Undoubtedly, any astronomers stationed on the Tenth Planet would completely ignore the planets. Any other world in the system would give them a better view. But they would watch the stars. The Tenth Planet would offer them the largest parallaxes in the system, because of its mighty orbital sweep. (Of course, they would have to wait 340 years to get the full parallax.) Measurements of stellar distance by parallax, the most reliable of all methods for the purpose, could be extended one hundred times deeper into space than is now possible.

One last point. What ought we to name the Tenth Planet? We've got to stick to classical mythology by long and revered custom. With the Ninth Planet named Pluto, there might be a temptation to name the Tenth after his consort Proserpina, but that temptation must be resisted. Proserpina is the inevitable name for any satellite of Pluto's that may ever be discovered and should be rigidly reserved for that.

However, consider that the Greeks had a ferryman that carried the souls of the dead across into Hades, the abode of Pluto and Proserpina. His name was Charon. There was also a three-headed dog guarding the entrance of Hades, and its name was Cerberus.

My suggestion then is that the Tenth Planet be named Charon and that its first discovered satellite be named Cerberus.

And then any interstellar voyager returning home and approaching the Solar System on the plane of the ecliptic would have to cross the orbit of Charon and Cerberus to reach the orbit of Pluto and Proserpina. What could be more neatly symbolic than that?

9

JUST MOONING AROUND

Almost every book on astronomy I have ever seen, large or small, contains a little table of the Solar System. For each planet, there's given its diameter, its distance from the sun, its time of rotation, its albedo, its density, the number of its moons, and so on.

Since I am morbidly fascinated by numbers, I jump on such tables with the perennial hope of finding new items of information. Occasionally, I am rewarded with such things as surface temperature or orbital velocity, but I never really get enough.

So every once in a while, when the ingenuity-circuits in my brain are purring along with reasonable smoothness, I deduce new types of data for myself out of the material on hand, and while away some idle hours. (At least I did this in the long-gone days when I had idle hours.)

I can still do it, however, provided I put the results into formal essay-form; so come join me and we will just moon around together in this fashion, and see what turns up.

Let's begin this way, for instance . . .

According to Newton, every object in the universe attracts every other object in the universe with a force (f) that is proportional to the product of the masses (m_1 and m_2) of the two objects divided by the square of the distance (d) between them center to center. We multiply by the gravitational constant (g) to convert the proportionality to an equality, and we have:

$$f = \frac{gm_1m_2}{d^2} \qquad \text{(Equation 12)}$$

This means, for instance, that there is an attraction between the Earth and the Sun, and also between the Earth and the Moon and between the Earth and each of the various planets and, for that matter, between the Earth and any meteorite or piece of cosmic dust in the heavens.

Fortunately, the Sun is so overwhelmingly massive compared with everything else in the Solar System that in calculating the orbit of the Earth, or of any other planet, an excellent first approximation is attained if only the planet and the Sun are considered, as though they were alone in the Universe. The effect of other bodies can be calculated later for relatively minor refinements.

In the same way, the orbit of a satellite can be worked out first by supposing that it is alone in the Universe with its primary.

It is at this point that something interests me. If the Sun is so much more massive than any planet, shouldn't it exert a considerable attraction on the satellite even though it is at a much greater distance from that-satellite than the primary is? If so, just how considerable is "considerable"?

To put it another way, suppose we picture a tug of war going on for each satellite, with its planet on one side of the gravitational rope and the Sun on the other. In this tug of war, how well is the Sun doing?

I suppose astronomers have calculated such things, but I have never seen the results reported in any astronomy text, or the subject even discussed, so I'll do it for myself.

Here's how we can go about it. Let us call the mass of a satellite m, the mass of its primary (by which, by the way, I mean the planet it circles) m_p, and the mass of the Sun m_s. The distance from the satellite to its primary will be d_p and the distance from the satellite to the Sun will be d_s. The gravitational force between the satellite and its primary would be f_p and that between the satellite and the Sun would be f_s—and that's the whole business. I promise to use no other symbols in this chapter.

From Equation 12, we can say that the force of attraction between a satellite and its primary would be:

$$f_p = \frac{gmm_p}{d_p^2} \qquad \text{(Equation 13)}$$

while that between the same satellite and the Sun would be:

$$f_s = \frac{gmm_s}{d_s^2} \qquad \text{(Equation 14)}$$

What we are interested in is how the gravitational force between satellite and primary compares with that between satellite and Sun. In other words we want the ratio f_p/f_s, which we can call the "tug-of-war value." To get that we must divide equation 13 by equation 14. The result of such a division would be:

$$f_p/f_s = (m_p/m_s) \quad (d_s/d_p)^2 \qquad \text{(Equation 15)}$$

In making the division, a number of simplifications have taken place. For one thing the gravitational constant has dropped out, which means we won't have to bother with an inconveniently small number and some inconvenient units. For another, the mass of the satellite has dropped out. (In other words, in obtaining the tug-of-war value, it doesn't matter how big or little a particular satellite is. The result would be the same in any case.)

What we need for the tug-of-war value (f_p/f_s), is the ratio of the mass of the planet to that of the sun (m_p/m_s) and the square of the ratio of the distance from satellite to Sun to the distance from satellite to primary $(d_s/d_p)^2$.

There are only six planets that have satellites and these, in order of decreasing distance from the Sun, are: Neptune, Uranus, Saturn, Jupiter, Mars, and Earth. (I place Earth at the end, instead of at the beginning, as natural chauvinism would dictate, for my own reasons. You'll find out.)

For these, we will first calculate the mass-ratio and the results turn out as in Table 21.

As you see, the mass ratio is really heavily in favor of the Sun. Even Jupiter, which is by far the most massive planet, is not quite one-thousandth as massive as the Sun. In fact, all the planets together (plus satellites, planetoids, comets, and meteoric matter) make up no more than 1/750 of the mass of the Sun.

Table 21

PLANET	RATIO OF MASS OF PLANET TO MASS OF SUN
Neptune	0.000052
Uranus	0.000044
Saturn	0.00028
Jupiter	0.00095
Mars	0.00000033
Earth	0.0000030

So far, then, the tug of war is all on the side of the Sun.

However, we must next get the distance ratio, and that favors the planet heavily, for each satellite is, of course, far closer to its primary than it is to the Sun. And what's more, this favorable (for the planet) ratio must be squared, making it even more favorable, so that in the end we can be reasonably sure that the Sun will lose out in the tug of war. But we'll check, anyway.

Let's take Neptune first. It has two satellites, Triton and Nereid. The average distance of each of these from the Sun is, of necessity, precisely the same as the average distance of Neptune from the Sun, which is 2,797,000,000 miles. The average distance of Triton from Neptune is, however, only 220,000 miles, while the average distance of Nereid from Neptune is 3,460,000 miles.

If we divide the distance from the Sun by the distance from Neptune for each satellite and square the result we get 162,000,000 for Triton and 655,000 for Nereid. We multiply each of these figures by the mass-ratio of Neptune to the Sun, and that gives us the tug-of-war value, in Table 22:

Table 22

SATELLITE	TUG-OF-WAR RATIO
Triton	8,400
Nereid	34

The conditions differ markedly for the two satellites. The gravitational influence of Neptune on its nearer satellite, Triton, is overwhelmingly greater than the influence of the Sun on the same satellite. Triton is firmly in Neptune's grip. The outer satellite, Nereid, however, is attracted by Neptune considerably, but *not* overwhelmingly, more strongly than by the Sun. Furthermore, Nereid has a highly eccentric orbit, the most eccentric of any satellite in the system. It approaches to within 800,000 miles of Neptune at one end of its orbit and recedes to as far as 6 million miles at the other end. When most distant from Neptune, Nereid experiences a tug-of-war value as low as 11!

For a variety of reasons (the eccentricity of Nereid's orbit, for one thing) astronomers generally suppose that Nereid is not a true satellite of Neptune, but a planetoid captured by Neptune on the occasion of a too-close approach.

Neptune's weak hold on Nereid certainly seems to support this. In fact, from the long astronomic view, the association between Neptune and Nereid may be a temporary one. Perhaps the disturbing effect of the solar pull will eventually snatch it out of Neptune's grip. Triton, on the other hand, will never leave Neptune's company short of some catastrophe on a System-wide scale.

There's no point in going through all the details of the calculations for all the satellites. I'll do the work on my own and feed you the results. Uranus, for instance, has five known satellites, all revolving in the plane of Uranus's equator and all considered true satellites by astronomers. Reading outward from the planet, they are: Miranda, Ariel, Umbriel, Titania, and Oberon.

The tug-of-war values for these satellites are given in Table 23:

Table 23

SATELLITE	TUG-OF-WAR RATIO
Miranda	24,600
Ariel	9,850
Umbriel	4,750
Titania	1,750
Oberon	1,050

All are safely and overwhelmingly in Uranus's grip, and the high tug-of-war values fit with their status as true satellites.

We pass on, then, to Saturn, which has ten satellites: Janus,* Mimas,

* The satellite Janus was discovered four years after this article was first published, so it wasn't included. I am adding it now.

Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, and Phoebe. Of these, the eight innermost revolve in the plane of Saturn's equator and are considered true satellites. Phoebe, the ninth, has a highly inclined orbit and is considered a captured planetoid.

The tug-of-war values for these satellites are given in Table 24:

Table 24

SATELLITE	TUG-OF-WAR RATIO
Janus	23,000
Mimas	15,500
Enceladus	9,800
Tethys	6,400
Dione	4,150
Rhea	2,000
Titan	380
Hyperion	260
Iapetus	45
Phoebe	3½

Note the low value for Phoebe.

Jupiter has twelve satellites and I'll take them in two installments. The first five: Amaltheia, Io, Europa, Ganymede, and Callisto, all revolve in the plane of Jupiter's equator and all are considered true satellites. The tug-of-war values for these are given in Table 25:

Table 25

SATELLITE	TUG-OF-WAR RATIO
Amaltheia	18,200
Io	3,260
Europa	1,260
Ganymede	490
Callisto	160

and all are clearly in Jupiter's grip.

Jupiter, however, has seven more satellites which have no official names, and which are commonly known by Roman numerals (from VI to XII) given in the order of their discovery. In order of distance from Jupiter, they are VI, X, VII, XII, XI, VIII, and IX. All are small

and with orbits that are eccentric and highly inclined to the plane of Jupiter's equator. Astronomers consider them captured planetoids. (Jupiter is far more massive than the other planets and is nearer the planetoid belt, so it is not surprising that it would capture seven planetoids.)

The tug-of-war results for these seven certainly bear out the captured planetoid notion, as the values given in Table 26 show:

Table 26

SATELLITE	TUG-OF-WAR RATIO
VI	4.4
X	4.3
VII	4.2
XII	1.3
XI	1.2
VIII	1.03
IX	1.03

Jupiter's grip on these outer satellites is feeble indeed.

Mars has two satellites, Phobos and Deimos, each tiny and very close to Mars. They rotate in the plane of Mars's equator, and are considered true satellites. The tug-of-war values are given in Table 27.

So far I have listed 31 satellites, of which 22 are considered true satellites and 9 are usually tabbed as (probably) captured planetoids.* I would like, for the moment, to leave out of consideration the 32nd satellite, which happens to be our own Moon (I'll get back to it, I promise) and summarize the 31 in Table 28:

Table 27

SATELLITE	TUG-OF-WAR RATIO
Phobos	195
Deimos	32

Table 28

	NUMBER OF SATELLITES	
PLANET	TRUE	CAPTURED
Neptune	1	1
Uranus	5	0
Saturn	9	1
Jupiter	5	7
Mars	2	0

* I am including Janus in the list, remember, although it was unknown when the article first appeared.

And now let's analyze this list in terms of tug-of-war values. Among the true satellites the lowest tug-of-war value is that of Deimos, 32. On the other hand, among the nine satellites listed as captured, the highest tug-of-war value is that of Nereid with an average of 34.

Let us accept this state of affairs and assume that the tug-of-war figure 30 is a reasonable minimum for a true satellite and that any satellite with a lower figure is, in all likelihood, a captured and probably temporary member of the planet's family.

Knowing the mass of a planet and its distance from the Sun, we can calculate the distance from the planet's center at which this tug-of-war value will be found. We can use Equation 15 for the purpose, setting f_p/f_s equal to 30, putting in the known values for m_p, m_s, and d_s, and then solving for d_p. That will be the maximum distance at which we can expect to find a true satellite. The only planet that can't be handled in this way is Pluto, for which the value of m_p is very uncertain, but I omit Pluto cheerfully.

We can also set a minimum distance at which we can expect a true satellite; or, at least, a true satellite in the usual form. It has been calculated that if a true satellite is closer to its primary than a certain distance, tidal forces will break it up into fragments. Conversely, if fragments already exist at such a distance, they will not coalesce into a single body. This limit of distance is called the "Roche limit" and is named for the astronomer E. Roche, who worked it out in 1849. The Roche limit is a distance from a planetary center equal to 2.44 times the planet's radius.*

So, sparing you the actual calculations, here are the results in Table 29 for the four outer planets:

Table 29

DISTANCE OF TRUE SATELLITE
(MILES FROM THE CENTER OF THE PRIMARY)

PLANET	MAXIMUM (TUG-OF-WAR=30)	MINIMUM (ROCHE LIMIT)
Neptune	3,700,000	38,000
Uranus	2,200,000	39,000
Saturn	2,700,000	87,000
Jupiter	2,700,000	106,000

* The Roche limit only holds true exactly for satellites of more than a certain size and a few other qualifications but we don't have to worry about that here.

As you see, each of these outer planets, with huge masses and far distant from the competing Sun, has ample room for large and complicated satellite systems within these generous limits, and the 22 true satellites all fall within them.

Saturn does possess something within Roche's limit—its ring system. The outermost edge of the ring system stretches out to a distance of 85,000 miles from the planet's center. Obviously the material in the rings could have been collected into a true satellite if it had not been so near Saturn.

The ring system is unique as far as visible planets are concerned, but of course the only planets we can see are those of our own Solar System. Even of these, the only ones we can reasonably consider in connection with satellites (I'll explain why in a moment) are the four large ones.

Of these, Saturn has a ring system and Jupiter just barely misses one. Its innermost satellite, Amaltheia, is about 110,000 miles from the planet's center, with the Roche limit at 106,000 miles. A few thousand miles inward and Jupiter would have rings. I would like to make the suggestion therefore that once we reach outward to explore other stellar systems we will discover (probably to our initial amazement) that about half the large planets we find will be equipped with rings after the fashion of Saturn.

Next we can try to do the same thing for the inner planets. Since the inner planets are, one and all, much less massive than the outer ones and much closer to the competing Sun, we might guess that the range of distances open to true satellite formation would be more limited, and we would be right. Here are the actual figures in Table 30 as I have calculated them:

Table 30

DISTANCE OF TRUE SATELLITE
(MILES FROM THE CENTER OF THE PRIMARY)

PLANET	MAXIMUM (TUG-OF-WAR=30)	MINIMUM (ROCHE LIMIT)
Mars	15,000	5,150
Earth	29,000	9,600
Venus	19,000	9,200
Mercury	1,300	3,800

Thus, you see, where each of the outer planets has a range of two million miles or more within which true satellites could form, the situation is far more restricted for the inner planets. Mars and Venus have a permissible range of but 10,000 miles. Earth does a little better, with 20,000 miles.

Mercury is the most interesting case. The maximum distance at which it can expect to form a natural satellite against the overwhelming competition of the nearby Sun is well within the Roche limit. It follows from that, if my reasoning is correct, that Mercury *cannot* have a true satellite, and that anything more than a possible spattering of gravel is not to be expected.

In actual truth, no satellite has been located for Mercury but, as far as I know, nobody has endeavored to present a reason for this or treat it as anything other than an empirical fact. If any Gentle Reader, with a greater knowledge of astronomic detail than myself, will write to tell me that I have been anticipated in this, and by whom, I will try to take the news philosophically. At the very least, I will confine my kicking and screaming to the privacy of my study.

Venus, Earth, and Mars are better off than Mercury and do have a little room for true satellites beyond the Roche limit. It is not much room, however, and the chances of gathering enough material over so small a volume of space to make anything but a very tiny satellite is minute.

And, as it happens, neither Venus nor Earth has any satellite at all (barring possible minute chunks of gravel) within the indicated limits, and Mars has two small satellites, each less than 20 miles across, which scarcely deserve the name.

It is amazing, and very gratifying to me, to note how all this makes such delightful sense, and how well I can reason out the details of the satellite systems of the various planets. It is such a shame that one small thing remains unaccounted for; one trifling thing I have ignored so far, but—

WHAT IN BLAZES IS OUR OWN MOON DOING WAY OUT THERE?

It's too far out to be a true satellite of the Earth, if we go by my beautiful chain of reasoning—which is too beautiful for me to abandon. It's too big to have been captured by the Earth. The chances of such a capture having been effected and the Moon then having taken up a nearly circular orbit about the Earth are too small to make such an eventuality credible.

There are theories, of course, to the effect that the Moon was once much closer to the Earth (within my permitted limits for a true satellite) and then gradually moved away as a result of tidal action. Well, I have an objection to that. If the Moon were a true satellite that originally had circled Earth at a distance of, say, 20,000 miles, it would almost certainly be orbiting in the plane of Earth's equator and it isn't.

But, then, if the Moon is neither a true satellite of the Earth nor a captured one, what is it?* This may surprise you, but I have an answer; and to explain what that answer is, let's get back to my tug-of-war determinations. There is, after all, one satellite for which I have not calculated it, and that is our Moon. We'll do that now.

The average distance of the Moon from the Earth is 237,000 miles, and the average distance of the Moon from the Sun is 93,000,000 miles. The ratio of the Moon—Sun distance to the Moon—Earth distance is 392. Squaring that gives us 154,000. The ratio of the mass of the Earth to that of the Sun was given earlier in the chapter and is 0.0000030. Multiplying this figure by 154,000 gives us the tug-of-war value, presented in Table 31:

Table 31

SATELLITE	TUG-OF-WAR RATIO
Moon	0.46

The Moon, in other words, is unique among the satellites of the Solar System in that its primary (us) *loses* the tug of war with the Sun. The Sun attracts the Moon twice as strongly as the Earth does.

We might look upon the Moon, then, as neither a true satellite of the Earth nor a captured one, but as a planet in its own right, moving about the Sun in careful step with the Earth. To be sure, from within the Earth-Moon system, the simplest way of picturing the situation is to have the Moon revolve about the Earth; but if you were to draw a picture of the orbits of the Earth and Moon about the Sun exactly to scale, you would see that the Moon's orbit is everywhere concave toward the Sun. It is always "falling" toward the Sun. All the other satellites, with-

* This article was written in 1963. It was hoped that once the Moon was actually reached, a study of its surface might tell us how it originated and whether it was captured or not. So far, however, although the Moon has been visited several times, no answer has been obtained. The information we have received offers more puzzles than answers.

out exception, "fall" away from the Sun through part of their orbits, caught as they are by the superior pull of their primary—but not the Moon.

And consider this—the Moon does not revolve about the Earth in the plane of Earth's equator, as would be expected of a true satellite. Rather it revolves about the Earth in a plane quite close to that of the ecliptic; that is, to the plane in which the planets, generally, rotate about the Sun. This is just what would be expected of a planet!

Is it possible then, that there is an intermediate point between the situation of a massive planet far distant from the Sun, which develops about a single core, with numerous satellites formed, and that of a small planet near the Sun which develops about a single core with no satellites? Can there be a boundary condition, so to speak, in which there is condensation about two major cores so that a double planet is formed?

Maybe Earth just hit the edge of the permissible mass and distance; a little too small, a little too close. Perhaps if it were better situated the two halves of the double planet would have been more of a size. Perhaps both might have had atmospheres and oceans and—life. Perhaps in other stellar systems with a double planet, a greater equality is more usual.

What a shame if we have missed that . . .

Or, maybe (who knows), what luck!

10

STEPPINGSTONES TO THE STARS

There's something essentially unsatisfactory to me about the conquest of the Solar System which now seems to be at hand.* We know too much about what we'll find, and what we'll find won't be enough.

After all, except for some possible lichenlike objects on Mars, the other worlds of the Solar System are all barren (barring a most unexpected miracle).

Sure, we'll get all sorts of information and knowledge. In the process of reaching these barren worlds, we'll develop valuable alloys, plastics, fuels. We'll work up useful techniques of miniaturization, automation, and computation. I wouldn't minimize any of these advances.

But—there will be no Martian princesses, no tentacled menaces, no superhumanly intelligent energy beings, no dreadful monsters to bring back to zoos. In short, there won't be any romance!

For the proper results and rewards of space travel, we must reach the stars. We must find the Earth-type planets that possibly circle them, car-

* This article first appeared in print in 1960 and shows me with my usual optimism. The Moon has been "conquered," to be sure, but how far we will be able to continue space exploration in the present mood of disenchantment, I can't say.