PIONEERS IN ASTRONOMY

NAVIN SULLIVAN

Illustrated by
ERIC FRASER

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By the same author
Pioneers Against Germs

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Preface

In this book I have tried to explain a little of the way in which men have explored the Universe. When men had no telescopes, they believed that the Universe was a fairly small and simple place, and that they were the most important part of it. Today we know that the Universe is very large and very strange, and we think differently about ourselves.

I have not dealt with all the different sorts of work which astronomers do. Instead, I have singled out pioneers who helped us to explore farther and farther into the Universe. As you will see, each step they took depended on one taken by some one else before. And at each step they found that there was more and more to explore. Today, we know that astronomy, the oldest of the sciences, is only just beginning.

N. S.

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Contents

I

COPERNICUS

The Moving Earth

MARIA DA NOVARA, professor of astronomy, looked round at his new students. It was the autumn of 1496 and the beginning of an academic year. His students had come from many countries, for the University of Bologna was one of the greatest in Europe. Among them was a freshman from the borderland between Germany and Poland. His name was Nicolas Koppernigk, or, in the Latin preferred by scholars, Copernicus.

As Novara prepared to speak, Copernicus leaned forward eagerly. He was very interested in astronomy.

"It is generally believed," said Novara, "that the Earth is a globe standing still at the centre of the Universe. Around it move the Moon, the Sun, and the five planets we know. Beyond these, but still quite near, are the stars, turning on a transparent sphere. We are therefore at the very centre of the whole Universe and everything revolves around us."

Novara went on to explain that the planets appeared each night in a different place against the patterns of stars. They slowly wandered eastward, but at intervals they would pause and move backward for a while, after which they would resume their eastward journey. For some reason they traced out loops in the heavens.

"This was explained over thirteen hundred years ago by the great Greek mathematician Ptolemy," said Novara. "According to him, all heavenly bodies must move in circles. This is because the circle is the most perfect geometrical form, and heavenly bodies must be perfect. Now since the planets move in loops they evidently cannot travel in simple circles. However, Ptolemy was able to account for this and still keep the planets moving in circles. He showed that mathematically the loops can be thought of as a combination of small circles moving round in large circles. The planets go round in a series of circles-upon-circles. By using a total of thirty-nine different circles, Ptolemy and his followers have accounted for the apparent movements of the Moon, the Sun, and the five planets."

Copernicus wrinkled his nose suspiciously. He knew that Ptolemy was a very important man. For as long as men could remember, what Ptolemy said had been law. His ideas had seemed to work for over a thousand years. In fact, Columbus had used them successfully when navigating his way to the New World. All the same, Copernicus could not help thinking that thirty-nine circles was a lot to explain how only seven bodies moved.

"There ought to be some simpler explanation," he told himself.

* * *

As he continued with his studies, Copernicus learned how to make astronomical observations with the crude instruments of the time. Novara taught his students the use of the triquetrum, for measuring the heights of the stars in the sky. There was the Jacob's staff, for gauging the angle between two stars. For fixing the height of the noonday sun he showed them the plinth, which Ptolemy had invented. In fact, none of their instruments was better than those used over a thousand years earlier. Copernicus felt dissatisfied with this musty old science in which nothing ever seemed to change.

One day he plucked up courage and asked Novara whether men had ever had other ideas about astronomy. Novara was delighted.

"Certainly they have," he said. "My teacher, the famous Regiomontanus, never liked Ptolemy's system. He preferred the ideas of another ancient Greek, Aristarchus of Samos. According to Aristarchus, the Sun only appears to move across the sky each day and round the other side of the Earth at night. Instead, he thought that the Earth turns on its axis like a top, carrying us from sunlight to darkness to sunlight again. This spinning would also make the stars seem to move across the sky each night. What is more, Aristarchus believed that the Earth went in a great circle round the Sun each year!"

"But if the Earth were spinning round, surely we would be thrown off!" protested Copernicus. "And when a stone is thrown up in the air, it should be left behind."

Novara could not explain this. All he could suggest was that everything on the Earth might be carried round in a sort of protecting envelope of air.

"I do not know which explanation is correct," he confessed. "But I believe that the geometry of the skies should be simple. Whichever is the more simple idea is probably the right one."

Copernicus listened eagerly. Here was some one who, like himself, suspected complicated explanations. Perhaps, then, he was right to question the ideas of the great Ptolemy!

* * *

Now Copernicus plunged deeper into his studies of astronomy, with Novara encouraging him. He learned Greek and read Ptolemy in the original, sitting up half the night to wrestle with those circles. His brother Andreas came battering at his door, urging him to leave his books and enjoy himself, but Nicolas shook his head. He was enjoying himself too much where he was. The ideas of Aristarchus had kindled his imagination and he was determined to see where they led.

But he had to study other subjects too. He learned the geometry he needed before he could fully master Ptolemy's ideas. He learned the outlandish medicine of the time, jotting prescriptions down wherever was handy, even on the back of his textbook of Euclid.

"Take lizards in olive oil," he noted solemnly, "and earthworms in wine . . ." He might have ideas of his own in astronomy, but in medicine he was content to follow others.

Now officially a canon of the Church in his homeland, thanks to special recommendations by his uncle, who was a bishop, Copernicus also studied Church law. From Bologna he went to Rome, from Rome he went to Padua. Basking under the sunny Italian sky, he thought with a shudder of his colder northern homeland.

But at last, in 1506, he had to leave. His uncle the Bishop of Ermeland summoned him to be his private physician. Sorrowfully, Copernicus packed up and said good-bye to Italy, realizing that his student days were over. It was about time: he was thirty-three years old.

Living in the bishop's official residence of Heilsberg Castle, Copernicus had to observe elaborate formalities. At noon, the dinner bell sounded, and all the castle residents had to come to the doors of their apartments and wait respectfully for the bishop. Then, to the sound of the baying hounds he had just fed, the bishop would appear in the courtyard, splendidly dressed even to mitre and purple gloves, and carrying his staff of office. Every one would follow him to the Hall of Knights, where they sat at tables strictly allocated according to their social rank. The bishop naturally sat at the principal table. Copernicus, as his nephew and physician, sat at the second. The ninth table, which was the bottom of the scale, was reserved for jugglers, jesters, and other entertainers.

It was in the strange surroundings of this medieval court that Copernicus struggled to reform astronomy and alter the whole picture men had of themselves in the Universe. He was like a revolutionary secretly trying to make a bomb that would blow everything upside down, but instead of explosive his bomb was filled with ideas.

Yet although Copernicus was willing to overthrow Ptolemy by supposing that the Earth could travel round the Sun, he clung to Ptolemy's basic idea of circles-upon-circles. He tried to use this complicated mathematical machinery to explain a concept that really needed much simpler and more powerful ideas. In modern times the same sort of thing happened when men struggled to make more and more powerful piston-engines for aircraft, until they turned to a new principle, jet-propulsion, which is far more efficient.

Although handicapped by his antiquated mathematics, Copernicus was determined to succeed. During the six years he spent at Heilsberg Castle, he became convinced that the Earth did indeed go round the Sun, for he saw that this explained away the planetary loops. At last he had found some of the simplicity he had longed for!

"The Earth takes a year to go round the Sun," he told himself, "but Mars takes two years and Jupiter nearly twelve. Surely, then, as the Earth rushes round and round, it will regularly pass by these slower-moving planets. And every time that it overtakes one of them, that planet will go backward for a while, in relation to the Earth."

It was a brilliantly simple idea. Like many great ideas, it may now seem obvious, but when Copernicus was thinking of it, it was difficult to imagine. Nowadays we know that if we look out of a train in which we are passing a train on the next track, that slower train often seems to be going backward. Later, however, when we are well past, we see it from a distance and realize that it is going forward.

"Only suppose that the Earth is moving, and we can explain the planetary loops as an illusion," Copernicus noted with triumph.

Once he accepted that the Earth went round the Sun, he was ready to believe that it spun round like a top as well. Some men had argued that if it spun fast enough to turn round once in a day, it would shiver into pieces like a wooden wheel that was spun too fast. Copernicus countered this by reasoning that if the great sphere carrying the stars revolved instead, it would have to go much faster and be all the more likely to break apart. All the same, the speed at which the Earth must turn was frightening.

"We are all spinning around at a hundred and fifty double paces every second!" he breathed, hardly daring to grasp the fact. Why, if he were looking on from a distance, everything would go flashing by in the blink of an eye. And he could not explain why everything was not thrown off the Earth: he never thought of the Earth's gravity as a safe anchor on this ride through space.

There was another puzzle, too. Aristarchus had made a rough measurement of how far the Sun must be from the Earth. Using crude data, he reckoned that it was at least 4 or 5 million miles away. (Actually it is 93 million.) If the Earth went round the Sun, this meant that it must travel in a gigantic circuit some 10 million miles across. But as men believed the stars were not far away, they correctly argued that such a tremendous journey would surely bring the Earth close to the stars, first on one side of the circuit, then on another. However, no one could see groups of stars looking nearer at one part of the year than at another. This proved, they decided, that the Earth was not moving round the Sun.

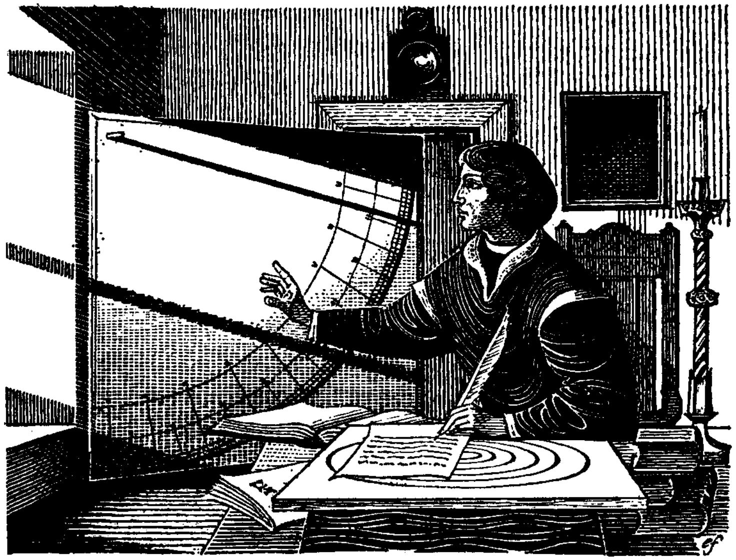
Copernicus, however, saw things differently.

"It proves instead that the stars must be very far away—much farther than anyone has imagined," he stated. "In fact, they must be so far away that even a journey of ten million miles is trifling in comparison, and the distance between us and them remains almost the same!"

Copernicus was bold enough to imagine a Universe very different from the one he had been brought up to believe in. Instead of being tranquilly at rest, the Earth was whirling at terrible speed around the central Sun. The familiar stars, that looked so near, became unimaginable fires very far away from the Earth.

However, although he had explained the planetary loops, Copernicus still could not explain the planetary orbits as simple circles. He therefore clung to the basic idea of circles-upon-circles, modifying them to map detailed orbits round the Sun. To do this, he had to ensure that they squared with all the observations men had made of the positions of the planets. This meant checking every possible arrangement of circles-upon-circles against thousands of records piled up by ancient astronomers. It was a frightful job!

Gradually he thought he could see that his calculations would work out all right in the end. Unable to keep the news to himself any longer, he began dropping hints to favoured visitors to the castle. Finally, in 1512, he wrote a short book explaining the general scheme of his ideas, but omitting any detailed mathematics. He sent a few handwritten copies of this book privately to various scholars.



"Thirty-four circles," he wrote proudly, "suffice to explain the entire structure of the Universe and the entire ballet of the planets."

* * *

Unfortunately Copernicus still had to complete the detailed calculations. He found to his dismay that the longer he worked at them the more complicated they became. Circles were piled on circles in nightmarish profusion. In the end, after no fewer than twenty years of struggling, he found that he needed forty-eight circles—nine *more* than Ptolemy had used! It was a bitter disappointment. No longer sure of his theory, he locked his manuscript away and did not try to publish it.

Meanwhile his short handwritten book had been read by scholars in different parts of Europe. One, a young professor named Joachim Rheticus, was so enthusiastic about it that he came to see the ageing astronomer. He brought precious gifts of first printed editions of Euclid and Ptolemy in Greek. More important, he brought boundless energy and belief in Copernicus and his ideas.

"My Teacher," he declared, "your system will open a new era in astronomy. You must publish it, for the good of mankind!"

Copernicus was not so sure. That nightmarish arrangement of circles haunted him. But young Rheticus would not give in. Day after day he argued and pleaded. He even offered to go through the manuscript for stray errors, and then to arrange for the printing. Anything if only the obstinate old man would agree!

And eventually Copernicus yielded. He took the bulky manuscript out of its hiding-place and handed it over to his enthusiastic disciple. In 1543 it was published, under the title

On the Revolutions of the Heavenly Spheres. But its author had waited too long to see how it was received. At the end of 1542 he had a stroke, and when the first copy was brought to him he was at the end of his strength. He touched it, and that was all. A few hours later he was dead. It was May 24, 1543.

* * *

Copernicus was right to be worried about his complicated system of circles. We now know that, although the Earth does go round the Sun, his circles are not needed to explain this. Indeed, even the astronomical observations he used are inaccurate!

Yet in spite of this he succeeded. He was the first man to try to show, precisely and mathematically, how the Earth might move round the Sun, and his explanation of the planetary loops holds good today. More important still, he helped people to believe in the idea of a moving Earth. Maybe it moved in circles-upon-circles, maybe it didn't—but at any rate it moved! Man was no longer the centre of the Universe. And once that was accepted, the way was open for someone to start finding out how the Earth really does travel.

2

KEPLER

The Planetary Laws

IN 1596 an unknown German mathematics teacher named Johannes Kepler wrote a book that startled scholars everywhere.

"Copernicus was wrong," he declared. "The planets move in simple circles round the Sun. And I have discovered a beautiful mathematical scheme that explains the distances between these circles."

The idea had come to Kepler one day while standing at the blackboard. It struck him with such force that he was sure it must be true. The distances, which were ratios, not actual distances, had been calculated by Copernicus. The only trouble was that these ratios did not fit exactly into Kepler's scheme.

"That is because Copernicus used faulty observations in his calculations," claimed the young mathematician boldly. "With accurate observations I shall be able to show that my scheme is correct."

He knew that the most accurate observations in the world were being made by a Danish nobleman named Tycho Brahe. This astronomer had built an observatory on his private island of Hveen, off the Danish coast.

"If only I could get hold of Tycho's observations!" yearned Kepler.

However, he was a poor teacher living at Graz, in Austria. He could not afford to go all the way to Denmark. Sorrowfully, he decided that he would never be able to check his beautiful theory.

And then, in 1597, Tycho Brahe quarrelled with the Danish king. As a result, he packed up and left Hveen, taking all his instruments with him. For two years he roamed about Europe, and finally, in 1599, he settled down in Prague as official astronomer to Rudolph the Second, Emperor of Bohemia.

When Kepler heard of this he was overjoyed. Prague was near enough for him to be able to go there. At last he would be able to study Tycho's observations!

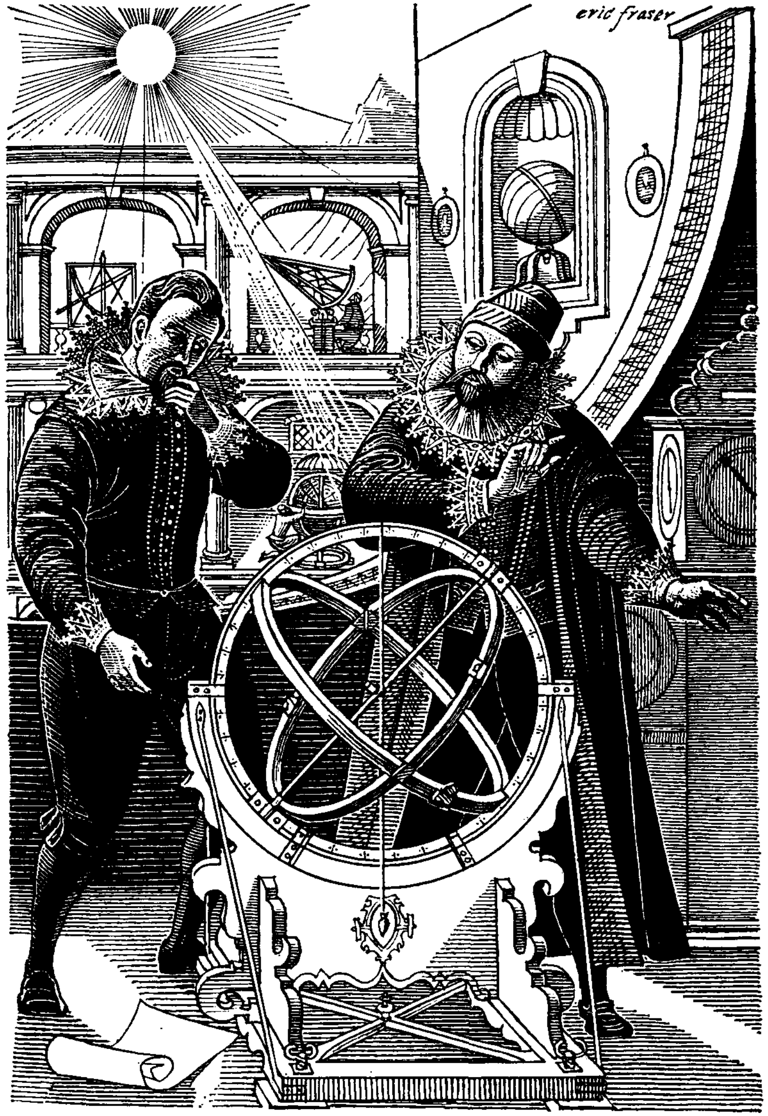
"With his observations, I shall build a new model of the Solar System," he told his wife, Barbara.

Luckily the Baron Hoffmann, Councillor to the Emperor, was in Graz. The hard-up mathematics teacher begged a lift in his coach, and on January 1, 1600, the journey began.

It was the first day of a new century. For Kepler, it was the first day of a new life.

* * *

The two men met on February 4 at Brahe's observatory in the castle of Benatek, near Prague. Kepler was a thin, shabbily dressed young man with melancholy, short-sighted eyes. Brahe was splendidly dressed, and had a bald head and large moustaches. More striking still, he had a false nose because his real one had been cut off in a duel. Brahe had made it himself out of gold and silver alloy. It shone in the light, and Kepler could not help staring curiously at it.



Kepler [*left*] being shown an astrolabe by Brahe

"I do not receive you as a guest, but as a very welcome friend and colleague in the contemplation of the skies," said Brahe grandly.

He showed Kepler the instruments with which he made observations ten times more accurate than those known to Copernicus. There were giant wood-and-metal sextants. There was a brass quadrant, 14 feet in diameter, for gauging the heights of stars or planets. Most splendid of all, there was Brahe's special pride, a great equatorial armillary with which he measured the angles between stars or stars and planets. And engraved on a magnificent brass globe were the results of his observations—the positions of a thousand stars.

Kepler blinked in astonishment. The globe alone was worth eighty years of his salary. The splendour of Brahe's equipment was beyond anything he had imagined. At the thought of the work that had gone into recording those one thousand positions, he began to see what grinding hard work was needed to start an exact astronomy. He could hardly wait to get his hands on the precious data Brahe had so laboriously collected.

"You must have many books full of observations!" he breathed. "When may I examine these?"

To his dismay, Brahe began to look secretive. "Oh, as to that, we shall see," he replied. "There is no hurry."

Brahe knew very well what the young mathematician was after, but the observations had cost so much effort that he could not easily give them away.

Kepler saw that the great astronomer wanted to hoard his precious data. It was a great disappointment. After coming all the way from Graz, his home and his wife, was he to be left empty-handed?

Kepler followed the imperious Dane about the castle. He saw the positions where observations were taken, and he met the senior assistant, Longomontanus.

"Longomontanus has been studying the orbit of Mars," Tycho Brahe said. "He is having difficulties with it. Mars seems more unpredictable than any of the other planets."

He went on to explain that the other planets seemed to move pretty well in circles, which was how they believed *all* the planets moved, but the circle for Mars had not so far been plotted.

For the next few weeks Kepler tried to get details about the planetary movements out of Brahe. His eagerness was obvious, but the imperious astronomer would do no more than mention a figure here and there, in passing. Kepler ground his teeth, and waited doggedly, hoping that he might yet persuade this miserly Dane to change his mind.

And then one day Brahe called him into his study.

"As I told you," he said, "Longomontanus has been having trouble with Mars." He paused, eyeing Kepler. Taking out the box of ointment he always carried, he thoughtfully rubbed some ointment on his metal nose.

"I have decided to assign him to the Moon instead," he announced. "Will you take over Mars?"

Kepler started joyfully. If he took over work on Mars, Brahe would have to disgorge all his observations for the planet!

"Give me eight days," he cried, "and I will solve its orbit!"

* * *

But he did not solve it in eight days. For the next eighteen months, he slaved away at the orbit of Mars, and still did not succeed. Meantime he had also to take on various chores for Brahe, tedious, time-wasting work which he hated.

Nor did he get data about other planets. As he had expected, Brahe gave him the Mars data, but with the rest he was as secretive as ever. At dinner Kepler was tantalized with scraps of information which Brahe threw him like so many bones to a dog. Once, unable to bear it any longer, Kepler fled to Prague and stayed with the kindly Baron Hoffmann, but Brahe persuaded him to return.

And then, on October 13, 1601, the great astronomer was taken ill after a banquet, and eleven days later he died. In a delirium on his death-bed he kept repeating, "Let me not seem to have lived in vain."

A fortnight afterwards, Johannes Kepler was officially appointed Brahe's successor. At last he could have all the data to work on.

* * *

However, he went on trying to solve the orbit for Mars. A lot of figures were available for this planet, and besides he was too immersed in the problem to give it up now.

"Assuming that Mars moves in a circle round the Sun, the difficulty is to find the circle corresponding with the observations," he mused.

He knew already that Mars was not always at the same distance from the Sun. He also knew that its speed varied: the nearer it was to the Sun the faster it moved.

"Wherever this circle lies, the Sun cannot be at its centre, or Mars would always be the same distance away," he reasoned. "Perhaps the Sun is a little to one side of the centre."

But what about the changing speed? Kepler supposed that some force was needed to keep a planet circling the Sun. He guessed that this force might come from the Sun, and push the planet on its way. Of course, he had no idea what this force might be.

"If the force spreads out from the Sun, it will grow weaker as it travels farther away," he told himself. "In other words, it will have less push on a planet when it is farther from the Sun, and more push when it is nearer. This could explain the way Mars changes speed, going faster when it is nearer the Sun!"

Enthusiastically Kepler set about trying to fit Brahe's observations to this idea. Sifting through the mass of data, he selected four key observations and tried to fit a circle to them. Many circles were possible, and every time he tried one he had to check it against all the other observations for Mars.

It was a tremendous job. Only some one as untiring as Kepler would have stuck at it. He made over seventy trials, and covered nine hundred pages with calculations in his small handwriting! At last, after several years of work, he found a circle which seemed to fit, allowing for the fact that even Brahe's observations might not be accurate within two minutes of arc. (One minute of arc is the same as the width of the head of a pin seen from about 5 yards away.) He was overjoyed.

"One more test," he whispered, driven by that relentless thoroughness of his. Turning to the records, he chose two rare observations and confidently tested his circle against them.

To his consternation, they did not fit. They were out by as much as eight minutes of arc. He knew that Brahe was too exact an observer to be inaccurate by such an amount—so there was no help for it, the circle was wrong! Kepler groaned and tore at his hair. All his work was wasted: he would have to start again.

* * *

And start again he did, with truly heroic courage and persistence.

"Those eight minutes," he wrote, "point the way to a complete reformation of astronomy."

He had lost faith in circular orbits, and saw that he must try some fresh approach. He was determined to obey the facts, the wonderfully exact observations collected by that impossible old Dane. No theory was any good unless it accounted for all of them.

A wild, improbable idea came to him. "Perhaps an oval would fit," he muttered, as he thought of the shape of a hen's egg.

He plunged into fresh calculations. Thousands were needed to check the idea. On July 4, 1603, he wrote to a friend that he could not solve the geometrical problems of this oval.

"If only," he added, "the shape were a perfect ellipse."

Yet he went on struggling with the oval for several more months. When he finally admitted himself beaten, he decided not to start with any fixed idea of what shape the orbit might be, but to let the observations speak for themselves.

Very carefully, he calculated afresh twenty of the points of the orbit.

"They certainly fit into some kind of oval," he muttered, staring owlishly at them. "But the shape is like a circle too . . . perhaps between the two, like a circle flattened a little at two opposite sides. . . ."

It was around Easter, 1605, when he had the necessary inspiration and all the figures fell into place in his mind. Just as he had wished in his letter two years earlier, the orbit really was a perfect ellipse! He had solved the orbit of Mars at last—not after eight days, as he had once boasted, but he had solved it all the same. And in his triumph he drew a little sketch beside his proof, showing the goddess of victory riding in her chariot over the clouds.

* * *

It is no wonder that the planetary orbits were for so long thought to be circles. As Kepler found with Mars, and went on to discover for the other known planets (including Earth), the orbits are all ellipses, but ellipses that are very nearly circles. And the Sun is in one focus of each ellipse.

But *why* are the orbits elliptical? *Why* do the planets travel at shifting speeds, accelerating as they near the Sun, decelerating as they draw away? And *why* do the outer planets travel more slowly than the inner ones, as Copernicus had known? Kepler asked himself all these questions but he could not answer them. It was not until some eighty years later that an Englishman, Isaac Newton, showed that all these facts could be explained by one universal concept, gravity.

Before then, however, men were to have a better way of exploring the skies. The great quadrants and armillary spheres of which Tycho Brahe had been so proud were to be thrown away for ever. Instead, men were to use a marvellous new instrument, first devised by a humble spectacle-maker in Holland, and turned skyward by a brilliant Italian professor named Galileo Galilei. This was the telescope.

3

GALILEO

Exploring the Skies

One May evening in 1609 a carriage rattled briskly through the streets of Padua, in Italy. In it was Galileo Galilei, professor of mathematics, returning from a trip to Venice. While there he had received news from a former pupil named Jacques Badovere—news that sent him hurrying home.

"A marvellous tube is on sale here," wrote Badovere, who was now living in Paris. "This tube makes objects appear close. A man two miles away can be seen distinctly! People call these tubes 'Dutch perspectives' or 'Dutch cylinders.' Some say that they were invented by Hans Lippershey, an unknown spectacle-maker in Middleburg, Holland. What is sure is that they employ two lenses, one convex and the other concave."

The carriage turned into the Borgo dei Vignali and stopped outside Galileo's house. Pausing only to glance at his garden, Galileo hurried indoors, and went to his study.

"One convex and one concave," he repeated as though in a trance. He drew writing-paper towards him, dipped a sharpened quill in the ink, and began to draw.

"Suppose the convex lens is placed in front, to gather the light," he muttered. "Then if the concave lens is placed the right distance behind, it should magnify the gathered light."

He only had to work out the distance and he would be able to make one of these marvellous "Dutch perspectives" for himself! He had already taken the precaution of bringing a good assortment of spectacle-lenses from Venice.

By the time that Galileo went to bed he felt pretty sure that he had solved the problem. Early next morning he hurried to his workshop. The place was filled with gadgets he had already invented, including an apparatus for indicating temperature and another for timing the pulse of a patient. Now he would make a tube to demolish distance!

Seizing a handy piece of lead tubing, he cut it down to a certain length. Then he took a convex spectacle-lens and placed it in one end, and placed a concave lens in the other. Excitedly he held the tube to his eye and peered through. Immediately he gave a cry of delight. It worked! The church tower several streets away might have been just outside.

How much did his tube magnify? To find out, Galileo cut different-sized circles of paper and pinned them up on a wall. When he found that his tube made a small circle look the size of a larger one seen with the naked eye, he could work out the magnification by comparing the actual sizes of the circles. In this way he found that this first telescope of his magnified three times.

Proudly he sat down and wrote to his friends in Venice telling them of his success. Then, after getting the lenses mounted in a more imposing tube made of wood, he hurried back to Venice himself. The Venetians were famous as sailors and navigators. This tube would show them ships out at sea long before they could be seen with the naked eye. Surely, thought Galileo, the nobles of Venice would pay well for that!

His scheme worked well. On August 8, 1609, the aged members of the Venetian Senate clambered painfully up to the very top of the tower of St Mark, the highest building in Venice. There they gazed out to sea through Galileo's primitive telescope and, to their delight, found that they could see ships sailing towards them a good two hours before they were visible with the naked eye. They promptly doubled Galileo's salary as professor of mathematics, which, although at the University of Padua, was controlled by them.

Galileo returned triumphantly to Padua and disappeared into his workshop. Already he was planning better lenses and longer tubes. He would teach himself lens-grinding. He dreamed of magnifications of 8, 20, even 30!

And when he had made these telescopes, he was going to use them to look not at the sea but at the sky. Five years earlier all Padua had seen an extraordinary happening: a new star had appeared in the sky. (Kepler had seen it too, and had pointed out that evidently the stars were not unchanging, as men then believed.) Like every one else, Galileo had been surprised and puzzled by the new star. Now he promised himself that he was going to look more closely at the heavens.

* * *

It was four days after new moon. Galileo's newest telescope, magnifying 30 times, was resting in its cradle on a tripod stand. He squinted through it at the bright crescent, then drew what he saw by the light of a flickering candle.

The Moon was, he knew, lit from one side by the Sun. He noticed that the boundary between light and dark on the Moon's surface was wavy and uneven. Also he saw bright spots of light dotted over the dark area. What could they be?

He puzzled over them for a while and then he made a bold deduction.

"These spots of light are mountain peaks just catching the sunlight," he decided. "At the wavy line there are other mountains. It is sunrise up there and, just as on Earth at dawn, the mountain peaks are bathed in sunlight while the valleys are still dark. Yes, there are mountains on the Moon, as there are on our Earth!"

Until then no one had seriously supposed that the Moon might be something like the Earth. They had thought of the Moon and planets as heavenly bodies, things quite different in kind from the Earth.

How high were these mountains? Galileo could not measure them directly, but he devised a way of comparing them with the diameter of the Moon, which was fairly accurately known. When he had worked out the figures he could hardly believe them.

"Why, they are enormous!" he exclaimed. "They are as high as our earthly mountains: up to four miles high!"

It was a whole new world he was looking at. But was it full of living creatures or was it dead? He wondered if there was air on it, and shuddered at the idea that it might be cold and silent, a dead world for ever circling the Earth.

Then he began to explore the sky. Night after night he gazed upward, and what he found was a revelation. With the naked eye only about two thousand stars are visible at one time. Even with his relatively low-power telescope, Galileo found myriads more than that.

He examined the belt and sword of Orion: instead of the usual nine stars he found eighty-nine! The constellation of the Pleiades, in which sharp-eyed observers could only see seven

stars, became a swarm of forty-three. As for the Milky Way—it was impossible to think of counting the stars in it. Wherever Galileo looked, his telescope showed him crowded clusters of them.

"Many of them are tolerably large and extremely bright," he noted, "but the number of small ones is quite beyond determination."

On January 7, 1610, while gazing at the sky an hour after sunset, he noticed the planet Jupiter was visible. Immediately he turned his telescope on to it, eager to examine one of the planets for the first time.

He saw that it was a small, round disc, not sparkling like a star. Peering more closely, he saw something else: three bright little points of light were grouped near it, two to the east of Jupiter, one to the west:

(East) + + O + (West)

At first he told himself that these bright points must be three fixed stars. But the next night, to his astonishment, they were differently grouped: all three were to the west of Jupiter.

(East) O + + + (West)

"Can Jupiter have moved past them?" Galileo asked himself in bewilderment. "If so, it is not travelling in the way astronomers have always said it does."

He waited impatiently to find out what had happened the next night, but to his disappointment the sky was cloudy. However, the following night was clear. He rushed to his telescope and turned it with trembling hands towards Jupiter. This is what he saw:

(East) + + O (West)

For a moment he wondered whether he was going crazy.

There were only two points of light, and both were now to the east of Jupiter again!

"Is Jupiter moving backward and forward like a pendulum?" he asked himself.

He searched the sky near by, checking to see if Jupiter had moved in this way against the background of the fixed stars. It had not: it was on the course that astronomers had always charted for it.

"If Jupiter is not swinging to and fro, then the little points of light are," reasoned Galileo. "And as one of them has disappeared tonight, it is probably hidden by Jupiter—it has probably gone behind the planet. It looks as though these points of light are swinging to and fro *round* Jupiter!"

This meant that the points of light could not be stars. To make sure that they were swinging round Jupiter, Galileo began a methodical series of observations.

On the next night, January 11, he still saw only two of them, but now they had moved farther away from the planet. On the 12th, they were closer again, and now a third had appeared on the west of the planet. On the 13th, he had another surprise: there were four of these points of light!

(East) + O + + + (West)

He doubted no longer. "These are not fixed stars, but bodies belonging to Jupiter and going round it in various orbits," he decided. "Jupiter has four satellite moons of its own, just as the Earth has one!"

Full of excitement, he settled down to write a short account of all that he had discovered with his wonderful telescope. Two months later this was published in Venice, under the title of *Messenger from the Stars*. His discoveries amazed the whole of

Europe. Soon they were even being discussed in far-away Peking.

* * *

Galileo had opened up a new vision of the heavens. He had shown that the Moon is a rocky, mountainous globe, that the Earth is not unique in having a satellite moon, and that millions upon millions of stars exist. Soon he went further, and discovered that Venus appears now as a crescent, now full, now dark, as it circles the Sun and reflects light at different angles. He even traced the movement of mysterious spots in one direction across the face of the Sun. The fact that the Sun has spots shocked some people, who felt that this celestial object ought, like a woman, to be without blemish. Galileo, however, was very interested, for the movement of the spots indicated that the Sun, like the Earth, was spinning round on its axis.

To many people this probing of the skies was exciting. They realized that for the first time men had a means of exploring space. But to others it was unsettling, even dangerous. This was because, although they were living seventy years after Copernicus, they still believed that the Earth did not move and was the centre of the Universe. The Church of Rome officially agreed with this belief, although some of its members did not.

Until now Galileo had not dared to defy the Church openly and declare that the Earth moved round the Sun.

"I would certainly dare to publish my ideas at once if more people like you existed," he had once written to Kepler. "As they don't, I shall refrain from doing so."

However, his discoveries had made Galileo a much more important man. He decided that the Church would not dare to curb him now, and he began to state publicly that the Earth circled the Sun. Those diehards who objected that what he said was heresy felt the lash of his sarcasm.

"Let them try to prove me wrong!" he exclaimed.

For some years the Church of Rome let Galileo talk freely, but some of its high officials remained unconvinced. And, in fact, whatever Galileo said, he could not *prove* that the Earth goes round the Sun; he could only say, with Copernicus, that it seemed likely. (It was not until 1728 that conclusive proof was given, by James Bradley, third Astronomer Royal of England.)

In 1623 a new Pope was elected, and the Church hardened against Galileo. He received warnings, but would not give way. In 1632 he published a brilliant argument in favour of his beliefs, entitled *Dialogue on the Great World Systems.*

This was open defiance of the Church, and Galileo was summoned to appear before the Inquisition in Rome. Interrogation began on April 12, 1633. Galileo was asked to declare that he was wrong and that the Earth stood still. The questioning continued for a month.

The great astronomer was now seventy years old, and he was worn out by fatigue and by fear of the Inquisition. In the end, Galileo did as he was told. Never again did he say in public that the Earth moved.

* * *

Forbidden to concern himself with astronomy, Galileo now returned to an old interest of his: the study of how things move. And, although he did not suspect it, these studies were later to help in explaining just why the Earth moves.

Years before, he had shown that, contrary to all common sense, everything falls at the same speed whatever its weight. He had actually dropped balls of different weights—some made

of wood, some of lead—and found that they hit the ground at the same time. We now know that this is because, although a heavy weight is pulled more strongly by the Earth's gravity than a light weight, it needs just that much more of a pull to move it downward at the same speed. Galileo did not realize this, but he did see that the Earth's gravity moved the different weights at the same speed.

He had also found something more: as the weights fell, they moved faster and faster—they accelerated.

"If I can measure this acceleration, I shall be measuring how the Earth's gravity pulls," he told himself. He knew that the Earth's gravity must be a pull, or an attraction, because things always fall towards the Earth, not away from it. (Men had long thought of gravity in this way, but later Newton was to extend their ideas.)

Galileo believed that the pull of the Earth's gravity should make a falling object accelerate at a steady rate. Others before him had prophesied this. But how could he prove it?

"Ideally, I would drop things and measure just how they fall. The trouble is, they fall too fast for me to measure exactly," he told himself. "I need to find a slower, but similar, movement which I can gauge precisely."

He thought of a ball rolling down a slope.

"Just as a ball falls downward because of gravity, so it rolls downward because of gravity," he reasoned. "Can I use the way it rolls as a guide to the way it falls?"

He decided that he could, and in the quiet villa near Florence where he now lived he began a series of experiments. Taking some very smooth wooden chutes, he rolled polished bronze balls down them and timed their progress. And he found that, however steep the slope, and however fast a ball rolled, the rate at which it increased its speed did indeed remain steady.

"This must mean that the pull of gravity is steady," he noted.

He knew how fast this acceleration was for a ball rolling down a slope, but not for a freely falling ball. However, he could be pretty sure that a freely falling object would also accelerate at a steady rate. The exact value of this acceleration was to be measured later by a great Dutch physicist named Christian Huygens.

Now Galileo did a different experiment. He let a ball roll down one sloping board and up another board opposite. He found that the ball rolled up until it was level with the height from which it had started. He varied the slopes but always got the same result. Even if the ball had to roll a greater distance upward than downward, it went on until it had reached its original height.

"The ball is like the weight on the end of a pendulum," he told himself. "When released, that always swings up to the height from which it has started."

In his imagination he now played a trick on the ball. If it always tried to roll up to the height from which it had started, what would it do if it could never get up to that height? In other words, what if the opposite slope were not a slope at all, but level ground going on and on?

"If the ball can never reach the height from which it started, it ought to go on for ever!" he exclaimed.

Until then, men had always supposed that a continual force would be needed to keep something moving for ever. Galileo, in an inspired moment, saw that this was not true. Once started, something could keep going on and on of its own accord. A force would be needed to stop it, not keep it moving!

This was a brilliant paradox of the kind that Galileo loved. Of course, he knew that in the real world a ball will not go on rolling for ever, but then that is because it is stopped by friction —which is a force.

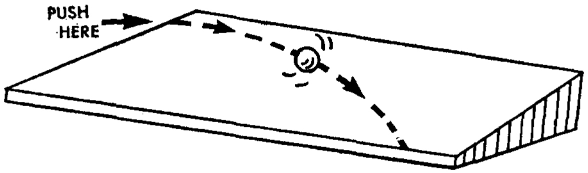
Galileo called this tendency to keep moving 'inertia,' because the moving object does not alter speed or direction unless it is forced to do so.

Now he went still further. In another imaginary experiment he very cleverly combined what he had discovered about the pull of gravity with the idea of inertia.

"Suppose a cannon-ball is fired out of a cannon," he muttered, drawing a diagram for himself. "The inertia of the moving ball will tend to make it keep going on in a straight line. Meanwhile, however, the Earth's gravity will be tugging the ball downward. How will the ball actually travel?"

He worked out that the ball's tendency to go on in a straight line could be combined mathematically with the pull on the ball from the Earth's gravity. The ball would, he found, travel in a special kind of curve called a 'parabola.' How sharp this curve was would depend upon the speed of the ball when it was fired.

He could not test his idea by firing a cannon. However, he did



Galileo's test. He started the ball rolling straight across the top of the sloping side, and the route taken by the ball was a parabola.

something like it. He took a big wedge and started a ball rolling straight across its sloping side near the top. This was the firing of the cannon. But the ball, while going forward, started to roll down the sloping side of the wedge as well. The forward movement and the downward movement were being combined. And the route actually taken by the ball was, as he had prophesied, a parabola.

* * *

Galileo's studies of rolling bronze balls had led him to the parabola, but he never imagined that this would help to explain why the planets travel as they do round the Sun.

Yet the ellipses of Kepler are closely related to the parabolas of Galileo. In 1642, the very year that Galileo died, the man who would prove this was born at Woolsthorpe, in Lincolnshire. His name was Isaac Newton.

4

NEWTON

The Invisible Mechanism

"WHY do the planets go round the Sun?" Isaac Newton asked himself one summer day in 1666. He was sitting in the garden at home. Behind him was the grey stone house in which he had grown up. Its walls still bore sundials which he had made while a boy. Indoors, his mother was preparing the evening meal. Her three younger children, Benjamin, Mary, and Hannah, were across at the farm helping with the harvest. However, she had long ago given up trying to turn Isaac into a farmer.

A year earlier, he had been studying at the University of Cambridge. Then a terrible plague, the Black Death, had begun striking at towns all over England, and the university had sent its students home to avoid it. Now Newton was spending his time in thinking and experimenting.

He did not ask himself why the planets moved, for he realized that they would keep going out of inertia. There was no friction in space to slow them down. But why did they move round and round, instead of going off in straight lines?

"Some force must be pulling them into closed orbits," he reasoned.

He remembered how, when a boy, he had used a sling to whirl a stone round before letting it fly. The cord of the sling had held the stone, pulling on it to stop it from flying off. Now it occurred to him that the pull on the planets did rather the same thing.

"It is as though a cord from the Sun were pulling on the planets," he thought. "But there are no cords up in the sky!"

This mysterious pull was invisible, yet stronger than the toughest cord.

As Newton sat pondering, the wind, coming in gusts, swayed the branches of a tall apple-tree that stood near by. The branches were laden with ripe fruit, and suddenly an apple was blown off one of them. With a thud, it landed some distance away.

The thud roused him, and he glanced round. Seeing the apple, he noted how far the wind had blown it. His mathematical mind instantly considered why the apple had fallen just as it had. Why had it not fallen farther, or nearer?

"The wind hurled it forward, and at the same time the Earth's gravity pulled it downward," he mused. "Like Galileo's cannon-ball, it travelled in a parabola. How far it went depended on the force of the wind."

He played with the idea. Suppose the wind were much, much stronger: how far would the apple travel then? Would it be blown right across Lincolnshire before it fell? Across the North Sea? How far?

By now Newton was not thinking about a real wind, but an imaginary one. He could make his imaginary wind as strong as he liked.

With a fairly weak wind the apple would land, say, one mile away, he told himself. Then, as it was hurled faster and faster, it would land farther and farther away—2, 5, 10, 100, and even 1000 miles away!

At each distance the parabola travelled by the apple would be getting larger and larger. Now Newton asked himself what sounded like an absurd question. What if the parabola became so big that it was larger than the curve of the Earth's surface?

"The apple will go in a curve round the Earth and come back to where it started," he decided. "With a large enough curve, the apple will never come down at all! It will keep going round and round the Earth."

Newton could not know that three hundred years later men would launch artificial satellites into orbit round the Earth. But he had seen that if his imaginary apple, or any other projectile, were moving fast enough it would go on and on round the Earth. The Earth's gravity would be pulling on it all the time, and so it would be "falling" all the time—but it would never hit the ground! We now know that such a projectile must travel at a minimum of 18,000 miles an hour. As long as it is outside the atmosphere, which would drag on it by friction, this speed will keep a satellite circling endlessly round the Earth.

And then he had an inspiration. If the Earth's gravity would hold a projectile in orbit, maybe it would serve to hold the Moon in orbit too! Maybe the pull of the Earth would operate even 238,000 miles away—the distance of the Moon from the Earth.

Now that he had this idea of gravity pulling far across space, he saw that it might be the invisible cord he had been thinking of earlier. Just as the Earth pulled on the Moon, so the Sun pulled on the planets. Perhaps the pulls were of the same kind!

"Universal gravity," he whispered, imagining this strange, subtle attraction acting throughout space, so that every planet was affected by it. It was a prodigious vision—the most prodigious ever known to science. If only he could check whether it was correct!

* * *

Day after day Newton tussled with this gigantic problem. He had once partitioned off a little study from a bedroom, and decorated it by drawing a pheasant and a near-by church on its walls. Now he sat here searching through his books and looking for clues.

"Kepler found that the farther a planet's orbit lies from the Sun the more slowly the planet travels," he noted.

He examined the mathematical way of stating this fact which Kepler had devised. By itself this explained nothing, but Newton began to take it to pieces and see what it meant. Finally he saw that it fitted in with the idea of a pull from the Sun which spread out in all directions, steadily growing weaker, just as light does.

This meant that the pull obeyed the inverse square law, getting weaker in proportion to the square of the distance. Two miles away it would be four times weaker than it was 1 mile away, while 3 miles away it would be nine times weaker, and so on.

"If the Sun's gravity obeys the inverse square law, then surely the Earth's gravity does too," Newton brooded.

But would the Earth's gravity, acting in this way, be strong enough to keep the Moon in orbit? Newton knew that the pull needed to keep the Moon in orbit had to make the Moon 'fall' towards the Earth 0·0539 inch each second. Now he had to check whether the Earth's gravity would produce the necessary 'fall.'

To handle this calculation, he had to assume that the Earth's gravity acted as though its pull came from the centre of the Earth. The Moon was just sixty times farther away from this centre than was the surface of the Earth.

"By the inverse square law, the Earth's pull will be 60 × 60, or 3600, times weaker at the Moon," he noted.

He knew that the pull at the Earth's surface was a little over 16 feet in a second. Dividing by 3600, he found that the pull at the Moon came out at a 'fall' of 0·0536 inch each second. This was only 0·6 per cent. short of the necessary amount!

"The answers agree pretty well," commented Newton.

* * *

So far, he had only made a rough calculation. He had made it simpler by pretending the Moon's orbit is a circle, not an ellipse. And he had yet to prove that he could assume the Earth's pull acted as though it came from the centre of the Earth.

However, Newton now felt sure that gravity would explain the way the entire Solar System moved. Most scientists would have wanted to tell every one of this tremendous discovery, but Newton said nothing. He was a shy and withdrawn person, who was content to keep his ideas to himself. Also, he may have felt that he should not announce his work until he had proved it in strict mathematical detail.

Whatever the reason, Newton now turned his attention to something quite different. Several years earlier, while at Cambridge, he had been trying to make a better telescope than any so far devised. Galileo's telescopes, and bigger ones that other men had later developed, all had one important defect. Their lenses made things appear nearer, but they also made them appear fringed with colours. It was impossible to see stars or planets sharply and clearly in their real colours. (Cheap opera glasses today have the same fault.) Newton wanted to find out why these colours appeared. If he could do that, he reasoned, he might be able to devise a way of making better lenses which did not produce unwanted colours.

He had already tried grinding lenses of different shapes, in the hope that some shapes would give better results. It was laborious, finicky work, this lens-grinding, but he stuck at it until he had tested every shape he could think of. None of them made any real improvement.

"If the shape of the lens makes no difference, the glass of the lens must be the cause of the trouble," he decided.

How could he investigate what happened to the light because of the glass? He knew already that the same kind of colour effects occurred in triangular glass prisms. These glint with all the colours of the rainbow, just as cut diamonds do. Prisms were sold as toys for people to see these colours, and Newton had once bought one at a fair. Now he began a careful series of experiments with glass prisms to see if he could find out just why these colours appeared. At that time many people thought that white light—sunlight—was pure, basic light and that coloured light was some kind of alteration to this. They thought that if sunlight shone through a piece of red stained glass in a church window it was somehow dyed red, rather as white cloth can be dyed. But the glass in a prism or a lens was not coloured: why should colours appear there?

To get a small, easily managed beam of white light, Newton darkened his little study by covering the window with a shutter and cut a little hole in this shutter. He now had a thin shaft of sunlight slanting through the air in his darkened room. He put a white screen in the path of the beam, so that a small round patch of light appeared on the screen. The next step was to find out what happened when he put a prism in this shaft of sunlight.

Holding a large prism on a metal stand, he carefully placed it in the path of the light. The beam bent as it travelled through the prism and splayed out into colours. By using a lens he was able to focus these sharply on the screen. To his delight, they stood out in beautiful, brilliant bands of colour: red, orange, yellow, green, blue, and violet.

"Here are all the colours of the rainbow!" he exclaimed.

He moved the prism this way and that, and found that the colours always appeared in the same order. He also found that each colour of light was bent at its own particular angle by the prism. Violet light was bent most, then blue, and so on through the range to red, which was bent least.

"Each colour is bent differently and so the beam of light is spread out by the prism," he noted.

Now he could see why telescope-lenses did not show things clearly. To work properly, a lens must bend light to one sharp focus. If the glass of the lens bent different colours by different amounts, they could not come to the same focus. The result would be a blurred picture ringed with colour, just as actually occurred.

What was this coloured light? Was each colour really white light 'dyed' in some way?

"If it is, another prism should alter it still further," he told himself.

To get only one colour, he pierced a small hole in the screen where the red band struck it. Some of this red light now travelled on through the hole. He took a second prism and placed it in this shaft of red light.

The red light went through the prism, and bent through the same angle that it had in the first prism, but it did not spread out, and no other colours appeared.

"If red light cannot be altered by a prism, perhaps it is a basic kind of light—more basic than white light," Newton mused.

What about the other colours? He tried each in turn and found that they too stayed the same. There seemed no doubt that these colours were the fundamental kinds of light.

"Somehow white light must be a mixture of all these colours," he decided.

It was an astonishing paradox, to think that whiteness had to be made by combining colour. But Newton proved it quite simply by passing the whole range of colours coming from one prism through another prism placed upside-down compared with the first. The colours closed together, united, and came out as a shaft of pure white light!

Newton decided to call the range of colours that make up white light the 'spectrum.' Usually we say that there are six colours in the spectrum, but Newton, who was especially good at distinguishing colours, saw a seventh, indigo, between the violet and the blue.

Now that he had made these fundamental discoveries, Newton decided that the colour trouble with lenses could never be cured, because white light would always split into colours when focused. We now know that he was wrong, because different kinds of glass bend light by different amounts, and a clever combination will yield a colour-corrected lens.

However, Newton did not know this and so he resolved to sidestep the whole problem.

"Different colours are bent through glass at different angles but they are all reflected at the same angle," he remembered. "I

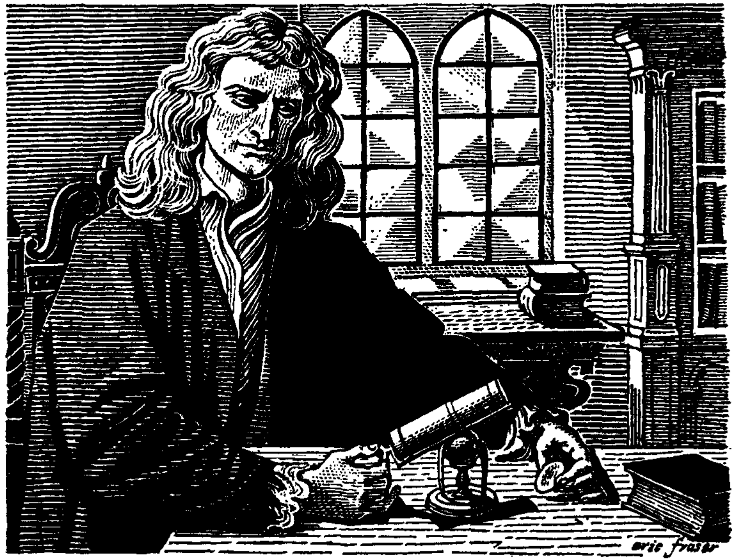
must make a telescope which magnifies by means of a mirror instead of a lens!"

The idea of using a curved mirror to magnify in a telescope had already been suggested by James Gregory. Because of his experiments, Newton decided that Gregory's idea was the only way he could avoid the colour trouble. He promised himself that he would try it out as soon as he got back to Cambridge.

* * *

Newton was back in his rooms in Trinity College, Cambridge, towards the end of March the following year. Buying the necessary equipment, he now set about making his telescope.

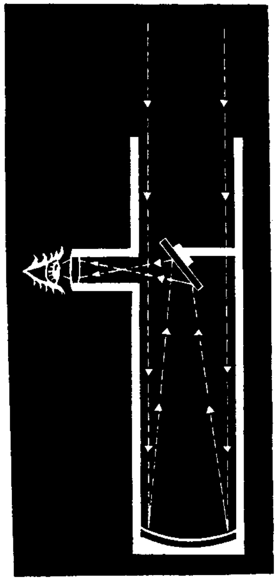
For the mirror he had to use polished metal, because at that time people had not discovered how to make glass mirrors by depositing silver on the glass. The metal was of an alloy he



invented specially, composed of copper and tin together with a little arsenic. He bought a crucible and melted the metals in this, keeping as far away as he could because of the poisonous fumes. Then he turned and polished the metal until he had an excellent mirror.

The tube of the telescope, which he also made, was about 6 inches long and 1 inch across. It was mounted on a ball fitting in a socket so that the tube could easily be swivelled in any direction. The mirror rested at the closed bottom end of the tube and reflected the light back to a point near the open mouth. There it was deflected sideways by a little mirror, and enlarged by a lens eyepiece set in the side of the telescope tube. Newton still had one lens in his telescope, but it was small and did not give the trouble that a large lens would.

He tested his telescope and was delighted to find that it worked beautifully. Although it was hardly larger than a toy, a friend saw the moons of Jupiter perfectly through it.



How a Newtonian reflector works. Light rays are gathered by the curved mirror at the bottom of the tube and reflected on to a mirror near the mouth. Then they are reflected again and focused (where the light rays cross). Finally they are magnified by the lens eyepiece. Different eyepieces give different magnifications.

"My little telescope works better than an ordinary lens telescope four feet long," Newton wrote proudly. He had calculated that it magnified some 35 times.

Later he made a larger reflecting telescope, which he gave to the Royal Society, a body of learned men which had been recently formed in London. It is still treasured by the society. However, Newton never made any systematic observations of the heavens, and in fact he was shortsighted.

Other men seized eagerly on his work and developed it. By the time that colour-corrected lenses had been devised, other advantages for mirrors were known. Today the biggest light-gathering telescopes in the world are all reflectors.

* * *

But what of Newton's greatest discovery, the effects of gravity? Having forged the mathematical tools which he needed, he eventually worked out his theory in detail. Urged on by an English astronomer named Edmond Halley, he was able to show that he could account exactly for all the known movements in the Solar System. (Using Newton's work, Halley correctly prophesied that a comet seen in 1682 would reappear in 1758.)

However, tremendous as this feat was, Newton did not feel sure of explaining the mechanism of the Universe beyond the Solar System. The man who was to probe far into the Universe for the first time was William Herschel, using reflecting telescopes better than any the world had known.

5

HERSCHEL

A Leap into Space

On the night of March 1, 1774, Herschel had just finished making his first telescope. It was a 5½-foot-long reflector of the Newtonian type.

Staggering under its weight, he and his brother Alexander proudly carried the instrument out into the garden. Their sister Caroline followed closely.

"Just here will do," said William, and the heavy telescope was put down on its stand.

Herschel was a successful music teacher and conductor in the fashionable city of Bath. His brother played the 'cello in the Bath Orchestra, and his sister was studying to be a singer. However, a year earlier William had suddenly developed a passion for astronomy. Beginning by poring over books until he fell asleep buried under them, he went on to look at the skies himself.

To start with he had hired telescopes, but none were good enough for him, and so he had resolved to build his own. Stumblingly, with nothing but a half-understood textbook on optics to guide him, he had designed his first telescope. Then, in moments snatched from his music, he had taken on the tedious chore of grinding the mirror and polishing it by hand. His

brother Alexander had learned how to use a turning machine and had rigged one up in a bedroom, where he made the eyepiece. The drawing-room was given up to a cabinetmaker for producing the necessary tube and stand.

Now William was going to see the results of all this work. Eagerly he tilted the telescope towards the sky, and, with cries of delight, identified one object after another.

"Lina," he called to his sister, "I can see the rings of Saturn! How beautiful they are!"

He swung the telescope towards the constellation of Orion.

"There is a hazy white spot in the sword-belt," he announced, puzzled. "Whatever it is, it does not look like a star."

Caroline looked through the telescope, only just able to see because she was very short and the eyepiece was at the upper end of the tube.

Meanwhile William made notes about what he had seen. This was the beginning of his astronomical journal. (Later he was to know that the hazy spot was a vast cloud of gas, or nebula.)

The 5½-foot telescope was a good beginning but it did not satisfy Herschel for long. He yearned to look farther and farther into the heavens. A grand and audacious plan was shaping in his mind.

"I want to understand the construction of the heavens!" he resolved.

Now he began work on a 7-foot reflector, with a correspondingly larger mirror.

"This will gather more light and reveal stars too faint to be seen with a smaller mirror," he reasoned. "And the fainter the stars I can see the farther I shall be looking into space!"

He assumed that stars were, on average, of the same real brightness, so that if a star appeared faint that meant it was a long way away. He was not entirely correct but he did realize the very important fact that the more light he gathered the farther he saw. Later he worked out that this depended on a simple proportion.

"If I double the diameter of a mirror, I double the distance I can see," he wrote.

The 7-foot telescope was still not enough for him. Intent upon increasing the power of his instruments, he followed it with a 10-foot, which had a mirror nearly 9 inches across instead of about 6½ inches. Then he went still further, and made a giant 20 feet long, with a mirror 1 foot across! This was easily the most powerful telescope in the civilized world, and he had made it unaided and in his spare time. Also, as his knowledge of optics was so shaky, he made literally dozens of mirrors, trying them out until he found which the best were. If he could have worked out the necessary optical calculations he might have saved himself a lot of trouble.

Yet as well as this Herculean labour, Herschel accepted the job of directing the Bath Orchestra. He was a glutton for work!

* * *

By 1779 Herschel had amassed the best selection of telescopes in the world. Each was suitable for certain kinds of observing. Now he embarked on the immensely ambitious project of systematically cataloguing the heavens.

"By reviewing the heavens I should get a clearer idea of their structure," he thought.

For his first review he used a 7-foot Newtonian reflector which magnified 222 times. He noted the position of every star from the brightest down to fainter ones of the 4th magnitude. (A fairly bright star is of the 1st magnitude: the faintest visible with the naked eye are of the 6th.)

Besides doing this he was completing a still better 7-foot instrument, and in August 1779 he began a second review of the heavens with this. It had a mirror just over 6 inches across and magnified 227 times.

Because he had now rather foolishly moved to a house without a garden he had to set up his telescope in the road outside. Of course in those days there were no street-lamps to spoil the view of the night sky. One night towards the end of December he was looking at the Moon, because he had also decided to measure the heights of the lunar mountains. A passer-by stopped and watched him curiously, but Herschel, who was not at all self-conscious, went on observing.

"Would you permit me to look through your telescope, sir?" asked the stranger eventually. He was elegantly dressed, with freshly curled wig and immaculate lace ruffles.

"Certainly," said Herschel with his usual generosity, and he stood aside at once.

The stranger peered, and gave a gasp of surprise. He had looked through telescopes at the Moon before, but this instrument was better than any of them.

"A marvellous view, sir," he said as he stepped back. Then he bowed courteously. "Thank you, and goodnight."

The next morning the mysterious stranger called at Herschel's house, No. 5 Rivers Street. The usual pandemonium of simultaneous music-teaching and telescope-making was going on.

"I am Dr William Watson," he told Herschel. "I am a Fellow of the Royal Society and a member of the Bath Literary and Philosophical Society. After looking through your telescope last night I realize that you are deeply interested in astronomy. I hope you will join our Bath society."

Herschel was pleased, for evidently Dr Watson was not only learned but prepared to take him seriously. Until then the people of Bath had only thought of Herschel as a musician with an eccentric taste for star-gazing.

Herschel joined the Literary and Philosophical Society and within a few days began to bombard them with accounts of his work. Between January 1780 and March 1781 he sent them thirty-one papers!

And then, on March 13 he saw something that was to make him known as an astronomer not only in Bath but throughout the world.

Using his best 7-foot reflector, he was busy with his second review of the heavens. This was a much more ambitious one than his first: he was now cataloguing every star down to the 8th magnitude, as well as noting all double stars—that is, stars that appeared close together in pairs. Having just moved to a house with a garden, he was observing from the lawn. His sister Caroline usually sat near by, noting down his observations, but tonight she was still at the old house, tidying up.

Methodically, Herschel swept his telescope across the sky, pausing, counting, and moving on. Between ten and eleven o'clock he had reached a sector of sky in the constellation Gemini. Near one of the stars in the constellation he noticed something new. It did not look like an ordinary star.

"Curious," he muttered, and looked harder. To see if it was definitely a star or not, he selected higher-power eyepieces and looked at it with these. One brought the magnification up to 460, and the other to 932. The object looked proportionately bigger. This meant that it was fairly close, not a distant star which, because of certain optical effects, would not be magnified in proportion.

"Probably it is a comet," he decided.

To check whether it was moving, he measured its distance from a neighbouring star with his home-made micrometer and then, towards dawn, measured the distance again. It had changed.

"The object is definitely moving," he noted. "It must be a comet."

He was not very interested. What was one comet more or less, compared with the structure of the Universe? Still, he dutifully wrote an account of what he had seen, and sent off two copies, one to an astronomer at Oxford Observatory and the other to Dr Watson. The good doctor was intrigued, and quickly passed the news on to the Astronomer Royal.

Dr Nevil Maskelyne, the Astronomer Royal, was at Greenwich Observatory. He started hunting for the new comet as soon as possible, and found it on April 3. Immediately, he was convinced that there was something strange about it.

"If it is a comet, it is very different from any that I have read about or seen," he wrote excitedly to Dr Watson. "It is either a new sort of comet or a new planet."

A new planet! The idea was breathtaking. Throughout recorded history men had known of five planets, and five only. No one had ever imagined there might be others.

Maskelyne pursued the idea. "It is as likely to be a regular planet moving in a nearly circular orbit round the Sun as a comet moving in a very elongated ellipse," he wrote to Herschel on April 23. "I still have not seen any tail to it."

This made it less likely to be a comet, for all comets have tails as they near the Sun.

Meanwhile Herschel, who wanted to return to the depths of space, had been noting the position and size of the object each night. On April 26 the Royal Society received his description of the new comet, as he still believed it to be. Then he abandoned the matter to other astronomers.

They took the problem up eagerly. Everything depended on the shape of the orbit, as Maskelyne had pointed out. Was it a near-circle or an elongated ellipse?

Observations were collected, and in a few months the calculations could be made. Two mathematicians, Anders Johann Lexell, of the St Petersburg observatory in Russia, who happened to be in London, and Laplace, in France, worked out the answer at the same time. The object was a planet circling the Sun beyond Saturn, and taking eighty-four years over a complete circuit. It was later christened Uranus.

For his part in this discovery Herschel was awarded the Copley Medal, which is the highest honour the Royal Society can bestow, and on December 6, 1781, he was unanimously elected a Fellow of the Royal Society. This meant that he was recognized as a scientist of the first rank.

* * *

Thanks to recommendations by the Astronomer Royal and others, King George III now granted Herschel an annual income. The only condition was that he should let the royal family peer through his telescopes from time to time.

It was just what Herschel wanted. He could give up his music-teaching and throw himself full-time into astronomy. In 1782 he moved to Datchet, conveniently near the royal household at Windsor. Aided by the indefatigable Caroline, he started on a still more ambitious programme of work. (His brother

Alexander was left in Bath to go on making his living as a musician.)

He also became a professional telescope-maker. By now his instruments were generally agreed to be the finest in the world. After looking through Herschel's best 7-foot reflector the Astronomer Royal had little more use for his own 6-foot instrument.

"I doubt that it even deserves a new stand," he commented ruefully. Soon he ordered two of Herschel's 7-foot reflectors.

Other orders came pouring in. The King alone bought five 10-foot reflectors. Eventually Herschel found himself supplying leading astronomers all over Europe, to say nothing of various kings and princes. And somehow the incredible labour of making all these instruments was fitted in during the day while at night he went on with his observing.

* * *

A few months after the move to Datchet Herschel received a letter from a friend named Alexander Aubert, who was an amateur astronomer. With the letter was a list of strange, cloudy objects, or nebulae, that had been noted by a famous French comet-hunter, Charles Messier. The Frenchman had noted that these objects were different from star clusters, containing thousands of stars, which he saw through his telescope.

"This sounds intriguing, Lina," commented Herschel. "Messier has catalogued these cloudy objects because they look like comets and he does not want to keep mixing them up. I must have a look at them!"

He started to examine all 103 of the listed objects. At first he used his old 20-foot reflector, but then he transferred to his latest, most powerful model with a mirror 1½ feet across.

To hold the telescope, Herschel had a big wooden structure rigged up in the garden. There was a system of ropes and pulleys for adjusting the direction and angle of the tube. He observed from an adjustable wooden gallery above the ground. Caroline sat below to note the observations he called out, a star atlas open before her.

With this excellent telescope, Herschel soon discovered something that Messier had never been able to see.

"Many of these apparently cloudy nebulae are really more clusters of stars," he announced.

Where did these great clusters of stars lie? With an inspired bound of imagination, Herschel wondered whether they could be much farther away than ordinary stars, and whether our Sun was in a similar system, visible to us as the Milky Way.

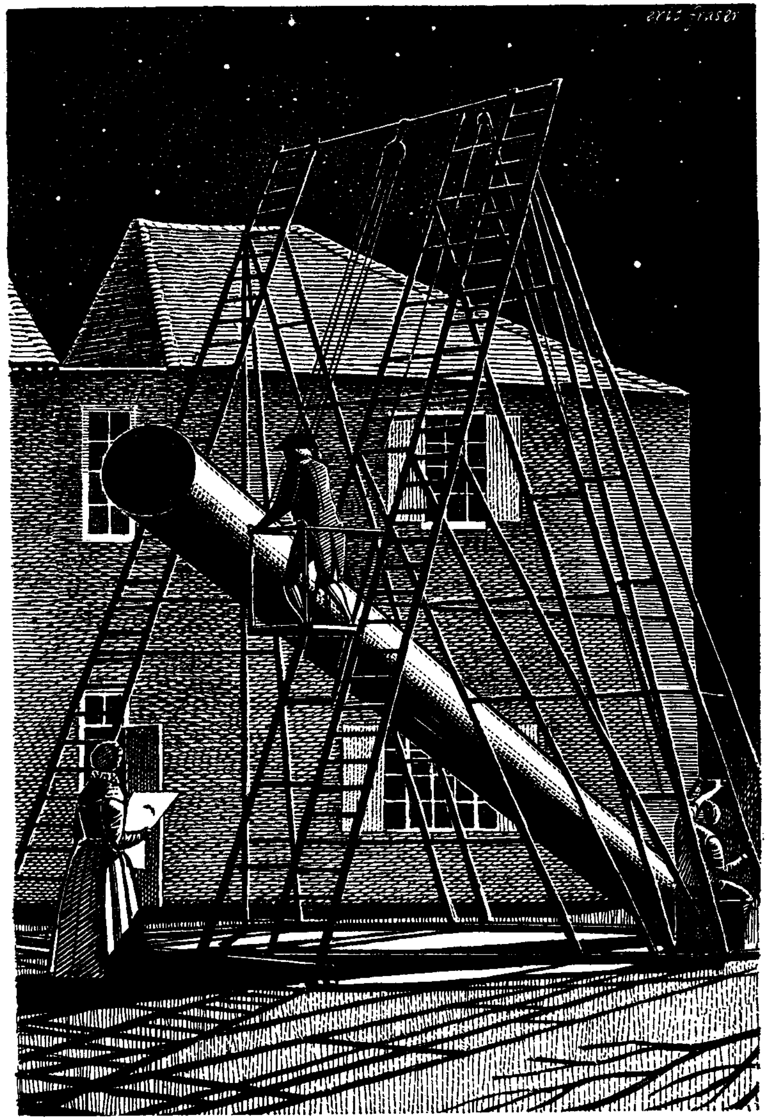
"Perhaps there are many of these great systems, all separate from each other," he breathed. "Perhaps they are whole separate universes—island universes!"

When they heard of this idea, his contemporaries laughed. The astronomer in Datchet had excellent telescopes, but this was pure imagination, not hard-headed observation! They could not believe in systems of stars beyond the ordinary stars they were used to.

But Herschel was not deterred. He started to catalogue these mysterious groups of stars and any cloudy nebulae as well, supposing that with a better telescope they too would appear as star systems.

"I have discovered fifteen hundred whole star systems, some of which may well exceed our own Milky Way in grandeur," he wrote later.

Then he really let himself go, and imagined that these



At work with the 20-foot reflector

faraway island universes might be peopled with inhabitants scrutinizing our own star system.

"To them, our system must assume different guises, depending on how far away they are," he brooded. "To some, it will be a small, nebulous patch; to others, an extended streak of milky light, or a very compressed cluster of small stars, or an immense collection of large, scattered stars."

Now he set himself the task of trying to decipher the shape of our own star system, assuming that we saw it as the Milky Way. He knew that this runs in a band across the northern sky and the southern sky as well. Eventually he pictured it as a view of a great layer of stars that stretched out all round in a flat disc. Being in the middle of this disc, he argued, we would see it as a band going round us.

But if this were true, how could he gauge the diameter and thickness of the disc? He decided to assume that all the stars in it were, on average, evenly spaced out—just as, on average, every one in a crowd has the same distance between himself and his neighbours.

"If this is so, the areas that seem to be crowded will really be those where I am looking at a deep layer of stars," he reasoned. "Similarly, an area with few stars will be a shallow layer."

To use this ingenious way of taking depth soundings, he had to count stars in selected areas. It was incredibly painstaking work. Night after night he mounted to the gallery and counted, while the faithful Caroline sat below and noted everything that he found. In some parts of the sky, on each side of the Milky Way, he might find only one star in view at a time. In the Milky Way itself, he might find as many as five hundred at once!

He spent all his observing time on this job from the beginning of 1784 until early in the next year. The general pattern became clear fairly soon, but he made 683 separate soundings, or star counts, before he was satisfied.

"The Milky Way is undoubtedly a most extensive disc of stars," he announced at last. "Its diameter is about four times greater than its central thickness. And our Sun is definitely one of the stars belonging to it."

* * *

Herschel had made a marvellous attempt to gauge the depths of our star system, or galaxy, as it is now called. However, since he had no way of measuring the distance of even one of its stars, he could do no more. Indeed, even his estimate of the galaxy's shape was crude.

And what of his great vision of other galaxies, or island universes, out in the deeps of space? His contemporaries could not follow him so far, nor could many astronomers later. In fact we now know that the groups of individual stars which Herschel saw are really globular clusters around our galaxy. However, many of the objects he classified as nebulae are other galaxies, just as he imagined. They are so far away that it was a long time before any one had a good enough telescope to see this. It was only after some hundred and fifty years that Edwin Hubble, an American astronomer, finally proved that Herschel's vision was true.

Long before then, however, the first step had been taken in making an exact measure of the scale of our own galaxy. The man to take this step was a German named Friedrich Wilhelm Bessel.

6

BESSEL

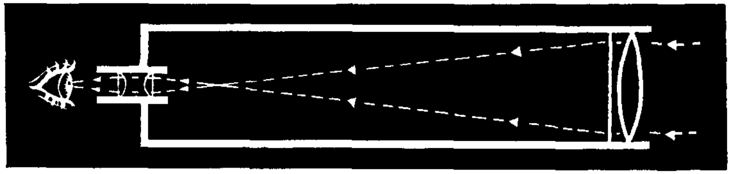
How Far is a Star?

ONE cold autumn day in 1829, a horse-drawn wagon creaked heavily through the cobbled streets of Königsberg, in East Prussia. It was bringing a new telescope to the observatory above the town. As it began labouring up the hill, Friedrich Wilhelm Bessel, the director of the observatory, watched it impatiently.

"At last, here is my Fraunhofer!" he exclaimed. "Now I shall find out if it is as good as it is meant to be."

Joseph Fraunhofer was an Austrian telescope-maker who had set out to design refracting telescopes which would work even better than Herschel's reflectors. By using special colour-corrected lenses, he had succeeded. The object glass at the front of a Fraunhofer telescope gathered as much light as a mirror double the size, because the metal mirrors then used were inefficient. Soon professional astronomers everywhere were clamouring for a Fraunhofer refractor.

Among them was Bessel. A refractor was especially suitable for making careful measurements, and a Fraunhofer refractor could yield more accurate results than any other. Every astronomer wants accurate instruments, but Bessel prized accuracy



How a modern refracting telescope works. Light is gathered by a colour-free combination of two lenses made of different kinds of glass. Then the light is focused (where the rays cross) and magnified by the eyepiece. Different eyepieces give different magnifications.

above everything. He had long ago stopped trusting ordinary instruments.

"Every telescope is made twice," he used to say, "first in the workshop and then by the astronomer."

With endless patience, he always checked the performance of his instruments and located any inaccuracies, however small.

The early equipment in his observatory had included a meridian circle by an English manufacturer, Cary. Used for measuring the apparent distance between two stars, this telescope turned on an axis that had to be precisely at right angles to its lenses. Bessel found that it was not. However, he worked out a way of compensating for this flaw. In his hands, the faulty instrument became equal to the best in Europe!

He ferreted out other sources of error. The atmosphere, like a prism, bends the light reaching us from the stars. But it does not always bend the light by the same amount: the bending varies with the temperature and pressure of the air. Bessel improved on earlier formulas to allow for these changes. Embodied in tables, his correcting figures were eagerly adopted by astronomers everywhere.

Bessel was dissatisfied with the Earth, too. As a platform from which to observe the stars, it is hopelessly unsteady. The axis on which it spins shifts in direction and wobbles slightly. However, he even managed to frame corrections for these movements.

And now he at last had a telescope designed by an equally exact man. It was set up on its heavy oak frame in a tower that had been specially built to house it. Bessel hurried to inspect it and his heart leapt with pride as he saw it. The polished wooden tube, some 10 feet long and covered with mahogany, shone like burnished copper. He touched it gingerly and found to his amazement that he could swing the heavy instrument anywhere at the touch of a finger, because of built-in counterweights. Better still, there was a motor which, geared to a clock, would keep the instrument automatically trained on a star for hours, despite the rotation of the Earth.

"This is good, very good!" murmured Bessel.

What of the object glass? Used for gathering light, it was 6¼ inches wide and made of a colour-corrected combination of glasses. Bessel peered closely at it with his large, acute eyes—eyes that, when he was a boy of thirteen, had shown him a double star where astronomers had noted only one. Then he drew a satisfied breath: the lens was not only of flawless glass, it was the best he had ever seen.

He thought of the lens mounting. In warm weather the lens would expand a trifle! He pounced on it suspiciously—and discovered that the indefatigable Fraunhofer had made a special split elastic frame to accommodate the lens as it expanded.

"Splendid!" cried Bessel. This Fraunhofer was a man after his own heart.

All the same, he checked over the whole instrument. Officially, it had been passed by Steinheil, at Munich, but the astronomer of Königsberg was not going to be satisfied by that.

When he had finished, he was delighted. Fraunhofer had foreseen everything—at least, everything except one minute detail. The scale of the micrometer, used when gauging distances in the field of view, would change fractionally in length with alterations in the air temperature.

"I shall measure the changes and make the necessary corrections," decided the careful astronomer.

He was happy: he had one of the finest telescopes in the world. The closest rival was another Fraunhofer built for F. G. W. Struve at the Dorpat Observatory, in Russia. But that was not so good for making precise measurements.

"With this telescope," thought Bessel, "I can try to find out how far away a star is!"

* * *

Bessel knew that since the time of Newton men had tried to do this and failed. The reason was the fantastically small measurements involved.

To find the distance of a star, they needed to measure its annual parallax. This is the apparent shift in its position throughout the year when compared with its background of more distant stars. The effect is due to the varying angle at which we view the star during our annual trip round the Sun. The same sort of effect occurs if we hold up a finger and look at it first with one eye, then the other. The finger appears to shift sideways in comparison with the wall behind.

As the Earth's orbit is 180 million miles across, every six months we see a star from positions this much apart. Using this fact, the six-monthly shift of the star can, by simple geometry, reveal its distance from us. The bigger the shift appears the nearer the star must be. However, even the nearest star is so far away that we cannot discern this shift with the naked eye. For this reason Copernicus rightly argued that the stars must be much more distant than men then supposed.

In Newton's time, astronomers turned their crude telescopes to the stars, hoping that these would reveal shifts due to parallax. At first they believed that they had succeeded, but later James Bradley, the third Astronomer Royal, proved that all they were measuring was observational error.

By refining his technique, allowing for one sort of error after another, Bradley managed to achieve an accuracy of one second of arc. This was over two hundred times better than Tycho Brahe's usual standard, but it still was not good enough to reveal any parallax!

After that astronomers gave up for a while. Struve even proved that with existing instruments it was just impossible to measure the minute changes involved. However, that was before he got his Fraunhofer.

Now that Bessel too was armed with a Fraunhofer, he felt ready to try making the necessary measurements. Even so, he wanted to choose a star that would show the maximum parallax.

"The nearer a star is to us, the greater the parallax," he mused. "But how can I find a near-by star?"

To decide this he did a little detective work. For some time, astronomers had realized that the so-called 'fixed' stars are not fixed at all. Within our galaxy, some of them can be seen to move steadily across the sky. Because they are so far away the movement is minute, but it can be measured.

In 1792 an Italian monk, Giuseppe Piazzi, had pointed out that one star was moving particularly fast. Located in the constellation of Cygnus, the Swan, it was designated 61 Cygni. Astronomers nicknamed it the 'flying star.' Not that it moves

fast enough to see with the naked eye: in fact, from the time of Kepler until the present day it has only travelled an amount equal to the apparent width of the Moon!

Bessel guessed that this speed indicated 61 Cygni was near by.

"Probably all the stars are really moving at much the same speed," he argued. "However, the nearer ones will appear to be moving faster just because they are near."

It was a bold deduction, but it gave him a good reason for choosing this star. There was another reason, too: it is near the Pole Star and so he could see it clear above the horizon most of the year.

In 1834, after completing a programme of other work, Bessel made his first attack on the problem. As reference points for judging the annual shift of the star, he chose two small, faint stars of the 11th magnitude. However, he soon found that it was too difficult to observe these faint stars accurately.

"I shall have to use brighter reference stars," he decided.

But now other interests kept claiming his time. Halley's comet reappeared in 1835, and Bessel, entranced, watched it on every clear night. Then he took on the complicated chore of calculating the length of one degree on the Earth's surface, or 1/360 of circumference.

At last, in August 1837, he was able to concentrate on his parallax measurements. For his new reference stars he selected two between the 9th and 10th magnitudes. One was in the line of travel of 61 Cygni, and the other was at right angles to this line.

Training his Fraunhofer on each of these stars in turn, and keeping 61 Cygni in view at the same time, he read off the angular distances between them and 61 Cygni. The micrometer screws were so finely adjusted that he could measure within one twentieth of a second of arc—which is less than the width of a pinhead viewed from a distance of 2 miles.

"The star in the line of travel is eleven minutes forty-six seconds away," he noted. "The other is seven minutes forty-two seconds away."

Now he had to record the changes in these distances throughout the year. Every night when the sky was clear, he said goodnight to his wife and three children and walked through the sleeping town to the observatory. On ordinary nights he repeated each measurement sixteen times, and when the air was particularly steady he took even more.

"I must be as precise as possible," he muttered as he jotted down his figures and peered again and again at that remote star.

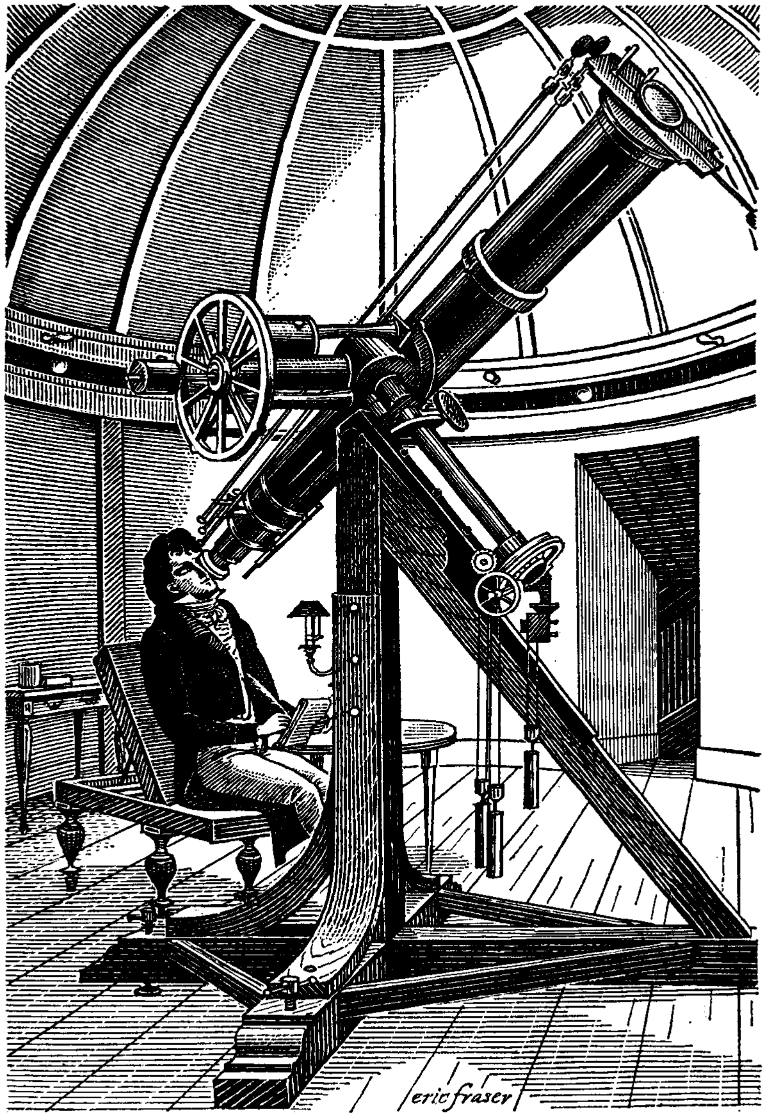
By day, Bessel shut himself away in his study and worked over his figures, whittling away the observational errors he knew he had to allow for. He also had to correct for the actual movement of the 'flying star,' and to do this he enlisted the help of a former assistant named Friedrich Argelander. Now at Bonn Observatory, Argelander used past observations of the star made in 1755 and 1830 to get at its rate of travel.

Bessel knew that the parallax effect would make the star appear to travel round a tiny ellipse during the year. As he pored over his figures each day, sifting them and correcting them, he watched eagerly for any sign of this tell-tale ellipse. In a month or so he was sure he noticed it.

"I'm on the right track!" he told his wife gleefully.

To the scientific world, however, he said nothing. He needed a full year's results first.

The autumn came, and Bessel went up to the unheated observatory tower in his overcoat. The first snow of winter settled on Königsberg, and then the ponds froze over. Bessel, who was



now fifty-four, doggedly continued with his observations. Every night he huddled in the tower, manipulating the micrometer screws with numbed fingers, trying not to let his breath fog the eyepiece . . . he was determined to get every observation he could!

By the time six months had passed, he knew that he had succeeded. The parallactic shift was plainly revealed in his figures. But he went right on observing, grimly resolved to get his full year's data.

At last, by the end of the summer in 1838, he had all he needed. To make quite sure, he checked them all through for possible errors, and then, in December, he published them.

"The annual parallax of 61 Cygni is 0·3136 second of arc," he announced proudly. "This means that it is 657,700 times farther away than the Sun. Light takes 10·3 years to travel from it to us."

He wrote his results down as matter-of-factly as though he were describing some survey of his backyard, but the figures were staggering. Astronomers had expected an immense distance, but even so they were appalled at the vastness of the Universe. As light travels at 186,000 miles a second, the 10·3 years represented 60 million million miles. And this was to one of the nearest stars!

* * *

We now know that even Bessel was not perfectly accurate. The modern parallax value for 61 Cygni is just about 0·30 second of arc, which represents a distance from us of 66 million million miles. However, his figures were the best available for a long while.

Soon after he had announced his result, two other astronomers came up with figures for other stars. Thomas Henderson, Astronomer Royal for Scotland, had been making measurements on Alpha Centauri, and F. G. W. Struve, at Dorpat, had used his Fraunhofer to get a value for Vega. However, both results were later found to be considerably too big.

With these measurements, men were beginning to understand the isolation of the stars. The nearest star to our own Sun is Alpha Centauri, which is 4·3 light-years away. A modern space probe going at 25,000 miles an hour could travel the distance to the Moon—nearly 240,000 miles—in ten hours, and in twenty years would reach the edge of the Solar System. However, it would need to keep going for about 120,000 years to reach Alpha Centauri.

Nowadays astronomers use photographs taken at different times to reveal parallax shifts. They can measure changes on the photographs with an accuracy of 1/200 second of arc. The distances of about five thousand stars have been determined in this way. Most stars, however, are so far from us that even this method is of no use.

* * *

Meanwhile Bessel, having disposed of 61 Cygni, turned to another problem. Astronomers everywhere were beginning to worry about the strange behaviour of Uranus, the planet discovered by William Herschel. An orbit had been calculated for this planet, and for a while men had believed that it was being followed exactly. And then, in 1825, they noticed that Uranus was running ahead of its expected positions.

"Perhaps we should try to calculate the orbit again," one or two astronomers thought.

But before they could do so, Uranus began slowing down!

By 1830 it was back on the track prophesied for it. Perhaps, the worried astronomers told themselves, their calculations were not so bad after all . . . but Uranus went on slowing down, and in another two years it was nearly half a minute of arc behind. This was an enormous discrepancy.

Hoping to solve the mystery, Bessel took on a promising young English astronomer named Flemming as an assistant. He had decided that the first step was to check the accuracy of all the existing observations of Uranus, and he needed help in this painstaking work.

By 1840 Bessel was sure of his results.

"The existing differences, which in some cases exceed a whole minute of arc, are not due to faulty observations," he told an audience at Königsberg.

This meant that Uranus was definitely running behind the schedule worked out for it. But why?

"I believe," said Bessel, "that the cause is an unknown planet whose pull is affecting Uranus!"

Soon after making this daring prophecy, Bessel became ill and could not go on with the work. However, two young men, one in France and one in England, took up the problem. Their results were to cause the biggest row in the history of astronomy.

7

ADAMS AND LEVERRIER

Prophesying a Planet

TOWARDS the end of June 1841, a quiet, shy undergraduate named John Couch Adams entered Johnson's bookshop in Cambridge. He often browsed in this shop, for it was in the same street as his college, St John's.

Glancing along the shelves, he noticed a dusty old astronomical report written ten years earlier. It dealt with the movements of Uranus, and its author was George Biddell Airy, who had since become the Astronomer Royal. Curious, Adams took it down and began to look through it.

"The movements of the planets can usually be prophesied from Newton's law of gravity," wrote Airy. "However, we cannot accurately prophesy the movements of Uranus."

Adams raised his eyebrows in astonishment. The movements of the other planets were so well known by now that the Solar System seemed like a piece of perfect clockwork.

"Some astronomers believe that this outermost planet is being affected by the pull of still another, unknown planet beyond it," Airy continued. "Other astronomers, including myself, believe our calculations are wrong because Newton's law does not apply so far from the Sun."

Adams put the report down indignantly.

"Newton's law has always been proved correct so far," he told himself. "Why assume it is wrong now, just because we are baffled by Uranus?"

He felt sure that Airy was wrong to doubt Newton's law. This meant that there must be a mysterious eighth planet lurking somewhere. But where?

As the young undergraduate left the bookshop, he was brooding over this problem. He crossed Trinity Street and walked through the mellow brick courts of his college to the staircase on which he lived. As he walked, a great ambition took hold of him.

"I will calculate whether the movements of Uranus can be explained by an eighth planet," he whispered. "Then, if they can, I will try to work out its orbit. This will probably lead to its discovery!"

* * *

It was two years before he could begin this complicated mathematical research. First came the studies for his degree, which he took at the beginning of 1843—and passed brilliantly. Then there was other work which he had to do during term-time. Meanwhile he told James Challis, the professor of astronomy at Cambridge, about his plan. Challis was eager to help.

"Here are some books you may need," he said, taking a selection from the crowded shelves in his study. "Let me know if I can help in any other way."

At last the long summer vacation began, and Adams had time to start work on his calculations. Taking a trunkful of books with him, he set off by stage-coach for his family's farm in Lidcot, Cornwall. Here he would have the peace and quiet that he needed.

All through that vacation John Adams grappled with his research. He went out for walks on Laneast Down with his brother George, but hardly noticed anything around him. His mind was full of equations and the data accumulated from hundreds of observations of Uranus. He sat late in the evening at a table in the little parlour, copying out columns of figures, adding and subtracting, giving the results to George to check, until his brother begged him to go to bed.

"In a minute," John Adams would mutter, and go on working for hours longer. All he wanted was to get those calculations out!

By the time that he returned to Cambridge in October, he had a rough answer worked out. He hurried to tell Challis of his result.

"I am sure that another planet is orbiting beyond Uranus!" he announced excitedly. "But I must have more data before I can map the orbit precisely."

Adams knew that Airy, the Astronomer Royal, was then extracting important data from observations made during the eight years between 1818 and 1826.

"Can you help me get these figures?" he asked Challis.

The professor was glad to aid his brilliant young student. He wrote off to the Astronomer Royal at Greenwich Observatory and got the essential figures by return.

However, Adams could not get to work on these for some while. He was now a Fellow of his college, and had various duties that took up much of his time. Instead of trying to discover a new planet he had to concentrate on teaching and official work! Fortunately, he was in no hurry. It was a fascinating problem but not, he felt, an urgent one.

In the spring of that year, 1844, he snatched time enough from his college duties to finish framing the formulas he needed, but he still had to see how the observations came out in these. He did not finish doing this until September. They gave the size of the unknown planet, and its exact orbit.

Proudly, he showed Challis the results. The professor examined them eagerly. It was a marvellous piece of mathematical analysis: every detail about the planet was prophesied.

"You must send these to the Astronomer Royal at once!" urged Challis.

"I can take them to him," replied Adams. "I am just about to go home to Cornwall and can deliver them on the way."

Challis agreed and wrote a letter of introduction for the young mathematician to present to the Astronomer Royal. But when Adams arrived at Greenwich, he learned that Airy was attending a conference in Paris. Disappointed, he left the letter of introduction and went on to Cornwall.

A week later, Airy returned and found the letter. He wrote immediately to Challis.

"I am very interested in Mr Adams' investigations," he said. "I should be delighted to hear of them by letter from him."

However, Adams still wanted to deliver his results personally. Returning from Cornwall near the end of October, he tried again. He called in the morning at the imposing house occupied by the Astronomer Royal, and found only the butler. He left his card, to show that he had called, and also left the precious results, promising to call again in the afternoon.

When he came back at about four o'clock, he was sure that at last he would see the great astronomer and be able to explain his work. To his amazement, the butler turned him away.

"The Astronomer Royal is dining and cannot be disturbed," he said haughtily.

In actual fact, the butler wanted to protect his master from being disturbed at mealtime. He never told him of Adams' visit! But Adams, who did not know this, was very upset.

"The Astronomer Royal regards his dinner as more important than my new planet," he thought. "He cannot even be bothered to see me."

Adams returned to Cambridge but he had left the crucial data behind. In this he prophesied that the unknown planet would be in an orbit lying some 2800 million miles from the Sun—or roughly twice as far as Uranus. Its weight would be a little more than that of Uranus, and about seventeen times that of the Earth. He also stated just where it would have been in the sky three weeks earlier.

This prediction was an extraordinary mathematical feat.

However, the Astronomer Royal was not enthusiastic about it: if correct, it would prove him wrong. He still believed that the discrepancies in the movements of Uranus were only apparent, and that Newton's law of gravity did not hold good so far from the Sun.

"Has some young nobody of twenty-six really solved a mystery that has baffled leading astronomers for years?" he asked himself suspiciously.

It was too much for Airy to swallow. He could easily have tested the prophecy by turning the Greenwich telescope to the sky where Adams indicated. Instead, he stalled by writing a non-committal letter to Adams, asking for further, but quite unnecessary, information.

The poor young mathematician was baffled. He had eagerly given the result of all his painstaking work to the official leader of British astronomy. Now he felt utterly discouraged, and gave up trying to persuade Airy of the worth of his work.

"I have done all I can," he thought.

* * *

Meanwhile a brilliant young astronomer in Paris had begun working on the same problem. His name was Urbain Jean Joseph Leverrier, and he was some eight years older than Adams. He delighted in long, complicated mathematical analysis of the kind needed. Now, spurred on by François Arago, the leading French astronomer, he determined to explain the movements of Uranus. He had no idea that someone else across the Channel had been attempting the same thing.

He started work in June 1845—just two months before Adams had completed his calculations. Leverrier threw himself into the task and by November he had already made his preliminary

analysis of the problem. He worked to unheard-of accuracy, noting every discrepancy down to as little as one twentieth of a second of arc.

"The cause of the discrepancies is an unknown planet beyond Uranus," he told the French Academy of Sciences.

But where was this planet and how big was it? Like Adams, Leverrier saw that if he could calculate this, astronomers should be able to identify the planet with their telescopes.

Day after day, he went to his study in the École Polytechnique and grappled with thousands of figures. The clatter of horses hooves and the shouts of street-vendors came up from below, but he hardly heard them. Sifting figures, and fitting them to formulas he devised, he gradually whittled down the possibilities. By the early summer of 1846, he was able to state where the planet should be at the beginning of the next year. Although he did not know it, the position was only one degree of arc different from that prophesied by Adams!

"Let us hope," wrote Leverrier, "that we will succeed in sighting the planet whose position I have given."

His results reached George Airy towards the end of June. Despite himself, the Astronomer Royal was impressed.

"Adams and Leverrier have independently got the same result," he thought. "Maybe there is something in this idea after all."

And so, eight months after getting the data from Adams, the Astronomer Royal at last began to take action. On July 9 he wrote to Challis asking him to use his great 12-inch refractor to search for the planet. At that time the Cambridge telescope was the largest in Britain.

"I suggest that you search three times over a band of sky 30 degrees long and 10 degrees broad, mapping all the brighter stars," he wrote. "In this way you should eventually find the planet."

There were some three thousand stars to map. The method of search was hopelessly inefficient—rather like trying to find a friend in a crowded grandstand by noting who is in every seat! However, Challis gallantly agreed to try it.

Meanwhile Leverrier came up with an incredibly exact prophecy of the planet's position and sent it to the French Academy of Sciences at the end of August.

"The planet is now very well placed for observation," he added excitedly. "Its disc should appear near its maximum, about 3·3 seconds of arc in width."

The French astronomers, however, did nothing. Like Airy, they were doubtful whether a young man using only pencil and paper could achieve so much. Not one of them even suggested turning his telescope to the place Leverrier had computed.

"If only I had my own telescope!" mourned Leverrier. He was growing desperate.

And then he remembered Johann Gottfried Galle, a young astronomer at the Berlin Observatory, who had written to him earlier about another matter.

On September 18, 1846, he wrote begging Galle to search for the planet. With the letter went all the data for its orbit.

Galle seized the chance immediately.

"Can I search for this planet?" he asked Johann Franz Encke, the elderly director of the observatory.

"It sounds a waste of time to me," muttered Encke testily.

Galle pleaded and argued to be allowed some precious telescope time. At last the director gave way. That night, September 23, the dome of the observatory slid open and the 9-inch Fraunhofer refracter turned towards the area indicated by Leverrier. Galle sat at the controls, and a student named Heinrich Louis d'Arrest was at a desk with a star atlas.

To start with, Galle trained the telescope exactly on the spot predicted for that night by Leverrier.

"Right ascension twenty-two hours forty-six minutes, and declination minus thirteen degrees twenty-four minutes," he breathed.

Excitedly, he peered at the tiny area of sky. There was nothing resembling a planet!

"We shall have to search around the area," he told d'Arrest. "As I call out the position and appearance of each object, check if it is a star by seeing whether it is marked on the star map."

The first object was definitely a star. So was the second. So was the third. The fourth seemed to be of the 8th magnitude. Galle called out its position.

"Right ascension twenty-two hours fifty-three minutes 25·84 seconds."

Feverishly, d'Arrest searched for it.

"That is not on the map!" he exclaimed at last.

The two young men stared at each other, their faces alight with excitement.

"The eighth planet," whispered Galle, hardly daring to believe. "And less than a degree from where Leverrier prophesied!"

The next night he managed to measure its movement, thus confirming it was the unknown planet. Jubilantly, he dashed off a letter to the French astronomer.

"The planet whose position you have pointed out *actually exists*," he wrote.

Within a few days Leverrier had christened the new planet Neptune.

* * *

When Challis heard the news, he was still doggedly searching the sky according to Airy's advice. Now he checked his records and found, to his chagrin, that he had seen the planet twice without realizing!

"After only four days of observing, the planet was in my grasp," he wrote mournfully to Airy.

He blamed himself for not spotting the planet, but British astronomers blamed Airy more. Soon they were angrily asking why he had not acted earlier, instead of letting the prize go to France.

"Adams had the results long before Leverrier," they said. "He should be regarded as the discoverer of Neptune."

When Leverrier heard of this, he was very upset.

"If Mr Adams had the result, why did he keep silent?" he wrote to Airy. "And why did you not mention his results if you knew of them?"

Arago also challenged the British claims. In a sarcastic speech before the French Academy of Sciences, he jeered at Airy and Challis for failing to act on Adams' calculations, or even to accept his theory officially.

"There is no mention of any publication of Mr Adams' work," he cried. "Without publication, how can we believe any of these claims? Mr Adams has no right to figure in the history of the discovery of the planet!"

The quarrel between the British and French astronomers went on for the best part of a year. However, it was soon a national quarrel between the two countries rather than a scientific quarrel. And the two men most concerned, Adams and Leverrier, took no part in it.

In June 1847 the British Association for the Advancement of Science held its annual meeting. Sir John Herschel, son of the great William and distinguished astronomer himself, invited Leverrier and Adams to his home at Collingwood afterwards. There they strolled together under the elms, obviously admiring each other, and quite free of jealousy. They were to remain friends for the rest of their lives.

* * *

Adams and Leverrier proved that Newton's law of gravity could be used to deduce the existence of objects far out in space. Their methods have since helped to make further discoveries.

By studying the behaviour of Uranus still more closely, Percival Lowell, in America, decided that Neptune did not explain all the irregularities in its movement. A search therefore started for yet another planet in the Solar System. After many years, it was finally successful when an assistant at the Lowell Observatory named Clyde W. Tombaugh identified it on February 18, 1930. It was named Pluto.

Similar methods have shown that other stars have their own planets. By studying any wobbles in the way the star moves, astronomers can deduce the presence of a planet, and its size. The latest to be discovered was announced by Peter Van de Kamp, director of the Sproul Observatory in Pennsylvania, in April 1963. Belonging to Barnard's Star, which is 6 light-years away, it weighs about five hundred times as much as the Earth.

However, this method only works with near-by stars whose movements can be studied closely. Millions of other stars probably have attendant planets, but astronomers do not expect that they will ever detect them.

8

FRAUNHOFER AND KIRCHHOFF

The Spectral Code

THE large room was dark except for a narrow shaft of sunlight coming through a vertical slit in the window-shutter. Twenty-four feet away, Joseph Fraunhofer adjusted a special flint-glass prism in front of the small telescope of a theodolite. The sunlight entered the prism, bent through it, and passed into the little telescope. By looking through this, Fraunhofer could see the spectrum of sunlight under high magnification.

Carefully he adjusted the eyepiece until the spectrum came sharply into focus. He expected to see bands of colour, just as Newton had. Sure enough, he did—but he also saw hundreds of fine dark lines running down them!

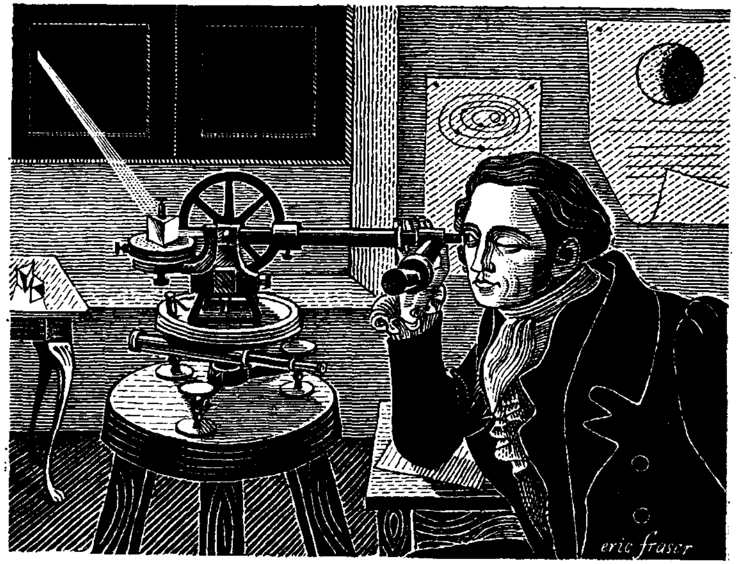
Puzzled, he wiped the eyepiece and looked again. The lines were still there.

"Perhaps there is some fault in the prism," he muttered.

Getting up, he exchanged the prism for another. But when he settled himself and examined the spectrum again, he still saw the mysterious lines.

"These lines must be part of the sunlight," the young scientist decided. "Are they in other kinds of light as well?"

He wanted to find out because the more he knew about light



the better would be the lenses he made. Already he was famous for the wonderful refracting telescopes he designed, but he never stopped trying to improve them still more. The Austrian firm of Utzschneider and Reichenbach were beginning to realize that young Fraunhofer was not only a technician but a research worker. Wisely, they let him experiment when he wished.

Now Fraunhofer examined the spectrum of candlelight. To his surprise, there were no dark lines, but there were two bright lines in the yellow part of the spectrum. What could this mean?

The young Austrian did not know, but at least he had discovered that not all kinds of light are the same. He set himself to describing the strange dark lines in sunlight. Some were darker than others, and stood out like definite bars: there was one in the red, a strong one in the blue, two close together in the yellow . . .

"Two in the yellow!" he exclaimed, remembering the bright lines in the yellow of candlelight.

Going back to the spectrum of candlelight, he checked the exact position of the two bright lines. They were in just the same place as the dark lines in the yellow of sunlight.

Without knowing what this could mean, Fraunhofer noted it down. Then he went on studying the spectrum of sunlight. He had decided to draw a map of all the dark lines he could see. There were eight particularly prominent lines, and he labelled these by letters, from A to H. The two lines close together in the yellow were allocated just one letter, D. Using a home-made micrometer, he measured how far apart these lines were and began drawing them out carefully. Then he began drawing all the fainter ones in between. This was a terrible job, but he stuck at it day after day until he was red-eyed and weary. Eventually he noted a total of 574 separate lines, and there were many others too close together for him to count.

Fascinated by these mysterious spectral lines, Fraunhofer now decided to investigate light from the planets and the stars.

"Perhaps some of this light will be different from sunlight," he thought.

To do this work, he made a $4\frac{1}{2}$-inch refracting telescope and mounted a prism in front of it. Then he took his special telescope up to his apartment and, as soon as it was dark, began by looking at Venus. No shutter and slit were needed this time: there was little enough light anyway.

By peering hard, Fraunhofer could see the dark spectral lines, although they were only just visible in the red and violet parts of the spectrum, which are dimmer in any case. The spectrum looked like that of sunlight. This was what he expected, because Venus and other planets only shine by reflected sunlight and have no light of their own. To make sure, he measured the positions of the main lines with his home-made micrometer. They were identical to those in sunlight.

Now Fraunhofer turned to some stars. Selecting the brightest to start with, he looked at Sirius.

"Only three dark bands!" he exclaimed.

He gazed until his eyes watered, but still he could not see any more lines. This spectrum was quite different from sunlight.

"One band is in the green, and two are in the blue," he noted.

But what did this mean? The young Austrian realized that he had stumbled on some secret of the stars. These strange lines contained a message in code. He could not read the code, but for a while he went on hunting spectra. He found that Castor was like Sirius, but four other stars—Pollux, Capella, Betelgeux, and Procyon—resembled our own star, the Sun. In all these he saw the same two D lines that were in sunlight.

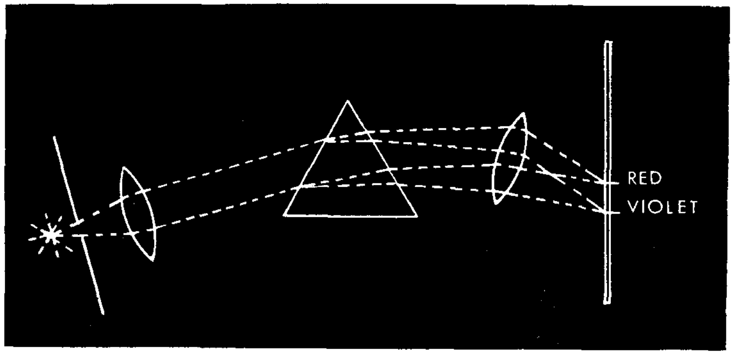
This was as far as he could go. In 1815 he announced his results to the Munich Academy. However, he was no nearer explaining them. The spectral codes remained unbroken.

* * *

The man who solved the codes was Gustav Robert Kirchhoff, a precise and rather pedantic professor of physics at the University of Heidelberg, in Germany.

However, he started not by studying dark lines but bright ones. Together with Robert Wilhelm Bunsen, professor of chemistry at the same university, he was studying the fact that chemical elements give out light when heated—just as an electric lamp does. To heat chemicals, they used a special kind of gas burner invented by Bunsen. Each chemical coloured the flame with its own colour, and this gave a way of identifying the chemical.

Through a spectroscope—which was an improved version of Fraunhofer's little theodolite telescope—the two men could see the coloured light as bright bands of light, located in just certain parts of the spectrum. Thus table salt gave off a bright yellow light, and the spectroscope revealed that this came in two bright lines close together in the yellow region of the spectrum.



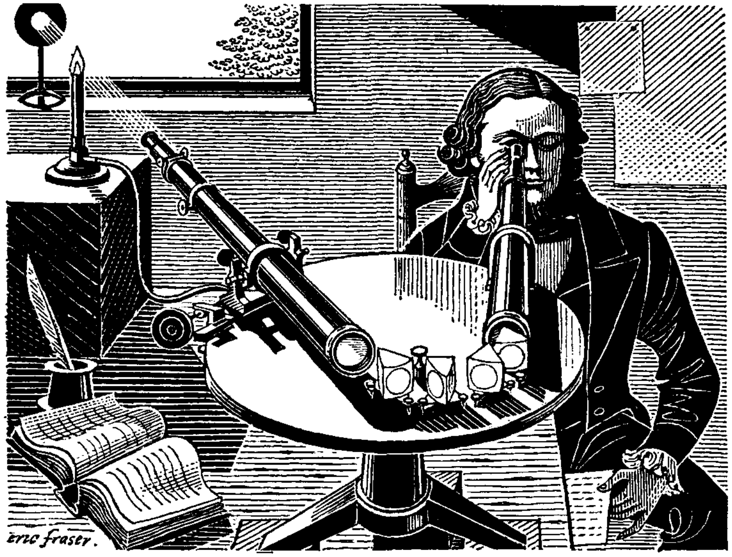
How a modern spectroscope works. Light comes through a narrow slit and is made into a parallel beam by a lens. Then the light is bent by a prism which separates the constituent colours. The colours are focused by another lens, giving a sharp spectrum. This spectrum can be viewed on a screen as shown or through a lens eyepiece which magnifies it.

These two lines were the same that Fraunhofer had labelled D lines. Table salt contains sodium, and the two bright D lines were the spectral code for sodium.

By heating chemicals containing other metals, they found the codes for these too. A bright red line plus a bright orange one meant lithium. Barium was revealed by four bright lines of various colours. For iron there were over a thousand lines!

These bright lines meant that the chemical element concerned was sending out light in just those parts of the spectrum, and no other. Some elements sent out light at many parts, some sent out light at only a few. But what about the dark spectral lines which Fraunhofer had found? These were the opposite: they meant that no light was being sent out at the parts of the spectrum where they occurred. Why was this?

To try solving this problem, Kirchhoff set up a new series of experiments. He began them one sunny morning in October 1859. Going into his laboratory, the frock-coated and bearded professor set up his usual arrangement of Bunsen burner and table salt to give the bright yellow spectrum of sodium. Now he took his beautiful Steinheil spectroscope and arranged it so that he could examine sunlight from the window after it had passed through the sodium flame.



"I shall see all the dark lines in the sunlight except for the two D lines," he prophesied as he settled himself on a stool. "The D lines will be overlaid by the bright D lines from the sodium."

Eagerly he peered through the spectroscope to see if his guess was correct. Then he caught his breath: the dark D lines had not disappeared. On the contrary, they were sharper than ever!

"The sodium flame must have stopped sending out its bright lines," mused Kirchhoff. "It must have done this because of the sunlight."

He could not imagine why this should have happened. However, he wondered whether the brightness of the sunlight had anything to do with it. To find out, he tried reducing the amount of sunlight reaching the sodium flame. As the sunlight was dimmed, he saw the dark spectral lines grow fainter. And then, without warning, the two bright D lines suddenly shone out again!

"When the sunlight is dim enough, the sodium flame sends out its yellow light again," noted Kirchhoff. "But why did it ever stop?"

Now he decided to send pure white light, free of dark lines, through the flame. The dark lines in sunlight made it difficult for him to see exactly what was happening to the sodium spectrum.

To get pure white light he used a special Drummond lamp. The light in this came from white-hot lime heated by oxy-hydrogen gas. Through the spectroscope, this light showed the whole spectrum of colours. Each was pure and had no dark lines running down it.

Now he moved his sodium flame between the spectroscope and the lamp and looked again. The two D lines were there, all right—but they were dark!

"The flame is somehow stopping yellow light from the lamp at those parts of the spectrum," he breathed.

Excited, he realized that this was no coincidence. The sodium atoms in the flame had stopped, or absorbed, light at the very parts of the spectrum where they usually sent out light.

"Because the sodium only absorbs the light at the two D lines, these dark lines identify sodium just as well as their bright counterparts," he noted.

Now the precise Kirchhoff started checking whether other chemical elements also showed this duplicate code of dark lines. And he found that in each case, as long as the light behind were bright enough, they did. On December 15, 1859, he sent the news of his discovery to the Berlin Academy.

Once he had got this far in explaining dark spectral lines, Kirchhoff began to understand why dark lines exist in sunlight.

"They exist because sunlight is not pure," he argued. "Somewhere on its journey to us parts of its light are absorbed, leaving dark lines in the spectrum."

But what could be soaking up parts of the sunlight in this way? Arguing from his experiments with the bright lamp and the dimmer sodium flame, he reasoned that the bright sunlight must pass through some dimmer vapour before reaching us.

"All the dark lines show that this vapour must be full of different chemical elements," he told himself.

But where were these elements? They were not in the sky! And then the truth flashed upon him: they were in the Sun itself.

"The Sun must be a gigantic chemical factory!" he exclaimed. "And its outside must be less bright than its inside, so that it absorbs the light coming from the inside."

Exultantly, the precise Kirchhoff realized that he had found a marvellously accurate way of analysing the Sun. Sitting quietly

in his laboratory in Heidelberg, he could probe delicately and surely into the secrets of a vast mass of gas burning 93 million miles away!

Now he began the laborious business of identifying the many dark-line spectra jumbled together in sunlight. Gradually he checked off one after another. Like some celestial miner, he found metal after metal: sodium, iron, magnesium, calcium, chromium, copper, zinc, barium, nickel—all were there.

He went further: he made a beautifully detailed map of the Sun's spectrum. As photography was not yet good enough for this, he had to draw it all. He used three shades of crayon to portray different strengths of line.

In the middle of this painstaking, detailed work his eyes, which had been strained before, grew too weak for him to continue. He handed the remainder of the job over to a pupil named Hoffmann.

When completed, the map was nearly eight feet long and showed two thousand separate lines. Yet, careful as it was, his map had less than a tenth of the lines in a modern one!

9

HUGGINS

Analysing the Stars

KIRCHHOFF had showed men how to analyse one star, the Sun. For William Huggins, an amateur astronomer living at Tulse Hill, near London, this work was an inspiration.

"Here is a way to lift a veil that has never before been lifted!" he cried enthusiastically. "Now I will start to analyse the stars."

However, he knew that he needed to find out more about spectrum analysis before he could do this. Fortunately, a friend and neighbour of his was expert at spectrum analysis in the laboratory. This was William Allen Miller, professor of chemistry at King's College, London.

One winter night in January 1862, Huggins went to hear his friend lecture on this subject in London. Afterwards, the two men drove back to Tulse Hill. As their horse trotted through the quiet streets of London and out into the countryside, Huggins told Miller of his plans.

"You described Kirchhoff's methods tonight," he said. "I would like to apply them to the analysis of starlight. Will you help me?"

"It sounds a bold undertaking," replied his friend. "I would like to join you in it."

By the time the carriage pulled up at 90, Upper Tulse Hill, they had started making plans.

"Come in," said Huggins eagerly, "and look at my equipment."

Adjoining the house was his private observatory. It was a modest affair with a 12-foot dome and several fairly small telescopes. The best was an 8-inch refractor driven by clockwork, and with a special object glass made by Alvan Clark, a great American lens-maker.

"We can use this," said Huggins proudly. "But of course we need to fit a spectroscope to it. Have you got one that is suitable?"

Miller shook his head. "Nothing that will do for this job," he said. "No one has. We shall have to design one and get it made." He stared thoughtfully round the little observatory. "We shall have to identify the star spectra by comparing them with spectra of chemicals here on Earth," he added. "I will rig up an electrical sparking apparatus to produce comparison spectra."

The two men quickly set about designing and collecting the necessary apparatus. Huggins, who was a wealthy bachelor, spent his days in chasing about London and bullying instrument-makers. Miller came back triumphantly one day with an enormous induction coil and Leyden jars to give them sparks. By sparking between different metals, he could get the spectra of those metals. Then he could compare these with the spectra in starlight.

At last everything was assembled, and the Clark refractor, with the spectroscope at the eyepiece, came into action. The bearded astronomer sat at the controls and his friend took charge of the induction coil. For each star, they checked off lines by comparing them with one home-made spectrum after another.

To test their methods, they started with a quick general survey. They found metals were definitely present in stars, as in the Sun. On February 19, 1863, they sent a note of their results to the Royal Society.

"Now let us analyse one or two stars as completely as we can," said Huggins.

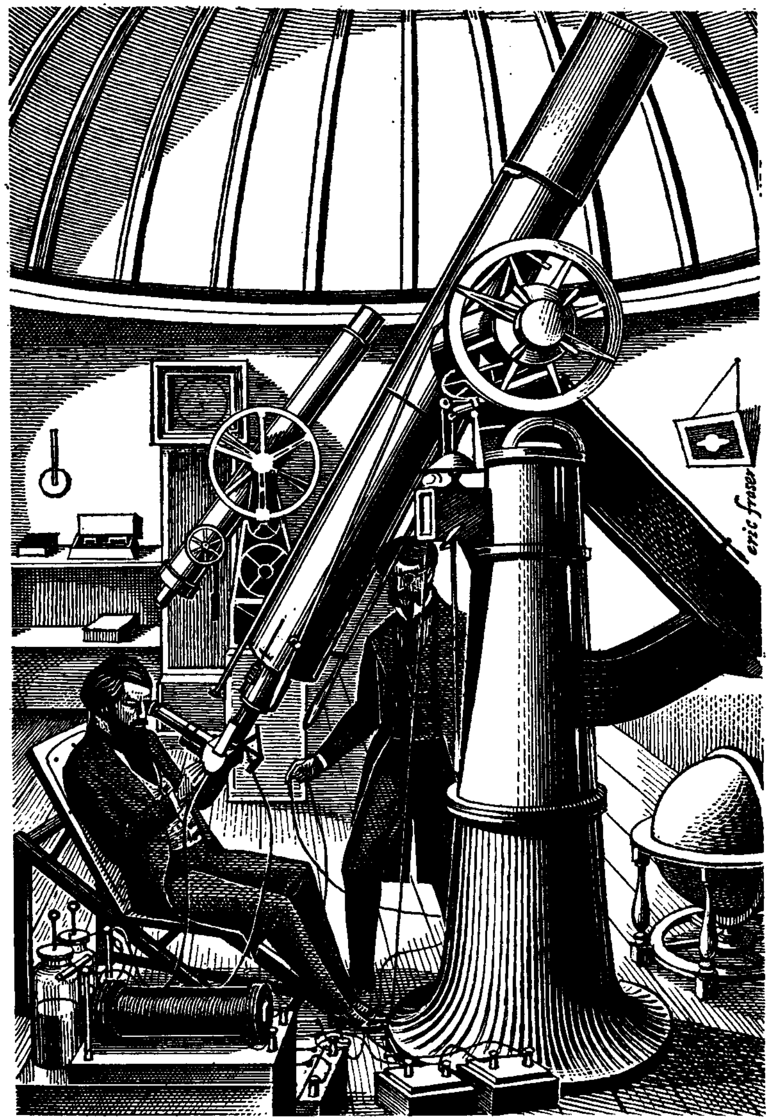
They decided to concentrate on two prominent red stars, Betelgeux and Aldebaran, and a very bright star, Sirius.

Night after night they shut themselves up in the little observatory and strained to identify the faint spectral lines. It was a tremendously difficult job: the air is constantly quivering, and often the lines danced before their eyes until they felt like giving up.

However, they went doggedly on, peering into the spectroscope, sparking their comparison spectra, and peering again. They also tried using the primitive photographic equipment then available, yearning to pin down the lines that flickered so tantalisingly before them. Then they would be able to examine the star spectra at leisure. However, they had little success and had to keep relying on their eyes.

After a year's work, they had succeeded in identifying a number of metals in each of their chosen stars. Betelgeux had five metals: sodium, iron, calcium, magnesium, and bismuth. Aldebaran had these too, plus tellurium, antimony, and mercury. Sirius had only three metals—sodium, iron, and magnesium—but they found hydrogen in it as well.

"Although stars vary in the elements they contain, they are all constructed on the same chemical plan as our Solar System," the two research workers announced in April 1864.



Peering across millions of miles of space, they had found some of the very same elements that exist on Earth!

Now Miller went back to his laboratory at King's College and Huggins worked on alone. At the end of August he decided to investigate a nebula. Astronomers were not sure whether these strange patches of light were really far-away star systems, or whether some were great clouds of shining gas.

Huggins realized that his spectroscope gave him a new way of finding out. Star systems would show spectra full of dark lines. A shining gas would show a simple spectrum of bright lines.

Excited and full of awe, he turned his telescope towards a round nebula in the constellation of Draco.

"I am going to look into a secret place of Creation," he whispered as he put his eye to the spectroscope.

All he saw was a single bright line. The nebula was a gas! Now he swung the 8-inch refractor towards the Great Nebula in Orion, which Herschel had once described as a hazy white spot. It, too, was a gas.

"Maybe stars gradually condense out of these great clouds," mused Huggins.

From his little observatory in London, he might be looking at the birthplace of thousands of suns!

For Huggins this was an inspired vision: he could not prove he was correct. Today, astronomers think that he was.

Soon Huggins went on to investigate other nebulae. By 1868 he had checked the spectra of another seventy. One third turned out to be masses of gas. The rest, however, had long, complicated star spectra, and so he knew that they were great systems of stars. He had proved that there were two kinds of nebula.

* * *

Using light, Huggins had succeeded in doing chemical analysis on a truly cosmic scale. But he knew that light carried another kind of message, too. In 1842 an obscure Austrian professor of physics named Christian Doppler had prophesied that the light coming from a star would be altered by the speed and direction of the star.

The kind of effect he had in mind occurs with sound. When we hear a change in the note of a diesel train horn as it rushes by us the change is caused by the train's movement. The note of the horn sounds shriller as the train approaches, and grows deeper as the train goes away. Doppler argues that if a star was moving fast enough, its light would change colour for the same sort of reason. Today we know that at very high speeds this colour change does occur.

At lower speeds there is no colour change but there is a shift in the placing of the spectral lines. As a French physicist named Armand Hyppolyte Louis Fizeau pointed out in 1848, the greater the speed the greater the shift. Here, then, was a way of measuring the speed at which a star was moving. Fizeau also said that the direction of the shift would depend on the direction of the star's travel. If the shift was towards the blue, the star would be approaching. A shift to the red would mean that the star was receding.

"I will try to measure spectral shifts," Huggins told himself. "But which is the best spectral line to use as a reference point?"

To settle this problem, he wrote to James Clerk Maxwell, a great physicist, for advice. Maxwell told him to concentrate on the F line of hydrogen.

And so in the spring of 1868 the indefatigable amateur turned his telescope towards Sirius once more. Gingerly, he adjusted the micrometer screws to register any shift in the F line. Hour after hour he was baffled by tremors in the air that made the precious spectral lines leap about. Hour after hour he struggled to keep the slit of the spectroscope, which was only 1/300 inch wide, trained exactly on the star. (1/300 inch is about the width of a thin pencil line.) Although driven by clockwork, the telescope needed constant slight adjustment.

Eventually Huggins succeeded. The size of the shift was fantastically small but it indicated an enormous velocity.

"Sirius is moving away at about 30 miles per second, or over one hundred thousand miles an hour!" he exclaimed, his mind reeling at the idea.

He sent a note of this value to the Royal Society on April 23. Later he was to revise the value, bringing it down to about 20 miles per second. This is pretty much the modern figure.

Huggins went on measuring spectral shifts. He found the stars were rushing about in a wild random way, very different from the way they seem to the naked eye. Some, such as Betelgeux, Rigel, Castor, and Regulus, were retreating. Others, including Arcturus, Pollux, and Vega, were advancing. All were travelling at frightening speeds, though the speeds seem small because the stars are so far away.

Still trying to use photography, he struggled to record these shifts with a camera. At last, with the aid of improved techniques, he got a picture of the spectrum of Vega in 1876. Later, he managed to photograph many more spectra.

* * *

With the use of spectrum analysis, a new era began in the history of astronomy. Techniques of spectral photography were quickly improved. An American named Henry Draper recorded seventy-eight different spectra between 1879 and 1882, and in

1886 Edward Charles Pickering and his co-workers at Harvard College Observatory began making a complete survey of stars in the northern skies. By 1890 a new Harvard installation in Peru was being used to investigate the southern skies as well. Today, over fifteen thousand separate star velocities are known and some 360,000 stars are catalogued according to the kind of light which they emit. With spectrum analysis, we can work out the chemistry of these stars.

But the study of starlight was to do more than tell men about the chemical make-up of stars: it was to open up new ways of measuring the Universe.

Until 1900, the only yardstick known to astronomers was parallax, the method used by Bessel. With it, the distances to some five thousand stars had been painstakingly calculated. However, these were only a minute fraction of the visible stars. Also, they were all relatively close stars, because the parallax method could not be used with more distant ones. Astronomers were therefore seeking some way of gauging much greater star distances.

And then in 1912 a serious-minded clergyman's daughter named Henrietta S. Leavitt made a discovery that was to revolutionize distance measurements. It concerned some curious stars named "cepheid variables."

10

SHAPLEY

Beacons in Space

WEARING a high-collared blouse and long skirt, Miss Henrietta S. Leavitt sat at her desk. Through the window she could see the low, ivy-covered buildings and four small domes of Harvard College Observatory. On the desk before her were piles of photographs and a low-power microscope.

She took up one of the photographs and placed it under the microscope. It showed a vast, ragged mass of stars looking like a piece torn out of the Milky Way. This was the smaller of the two Magellanic Clouds. Only visible from the southern skies, this had been photographed at the Harvard station in Peru.

Now she consulted a special catalogue of stars. This listed 1777 variable stars in the two Clouds. Intently, she searched the photograph until she had found one of the listed stars. She estimated its brightness, noting the time when the photograph had been taken. Then she began hunting through other photographs showing the same star at different times. Each time she found it, she noted its brightness and when it had been photographed. Slowly, very slowly, she was building a picture of the way these strange stars kept fading, brightening, and fading again.

A few years earlier, about 1908, another Harvard astronomer had been hunting variable stars. This was a lean, hawklike man named Solon I. Bailey. He had found lots of them in certain tight clumps of stars known as "globular clusters." He had identified them as a particular kind of variable stars, cepheid variables, named after a bright variable star in the constellation of Cepheus.

"Most of the cluster cepheids change very quickly," he announced. "They go through a complete cycle in only about twelve hours. Some, however, fluctuate more slowly, taking twelve to twenty days."

No one knew why cepheids should wink away like this. Nor did they know the whole range of winking speeds. Miss Leavitt had decided to time those in the Magellanic Clouds.

Patiently she searched day after day for cepheids. One trouble was that most of those in the Clouds were very faint, around the 15th magnitude. Long exposures were needed to photograph them, and many of her photographs did not show them. Also, there was a lot of obscuring dust in the Clouds, and so she concentrated on the smaller Cloud, which was clearer.

At last, after months of careful work, Miss Leavitt managed to get out the times for just twenty-five of the 1777 catalogued stars. Most of them took from a day to a fortnight to vary.

Now she listed these figures in order, from the fastest to the slowest. Alongside each she put a note of maximum and minimum brightness. And then she noticed something, something that made her sure she had stumbled on some secret of the cepheids.

"The slower stars are brighter than the faster ones!" she exclaimed.

Excitedly the young woman astronomer plotted a graph to show brightness and winking speed were related. The result was a beautifully smooth curve. This proved the link between brightness and winking speed was no accident. However, it did not explain why the two were linked.

In 1912 she published her results. Although she did not know it, they were to provide a new way of measuring the Universe.

* * *

In 1914 a young Missourian named Harlow Shapley was doing research at Princeton University. His speciality was another kind of variable star and he had just got his doctorate for work on this.

One day the director of Princeton Observatory, Henry Norris Russell, called Shapley into his study.

"Hale is coming on a visit from Mount Wilson," he said. "He wants to meet you."

The young astronomer was thrilled. George Ellery Hale was famous for the great observatories he had created. First had come Yerkes, at Williams Bay, Wisconsin, with its big 40-inch refractor—still the world's largest. Then he had created Mount Wilson, an observatory specially built high up in the clear air of Southern California.

When Hale met the young astronomer, he looked sharply at him through his spectacles.

"I know of your work," he said abruptly. "I would like to have you join the Mount Wilson team."

To go to Mount Wilson meant using the best astronomical equipment in the world. Amazed at his good luck, Shapley gazed at the almost legendary Hale.

"I shall be able to use the 60-inch reflector," he murmured happily.

Hale gave a small smile. "Just so," he said briefly.

Shapley needed no urging. With his wife, Martha, he packed up and made the long, slow journey across the continent. From Pasadena he went up the long, winding road that led at last to the peak of the mountain, 5714 feet above sea-level. It was up this road, just 8 feet wide, that the parts of the giant 60-inch reflector had been painfully brought seven years earlier.

When he came to the top, he caught his breath at the beauty of it. There among the pine-trees were the white derrick-like towers of Hale's solar telescopes, and the silver dome housing the great reflector. The air was pure and clear—clearer than any Shapley had seen back in the East. He gazed around, thinking of the marvellously clear nights of observing ahead. This was a dream observatory!

* * *

Shapley went on studying variable stars, but this time he chose to work on cepheids. With the 60-inch reflector he could take photographs finer than any before. In particular, he could study the star spectra more closely.

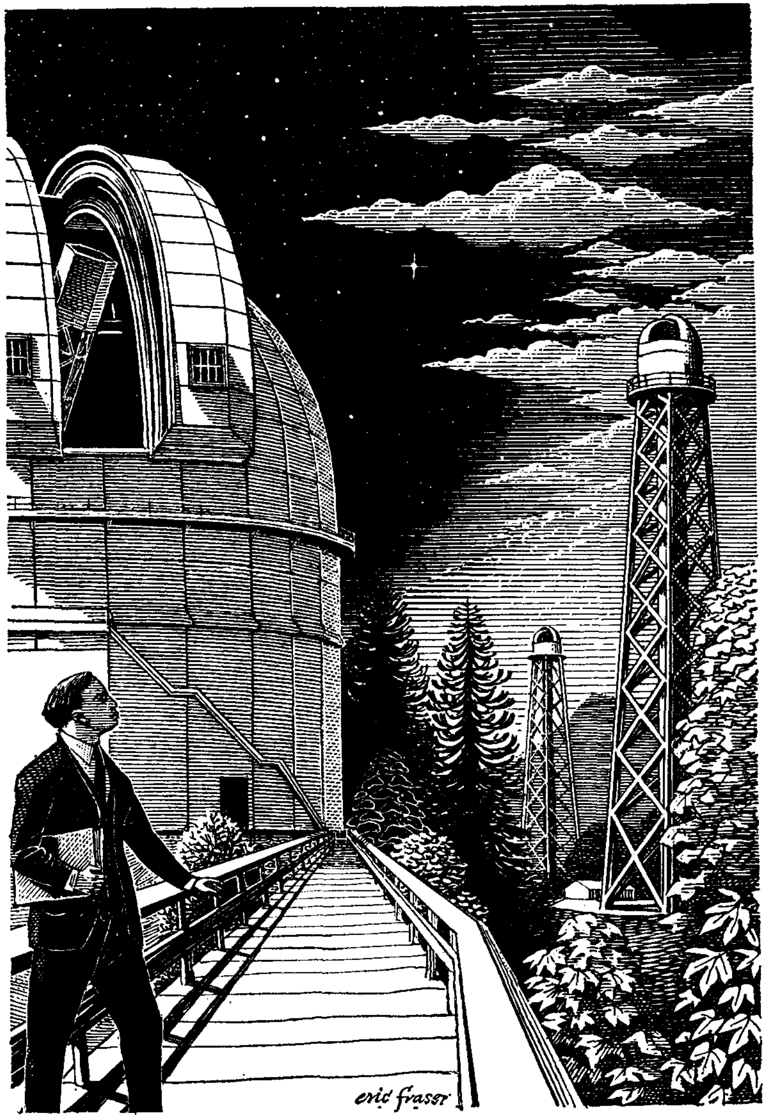
Like Bailey, he concentrated on the rapidly winking cepheids in globular clusters. The 60-inch revealed thousands of separate stars in these, opening them up as no other telescope had. The great mirror gathered so much light that photography was speeded up. Shapley could get the spectrum of an 8th magnitude star in seventy minutes and of a 10th magnitude in four hours.

Night after night, as soon as the dome slid open, the stocky young astronomer climbed to the Newtonian focus near the top of the great telescope tube. There he guided the telescope for hours at a time while he took his photographs. Then, in the daytime, he pored over the results.

Soon he noticed a strange fact about the cepheid spectra. When a cepheid was at its brightest, the lines were shifted towards the blue. When it was dimmest, the lines were shifted towards the red.

"Normally spectral shifts mean a star is moving towards us or away from us," muttered Shapley. "Blue shifts mean it is approaching, and red shifts mean it is receding. But surely these cepheids cannot be doing both, rushing first one way and then the other!"

And then he had a brilliant idea. Perhaps the stars were not actually moving to and fro, but their surfaces were moving in



and out. Perhaps they were constantly expanding and contracting!

"The spectral shifts would be the same," he thought, struggling with the idea. "And yet . . . and yet . . ."

He calculated that the gases of the stars would be rushing in or out at many miles per second. Some of the stars would change their diameter by as much as 10 per cent. in a few hours. It was obviously ridiculous! And yet, what other explanation was there?

He went over the problem again and again, seeking some other explanation. At dinner in the observatory he hammered the idea out with other astronomers such as Adams, Seares, and Pease. Fantastic it might be, but his idea certainly explained the observations.

Later an English astronomer and mathematician, Sir Arthur Eddington, took up the theory. He was able to calculate that this extraordinary pulsing could go on without the star blowing itself to pieces. Today, astronomers believe that cepheids do keep on swelling and shrinking like this. Indeed, they hope that soon they will be able to explain why.

* * *

Meanwhile a Danish astronomer, Ejnar Hertzsprung, had suggested that these winking stars could be used as distance indicators.

He started from the fact that once we know how bright a star really is, we can work out its distance by seeing how bright it appears to be. By the inverse square law, the amount of light reaching us from it falls off in proportion to the square of the distance.

Turning to Miss Leavitt's discovery of the link between the brightness of cepheids and their winking speeds, he had seen that winking speed might be used to indicate real brightness. Once that was done, it would be easy to work out how far away any particular cepheid was.

But how could he find the real brightness that went with any winking speed? The brightnesses noted by Miss Leavitt were the apparent ones as seen on Earth, not the real ones.

The only method was to start the other way round, and get the real brightness of some cepheids by measuring the distance to them, and then calculating the real brightness by the inverse square law. This looked like an insoluble paradox: to use cepheids as distance indicators he had first to know the distance to some cepheids!

Fortunately, however, there was a way out of this difficulty. Some relatively near-by cepheids were known, and Hertzsprung could gauge the distance to these by another method. This method depended on a statistical analysis of how much these near-by stars seemed to move across the sky over the years. On average, the nearer stars appeared to move more than the farther ones.

So the Danish astronomer hunted up the recorded movements of thirteen near-by cepheids and worked out how far away they were. Now he could calculate how bright they really were by working back from how bright they seemed to be.

All these particular cepheids were fairly slow winkers, taking between 1·3 and sixty-six days per wink. As the cepheids studied by Miss Leavitt had much the same winking speeds, Hertzsprung reckoned that he could transfer his brightness figures to them. This meant that he could measure the distance to the Magellanic Clouds which she had studied.

The result came as a shock to every one. At that time astronomers believed that our galaxy, which they took to mean the Universe, was no more than 23,000 light-years across. The Dane cheerfully came up with the fact that the Magellanic Clouds seemed to be a whole 10,000 light-years farther away!

While astronomers everywhere were trying to understand what this meant, Shapley pounced on the idea of using cepheids as distance beacons.

"I will use them to find out how far away the globular clusters are," he decided.

The snag here was that, as Bailey had found, most cepheids in the clusters winked a lot faster than those used by Hertzsprung. However, by hunting around, Shapley located slowly winking cepheids in a few globular clusters, tucked away amongst the fast winkers. Hoping they were comparable, he used these to work out the brightness of the fast winkers. Now he was ready to gauge the distances to as many globular clusters as he could see!

The results were staggering. Even a near-by cluster, M 13 in Hercules, was 36,000 light-years away. The farthest went out to nearly a quarter of a million light-years!

Some clusters, however, did not contain any cepheids. To deal with them, Shapley boldly switched to a new method. He compared whole clusters with each other, and reckoned distances to the farther ones from his other data for the nearer.

All this was causing a revolution in astronomical thinking, but Shapley had not finished. He determined to use the globular clusters to map our galaxy. He believed that they were a part of it.

Astronomers had already noted a strange fact about the clusters. Instead of being scattered all over the sky, most are in the southern hemisphere. Further, one third are crammed together in a mere 2 per cent. of sky, in the region of Sagittarius.

"It is unlikely that the clusters are really all bunched together," argued Shapley. "More probably they are evenly spaced around the galaxy and this bunching is just an effect of perspective."

If he were right, our Sun could not be near the centre of the galaxy, as astronomers thought. Instead, it would be towards one side, so creating the perspective effect. And the centre of the galaxy would be where the bunching appeared, in the region of Sagittarius.

By 1917, Shapley had drafted out his map. He had studied ninety-three different globular clusters in doing so.

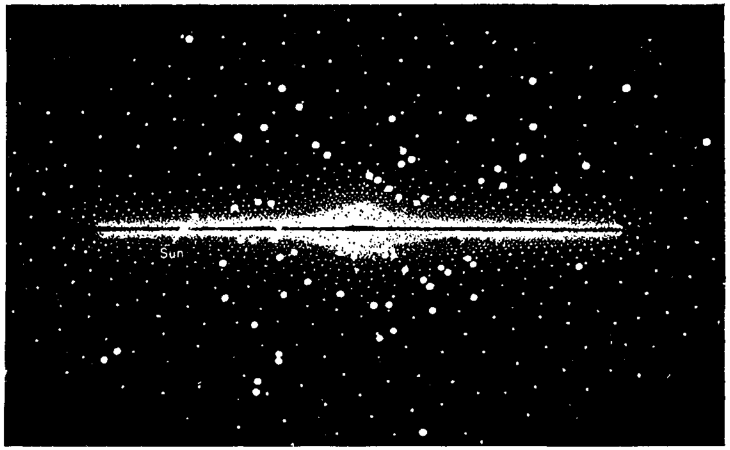
"Our galaxy is a disc 300,000 light-years in diameter and 30,000 light-years thick," he declared. "The centre is in Sagittarius, about 50,000 light-years away from us."

* * *

Today we know that Shapley was right in believing our galaxy is made on a far larger scale than anyone had dreamed. He was also right in deducing that we are tucked away near one rim.

However, his distances were too large. The reason is that he did not know of interstellar dust, which dims the way stars appear by absorbing light. Consequently they all appear farther away than they are.

Although our galaxy has shrunk as a result, it is still quite large enough. Still disc-shaped, and with a central swelling, it is now reckoned to be about 90,000 light-years in diameter and 10,000 light-years thick at its deepest point. Our Sun is about two-thirds of the way out from the centre at a distance of 27,000



How our galaxy would look edge-on if viewed by some one in outer space. It is surrounded by its globular clusters and has a dark disc of interstellar dust running through its middle. Our Sun is about two-thirds of the way out from the centre and looks just like any of the other 100,000 million stars in the galaxy.

light-years. And there are another 100,000 million stars in the galaxy to keep us company.

And what of other galaxies? Back in the 1780's William Herschel had believed that countless other "island universes" exist. However, when Shapley announced his model of our galaxy, astronomers were still not sure about this. The man who finally proved Herschel right was Edwin P. Hubble, another astronomer at Mount Wilson. But the universe he revealed was even more fantastic than that imagined by Herschel.

II

HUBBLE

The Expanding Universe

His tall, vigorous figure silhouetted against the night sky, Edwin P. Hubble stood at the Newtonian focus of the 60-inch reflector. He was making sure that the great telescope was exactly trained on a faint clump of stars and nebulae while he photographed them. There was a brisk wind and he wore his military trench coat, a reminder of his recent Army days in the First World War. As usual, a pipe was clenched between his teeth and sparks from it were flying out into the great dome.

At last he stepped back with a sigh of relief. The photographic plate was exposed.

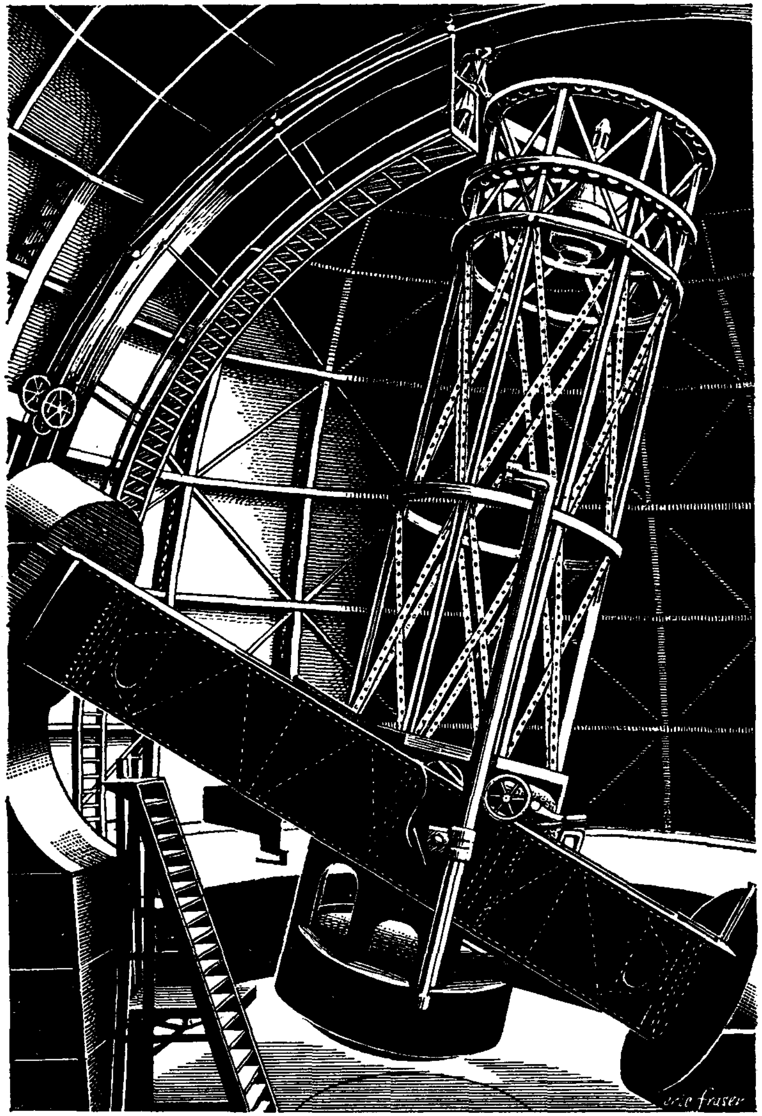
"We reckon seeing conditions are pretty bad tonight," said Milton L. Humason, who had been watching him. "I hope you get something out on that plate."

"We'll soon know," said Hubble, and he carried the plate off to the darkroom for developing.

When he came back he was jubilant.

"If this is a sample of poor seeing conditions, I shall always be able to get usable photographs with Mount Wilson instruments!" he declared.

It was 1919, and Hubble had just started working at Mount



The 100-inch reflector

Wilson. He was delighted by the marvellous equipment at his disposal. Not only was there the trusty 60-inch, but a new giant which Hale had created—the 100-inch reflector. Housed in a vast new dome, this machine weighed 100 tons and the mirror had taken six years to grind. Over thirty electric motors controlled every movement of telescope and dome. With three times the mirror area of the 60-inch, Hale knew that it should reveal secrets that the older telescope only hinted at.

To Hubble, these giant telescopes were vital. Only with them could he try to fulfil his great ambition—to explore the galaxies.

"I will find out whether they are within our own Milky Way or far outside," he promised himself.

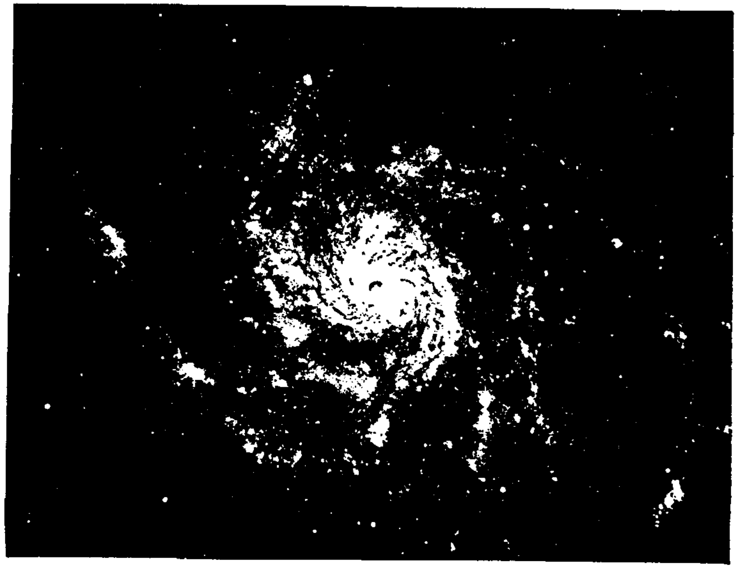
At this time the problem of whether the galaxies belonged to our star system or not was being debated hotly by astronomers. Although Huggins, and later workers, had proved that galaxies are great groups of stars, no one had been able to find out if they were truly separate systems. Some echoed Herschel, believing that each was a far-away system equivalent to our own Milky Way. Others thought they lay within the vast disc which Shapley had just been measuring. One definite fact was that most were either elliptical, rather like rugby footballs, or spiral, like whirling Catherine-wheels, apparently trailing curved arms of stars.

"The crucial point at issue is their distance," noted Hubble.

But how was he to measure the distances to any of these strange, remote systems?

"Maybe I can use cepheid beacons in the same way that Shapley has," he mused.

He began by hunting for cepheids in a raggedly shaped system looking rather like one of the Magellanic Clouds, and catalogued as NGC 6822. Night after night he probed this system with the



Many spiral galaxies look like whirling Catherine-wheels. This drawing is from a photograph of galaxy M 101 in Ursa Major and only shows the brightest parts of the galaxy.

60-inch reflector, yearning for reliable photographs of even one or two cepheids.

By 1923 he had at last managed to pick out a dozen variable stars in the system. But he was cautious about what kind of variable star they were.

"They look like cepheids but I cannot yet be sure whether they are," he said.

Hubble realized that the 60-inch reflector was not adequate for this sort of job. He had to have more light-gathering power. And so he turned eagerly to the great 100-inch.

A great spiral catalogued as M 31 and lying in Andromeda caught his attention. (This is the only galaxy outside our own

which is visible to the naked eye.) On the very first good plate Hubble found two ordinary novae, or flaring stars, and a faint, 18th-magnitude star that he could not identify. At first he thought it was another nova. However, after checking through a long series of old plates assembled at Mount Wilson he found to his delight that it was a cepheid.

"It takes a month to vary and has a real brightness around seven thousand times that of our Sun," he noted happily. "Here is my first marker beacon!"

Reading off the scale linking brightness and distance he soon calculated how far away the great spiral was. The answer staggered him.

"About 900,000 light-years," he whispered.

This proved that it was far, far outside our own Milky Way. As soon as other Mount Wilson astronomers heard the news they concentrated work on the great galaxy. Relying mainly on long-exposure photographs with the 100-inch, they managed to sort out thirty-six variable stars from the millions in the great spiral. Of these, twelve were identified definitely as cepheids. Checking the brightnesses of these, they found Hubble's distance estimate held good.

Meanwhile Hubble returned to NGC 6822. This time, he located some definite cepheids. From these he found the system was 700,000 light-years away. Here, then, were two great star systems far beyond the confines of our own galaxy!

He went on hunting cepheids. By 1926 he had spotted thirty-five of them in another great spiral, M 33. This turned out to be about 850,000 light-years away.

And these were only three galaxies out of thousands he could see!

* * *

Meanwhile an astronomer named V. M. Slipher had been working quietly away on his own at the Lowell Observatory in Flagstaff, Arizona. Like Huggins, he was interested in measuring velocities through spectral shifts. Unlike the British astronomer, however, Slipher wanted to find the velocities not of single stars but of great groups—the groups Hubble was now finding to be separate galaxies.

He had begun some fourteen years earlier, in 1912. Curiously enough, he had chosen to start with the very same spiral in Andromeda that was later to give Hubble his first success. Using a fast camera, Slipher pinned its spectrum down clearly and then measured the shift. It was towards the blue: the star system was coming nearer—and at what a speed! Slipher pored over the plate, hardly able to believe his result. But there it was: the frightening speed of 190 miles a second! (Not that we need worry about a collision: the Andromeda spiral will not get anywhere near us for over 1000 million years.)

By 1914, Slipher had measured thirteen velocities for different star systems, and by 1923 the number was up to forty-one. Other observers had by this time added five more, but Slipher still had a near-monopoly in this field of research. He discovered that although M 31 in Andromeda seemed to be moving towards us, nearly every other system was moving away. They were travelling at dizzying speeds, too—averaging about 375 miles a second and in one case going as fast as 1125 miles a second. No astronomer had dreamed such speeds were to be found.

Now, in 1929, Hubble had measured the distances to twenty-four of the galaxies whose speeds Slipher had found. And he noticed a strange fact: the farther away the galaxies were the faster they were receding from us.

"On average, velocities are stepped up by about 100 miles a second per million light-years of distance," he noted.

What could this mean? Was it just coincidence or had it some real importance?

Sitting in his home at San Marino, Hubble brooded over the problem. A cheerful fire blazed in the hearth, and a fine selection of dry flies was at his side. A keen fisherman, he was planning a fishing-trip in the Rocky Mountains. But his mind kept slipping away from fishing, returning to this mystery of the galaxies.

He could find only one explanation. Yet he hesitated to adopt it, for it seemed to start so many more questions.

"It looks as though the Universe is expanding," he told his wife, Grace, at last. "Why else should all the galaxies be accelerating away in all directions?"

His wife gazed at him as though he had gone crazy.

"Expanding?" she asked. "How can it? What is it expanding into?"

"I don't know," muttered Hubble. "But I guess it is, all the same!"

* * *

To try and clinch the matter, Hubble decided on a big programme of research.

"Slipher only used a 24-inch refractor," he told Humason when he next saw him. "Imagine what we could do with the 100-inch reflector!"

The two men discussed the project with W. S. Adams, now director of the observatory in place of Hale. Adams was fired by their enthusiasm.

"I will allocate you every possible amount of time with the

100-inch," he told them. "This is the most ambitious project astronomy has ever known. Maybe you will reach out to the very edges of the Universe!"

Hubble's plan was to measure distances right out to the farthest galaxies, and to check these against velocities obtained by Humason. If his hunch about the expansion of the Universe were correct, the velocities should go on increasing with distance.

To test his equipment, Humason began by checking the shifts in spectra for a few bright galaxies whose velocities were already known. Then he explored. Slipher had gone out far, but the giant reflector could go thirty-five times farther!

To photograph the spectra, Humason had to make very long exposures, keeping the telescope exactly on target all the while. This meant that he had to watch out in case air tremors shifted the image unpredictably. The telescope's automatic drive was no help for this.

As he reached out farther, the galaxies appeared fainter and fainter. Longer and longer exposures were required. Eventually he needed ten successive nights just to get one picture! Only a man as untiring as Humason could have kept at the job.

By 1935 he had measured 150 new velocities. They grew larger with every increase in distance. The distances were being independently checked by Hubble from the way apparent brightness diminished. Starting with a relatively near-by cluster of galaxies in Pegasus, travelling at a mere 2400 miles per second, Humason ended with galaxies some 240 million light-years away and receding at 26,000 miles a second, or about one seventh the speed of light!

"The velocity-distance relation is established over an immense volume of space," wrote Hubble. "The Universe definitely seems to be expanding."

However, like a good scientist, Hubble cautiously pointed out that everything hinged on the observed red shifts.

"Either these reveal velocities or they depend on some unknown principle of physics," he said.

As scientists normally do, Hubble preferred to explain the shifts with known facts if possible. He supposed that the galaxies really are receding faster and faster.

Now the exact astronomer sat back for a little and let himself dream about the implications of his extraordinary discovery.

"If the Universe is expanding," he wrote, "it may finally be possible to determine the nature of the expansion and the time at which the expansion began—that is to say, the age of the Universe."

* * *

Today astronomers agree with Hubble that the Universe seems to be expanding. In fact, this expansion was predicted by Albert Einstein long before Hubble's work. We also know that it is even larger than Hubble supposed. Walter Baade has shown that there is more than one type of cepheid variable, and this means that Hubble's original marker beacons must be used rather differently. His distance estimates are between 2 and 3½ times too small.

Whether we shall ever know the age of the Universe is another matter. In trying to find out, astronomers are probing farther and farther into the recesses of the Universe. In doing this they now have an even larger light-gathering telescope, the 200-inch reflector on Palomar Mountain. So far, this has seen 5000 million light-years into space and shown us galaxies fleeing away at 86,000 miles a second, or nearly half the speed of light. But they also have an entirely new way of exploring the Universe, and one which can penetrate even farther than we can hope to see.

Strangely enough, the man who first hit upon this new way was no astronomer. In fact, most astronomers never knew of his work for a long time. His name was Karl Jansky.

12

JANSKY AND REBER

Broadcasts from Space

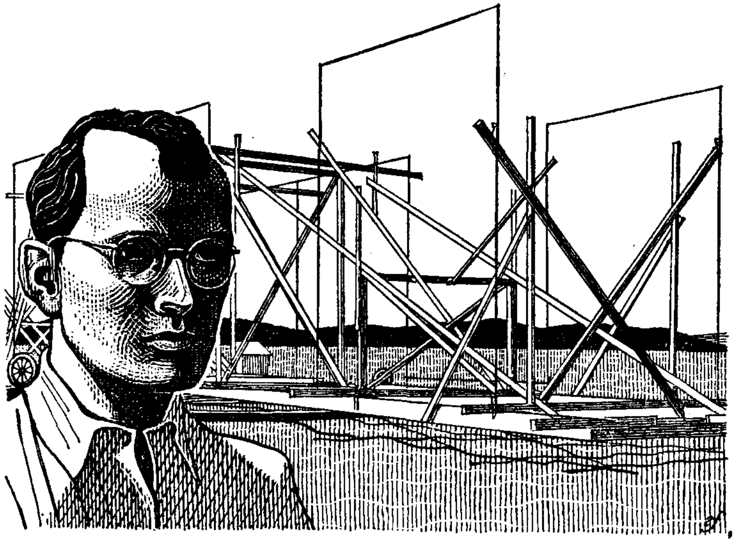
FIFTY miles south-west of New York, a lean, balding young radio research engineer sat intently at a radio receiver, headphones over his ears. It was a fine evening in the summer of 1931. Through the window he could see a 100-foot-long contraption of brass pipes and wood struts, looking like the framework of some giant trough. It was creaking round and round like a weather vane, making one complete turn every twenty minutes. And every twenty minutes the young engineer frowned in bewilderment as he listened.

"There it is," he muttered. "The same weak, steady hiss! And it seems to be going down in the west, along with the Sun."

The young engineer, whose name was Karl Guthe Jansky, tracked the mysterious noise across the sky until it went below the horizon around sunset. Then he wearily removed his earphones, put on his jacket, and left the building.

Outside, the flat New Jersey countryside was already growing dark. Jansky cranked his car up, got in, and drove noisily off along the highway towards his home in Little Silver.

As he peered through his rimless glasses at the road ahead, Jansky brooded over the mysterious noise. Storms, he knew,



generated radio noise, or "static," but it was quite different from this. He had been hunting storm static with his big aerial and had proved that ferocious bursts were generated by thunderstorms. He had listened in to storms as much as 140 miles away. But this faint hiss was continuous, and it followed a set course across the sky, instead of coming from all over the place like storm static.

"Whatever it is, it certainly is not due to storms," Jansky told himself. "And, so far as I can tell, it seems to follow much the same track across the sky as the Sun does. Maybe it *is* the Sun!"

When he got home he told his wife Alice that he believed he had been listening to radio noise coming from far beyond the Earth.

As the days went by, Jansky sat in his room in the laboratory and listened in to the faint hiss. It was so faint that few people would have bothered had they heard it, for it was hardly louder

than the ordinary hum of the receiver. But Jansky, who was hunting every source of radio noise for his employers, the Bell Telephone Company, hung on to it like a bulldog.

"If it's so faint, Karl, why bother with it?" asked Harald Friis, Jansky's immediate superior. "After all, your job is to search out noise that will interfere with radio-telephone communication. That's what Bell Telephone are interested in."

Jansky had no good answer to this, but he went on listening. He was determined to locate the source of the noise, whether it mattered or not. He just wanted to know!

By now he was recording the hiss—not as sound but as a wavy line traced out on hundreds of feet of moving chart. And after a while he realized, with mounting excitement, that it was starting earlier every day. It came up over the horizon before the Sun!

"So it doesn't come from the Sun after all," noted Jansky, getting up earlier too. Before long he was getting up in the middle of the night to go over to the laboratory at Holmdel and track the hiss.

Then, as he yawned over his charts early one day, he noticed something which, although he could not explain it, was obviously important. The hiss started up exactly four minutes earlier each day. In a month, it gained two hours.

"What is it that comes up over the horizon four minutes earlier each day?" the puzzled engineer asked himself.

No one at the laboratory could help him, and so he chased off to the nearest library and searched through books on astronomy.

He read how the spinning of the Earth on its axis makes the Sun appear to go round it once every twenty-four hours. He also read that while we turn once in twenty-four hours in relation to the Sun, we turn a little more in relation to the stars. This is because of our annual circuit of the Sun. After one year, this causes an additional complete turn-round in relation to the stars. We turn 365 times a year in relation to the Sun, but 366 times in relation to the stars.

"This means that the stars rise and set more quickly than the Sun," breathed Jansky, feverishly jotting the figures down. "They rise and set 366 times each year instead of 365 like the Sun. So instead of having twenty-four hours for each of their risings and settings, they have a little less."

The calculation was easy. The 'star day' came out at twenty-three hours fifty-six minutes instead of twenty-four hours—just four minutes less. Jansky gave a cry of joy. He had found his four minutes!

"The mysterious hiss is coming from the stars," he whispered, and hurried back to the laboratory.

Now he eagerly began to try narrowing down the area of sky from which the radio noise came. His rotating aerial could record the position of the hiss in an east-west direction but was not much good at gauging the altitude. However, after months of work he finally decided on two likely areas.

"The radio waves may be coming from the centre of the Milky Way, or from the constellation of Hercules," he wrote in the spring of 1933.

His announcement caused a sensation. Newspapers and magazines reported his work, and the strange hiss was broadcast to the American nation from a radio station in New York.

"Our broadcast tonight will break all records for long distances," the announcer told a wondering audience. "We shall let you hear radio waves from somewhere among the stars!"

But it was a disappointment. This voice of the stars was just like the hiss of steam escaping from a radiator.

* * *

The New Jersey engineer wanted to go further. He even dreamed that he might build a great dish-shaped aerial 100 feet across to use for short-wave studies. However, his employers saw little practical benefit in such ideas, and so, in April 1937, Jansky reluctantly abandoned his research.

Professional astronomers were mostly sceptical about what he had achieved.

"It is hard to believe," they said. "Billions and billions of kilowatts would be needed to produce even the feeble effects noted by Dr Jansky."

Fortunately, however, Jansky's results fired the imagination of at least one man. This was a radio enthusiast living in Wheaton, Illinois, and his name was Grote Reber.

"I will build a better aerial for listening to the stars!" he promised himself one day in the summer of 1937.

Each morning Reber drove into Chicago, 30 miles away, to design home radio receivers for a local radio company. But now, as he sat at the drawing-board, he began designing a very different sort of receiver.

"About thirty feet across," he decided, drawing out a great dish shaped rather like an umbrella.

He even had spokes for it—though very short ones. There were just four, meeting over the centre of the hollow of the dish. Where they met, the radio waves would be focused by the dish.

"I will have my collector here, and have a cable from it to carry the signals to my control-room," mused Reber.

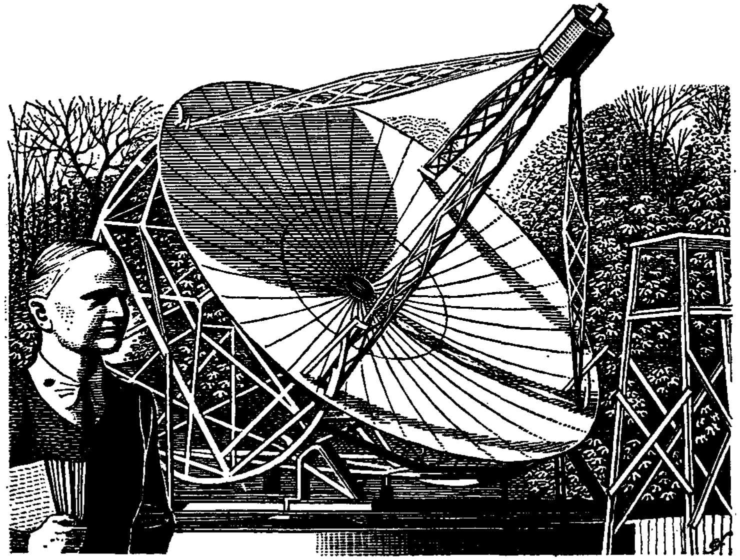
His control-room was not as grand as it sounded—it was his basement. Anyway, he had solved his signal-collecting problem. But how was he to steer the dish?

"The rotation of the Earth will swing it round from east to west," he told himself. "So I only need to tilt it up or down."

To do this, he devised two semicircular tracks under the dish, standing up like horseshoes, one on each side.

Now he had to get the apparatus off the drawing-board and into operation. He ordered over forty pieces of galvanized sheet iron from a startled supplier, and demanded that they were to be cut to special shapes and numbered in sequence. He also got wooden struts cut out and fitted to make sections in the same way.

Working through the hot summer evenings, he began assembling all these in his garden at home. Neighbours stopped to see what was going on, craning over the fence at the great dish that was beginning to rise above the trees. But Reber was unperturbed, and by August he had finished. His radio telescope was ready.



That first evening he dashed home from work and went straight to the basement. But although he sat for hours with the headphones clamped to his ears, he heard nothing. It was a bad disappointment.

He went on listening, day after day. And day after day the result was the same.

"Maybe the apparatus isn't sensitive enough," he worried, checking his calculations. "Maybe with a better amplifier . . ."

But better amplifiers did not help. And yet he knew radio waves must be bouncing off his dish all the time! It was exasperating.

"I will try tuning to longer waves," he decided at last.

Jansky had listened in on wavelengths between 14 and 20 metres. Reber had been trying only $3\frac{1}{2}$ inches, or about 200 times shorter. Now he retuned the apparatus, and settled once more in his basement. But he still heard nothing.

Desperately, Reber began tuning to longer and longer waves. From $3\frac{1}{2}$ inches he went to 13 inches, and then to over 2 feet, over 3 feet . . . And one night in October 1938 he had his reward. He was tuned to 6-foot waves, and as he switched the receiver on he saw a sight he had almost given up hoping for. The needle on his meter was swinging across the dial.

"A signal!" he cried, grabbing his earphones.

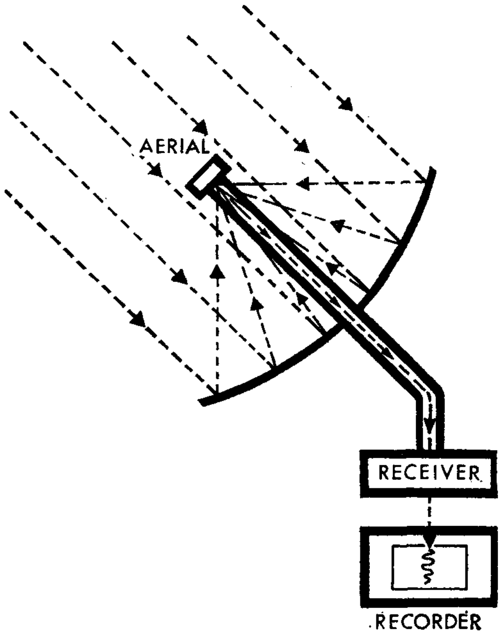
All night he listened, with a contented smile on his face. It was the beautiful hiss he had dreamed of for so long.

Now the young engineer gave up all his nights to listening. He came back from work, had dinner, and slept until midnight. Then he took his readings. At six in the morning he reluctantly emerged from his basement, had some good strong coffee, and drove off to work. Instead of seeing the rich black farmland around him as he drove, he saw only traces drawn on paper, charts of an unknown universe that he was beginning to explore.

But he had to know more about astronomy. He was getting plenty of records now, but he did not know how to interpret them. And so he enrolled at the University of Chicago, and there, surrounded by gloomy stone buildings, he swotted up astrophysics.

When he could interpret his maps, he took them to astronomers at Yerkes Observatory.

"Each line indicates a definite signal intensity," he said,



In a dish radio telescope the incoming radio waves are focused at the aerial and fed to a receiver. After amplification they can be recorded as a wavy line showing varying signal strength.

spreading out a map that looked like a series of contours for height above sea-level.

Otto Struve, the director of the observatory, pored over the drawings. His spectacles flashed in the light as he looked from one to the next.

"Very interesting," he muttered. "Quite remarkable!"

"I am sure these confirm Jansky's work," Reber went on excitedly. "You see the rise in intensity here? This indicates exactly when the Milky Way passes over my aerial!"

Struve called in a young Dutch astronomer at the observatory named Gerard Kuiper, and asked him to take a look. Then other Yerkes astronomers came in. Every one was puzzled by what could be sending out such powerful radio waves. They knew of no mechanism inside the stars that would produce such waves.

"And what are these violent wiggles?" asked Kuiper hopefully, pointing at some tracings of signal strength.

Reber laughed bitterly. "A dentist three blocks away! Every time he starts drilling I pick up static from the motor of the drill. Traffic is just as bad: the waves from their ignition systems is murder. That's one reason for starting my recording after midnight—there's less traffic around."

* * *

By 1940 Reber had published his first results. Then, hoping to track down definite emitters of radio waves, he aimed his dish at some bright, near-by stars. He selected Vega, Sirius, Antares, Deneb—and the Sun. To his surprise, he heard nothing from any of them. However, some four years later he did manage to detect a faint noise coming from the Sun.

Meanwhile he went on refining his radio contour maps. He discovered that certain areas contained especially strong broadcasts.

"One is towards the centre of our galaxy, in the direction of Sagittarius," he wrote in 1944. "Others are placed as though in arms projecting from the galaxy—perhaps in spiral arms of the type seen in other galaxies."

This was as far as he could go at the time. Today we know that his hunch about the spiral arms is correct. Radio astronomers have found that our galaxy is indeed a spiral. In fact, it looks very like the great galaxy of Andromeda, which is the nearest neighbouring galaxy. We now know that its radio waves come mainly from gas between the stars, instead of the stars themselves, but the powerful waves from the centre are still a mystery.

However, other sources of radio waves have now been located. Certain stars apart from the Sun are known to be radio emitters. Clouds of excited gas, probably left after the explosion of a star, send out waves as well.

Other galaxies also broadcast. Normally they are fairly quiet, like our own galaxy. The Andromeda galaxy is one of these. But there are some very loud galaxies, which astronomers call "peculiar" galaxies. The first of these to be identified through an ordinary telescope was Cygnus A, the second-loudest source in the sky. Its appearance amazed astronomers everywhere.

13

SMITH AND BAADE

A Peculiar Galaxy

THE radio source in Cygnus had originally been noted by Grote Reber. Later three Englishmen named Stanley Hey, S. J. Parsons, and J. W. Phillips made a more accurate map of it by using longer wavelengths. They found it was concentrated in a small area which they called Cygnus A.

However, this area still covered a good deal of sky. Optical astronomers who looked at it found the area peppered with objects, some being near-by stars and others distant galaxies. They could not pick out which of all these was the radio emitter. How, then, could this powerful radio source be identified?

"A more accurate type of radio telescope is needed," decided Martin Ryle, the director of the Mullard Radio Astronomy Observatory, near Cambridge. "Perhaps an interferometer will do the trick."

Ryle specialized in interferometers. He had set up a number of different ones on a disused rifle range out in the countryside. Each consisted of twin aerials, and the signals gathered by these were combined for the final reading. This made them much more effective than aerials on their own. Also, the twin aerials were particularly good direction finders. If signals from a radio source arrived simultaneously at each aerial, this proved the source was the same distance from each, right between the two. If the source was a trifle to one side, the signals did not arrive simultaneously, and this immediately showed up on the record.

Among his twin aerials, Ryle had two steerable dish aerials 27 feet across. These had once been used for radar detection. Now they were set up 1000 feet apart. Together, they made an especially exact interferometer.

"With these, we may be able to track down the exact position of Cygnus A," thought Ryle.

Another member of the Cambridge team, Graham Smith, was very interested in locating radio sources. He now took on the difficult job of trying to pinpoint Cygnus A.

In August 1951, the twin aerials turned towards a tiny area of sky. Sitting tensely inside the yellow-brick control building, Smith watched as their recordings were automatically written out. A wavy line was traced on a roll of paper emerging from the machine.

Outside, farmers were hard at work gathering the harvest. The *putter-putter* of their tractor engines came in through the open window. However, the engines did not affect radio reception because the Cambridge astronomers had fitted suppressors to them.

The wavy line traced out larger and larger waves as the signals grew stronger. Smith ran his hand through his thick fair hair and crouched eagerly over the paper. Hour after hour, the source crept nearer and nearer to the central position between the two aerials. Agitatedly, Smith wiped his spectacles and peered harder. He wanted to see the precise point at which the signals were strongest.

The moment came when he was not sure whether the waves were still getting larger. Then he was sure: the peak had been passed. Cygnus A had crossed over the centre point!

He got up and raced along the corridor to Ryle's office. The thin, taut astronomer was hunched at his desk.

"Martin, I've got it!" Smith exclaimed. "Come and look at the recording."

Ryle jumped up and followed the other man back to his room. The recorder was still working away, steadily feeding out its paper. Ryle picked up a length and looked along it. The peak showed up splendidly.

"This gives a really exact position," he said, and smiled with pleasure. "Graham, we can ask Baade to look for the source with the 200-inch."

* * *

On a table-top mountain in Southern California, a great silver dome 137 feet across stands up into the blue sky. It houses Hale's crowning masterpiece, the 200-inch reflector. Costing 6 million dollars and weighing 140 tons, it is the biggest light-gathering telescope in the world. The tube is so large that the observer can sit in a cage at the top *inside* the tube, and still let enough light by for the great mirror below!

Astronomers using this telescope live down in Pasadena and await their turn at observing. One of them, Walter Baade, had long been interested in radio sources. Around eleven o'clock one morning at the end of August, he came into his office at the nearby Mount Wilson Observatory and found a flimsy air-letter on his desk. It was from Graham Smith.

Baade tore it open, scanned it, and whistled softly with surprise. Then he went to a neighbouring office where his friend Rudolph L. Minkowski was at work.

"Say, it looks as though the Cambridge men have located Cygnus A," he said, handing Minkowski the letter.

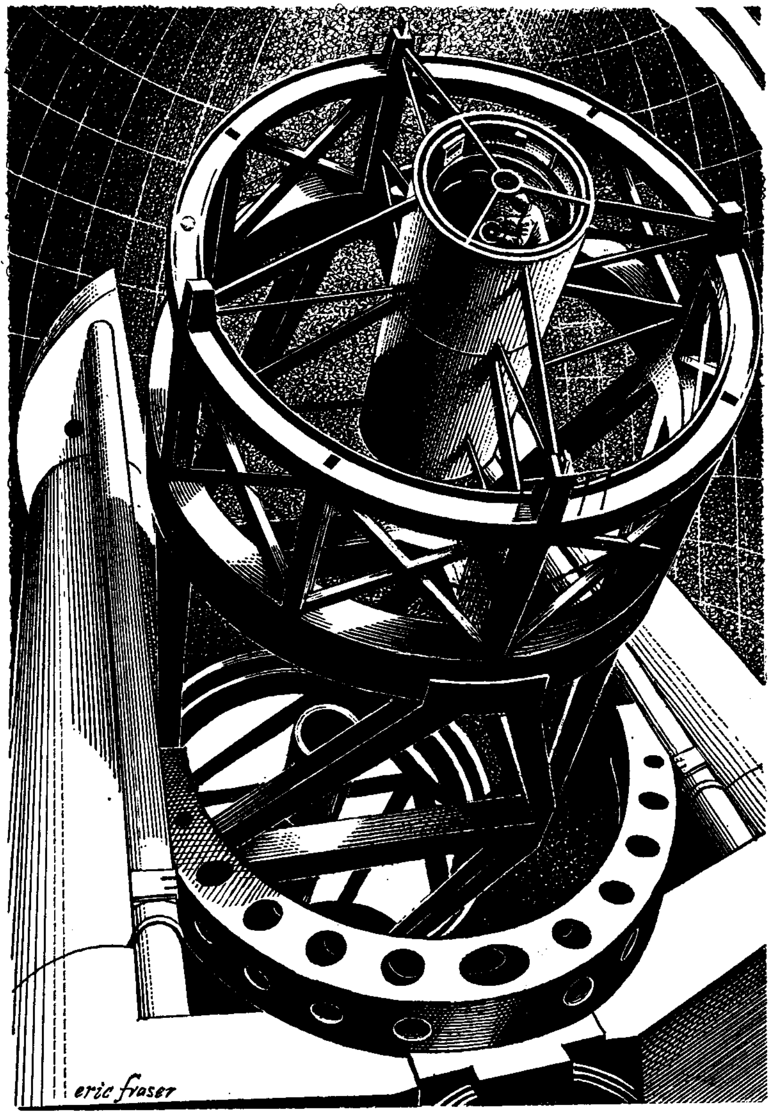
Minkowski read the letter and nodded.

"This is much the most exact position anyone has got," he said. "Are you going to look for it?"

"With this data, it's worth trying," declared Baade. "I'll aim to fit it in during my next trip to Palomar."

It was September 4 when his next chance to use the great telescope came up. That afternoon he said good-bye to his wife Johanna and drove the 125 miles to the observatory. This was to be his home for the next ten days.

At sunset the dome, closed during the day to protect the mirror from the Sun's heat, slid open. Baade rode a little lift to a deck running round inside the dome's base, and then stepped on to a moving platform which carried him up to the mouth of the



Observing with the 200-inch reflector

telescope tube. It was tilted to one side of the dome so that he could get in from the platform. Now the elderly astronomer let himself down gradually into the 5-foot-wide cage. Here he would spend the night, taking photograph after photograph. As always, he was formally dressed in jacket and tie for his meeting with the stars. He was also as tense as a runner at the starting line, determined to achieve the most he could in the time available.

It was a perfect night. Below, the dark hump of the south shoulder of the mountain curved downward to the lights of the valley below. To the east, mountain peaks stood out against the velvety blue sky.

On the floor below, the night assistant pressed a switch and set the great telescope swinging silently away from the platform.

Walter Baade

It stopped, and then with another switch he aligned it on Baade's first target for that night. This was the Andromeda galaxy, which Baade was studying closely in his revision of Hubble's cepheid distance scale.

For several hours, Baade methodically went through his arranged programme. And then, just before midnight, he was able to fit in the Cygnus work. He had the great telescope trained on the exact position specified by Graham Smith and took two photographs.

The next afternoon, he developed the prints in one of the observatory darkrooms. As soon as he saw the negatives, he knew that he was looking at something unusual. There were galaxies all over the picture—more than two hundred—but the one in the very centre was unlike any which Baade had seen before.

"It has a double nucleus," he muttered in astonishment, peering at the dark discs. "And there seems to be some distortion, as though due to gravitational pull."

He brooded over the picture on his way to supper. What could this strange double shape possibly mean? And then he remembered a purely theoretical study he had made earlier in the year. With a Princeton astronomer, Lyman Spitzer, he had tried to work out what would happen if two galaxies collided. Such a collision would be very unlikely, they agreed, but not impossible.

"Maybe this is a picture of just that!" he whispered. "Two galaxies colliding—the biggest traffic accident in the Universe!"

That night he looked once again at the pictures before entering the observing cage. He wanted to fix them in his mind and think about them. All night he pondered, as he went on with his routine work of photographing. And the more he thought the more he was convinced he was right.

* * *

Back at Mount Wilson, Baade told Minkowski of his idea. Minkowski removed his spectacles, looked quizzically at Baade, and put them back on his nose.

"No, Walter, I cannot agree," he said finally. "The trouble is that you and Spitzer have been dreaming about colliding galaxies. Naturally you want to see them! But what proof have you that that's what these blobs of light really are? Absolutely none!"

Baade was discouraged. He sounded other astronomers, and they agreed with Minkowski. With a sigh, he let the idea drop.

However, he did not forget it. Some six months later, he heard Minkowski making fun of it at a seminar.

"Bet you a thousand dollars I'm right," he said sturdily.

Minkowski laughed. "Walter, I can't afford a sum like that! Apart from anything else, I've just bought a house."

"All right, a case of whisky," Baade persisted.

Minkowski shook his head. "Not even that."

Eventually the two men settled for a single bottle. But how could they try to prove whether Baade was right or not?

"If the galaxies really are colliding, the interstellar gas will be swirling violently about," said Minkowski. "Probably neon V would be formed—the activity would strip off the outer electrons of the neon atoms."

"Then that is the test!" declared Baade. "If neon V is there, it will show up on the spectrogram. Why don't you photograph the spectrum of the galaxies?"

Minkowski agreed to do this tricky job. A few weeks later, in May 1952, Baade was sitting in his office when Minkowski walked in.

"What brand shall it be?" he asked, and from the crestfallen look on his face Baade knew that he had won the bet.

"Hudson's Bay Best Procurable," he said happily. "And now show me your results."

Minkowski brought the precious photograph out. On it the thick dark line indicating neon V stood out clearly. It looked as though Baade was right: a fantastic collision had taken place 700 million light-years away, and they were witnesses to it!

* * *

Today, astronomers are not so sure. The strange object in Cygnus may be a pair of colliding galaxies, but other explanations are possible. One is that a single galaxy is splitting into two. Another is that a galaxy is breaking up after violently collapsing inward.

What is certain is that the radio waves are not coming from the visible areas, but from two great wing-shaped haloes on each side, going out about 100,000 light-years. This has been discovered by two Jodrell Bank astronomers, Roger Jennison and an Indian named Morinal K. Das Guptal. Why these haloes exist is a mystery.

Many galaxies with such double radio haloes are now known. They do not look particularly alike, but they all send out tremendously powerful radio waves. These "peculiar" galaxies are evidently quite different from ordinary galaxies like our own.

Today, radio astronomers are trying to find out just why peculiar galaxies exist. If they eventually find the answer, we shall know a lot more about the nature of galaxies, and about the Universe itself.

Epilogue

As we look farther and farther into space, we look farther and farther into the past. The 200-inch reflector has revealed a cluster of galaxies in Bootes, 5000 million light-years away. We see these galaxies with light that has taken 5000 million years to travel from them to us. This means that it began its journey at about the time our Earth was born. We are looking at a part of the Universe as it was then.

Some men believe that the Universe is changing, or evolving. They believe that at some time in the past, perhaps some 10,000 million years ago, all the material which now forms the galaxies was close together, and that since then it has been flying apart and ageing.

Others believe that the Universe is, on average, the same all the time. Although it is expanding, and galaxies are rushing away in all directions, more galaxies are being created as well. In 10,000 million years from now, they declare, the Universe will look the same. If they are right, there was no beginning to the Universe and there will be no end.

By finding out what the Universe was like in the past we can try to judge whether it has been changing. Our telescopes are time-machines for visiting different epochs. But so far we have not been able to go back far enough to find definite changes.

In reaching out so far, we cannot expect to use light. The light coming from very distant galaxies is likely to be so faint that it cannot be photographed. However, some galaxies emit radio waves much more strongly than light waves. If the peculiar galaxy in Cygnus were ten times farther away than it is, optical telescopes would not reveal it but radio telescopes would easily record it. Thus it is with radio waves that astronomers expect to explore the still farther reaches of the Universe. By recording how galaxies were when the Universe was very much younger, they hope to find out whether there is any answer to the greatest question in astronomy: How did the Universe begin?

Bibliography

I hope that reading this book has made you want to find out more about astronomy and astronomers. Some more books about astronomers which you could try are:

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