Venus and its Transits

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VIGYAN PRASAR

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Some of the details regarding the circumstances of the June 08, 2004 Venus transit are due to Fred Espenak, NASA; and made available through Vigyan Prasar. We are grateful for the material made available and used in the book.

The figure showing the crescent phase of Venus near the inferior conjunction has been adopted from "The Flammarion Book on Astronomy" originally written by Camilla Flammarion. English translation of the revised version (translated by Annabel and Bernard Page) has been published by Simon and Schuster, N.Y. in 1964. Chapter 2 of the same book also contains a detailed account of the determination of "Astronomical Unit" prior to the radio sounding and the space age.

Foreword

Vigyan Prasar has brought out a number of publications on a variety of topics of science and technology on an experimental basis. Popular Science Classics, India's Scientific Heritage, Natural History, Health, and Do-It-Yourself are some of the series that have evolved over the years. Our emphasis has been on bringing out quality publications on various aspects of science and technology at affordable prices. Further, Vigyan Prasar is putting in efforts to bring out publications in major Indian languages for various target groups.

Vigyan Prasar has undertaken a countrywide campaign to popularise astronomy in particular and Science & Technology in general with activities built around the very rare celestial event of Venus Transit on 08 June 2004. The present book, "*Venus and its Transits*" by S.P. Pandya, J.N. Desai and S.R. Shah, is a part of this effort. The book describes various aspects of Venus and its transits including the quest of the Astronomical Unit. The book written in a popular style will enable the readers to understand this rare celestial phenomenon and inspire them to view it with due precautions.

New Delhi
April 2004

Vinay. B. Kamble
Acting Director
Vigyan Prasar

Preface

On June 08, 2004, the seventh transit of Venus since the invention of the telescope and the sixth to be observed by the mankind will take place. Historically, the Venus transits have played an important role in the advancement of our knowledge of the scale of our Solar System. However, now the event attracts the attention mainly because of the rarity of its occurrence. Taking 70 years as an average active human lifetime and 25 years as an average generation gap, the opportunity to see the event (actually a pair of events) is offered only after two to three generation gaps. So we are indeed the fortunate ones.

Such events provide an opportunity to the science educators to draw the attention of general public and educate them in celestial matters! Our knowledge about the solar system in particular and the universe in general has taken a big leap forward in past forty years through spacecraft-based studies. We have taken this opportunity to enlighten our readers with some facts revealed through such studies, regarding our neighbouring planet. Also being of topical interest, transits and their history have been given some prominence.

We are grateful to Vigyan Prasar, Dr. V. B. Kamble and Dr. S. Mahanti in particular, for encouraging us to undertake writing of this book and for publishing it. We are sure, a lot more material on Venus and Venus Transit will be available to the interested readers from Vigyan Prasar in addition to this book.

S.P. Pandya

April 30, 2004 **J.N. Desai**

S. R. Shah

Chapter - 1
Introduction

At times seen in the eastern sky at the dawn, and at times in the western sky at the dusk, shining like a diamond, the planet Venus conspicuously attracts our attention. In the Greek mythology it symbolizes "goddess of love", in the Indian mythology it represents the "Asura Guru" (teacher of demons) Shukracharya. Because of its appearances either only in the morning skies, or in the evening skies, earlier Greeks thought that these were two separate bodies and called them "morning star" and "evening star" (although Babylonians knew that they were one and the same object and called it "Nin-der-Anna".) Barring occasional very bright meteors, and bright supernovae occurring once in a couple of centuries, it is surpassed only by the Moon in the night sky.

The most conspicuous amongst the five "wanderers" of the Babylonian Culture (the planets), Venus has been mentioned as early as BC 684 in the Ninevah clay tablets. Amongst the seven celestial objects which daily change their positions against the background of stars, the Venus comes third in the rapidity with which it changes its position (after Moon and Mercury). So in the Aristotelian-Ptolemaic model for the universe, it was placed third in its distance from the Earth (which was supposed to be fixed at the centre. (It may be mentioned here that this "arrangement" had its roots in the earlier Babylonian astronomy, and has an interesting bearing on the sequence in which our week days are named. Interested readers may consult references*.

**Report of the Calendar Reform committee" (Govt of India), CSIR Publication (1955)*

"Time and Calendars" W.M. Oneil. Sydney Univ. Press (1975).

In the "Aristotle-Ptolemy model," Moon, Mercury, Venus, Sun, Mars, Jupiter and Saturn (in this order of distances) were supposed to orbit around the fixed Earth, after which came the sphere of fixed stars. The description of the motion of these seven bodies has been given by Ptolemy (AD 100-170) in his famous book "Magnum Opus" (better known through the translation "Almagest". This model held the sway (and the support of the Church at that time) till the "Copernican revolution" in 1543, the year in which Nicolaus Copernicus (1473-1543) published his famous book "De Revolutionibus Orbium Coelestium" in which he displaced the Earth from the centre of the universe and placed the Sun there instead. Copernicus withheld publication of this book till on his death bed, fearing adverse reaction from the Church (he was himself "canon" of the cathedral of Frauenberg in Poland). Preface to his book was written by one protestant theologian and a reformist, Andreas Osiander, and in which it is stated that "Contents of the book are hypothetical and should be regarded as an intellectual and mathematical exercise only, and is not intended to represent any physical reality!" Such was the fear of the Church at that time.

Publication of this book is considered as a landmark representing an ideological revolution in Europe; and in the times to follow, the rational thinking found increasing acceptance against the dogma, albeit not without a tough opposition from the established Church. This led to the rise of the modern science in Europe. (In this regard it is worth having a look at the situation prevailing in our society at the current times!).

Once it was recognized that our Earth is also just one of the planets orbiting the Sun, the natural question to arise was "do other planets harbour life?" The most likely candidates were the ones placed on the either side of the Earth, Venus towards the Sun and Mars on the otherside. So along with Mars, Venus was also considered a possible abode for life. It may be mentioned that in 1877 Schiaparelli had "observed" markings on Mars which he called "Canali" and this was translated to "Canals" in English which generated a speculation that Mars is inhabited by intelligent beings. This idea persisted till middle of the last century. There are a few other points which also made study of Venus a special attraction :

1. Being an inner planet, it exhibits "phases" somewhat like those shown by the Moon. The elongation (apparent angular distance from the Sun) at which it shows exactly "half moon" like phase (called dichotomy) permitted the earliest determination of the relative distances of planets in the Solar System.

2. The possibility of occurrence of "transits", i.e., the passage of the planet across the solar disc, when the planet appears like a "black dot" on the Sun.

3. During an observation of transit of Venus in 1761 (the second recorded transit) Lomonosov observed that when the disc of Venus is "immersed" in the Sun it appears to be surrounded by some "halo". He rightly interpreted this as to be due to strong refraction of sun rays passing around Venus and inferred a thick atmosphere for the planet. He also discovered the "inkdrop effect" (also called the "teardrop" and explained in the chapter on "Transits"). Due to the refraction by its atmosphere, when Venus is "crescent", the horns appear fairly advanced as if to meet each other (Fig. 1), and when the planet is close to the solar limb near inferior conjunction, at times its dark limb is seen surrounded by a bright annular ring.

4. Schröeter (1792) observed that the exact dichotomy (half moon) occurs for Venus a little later than expected according to the calculations after the inferior conjunction and a little earlier before the same. This has been named Schroeter effect and is possibly due to refraction in Venus atmosphere.

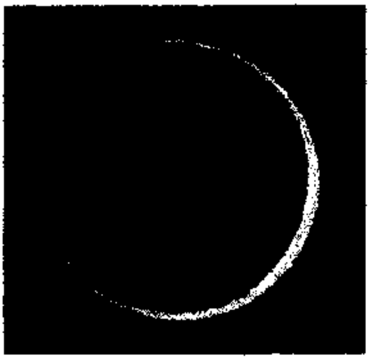


Fig :1 Venus in crescent phase. Note extension of the horns which is very much unlike Moon at the crescent phase.

Although, both the Mercury and the Venus being the inner planets show the phenomena of transits, the transits of Mercury are much more frequent, being about fourteen times in a century. (The last transit was on 7^{th} May 2003 and was seen from India). On the other hand transits of Venus are a rarity. At intervals of alternately 105½ and 121½ years, they occur in pairs separated by eight years. The next pair to occur after the 1874 and 1882 December pair, will be the June pair of 2004 and 2012. The first one will be on 8 June 2004 and will be seen very well from India. Venus transit pairs being more than a century apart, only alternate generations are fortunate enough to see them ! Although the famous scientist Edmond Halley had proposed one most notable experiment to be conducted during such a transit (the one to determine the precise value of the mean Earth-sun distance—the astronomical unit") he himself could not see any!

Why does Venus appear so bright? It is due to its high "albedo" (diffuse reflectivity). Planetary rocky surface reflect only ~16% light, but the Venus shows 72%, which canbe attributed to a thick cloud deck in its atmosphere. Because of its cloud deck, its surface has not been seen in the visible, either by ground telescope or by Cameras aboard the orbiting spacecrafts. Surface of Venus has been studied by radar mapping at cm. wavelengths. But even the early radio brightness measured in 1958 indicated a high surface temperature, and later direct measurements have shown its surface to be at a temperature of 470^0 C. Also the atmosphere of Venus is very dry. Then what are the cloud drops made of? Light scattering studies have shown that these are drops of concentrated sulphuric acid! Venus is certainly no place to search for life! And its thick atmosphere which is mostly of carbon dioxide exerts a pressure 90 times that of the Earth's atmosphere.

Distance of Venus from the Sun is 0.7 times that of the Earth and thus it receives twice the solar radiation. That itself should not make it so hot. The high surface temperature of Venus is due to what is called a "runaway greenhouse effect". When a planetary atmosphere allows visible radiation (like that of the Sun) to pass through and heat the surface, but does not allow the infrared radiation from the heated surface to be radiated back to the space, the surface will attain higher than the normally expected temperatures. Earth's atmosphere also shows this "green house" effect, without which the Earth would have been a place colder by about 20^0 C. But in the atmosphere of Venus the effect has been excessive, resulting in abnormally high surface temperatures. In the fourth chapter, "Atmosphere of Venus" we will see what has made this difference. It also bears a lesson for us, warning us of possible consequences of not controlling pollution of our atmosphere.

A peculiar fact about Venus is its extremely slow rotation about its axis, sidereal rate of 243 days for one rotation, and that also in a direction opposite to its revolution around the Sun (i.e, retrograde). In combination with its 223 day period for revolution around the Sun, this slow retrograde rotation effectively gives 117 day "day-night" cycle on Venus, with the Sun rising in the west and setting in the east. This, together with a detailed description of the phases of Venus are covered in Chapters II and III. Little is known about the interior of Venus and much is inferred from comparison with the Earth, and surface features as observed by the radar mappings. These details are covered in the Vth Chapter.

Finally a brief mention of "Aschen lights". This is somewhat of a mysterious effect, and it is not certain whether the effect is genuine or a visual deception. Between cresent phase and "half moon" phase, the dark part of Venusian disc seems to emit a sort of faint crimson light, in the visual telescopic observations, and this light has been named "Aschen light". The phenomenon is mostly reported at 10^0 elongation from the inferior conjunction, that is when Venus is separating away from the Sun during the morning appearance or closing in on the sun during the evening appearance. It should be worthwhile for the readers having a small telescope and located at good dark site, to verify for themselves this phenomenon.

Chapter – 2
VENUS : Comparison with Earth, and its Phases.

Till the middle of the last century, formation of the Solar System planets was a much debated problem. Was it due to a chance encounter of the Sun with a star passing nearby that pulled out a cigar-shaped cloud from the Sun, which then condensed into planets? Such an idea was suggested by Chamberlain and Moulten and was elaborated by Sir James Jeans and Jeffreys, middle of the last century. An alternative idea was put forth as early as in eighteenth century by a Philosopher Immanuel Kant and developed scientifically by mathematician Laplace; according to which the Sun and the planetary system were formed simultaneously through condensation of a protosolar cloud. Core of the cloud formed the Sun and the condensation of the surrounding disc material formed the planets. An important point is, if the former scenario (chance encounter) is correct, then formation of planetary system surrounding a star would be a rare event. On the other hand, according to the second idea such an event is a part of the process of star formation. Quite a large number of extra solar system planets have now been discovered, and the Hubble Space Telescope has also observed in the infrared, the residual gaseous discs surrounding some newly forming stars, which basically corroborates Kant-Laplace hypothesis.

Accretion process in the protostellar disc leads to formation of large chunks of matter, which come together to form couple of hundred kilometer sized bodies called "Planetesimals". These planetesimals grow through mutual collisions to form the planets. Composition of a planet would depend upon the distance form the Sun where it forms. Volatile material would condense only at large distances where temperatures are low enough. Thus, the Solar System planets are neatly divided into two categories, upto "Mars" we have small "rocky" bodies with most of their mass in the solid silicate type material and metallic compounds, whereas in the realm beyond, one has gaseous giants Jupiter and Saturn and large planets like Uranus and Neptune mostly of frozen volatile material. [Pluto is a class by itself, a much smaller icy body. Astronomers consider it more like a trans-Neptunian body similar to comets]. In this, the Earth and Venus having been formed at the similar range of distance from the Sun, are expected to have similar composition, a fact which is borne out when we compare them. Also, these two planets are very similar in their sizes. Earth has a mean diameter of 12,756 km., whereas that of Venus is 12,100 km. Mass of Venus is only 19% less than that of the Earth and its mean density is 5.25 gm/cc compared to 5.52 gm/cc of the Earth. The outer crust material of Earth is of lower density of silicates having density 3.09 gm/cc. Venera lander spacecraft also found surface material on Venus that is of silicates. How come both the planets have a mean density much higher than the density of the surface material? That is because both are "differentiated". These planets have passed through a molten or semi-molten stage during their early history, and at the time heavier material like iron and cobalt migrated towards their centre, giving rise to high density core material and low density surface material.

We stated that the mass of Venus is 19% less than that of the Earth. But how do we "weigh" Venus? Or in that respect how do we "weigh" any celestial body? Masses of celestial bodies can be determined only through their mutual gravitational attractions. In case of binary stars, due to the gravitational attraction, each star moves in an elliptical orbit about their common centre of mass (called the barycentre); and from the major axis of the ellipse and the period of the orbit, masses of stars can be inferred. In fact, it is only the binary systems in which stellar masses can be determined. Mass of the Sun is determined from its gravitational attraction on the planets which decide the relation between the semi major axis of a planetary orbit and the period. Earth's mass is obtained from the gravitational force it exerts on the Moon which decides the size and the period of Moon's orbit. But mass of a planet cannot be obtained from its gravitational attraction on the Sun, because the Sun is much more massive. After the space age, it has become possible to precisely determine planetary masses through the study of orbital paths of spacecrafts passing close to the planets. Then how was the mass of Venus determined prior to the space age, when Venus has no natural satellite? This was done in an interesting way. Earth's orbit has a radius of 150 million kilometres, and orbit of Venus has a radius of 110 million kilometres. Hence, during the inferior conjunctions of Venus when Venus passes between the Earth and the Sun, the distance between Earth and Venus is only 40 million kilometres, small enough to cause significant deviation in the orbital path of Venus, due to Earth's attraction. Measuring this perturbation in the orbital path of Venus it was inferred that the mass of Venus is 0.81 times that of the Earth. More recent measurements with spacecrafts have fully corroborated this result.

With its mass 0.81 times that of the Earth and a radius only slightly less than that of the Earth, the value for the acceleration due to gravity on the surface of Venus is 0.88 met/sec^2, compared to 0.98 met/sec^2 for the Earth. The "escape velocity", is the velocity required by a projectile (or a spacecraft) launched from the surface of Venus, to free itself from the gravitational bond of Venus is 10.8 km/sec (for the Earth it is 11.2 km/sec). Note that this velocity will free the object only from the gravitational bond of Venus, it will still be bound in the Solar System. To free itself from the Solar System it needs much more velocity. (And then it would still be bound in our galaxy, freedom from which needs much larger velocity!)

All the planets of our Solar System move in orbits which are not exact circles but are slightly elliptical, with the Sun at one of the focus of the ellipse. The oblongness of the ellipse is measured by the eccentricity "e" of the ellipse. If "a" and "b" are the greatest distance (aphelion) and the shortest distance (perihelion) of a planet from the Sun in its orbit, then $a/b = (1+e)/(1-e)$. Oblongness, as measured by the ratio x/y of the semi major to the semiminor axis is determined by $e^2 = (a^2-b^2)/a^2$ (Fig 2). Amongst Solar System bodies, planetary orbits have in general low values of eccentricity, ($e<<1$) asteroids have a moderate value ($e<1$) and comets have at times eccentricities almost approaching "1", (but always slightly less than unity). Eccentricity of an orbit >1 would imply a hyperbolic orbit and such an object would

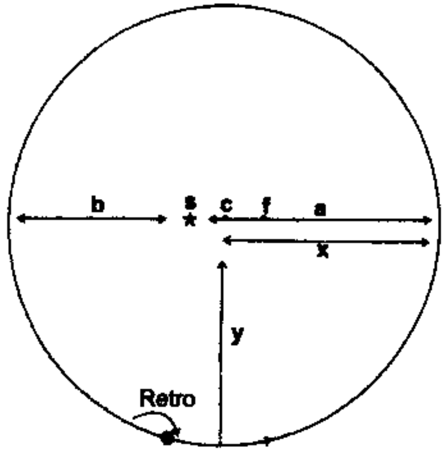


Fig 2. Elliptical planetary orbit (figure shows an ellipse with eccentricity = 0.2 like the orbit of Mercury). a = aphelion distance, b = perihelion distance, Sun is at one focus. X and Y are semimajor and semiminor axes. Note that even with e=0.2 the two axes do not differ noticeably. Retrograde rotation is also illustrated.

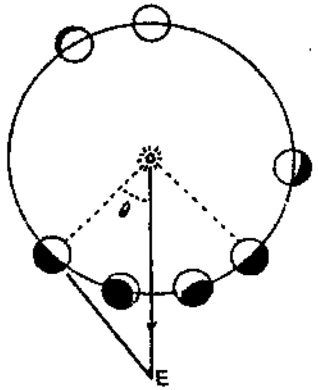
not be gravitationally bound in the Solar System. Amongst planets, only the closest planet Mercury and the farthest planet Pluto have significantly eccentric orbits with eccentricities respectively 0.21 and 0.27. Orbit of Mars also has a rather large "e" = 0.093, which therefore comes at times quite close to us (this happened in September 2003). The orbit of Venus is almost circular, with the eccentricity of 0.0068 which is the lowest among all the planets, and its aphelion and perihelion distances are respectively 108.9 million km and 107.4 million km.

We will now discuss in details the full cycle of phases exhibited by Venus over its synodic period of 584 days. Venus goes around the Sun with a period of 224.7 days, whereas the Earth completes its orbit in 365.2 days. Therefore, as seen from the Earth, Venus will appear at the same position with respect to the Sun at an inteval of $[1/224.7-1/365.2]^{-1}$ = 584 days. This is called the "synodic period".

We start with the "inner conjunction", when Venus passes between Earth and the Sun. As explained earlier it is only on rare occasions that, at the time of inner conjunction, it is seen crossing the solar limb (ie "transit"). Most of the time it will pass either slightly to the north or to the south of the Sun. The inner conjunction of Venus is like a "new moon" (*Amavasya*), its unilluminated side is towards the Earth, so it cannot be seen. But at times when it is sufficiently close to the Sun, the unilluminated disc of Venus is seen surrounded by a bright annular ring (which is unlike new moon). This phenomenon is due to the refraction of Sun rays crossing the thick atmosphere of Venus. (Although this can be seen in telescope observations, one has to be careful that the Sun does not get into the field, and hence this should not be attempted except by trained observers).

After the inner conjunction, Venus starts appearing close to the Sun before sunrise on the eastern horizon, showing a crescent phase, but the shape of the crescent is quite unlike the crescent moon (Fig.1), again due to atmospheric refraction. Now as the separation between Venus and Sun increases, it shows more advanced phases and also appears higher in the eastern sky at the sunrise. To the naked eye, it appears to become brighter day by day. But here, two opposite effects operate. On one side, because it shows more of its illuminated side to us it would brighten. On the other hand because the Earth-Venus distance is increasing, it should become less bright. The net result of these two opposing factors is that the Venus attains its maximum brightness 36 days after the inner conjunction, when it appears 35^0 away from the Sun and its separation from the Sun is still increasing. This is much before it attains "half moon" phase (the "dichotomy") when its angular separation from the Sun (i.e. the elongation) is the maximum.

Seventy-two days after the inner conjuction, it attains this maximum elongation (46^0) when it appears highest in the eastern sky at the sunrise. At this time, the Sun-Venus–Earth angle is exactly 90^0 and Venus should show exactly "half phase". However, as noted by Schroeter in 1792, the exact half phase appears a few days later. This effect has been called the "Schroeter effect" and is believed to be due to refraction effect in the dense Venus atmosphere. From the mesurement of the maximum elongation angle (46^0), the ratio of "Sun-Venus" distance Dv to the "Sun-Earth" distance De can readily be obtained, as Dv: Ds= sin 46^0 (Fig 3). At the time of inner conjunction, the distance between Earth and Venus is "De-Dv". This was measured very precisely in 1962 by sending a radar pulse from the Earth and noting precisely the time it takes for the reflected pulse from Venus to be received back. This way, from "De-Dv" and Dv : Ds, the Earth-Sun distance (astronomical unit) has been precisely determined.



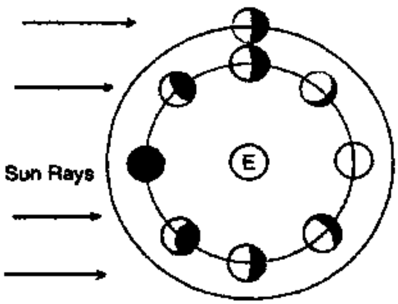


Fig 3. Phase cycle of Venus compared with the phase cycle of Moon. ø shows the position of maximum elongation and the "half phase". E is location of Earth. [Venus shown very much enlarged to illustrate phase]. Note especially that "halfmoon" occurs at ¼ phase cycle for the moon, but not in the case of Venus.

After the dichotomy, one sees more and more of the disc of Venus, but it now gets closer to the Sun, and its brightness is decreasing. Half the synodic period, i.e, 292 days after the inferior conjunction, it is on the other side of the Sun as seen from the Earth. This is called the "Superior conjunction". Its entire illuminated side is now towards us like a full moon, but cannot be seen because it is in the direction of the Sun. After superior conjunction it now makes its appearance in the western sky at the dusk. 220 days after the superior conjunction it attains the maximum elongation in the western sky, and 256 days after the superior conjunction it attains its maximum brightness in the western sky, when it is 35^0 away from the Sun and gradually closing in on the Sun. Due to the "Schroeter effect", the half moon like phase will be shown by Venus, a few days before it attains the maximum elongation in the western sky.

During the entire cycle of its phases, the net change in the brightness of Venus as seen by the naked eye is only a factor of 2 ½ which is small and not very readily discernible. This is because, all the time the two opposing factors operate. When more of its illuminated disc is seen, it is moving away from us. Also, one would have noticed that, there is good amount difference between "phase cycle" of moon and the "phase cycle" of Venus. This is also seen in Fig 3 where the two are compared.

When at the maximum brightness, the visual magnitude of Venus is – 4.40. For comparison, that for the brightest star Sirius is –1.57 and the visual magnitude of Jupiter is –2.6. Difference of magnitude is related to the ratio of brightness as $\Delta_M = M_1 - M_2 = -2.5 \log B_1/B_2$; which means, lesser the magnitude, brighter the object. Thus, Venus is 5.2 times brighter than Jupiter and 13.5 times brighter than Sirius. The faintest star that can be seen with naked eye has a magnitude ~6, which will be almost 15000 times fainter than Venus !

Chapter - 3
A "Day and a "Night" on Venus

All the planets of our Solar System revolve around the Sun, with their unique orbital periods which are decided by their distances from the Sun. Further, the distances at which the planets are placed seem to follow an empirical law Called the Bode-Titius law, according to which, if we take a series of numbers 0,3,6,12....., add 4 to each and then divide by 10, we get respective distances of the planets in units of the mean Earth-Sun distance (the astronomical unit). The law works quite well upto Uranus but shows marked discrepancy for Neptune and fails completely for Pluto. Also, one has to accommodate for "asteroids" between Mars and Jupiter. All the planets revolve around the Sun in approximately the same plane and in the same direction. If we take the plane of orbit of the Earth (the ecliptic plane) as a reference, perpendicular to the plane towards the pole star defines the "Celestial North" (Rotation axis of Earth presently points towards the pole star and is at an inclination of $23\frac{1}{2}^0$ form the celestial north). Seen from the celestial north, all the planets will be seen orbiting the Sun in a Counter clockwise direction (Fig 4).

All the planets also have some rotational motion, but neither the direction of their axes of rotation; nor their rotational speeds seem to show any pattern. Thus, whereas the rotation of our Earth is around an axis which points presently towards the pole star (this direction also revolves around the celestial north with a period of 25,800 years,

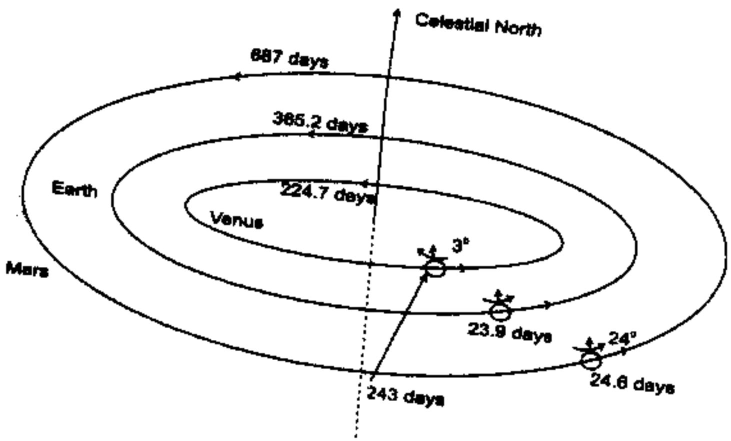


Fig 4. Orbital Periods, axial rotations, and the inclinations of the rotation axes to the celestial north, of Mars, Earth and Venus.

called precessional motion) and is counter-clockwise as seen from the north with a period of 23^{Hr}- 56^{mnt}; rotation of the planet Venus is about an axis which has only 3^0 inclination from the celestial north but has an extremely slow rotation period of once in our 243 days and that too in a direction opposite to the direction of orbital motion (i.e. clockwise as seen from the north). [Uranus rotates about an axis which is almost in the orbital plane, i.e., inclined at 82^0 to the celestial north!] Thus, planetary rotation rates and directions seem to have been result of "accidents" involving collisions with Planetesimals from which the planets were built up. Extremely slow and retrograde rotation of Venus result in its abnormally long "day-night" cycle of a duration of our 117 days, during which the Sun rises on the western horizon and sets in the east ! But before we understand this, let us know how the rotation of Venus was accurately measured.

As already mentioned in Chapter 1, Venus is a cloud covered planet, so its surface could not be studied visually, and hence obtaining its rotational period was a problem. In the ultraviolet observations, Venus atmosphere shows some markings, but inferring the rotational period from their observations was inconclusive. Such markings could be atmospheric motions and need not relate to the surface motion. But it did indicate that Venus rotates very slowly. So it was postulated that the rotations of Venus may be locked to its revolution; (similar to the tidal locking of rotation of our Moon with its revolution around the Earth). The exact rotation speed of Venus could be determined through radar sounding methods using microwaves. At suitable wavelengths microwaves face no obstruction from the clouds of Venus and could reach the surface of Venus. Because of sensitive heterodyne detection techniques used in the radio detection, such waves when reflected from the surface of Venus could be detected back on large Earth-based telescopes. Rotation of Venus was inferred from the Doppler shift in the frequency of such reflected waves. Doppler shift is the apparent change in frequency of any type of wave when a source emitting the waves, and a receiver, receiving the waves are in a relative motion along the propagation direction. In the case of sound waves it is the familiar "sharpening" of the tone of whistle of an approaching engine and "lowering" of its pitch when it is receding. The frequency perceived is higher than that emitted, if the source is approaching and is lower when it is receding, and this apparent change in the frequency is called the "Doppler Shift". In case of electromagnetic waves (such as light waves, radar waves, etc) the Doppler shift Δf in the frequency f is related to the relative velocity "v" between the source and the receiver through an expression $\Delta f/f = v/c$ if v is not too large. [It was through such a Doppler shift in the optical region, that the expansion of our universe was also inferred]. The Doppler shift also occurs when a wave is reflected from a moving surface. Now, when Venus is at inferior conjunction it is moving perpendicular to the line of sight, and has almost no component along the line of sight. But, due to its rotation one edge of its limb is approaching us, and the other edge is receding from us. So the waves reflected from the two edges will show different Doppler shifts and from this, the rotation velocity can be deduced. Although "V" being small, the shift is small, radio wave detection techniques are developed to such an extent that the frequency change can be measured to better than 1 part in 10^9; so rotation could be accurately deduced. This way it was found that Venus rotates about its axis once in (our) 243 days, and the direction of this rotation is "retrograde" (i.e. opposite to its revolution), Radar sounding not only could measure the rotation, it could also accurately measure the "true" diameter of Venus. The distance between the Earth and Venus at the inferior conjunction could also be measured very accurately from the "to" and "fro" transit time of the reflection. This has provided us the most accurate determination of the Value of "astronomical unit" (AU).

Subsequently spacecraft have "observed" surface features of Venus using radar techniques. The most detailed survey of this type till now, has been the one carried out by the spacecraft named "Magellan" in early nineties, and our knowledge about the details of surface features on Venus is mostly through this study. More of that will be dealt with in the fifth chapter.

We will now try to understand the consequence of this slow and retrograde rotation of Venus on the durations of its "day" and "night". Note that, because the rotation axis of Venus is almost perpendicular to its orbital plane, Venus will not experience any "seasons". Seasons on the Earth are due to $23\frac{1}{2}^0$ inclination of Earth's rotation axis with the perpendicular to its orbital plane because of which the sun appears to move south of equator for six months and north of the equator for the other six months. Earth rotates "prograde" (i.e. same direction as its orbital motion), and its actual rotation rate is 23^h-56^m. Thus if we take an imaginary circle in the sky passing from north to south through the zenith, all stars will appear to cross this circle from east to west once in 23^h-56^m. This circle is called the "meridional circle" and crossing of this circle by a celestial object is called its meridional transit". The interval of time, (23^h-56^m) between successive meridional transits of any star is called a "sidereal day". But, our usual day is adjusted to the meridional transit of the sun. Because of the revolution of Earth around the sun, the sun appears to us shifted approximately one degree "eastward" with respect to the background of the stars $\{360^0/365 \sim 1^0/\text{day}\}$. Meridional transit of Sun is the "apparent" local noon. But, due to the apparent north-south movement of the sun during a year, and also due to the ellipticity of Earth's orbit due to which its orbital speed slightly changes during a year successive meridional transits of the sun do not occur at equal intervals of time. But our usual day, the "civil" day has to be tied up with the sun and must be of constant length, so astronomers replace the "actual" sun with a "mean" sun, and time interval between successive meridional transits of the mean sun defines the 24 hour length of the civil day. During the course of a year, actual sun may either be slightly "ahead" of the "mean" sun, or may be slightly behind.

Thus actually we have two different types of days; one, siderial day referring to the rising and setting of stars having a duration of 23^h-56^m; another civil day referring to the rising and setting of the Sun, having a duration of 24^h. Because the Earth's rotation is much faster than its orbital revolution period, the difference between the two is only 4 minutes, and we usually recognize this by saying "stars rise 4 minutes earlier on successive days". With this background now let us undestand the "day" and "night" on Venus. Venus has 243 days of "retrograde" rotation. So, for any particular star, its successive meridional transits would occur at the intervals of 243 days, but from west to east. (It is another matter that, because of its permanent and thick cloud cover one would not see any star in the Venusian Sky anyway!) But unlike Earth the year on Venus is ~225 days — which is shorter than its sidereal day. How the motion of the sun would appear to an observe on Venus in his sky can be understood from fig 5, which shows four different positions of Venus

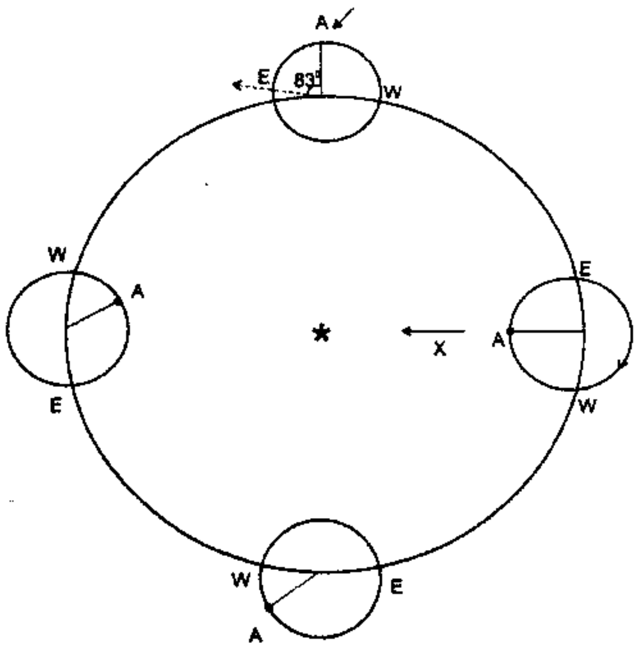


Fig 5. "Day" and "Night" on Venus. The figure shows the resultant changes in the location of a fixed point 'A' on the surface of Venus with respect to the Sun; as Venus rotates about its axis in 243 days (retrograde) and revolves round the Sun in 225 days. Position of point A is shown at intervals of quarter Venus year.

as it moves around the sun, at intervals of 56 days which is a quarter of its year. Also shown in the figure is the location of an observer experiencing "midnoon" at the starting time. Direction X shows a fixed direction in space with reference to which A will rotate at 243 day interval. So when Venus comes to the point "2", it would have rotated by ~83^0 and would be approaching midnight. Similarly, after half the Venus year, after ~112 days. A would again be close to midnoon, almost facing the Sun. Note that, because of the opposite directions for the revolution and rotation, length of the solar day on Venus becomes shorter than its year, and the net motion of Sun in the sky would be from west to east. Mathematically, one can say that, due to a revolution period of 224.7 days and a rotation period in opposite direction of 243 days; the effective rotation with respect to the sun will be $[1/224.7 + 1/243]^{-1} = 116.7$ days, which is the length of a solar day on Venus. Also, the sunrise will be seen in the west and the sunset in the east!

It is a point worth noting that this rotation of Venus is fairly closely coupled to its inner conjunctions with reference to the Earth, and as a consequence, at each inner conjunction, the same side of Venus approximately faces the Earth. However, this coupling is not exact as was thought sometimes earlier.

Chapter – 4
Atmosphere of Venus

Of the four inner planets, the Venus has the densest atmosphere, some ninety times denser than that of the Earth; but composed mainly of carbon dioxide. Mercury has no atmosphere. The three other planets – Venus, Earth and Mars differ remarkably among themselves with respect to their atmospheres. Carbon dioxide again is the main constituent of the Martian atmosphere, but the atmosphere of Mars is very thin, only 1/200 that of the Earth. The principal constituent of Earth's atmosphere is nitrogen (78%) and the next important gas is oxygen (21%); whereas carbon dioxide is a minor constituent. Obviously these atmospheres could not have been the primary atmospheres with which these planets were formed. Composition of the protosolar nebula from which the planets were formed, was quite different and has been preserved only on the outer gas giants viz., Jupiter and Saturn whose atmospheres are made largely of hydrogen (~90%) and helium (~10%). The primary atmosphere of the inner planets also must have been of gases like hydrogen, helium together with methane, ammonia carbon monoxide etc. Chemically, such atmospheres are "reducing" atmospheres. Light gases escaped from these atmospheres because of the smaller size and consequenty the lower gravity of these planets; as well as higher temperatures due to proximity to the Sun.

The heat generated in the interiors of these planets must have been much more because of the radioactive decay of shorter life time active nuclei, and consequently volcanic activities of these planets would also have been much more intense in the past. Space borne observations of the surfaces of these planets clearly show evidence of this. Due to this volcanic activity of the past, lots of gases were exuded from their interiors, and these formed the "Secondary" atmospheres of the inner planets.

Carbon dioxide was the most important gas expelled this way. However, emergence of the plant life on Earth converted large amount of carbon dioxide into oxygen, on the Earth. Also, the action of running water and life fixed large amount of carbon dioxide in the form of carbonates, making carbondioxide a minor constituent on the Earth. Then what made Venus so different ! How did its surface go to a temperature so high that liquid water cannot exist !

"Young" Sun, when formed was about 30% less luminous than what it is today and has been slowly "warming up". This is very well established from our understanding of stellar evolution – especially the stages which newly formed solar mass stars pass through immediately after their formation. In that remote past couple of billion years back, the temperature on Venus must have been more equable, with oceans of water on its surface. But as the Sun warmed, there was more evaporation, (and in this regard the difference between the Earth and the Venus was crucial) hence Venus atmosphere became more laden with water vapor. Water vapor transmits the visible solar radiation but absorbs the infra-red. So the Venus surface, warmed by the solar radiation in the visible, could not radiate back to space efficiently and its temperature went higher than that for the Earth. In other words it had a stronger greenhouse effect, and consequently the oceans completely evaporated. Lack of water could not then fix the carbon dioxide as carbonates and was added to the atmosphere. Carbon dioxide is also an efficient "greenhouse gas". Thus the effect on Venus became a "runaway effect". It is the absorption at 5 micron to 10 micron wavelengths (micron = 1/1000 mm) that play major role in deciding the importance of a gas towards contributing to greenhouse effect, and these absorptions are due to the molecular vibration rotation bands. These are forbidden transitions for symmetric diatomic gases like 0_2 and N_2 and hence these gases do not contribute to the greenhouse warming. However, pollutant gases like methane, carbon dioxide etc. can contribute towards the greenhouse effect, and increased warming can make the effect "runaway" by the contribution of the evaporated water. This is why atmospheric scientists are concerned about pollution and are meticulously developing models to understand its effect on our climate.

Spacecraft studies of Venus atmosphere

To know the nature of constituents in the Venus atmosphere, observations of its spectra were initiated with spectrographs on large telescopes, during the mid-twentieth century. As already mentioned earlier, optical effects due to the refraction of sunlight traversing the thick Venus atmosphere, and seen during inner conjunctions (Venus passing between Earth and the Sun) had shown the presence of such an atmosphere. With measurements on the radio brightness from the ground based radio telescopes, its high (~500^0 C) surface temperature was also deduced. However, a detailed information on the atmospheric pressure, constituents and temperatures, as also the nature of its cloud cover could only be elucidated after the beginning of the space craft based studies. Russia (Soviet Union at that time) pioneered this study by an intensive program of sending a series of spacecraft named "Venera" to Venus. However, due to the adverse pressure and temperature conditions on Venus, the first success was recorded only on 18 October 1967, when Venera 4 could probe the Venus atmosphere to a height of 34 kilometres above the surface, before falling silent. It measured an atmospheric pressure of 75 Earth atmospheres and 95% composition of carbon dioxide at that height. Just a day after Venera 4 entry, USA's Mariner – 5 flew past Venus and observed it from a distance of 3391 km; and found that Venus has practically no magnetic field. Prior to Mariner-5, Mariner-2 had also flown past Venus in 1962 at a distance of 34833 km, and from its brightness in the radio region had inferred a temperature of ~425^0 C. Mariner – 5 data also showed absence of trapped charged particle zones surrounding Venus (similar to Van Allen belts surrounding the Earth) because it has no magnetic field. Because of the lack of magnetic field, interaction of solar wind (stream of high velocity charged particles, mainly electrons and protons) with the ionosphere of Venus is also of different kind. In case of Earth, solar wind is stalled by Earth's magnetic field thousands of km above the surface and is guided to the polar regions; where it precipitates at times to create phenomena like polar aurorae. In case of Venus, the solar wind directly impinges on the ionosphere only a couple of hundred kilometers above the surface.

Venera-7 was the first probe to successfully function on the surface of Venus, albeit only for a short duration of 28 minutes; in 1970. During its descent in the atmosphere it observed winds which were ~100 metre/sec at 48 km height, decreasing to ~1 metre/sec at the surface. But in later observations it has been found that even such slow surface winds can cause significant erosion of the surface, because of the heigh density of the atmosphere. Venera - 9 and Venera - 10, launched in 1975 were each of two parts, one lander probe and one orbiter going round Venus. They observed that the cloud decks of Venus are distinctly divided into three layers with height ranges 70-57 km, 57-52 km and 52-49 km. Composition of the cloud droplets was a mystery. Ground-based spectroscopy as well as the space-borne experiments had clearly shown that the atmosphere of Venus is very dry and therefore water drops are ruled out. The mystery was solved by three NASA scientists, who proposed on the basis of the study of light scattered and polarized by these drops, that they should be "Sulphuric Acid' drops ! This has subsequently been confirmed, and based on extensive data of Pioneer-Venus mission, the $S0_2 \leftrightarrow H_2S0_4$ chemistry is now well understood. In the later part of this chapter we discuss this further.

Venera - 9 and Venera - 10 landers were equipped with cameras to photograph the surface of Venus. Anticipating a rather very dark sky because of the thick cloud cover, they were also equipped with search lights ! However, these were not required to be used. About 3% of the sunlight reaches the ground making the brightness level somewhat like a thick cloud covered day on Earth. Later, "Venera" spacecraft have also investigated the soil of Venus. On 3 November 1973, USA sent its Mariner-10 to visit mercury, but to go in a suitable orbit around Mercury, it took help of the gravitational field of Venus, and passed at a distance of 5793 km from Venus on 5 February 1974. This was equipped with cameras to take photographs and it observed the cloud tops of Venus in the ultra violet; where it shows distinct features. From the study of the motion of these "markings" appearing in UV, it found that the Venus atmosphere makes a complete round in 4-5 days at this height and that the direction of circulation is in the same sense as its surface rotation.

Such super rotation is an interesting problem in atmospheric dynamics. After its "Venus fly bye', Mariner – 10 went around a very elliptical orbit around Mercury and photographed that planet during three passes, 29 March 1974, 21 September 1974 and 16 March 1975. However, the period of this orbit and the rotation period of mercury were so related that it could observe its only one hemisphere.

USA launched its comprehensive mission "Pioneer-Venus" to study Venus, in 1978. Under this mission, two spacecrafts, Pioneer 12 and Pioneer 13 (also called Pioneer-Venus – 1 and Pioneer-Venus - 2) were launched respectively on 20 May 1978 and 8 August 1978. Pioneer 12 reached Venus on 4 December 1978 and was placed in a highly elliptical orbit to go round Venus. The nature of its orbit brought the spacecraft close to Venus (~200 km from the surface) once during each orbital revolution; in order to sample Venus atmosphere. At the same time for the remaining part of the orbit it went far away. This reduced the net atmospheric drag and lengthened the life of the mission. This orbiter carried a synthetic aperture radar to map Venus surface by the radio sounding, and also instruments to sample the ionosphere. The orbiter also carried an ultraviolet spectrometer to study the cloud tops. The ultraviolet image by the orbiter clearly showed the nature of incoming solar wind particle interaction with the ionosphere of Venus, through the ultraviolet aurora created by the protons of solar radiation interacting with Venus ionosphere on the day side of its ionosphere. On Earth, the solar wind impinging on Earth, encounters the magnetic field of the Earth thousands of kilometers above its surface and the solar wind particles are then guided by this field to enter the magnetic polar regions (which are somewhat away from the geographic poles) where they create bright visual auroras in the Earth's ionosphere.

Pioneer 13 (the Pioneer-Venus 2) carried probes which descended on Venus, probing its atmosphere with several probes sampling it both at high and low latitudes as well as from dayside and night side. Instruments like gas chromatograph and mass spectrometer, studied the composition of the atmosphere from the cloud tops to the ground. Some sort of haze layer was observed above the cloud tops, upto 90 km height whereas between 49 to 30 km again, haze with micron size particles was observed. In between the haze layers are the sulphuric acid clouds.

Below 30 km, the atmosphere of Venus is clear. The $SO_2 \leftrightarrow H_2SO_4$ chemistry of Venus atmosphere as now understood, is depicted in Figure 6.

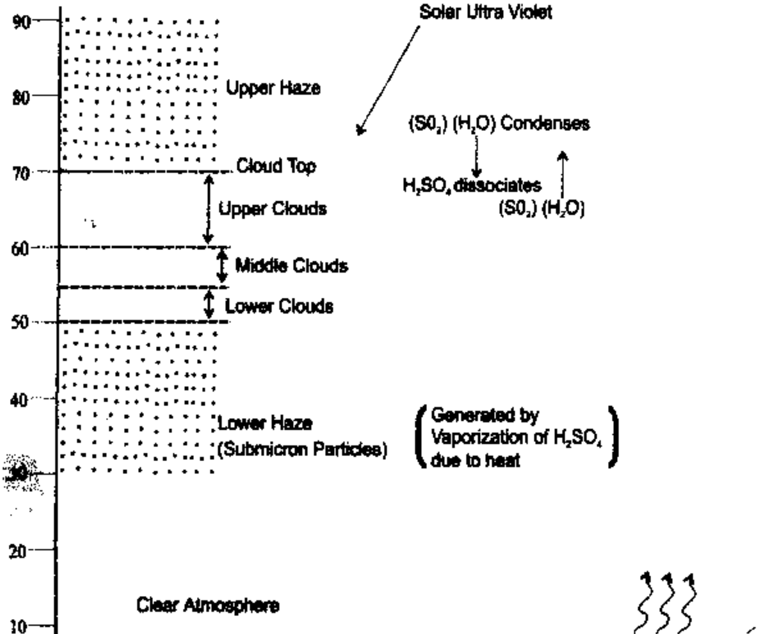


Fig: 6 : Recycling of $H_2SO_4(nH_2O)$ and $SO_2 + H_2O$. Surface heat vaporizes H_2SO_4 $(n\ H_2O)$ forming lower haze. Under Solar Ultraviolet, SO_2 and H_2O undergo photochemical reaction to form H_2SO_4 droplets that form clouds.

The orbiter which started operating in December 1978 worked for almost fourteen years till it entered too low in the Venus atmosphere and burnt up, in October 1992. One surprise that was seen during this long coverage of cloud tops and $S0_2$ was a steady decline in the concentration of the gas above the cloud tops. According to one interpretation of this observed decline, a giant volcanic eruption could have taken place on Venus, spewing a large amount of $S0_2$, gas in its atmosphere, just prior to the Pionner-Venus observations; and the $S0_2$, concentration could be steadily declining since then. However, later radar survey with much higher resolution, carried out by the spacecraft "Magellan" has detected no evidence of volcanic activity of recent past, although a large number of extinct volcanoes have been seen. At the time of last appearance of Comet Halley (1985-86) Russia sent two spacecraft, Vega-1 and Vega - 2 to study the plasma of the comet. Their orbits were such that they flew past Venus before preceding towards the Comet and during the encounter with Venus it threw two parachutes carrying balloon born instruments in the Venus atmosphere and also a probe to land on Venus. The balloons travelled in the Venus atmosphere for 48 hours and were tracked from the Earth by Very Long Base Line radio technique, giving extensive information on its atmospheric circulations.

Although the Venus surface is at a high temperature of 470^0 C; as one proceeds higher up in the atmosphere it rapidly decreases, and at the level of cloud tops (~70km) it is as low as -20^0 C ! Venus has been one of the planets most extensively studied by spacecrafts, and some 21 space crafts have either visited it or had its flybye observations. In the next chapter we will summarise what we now understand about the surface and the interior of Venus.

Chapter – 5
The Surface and the Interior of the Venus

The Earth and the Venus are fairly similar in their size and mass. Also, both were formed in similar regions of the solar nebula (being at comparable distance from the Sun). So one would expect them to have similar compositions. They could have undergone somewhat similar evolutionary histories and therefore, one may also expect them to have similar internal structures. However, in the last chapter we saw that the two planets have grossly different atmosphere and have also indicated a plausible reason why their atmospheres evolved to be so much different. With regard to the internal structures, the spacecraft observations cannot be immediately useful. But some inferences can be made based on what surface features are observed today (like mountains, volcanoes, valleys, ravines etc.). These are the indicators of what internal processes the planet must have undergone in the past. One important point that we must bear in mind in this regard is, both the planets (Earth and Venus) must have undergone a "differentiation" process in the past. "Differentiation" means that the heavier density materials like iron and nickel have migrated to their core regions, leaving lighter silicates above in the mantle. Average density of Earth is 5.5gm/cc whereas that of Venus is 5.2 gm/cc. Surface material on both planets are silicates with density≈3gm/cc. [Surface of

Venus has been examined by Venera spacecraft of erstwhile U.S.S.R]. Thus it is clear that in both the planets, cores must be of higher density.

We know the internal structure of the Earth through the "Seismic Sounding" i.e. the study of propagation of waves generated during the earthquakes. Leaving aside the surface waves, there are two other types of seismic waves, the "P" waves and the "S" waves. P waves are the body waves of compression and are longitudinal. S waves are waves of deformation, i.e. shear waves. Both types of waves propagate with a velocity that depends upon the density of medium; and are strongly reflected at a boundary where the density sharply charges. Further, "S" waves cannot propagate in a liquid media. From the propagation of P and S waves generated during earthquakes, we know that at a depth of 300 km in Earth, the density suddenly changes. The region below is called the "mantle". Also at a depth of ~3000 km, we encounter a liquid region. Central 1200 km radius is the solid core with material having density ~10 gm/cc mostly likely to be iron and nickel and their sulphates. But for the Venus, we do not have any seismic data; so its internal structure has to be only indirectly inferred. Spacecraft observations have shown that Venus does not have any magnetic field, but that does not rule out liquid region near the centre. Earth's magnetic field is due to the currents generated in the liquid region outside the solid core, and these currents are due to Earth's rotation. Absence of the magnetic field on Venus could be due to its extremely slow rotation.

There is one aspect with regard to which the Venus and the Earth seem to have undergone different histories. On Earth, the present form of continents is a consequence of "Plate Tectonics". The lower region of the top 300 km of the Earth is known as "asthenosphere" and the asthenosphere is semi-molten at a depth of ~150 km at some places. This is due to silicates being at temperatures as high as ~1000^{0}C. In the mid-Pacific and mid-Atlantic oceans, this molten silicate rocks from the depth of the asthenosphere oozes out (like toothpaste) along what are called the mid-oceanic ridges. On reaching the ocean base, the molten silicates solidify and form a new "crust" on the ocean basins. This newly formed rock pushes away the older rock, and all these float on the partially fluid deeper asthenosphere, like material moving on a conveyor belt. This moving plate, when it meets the older continental plate margin, it is pushed underneath by pressure and remelts. Thus the circulation of crustal material formed from the upper mantle material continues. Where the "Subduction" is occurring (Oceanic plate- continent margin) some of the deepest oceanic trenches are to be found. Also these are the locations of the most intense volcanic activity on the Earth; like the pacific ocean "ring of fire" [the "ring" formed by Japan, Indonesia, New Guinea, Philippines and the Andes and Rocky mountains on the western coast of Americas]. This process called plate tectonics has been responsible for "reworking" the surface of Earth (and also has shaped our present continental forms) over millions of years. The whole process operates due to

i. The internal heat of the Earth, and
ii. The lubricating effect of the oceanic water mass, to allow the rising and the subduction.

On Venus, the internal heat source due to the decay of radio active material is likely to be of similar magnitude as on the Earth. The surface of Venus is also geologically fresh; and not very old. (Geologically ancient surfaces bear the marks of intense cratering by meteorite impacts, such as seen on Mercury, Moon and to some extent some areas of Mars). But the surface features do not show indications that the plate tectonic process has operated on Venus. This can be due to absence of oceans which seem to play an important role in the process. Venus must be losing internal heat through some other mechanism like intensive volcanism, although at the present epoch there are no active volcanoes seen on Venus. High surface temperature could itself be one source. The surface features of Venus have been extensively mapped by the synthetic aperture radar carried by the NASA orbiter spacecraft Magellan, placed in orbit of Venus in 1990. This spacecraft was in an elliptical orbit around Venus. When it was close to Venus at a distance of ~300 km, its radar turned towards Venus and mapped its surface at 12.6 cm wavelength with a surface resolution of 120 met x 120 met, when it went farther, the radar turned towards the Earth to transmit data acquired to Earth. After giving some anxious moments initially, the spacecraft settled down to a smooth operation over quite long period and mapped 80% of the surface.

In addition to some large volcanoes (Rhea Mons and Theo Mons for instance which are ~ 4 km high) hundreds of small cone-shaped peaks are indicative of extensive and strong volcanic activity of Venus in the past. Also number of Valleys are seen, a valley joining Rhea Mons and Theo Mons is 3000 km long. In addition an unusual type of past volcanicity has also been seen on Venus, of a type seen nowhere else in any other solar system bodies. These are rather flat volcanoes only about a kilometer in high but spread over a diameter of 20-25 km, and apparently associated with "toothpaste" like lava flow.

These are called "Pancake" volcanoes. A most remarkable feature seen on Venus by Magellan is the "rivers of lava". These are flow marks very similar to these formed by rivers of water on Earth, showing ravines, meander and delta formation and must be due to some unusual form of very fluid lava. The most likely candidate is "Carbonatite" formed by melting of carbonate rocks (melting point ~ 500^{0}C) due to higher surface temperature on Venus, perhaps only few million years back. One such valley associated with such lava flow is the Baltis Valley which is 6800 km long! [Ordinary lava has chains of polymerized SiO_2 and is hence not very fluid. Carbonatite when melts is watery].

In addition to the high volcanic mountains, Venus also has "fold mountains" created by crustal pressures, as on the Earth. Thus, Venus has been tectonically active (but no undergoing plate tectonic process). One of the fold mountains, "Maxwell Mont" is 11 km high ! Another peculiar feature of Venus is the "Tessera" (Greek word for tiles). Tessera areas are few thousand square kilometre, and look like areas "paved" with ~20 km size rocks !

Thus the "Radio" eye of Magellan has revealed considerable details of its surface, through hidden from us by the thick cloud decks in the optical region. However, to interprete these features in details, in terms of the geological processes the planet has undergone in the past and may still be undergoing, will be for the future studies.

Chapter – 6
Transits

In this final chapter, we now take up what may aptly be called, "the event(s) of the 21st century" – a pair of transits of Venus across solar limb to be seen in June 2004 and 2012. Such rare astronomical events create great interest amongst general public, and also serve a very useful purpose of science education for the general public, as well as, inculcating a scientific spirit. In this respect, it is interesting to note that just about four centuries back, a general belief (driven by theological considerations) was that, it is only on the Earth that "events" and "changes" occur because it is "imperfect", the God's world above is permanent and immutable. Such a belief had Aristotelian idea of the universe where the Earth was supposed to be fixed at the centre, with various spheres of Sun, Moon, planets and the stars revolving about it. This belief had the backing of the current religion to such an extent that, to think otherwise was considered as "blasphemy" and appropriately inviting a punishment! Rare events like appearance of a comet were believed to be "atmospheric" in origin, and when Tycho Brahe compared the observations of the bright comet of 1577 from various European locations and concluded that comets are at distances greater than that of the Moon, it was a big jolt ! Around the same time (1572) another remarkable event was seen in the sky which also showed that the universe above the Earth also underwent changes: a new star was seen ! This event, which was also studied by Tycho Brahe, is now known as Tycho's supernova (a stupendous stellar explosion). At those times, such events contributed significantly towards moulding the thinking in Europe, and turning it from "dogma" to "reason". Today such events provide an opportunity for "public education in science"! Amongst such events, we have eclipses (around 2 for a given location, although viewing a total solar eclipse may be a life time opportunity"), appearance of a bright comet once in a decade on the average, disappearance of Saturn's rings at ~15 years interval (next being in 2010), periodic favorable oppositions of Mars (last event being in September 2003), transits of inner planets Mercury and Venus, those of Venus being exceptionally rare; etc. All such events help towards arising the curiosity of ordinary public, otherwise only "casually" interested in science.

Coming back to the 'transits' of the inner planets Mercury and Venus, whereas those of mercury are fairly frequent (~14 in a century), those of Venus are quite rare, and roughly speaking only alternate generations have an opportunity to witness them ! They occur as "pairs" with a gap of 8 years; but the pairs themselves are spaced alternately 113½ and 129½ years apart! (Reasons for this regularity will be discussed later in this chapter). Also although a transit event of an inner planet across solar disc is very much like a solar eclipse (transit of moon !) whereas solar eclipses have been recorded for several thousand years, the first transit of inner planet was observed only in 1631 (Mercury), and till to date only five transits of Venus have been recorded (1639, 1761, 1769, 1874 and 1882). Why? Mercury's disc when transiting makes only ~10 arc seconds in angular size and that of Venus is also only ~1 arc minute and a "black spot" of this size cannot be easily seen with a naked eye on the solar disc. So observing transit of a planet needs two things; one, a telescope and second, an exact prediction.

Telescope was invented by a Dutch optician, Hans Lipershe, in 1608 and was first used for astronomical observations by Galileo in 1609. He observed the system of satellites going round Jupiter (now known as the four Galilean satellites) and was convinced of the heliocentric solar system. Of course, for announcing his faith in the heliocentric system, he had to face the inquision form the Roman Chruch; which is now a well known history. [Very recently, the church publicly declared that the inquisition of Galileo was a "mistake" on the part of the church].

Exact predictions of the planetary positions became possible through the laws of planetary orbits, by Johannes Kepler, in the beginning of the seventeenth century. On the basis of his now famous laws of planetary orbits, Kepler published tables predicting future planetary positions. The tables were named "Rudolfin Tables" in the honour of king Rudolf of Prague under whose support Kepler worked. Those tables which were published in 1672, gave for the first time a dates of prediction for the transits of Venus (Dec. 1631) and mercury (Nov. 1631). Venus transit could not be observed due to cloudy conditions, but the transit of Mercury was duly observed on 7 November 1631 by an astronomer named Gassondi. Not quite sure of the exact date of the transit, Gassondi. tried to observe it on three consecutive days and succeeded ! Thus, the November 1631 transit of Mercury became the first transit of an inner planet to be predicted and observed, in the history of astronomy.

As already mentioned, the transits of Venus occur in pairs separated by 8 years, and the next transit was to occur in December 1639. But at that time the 8 year pairs were not known, and Kepler's Rudolfin tables were slightly in error. Hence the tables did not predict a transit in 1639. However, a mathematician named Jeremiah

Horrox, used a refined "Lansberger Catalogue" of planetary positions and found errors in Rudolfin tables. His corrected predicted positions of planet Venus showed the transit to occur on 4 December 1639; which was duly observed independently by Horrox as well as his colleague Crabtree. But before going into detailed account of their observations, let us get a glimpse of the life sketches of Nicolaus Copernicus. Tycho Brahe and Johannes Kepler, the trio which laid the foundation of our understanding of planetary orbits.

Nicolaus Copernicus (of whom we made a reference in Chapter 1) was born at Tarun (Poland) to a wealthy merchant family in 1473. His father died when he was young and was then taken care of by his uncle, Bishop of Ermland. He studied law, and although interested in astronomy, till 1530 was mainly preoccupied with various administrative duties. At around this time, he published a writing of relatively limited circulation regarding his idea of heliocentric universe, which attracted the attention of the then pope Clement in 1533, and was asked an explanation. [English translation of this early writing has appeared in Proc. *Amer. Phil. Soc.* 117(6)(1973), 423]. So, probably fearing wrath of the established Church he withheld the publication of his famous "Revolutionibus …….("*On the revolutions of the heavenly bodies*") till on his death-bed. Of course, the Copernican system was not significantly more successful in predicting exact planetary positions, compared with the Ptolemaic system.

As already mentioned, the exact equations for the Planetary orbits were discovered by Kepler, but his formulations of the orbital equations were based on the precise planetary position measurements over a long period made by his predecessor, Tycho Brahe. Tycho is reputed to be the last of the naked eye astronomer, and earned a reputation for the precision of his position measurements in astronomy, and constructed his own devices for that purpose. He was born in 1546 in a noble family of Sweden, and was adopted at a young age by a rich uncle who saw to it that Tycho received good education at some of the then best institutions of Europe. (An interesting episode of his student life was a duel fought by him with a costudent also of a noble family, arising out of a dispute regarding "who was more apt in mathematics ! As a result of this duel, he lost the tip of his nose and spent the remaining life wearing an artificial nose made of gold-silver alloy !) His interest in astronomy was aroused when, at the age of 14 years he saw a total solar eclipse. He then acquired a device called "astrolabe" and started his own observations. When he was 17 years, the famous supernova explosion of 1572 (now known as Tycho's supernova) took place. Tycho took systematic observations of its day–to-day light variations, and became well recognized over Europe as an astronomer. [In passing, we remark here that an earlier well recorded supernova explosion was in the year 1054 which took place in the "Taurus" constellation. That supernova, now known as the "Crab" supernova, named after the shape of its remnant nebula, was recorded by the Chinese, Japanese and Korean chroniclers, but not in Europe. Crab supernova was a supernova type II, explosion of a massive star which leaves behind a compact object at its centre which may be a neutron star or even a black hole. The central compact object left behind in Crab supernova is the well known Crab pulsar – a neutron star. The Tycho's supernova, and the other supernova to occur immediately afterwards in 1604 (Kepler's supernova) were supernova of another type – type I in which the explosion is of an intermediate mass star, possibly in a binary stellar system and does not leave any compact object at its centre].

As a result of his spreading reputation, the then king of Denmark, Frederick II, gave him an island named Hven near Copenhagen to establish an astronomical observatory and also provided a substantial support towards that. Thus Tycho established his "Uraniborg observatory where he had a fairly long career, and equipped the observatory with many precision devices like astrolabe of high quality developed by himself. However, after king Frederick's demise in 1588 Tycho faced some difficulties. The new king was not prepared to provide unstinted support. Meanwhile, Tycho's reputation had spread all over Europe as an astronomer, and king Rudolf of Prague offered Tycho a position as his Principal Mathematician, as well as financial support to establish an observatory at Benatek near Prague. So Tycho shifted to Benatek along with his equipment from Uraniborg. It was when at Benatek, that Tycho was contacted by a relatively unknown mathematics teacher 'Kepler' in 1597.

Kepler was born in a large family of very ordinary circumstances in 1571 at a small place called Weil-der-stadt in Germany. He contracted small pox at a very young age of 4 and as a result developed weak eyesight. However, fortunately for him, the local nobleman in authority of that province was a philanthropist and helped towards education of poor deserving children. Right from childhood, Kepler had shown a promise of academic brilliance and as a result received good education upto the University level. He was destined towards a career of teaching religion, when studying at the Tubingen University, a small event changed the course. At a public debate arranged at the University, Kepler gave an eloquent support to the Copernican heliocentric world model. But to hold such a view was probably considered as inappropriate, for a "future priest" by the University authorities. Fortunately for Kepler, around that time, a mathematics teacher, for a school in the neighborhood town of Graz had expired, and the school authorities approached Tubingen University for getting a suitable candidate. Considering proficiency and aptitude of Kepler in mathematics (and his views on Copernican world system which were unsuitable for a priest !) the university authorities suggested his name even when Kepler did not have exactly the required qualifications for the job. Thus Kepler took up the teaching of mathematics; and it was at this time that he started working on the planetary orbits. However, his initial ideas were based more on belief in "harmony prevailing in nature" and the "geometrical perfections in the orbits", and in order to verify actual planetary motions against his model he needed exact planetary positions, for which Tycho had a great reputation and accurate tables over a long period. To gain access to that, Kepler contacted Tycho, sending him one of the book written by him. Tycho needed an assistant well-versed in mathematics, and offered a job. Kepler saw it as an opportunity to gain access to Tycho's observational records and accepted the job in 1597. However, Tycho wanted Kepler only to assist him in mathematics and would not entertain an idea of making all his observational record available to Kepler. So the relations between the two were strained. Physically also the two were poles apart! Tycho was of robust constitution and fond of good eating, whereas Kepler was of weak constitution. Tycho was from "nobility" and had his own belief regarding the world system, according to which the Earth was supposed to be at the centre, with the Sun going round it and the five known planets (at that time), Mercury, Venus, Mars, Jupiter and Saturn were supposed to be going round the Sun. On the other hand, Kepler firmly believed in the Copernican model. So, getting hold of Tycho's log-book of observations was out of question. Disillusioned, Kepler returned to Graz. But in the meantime the situation at Graz had also changed. The new nobleman in charge of the province had rather firm belief in the church supported doctrine of geocentric world model, and would not tolerate Copernican views. So Kepler again approached Tycho. Tycho took him back but with an understanding that Kepler had to be strictly an assistant to him.

However, luck again favoured Kepler, when Tycho died suddenly in 1601 under peculiar circumstances. (It is said that, during a party hosted by the local nobleman, the host was careless in not giving time to "ease" for the guests, and it was considered "out of etiquette" for a guest to rise before the host did. As a result, Tycho died of kidney failure !) Kepler lost no time in getting his hands on the log book of observations of Tycho – the purpose for which he had joined Tycho – the purpose which was now fulfilled !

With the observational record on hand, Kepler lost no time in working out the form of planetary orbits, and by 1609 he had arrived at the first two laws. To derive the third law of planetary orbits, he took nine more years. The first law states that planets revolve round the Sun in elliptical orbits with the Sun at one of the foci. The second law states that during this motion the areal velocity of the planet round the Sun remains constant; and the third law gives a relation between the orbital period "p" and the semi major axis "a" as $p^2 \propto a^3$. [This "third law" enabled the relative distance scale for Sun-planet distances to be established. Absolute distance between Earth and the Sun (astronomical unit) could then be obtained from the Earth-Mars distance measured for the first time in 1672 during an opposition of Mars. The mathematical genius of Kepler is seen here. Till that date, the planets were taken to be moving essentially in circular orbits (both in the geocentric system of Ptolemy and the heliocentric system of Copernicus). The centres of circles were taken slightly displaced from the central body (Earth or Sun) and the actual paths of planets were taken as to be on "epicycles" centered on circular orbits (called deferents) to match the observed planetary postions. [The "Siddhants" of Indian astronomical systems are also based on similar models]. Of course, Kepler's laws can be derived from Newtonian gravitation, but when Kepler formulated his laws, the discovery of law of gravitation was still a matter of half a century in future ! Due credit must be given to Tycho because it was only on the basis of precise observational data of Tycho, that kepler could arrive at his laws.

On the basis of his orbit laws, Kepler published a table of future planetary positions, called "Rudolfin Tables" (in the honour of king Rudolf under whose support the Benetek observatory was functioning). It was in these tables that the first definite predictions of transits of Mercury (November 1631) and Venus (December 1631) were indicated. Rudolfin tables were published in 1627, and in 1630 Kepler expired. But his prediction of the transit of Mercury was verified when an astronomer named Gassondi: observed the transit on 7 November 1631. So this transit became the first transit of an inner planet across the solar disc to be observed. That time the actual distances to the planets were yet unknown, so interest was also to measure the angular diameter at the time of transit, and this was determined to be ~20 arc seconds (modern value is ≈ 11"). The transit of Venus predicted for December 1631 could not be observed because the period happened to be cloudy over Europe. It may be mentioned here that the transit of mercury was observed by Pierre Gassendi with an effort for three consecutive days ! (One did not have sufficient confidence in predicted planetary positions at that time).

The next transit of Venus, to occur in 1639 December, was actually not indicated in Rudolfin tables, according to which, during that inferior conjuction path of Venus was just missing the solar disc. This small error was arising out of the fact that the Rudolfin tables gave planetary postions with centre of Earth as the origin, whereas the observer is actually on the surface of the Earth; and the small parallax appropriate to the radius of the Earth makes a small change in the actual positions of planets as observed. A British mathematician named Jeremiah Horrox recalculated the path of Venus for the inferor conjuction of Venus to occur in December 1639, using a refined Lansberger tables prepared by a Belgian astronomer and found that Venus was to actually transit the solar disc during that conjunction. [Venus transits occur in pairs separated by 8 years only during the current epoch. Complete cycle of transits is of 243 years and in the previous cycle only one transit of 1396 would have occurred. More about this later when we discuss the 8 year pairs in same details]. Horrox had studied mathematics and astronomy from the Cambridge University and "was then employed as a school teacher and a priest in charge" of a cathedral in a small town near Liverpool. According to his calculations the transit was to occur on 4 December, and he also motivated his Cambridge costudent William Crabtree to try to observe it. The day was a Sunday and Horrox had special duties at the church for the day. But immediately on completion of his church duties at 3.15 PM, he rushed to observe and was in time to record the second contact, (time at which Venus just appears completely submerged in the Sun). His friend Crabtree had some problems due to clouds but he also could intermittently see the transit, and thus confirm observations of Horrox The angular diameter of Venus was measured as 1 arc minute (close to the actual Value)

Emergence could not be observed because the sunset occurred prior to that. Thus Horrox and Crabtree became the first persons to observe this rare event. On the basis of their observations, Horrox estimated the Earth-Sun distance as 56 million miles (90 million kilometres, mean actual value is 149 million kilometres). Note that in those days the actual planetary and Earth distances from the Sun were totally unknown and even a rough estimate was valuable.

The period after the early part of the seventeenth century was the time of intellectual "awakening" over entire Europe. It saw a great change in the "mind-set" turning from the "dogmatic thinking" to the "rational thinking". The ruling class as well as the general public increasingly turned towards science as a means to "power and prosperity". So the scientific research and expeditions towards that found increasing support from the rulers. An important unsolved problem at that time – till the late seventeenth century was to obtain the actual value for the Earth-Sun distance, which would establish the absolute scale for the distances in the solar system. As already mentioned, the relative distances of various planets from the Sun could readily be derived from the Kepler's orbital law $P^2 \propto a^3$; but not the actual scale. The problem was finally solved by Cassini (and also Flamsteed independently) who measured the parallax in the position of Mars with respect to the stellar background when observed from widely separated locations on the Earth. The value of this parallax was successfully measured for the first time in 1672 when Mars was in "opposition" (in its near position to the Earth).

Cassini was the first Director of the Paris Observatory and is known for his discovery of the gap between two bright rings of Saturn, now called the "Cassini division".

In his honour, the recent European space Agency's mission to Saturn is named the "Cassini-Huygens mission". This spacecraft has two parts. The orbiter "Cassini" to study the Saturn, will eject a lander "Huygens" to land on the largest satellite of Saturn – "Titan". Titan is the only satellite in the solar system to posses a rather dense atmosphere. Further, this atmosphere has some peculiar type of particles creating a "haze". These particles are believed to be some type of hydrocarbon polymers. The surface of Titan has possibly seas or lakes of liquid methane with solid methane blocks floating in it ! The type of environment may be suitable for evolution of prebiotic molecules and hence its study holds a special attraction to scientists.

"Parallax" in the position of Mars was observed for the observations carried out from two widely separated locations: Paris and French Guyanae (where ESA's famous launching site at kourou is now located). The Earth-Sun distance derived from this by Cassini came out to be 140 million kilometers; much larger than 90 million kilometers estimated by Horrox. The most modern value accepted now is 149.59787066 million kilometres – accuracy of ± 20 metres ! This is from radio propagation time from Viking landers on mars to the Earth.

Because of the importance of the mean Earth-Sun distance (the astronomical unit) in the distance measurements within the solar system; its accurate determination was an important problem in 17th and 18th centuries. Famous British Astronomer Royal Sir Edmond Halley suggested that observations of a transit of Venus from two locations on the Earth having a large separation in north-south directions could give very precise value for a measure of the astronomical unit. Halley's name is much better known in the history of astronomy in connection with the comet Halley named after him. He was the first person to suggest that comets, are the solar system bodies moving under Sun's gravity in periodic orbits, but unlike approximately circular orbits for the planets, their orbits are highly elliptical. Specifically, he suggested that a bright comet seen in 1682 is a periodic comet that reappears every ~76 years; and should appear again in 1758.

The idea that transits of inner planets could be used for the determination of the astronomical unit was in fact suggested earlier by a Scottish astronomer Gregory, Halley suggested a method by which the transit paths could be accurately located on the solar disc. At that time, photography was still a matter of future and obtaining the transit paths with sufficient accurancy to determine the angular separation of the paths as observed from two distant locations would have been an impossible job. But Halley suggested a method by which the transit paths could be accurately derived from the exact duration of the transits observed from these stations. This reduced the problem to the exact recordings of the contact times; and accurate clocks had been developed at that time. [In 1760, a British Clock maker John Shelton supplied 5 clocks, called "Astronomical regulators" which were very accurate, to the Royal Society. All of these still exist, and in addition to their use for the timings of Venus transits, they have played very important role in several other experiments like accurate measurement of the "acceleration due to gravity-g"] Halley's method is schematically shown in Fig.7. The transit paths on the solar disc are determined accurately from two locations P_1 and P_2 having a large north-south separation on Earth. From the difference of the paths observed (due to parallax), the angle ψ is determined. Now $\psi = \theta - \phi$, as shown in Fig. 7. But $\theta \sim L/Dv$ and $\phi = L/Ds$ where Dv and

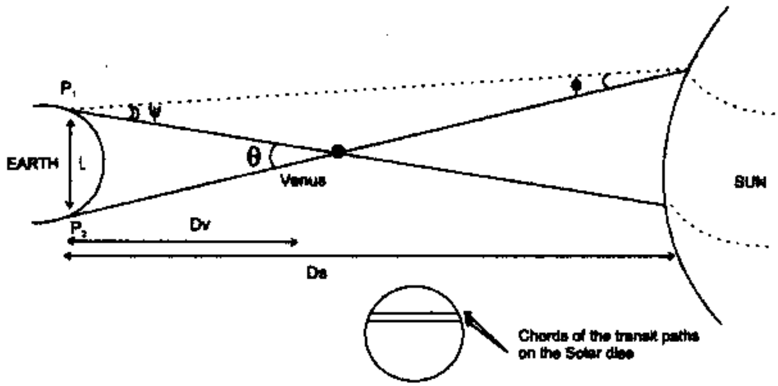


Fig. 7: Schematic diagram explaining the illustrating determination of the "astronomical unit" Ds from the observations of transit of Venus.

Ds are the distances to Venus and Sun respectively. Also, as explained earlier, the ratio Dv/Ds is precisely known using Kepler's equation giving the period-semi major axis relation $P^2 \propto a^3$. Combining these equations both Dv and Ds can be determined.

Halley expired in 1742 before the next Venus transit of 1761 took place (also before the famous comet named after him reappeared !). But to observe this event both British as well as French astronomers organized expeditions (also a couple of other countries). History of these expeditions is quite interesting, but we will only narrate a few episodes. A French astronomer, Le Gentil, had planned observing from Pondicherry in India, but to his misfortune war broke out between French and British. Before Le Gentil could land, Pondicherry was captured by the British. Le Gentil's ship returned towards Mauratius and he had to satisfy himself observing the event from the ship! Le Gentil spent then several years in Mauritius studying the local fauna and fluora. He then decided to return to India to observe the 1769 event and built an observatory for that. (He also studied Indian Astronomical system in the meantime) Unfortunately for him a storm swept over Pondicherry just on the day of transit!

The British scientists also had their share of problems they were to observe the 1761 event from "St. Helena" and Sumatra. But the team heading for Sumatra had to stay back at Cape of Good Hope, due to a French naval attack. However, they had some successful observations, but the observers from St. Helena were unsuccessful due to cloudy conditions.

A French astronomer, Chappe d' Autroche, successfully observed from Siberia (It is also possible to infer the distance to Venus by measuring the time difference for the event as observed from two locations with a large East-west distance]. French government then appointed him to lead a team to observe the next transit of 1769, for which he went to Baja (California). They had successful observations, but subsequently he and some of his team members contracted some mysterious fever and died.

A Russian scientist, Lomonosoff made one important observation from St. Petersberg, that during the transit the black disc of Venus appears to be surrounded by a bright halo. This observation was important in inferring existence of a dense atmosphere surrounding the Venus. The effect is due to refraction of Sunlight in its passage through the atmosphere of Venus. Another important effect (also due to refraction in the Venus atmosphere) observed was the "blackdrop" or the "tear drop" effect. Due to this effect, the disc of Venus continues to remain connected to the solar limb by a dark "bridges" even after the second contact (i.e. complete immersion of Venus). Similar effect also appears on the third contact when Venus is emerging from the solar disc. These atmospheric refraction effects make it difficult to precisely time the contacts in the case of transits of Venus (but not for the Mercury which does not have any atmosphere).

On the whole, the 1761 transit observation did not fulfill the goal of precise determination of the astronomical unit.

The next transit to occur in 1769 also attracted number of expeditions – especially to islands in the Pacific Ocean where the event was best observed. A most notable was that of Sir Joeseph Banks who was with Captain Cook's circumglobal navigation team. To Sir Banks, observing the event was the most important but for Captain Cook it, was perhaps a good justification for his tour! They observed the event from a place in Tahiti, and the point from where the observations were made is now known as the "Point Venus". This was during the first of Captain Cook's three historic journies. It was on his third journey that he was murdered at Sandwich Island in 1779 in a local feud.

An amateur astronomer named John Bevis (medical practioner by profession) observed this event from Richmond (USA) and published the notes in "Philosophical Transactions". John Bevis is better known for his discovery of the "Crab Nebula" which is the remnant nebula of the 1054 supernova explosion recorded by the Chinese as a "guest star". This nebula has now at its centre a compact neutron star from which pulses at radio wavelengths are received ~30 times a second. Such objects are known as pulsars, and the Crab pulsar being one of the youngest pulsars known (formed through supernova type II explosion) also emits pulses at gamma ray, X ray and optical regions. Coming back to the transit event even this transit could not give the measure of "astronomical unit" with an accuracy better than that obtained by Cassini earlier. The main difficulty was accurately recording the transit paths from two separate stations which could then be intercompared. Photography was not yet invented. Some European observers also observed from India, but the results did not have any scientific value.

The next transit of 1874 changed the scene drastically. By this time photography was invented (1835) which could enable accurate intercomparison of paths. Also much better telescopes and time keeping methods had been developed. As a result the 1874 transit observations gave fairly satisfactory value of the astronomical unit as 149 million kilometres (which may be compared with the modern accepted value of 149.597870 million kilometres as derived from the radio sounding to Venus at the time of its inner conjuction in 1961). The 1874 transit was observed also by Ernst Emil Baker of the Berlin observatory.

The French made concentrated efforts during the 1874 and the 1882 transits. Teams were sent as far as Nagasaki, Peking, Saigon, Noumea, St. Paul and Maurice Islands as well as expeditions spread out between North Africa, Maxico and Chile. On the basis of transit observations, Newcombe fixed the soalr parallax (parallax at the Sun) of 8.794" giving the value 149 million km for the astronomical unit. Pingre had also deduced a very similar value from the earlier transits, through the individual observations were quite divergent. A noteworthy point is that, the Yale heliometer established at that time at a height of 4300 meters in Rocky mountains (USA) and the largest instrument of its kind at that time, started scientific programme with observation of this event.

However, now the transits have lost their value for this purpose as more accurate determination of the astronomical unit has been possible through the radar echo. Transits of Venus are now attractive only because they are rare phenomena of nature, attracting attention mainly of amateur astronomers and science communicators ! The 8 June 2004 transit is the next Venus transit to occur after December 1882. As already mentioned, the event can be seen with naked eyes by persons having keen eyesight, but appropriate safety device to reduce solar brightness must be used.

Observations of transits of the other inner planet, viz. the Mercury have played a more important role in fundamental physics. These transits which are as frequent as ~14 per century have been carefully observed for the precise timing and locations of the "contact points" with the solar disc, to get the accurate orbital parameters. Orbit of Mercury is markedly elliptical and the point on the orbit closest to the Sun, the perihelion point, executes a precessional motion (i.e. its direction in space rotates with a specific rate). This "precessional" motion is due to the perturbing effects of the gravitational forces by other planets exerted on Mercury, and has been precisely calculated using Newton's gravitation theory. But the transit observations showed a nagging discrepancy between the observed precessional rate of 574 arc seconds per century and the calculated rate of 531 arc seconds. Earlier, a French astronomer – mathematician Le Verrier had successfully predicted existence and position of the planet Neptune from the perturbations caused by it on the orbit of Uranus. So, encouraged by his earlier success, he predicted existence of a planet within the orbit of Mercury and also gave a name to it – Vulcan ! Many attempts were made to find the "Vulcan" during total solar eclipses, but without success. Finally, the mystery was solved in 1915 when Einstein showed on the basis of general relativity, that calculated according to his theory, the precessional rate should indeed be 574 arc seconds per century, and no "Vulcan" was needed for that ! This, together with the measurements on the apparent shift in the positions of stars close to the Sun due to curvature of space near the Sun (observed in 1919 by a team led by Eddington during a total solar eclipse) were the two early observations supporting the general theory of relativity.

The transits of the inner planets as phenomena, are very similar to the solar eclipse by the Moon. Moon's orbital plane is inclined at 5^0 to that of the Earth's ecliptic). So on each new moon (Amavasya), Moon does not obstruct the Sun; it may pass either slightly to the north or to the south of the Sun. The points where the Moon's orbit "intersects the ecliptic plane are the nodal points of Moon's orbit" and have been given the names "Rahu" and "Ketu". Only if on a particular new moon day the Sun happens to be near one of these nodes, an eclipse of Sun will occur. The margin of tolerance for the "nearness" is $+15^0$ for an eclipse. Similarly the orbit of Venus is inclined to the ecliptic by 3^0 and the points of its intersection with the ecliptic are the nodes of the orbit. If during a particular "inner conjunction" of Venus, the Sun happens to be close of one of the nodes, then only Venus will be seen to transit the solar disc, otherwise Venus will pass either slightly to the north or to the south of the Sun. The degree of tolerance in the "nearness" is much smaller than in the case of solar eclipse because Venus is much farther than the Moon. At the present epoch, the Sun is in the direction of the nodes of the orbit of Venus, when Earth in its journey round the Sun is at positions corresponding to December 8 and June 7; so the transits of Venus will be seen if the inner conjunction of Venus happens to be within two days of these dates. Hence transits of Venus are much rarer events than the eclipses. Another factor contributing to the rarity of transits of Venus is the long synodic period (time interval between the successive inner conjunctions) of Venus — 584 days. The corresponding period for the Moon is only 29.5 days.

In case of Mercury the transit probability dates are within 3 days of May 8 and 5 days of November 9. Difference is due to the large ellipticity of the orbit of Mercury. Also, because the synodic period of Mercury is only 116 days, its transits are comparatively more frequent, and more in November than in May. Due to the precessional motion of orbits, the directions of the nodal points slowly change. Thus the "central dates" for the transit of Venus are slowly receding at about a day in a century. "Transits recorded couple of centuries before were earlier in June and December; than the current dates.

Transits of Venus take place in pair of eight year separation, alternately in December and June. December and June are alternately the dates when the Sun appears in the direction of ascending and the descending nodes the orbit of Venus. [Ascending node is where the planet crosses the cliptic plane from south to north. The other node is called the descending node]. But why are they in pairs? The explanation is interesting. As already mentioned, the synodic period for Venus (internal between the successive inner conjunctions) is 583.9 days.

The synodic period of Venus (interval between the successive inner conjunctions) is 583.9 days; where as the Earth's orbital period is 365.25 days. Thus after 8 years (2922 days) Venus will have completed 5 synodic periods and will have further advanced 2 days in its orbit. Inclination of the orbit of Venus to the ecliptic is so small that, in 2 days time Venus shifts north-south only by 22 arc minutes. This being less than the angular dimension of the Sun (30 arc minutes), if on a particular inner conjunction a transit is seen on the disc more than 7 arc minutes away from the centre of the solar disc, then after 8 years, at the time of the inner conjunction, the path of Venus will again fall on the solar disc shifted by 22 arc

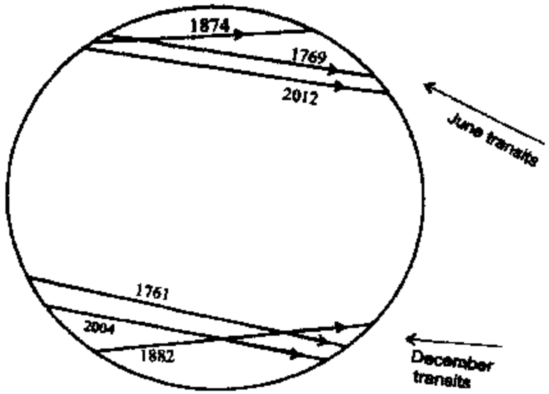


Fig. 8. Figure showing the downward (southward) drift of the transit paths. After several centuries, the leading transits of the June pairs and the trailing transits of the December pairs will miss the solar disc and single transits rather than pairs will be observed.

minutes from that of the earlier transit. But this need not be always so. If the first transit is within 7 arc minutes of the centre, the one after 8 years will miss the disc. As shown in Fig. 8, transit paths in successive cycles are slowly drifting southwards. At the present epoch, the transits are occurring with the intervals like 105½ and 8 years (December transits) and then 121½ and 8 years (June transits) making a complete cycle of 243 years. But 1396 transit in December must have been a single transit, with 1388 path missing the disc. As these paths are slowly drifting southwards, several centuries from now again there will be only two transits in a complete period of 243 years, the ascending node transit in December occurring 105½ years after a descending node transit of June, and the next June transit following after 137½ years. The inequality in the intervals is mainly due to the non-uniformity in Earth's orbital motion because of small ellipticity of its orbit. The 243 year cycle corresponds to a very close match with 152 synodic periods.

Although the solar eclipse and the inner planet transits are very similar as phenomena, some differences must be noted. Firstly of course the angular diameter of lunar disc is much larger than the angular diameter of the inner plants, and obstruction of the solar disc by the Moon is so conspicuous that the eclipses have been known since prehistoric times. In comparison, the disc of Venus makes only 1 arc minute (1/30 of the solar disc) at the time of transit. The average human eye can resolve objects upto ~4 arc minutes; so during a transit the disc of Venus cannot be "resolved" by the naked eye, but can be "seen" if an observer "looks for it". This is why the transit of Venus could not have been even accidentally discovered; before the invention of telescope and definite prediction of the phenomena. (Disc of Mercury is even smaller, ~10 arc seconds at the transit). Of course, one must take great care in protecting the eye against solar radiation by using an appropriate Solar filter when attempting to visually see the transit.

The second major difference is the direction from which the transit occurs. Moon is revolving round the Earth, so when passing between the Earth and the Sun, it moves across the Solar disc from the west to the east. The planets move around the Sun and are "overtaking" the Earth in their counter clockwise orbital motion, so transit will begin from the eastern limb of the Sun and end at the western limb. The third major difference is in the speed of the "shadow". The Moon being very close, the shadow speed is much smaller, less than a kilometer per second. In fact, at the time of totality, one can actually make out the shadow approaching from the west. The planets being much farther, the "shadow" (of course there is no marked shadow, technically it is an inconspicuous "penumbral" shadow) moves much faster from east to west; speed of few tens of km/sec. Also due to the same reason, whereas the solar eclipse appears different from different locations and may not even be seen from some locations even if the Sun is above the horizon at the time; the transit will appear almost the same from all locations from where the Sun is seen at that time (except for a small shift in the transit path due to the parallax),

Finally, some "tips" about safely seeing this rare celestial event, which although Kepler predicted he himself had no chance of seeing it, and though Halley proposed a very important astronomical aspect, he too did not have a chance ! As already mentioned, the event itself can be seen looking directly at the Solar disc wearing appropriate qualified sunsafe goggles. One must note that, it is not quite as risky to look at the Sun during the transit, as during the total eclipse. During the total eclipse the background is dark and the iris of the eye is fully dilated to see in faint light, so the image of the remerging disc on ratina can be very harmful. However, during the transit, the backgrounds very bright so the iris is fully contracted. But to see the transit one has to "stare" at the disc, and that can be quite injurious to the eyes. If your goggles are not adequately dark, do not stare at the Sun.

A much better way is to project a magnified image of the Sun on a screen with the help of a small telescope. Image with a suitable magnification can be obtained on a screen when the eyepiece is slightly drawn away from the usual focal position. A Newton telescope is very much suitable as it readily permits projecting the image in a dark room, where it can be simultaneously be seen by a larger group. If direct viewing telescope (a refractor or a Cassegrain) is used then it is better to provide some shade to the projection screen for a comfortable viewing on the screen.

If it is desired to time the contact (1st contact when Venus touches the limb, 2nd when Venus is completely submerged and similar two other contacts during the emergence) then directly seeing through a good telescope (~ 100 to 150 mm aperture) is more appropriate, but the telescope must have a properly qualified solar filter by a standard manufacturer placed on the objective [or you must yourself be a good astronomer to judge what is ok!] Of course, seeing with such a telescope can be much more satisfying as various phenomena, like the inkdrop effect, and the halo around venus after submergence, due to refraction can also be seen. It is good to detect Venus before contacts, when it should show a complete ring around it (only possible from good sites with deep blue sky).

In absence of a small telescope, one can project the solar image on a screen using good spectacle lanses. Use ~2 diopters as the objective and ~5 diopter (both +) for projection.

So, with these tips (and many more you are sure to receive before the event) watch out for the June 08 event! The entire event would be seen from all over India.

Transit of Venus - 2004 June 08
Circumstances for some important Indian Cities

Venus will pass across the disk of the Sun during a rare transit on 2004 June 08. This uncommon event will be visible from the entire Indian subcontinent. The following table presents detailed predictions for a number of Indian cities. The start and end times are given in Indian Standard Time.

Transit Contacts

Location Name	Contact I External Ingress h m s	Contact II Internal Ingress h m s	Greatest Transit h m s	Contact III Internal Egress h m s	Contact IV External Egress h m s
India					
Agartala	10:44:34	11:03:32	13:46:43	16:31:06	16:50:20
Agra	10:46:01	11:05:04	13:48:01	16:31:37	16:50:48
Ahmedabad	10:46:24	11:05:25	13:48:37	16:32:15	16:51:22
Allahabad	10:45:35	11:04:35	13:47:39	16:31:30	16:50:42
Asansol	10:45:00	11:03:58	13:47:08	16:31:20	16:50:32
Bangalore	10:45:31	11:04:24	13:48:14	16:32:44	16:51:46
Bhopal	10:45:57	11:04:56	13:48:07	16:31:56	16:51:04
Bhubaneswar	10:44:58	11:03:54	13:47:16	16:31:38	16:50:48
Chandigarh	10:46:14	11:05:20	13:48:06	16:31:27	16:50:40
Chennai	10:45:15	11:04:07	13:47:56	16:32:33	16:51:36
Coimbatore	10:45:30	11:04:22	13:48:19	16:32:57	16:51:58
Delhi	10:46:09	11:05:13	13:48:05	16:31:34	16:50:46
Dhanbad	10:45:04	11:04:02	13:47:12	16:31:21	16:50:34
Gangtok	10:44:59	11:04:56	13:48:36	16:32:46	16:51:49
Guwahati	10:44:38	11:03:37	13:46:41	16:30:55	16:50:11
Hyderabad	10:45:37	11:04:32	13:48:04	16:32:19	16:51:24
Imphal	10:44:21	11:03:19	13:46:28	16:30:54	16:50:10
Indore	10:46:05	11:05:05	13:48:17	16:32:04	16:51:12
Itanagar	10:44:29	11:03:29	13:46:30	16:30:46	16:50:03
Jabalpur	10:45:41	11:04:40	13:47:51	16:31:47	16:50:56
Jaipur	10:46:13	11:05:16	13:48:15	16:31:46	16:50:57
Kanpur	10:45:46	11:04:48	13:47:48	16:31:31	16:50:43
Kavaratti	10:45:56	11:04:49	13:48:49	16:33:17	16:52:16
Kolkata	10:44:49	11:03:46	13:47:00	16:31:20	16:50:32
Lucknow	10:45:44	11:04:45	13:47:44	16:31:28	16:50:40
Madurai	10:45:20	11:04:11	13:48:13	16:32:58	16:51:58
Mumbai	10:46:15	11:05:13	13:48:39	16:32:33	16:51:38
Nagpur	10:45:42	11:04:40	13:47:58	16:31:59	16:51:07
NewDelhi	10:46:09	11:05:12	13:48:06	16:31:34	16:50:46
Patna	10:45:16	11:04:16	13:47:19	16:31:18	16:50:31
Port Blair	10:43:51	11:02:40	13:46:38	16:31:56	16:51:04
Pune	10:46:08	11:05:05	13:48:33	16:32:31	16:51:36
Shillong	10:44:36	11:03:34	13:46:40	16:30:57	16:50:13
Srinagar	10:46:32	11:05:40	13:48:17	16:31:22	16:50:37
Surat	10:46:19	11:05:19	13:48:38	16:32:23	16:51:29
Thiruvananthapuram	10:46:24	11:04:14	13:48:22	16:33:10	16:52:10
Varanasi	10:45:28	11:04:28	13:47:32	16:31:27	16:50:39
Vishakhapatnam	10:45:08	11:04:02	13:47:33	16:31:59	16:51:06

Glossary

Albedo : Diffuse reflectivity of a planetary surface. Apparent brightness of a planet will depend (1) on its distance from the Sun, (2) distance from the Earth and (3) its surface albedo. Venus, being cloud covered has a high albedo of more than 70% in comparison to a surface like that of Moon ($\approx$16%) and hence appears so bright.

Aphelion (and Perihelion) : The maximum distance of a planet going round the Sun in an elliptical orbit is called its aphelion distance; and the minimum distance is called the perihelion distance. The difference between the aphelion and the perihelion distances will be large for orbits having large ellipticity. Comets go round the Sun usually in highly elliptical orbits and may have their perihelia inside orbit of Venus, but aphelia beyond the orbit of Neptune !

Asthenosphere : A high temperature region below the crust of the Earth, but above the mantle where the silicate rocks are in molten or semi-molten condition. This region is the seat of Earth's volcanism and the lava originates here. Plate tectonic processes are due to the crustal plates sliding on semifluid asthenosphere.

Astrolabe : An ancient device to obtain positions to celestial objects without going through the spherical geometry calculations, was used upto the middle ages. Now only of historical interest.

Astronomical Unit (AU) : Mean Value of the Earth–Sun distance. The relative distances of the planets from the sun can readily be obtained from their orbital periods using Keplar's third orbit law which relates the orbital period with the semi major axis; and can thus be expressed in the AU measure. Finding the value of AU in kilometers was a formidable problem, first tackled reasonably well by Cassini in 1672. The presently accepted value for AU is 149597871 km.

Aurora (and Radiation Belts) : The Sun continually emits a high velocity stream of charged particles (plasma) called the "solar wind". This plasma stream is deflected thousands of kilometres away from the Earth by the magnetic field of the Earth. The Earth is thus covered with a protection sphere against the direct solar wind particles – called Earth's magnetosphere. However, the charged particles can enter via the magnetic field lines to the polar regions where it excites the atmospheric atoms and molecules to radiate. The visual radiation is called the Polar Aurora. Also, the magnetic field of the Earth traps the solar wind particles in two belt-like regions couple of thousand kilometres above, called the "Van Allen radiation belts". Venus has no significant magnetic field and hence no "magnetosphere" or "radiation belts".

Black Drop (Also Called Ink Drop/Tear Drop): At the start of transit of Venus, (and also near the end of it) the Sun's rays will be "skirting" the thick atmosphere of Venus and will be strongly refracted, in that atmosphere. This causes an optical effect in which the disc of Venus seems to be joined by a darkish looking "bridge" to the solar limb even after the exact time of the second contact (i.e. when Venus is just submerged in the Sun's disc). Similar effect is also seen near the third contact at the time of emergence of Venus. This effect is called the "black drop effect" and is mainly responsible for the difficulty experienced in the exact timings of the contacts.

Conjunctions : Just as the places on the Earth are located by their geographical latitude and longitudes, the celestial objects are also assigned similar co-ordinates on the celestial sphere. However, in the case of celestial objects two alternative systems are used. Stars are usually located through their "Right Ascention" and "Declinations" which use celestial equator as a reference circle, whereas positions of the solar system objects like planets are usually given in terms of their celestial latitude and longitudes which use the ecliptic circle as the reference (co-ordinate giving the position on this circle is the "longitude"). When two celestial objects have the same longitudes they are said to be in "conjunction"; (but due to their possible latitude differences their positions need not overlap). Inner Planets will have two types of conjunctions with the Sun. At the time of inferior conjunction, the planet will be between the Earth and the Sun; whereas, when the Sun is between the planet and the Earth it is the superior conjunction. If at the time of inferior conjunction, both the Sun and the planet also have the same celestial latitude then the planet will "transit" the solar disc. At the superior conjunction a similar situation will result in the Sun hiding the planet (but obviously the event cannot be readily seen).

The exterior planets will have only the "superior" conjunctions. The other position will be the "opposition" where the planet is at 180^0 latitude difference with the Sun, of course, at that time an imaginary inhabitant of that planet will see the Earth having "inferior conjunction" with the Sun!

Contacts : During transits, four "timings" are important. First is the time at which the planets disc just touches the solar limb. This is the first contact; beginning of the transit. Next is the second contact when the planets disc just gets totally submerged in the solar disc. Similarly during the emergence of the planet one has the "third" and the fourth" contacts.

Dichotomy : Position of exactly "half phase" (like the half moon). At the time of "dichotomy" the angle between the Sun, the object (whether an inner planet or the Moon) and the Earth will be exactly 90^0. The moon being very close to the Sun at the time of its dichotomy, will also appear to be "almost" perpendicular to the direction of the Sun (that is why Moon's half phase occurs almost 7-8 days after thee "new moon"). But for the inner planets the situation is very different, (see Fig.3).

Ecliptic : The plane in which the Earth orbits around the Sun, is the ecliptic plane. Projection of this plane on the celestial sphere is the ecliptic circle, and the Sun will always be found at some point on this circle any time in the year. The orbital planets make only small angles with this plane, only Mercury and Pluto are exceptions and make rather large angles of 7^0 and 17^0 respectively.

Elongation : Apparent angle made by a celestial object with the Sun as seen from the Earth. For the inner planets, this angle has as upper limit depending upon its distance from the Sun. For Venus it is $\sim 46^0$ and for mercury it is $\sim 28^0$. So these two planets are seen only in the western sky after the sunset or in the eastern sky at the dawn.

Green House Effect : Trapping of the energy in the visible light of the Sun by an atmosphere of a planet; when the atmosphere is transparent to the visible light but opaque to the infrared. Visible radiation heats the surface which then radiates in the infrared. But as the infra-red cannot escape, the surface attains a high temperature. Strong greenhouse effect in the atmosphere of Venus has resulted in its abnormally high surface temperature of $\sim 470^0$ C.

Nodes : Planetary orbits (and that of the Moon also) make a small angle with the ecliptic plane and hence will intersect it at two diagonally opposite points of the orbit. These are called the nodal points of the orbit. Point at which the planet in its orbit crosses the ecliptic plane from south to north is called the "ascending node" and the other the "descending node". Twice during an year, the Earth will be at such a position in its orbit (almost six months apart) that the Sun will appear in the direction of node of a particular planet. If that planet is an inner planet and reaches inferior conjunction at the same time, it will be seen to transit the solar disc. Analogous consideration also holds for eclipses. The two nodes of lunar orbit are respectively called "Rahu" and "Ketu" in India.

Planetesimals : When the planets were under formation in the solar system through accretion of the protosolar disc material, initially very large number of planet like but much smaller bodies (around hundred to thousand kilometer in sizes) were formed. These are called planetesimals. Planets formed by the accumulation of such planetesimals. Rocky asteroids within the orbit of Jupiter and icy comet like bodies found outside Neptune's orbit (called trans Neptunian, or Kuiper belt objects) could be such remaining planetesimals.

Protosolar Nebula : Disc-shaped cloud of dusty gas from which the solar system and the Sun were formed. Central part condensed to form the Sun, and the planets were formed through condensation of the outer parts.

Retrograde (Rotation/Revolution) : If one is placed in space, north of the mean plane of orbital revolutions of planets, the planets would appear to be going round the Sun in a counter clockwise fashion. This type of motion is called the "prograde revolution" and an object going "clockwise" in the other direction is said to be having retrograde revolution. In the solar system, only some comets and some small satellites of larger planets show retrograde revolutions.

Also as seen above most of the planets would be seen to be rotating around their axis in an anti-clockwise fashion, which is called the "prograd rotation". Only the Venus is unusual in that it has a very slow retrograde rotation (i.e. to rotate clockwise as seen from north).

Siderial Period (Rotation) : Siderial rotation period of a planet is its axial rotation rate as referred to the background of stars and measures the true rotation. Its rotation referred to the Sun (and hence day + night duration) would in general be different due to the contribution of the orbital motion. For example, in case of Earth the sidereal rotation rate is 23^h- 56^m, but the duration of day + night (civil day) is 24^h. For Venus, the sidereal rotation is 243 days and retrograde, its "civil" day is nearly 117 days !

Supernova (Type I, Type II): Supernovae are stupendous stellar explosions in which a star destroys itself, but also brightens by about several billion times for a short duration. There are mainly two different types of such explosions. In type II, a star having an initial mass about 15 times or more than that of the Sun, undergoes nucleosynthesis processes all the way upto iron nuclei and then explodes. Actually, in this type of supernova the explosion is preceded by an implosion due to sudden large decrease of pressure at the core (the core collapse). The explosion is then a rebound effect, so at the centre a very compact object is left, which may either be a neutron star or even a black hole.

Supernovae type I are explosions of somewhat less massive stars and mostly in binary systems. Here one of the component star has reached a white dwarf stage and when the other companion star reaches a red supergiant stage, the supergiant's material is drawn towards the white dwarf. If the mass of the white dwarf then exceeds the Chandrasekhar limit of the white dwarf it will explode. Such an explosion leaves no residual compact object. Chandrasekhar limit is the theoretical upper limit for a white dwarf mass, established by S.Chandrasekhar on relativistic-quantum mechanical considerations around 1931.

Synodic Period : The time interval at which a particular planet apparently reaches the same position with respect to the Sun is its synodic period. Thus interval between successive inferior (or superior) conjunctions would be the synodic period.

Synthetic Aperture Radio Mapping : A high image resolution radio mapping technique in which signals received by separate radio telescopes are combined interferometrically to achieve high resolution radio imaging. In an extreme case, radio telescopes located thousand of kilometres away may be combined to give extremely high resolution which can "pinpoint" location of an object reflecting or emitting radio waves.

Tectonics: Internal processes (like volcanism, thrusts) by which a planetary surface is restructured. Plate tectonics is a particular case where the upper crust is broken up into separate plates, which then ride on semifluid "asthenosphere" region below. On Earth, plate tectonic processes operate giving rise to the continental drifts. About 200 million years back, the entire land-mass of Earth was forming a single continent (named "Pangaea") which then broke up, and the separate plates are sliding and have resulted now in the present continent forms. On Venus one does not have any evidence of plate tectonics, but volcanic process have operated.

Transits : A smaller celestial body orbiting a larger body can at times come in the line of sight as seen from the Earth, obstructing it. Such events are called "transits". Thus Jupiter's large moons are at times seen to be transiting Jupiter's disc. Similarly the planets Venus and Mercury which have their orbits inside that of the Earth are occasionally seen to transit the solar disc. Solar eclipse is technically a "transit" of moon across the Sun (but lunar eclipse is not. It is transit of Earth as seen from the Moon!) However, sporadically occurring events like occasional passage of a planet (or moon) over a star is called an "occultation" event.

Also note that the term "meridional transit" has a different meaning. The north-south circle on the celestial sphere passing overhead through Zenith point is called the "meriodional circle", and passage of a celestial body across this circle from east to west daily is called its "meriodional transit".

Suggested Further Reading

1. Aleksandr T. Bezilevskiy. "The Planet Next Door". *Sky and Telescope*, pp.360-368; April 1989

2. J. Kelly Beatty. "Working Magellan's Magic". *Sky and Telescope,* pp.16-21, August 1993

3. Ellen R. Stofan. "The New Face of Venus". *Sky and Telescope,* pp.22-31 August 1993

4. Janet G. Luhmann, Jam's B. Pollack and Lawrence Colin "The Pioneer Mission to Venus". *Scientific American,* pp.68-75 April 1994

5. J. Kargel. "The Rivers on Venus". *Sky and Telescope,* Aug. 1997

A summary of Spacecrafts to Venus and the results obtained therefrom canbe seen in : ***"The Astronomy Astrophysics Encyclopedia" Cambridge University Press.***