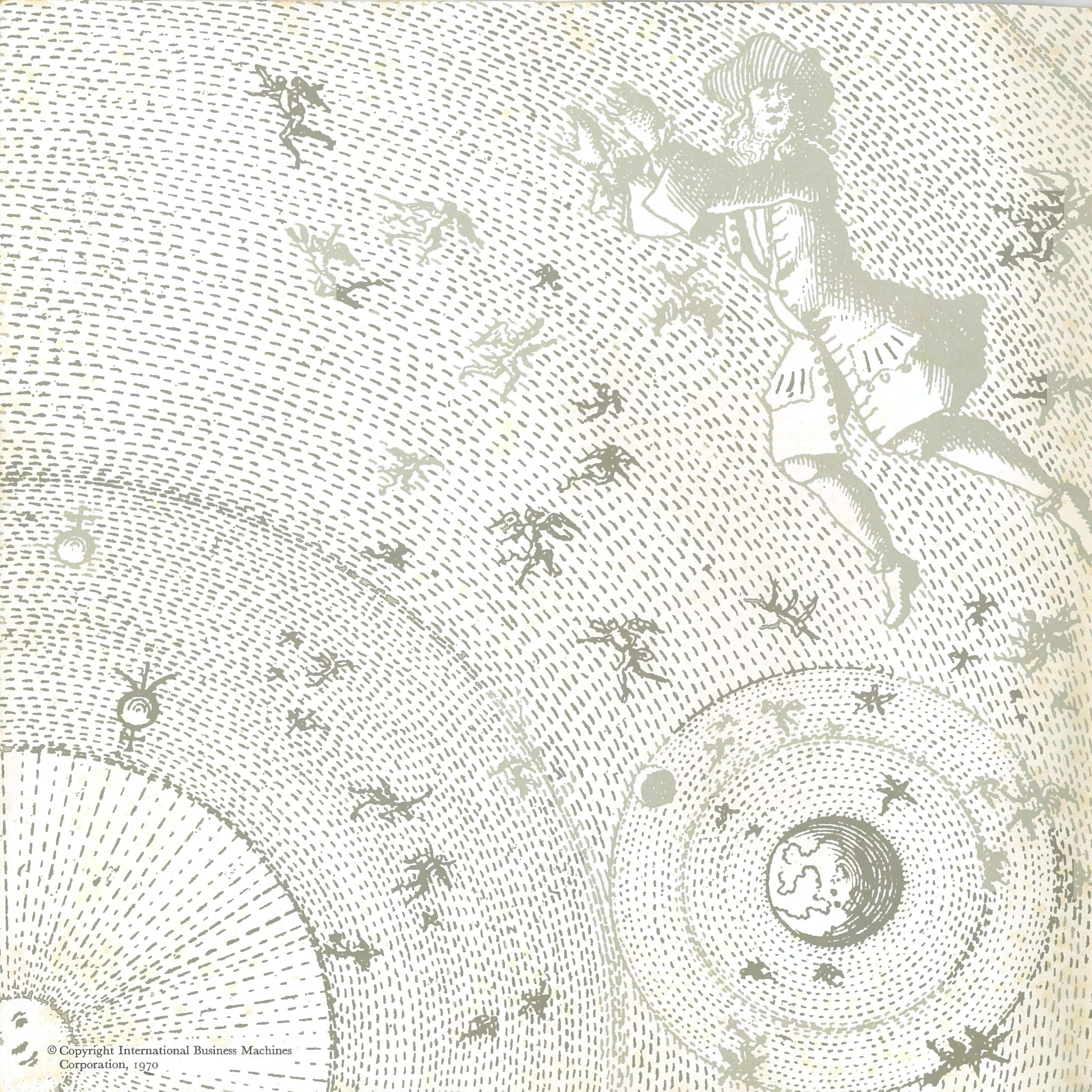
Suddenly, tomorrow came



On the shoulders of giants

Sir Isaac Newton wrote, "If I have seen farther than most men, it is because I have stood on the shoulders of giants." And we, in turn, stand on Newton's shoulders every time we rocket to the moon. Without the new picture of the Universe that he drew for us 300 years ago, we still would be earthbound victims of astrology.

Newton was not the first to search for an explanation of the universe. The search began when man first looked up and saw the sky, the Sun, the moon and the stars . . . and dreamed of ways to reach them.

The ancient Greeks dreamed, and sent Icarus into space on wings of wax. But Icarus flew too close to the Sun; his wings melted, and he fell into the sea.

Lucian dreamed, in the second century A.D., and sent a band of fictional explorers to the moon on a windstorm. He warned his readers not to believe a word of his *True History.*

Johannes Kepler, a 17th century astronomer, wrote one of the first truly scientific fictional trips to the moon in *Somnium* (Sleep). He anticipated the pull of gravity, weightlessness, and the lack of atmosphere on the moon. But he didn't know a practical way to get men there.

In the nineteenth century, in *De la Terre a la Lune*, Jules Verne shot a group of fictional Americans to and around the moon from a cannon buried in Florida. We still don't have a cannon big enough to pull off that trick.

Apollo took more than dreams, more than tricks.

It took fundamental scientific knowledge from many parts of the world . . . and years of dedication, hard work and teamwork by several hundred thousand people.

This brief booklet is the story of that long trip into tomorrow . . . of some of the giants who led us there . . . and of one tool that helped men to complete the trip, the electronic computer.

Contents:

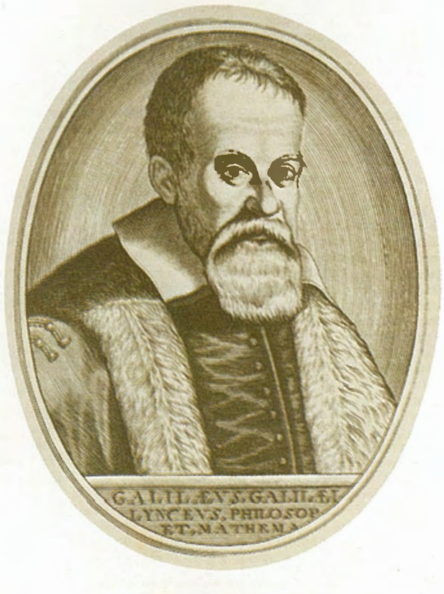
A nearsighted astronomer points the way

Johannes Kepler – born in 1571 and a victim of smallpox four years later – looked nothing like a giant. A slight, myopic man, he had to squint even to make out Tycho Brahe's shining silver nose (hand-made by Tycho himself, to replace the natural one he lost in a duel). Kepler turned out to be one of those giants who helped carry us to the moon.

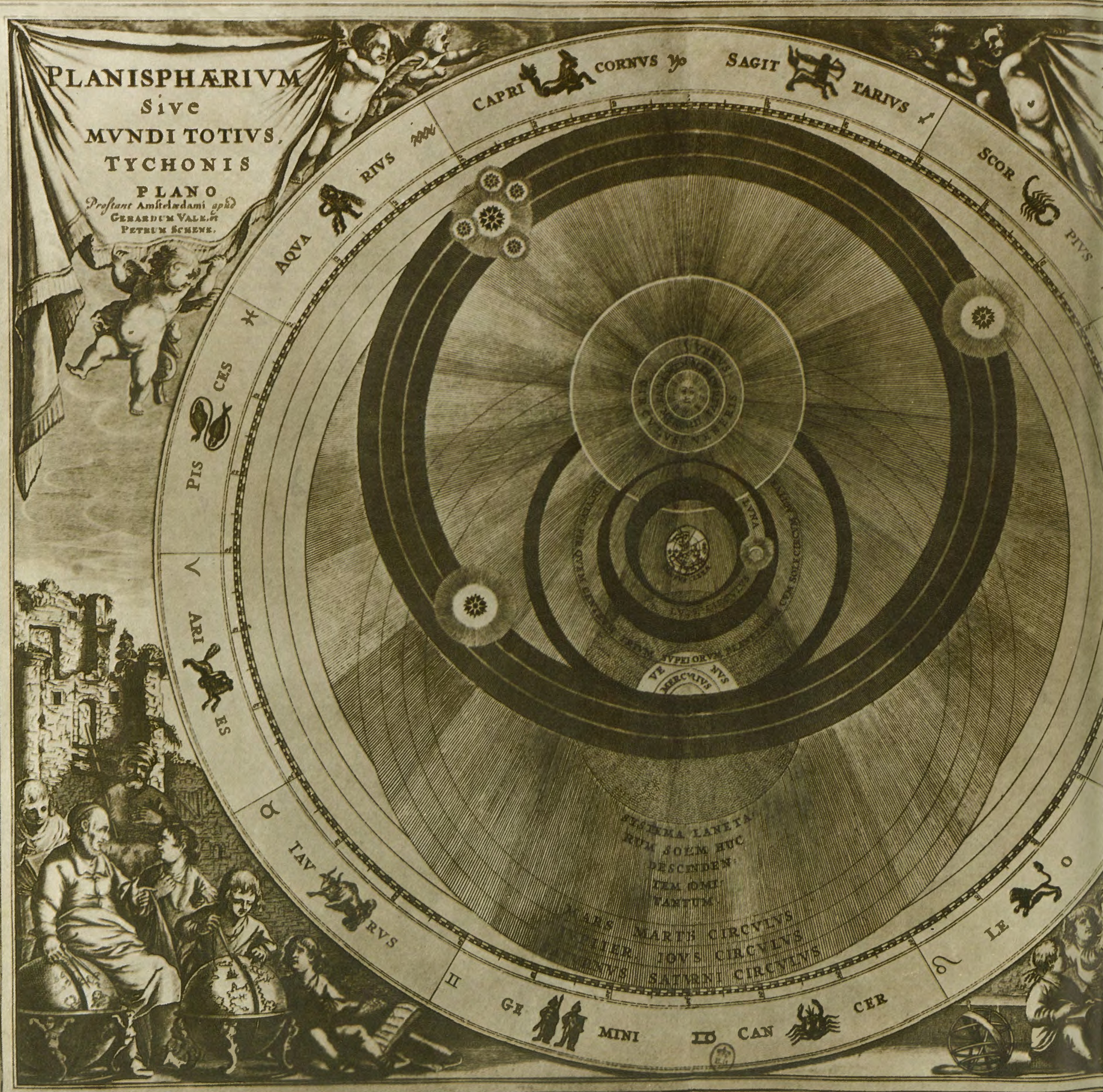
Scientist and mystic both, Kepler was searching for the music of the heavenly spheres which would describe the universe. He joined Tycho, an arrogant, noble, Danish astronomer, in 1600, in Prague. Together, they gave us the first realistic description of the orbits of planets. In their work and Galileo's, Isaac Newton later found the keys he needed to unlock the mysteries of gravity, to explain the orbits of planets and satellites, to explain the dynamic relationships between all bits of matter in the universe.

An Earth-centered universe
When Kepler joined Tycho in 1600, the old Ptolemaic System was still the accepted description of the universe. Ptolemy, following the theories of Aristotle and Hipparchus, placed Earth at the center of a geocentric universe. He believed that all other bodies in space moved in circular paths around Earth. While moving around Earth, they rotated in small circles in space, called epicycles.

This explained the movements of celestial bodies well enough, in most cases, to match the limited accuracy of astronomical observations. But 79 circular motions were required to explain the known universe.



Three giants of astronomy. A German, Johannes Kepler (1571-1630), opposite page, first described the elliptic movements of planets. He based his work on the theory of a Pole, Nicholas Copernicus (1473-1543), far left, who placed the Sun at the center of the universe. The Italian, Galileo (1564-1643), left, defended the Copernican theory and used his own telescopes to prove it through improved observations.


PLANISPHÆRIVM
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The sun at the center
Nicholas Copernicus' sun-centered (heliocentric) concepts eventually superseded Ptolemy's geocentric system. It is believed that Copernicus first encountered the notion of a sun-centered universe in Italy about 1496. He later developed a complete heliocentric system and backed it up with mathematical explanations.

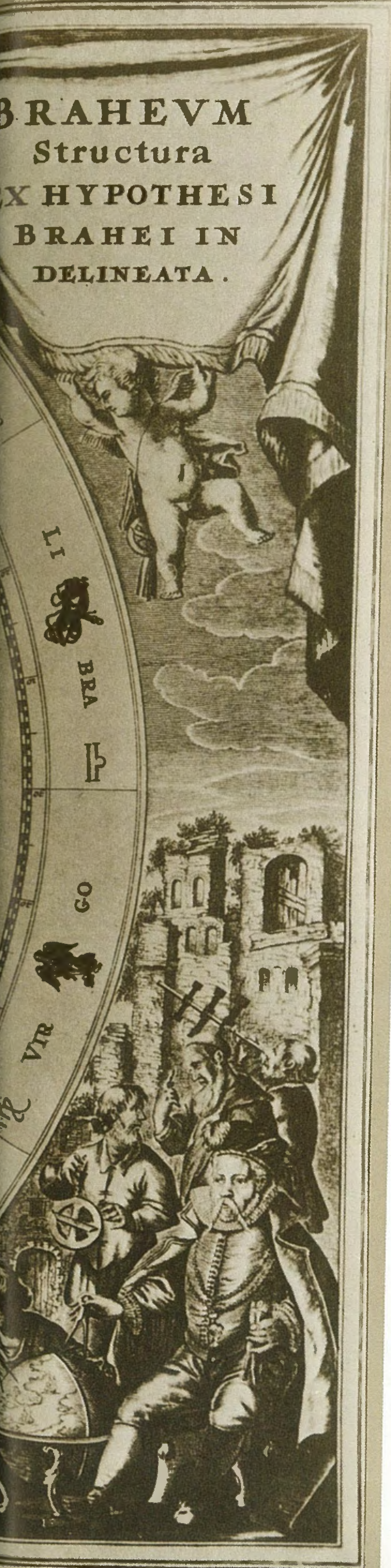
He, too, thought every body moved through space in circles; but by putting the sun at the center, he simplified the calculations (only 34 motions were needed) and explained some previously unexplained motions of planets.

Nevertheless, there was a lot of opposition to the Copernican System. Most people could not believe that Earth was not the most important and the controlling body in the universe. They thought that it sat motionless in the center of all things.

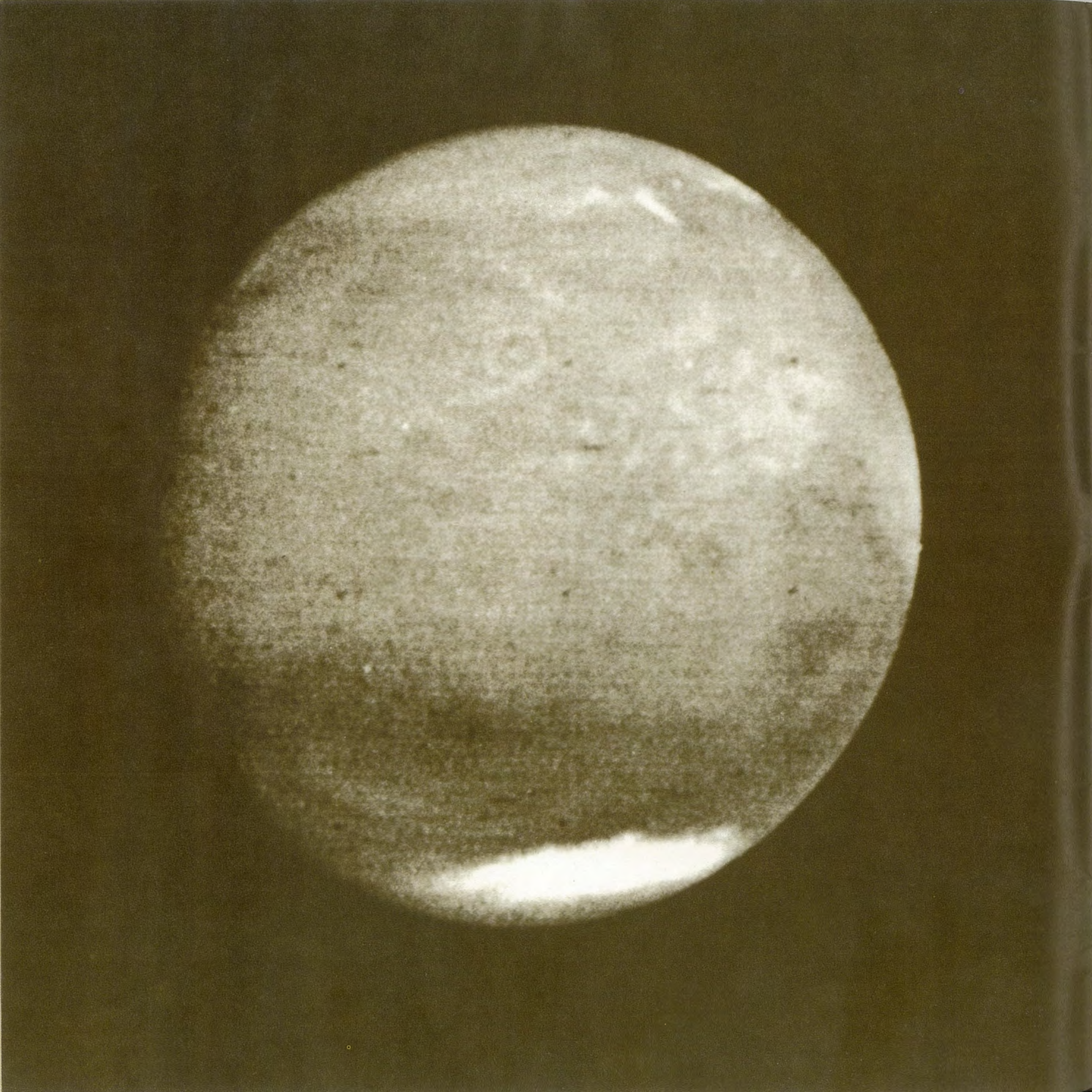
Tycho was among those who rejected the Copernican System. But his own precise observations helped to prove him wrong. Kepler's calculations, based on Tycho's records, along with more accurate observations made possible by the telescope and Isaac Newton's mathematics, eventually established the validity of a heliocentric system. But this came long after Copernicus' death and Tycho's, too.

Celestial precision
Tycho – who, like Copernicus, Kepler and Newton, now has a moon crater named after him – was a precise observer and measurer. For twenty years, in a castle observatory on Hven, an island near Copenhagen, he had peered at the sky with his unaided eyes. With handmade instruments, he measured movements and positions of six planets then known, the moon, and stars, more accurately than they had ever been measured before. He measured to an accuracy of two minutes of arc (a little less than one-thousandth of a circle). That was ten times more accurate than observations available to Copernicus.

Tycho accepted Ptolemy's concept of the universe and thought that the moon, the Sun and other stars moved around Earth in circles. He believed that other planets moved around the Sun in circles. The trouble was, the movement of Mars wouldn't fit the theory; it was out of "harmony" by eight minutes of arc in an orbit that takes 687 Earth days to complete.



Tycho could not accept Copernicus' Sun-centered universe. He believed that the Sun and moon moved around Earth in circles, that planets moved around the Sun in circles, that each rotated in a small circle called an epicycle, while traveling its large circular orbit. The illustration describes his concept of the universe.



How to explain Mars?
Kepler – the dogged German calculator and analyst – took Tycho's observations of Mars and tried to explain them. He gave himself eight days to complete the job. It actually took the better part of four years. Today, the same calculations take eight seconds in a digital computer.

In 1609, after laboriously examining, calculating and testing over seventy possible explanations, Kepler concluded that Mars and other planets traveled elliptic paths around the Sun. This is Kepler's first law of planetary motion, announced the same year Galileo Galilei invented his telescope.

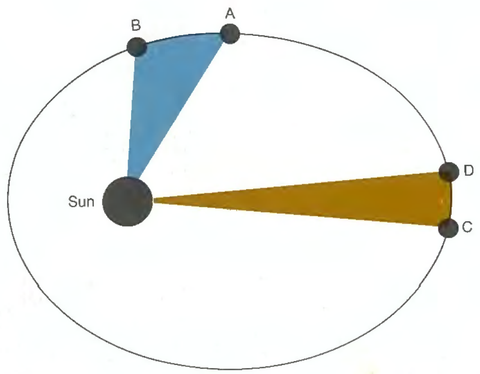
Kepler devised two more laws to describe the observed motions of planets more accurately and more correctly than Ptolemy, Copernicus or Tycho.

In 1609, Kepler announced his second law: During any given period of time of a planet's orbit, a line drawn from the center of the planet to the center of the Sun sweeps across an equal area of the ellipse, no matter where on the orbit we measure.

Ten years later
Kepler kept at the laborious job of observation, calculation, trial and error, and in 1619 drew another important conclusion, his third law: The square of the time it takes a planet to complete an orbit is proportional to the cube of the length of the major axis of the ellipse it travels.

These laws idealize the true erratic paths of planets, or the motion of any body in space. But they are extremely close approximations, approximations that have been refined again and again, ever since, by mathematicians and astronomers. They helped point the way to a better understanding of the universe and the matter it contains. They helped point the way for Newton, and, ultimately, our astronauts.

Mars, as photographed by Mariner 6 on July 30, 1969. Computers have been used to guide and control Mariner spacecraft on trips to Mars and Venus, and to improve the quality of pictures sent back from space. Observations of Mars in the sixteenth century led Kepler to develop his laws of planetary motion.



Using Tycho's and his own observations of planetary motion, Kepler determined that each planet moves in an elliptic, not a circular orbit and that it moves at varying speeds which cause its radius from the Sun to sweep across equal areas of space in equal times. In this sketch, the time it takes to move from point A to point B is the same as the time it takes to move from point C to point D. The shaded areas are equal in size.

A precocious Englishman tells us how a body acts 240,000 miles from London

The world – especially the scientific world – received an unusual sort of Christmas present on December 25, 1642. That's the day Sir Isaac Newton was born. He was to become one of the greatest figures in the history of science.

When he was a boy, his widowed mother tried to make a farmer out of him. But Newton was so preoccupied with mathematics and science, he neglected his chores.

An uncle suggested that the boy enter Cambridge University. His record there was outstanding and at age 26 he replaced his teacher as Lucasian Professor of Mathematics (at his teacher's suggestion!).

During the Great Plague, in 1666, school was closed; so Newton went home to think. His thoughts have been paying off for the world ever since.

During that hiatus, he invented the differential and integral calculus (the mathematics needed to work with variable quantities, like the movement of planets or spaceships). At that time, he also took the initial steps to explain the *reasons* that planets moved according to Kepler's Laws.

Working with mechanical forces that could then be measured, such as the pull of a horse on a wagon and the pull of gravity, Newton searched for universal relationships between forces.

He explains Kepler's Laws
Starting with Kepler's Laws and basic ideas of Galileo, Newton developed his Laws of Universal Gravitation, and explained Kepler's Laws of Motion mathematically. He explained why planets move about the Sun in elliptic paths.

He showed that the gravitational force of the Sun makes the planets change their velocity continuously, that the force is exerted toward the Sun, that the force is proportional to the product of the masses of Sun and planet, and that the force of gravity varies *inversely* with the square of the distance between Sun and planet.

These laws Newton said, hold for any two bodies in space. They explain the movement of the moon or a spacecraft around Earth.

From there, Newton tried to develop a general theory of forces, and described the theory in these three famous laws of mechanics:

1. In the absence of an external force, a body will continue at rest. If moving, it will continue its motion in the same straight-line direction, at a constant speed.

2. If a force is applied, a body will be accelerated in the direction of the force. The amount of that acceleration will be directly proportional to the force and inversely proportional to the mass of the body.

3. For any force applied in one direction, there is an equal force exerted in the opposite direction. (If you jump from a boat to the shore, you push the boat back with the same force you push yourself forward. If you burn fuel in the bottom of a rocket, the molecules of hot gas formed push the rocket *up*, with the same force that pushes the gas *down*. In order to escape, the gas must push against the rocket, just as air escaping from a balloon pushes against the balloon and moves it across a room.)

Isaac Newton (1642-1727) explained the laws of gravity in his *Mathematical Principles of Natural Philosophy*, usually called the *Principia*, which was first published in 1687. This work formed the basis for modern science for 200 years. Newton was knighted for his scientific work in 1705.

Why a ball falls
That sounds simple enough. Newton says, if you throw a ball in the air, it would continue, forever, in the same straight-line direction you throw it (the direction of the force) and at the same velocity it leaves your hand, except for two things: two other forces are acting on the ball.

One is the air. When the ball pushes against a molecule of air, the air molecule pushes back, with the same force. Some of that force is converted to heat. But some of it slows the ball down. Unless you throw very hard, the air wins, and the ball slows down to a stop. The ball would stay in that position, forever, if no other force were present. But there is: gravity. Gravity pulls the ball back down to Earth.

Earth gravity is pulling at the ball all the time, trying to pull it toward the center of Earth. And the ball, which exerts a force based on its mass, is trying to pull Earth toward its center of gravity. Earth wins this battle, of course, because it has so much more mass than the ball—and the attractive force a body exerts is proportional to its mass.

Mass, according to Newton, is that quality of a body that gives it an attractive force. We still don't have a better definition, although we can measure it and its attractive force much more accurately than was possible in Newton's time.

How to orbit a ball, or a spacecraft
Now let's assume there's no Sun and no moon or any other massive bodies to cause us trouble—just Earth and the ball.

Let's say we throw the ball hard enough to get it through most of the air that hugs Earth—about 100 miles of it. Then, say, we have enough force left over to just balance the force of gravity. The ball goes into a circular orbit, but not a perfect circle. A perfect circle isn't possible because Earth is not a perfect, uniform sphere; mountains and oceans and other local changes in density cause gravity to change slightly from place to place.

To maintain a circular orbit at a distance of 100 miles or so, the ball must travel over 17,000 miles per hour, so that the centrifugal force trying to pull the ball away from Earth balances the force of gravity.

Faster than gravity
If the ball is going a little faster than necessary to exactly balance gravity and move in a circle, it goes into an elliptic orbit, just as Colonel John Glenn did in 1962.

Friendship 7 followed an elliptic path that, at perigee, the nearest point on the orbit, was about 100 miles from the surface of Earth. At apogee, the farthest point, it was about 162 miles away.

To get back down to Earth, Colonel Glenn just slowed down by firing rockets, generating a force opposite to the direction the spaceship was going. Then, gravity took over and pulled the spacecraft back to earth.

The speed for any desired orbit is the same for a ball or a spacecraft, because mass works in two ways. The larger the mass is, the more the attractive force is between it and another mass. But the larger the mass is, the more the force must be to move the mass at a given speed. These two factors just happen to cancel out. That's why Galileo's two cannonballs of different sizes fell at the same speed and hit the ground at the same time.

Escape velocity
The faster we get our ball or our spacecraft moving, once it's out beyond our air, the farther out it will go before gravity makes it fall back.

Theoretically, if you can make the spacecraft go fast enough, you can escape Earth's gravity completely. The speed necessary is about 25,000 miles per hour (measured at the surface of Earth and ignoring the effect of air drag). At about 100 miles out, where we park temporarily before heading for the moon, escape velocity is a little over 24,000 miles per hour.

Falling apples are supposed to have given Newton insight that led to his Laws of Universal Gravitation. Whether it happened this way or not, his laws apply to apples as well as moons, planets, and all other bodies in the universe.

Since gravity keeps getting weaker, by the square of the distance, as we move away from Earth, escape velocity keeps getting smaller, too. So does orbital velocity – the velocity needed to keep a satellite, any satellite, from falling on Earth. At its mean distance of 238,856 miles, the moon has to average only 2,287 miles per hour to stay in orbit.

Too many bodies

Based on Newton's laws, space flight ought to be a simple matter of working out a few elementary problems in algebra, once we figured out how to get up to orbital speed. But it doesn't work that way.

As with most scientific principles, Newton's Laws are based on ideals. He assumed that all bodies were uniform throughout their mass, that the planets and Sun and moon were perfect spheres and that their masses were concentrated at their centers.

They are not. On Earth, when you measure accurately enough, you find that gravity varies with the composition and geography of Earth . . . that Earth doesn't spin at constant velocity . . . that it's a little flatter at the poles and a little fatter at the equator than we once thought it was.

In 1958, this caused Vanguard I to deviate from its predicted course. This new information was analyzed by computer and has been used ever since to guide spacecraft.

There's another problem, too. Newton dealt with only two bodies acting on one another. But the solar system contains many bodies, all exerting forces and influencing the acceleration and direction of movement of every other body. Newton didn't have a neat mathematical technique he could use to calculate the interactions of more than two bodies at a time. And we still don't, three hundred years later.

That makes space flight – and every other problem in celestial mechanics– very difficult. We can't swallow the problem whole. We have to break it down into a long series of two-body problems—and string out a long series of approximations that get us closer and closer to a precise answer.

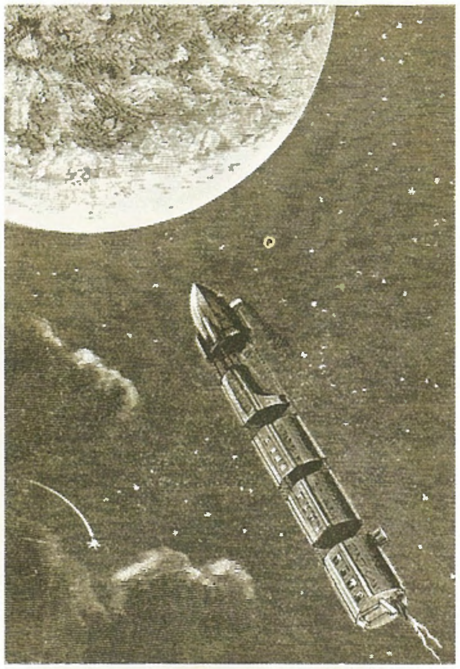
Where is the spacecraft?
Where is it going?

That's why every space launch is, to some extent, a brand-new journey along a brand-new route. Each time, we learn something new. And each time, all along the way, the location, the acceleration, the future path and every Newtonian wiggle of the spacecraft must be recalculated repeatedly . . . then compared with the planned route. When necessary, the spacecraft must be jogged back on course.

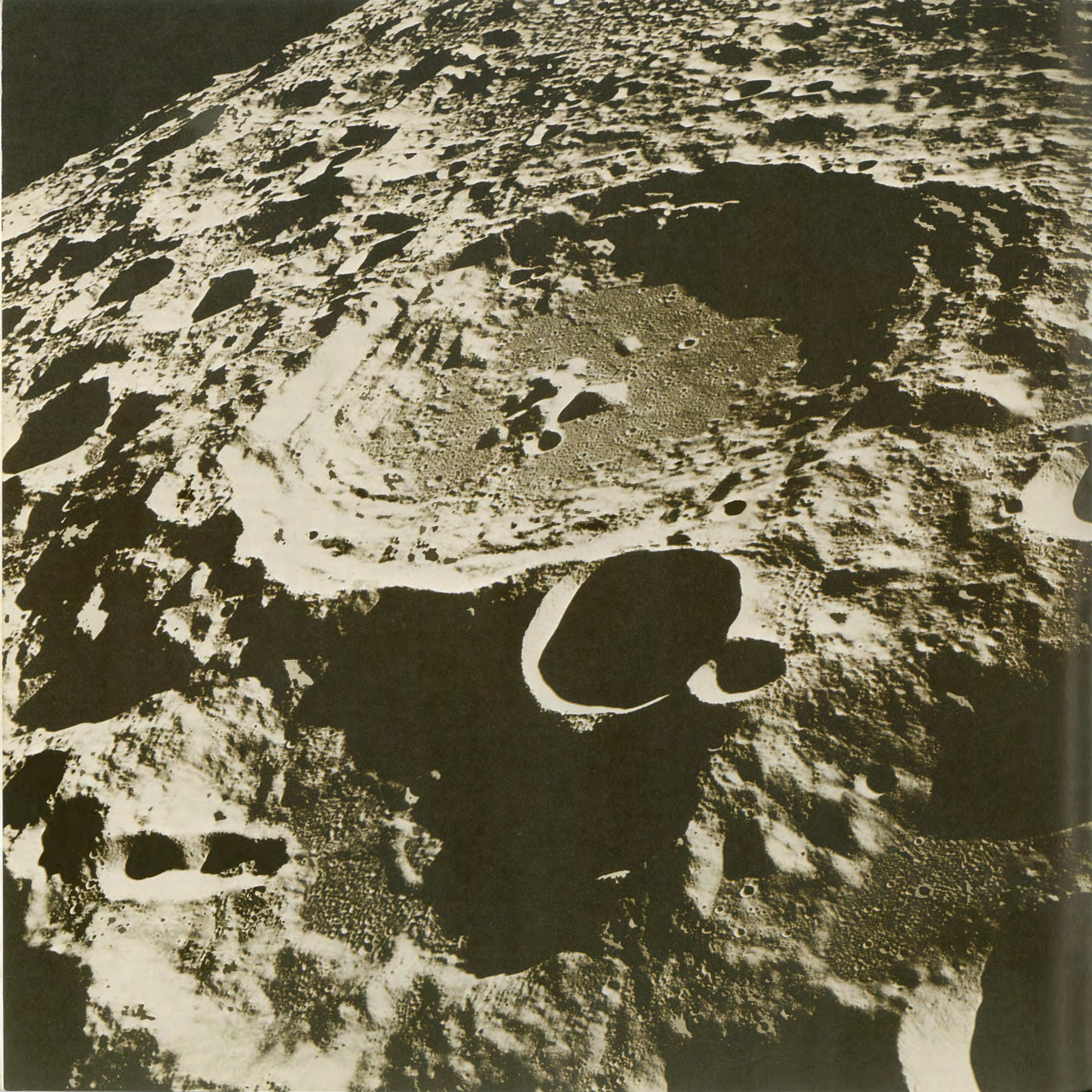
Computers are the tools that make it possible to handle millions of space flight calculations fast enough to keep astronauts on target.

The calculations are all based on Newton's 300-year-old laws . . . and on observations made with telescopes that have been improved as a result of optical studies made by Newton and others who came later . . . and on knowledge gained through spectrum analysis, a technique that evolved from basic concepts of light developed by Isaac Newton.

Without him, we might still be stranded on Earth, traveling by horse and wondering why apples fall to the ground and the moon doesn't.



Jules Verne's fictional moonship was shot off from Earth in a cannon. But it couldn't land on the moon and take off again, so Verne just sent it around the moon and back to Earth.



Many moon watchers

After several thousand years of moon watching, you'd think man would at least know where it is by now. But we don't, not with absolute precision.

The moon, our closest spatial neighbor, is pretty far away—a mean distance of 238,856 miles from the center of Earth—far enough to make one of Tycho's observations wrong by as much as 130 miles.

It doesn't help that the moon moves through space at an average speed of 2,287 miles per hour and spins at a speed of about 10 miles per hour. All the while it wobbles like a balloon on a string, because it isn't uniform throughout its mass, and Sun and Earth and other planets continually tug at it in different directions.

Then we have to look through more than 100 miles of turbulent air to see the moon. So it's remarkable that we know as much as we do. It took a long, hard time to learn so much – over 2,000 years and efforts by many of the most brilliant scientists and mathematicians the world has known.

A Greek geometer
Hipparchus, in the second century B.C., identified and measured the eccentricity of the moon's orbit – which is a mathematical measure of how stretched out the ellipse is. The moon's orbit is almost, but not quite, a circle.

Hipparchus also calculated that the plane of the moon's orbit inclined a little over five degrees from the plane of Earth's orbit around the Sun (the ecliptic, in the language of the astronomer). The ecliptic, as we'll see later, is important because it's one of the few geometric figures in our solar system that can be assumed to be stationary.

Without precise measuring instruments, Hipparchus was a little confused about which heavenly bodies whirled around which – he put Earth near the center of the universe. But his system, later adopted by Claudius Ptolemaeus (about 150 A.D.), was for nearly 1300 years the best available explanation of the universe and the movement of planets. Ptolemy's geocentric system helped explorers like Marco Polo and Columbus keep track of where they were.

Today begins
Once Galileo told the scientific world about his telescope, in 1609, and Kepler, Newton and others showed how to improve it, astronomy shifted into second gear.

Cassini, Euler, Laplace, Lagrange, Poincaré, Poisson, and many other scholars contributed important and still valid concepts that, combined with improved observations, enable us to better describe the moon's path, location and physical nature.

The twentieth century
The culmination of these three centuries of effort and thought came in 1919, with the publication of E. W. Brown's "Tables of the Motion of the Moon." Based on thirty years of investigation, this is the most exhaustive solution to the lunar problem ever developed. Although computers enabled men who came later to improve the accuracy of Brown's calculations, his theory of lunar motion is still the basis of all calculations.

Brown filled 650 printed pages with tables that gave navigators, as well as astronomers, accurate positions for the moon by the hour and by the day.

Left, view of the far side of the moon, photographed from Apollo 11 spacecraft in lunar orbit, looking southwest. The largest crater is International Astronomical Union No. 308, which has a diameter of about 50 statute miles.

Brown, as previous investigators had, broke the lunar problem into several parts. The "main problem," as he called it, involved calculation of the interaction of Sun, Earth and moon considered as masses concentrated at their center points. Then the effects of other planets were calculated; then the effects of the irregular shapes of Earth and moon; then the effects of variation in the speed of Earth's rotation.

Let computers do the calculating

For the past thirty years, automatic calculators and electronic computers have been used to relieve men of the burden of astronomical calculation. This, combined with improved observation techniques, has made it possible to increase the number of terms in the lunar equations from Brown's 1,500 to 6,000, and to calculate any desired point on the ephemeris – a mathematical map of the moon's and planets' journeys through space – to an accuracy of two one-hundred-thousandths of a *second* of arc!

New ways to see

We still need to improve our ability to investigate the universe – the stars and other planets, as well as the moon. So we have sent up scientific spacecraft to do some close-up looking for us. The unmanned Rangers, Surveyors, Mariners, Lunar Orbiters, and Russian spacecraft have sent back many thousands of photographs and billions of bits of electronic information that we couldn't have obtained any other way. Computers were needed to guide those probes to their targets, to capture the information sent back, to help men on Earth analyze and interpret the data. As a result, there have been fewer surprises – though more than enough – when man, himself, has gone up to look around.

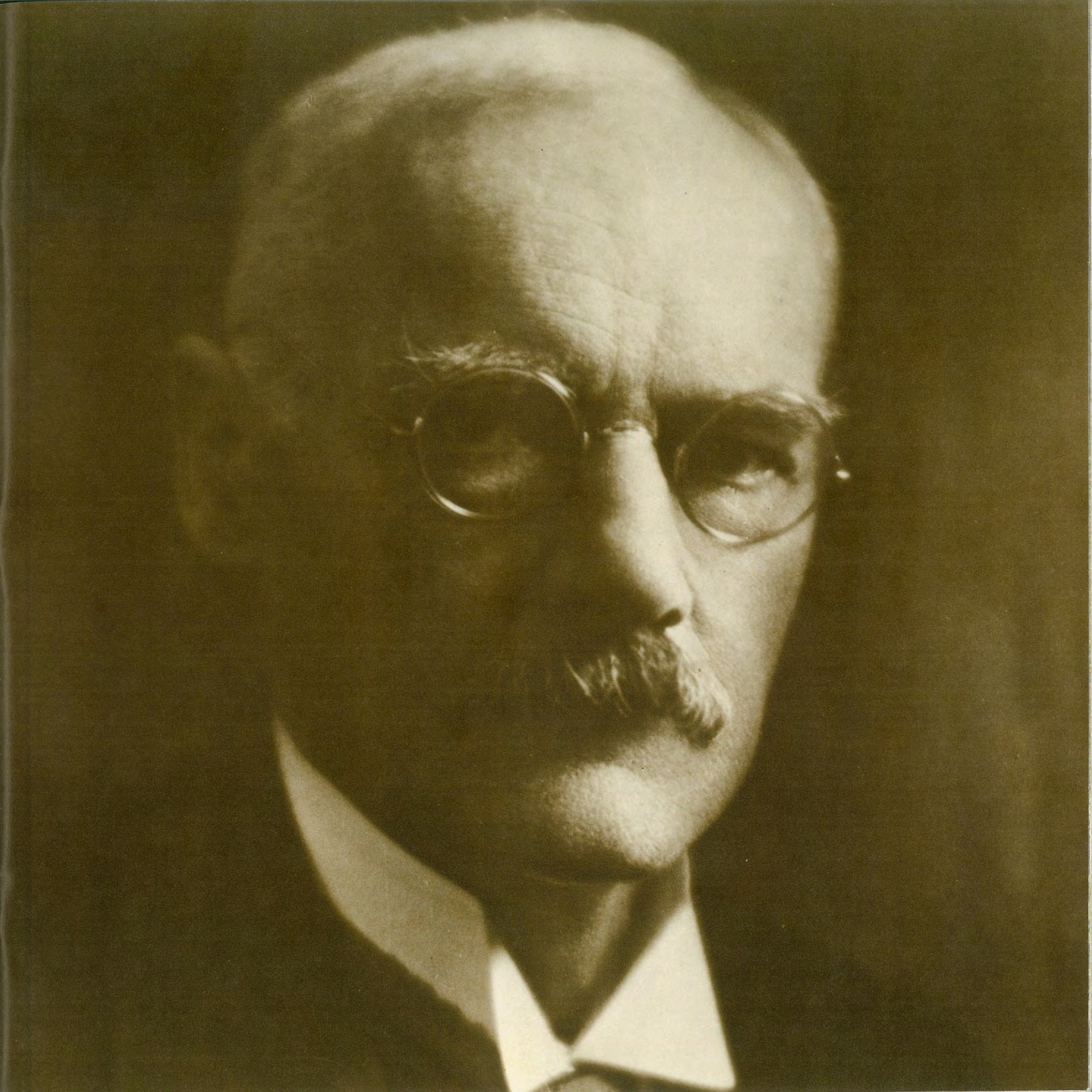
Top, before the invention of the telescope in the seventeenth century, astronomers like Hipparchus used handmade measuring instruments and their unaided eyes to observe celestial bodies.

Right, the Greek mathematician, Ptolemy, lived in the second century and wrote one of the world's fundamental scientific books, the *Almagest*. It explained the Earth-centered description of the universe, which dominated scientific thought until Copernicus' theory was published in 1543.

Opposite, E. W. Brown, whose analysis of the moon's orbit is still the basis for determining the moon's ephemeris. W. J. Eckert and others have used computers to refine Brown's calculations.

Moon Facts

Diameter	2,160 Miles
Mass	1/81.3 x Earth
Distance at perigee	221,463 Miles
Distance at apogee	252,710 Miles
Orbital speed (average)	2,287 MPH
Moon gravity	1/6 x Earth
Time for one orbit	27 Days 7 Hrs. 43 Min.
Surface never visible from Earth	41%
Inclination to ecliptic (mean)	5° 8′ 43″
Density	6/10 x Earth




A
B

The bleachers are ringside seats at Cape Kennedy during a launch. But they are three and a half miles away from the action. A few moments after lift-off, you learn why they are placed so far from the launch pad.

When Apollo's first-stage roar reaches you, in the bleachers, you can hear it and you can feel it. The shock wave thumps against your chest, as though someone hit you hard with a big balloon. The ground rumbles. The bleachers rattle. Your heart pounds.

And three and a half miles away, and a thousand feet in the air, up in the spacecraft, the astronauts already are travelling about 100 miles per hour and speeding up.

No cannon could do it

Our astronauts take off from Florida, just as Jules Verne's did in 1865. And they land in the Pacific Ocean, just as Jules Verne's did. But they take a much different approach to the propulsion problem.

No cannon is powerful enough to push a spacecraft into orbit. It takes a very special kind of Roman candle. It takes over six million pounds of engines, tanks, fuel and oxygen (in outer space, you have to take your oxygen with you – oxygen for breathing and oxygen for burning fuel).

The entire structure is 364 feet high – taller by a hundred feet than the tallest of the tall pines in Maine . . . taller than the tallest oak in the Midwest . . . even taller than the tallest Sequoia on the Pacific Coast.

A Russian school teacher gets a big idea

This building-sized Apollo, 36 stories high, blasts off with a power 50 times that developed at Niagara Falls. In two and a half minutes, it's about 40 miles high and traveling over 5,000 miles per hour. It took men fifty years to figure out how to build it and steer it.

The first suggestion of liquid-fueled rockets for space travel came in 1903 – the same year the Wright brothers were experimenting with airplanes. Liquid-fueled rockets are easier to control and steer than solid-fueled rockets which are similar, in concept, to Roman candles and ship's flares. While solid-fueled rockets have been used in China since the thirteenth century, liquid fuel was first suggested in a technical article written by Konstantin Eduardovich Tsiolkowski, an obscure schoolteacher in Kaluga, a town near Moscow.

After that first publication, Tsiolkowski continued to write and experiment, but his work generated little excitement in Russia until after World War I, and it was little known elsewhere.

More firsts

Tsiolkowski developed the idea of using stepped rockets (multiple stages), which can be dropped progressively as each stage burns up all its fuel. Each discarded stage is useless weight that would slow up the rocket, or require more fuel.

Tsiolkowski was the first to suggest mass ratio as a measure of the performance of a rocket. Mass ratio is the ratio of the total mass of a fueled rocket just before launch to its mass after all the fuel has been burned. It determines, in combination with the velocity of gases escaping from the rocket, the maximum speed attainable and, therefore, the height of the orbit a spacecraft can attain.

These ideas were later reinvented, independently, by Dr. Robert Goddard in the United States and by Herman Oberth in Germany. Dr. Goddard, a professor at Clark University, was the first man to successfully launch a liquid-fueled rocket. He did it on March 16, 1926, on an aunt's farm in Auburn, Massachusetts. That first rocket reached an altitude of 184 feet. By 1935, Goddard had sent his rockets up to 7,500 feet and achieved speeds of 700 miles per hour.

New technologies pave the way

That was the beginning – a modest one, by today's standards. But the Russian, the German and the American had taken the first steps in rocket science.

Before really great strides could be taken, however, new technologies and new knowledge were needed.

More had to be learned about the true position and path of the moon. New, more powerful telescopes had to be designed and installed to teach us more about that mysterious world outside Earth's atmosphere.

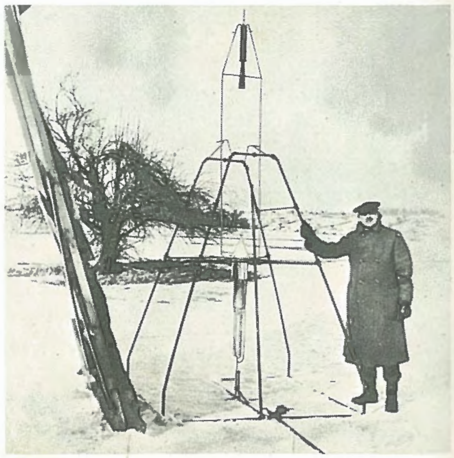
New ways to control the operation of a rocket were needed and electronic technology provided them.

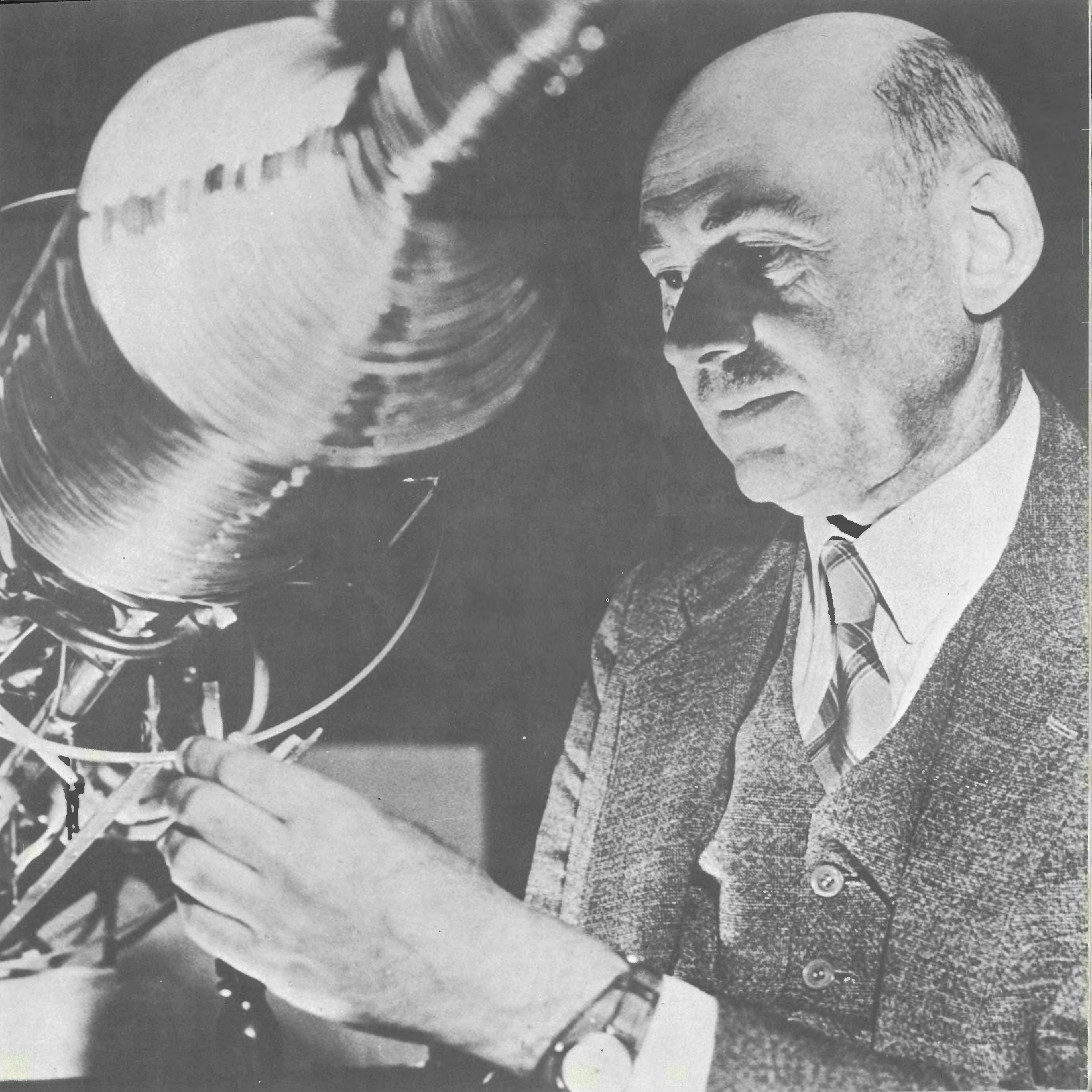
Faster ways had to be found to process information from electronic circuits and to control their operation. The digital computer provided that.

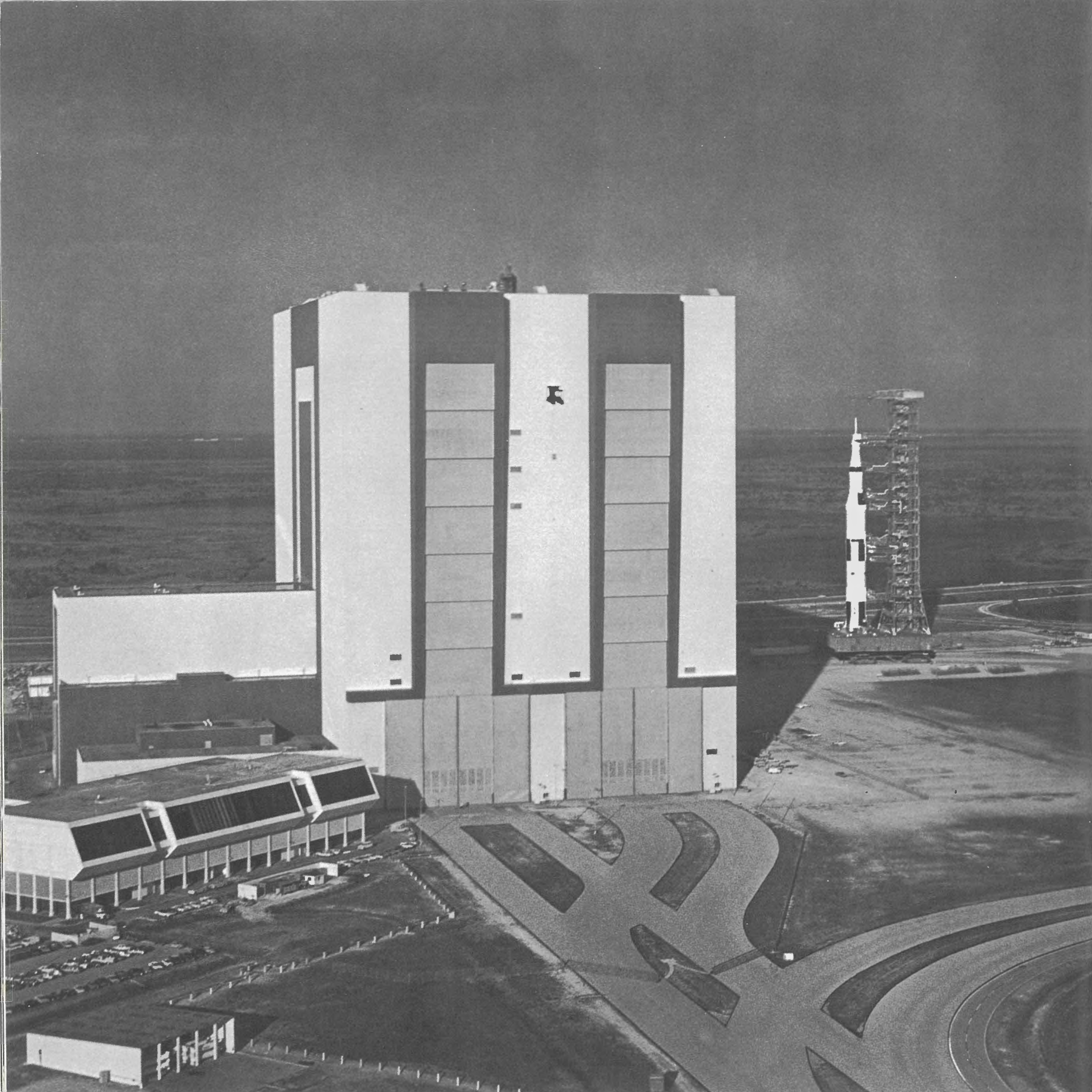
Without all these and many more technological developments, man's longtime dream of visiting the moon and the world beyond . . . of looking down at earth from space with a new perspective and a new ability to see what goes on here – these would still be tomorrow's dream.

Above, a Russian schoolteacher, Konstantin Tsiolkowski, first suggested the use of liquid-fueled rockets in a paper published in 1903. He built wind tunnels for testing models and continued to write on rocketry. Russia launched its first liquid-fueled rocket about 1933.

Right and opposite page, Dr. Robert H. Goddard, who launched the first successful liquid-fueled rocket in 1926, in Auburn, Massachusetts. In 1929, he launched the first instrumented rocket, carrying a barometer, a thermometer, and a camera to photograph the instrument readings. Apollo launch vehicles use the same principles as Goddard's rockets.







Before it flies, remove the bugs

Apollo contains about six million individual parts. Each one must work. Each one must work in harmony with thousands of other components. And NASA must be sure they work before they fly.

In fact, the testing of Apollo starts even before it is built. It starts in computers, which are used to develop basic designs. Then parts are tested when they are built. And again when they are combined with other parts. And again on the launch pad. At each step along the way, men use computers to hunt out every bug, or fault, in any part of the system and remove it.

Testing, testing, testing
Take the Saturn rockets, for example. Every function of the big engines is described mathematically. Then the thousands of equations are converted to computer programs.

These programs are used to simulate operation of the rocket electronically, from ignition, through lift-off, into orbit. Fuel consumption, thrust, temperatures, stress on rocket walls, all are described, recorded and displayed by the computer, over and over again, and total performance and reliability are steadily, methodically improved.

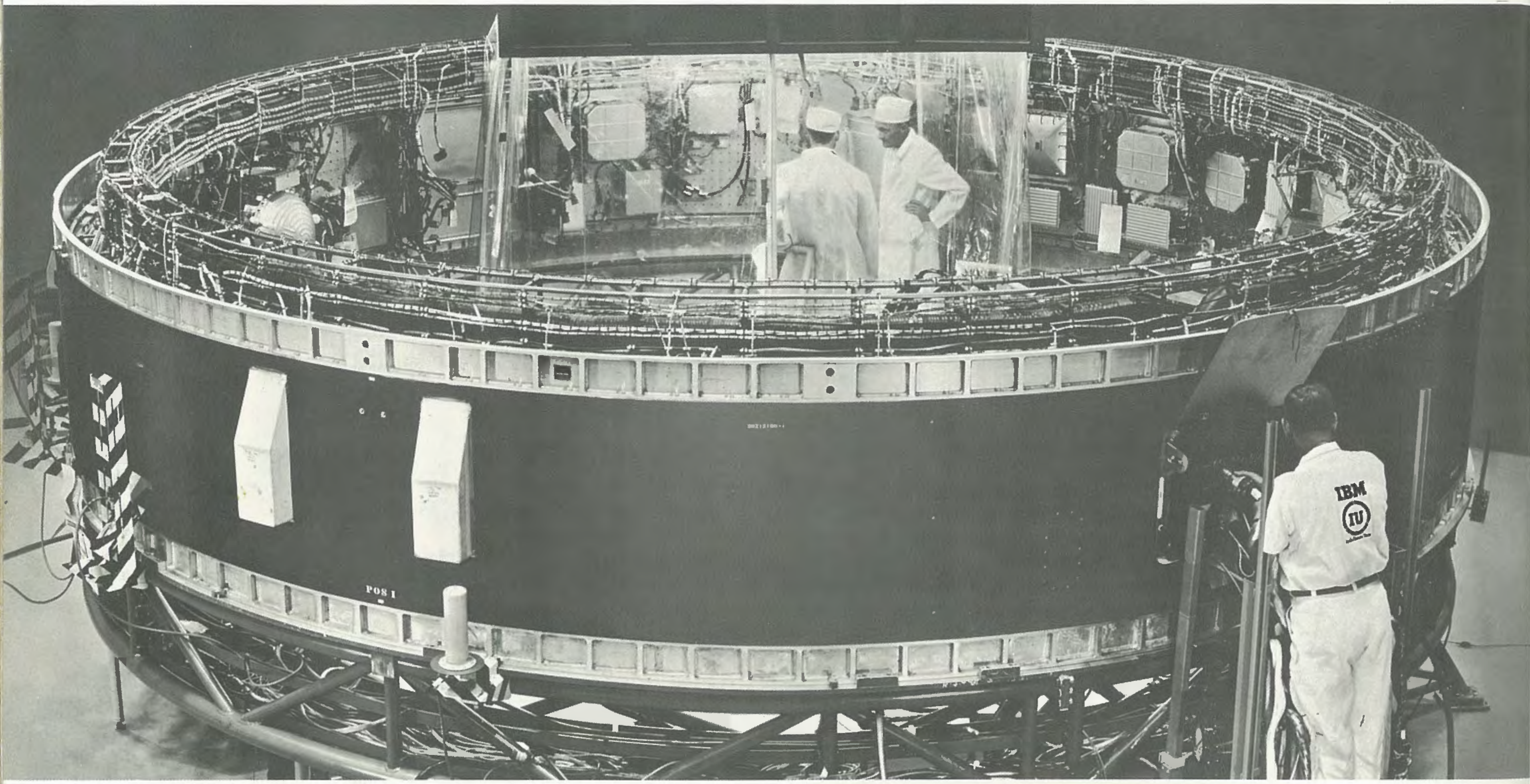
In static tests – when the rockets are fired, but held on the ground – computers are used to capture, to store and to analyze the billions of bits of performance data needed to determine a rocket's readiness.

Finally, by ship, truck, airplane and freight car, assembled chunks of Apollo come to Cape Kennedy, into a Vehicle Assembly Building that straddles an area the size of four football fields and rises a tenth of a mile above its foundation.

Here, months before a launch, assembly begins, and testing continues. Across the street, men at computers are at work, checking the test results, checking the readiness, finding the faults and getting them corrected.

On the pad, still more testing
A month before lift-off, a specially built six-million pound tractor moves under Apollo, lifts it, and carries it to the launch pad three and a half miles away. The operator of this giant carrier uses a computer to help keep the 364-foot, half-million pound pencil perfectly balanced for three and a half hours, as he crunches over a stone road and up a little hill to the launch pad.

In this Vehicle Assembly building at Kennedy Space Center—the second largest building in the world—the millions of parts in an Apollo launch vehicle and spacecraft are assembled and tested before the bird is moved to the launch pad.



The Instrument Unit of the Saturn rocket—a section 3 feet high, 22 feet across. Inside of it, an IBM computer and 56 other components are needed to keep Saturn on course—including equipment to distribute power, dissipate heat, communicate with the ground.

Then, for a month, 400 people peer at computer display consoles at the Cape Kennedy control room, while hundreds of others bustle about the bird on the pad. Every part is rechecked. Every function is rechecked. False errors are introduced to test and prove measuring systems that must indicate real errors during a mission.

This search for perfection has gone on for ten years, through 20 manned missions of Mercury, Gemini and Apollo . . . through more than 200 unmanned launches. It continues through the final hours of countdown. And it goes on after launch, during every moment of every mission, with computers on the ground and in the spacecraft giving the men in control the information they need to make split-second decisions.

A control room in the sky

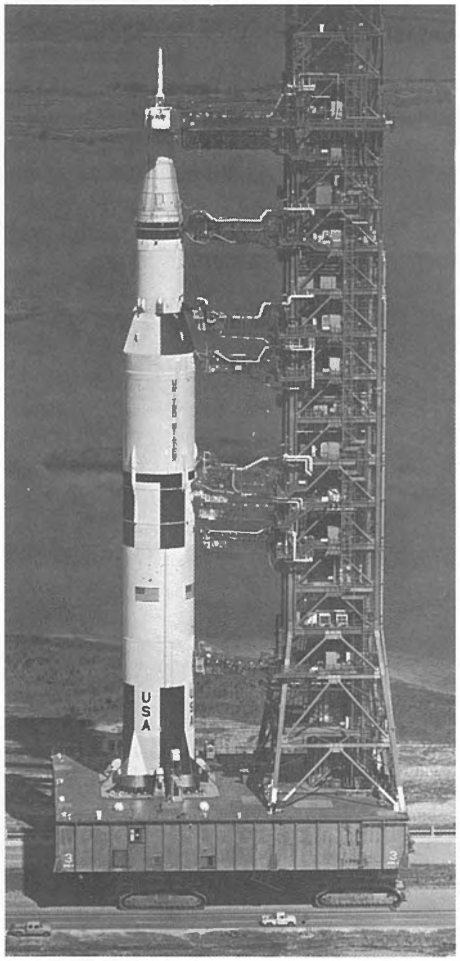
Once Apollo lifts off, it is controlled by a small electronic control room built right into the launch vehicle between the third stage and the Apollo spacecraft.

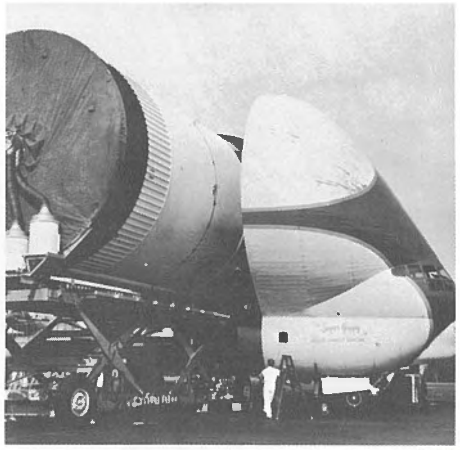
The computerized control room, the Instrument Unit, is just 22 feet in diameter and three feet high. It flies with Apollo for less than three hours. From lift-off until Apollo reaches Earth orbit, the Instrument Unit issues 25 steering commands a second.

It also checks rocket burning time, thrust, direction, speed, and recomputes Apollo's path through space. It starts propellant pumps, fires engines, separates stages, sends back a barrage of information on speed and acceleration and temperature and pressure and vibration – 2,342 measurements in all.

The digital computer and 56 other components in the Instrument Unit provide complete guidance and flight control until the Apollo spacecraft separates and heads for the moon. At that point, its job done, the Instrument Unit, along with the empty third-stage rocket, drops off and heads for the Sun. Then, the computers in the spacecraft and at Mission Control at Houston, Texas, take over.

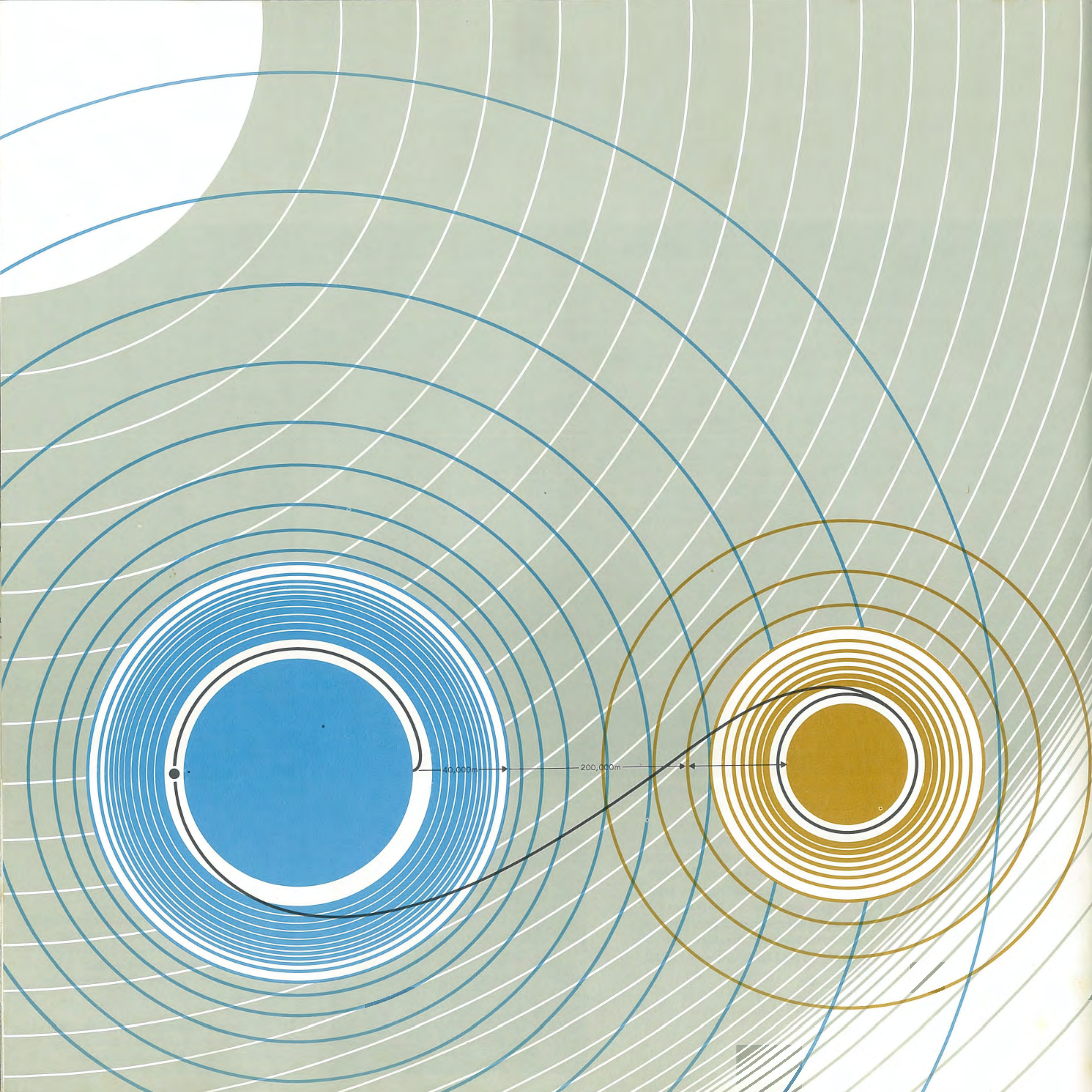
In less than three hours, the Instrument Unit has done more controlling than a power-station control room, three times as large, is likely to do in a week. And it has survived the shock during lift-off, as well as exposure to cosmic rays and the sun's heat above Earth's atmosphere.





Above, at Kennedy Space Center, a transporter carries 12.5 million pound load at an average speed of under one mile per hour. The unfueled Saturn V launch vehicle weighs one-half million pounds and the mobile launcher, on the right, weighs 12 million pounds.

Left, technicians unload the 58-foot long third stage of a Saturn V space vehicle from a Super Guppy aircraft at Cape Kennedy, following its arrival from California.


40,000m
200,000m

The way we customarily draw the path of an Apollo mission the shape looks a little like the mathematical symbol for infinity (∞).

That's appropriate. When Apollo's third-stage rocket bursts into life for the second time, to send the spacecraft into a translunar trajectory, it accelerates to about 24,200 miles per hour, a speed that, theoretically, would take it to infinity, if Earth and the spacecraft had space all to themselves.

But as we now know, the Sun tugs at those two bodies. The Sun's pull is negligible compared to Earth's, when the spacecraft is still near Earth. But once the spacecraft gets about 40,000 miles from Earth, the Earth's attraction has dropped enough so that the Sun exerts a significant influence on the spacecraft and must be included in orbital calculations.

At 200,000 miles, the moon's gravity is the dominant force acting on the spacecraft, and the forces of Sun and Earth can largely be ignored. At this time, the spacecraft is travelling at a speed of about 2,700 miles per hour (having been slowed down for two and a half days by the pull of Earth and Sun) and then is accelerated by the moon.

Timing the burn

The third-stage burn that vaults Apollo toward the moon should take place at a spot on the side of Earth that is away from the moon and on a direct line through the center of the earth and the center of the moon. This is called the antipode. Firing at this point gives the most efficient trajectory, reduces course corrections that might be needed later and, so, conserves fuel.

Men can't react precisely enough to initiate that rocket restart within a hundredth of a second, as required. But they can build machines to take action for them. The digital computer is one of those machines.

A computer in the Instrument Unit calculates the timing for that burn and signals the engines to start at the right moment.

This burn and every burn during the trip, every maneuver, every event, was planned months before launch. A precise ephemeris for the spacecraft during the entire trip was calculated and stored in computers. Into the computers also went performance characteristics for every piece of equipment in the rockets and in the spacecraft . . . exact timing of lift-off and stage separations . . . the constantly changing influence of gravity from Earth, moon and Sun . . . positions of moon, stars and planets along the way.

Are we on time?

The computers automatically check actual performance with planned performance. If lift-off is a tenth of a second late, if a high wind at Cape Kennedy blows the bird off course, if the parking orbit around Earth is just a few miles off target, a new ephemeris must be calculated to predict the actual course the spacecraft will take.

Once the bird clears the launch tower at Cape Kennedy, the computer at Houston starts gobbling a flood of information from tracking stations around the world . . . from the astronauts . . . from flight controllers and others on Earth who monitor the mission. During the same time, the computer is spewing out answers to a thousand questions the flight controllers might ask.

Every time a rocket fires or new readings of spacecraft position, velocity and direction are received, the computer recalculates a new trajectory and delivers the results, in just three seconds. Throughout the mission, it updates the ephemeris and predicts the path of the spacecraft for 40 hours of flight. It can flash this information to visual display units in Mission Control and up to the astronauts four minutes after it receives new tracking data.

The computer automatically compares the new, true ephemeris with that desired. If the course must be changed to keep the spacecraft on target, the Houston computer determines how much rocket thrust is needed, for how long, in what direction and the best time to make the correction.

Computers check computers

While the computer on the ground keeps a constant check on radar and radio tracking information, another computer in the spacecraft is doing its own calculating of position, speed, trajectory and equipment performance, based on information generated by instruments built into the spacecraft.

Other computers, at Houston and Goddard Space Flight Center near Washington, D.C., act as electronic shadows – mimicking operation of the primary computers. These back-up computers are ready, at any moment, to take over if trouble crops up in the primary computer at Houston.

Out in space everything is askew and moving in strange directions at high speed. So it's hard to keep your bearings. But it's important that you do if you plan to meet the moon at a particular time and a particular place – especially when you are traveling at a constantly changing speed of several thousand miles per hour.

On Earth, we can assume the equator and the North Pole are fixed at any given moment. We use them as references and position everything else and ourselves in relation to them.

Stars that stand still

In space, it's convenient to use, as references, the Sun and some fixed stars that don't move perceptibly during short periods of time. The basic reference can be the ecliptic, which is the plane of Earth's orbit around the Sun. The orbits of the moon and other planets are tilted at various angles to the ecliptic. Regulus, a fixed star that always appears near the ecliptic, can be used as a second reference. By observing, from the spacecraft, the positions of planets and moon in relation to these references and comparing them to known positions of these bodies, the astronauts can determine their exact position. In practice, the astronauts use several different reference points, depending on where they are in space.

Help from a computer

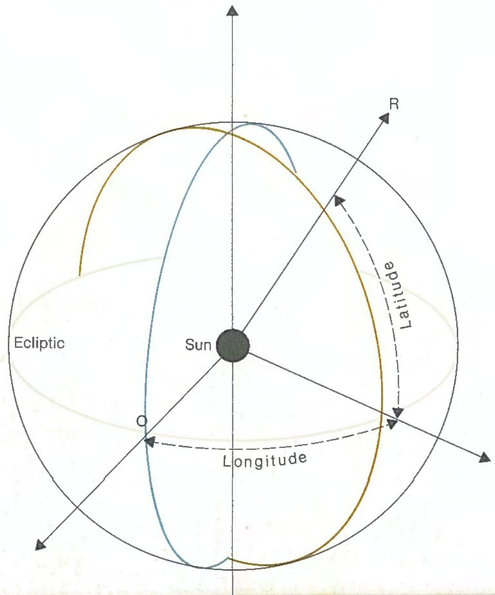
In space navigation, there isn't enough time to handle the necessary calculations by hand. Here, the compact, on-board computer again comes to the aid of the astronauts. An automatic sextant is used in conjunction with the computer. Before each major mission event the astronauts sight through the sextant. The readings are entered into the computer, where an exact position is determined, based on data and instructions stored in memory. The computer then aligns the on-board guidance and navigation system to establish a fixed, known reference in the spacecraft. Accelerometers in this system then measure magnitude and direction of acceleration caused by the firing of rockets. The computer compares this data with the reference and maintains a continuous record of speed, position and direction.

This makes it possible for the astronauts to navigate for themselves, if necessary, and furnishes an important backup to Earth-based tracking systems.

A tricky maneuver

That little on-board computer comes in handy during rendezvous, too. Without it, safe, smooth docking in space might not be possible.

Fish-eye camera lens provided this view of the interior of Lunar Module spacecraft simulator during prelaunch practice mission at Kennedy Space Center.



Right, one way to locate a body (R) is to assume the universe is a sphere with the Sun at the center. Then, draw the plane of Earth's orbit (the ecliptic). Let the Sun's position on the ecliptic, as seen from Earth at the vernal equinox, be a point of reference (O). By measuring what we will call longitude and latitude and the distance from R to the Sun, we can locate R in space. To handle calculations such as this quickly, astronauts use a computer.

Just the problem of catching up to and falling in behind another orbiting spacecraft boggles the mind.

Let's say you are at the controls of the Command Module and the LM has just come back up off the moon and is floating along a mile ahead of you in the same orbit.

If you speed up, you slow down

On Earth, you'd just gun your engine and speed up to close the gap. But in space, as soon as you speed up, you move up into a higher orbit. Once you're in that higher orbit, you slow down to a new orbital velocity, as Kepler's Laws suggest, and you drop farther behind your target.

If, instead, you slow down by firing retro-rockets, you drop to a lower orbit, where you speed up. But now you are below your target. Every time you gain in one direction, you are likely to lose in another.

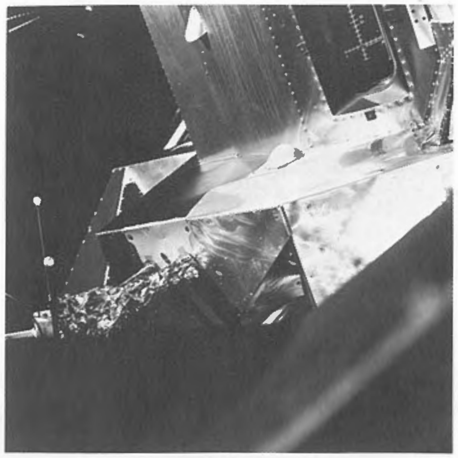
In Apollo, a complex guidance system and the astronauts' skill make docking look simple.

A radar, aimed at the target vehicle, keeps pulsing out radio signals toward the target and measures distance by measuring the time it takes signals to return.

The pilot carefully guides the spacecraft, using lights on the target and an alignment sight as visual aids. In response to the pilot's action, the on-board computer generates electrical signals that automatically select and fire the right combination of thrusting rockets to move the spacecraft where the pilot wants to go.

A 70-pound computer

The little computer that makes this possible weighs about 70 pounds. It can do an addition in 24 millionths of a second. It can ask the astronaut for more information when it needs it . . . or tell him where he is and where he's going by displaying information on a display tube. It's useless without him and the computer programmers who wrote its operating instructions. But without it, and many other NASA computers, no one would yet know what it's like to walk on the moon.



Far left, markings on the window assist the Command Module pilot in a gross determination of the range and range rate and attitude alignment during docking maneuvers. Left, a view inside the Command Module. Right, docking maneuver during Apollo 9, looking from Lunar Module toward Command Module. This and other test missions helped perfect procedures later used in lunar landing missions.


SATURN
GUIDANCE
BOEING

Space flight and computers —they go together

Today, wherever you find NASA people, you find computers and computer people – around the world, on the remote island tracking stations, on the tracking recovery ships, on the aircraft that pick up Apollo's signals when they can't be received at surface listening posts.

As in so many other technologies essential to the Apollo Program, successful use of the computer requires contributions and cooperation from the entire industry. Here are a few of the ways computers help Apollo, and just a few of the companies that make them work.

Launch. During final systems checkouts, Control Data Corporation computers test operation of command and lunar spacecraft modules . . . calculate early flight path during launch . . . predict abort impact points. General Electric computers are used to conduct crucial systems tests during the final stages of the Apollo countdown. Remington-Rand UNIVAC computers handle all message switching and control information flow between Apollo, tracking stations and the Goddard Space Flight Center; they also help navigate and process tracking information on communications ships. RCA computers are used to check out all three stages of the Saturn launch vehicle during final countdown. IBM personnel coordinate and program all computer functions used at Cape Kennedy during final countdown and systems check . . . supervise assembly, programming and testing of the Instrument Unit. An IBM digital computer and data adapter handle information processing and initiate rocket control signals in the Instrument Unit.

Communications Control. All information from NASA's worldwide listening and tracking network first passes through the computer complex at Goddard Space Flight Center, at Greenbelt, Maryland. People at Goddard test and monitor operation of every NASA communications link between Earth and space and handle data for both manned and unmanned spacecraft. Goddard has one of the most powerful concentrations of computers in the world. It is served by people and equipment from The Bell System, Bendix Corporation, Control Data Corporation, General Electric, IBM, RCA, UNIVAC and many, many other firms, as well as universities and government agencies which have played essential roles at this and other NASA installations.

Mission Control Center. IBM is responsible for systems planning, programming, maintenance and operation of the Real Time Computer Complex in Houston, which analyzes data from tracking stations and the spacecraft . . . computes and continually recomputes Apollo's flight path . . . signals rockets to fire through on-board computer systems . . . processes medical data for the Apollo crew . . . monitors Apollo equipment performance.

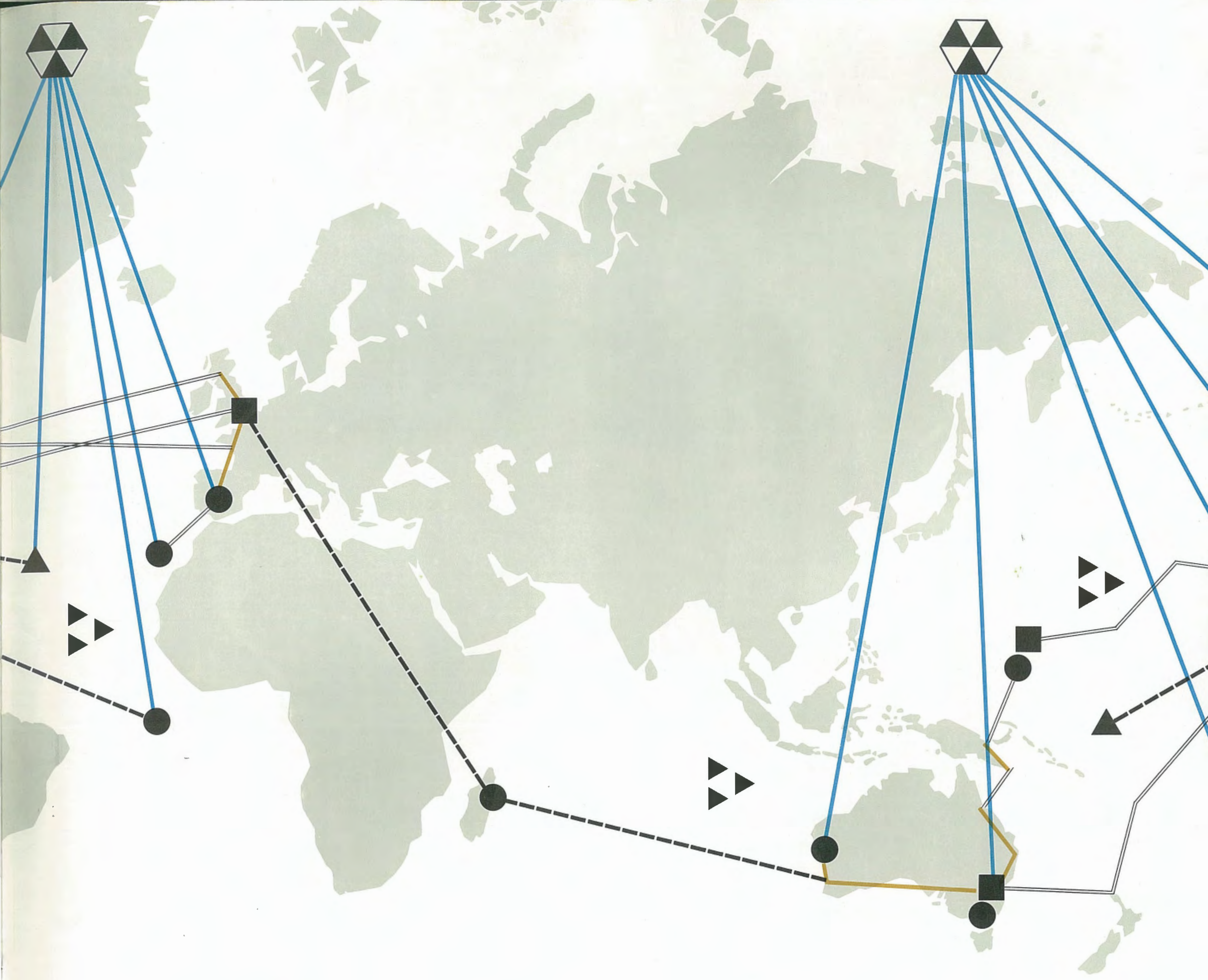
This computer center can generate information at the rate of a novel a minute when required. It can flash selected information on Philco-Ford display consoles, manned by industry and NASA personnel at Mission Control. It can report to the Flight Director, second by second, on the performance of any system or function in the Apollo launch vehicle or spacecraft. It follows Apollo from the time it clears the launch pad at Cape Kennedy, until it splashes safely back down on Earth.

Many other companies and many other computers at the Manned Spacecraft Center in Houston contribute to communications, control, testing and analysis of information before, during and after each mission.

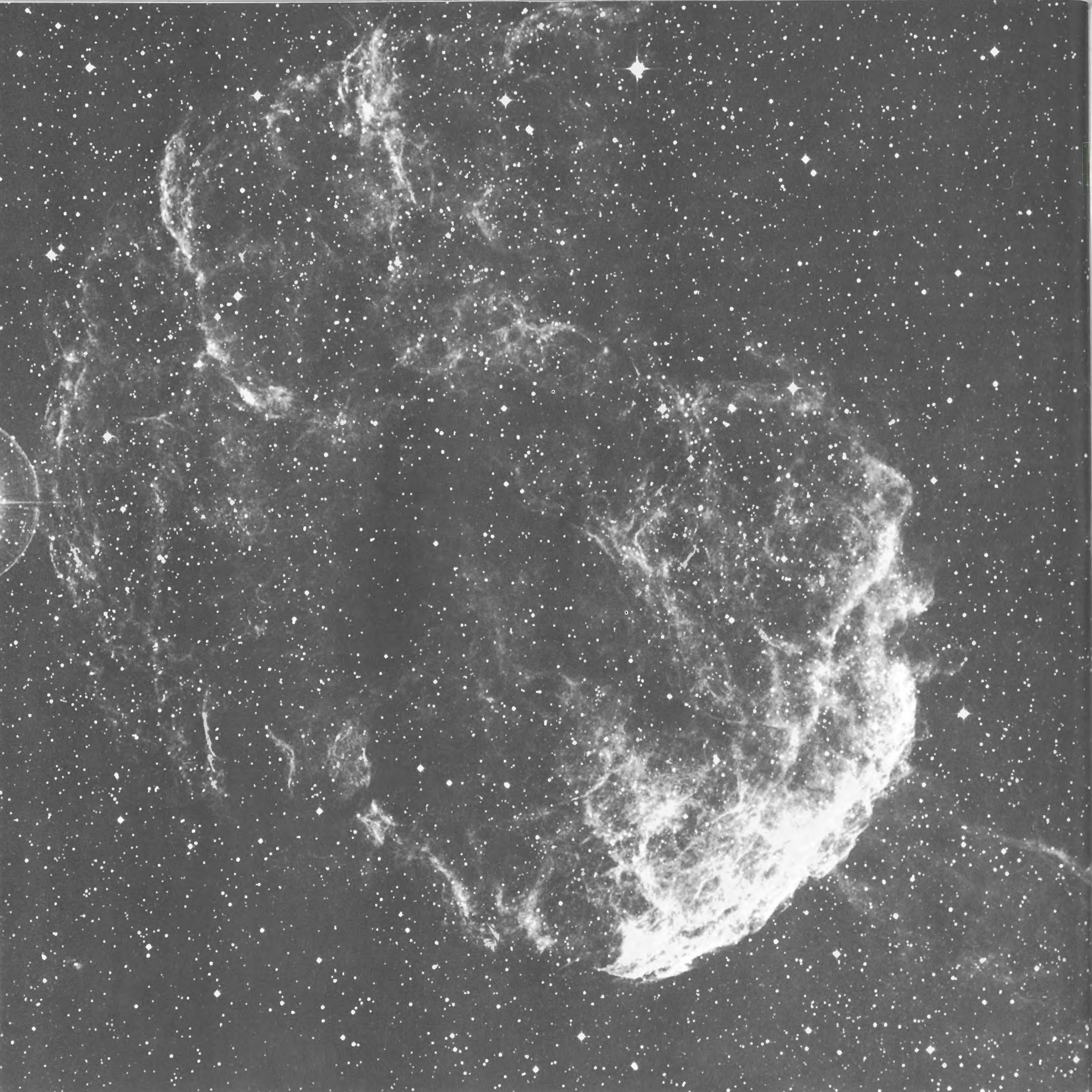
In orbit. The IBM computer in the Instrument Unit is used for guidance, navigation and operational control of the Saturn launch vehicle until the third-stage rocket separates from the spacecraft. Once in Earth orbit, astronauts take charge, using a spacecraft guidance and navigation system supplied by AC Electronics Division of General Motors. The 70-pound digital computer in this system was designed by Massachusetts Institute of Technology and built by Raytheon.

Left, engineers in Firing Room No. 1 at Cape Kennedy monitor final preparation for the Apollo 11 launch. Personnel operate 450 computer driven consoles in the firing room, located three and one-half miles from the launch pad.

Right, 85-foot antenna at Goldstone, California, and two others like it, in Australia and Spain, are used to send commands to and receive data from spacecraft. They are positioned around the world so that at least one of them is always able to communicate with the spacecraft.



The worldwide NASA communications network used to track satellites and spacecraft. Diagram shows communications links that could be used to follow a space vehicle or satellite on its trip around the world. All communications are monitored and processed by computers at Goddard Space Flight Center, near Washington, D.C. Information is analyzed by computers at Goddard and at Mission Control Center in Houston, Texas.



Toward a new tomorrow

Since 1952, hundreds of computers, dozens of companies and thousands of computer people have been at work in the space program, processing paperwork, analyzing scientific data, writing programs, plotting orbits of planets, testing and updating equipment, devising new and improved computing techniques.

Tomorrow, men will continue exploring and learning about the moon . . . perhaps tramping on Mars, studying the stars from orbiting observatories, learning more about our universe, our Earth and ourselves. And a lot of what we learn in space will be brought down to Earth, to help us solve problems here. A lot already has been brought.

Some of the ideas developed for Apollo already have been adapted for use by industries and governments and schools. Many more can be.

Many of the people, themselves, now are working on management and communications problems that are not directly related to the space program but are similar to those they had to solve to put men on the moon.

To help boost Apollo to the moon, these people stood on Newton's shoulders. Now we can stand on theirs, and, perhaps, see a little farther and see our earthbound problems and their solutions a little better than we have before.

Suggestions for further reading

There now are hundreds of books available on space exploration and on the operation and application of computers. The short list below is intended only as an introduction to basic principles. Your librarian or bookseller probably can direct you to additional references on subjects of special interest to you.

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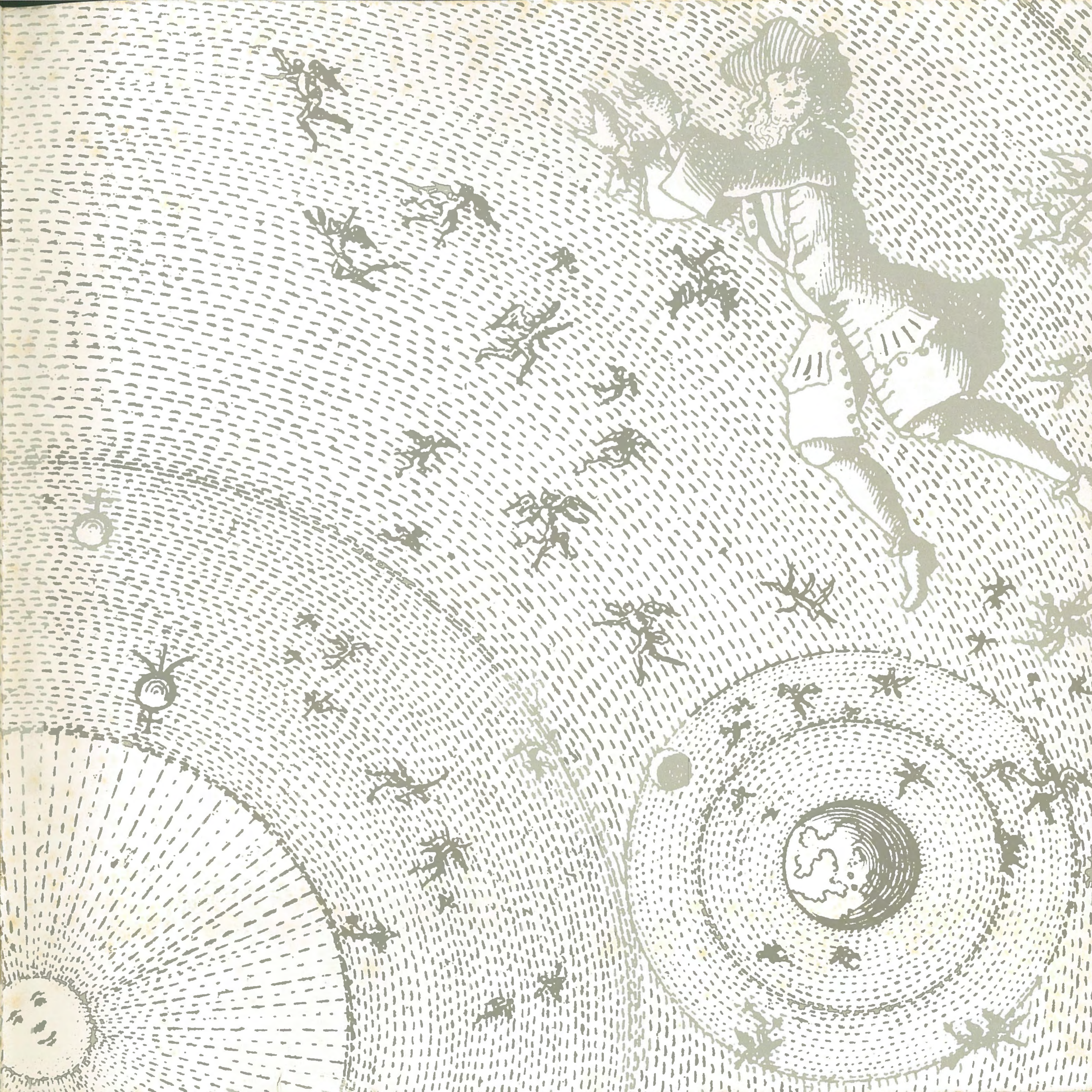

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