TELESCOPES AND THE FORCES THAT MOLD THEM: AN INTRODUCTION TO OPTICS AND MECHANICAL DESIGN

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This lecture is to serve in part as an introduction to optics and mechanical design. Where did I get such a title? It is from a little book by C. V. Boys, the Englishman who measured big G. He was also responsible for developing the methods of drawing fused silica fibers for torsion wires. On December 30, 1889, and on January 1 & 3, 1890, Boys gave three Christmas lectures to the children of London which were published in a book entitled, "Soap bubbles and the forces that mold them." Some of the telescopes that I'm going to talk about were built much earlier than this, and therefore did not benefit from the wisdom contained in Boys' little book. In particular, in Boys' December 30th lecture he discussed "water-bombs or cat-boxes," a folded shape into which you can put and hold water ... and if skillfully thrown has the property of being useful for dispersing cats. Boys pointed out that if one tries to make bigger and bigger cat-boxes (or water bombs), they will eventually fail and just collapse. The collapse results since the quantity of the containing paper skin increases as the square of a characteristic length while the disruptive volume force increases as the cube of the length -- and therefore increases more rapidly with size. Eventually the strength of the paper skin is insufficient to hold the water content of a large "box" and it simply collapses. Exactly the same problem occurs with telescopes. As they get bigger and bigger, the increasing body (or gravity) forces put more and more demands on their structural components.

Let's begin by getting some idea of what telescopes look like. The slides I will show are of drawings that were displayed in 1974 as part of an exhibit at the Smithsonian Institute in Washington, D.C. The first slide (slide 1) shows Galileo's telescope. His telescope consisted of a positive, objective lens and a negative (so as to yield an erect image) eyepiece lens separated by a somewhat decorative tube. Both lenses were singlets -- that is, made from a single type of glass. The next drawing (slide 2) shows a telescope designed fifty years later. Notice what they've done. They've made an enormously long telescope -- 158 feet from one end (where the eyepiece is), to the other end (where the objective is). Why? Because they still had only singlet lenses, and as you know, a lens looks and acts somewhat like a prism and accordingly focuses different colors at different distances from the lens. This difficulty is called chromatic aberration. The focal length that is needed to make a satisfactory-for-viewing singlet lens is, as it turns out, approximately 100 times the diameter of the lens in inches squared. If you have a 1 inch diameter lens, you need a focal length of 100 inches. If you have a 5 inch diameter lens, you need a focal length of 2500 inches (or 208 feet) if you want to obtain a reasonable image. That was the problem, and that's why early telescopes had enormously long barrels -- to minimize chromatic aberration.

The next slide (slide 3) shows Huygen's approach to the same problem. He said, "O.K., you need a long distance between the front and the back but you don't necessarily need the tube."

The next picture (slide 4) brings us to 1671 and Newton's first reflector telescope. Rather than accept the large chromatic aberration of a simple objective lens, Newton used a concave metal mirror for his objective, thereby avoiding all of the chromatic problems, since reflection at a mirror surface is independent of color. We now know that chromatic (color-corrected) lenses can be made which for the simplest type (a doublet involving two elements made from different types of glass) requires a focal length given approximately by 10 times the diameter of the lens in inches squared — a 10-fold shortening in the required length of the telescope when compared with a singlet lens of the same diameter. However, it was not until 1729 that the first achromatic doublet was designed. Why didn't someone make an achromatic lens a lot sooner? Basically, the answer is that Newton believed (and said) that glass of the required dispersive properties did not exist -- and so nobody bothered to try until some 60 years after Newton had built his first reflector. Newton's invention of a new kind of telescope resulted in his being elected as a Fellow of the Royal Society. Nevertheless, he held back the development of the achromatic lens for 60 years simply because people believed his pronouncement that it couldn't be done. There may be a lesson to be learned from this story.

The next picture (slide 5) shows the first of the large telescopes. This is a 48 inch diameter reflector built by Herschel, a German by birth who at the age of 19 moved to England and settled there. Herschel's telescope employed what we call an elevation-azimuth type of mount. The whole structure rotates in the horizontal plane while the telescope itself can be tilted up and down in elevation. The original mirror from this telescope is displayed in the London Science Museum. It's made of speculum metal which Herschel himself poured, cast, and polished. The most interesting thing about it is that it was a failure. This first large mirror that Herschel made, which was 48 inches in diameter, was only a few inches thick, and it sagged. It suffered from exactly the same "cat-box" problem that C. V. Boys was to point out 100 years later. As things are made bigger and bigger, they will sag more and more; and therefore, in the case of mirrors, they will distort to the point of being almost useless. The first mirror weighed on the order of half a ton. Nevertheless, Herschel, on recognizing the problem, made and used a second mirror that was twice as thick (and therefore 8 times stronger against sag).

The next slide (slide 6) shows an examination problem that I once set. If you had been a physics student when I taught the introductory course some years ago, this is the kind of problem you would have been asked to solve. The answer that I wanted was that as the kitten gets bigger, its mass (or its weight) goes up as its characteristic length cubed, whereas the held-to part only goes up as the square of this length (area) and so being lifted in this manner probably hurts.

The next slide (slide 7) shows the largest achromatic telescope that I know of. To make it, people had to learn to cast 40 inch diameter pieces of glass that were clear enough, and homogeneous enough, to yield a good optical image (not an easy task). The last of these drawings (slide 8) shows the 200 inch Hale telescope -- which is characteristic of modern large telescopes. Note the increase in mechanical complexity and bulk compared to the smaller and lighter-weight telescopes shown earlier.

Now let me discuss a few telescopes that are quite different from the ones described so far. I will begin with the mercury mirror telescope of R. W. Wood which was described in the Astrophysical Journal of 1909 (pp. 164-176). R. W. Wood was an extremely clever turn-of-the-century American physicist. Basically one could imagine his thinking going something like: Why should one constantly make bigger and bigger telescope mirrors which become more and more expensive, and still sag. If I use a dish of mercury as the mirror (which had been suggested earlier) and rotate it at a constant and uniform speed (which had been suggested but not seriously attempted previously) the surface that results is a parabola. Just how good a (vertical looking) telescope would this make?

The next slide (slide 9) is a picture of R. W. Wood and his 20 inch diameter mercury mirror. (You see a distorted image because the surface is a parabola and you are looking considerably off axis.) The answer to "how good" is contained in his paper. He shows star tracks obtained with his Hg-mirror telescope that are 2 or 3 seconds of arc in diameter.

Slide 10 shows a schematic side view of the "mirror," and slide 11 gives an overall view of his apparatus. Incidently, at the end of his paper he reveals that the cost of the experiments were defrayed by a grant of $200 from the Elizabeth Thompson fund -- that is apparently how much it cost to do science in 1906!

Before going on, I would like to point out two things in Woods' article which I found extremely interesting. On page 174, he says:

> "In the long run, then too, we may be able to discover some substance which can be rotated and fused while it's rotating with a constant velocity. Maybe one would have to refigure the image."

And somewhat later he writes:

> "I'm now making experiments to see whether solid mirrors can be made by this centrifugal method. Various methods have occurred to me. We may be able to take a cast of the Hg surface by pouring a hot viscous liquid over it which will solidify on cooling, and I have already obtained in this matter pretty good paraboloids of resin. These casts can be electroplated in silver." ...

The next slide (slide 12) shows a large epoxy-cast, 62 inch diameter mirror infrared telescope made by Robert Leighton at Cal Tech using exactly the method (spinning of epoxy) that Wood suggested. I don't know whether or not Leighton had read Woods' paper, but it provides an interesting example of applying new capabilities to an old problem.

Finally, let me describe some other, somewhat different, telescopes that I have been personally involved with. The first (slide 13) is a telescope that Paul Harvey, a student of mine at Wesleyan University, built as his senior thesis project. For this telescope, we took a piece of super insulation (thin aluminized mylar, about 4 mils thick), stretched it over a 36 inch diameter drum head (that's the biggest we could make with the lathe we had), pulled it tight, and then let a vacuum pull it into a bowl shape. The resultant figure is too flat in the middle -- rather than being a parabola or a sphere, it is an oblate-spheroid. The next slide (slide 14) shows the back and the tensioning attachments. We saw this "bubble-mirror" as a way of making very, very thin and lightweight mirrors; in our case the mirror itself weighed less than 2 ounces per square meter. And though the total structure clearly weighed more, one could, in principle, use such a thin film design, for example, in space to construct very large collecting optics in this fashion.

The next slide (slide 15) shows what we did to correct its figure. We put circular pieces of fiber-board just behind the mirror surface, coated them with conducting paint, and then put high voltages (500-2000 V) on them. Electrostatics, used in this way, provided enough force to actually reshape (tune) the surface of the mirror, thereby permitting us to correct it. The resulting mirror formed an image of a point source which was 30 seconds f arc in diameter. The image quality was not limited by any problems with the radially symmetric electrostatic tuning but by the 20% random thickness variations of the mylar which gave rise to local (and without the ability for local tuning, uncorrectable) "dimples" in the mirror surface.

This next slide (slide 16) shows one other kind of "thin-film" telescope that I worked on. This was another senior thesis project which was done the following year by Mike Sulzer. Mike happened to have a machine shop in the basement of his home and made this 47 inch diameter telescope. The next slide (slide 17) is another view. The idea here is that instead of one giant lens, a lot of smaller lenses are used. The light that comes through all the lenses, is collected and combined at a final focus. The "mirror" thickness is then dictated by the thickness of the individual lenses not by the diameter of the whole apparatus. This was the origin of the idea for the telescope I'll talk about next.

This, (slide 18) as you can see, is the framework for a somewhat larger telescope of this type. The next slide (slide 19) shows the base which was designed to set this structure on. It provides, just as in the case of Herschel's telescope, an elevation-azimuth control. The lead bricks, borrowed from the CU cyclotron, simulated the weight of the telescope. [There was no room in JILA big enough to allow me to assemble the two parts of this telescope.]

The next slide (slide 20) shows an optical schematic of the instrument. The optics involved merits some careful study. You have 80 7.5-inch-diameter lenses. Notice how thin this apparent "mirror" is. It weighs half as much as Herschel's too thin (48 inch diameter) mirror and yet it is almost twice the diameter. Why does it work? Because its aspect ratio (diameter-to-thickness) is dictated by the diameter of the individual lenses rather than by the diameter of the entire front plate. You might ask, "Aren't you going to create an image?" Actually you can, but for a great number of problems, astronomers look at "point" sources in which case you don't need to have a field, all you need is aperture.

Referring to the overall optical schematic, we see that after being collected by the initial 7.5 inch f/10 lens, the incoming light passes through an initial diaphragm (pinhole) which is 0.004 inches (100 μm) in diameter. This corresponds to a field diameter of approximately 11 seconds of arc. Each of these individual pinholes is mechanically co-registered and "referenced" to look at the same 11 seconds of arc in the sky. This is accomplished to essentially a second of arc accuracy by setting the instrument in a vertical position and auto-collimating each of the lens-pinhole combinations to a mercury reference table. This involves mechanically moving the individual pinhole assemblies in the horizontal plane of the back plate until they are correctly positioned. They are then secured in place.

Behind this initial pinhole the emerging f/10 cone of light passes through a smaller diameter lens of focal length 3 7/8 inches (9.8 cm). This smaller lens is part of a movable assembly that includes the pinhole and the lens at each end of a tube arrangement which translates axially using a ball slide bushing to permit focusing of different colors. The total movement possible with these assemblies is approximately 3/4 inch (1.9 cm). To achieve this, it is necessary to have a high degree of perpendicularity of the focusing mechanism with respect to the back plate. Also, the assembly must have essentially no mechanical play, otherwise the pinholes would sag depending on the orientation of the telescope at any given instant. To achieve this in-and-out focusing, all of the assemblies within a given 60° section are linked together and motor driven with cams in the shape of Archimedes spirals. This conveniently serves to convert angular motion into uniform linear motion. The focal requirements of the smaller lens, which is used to make the light parallel following this 11 seconds of arc pinhole, are necessarily less than those of the large initial lens (because of their smaller diameter), and hence do not require any adjustment with color. Emerging from this small lens is a parallel beam of light approximately 0.4 inches (1 cm) in diameter. This in turn reflects off two of the 160 small front-surface mirrors (two for each of the lenses in the front-face array) which are in this back plane area. Each small mirror is high-efficiency coated for the visible range of the spectrum. The center configuration of 80 mirrors gives the appearance of a cake covered with candles. The diameter of this cluster of 80 mirrors is only 6 inches. The group of parallel pencils of light that emerges from this central array of mirrors is focused by a 6-inch (15-cm) diameter f/5 lens onto a common pinhole.

The individual central mirrors can be finely adjusted about their axes of rotation, but only roughly adjusted in tilt. The mirrors farther from the center are finely adjustable in all coordinates. It is important to note that in this back plane area, where one has introduced reflecting elements, the beam diameter is smaller by a factor of 20 and therefore all angular sensitivities are less critical by exactly the same amount. In other words the stability requirements of this back-plate assembly are more nearly at the minute of arc level than at the second of arc level!

The pinhole at the final focus is, in fact, not one but a series of pinholes fixed onto an accurately registering wheel which can be rotated on electrical command to permit the field to be selected. The available field ranges, in five steps, from the full 11 seconds of arc down to about 3 seconds of arc.

The process of registering all of the initial pinholes onto the final common pinhole, while avoiding vignetting of the in-between rays, is straightforward and systematic but somewhat time consuming (2 days -- once one learns how). The essential requirement, however, is that once tuned they must stay tuned. Just as a multi-stringed instrument must stay tuned throughout a performance, so must all these multi-mirrored adjustments. Experience to date seems to indicate that this instrument, once tuned, stays tuned for performances of one-half year or longer.

One final important point on the overall optical scheme is that although it was conceived as an instrument with aperture but not field, the insertion of dove prisms (image rotators) in the parallel rear image plane rays would permit proper overlaying of the images up to the order of 120 seconds or 2 minutes in diameter while still maintaining a 1 second of arc image resolution quality. The field limit is set by the inequality in focal lengths of the various sets of lenses. Because the insertion of this type of prism involves only transmission optics, the mechanical problems associated with such an image restoration would be essentially trivial and had I thought of this possibility at the outset, it certainly would have been done.

Finally, I must confess that it took much longer to construct this telescope than I had ever imagined it would. You may not know that in the U.S., if you go to dinner in a Chinese restaurant, at the end of your meal you receive two things -- one is the bill and the other is a "fortune cookie" -- a little rice cookie with a piece of paper inside on which is printed a saying or prediction. The next slide (slide 21) shows one such "fortune" that was found pinned to the telescope one day. Eventually, however, and at long last, the project was completed and the big moving day arrived. The next slide shows the long-awaited birth announcement which I sent out as the telescope was enroute from Boulder to Hawaii (to be placed at the top of Mt. Haleakala).

The next slide (slide 22) shows the inside rear end of the telescope. The process of bringing all the light beams together, focusing them, and so on, extracts a fairly high price (as you can see) in mechanical complexity. The next slide (slide 23) shows the backside of the rear plate of the telescope with all the small steering mirrors in evidence. And finally the last slide (slide 24) shows what the completed instrument looks like.

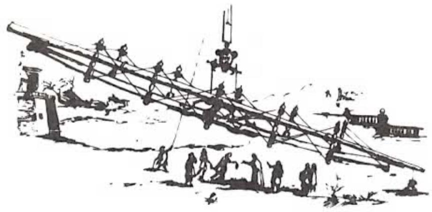
What I've tried to show you is that as telescopes have evolved from smaller to bigger, the attendant larger gravity or body forces have forced us to find different ways to build them. As a physicist, I was lucky to have the chance to make a telescope that was somewhat different. New ideas, as the fortune cooking saying suggested, always involve some risks. On the other hand, they also provide the only alternative to the brute force approach of simply making things bigger and bigger. Thank you very much for your kind attention.

GALILEO S TELESCOPE OLD DISCOVERER

Represented his best glass grinding and polishing efforts from which he discovered 4 satellites of Jupiter

1610

(1)

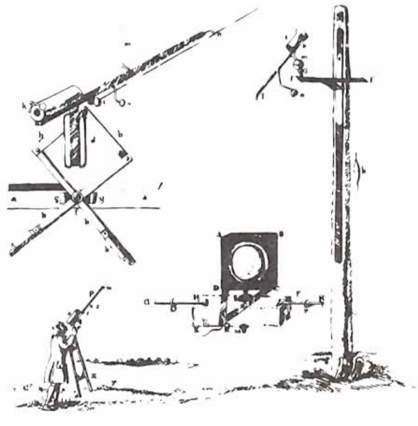


THE LONG FOCUS TELESCOPE OF HEVELIUS

Chromatic aberration obstacles were lessened with increased focal length (158 feet)

1660

(2)



THE AERIAL TELESCOPE OF HUYGHENS

Long focal lengths were also obtained by mounting the objective on a building roof and holding the eyepiece in hand

1660

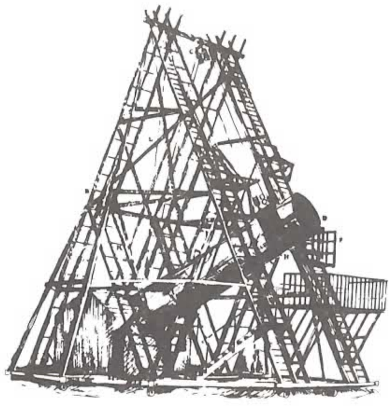
(3)

NEWTON'S FIRST REFLECTOR

The first practical use of the astronomical reflector had a 1.4 inch primary mirror

1671

(4)



48 INCH REFLECTOR OF HERSCHEL

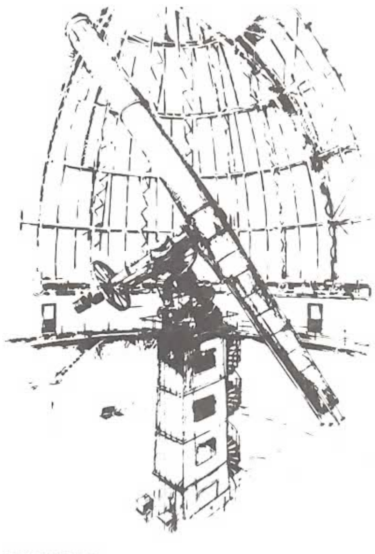
The astronomical reflector began to flourish in this period.

1789

(5)

A kitten seems to enjoy being carried around (in the mouth of its mother) by the scruff of its neck. If, however, one lifts a grown cat in exactly the same fashion, loud cries of dismay will be heard. Suggest a reason (other than psychological) for the difference in these two situations - You may wish to include in your answer some very simple arithmetic.

(6)



40 INCH YERKES

The largest astronomical refracting telescope resulted from new developments in glass technology.

1897

(7)

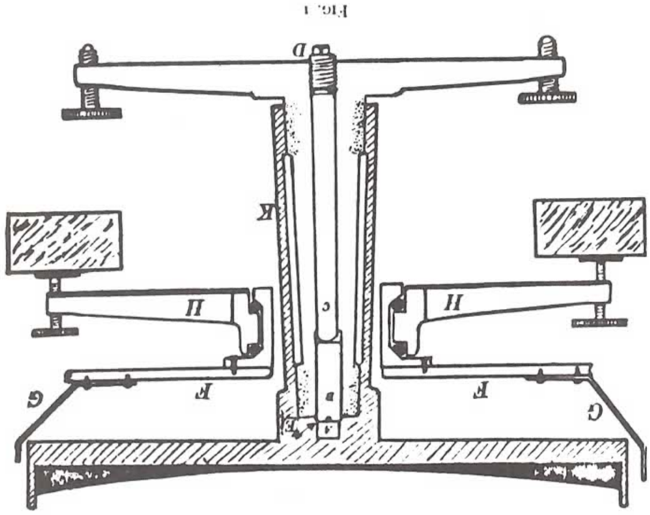
200 INCH HALE TELESCOPE

The world's largest completed ground-based telescope began operation in 1948 and significantly expanded astronomical research through its 200 inch aperture.

1949

(8)

(9)



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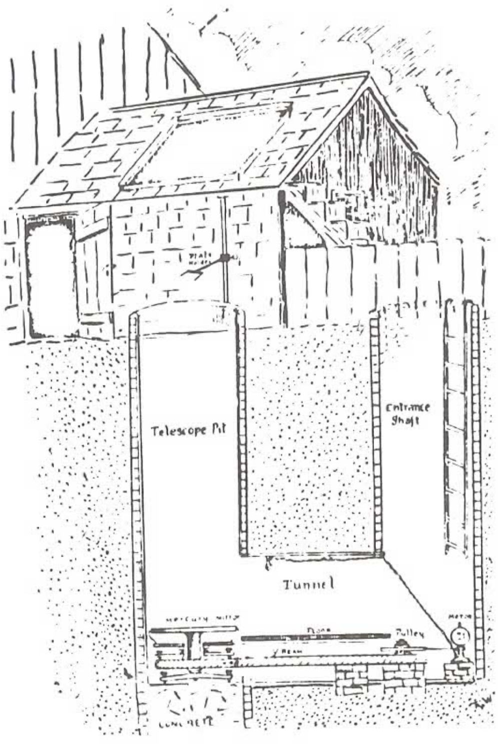

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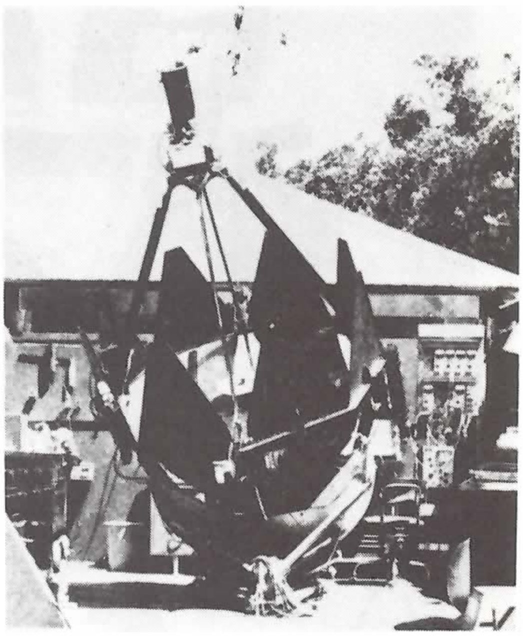

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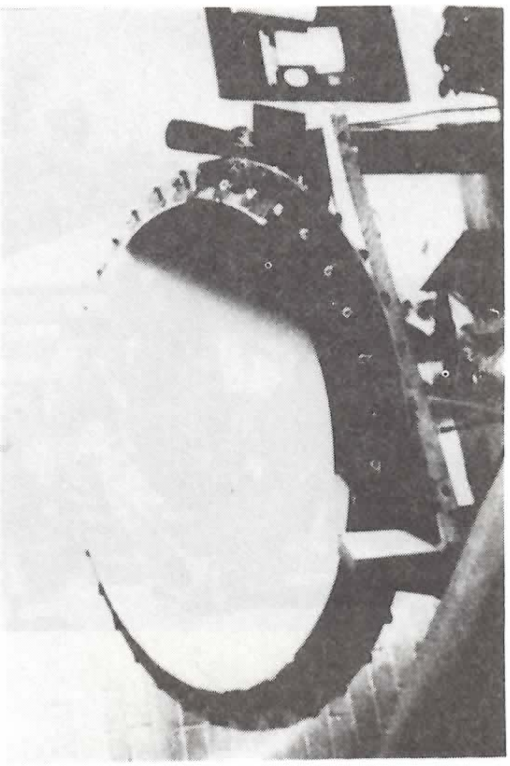

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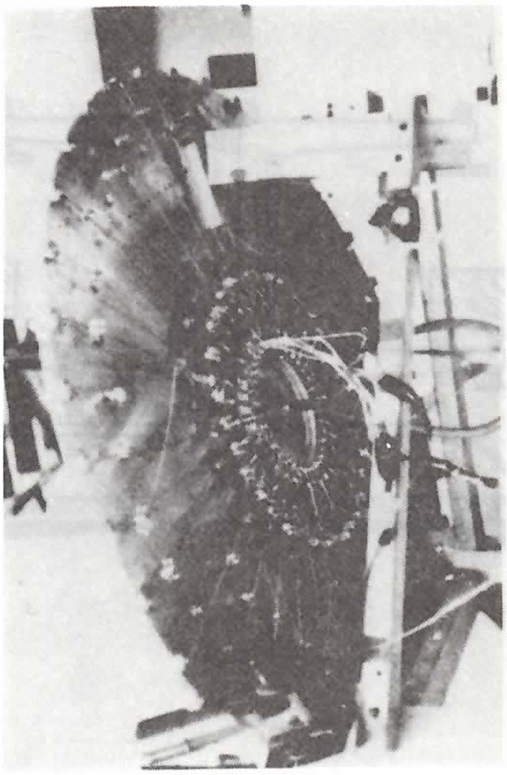

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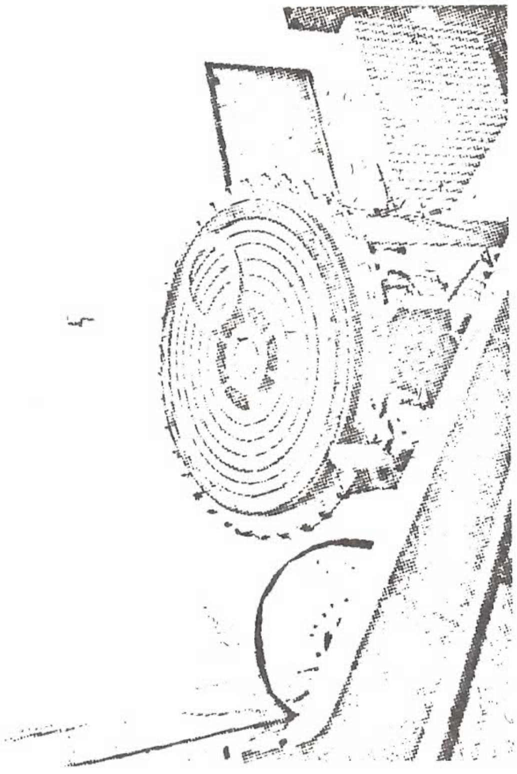

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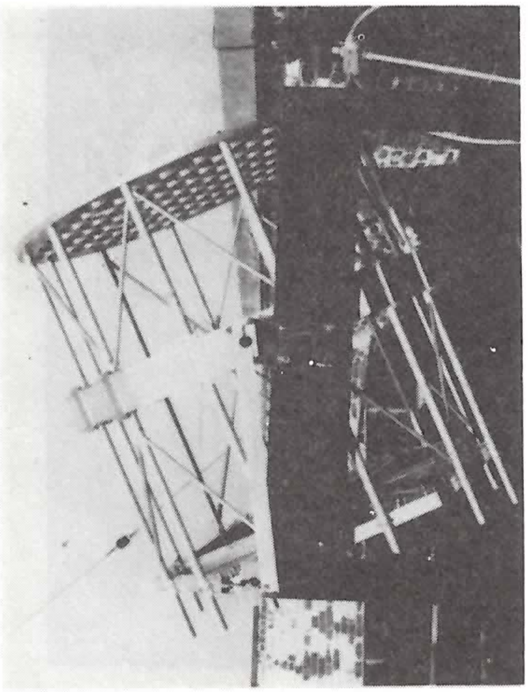

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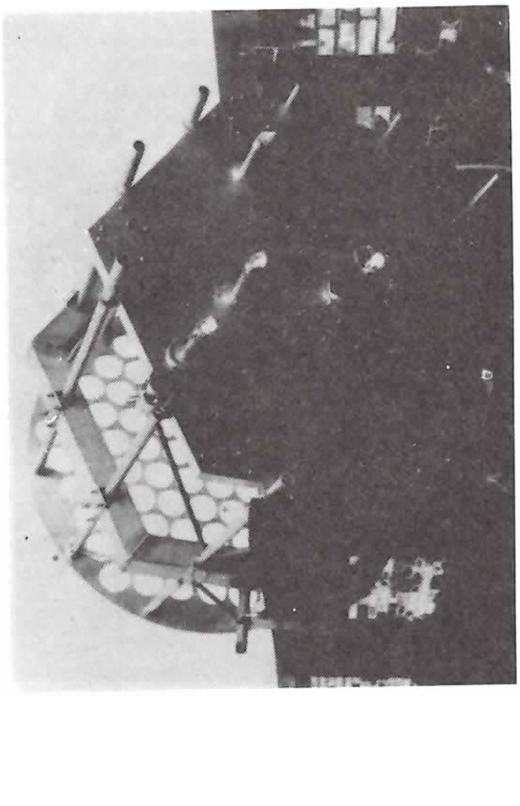

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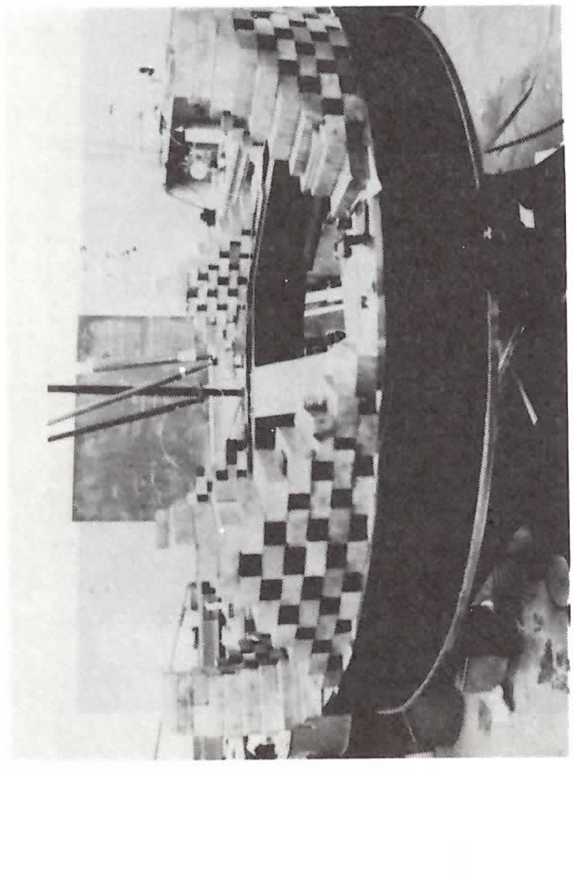
(18)



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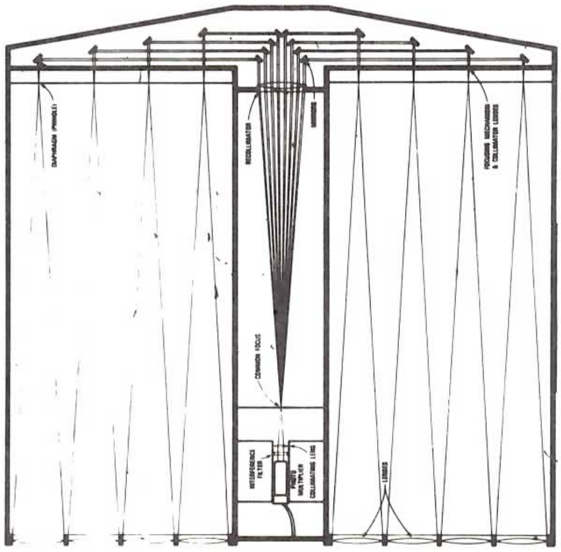


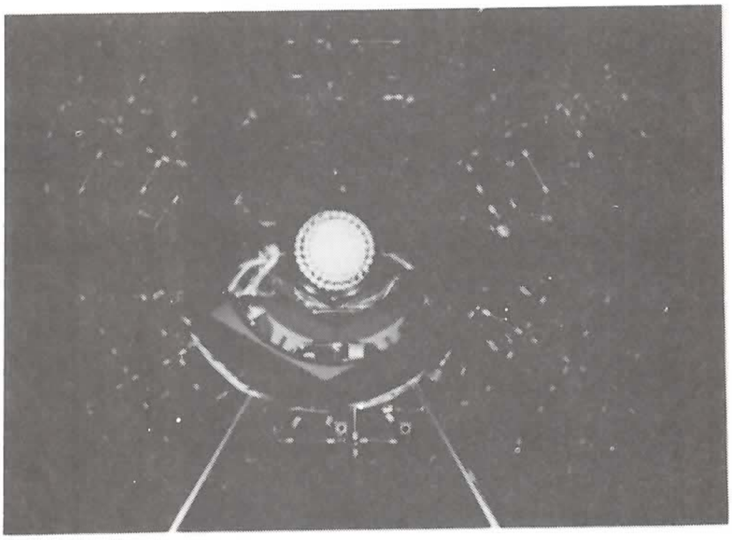
(20)

CHINESE FORTUNE COOKIE

saying:

Don't speculate in new ideas
at the cost of your reputation.

(21)



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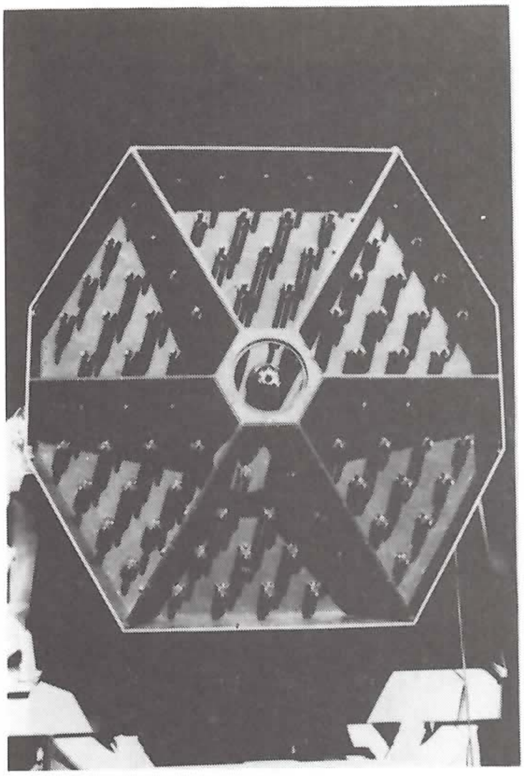

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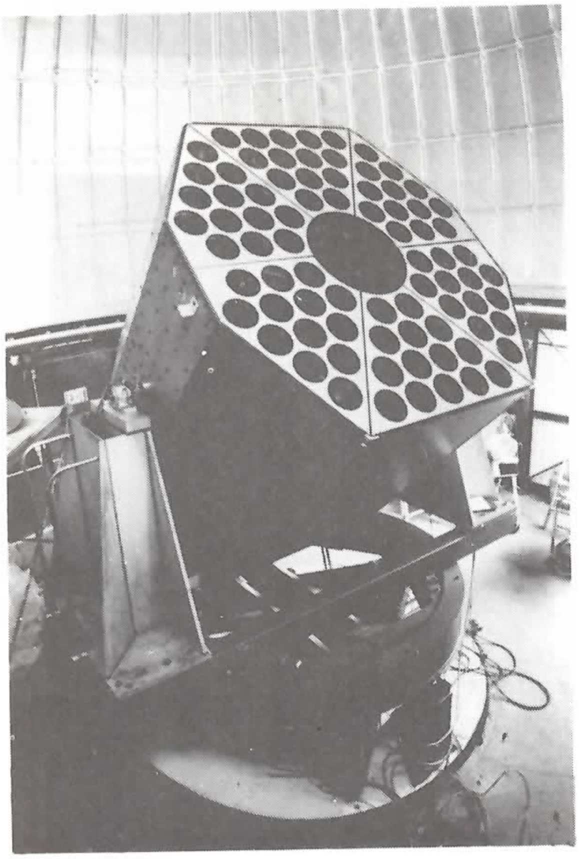

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