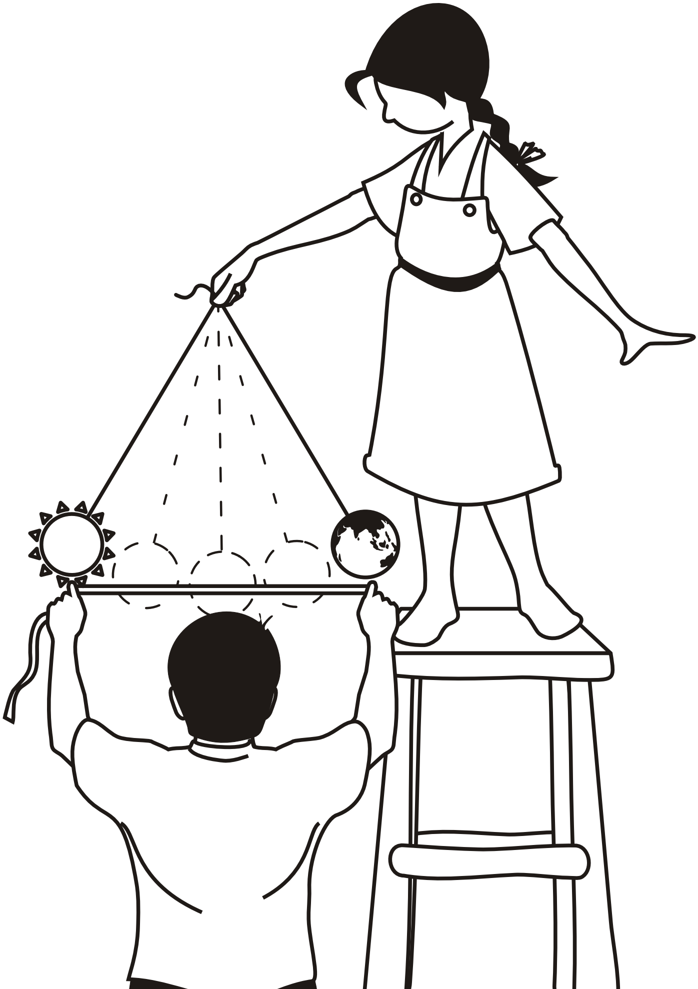
MEASURING THE UNIVERSE WITH A STRING AND A STONE

Transit of Venus Experiment 2004

Dr. Vivek Monteiro



MEASURING THE UNIVERSE WITH A STRING AND A STONE

Dr. Vivek C. Monteiro,

On June 8, 2004, the transit of Venus will be visible from most parts of the world. The entire transit will be visible from India. Occurring after 121 years, there is nobody alive today who has witnessed a TOV. None occurred in the entire twentieth century.

In the history of science, the TOV occupies an important place because it was the first time in human history when the astronomical unit (AU), the distance of the Sun from Earth, was measured with reasonable accuracy. Measuring the astronomical unit was the missing link in the edifice of Newton's Solar System. This was first done in 1761. The distance of the Sun was something that Newton and Galileo did not know.

That TOV can be used to measure the AU was proposed in a paper by Edmund Halley. Halley could not implement his proposal, because no TOV occurred in his lifetime. Halley's method involves some delicate measurements and fairly arduous spherical trigonometrical calculations. With one simplifying assumption, however, the measurement of the AU becomes so simple that any eighth standard school student can do it. This gives rise to the possibility of a mass scientific experiment involving millions of school students all over the world, because the TOV will be seen by 90 % of humanity.

In the following article, the series of activities for this mass scientific experiment is outlined in a form that can be used by any school teacher or high school student.

All the illustrations are by Russel Gonsalves.

Measuring the UNIVERSE with a STRING and a STONE.

In the third century BC a Greek scientist Eratosthenes first measured the size of the Earth. This was undoubtedly one of the ten greatest scientific experiments of entire history. However, it appears that Eratosthenes did not discover the method he used. It was discovered two hundred years earlier by a man named Anaxagorus, who was trying something else, something bigger, something far more ambitious .

Anaxagorus lived at a time when the Greeks were beginning to systematize geometry. As everybody knows, Geometry arose from measuring land.

Anaxagorus had the crazy idea of putting together Geometry and Astronomy to measure the universe. He wanted to obtain both the distance of the Sun from Earth, and its size. He got an answer of about 6500 kilometers for the Sun's distance, and about 60 kilometers for the size of the Sun. So sure was he of his calculations that he was willing to pay the heavy personal price of banishment for standing by his predictions.

Both his answers were wrong, of course. There was no error in Anaxagorus calculations. The only mistake was in one of his assumptions. Anaxagorus assumed the world was flat.
Though he was wrong , he had obtained the right answer to a different question- the question answered by Eratosthenes two hundred years later? - **"How big is the Earth ?**

Eratosthenes put in the right assumption - that the Earth was a sphere, and deduced that 6500 kilometers was not the distance of the Sun, but the radius of the Earth.

How far is the Sun ?

This question remained a mystery for thousands of years till the 18th century and beat the best minds. Even the great Galileo and Newton did not know the answer to this basic question. But Anaxagorus was right in one important point. He had discovered that the Sun is approximately 110 times as far as it is big. He may have been wrong, but what he had done was among the greatest of great breakthroughs in science.

An Extraordinary Possibility

Nobody can taste science merely by reading books. The only way to taste science is to do it. The thrill of discovery is even sweeter than the joy of doing . **The year 2004 offers us an extraordinary possibility** : Every child in school who knows eighth standard mathematics will be able to do and understand for himself / herself two of the ten greatest scientific experiments of human history to answer the following questions.

- **How big is the Earth ?**
- **How far is the Sun ?**
- **How big is the Sun?**

To answer the first question, we will have to observe the beautiful sight of the Sun setting into the ocean on a clear day at a beach on the west coast of India.

To answer the second and third question, we will have to observe the Sun on a very special day : the **8th of June 2004** . On that day will occur the extremely rare ***Transit of Venus***.

Between now and June 8, 2004 we will have to do a few more simple experiments. To do these great experiments in science we will not need any fancy expensive apparatus. We will need a string and a stone, a pocket mirror and a watch. But if we don't have a watch it doesn't really matter. We can make one with a string and a stone. And we will have to learn a little mathematics as follows :

1. What is an angle? How can we measure angles with a string and stone?.
2. What is a ratio of two numbers?
3. The sum of the angles of a triangle is always the same.
4. Similar triangles and their properties.
5. How to deal with large numbers?
6. The importance of approximation.
7. Pythagorus theorem.

We measure the universe by measuring angles, lengths and time intervals with the string and the stone. That’s all. That’s how simple it is.

> “Simplicity is the Essence of Generality”
>
> -M.K. Gandhi

What we can measure with a string and a stone

1. We can measure lengths.
2. We can measure angles.
3. We can measure Time.

1. We can measure lengths.

Take a one-meter length of string and use it as your measuring instrument. You can divide it into one hundred equal parts and use it to measure length in centimeters.

2. We can measure angles

Fig 1

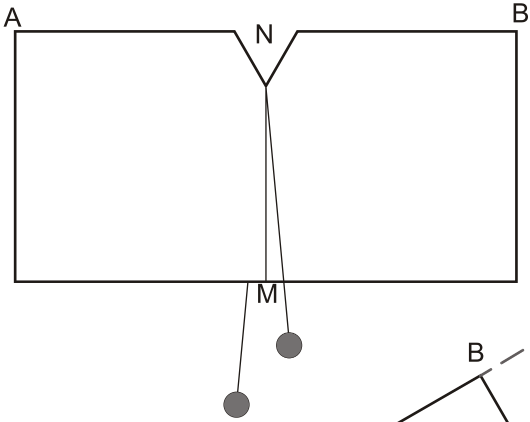
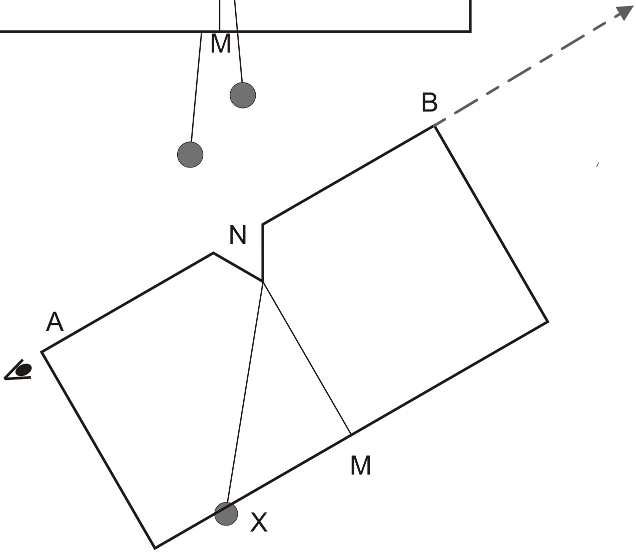


Fig 2



We can make an **angle dangle meter.**

I) Take a piece of string about a meter long. Tie two small stones at each end.

ii) Take a rectangular piece of stiff cardboard. Make a notch in one edge, near the middle. Hang the string from the notch so that the two stones dangle on either side of the card. This is your angle-dangle meter.

iii) At the notch, draw the perpendicular NM (**Fig-1**)

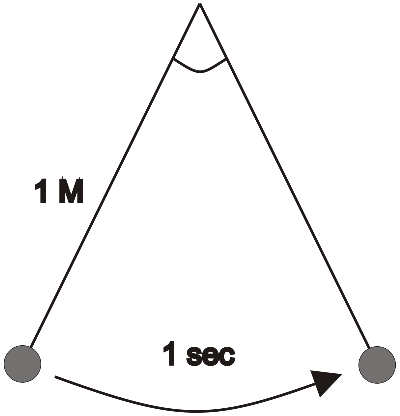
iv) To measure the angle of a star, or the angle of the top of a distant tower, hold A near to the eye, and hold the cardboard on that A,B and the star are all in a straight line, along the line of sight. (**Fig. 2**)

V) In this position, the stone on the string hangs down NX. Measure the angle XNM. This is the angle of the star with the horizontal.

3. We can measure Time

We can construct a one second pendulum with a one meter string with a stone. A one meter pendulum takes about one second swing from one side to the other. (**Fig.3**)

(**Fig.3**)



A) To measure how far the Sun is from us.

Here is how you can measure the Sun's distance from the Earth in a series of a few easy experiments which you can easily do by yourself

Step 1 - The Sun card.

Step 2 - TOV photograph.

Step 3 - Measuring the maximum angle between Venus & the Sun.

Step 4 - The ratio of the Sun - Venus distance to Sun - Earth distance.

Step 5 - How big is Venus?

Step 6 - How big is the Earth?

Step 7 - How high is the building?

B) How to build your own solar observatory.

1. Imaging the Sun with a Pinhole Mirror Camera
2. Imaging the Sun with a very long focal length Convex Lens
3. Imaging the Sun with a Telescope

Step 1 - The Sun card..

1.1 Take a card which can be of the size of a post card. Punch a small hole near the centre of the card with a paper punch. Also punch a slightly larger hole in the card at some distance from the first hole.

Hold the card in direct sunlight, so that it casts a shadow on the ground. Increase the height of the card and observe the shadow. You will observe two circular images of the Sun within the shadow.

1.2 Observe what happens to the images as you increase or decrease the distance between the card and the screen (ground).

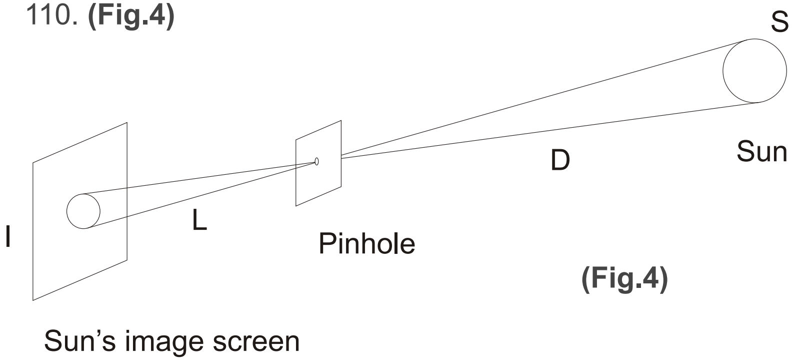
a. As the distance increases or decreases, the sizes of the circular images increase and decrease.

b. At any given distance, both the images are approximately the same size.

c. One image is brighter than the other, but both are approximately the same size.

1.3 Measure with a centimeter scale the diameter '**I**' of the circular image. Also measure the distance '**L**' between the card and the screen . Divide **L** by **I**. You will get a number which is approximately 100 (more accurately, about 110).

1.4 You can measure I and L for different distances. Then both I and L will change. However, the number which you get when you divide L by I will not change. It will always be approximately 110. Look at the shade of a tall tree. Within this shade you will see circles of light. Measure the diameter of the largest circle, divide this number by the height of the tree. You will get an answer of approximately 110. **(Fig.4)**



(Fig.4)

$$L / I = S / D = 110$$

In a pinhole camera the ratio **L/I** is equal to **S/D** where **D** is the diameter of the Sun and **S** is its distance. Since **S/D** is constant, therefore **L/I** is always the same i.e. **110.**

1.5 This number is the first hint of the Sun's distance. It tells us that the Sun's distance is approximately 110 times the Sun's diameter. But what is the diameter of the Sun? We will learn about this in the experiments to follow.

1.6 For now , we have the following result :

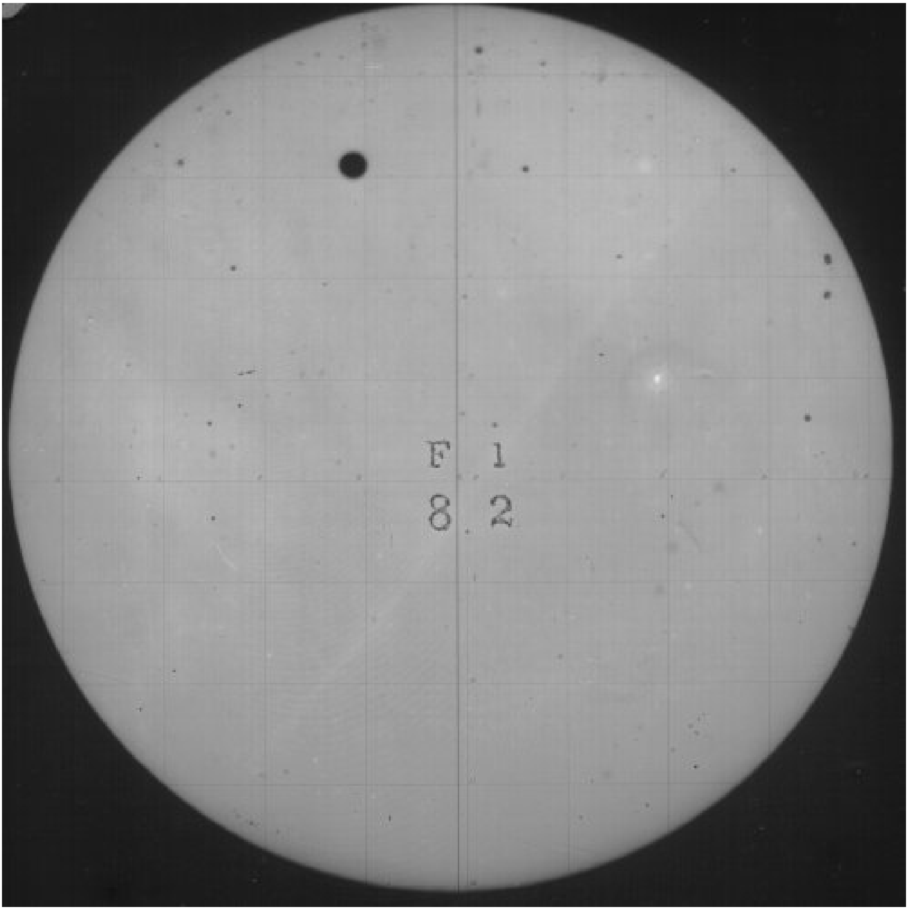
Distance of Sun = 110 x diameter of Sun

1.7 What is the diameter of the Sun? The Transit of Venus gives us an opportunity to measure the diameter of the Sun. It tells us **"<u>How Big is the Sun?</u>".** Here is how you can do it yourself.

Step 2 - TOV photograph.

2.1 Later in this article we will outline different ways of imaging the Sun. If we image the Sun on the day of Venus Transit, what we will see is something like the photograph shown here. The photograph below, of Venus transiting the Sun, was taken in 1882, more than 120 years back. On the bright background of the Sun, you can see the small dark disc of the planet Venus.

Fig 5



2.2 Measure as accurately as possible, the diameter '**D**' of the Sun in the image.

2.3 Measure as accurately as possible the diameter '**V**' of Venus in the image.

2.4 Divide **D** by **V**, you will get a number which is approximately equal to **33.**

2.5 But we must not forget that in the photograph , Venus, relative to the Sun, is appearing bigger than it really is . This is because, during a transit of Venus, Venus is much closer to us than the Sun. We are not seeing two objects which are at the same distance from us. The nearer object appears larger. (See 2.6 also). How much larger is Venus appearing?

2.6 (We know that the moon is much smaller than the Sun. But it appears to be the same size as the Sun due to the fact that it is nearer to us. There are innumerable instances of a nearer object appearing larger because of its proximity. The solar eclipse is due to this effect.)

2.7 We can calculate this from the next experiment, which involves measuring the maximum angle between the Sun and Venus as seen from the Earth. We measure this angle at different times of the year. The maximum angle will occur towards the end of March 2004. The maximum angle between the Sun and Venus is about 45º (precisely 47º). By a simple calculation, which is given in Step 4. We deduce that Venus at the time of transit, is approximately three and half times closer to us than the Sun.

Because of this, Venus appears approximately about three and a half times (more accurately 3.4 times) larger than it really is relative to the Sun.

2.8 We must now multiply 33 by 3.4. We get 112. This means that the Suns diameter is really about 112 times the diameter of Venus. So we now need to know the diameter of Venus. But **what is the diameter of Venus ?** Before we come to this question, let us understand a little better the subject matter of point 2.7 above.

2.9 Note also that we now have a simple formula for the Sun's distance :

Sun's distance = 110 x Sun's diameter
= 110 x 112 x Diameter of Venus.

Step 3 - Measuring the maximum angle between Venus & the Sun.

As the Earth and Venus go around the Sun, the relative position of Venus with respect to the Sun changes. At certain times of the year, Venus is a morning star, being visible before the Sun rises. In other months it is an evening star. From September 18th 2003 Venus will appear as an evening star.

3.1 We measure the angle which Venus makes with the horizon at the moment when the Sun sets. This angle will increase from September to the end of March. Each day, when the Sun sets Venus will appear higher in the sky.

3.2 We can measure the angle directly with our angle-dangle meter. It turns out to be approximately **45 degrees** , towards the end of March 2004.

3.3 Another way to measure the angle is to measure the time between the setting of the Sun and the setting of Venus. The maximum time turns out to be approximately three hours.

3.4 Since the Earth rotates once in 24 hours, the stars and the Sun appear to move through an angle of 360 degrees in 24 hours. They appear to move through 15 degrees (360 degrees divided by 24 hours) in one hour. The maximum three hours time difference between the two setting times means that the maximum angle between the Sun and Venus is approximately 45 degrees

3.5 From these measurements, and a few plausible assumptions, (like the assumption that the Earth and Venus go around the Sun in circles with the Sun at the center), we can calculate that the Sun - Venus and the Sun - Earth distance are approximately in the ratio **1 : 1.414.**
(See Step 4)

3.6 What this means is that at the time of transit the Earth-Venus distance and the Sun Earth distance are in the ratio **0.414 : 1.414**. From the properties of similar triangles we calculate that Venus appears to be magnified by a factor of **1.414/0.414**, which is approximately **3.4.**

Step 4 - The ratio of the Sun - Venus distance to Sun - Earth distance.

Fig 6

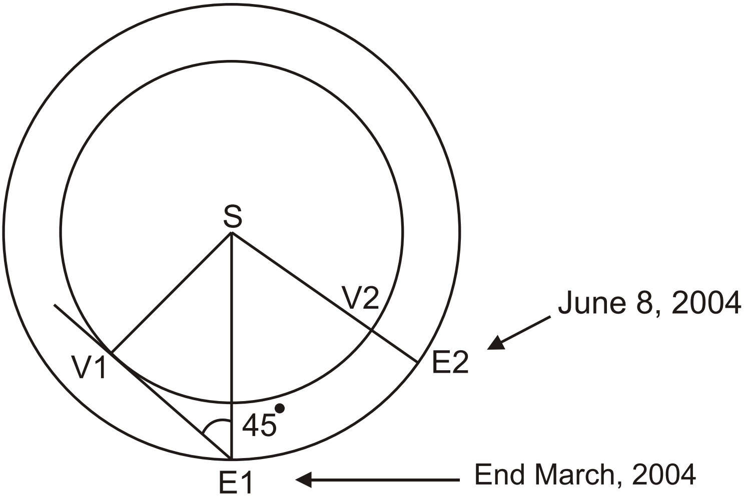
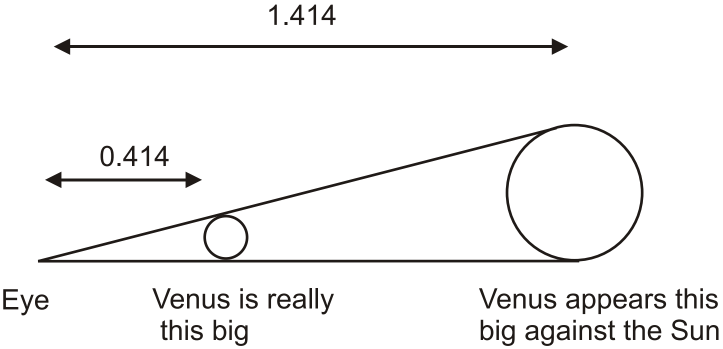


Fig 7



We assume that Venus And Earth both go around the Sun in circles with the Sun at center.

4.1 Venus moves in a circle around the Sun - the inner circle.

4.2 Earth also moves in a circle around the Sun - the outer circle.

4.3 The angle **VES** is what we observe. It is the angle made by Venus above the horizon as the Sun sets.**(Fig6)**

4.4 Note that this angle is maximum when **EV** is tangent to the circular orbit of Venus. At this juncture SV, is also at right angles to E_1V_1 because the radius of a circle is perpendicular to the tangent.

4.5 Since for Venus this maximum angle is approximately 45º, **V_1S / E_1S = 1/ sqrt(2) =1/1.414**

4.6 **V_1S / E_1S = V_2S / E_2S**

4.7 Therefore at the transit of Venus, when Venus is at V_2, and Earth is at E_2 then

V_2S / E_2S=1/1.414

Also E_2V_2 / E_2S = **0.414 /1.414 = 1 / 3.4**

4.8 In other words, at Transit, Venus is 3.4 times nearer to us than the Sun. It therefore appears 3.4 times larger than its real size relative to the Sun. (**Fig.7)**

Step 5 - How big is the Venus?

5.1 We have arrived at the formula:

Distance of the Sun = 110 x 112 x Diameter of Venus.

How big is Venus?

5.2 We answer this question by making a rather big assumption: That Venus, being a planet like the Earth, is approximately the same size as the Earth. You may question this assumption, and rightfully so. Why have we made this rather large assumption? Basically to have a method for measuring the Earth Sun distance that any child can do. We make the assumption in the interest of simplicity

5.3 But Venus may not be the same size as the Earth, you may protest. Justifiably. What we will get in that case is only a very rough idea of how far the Sun is from us. But in fact, the assumption we have made is luckily pretty good. Venus **is as big as the Earth** within a margin of less than 10 percent!

5.4 So, if Venus is as big as the Earth, to get the diameter of Venus, we must only measure the diameter of the Earth.

5.5 Because we have assumed that Venus and the Earth are the same size, we have the following formula :

Distance of the Sun = 110 x 112 x diameter of the Earth

5.6 We now need to find out how big is the Earth to complete our calculation

Step 6 - How big is the Earth?

6.1 We could do it by the method used by Eratosthenes, but there is a simpler method

6.2 Go to a beach on the west coast of your country where you can see the Sun dipping below the horizon into the sea at Sunset. Choose a beach with a tall building , or a high cliff, nearby. Do the following experiment with the help of a friend.

6.3 Your friend stands on the beach. You stand on top of the building on the terrace. Because you are at a height, you can see further.

6.4 Both of you watch the moment of the setting Sun. Because you can see further, you will continue to see the Sun even after it has dipped below the horizon for your friend on the beach.

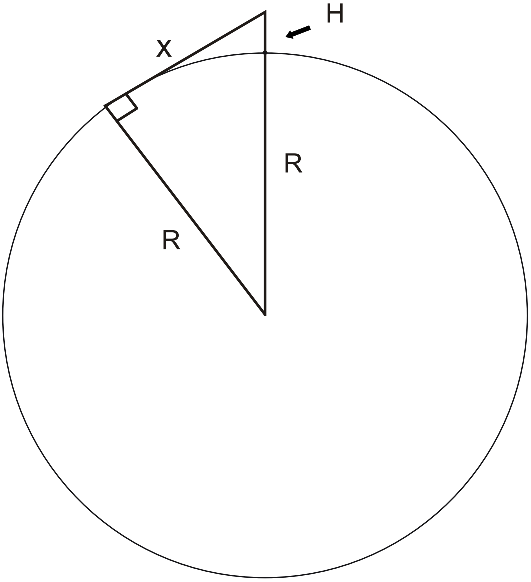
6.5 Your friend signals to you the moment when she sees the Sun dipping below the sea horizon. You measure the time between this moment and the moment when you see the Sun dipping below the horizon. You can measure the time with a stopwatch, or with your one second pendulum.

6.6 From a height **H**, how far can you see ? Lets call this distance **X**. You can calculate **X** from Pythagorus theorem . The answer is that you can see for a distance $\mathbf{X} = \sqrt{\mathbf{2 \times H \times R}}$, where **R** is the radius of the Earth. (See Box on next page)

6.7 Lets say that the time measured by you in step (5) above was half a minute. The ratio of 24 hours to half a minute is 2880.

6.8 This is also the ratio of the circumference of the Earth to $\mathbf{X}$

$$(2 \times pi \times R) / X = (24 \times 60) / (½) = 2880$$



$$X^2 + R^2 = (R+H)^2$$

$$= R^2 + 2RH + H^2$$

$$X^2 = 2RH + H^2$$

We can neglect H^2, which is small compared to 2RH

Therefore $X^2 = 2RH$

Or $X = \sqrt{2RH}$

6.9 From this we deduce that $\mathbf{X = (2 \times pi \times R) / 2880}$

Therefore, $\mathbf{X^2 = (4 \times pi^2 \times R^2) / (2880)^2 = 2HR}$

Therefore, $\mathbf{R = ((2880)^2 \times H) / 2\, pi^2}$

6.10 This gives us the radius of the Earth in terms of the height of the building. All that we have to do now is to measure the height of the building. How do you measure the height of a building with a string and a stone ?

6.11 In the above we assumed that the time difference was one half minute. In the actual measurement, lets say that it is $\mathbf{T}$ seconds. By the same kind of argument as in 6.8 above, we get

$$\mathbf{R=[((24 \times 60 \times 60)/T)^2] \times [H / (2 \times pi^2)]}$$

Step 7 - How high is the building?

Of course this is the easy part. We can measure the height of the building with a string or we can measure angles and use similar triangles. You walk a certain distance away from the building. You measure your distance from the building. From this position you measure the angle made by the terrace top using your angle dangle meter. Then you make a similar triangle on a piece of paper and measure the ratio of the height to the base. Use this ratio to calculate the height H of the building.

That's it. From the height H we calculate **R**. Once we have **R,** we use the formula :

Distance of Sun = 110 x 112 x R

B - How to build your own solar observatory.

Low cost/ No cost Solar Observatory

Astronomical observatories are built to observe and study the stars and galaxies in the universe. To study the stars and galaxies we need to use telescopes in order to gather and concentrate the faint light of these stars. This is because the stars are so distant from us.

The Sun is our nearest star. To study the Sun we do not need to gather and concentrate its light. On the contrary, we need to dilute the intensity of the light before we can comfortably observe the Sun. We can build a high power solar observatory which will give us images of the Sun with only a pocket mirror, a paper and a pencil.

Pocket Mirror
Pinhole Projector
Very Long Focal Convex lens
Telescope
Solar Filter

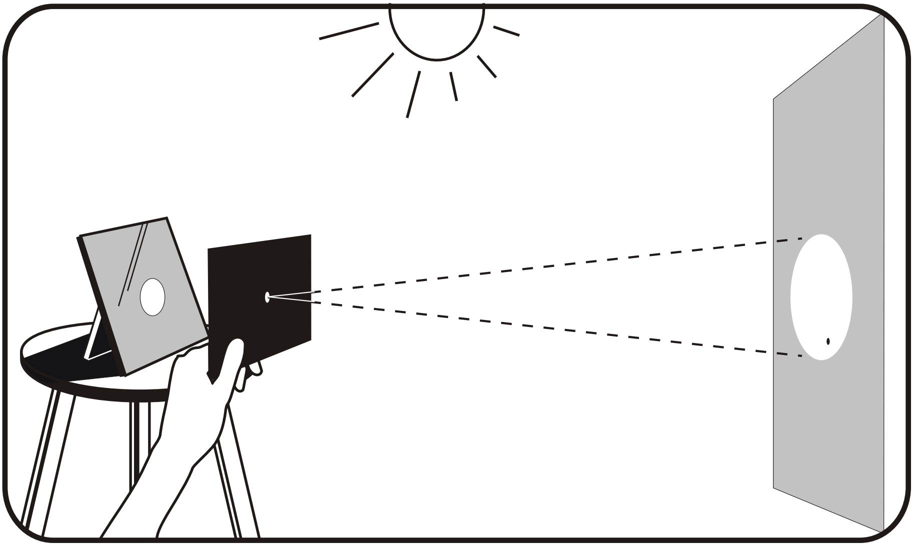
With just the above materials you can make your own Solar Observatory and image the Sun to observe the Transit of Venus.

(B.1) Imaging the Sun with a Pinhole Mirror Camrea

This is by far the simplest method to project the Sun's image, which works because the Sunlight intensity is so strong. This experiment can be done in any room which has a window or door opening outside, and which can be sufficiently darkened by putting cloth over the apertures from where light enters. Complete darkness is not necessary. Just how much darkness is needed you can discover for yourself by trial and error.

Take any available small mirror (like a face mirror selling on the footpath for Rs. 10) and keep it on a stool outside the room in a place where the Sun shines on it. Adjust the angle of the mirror so that the Sunlight is reflected in a bright patch on a wall of the darkened room. Increase the distance of the mirror so that it is about 30 meters from the wall. As you increase the distance the light patch will become more and more circular. This is the Sun's image with the mirror acting like a large 'pin hole'. At this stage the Sun's image will be bright and diffuse, i.e. not sharp.

Imaging the Sun with a Pocket Mirror



The next step is to take an opaque piece of card paper and punch a hole in it of around 2-3 mm diameter with an ordinary paper punch. Now hold the paper about 30 cm in front of the mirror so that the punched hole is in the center of the light patch, which now forms on the card paper. What happens to the image on the wall 30 meters away?

Surprisingly, the image does not decrease in size. It becomes dimmer and sharper. Cut off as much light as possible in the room (except of course the light coming from the mirror) so that the image looks clearer. Now keep a white piece of paper on the wall so that the image forms on this white screen. The method will give a big image of the Sun which around 30cm in diameter. During Transit, Venus will appear about 1cm in size on this image.

(B.2) Imaging the Sun with a Very Long Focal Length (VLFL) Convex Lens.

It is commonly believed that a convex lens concentrates the light from the Sun. This however is true only if the focal length is not too large. As the focal length of the lens increases the size of the Sun's image increases. For a very long focal length (VLFL), the diameter of the Sun's image did can be quite large, larger than the lens itself. (In a pinhole camera also, the size of the image depends on the distance of the screen from the pinhole).

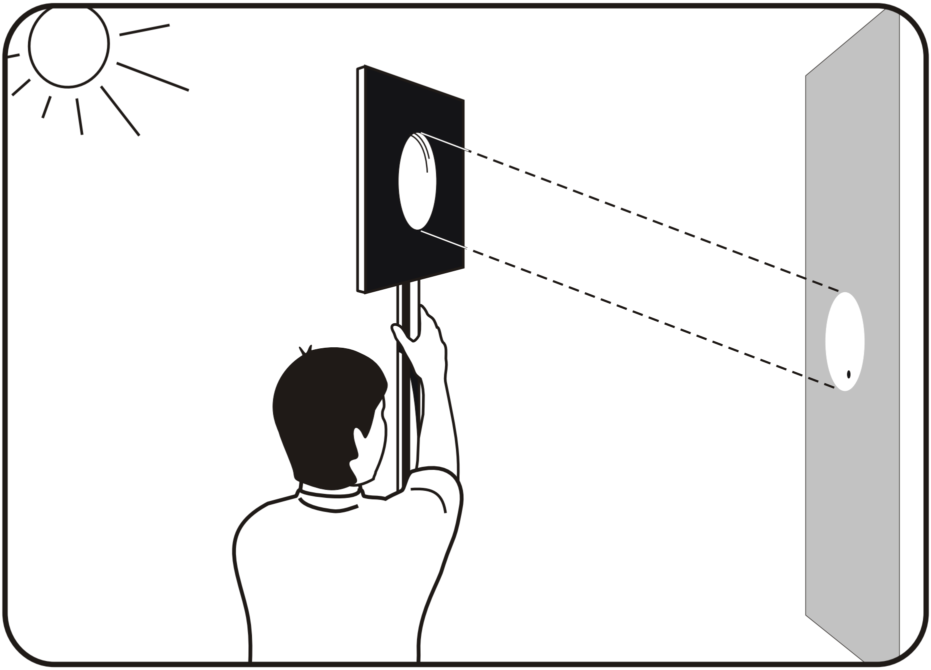
In general the following formula is true :

$$\textbf{(Diameter of the Sun's image disc) / (2 x pi x f) = } \frac{\textbf{(½ degree)}}{\textbf{(360 degrees)}}$$

(This is because the Sun subtends an angle of about ½ degree at the Earth.) From this we deduce :

Diameter of the Sun's image (in cm) = 2 x pi x 1/ 720 x focal length of the lens in cm.

Imaging the Sun with a very long Focal Length Convex Lens



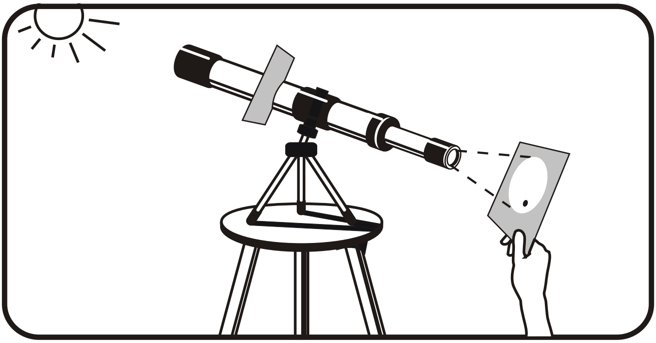
For a 50 mm diameter lens with a focal length of 6 meters, the image of the Sun will be larger than the lens itself, showing that a convex lens doesn't necessarily concentrate light. Using a **VLFL** convex lens, along with a cardboard shade with a hole cut in the center (see **fig**), you can get a nice big image of the Sun on which is clearly visible, if the lens is of reasonably good quality.

Where can you get a good quality **VLFL** convex lens? These are not easily available in toyshops selling lenses as the focal lengths available these are usually much smaller. But from your local optician it should be possible to get a lens ground with number + 0.25". This lens will have a focal length of around 4 meters, which should be good enough.

B.3 Imaging the Sun with Telescope

You can make a simple telescope with which to project Sun' image. Though you can look directly at the Sun through the telescope **with a proper filter**, we do not recommend this method as most common filters are not safe, and a telescope concentrates light making eye damage more likely.

A simple telescope can be made with only two lenses. The front lens (objective) has long focal length (about 1 meter is ideal), and the eyepiece should have a short focal length of around 5 cm or less. You will also require one long tube (1 meter), and one short tube which slides inside the longer tube with some packing. (see **fig.**)



The magnifying power of the telescope is given by the following formula:

(Focal length of the object / Focal length of eyepiece)

i.e. for 1 meter and 5 cm., the magnification is 20. The telescope can be used for projecting Sun's image as shown in the figure. The advantage of this method that with good lenses you can get excellent resolution and study some details of the Sun's image.

The following kits are available from Navnirmiti

1 **SOLAR FILTERS FOR VIEWING TRANSIT OF VENUS.**
Navnirmiti's Solar filter conform to international safety standard and have an optical density of 5. These filters are safe for viewing the Sun and reduce the intensity of light by a factor of 100,000.

These filters are priced at Rs. 5/-

For more than 100, they are priced at Rs 3.50 each. For more than 10,000 they are priced at Rs.2.50 **each.**

2 **Simple telescope lens kit: (Rs100 each).**

You can make a simple telescope with this kit.
(1 metre focal length objective, 3 cm focal length eyepiece)

3 **VLFL lens (75mm diameter, 4 meter focal length) (Rs100 each).**
Packaging & Postage charges extra

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