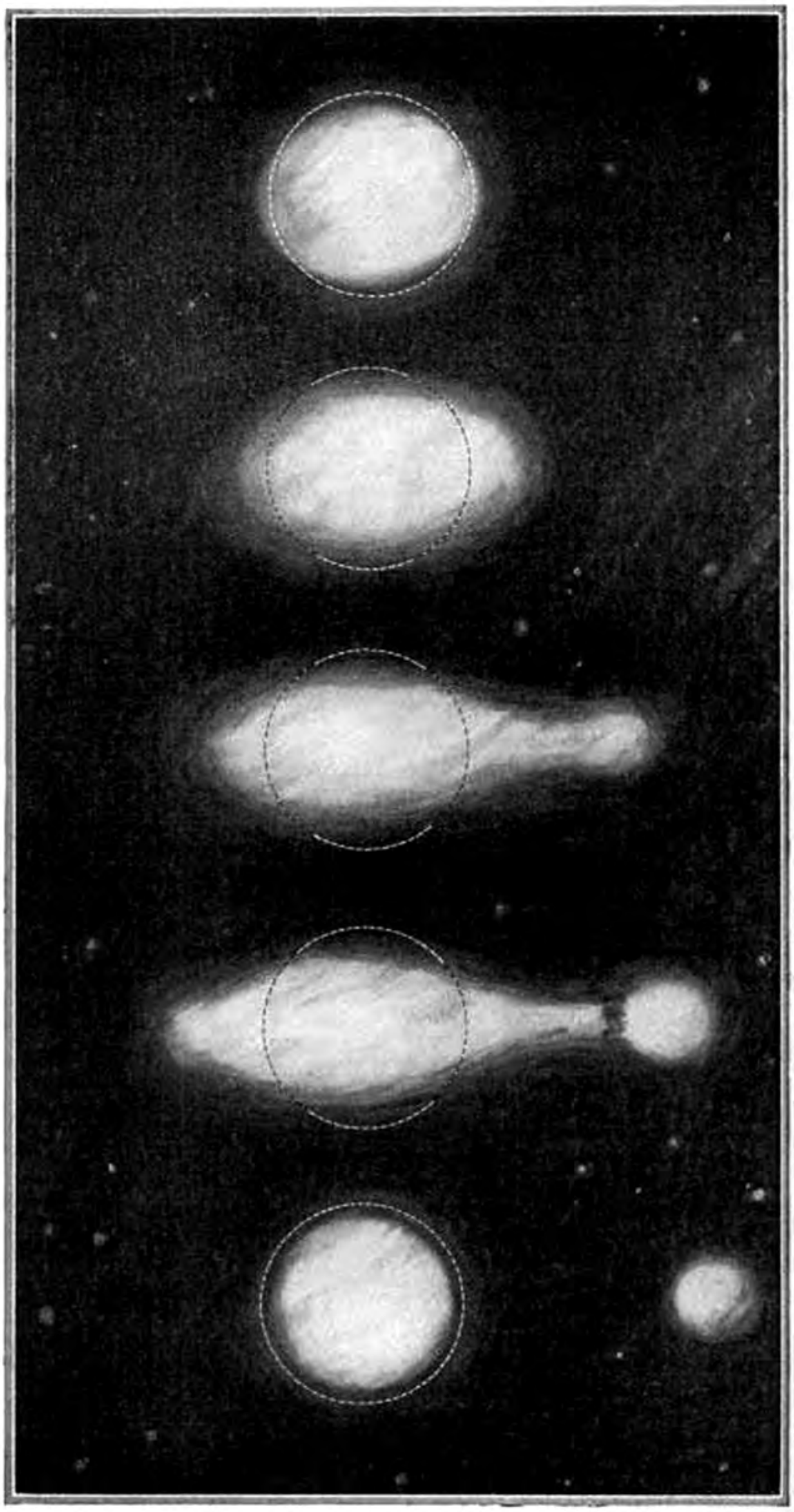
Now, this is not a matter of guess-work. Astronomers can compute these things. When the day was about three hours long, the month was also three hours, and the moon was grazing the earth. In other words, the moon was originally part of the earth, and was thrown off by some catastrophe. What was the cause of this catastrophe?

The Birth of the Moon

Here also the astronomer is ready with an answer. The earth is more or less plastic. In those days it may have been more so than it is now. It may have been largely liquid. Now, a plastic or liquid body of the shape of the earth is capable of vibrating, somewhat like a church-bell. Such a bell has a definite period or frequency, so many vibrations per second, according to its size and pitch. In the same way, the earth has a natural period of vibration, which can be approximately computed. It is found to be about 1½ hours for one vibration.

Now the sun raises two tides in a day. In the three-hour day it raised a tide every 1½ hours. But this is the natural period of vibration of the liquid earth. The globe, under these conditions, was thrown into gigantic pulsations of ever-increasing violence. Year by year the vast wave stormed to greater and yet greater heights. This world of ours, so solid now under our feet, was throbbing as if its heart-beats would rend it.

And then, one fateful day, the gathering flood rose as a great mountain to the sky, and out of the surging tide the far-flung moon was born.



The Birth of the Moon

This illustration shows in general principle (though not in scale) the process by which, many millions of years ago, the moon was thrown off from the earth by tidal action. The several pictures represent successive stages in the vibration that culminated in the throwing off of the moon.

"The day was at that time about three hours long. Now the sun raises two tides a day. In the three-hour day it raised a tide every ninety minutes. But this is the natural period of vibration of the liquid earth.

"The globe, under these conditions, was thrown into gigantic pulsations of ever-increasing violence. Year by year the vast flood stormed to greater and yet greater heights. This world of ours, so solid now under our feet, was throbbing as if its heart-beats would rend it. And then, one fateful day, the gathering flood rose as a great mountain to the sky, and out of the surging tide the far-flung moon was born"