The Mystery and Beauty of Total Solar Eclipses

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Prologue

"Soon it was 15.40 hours IST. Expectancy was at its highest. Suddenly a shrill voice rang out 'Shadow bands! Shadow bands'. Sure enough on the floor of the terrace in the murky light, we could see wavy band-like patterns of brightness and darkness, slithering across rapidly. Now very suddenly the twilight deepened into a darker shade. Before we realised it, the Moon's shadow had enveloped us. Totality had begun! It was 15 h 41 m 00 s IST.

We looked at this strange world in awe. The Sun was replaced by a dark hole and surrounding it was the pearly white corona shining in all its glory. It had an ethereal sheen which eludes all photographs. Coronal streamers – jet-like structures, could clearly be seen extending to several solar radii. Venus and Mercury added to the unearthly beauty of this strange scene. We went about our assigned tasks and feasted our eyes on the elusive corona whenever we had a spare moment. All too soon it was over. At 15 43 46 IST, precisely as predicted, the diamond ring – a tiny spot of photospheric light, flashed through a valley of the Moon and the corona vanished. We looked to the east to see a receding wall of darkness – the umbral shadow of the Moon leaving us. We had lived 2 m 46 s in a strange world, in another dimension, the memories of which are likely to last a lifetime".

I wrote these lines 22 years ago after witnessing my first total solar eclipse at Gadag, Karnataka. That was February 16, 1980. I am sure anybody who has had the good fortune of witnessing a total solar eclipse in its full glory would share my views. A total solar eclipse is the most wondrous and awesome spectacle of mother Nature. No wonder it has been an event marker in history and has been chronicled, often tinged with fear, by every

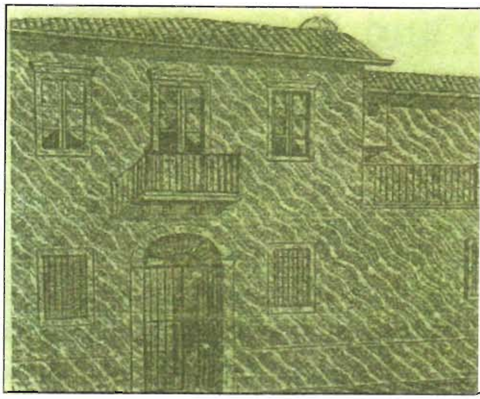
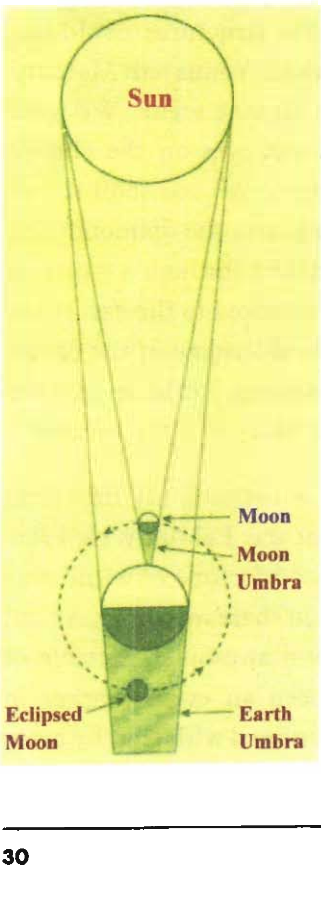


Figure 1a. Shadow bands criss-crossing the walls of a house moments before totality.

Figure 1b. Eclipse geometry : The maximum width of moon's shadow on earth is only ~ 240 km. That is the reason why total eclipses of the Sun are seen only over limited areas of Earth called belts of totality. On the other hand the lunar eclipse due to the much larger shadow of Earth is seen over a wide region.



civilization on this planet. The oldest records of an eclipse are probably from China dating back to 2165 BC. Ironically, it is associated with the tale of two errant astronomers Hsi and Ho who failed to predict the eclipse and paid for the lapse with their lives.

Geometry of an Eclipse

Every school boy knows how an eclipse happens! An eclipse of the Sun (total, partial or annular) occurs when the Moon comes between the Sun and the Earth and this can happen only on a new moon day. The solar eclipse becomes total in those parts of the Earth that are swept by the shadow of the Moon (called umbra). The maximum width of this shadow is about 260 km. Similarly a lunar eclipse occurs when the Moon passes into the much larger shadow of the Earth, which can happen only on a full moon day. (See *Figure* 1b)

Why don't we have a solar eclipse on every new moon day and a lunar eclipse every full moon day?

The reason is that the orbit of the Moon around the Earth is inclined to the Earth's orbit around the Sun by about 5 degrees. The Moon's tilted orbit crosses the plane of the Earth's orbit (ecliptic) in two places called the 'nodes'. A solar eclipse can happen only if the Sun were near one of the nodes. As seen from the Earth, the Sun appears to move eastward through the constellations of the zodiac at the rate of approximately 1 degree per day

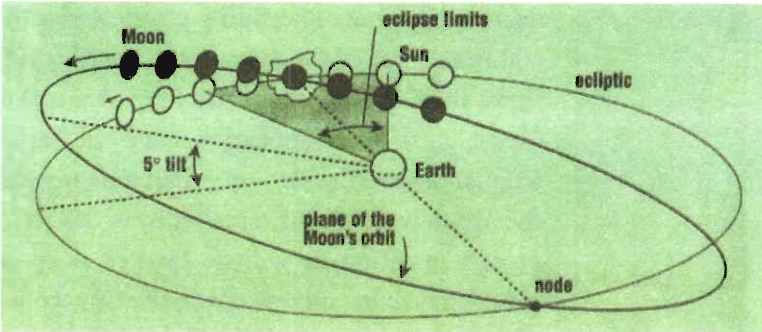


Figure 2. Nodes of lunar orbit. Whenever Sun is near the nodes it is the season for eclipses. The 5° tilt of the lunar orbit to the ecliptic ensures that eclipses do not happen every fortnight.

completing one revolution in one year. During the year the Sun crosses the nodes of the Moon's orbit twice and these are the times when eclipses can happen. An eclipse alert begins whenever the Sun is within about ± 15 degrees of the node and lasts for about a month. Since the Moon takes only 29.53 days to orbit the Earth, it is not possible for the Sun to 'escape' the eclipse zone without the Moon traversing it. A solar eclipse must occur each time the Sun approaches the node about every half year. It is possible to have two partial solar eclipses within a month (*Figure* 2), when the Sun is in the vicinity of the nodes. The closer the Sun is to the node, more central is the eclipse. If the Sun were within 10 degrees of a node, a central eclipse should occur somewhere on the Earth. Depending on the Moon's distance from the Earth the central eclipse could be *total*, with the bright solar disc totally cut off from our view or it could be *annular*, with the rim of the bright Sun still visible during mid-eclipse.

Does the existence of the eclipse season mean that eclipses will always occur at fixed times of the year?

No, the eclipse year does not correspond to the calendar year due to the shifting of nodes westward along the ecliptic. This effect called the 'regression of the nodes' is caused by the tidal effects of the Sun and the Earth on the Moon's orbit. It amounts to 19.4 degrees per lunar month and the eclipse year is shorter than the calendar year by 18.62 days. This results in the migration of eclipse seasons by 18.62 days every year (*Figure* 3). A remarkable coincidence which makes total eclipses possible is that the angular size of the Sun and the Moon, as seen from the Earth are

Acknowledgements

Several figures and tables in this article have been sourced from the excellent modern book on eclipses *'Totality - Eclipses of the Sun'* (Second Edition), Oxford University Press, 1999. (Authors Mark Littman, Ken Willcox and Fred Espenak)

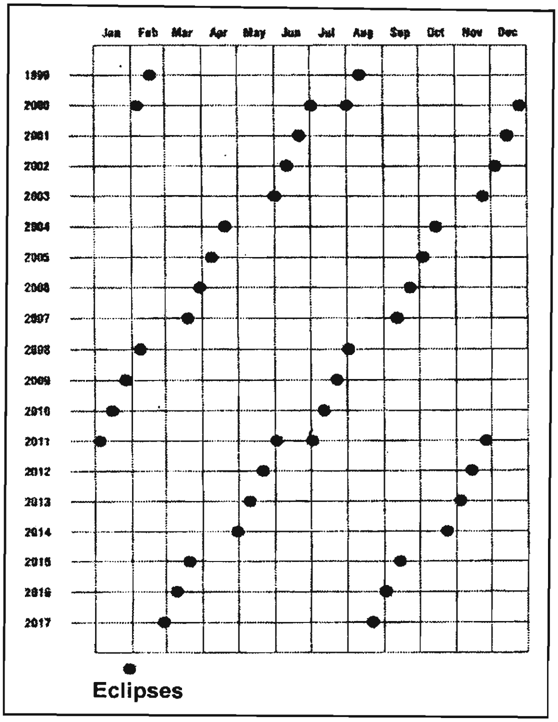


Figure 3. Migration of eclipse seasons. The times when the sun is in the vicinity of the nodes of lunar orbit causing eclipses occurs 18.62 days earlier each calendar year due to the precessional effect called 'regression of the nodes'.

nearly the same. The Sun's physical size is 400 times that of the Moon but it is also 400 times farther away from the Earth than the Moon is, so both appear to have the same angular size in the sky of ~ half a degree. If the Moon were slightly smaller by ~ 8% at its present position or a little farther away it would never be able to cover the Sun completely and we would be deprived of ever seeing a total solar eclipse. On the other hand if the Moon were much bigger or nearer, it would block out the beautiful inner corona during a total eclipse. We are indeed very fortunate to have this celestial coincidence.

Will total eclipses continue to occur forever?

Tidal action is slowing down the rotation of the Earth. In order to conserve the angular momentum of the Earth-Moon system, the Moon is moving farther away from the Earth. Scientists today can measure the distance to the Moon accurately by bouncing high-power laser beams from reflectors left behind on the surface of the Moon by the astronauts of the Apollo missions. The measurements indicate that the Moon is receding at a rate of 3.8 cm per year. If the mean Earth-Moon distance increases from its present-day value by ~23,410 km, the angular size of the disk of the Moon as seen from the Earth will become too small to completely block the Sun. All central eclipses will then be annular and not total. But we need not worry too much about missing the beauty of total eclipses, since at the presently measured rate of recession it will take another 620 million years before we lose sight of total eclipses of the Sun.

Table 1.

	Max.	Min.	Mean
Angular Diameter of the Sun	32 min 31.9 sec	31 min 27.7 sec	31min 59.3 sec
Angular Diameter of the Moon	33 min 31.8 sec	29 min 23.0 sec	31min 05.3 sec

The angular diameter of the Moon may exceed that of the Sun by as much as 6.6% (2.1 arcmins.) and still produce a total eclipse of the Sun. On the other hand the Sun's diameter may exceed that of the Moon by as much as 10.7% (3.1 arcmins) still producing an annular eclipse of the Sun. On an average the angular diameter of the Moon is smaller than that of the Sun resulting in more annular than total eclipses of the Sun. Annular eclipses outnumber total eclipses by a factor of 4 to 5.

Total	26.9%
Annular	33.2%
Annular/total	4.8%
Partial	35.2%

Table 2. Solar eclipses (average of 4530 years).

How many eclipses can we see in a year?

We have seen that eclipses happen in two seasons per year. Since the calendar year is longer than the eclipse year by 18.6 days we could have 2 1/2 eclipse seasons in a calendar year. As two eclipses, both partial, can happen a month apart in one season, we can have at most 5 solar eclipses in a calendar year (4 partial and 1 central). Total lunar eclipses are less frequent than solar eclipses (all types). In a calendar year we could have a minimum of 2 (both solar) and a maximum of 7 (4 solar + 3 lunar or 5 solar + 2 lunar) eclipses. The average number of solar eclipses per century is ~237.

The duration of a total solar eclipse depends upon the relative angular sizes of the Sun and the Moon and their relative motion which vary from one eclipse to another. The maximum duration of totality is 7 min 40 sec and it is possible only on the Equator. At the higher latitudes the duration of totality is always shorter. The 1973 eclipse over West Africa came very close to this theoretical limit. During this eclipse a Concorde Jet (supersonic aeroplane) was used to race the shadow of the Moon at an altitude of ~16 km. The Concorde could prolong the duration of totality to about 65 minutes. Total eclipses are not only short but they are also quite rare. We may try to see why. The area of an eclipse path which is typically 10000 km long and about 150 km wide is 1500,000 sq cm. The Earth's surface area is

$$4\pi \times (6400)^2 = 5.147 \times 10^8 \text{ sq km}.$$

The probability of our being on the path of a total eclipse is given

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by the ratio of the two areas and this equals 1/343. Total eclipses occur on an average of one every 1.5 years. Therefore one could expect to see a total eclipse at a particular location on the Earth once in $343 \times 1.5 = 514$ yrs. A more exact calculation by Jean Meeus gives a value of 375 years. An interesting aspect of eclipse rhythms was known to the ancient Chaldeans and is inscribed on their clay tablets in Cuneiform writing. If we take any solar or lunar eclipse date and add 6585.32 days (18 y 11.3 days) to it we will accurately predict an eclipse. For example, a total solar eclipse occurred over Indonesia on June 11, 1983. Adding 18 years 11.3 days we get June 21, 2001 which is the date of the recent total eclipse over southern Africa. The reason for this repetition is that in 6585 days the Moon completes 223 lunations of 29.53 days each, while the Sun completes 19 eclipse years of 346.62 days each and both return to the same relative positions near the nodes. Such cycles of eclipses form a Saros family. There are many such Saros cycles concurrently in existence. Saros cycles also have a lifetime and die out after about 1300 years.

Scientific Studies During Total Eclipses

We now turn from the aesthetic and geometric to the practical. Apart from being a glorious sight, a total solar eclipse is also the only time when the mysterious outer atmosphere of the Sun called the corona becomes visible to the naked eye in its full glory. At other times, even if the Sun is blocked out, the light from the bright solar disc (called the photosphere), gets scattered into the line of sight by molecules and dust of the terrestrial atmosphere and this scattered photospheric light is still several orders of magnitude stronger than the faint corona. So from the surface of the Earth the corona can never be seen, on normal days. Specialized instruments called coronagraphs, located at mountaintop observatories where the air is thin and clear, can isolate the corona in the restricted optical bandwidths of its major emission lines. With the advent of the space age the corona has become more accessible but from space. The absence of a scattering medium ensures that one can see the corona in

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space directly just by blocking out the Sun. Many spacecrafts keep a close watch on the Sun and on its enigmatic faint outer atmosphere, the corona. Solar telescopes in space such as the Solar and Heliospheric Observatory (SOHO), the Transition Region and Coronal Explorer (TRACE) and Yohkoh satellite look at the Sun in x-ray, ultraviolet and other wavelengths which do not reach the Earth. Many new discoveries have been made using these space-based facilities. Incidentally during a recent solar eclipse the solar batteries of Yohkoh satellite got drained out and the satellite lost its earth lock. It is not clear if it can be revived again – a strange case of an eclipse affecting satellites! However, a total solar eclipse continues to remain a poor man's method of studying many aspects of the solar corona during the short period of the totality. Further, unlike in most satellite observations which use larger occulting disks to block out the Sun, one is able to observe very close to the solar limb during a total eclipse from the ground and therefore study the inner corona better (*Figures* 4a, b, c).

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Scientific studies of the solar eclipses began with the eclipse of 1842 which crossed southern Europe and was well described by the English astronomer, Francis Bailey. For the next 100 years solar eclipses became events of intense study. One of the most

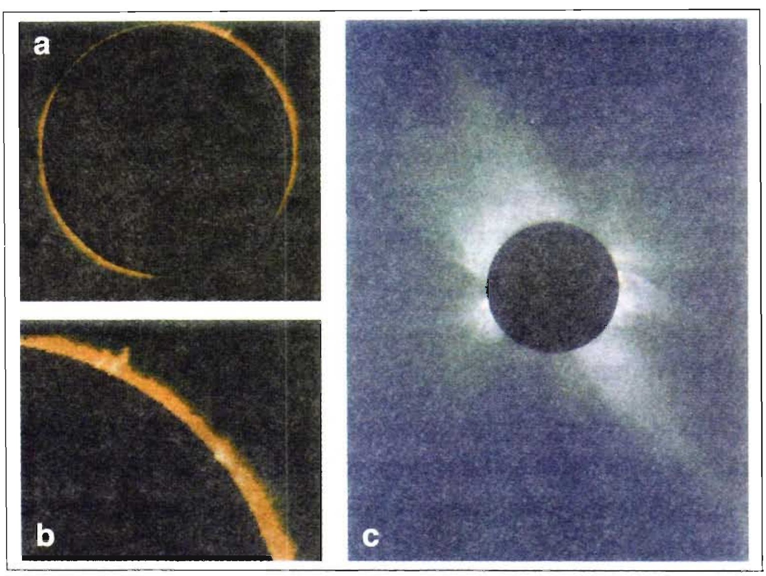

Figure 4a. Solar corona photographed on eclipse morning of 24th October 1995 at Neem Ka Thana in Rajasthan.

Figure 4b. A prominence or protrusion of cooler material into the corona seen in Figure 4a is shown expanded.

Figure 4c. A computer enhanced picture of the solar corona of July 11, 1991 which involved 500 hours of hard work to bring out details.

Lockyer carefully examined the spectrum of prominences and found a yellow line which he could not attribute to any known element. He invoked a new element to explain the presence of the yellow line and called it helium after 'helios' meaning the Sun in Greek.

scientifically rewarding eclipses, took place on Aug. 18, 1868 over peninsular India. An important discovery, made during this eclipse by W W Campbell, an American astronomer was that the pearly white corona was strongly polarized. This observation indicated the presence of material particles in the corona (to scatter the photospheric light). Today we know that scattering by the electrons in the corona is the reason for this polarization, but in 1868 electron was not yet discovered. From Guntur, the famous French spectroscopist Jules Janssen observed the brightness of prominences or bright red protrusions beyond the limb and found a way of monitoring them even outside eclipses, a method simultaneously evolved by English spectroscopist Joseph Lockyer. Later Lockyer also carefully examined the spectrum of prominences and found a yellow line which he could not attribute to any known element. He invoked a new element to explain the presence of the yellow line and called it helium after 'helios' meaning the Sun in Greek. It was only in 1895 that helium was found on Earth, trapped in radioactive rocks. In 1869, during an American eclipse, another spectrosopic discovery was made, this was the green coronal line. A new element 'coronium' was proposed as this line could not be identified in the laboratory. It was to take another 70 years before the green line was properly identified as due to emission not from a neutral iron atom but from an iron atom which had 13 of its 26 electrons stripped off. The existence of such highly ionized atoms in the corona indicated that the corona is very hot – for iron to exist in this highly ionized state it had to be as hot as of 2 million degrees. Today we know a lot more about the solar corona from both eclipse measurements and spacecraft observations:

1) the corona changes its shape during the 11 year activity period, appearing more rounded during peak activity,

2) it is the source of the solar wind – a stream of high speed energetic particles streaming past the Earth at 400 km/s and creating the beautiful ion tails of comets by blowing away the cometary material,

3) large magnetic fields are present in the corona, which can twist its shape in small regions.

But there are also many unanswered questions about the corona. The most basic question of all – what keeps the outer atmosphere of the Sun at an incredible 2-3 million degrees Kelvin while the bright photosphere, the Sun that we normally see is at a 'cool' 6000 degree K, is still unanswered today. The major scientific expeditions to the remote sites of totality of the eclipses of the modern era are basically trying to answer this unsolved problem of coronal heating in different ways. Some scientists are trying to record rapid oscillations in small active regions of the corona which could be signatures of the magnetic waves that come from solar interior to heat the corona. Others are trying to measure the coronal temperatures and velocities of ions at many portions in the corona by studying, at high resolution, line profiles of the coronal emissions like the green coronal line. Last year one such experiment was successfully carried out by a team of Indian scientists from the Physical Research Laboratory, Ahmedabad, who went to Zambia to observe the total eclipse of June 21, 2001 (*Figure* 5).

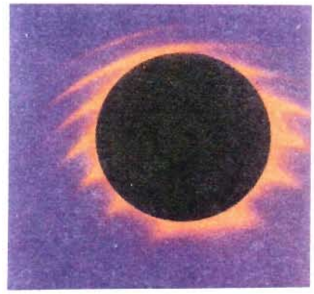

Figure 5. Coronal interferogram recorded by PRL Scientists at Lusaka, Zambia on 21 June 2001. This specialised picture of the solar corona was taken in the light of the green coronal line using a Fabry–Perot interferometer. The fringes (arcs cutting the coronal image) contain velocity and temperature information at many points in the corona.

General Theory of Relativity: 'Bending' of Starlight near the Sun

One of the most famous series of experiments conducted during total eclipses was to test the predictions of the general theory of relativity formulated by Einstein. Einstein himself had suggested the experiment. In his own words :

"For it follows from the theory here to be brought forward that rays of light passing close to the Sun are deflected by its gravitational field so that angular distance between the Sun and a fixed star appearing near to it is apparently increased by nearly a second of arc. As fixed stars in the parts of the sky near the Sun are visible during total eclipses of the Sun, this consequence of the theory may be compared with experience. It would be most desirable thing if astronomers would take up the question here raised".

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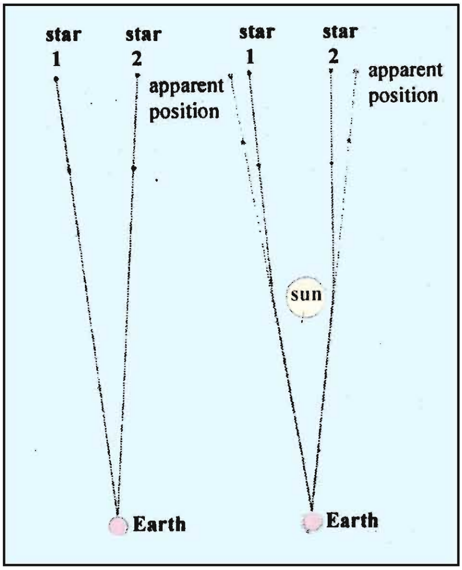

Figure 6. Gravitational bending of light near the limb of the Sun – a test for Einstein's general theory of relativity. The maximum deflection is only 1.75 seconds of arc or about (1/2000)th of a degree. It is difficult to measure such small angles and therein lies the experimental challenge!

According to the theory the maximum deflection of starlight at the limb of the Sun would 1.75 seconds of arc. The deflection would decrease in inverse proportion to the angular distance of the star from the centre of the Sun. The experiment would consist of photographing as many stars as possible in the vicinity of the Sun during totality followed by photographing the same field about six months later when the Sun is no longer in that part of the sky (*Figure* 6). Since measurements of extremely small angles are involved the experiment is difficult to perform in practice. Atmospheric abberations, distortions of the stellar image due to minute focussing effects add to the complications. The challenge was taken up by young Arthur Eddington in 1919. After measurements and reduction of the data Eddington found deflections ranging from 1.55 to 1.94 arcsecond with a mean error of 0.3 seconds and concluded that 'it is of the amount demanded by Einstein's generalized theory of relativity as attributable to the Sun's gravitational fields'. Eddington who later went on to become one of the leading theoretical astrophysicists of the early twentieth century referred to this occasion as 'the greatest moment of his life'. Eclipse experiments to verify the general theory of relativity with greater accuracy have continued, with increasing sophistication, well into the second half of the 20th century.

Is the Sun Shrinking?

Any change in the physical size of the Sun, however minute, has tremendous implications for the Earth's climate and hence for all life on Earth. An interesting way to determine whether the solar size is changing over time by minute amount was proposed by astronomers D W and J B Dunham. The Dunham method consists of stationing visual observers across the predicted northern and southern limits of the path of totality of a solar eclipse. An observer just inside the totality path will see the sunlight reduce to a point – Bailey's bead while one outside will never see a bead. A line of observers can establish the limit of the umbral

Suggested Reading

[1] Mark Littman, Ken Willcox and Fred Espenak, *Totality - Eclipses of the Sun*, (second edition) Oxford University Press, 1999.

[2] J B Zirker, *Total Eclipses of the Sun*, Van Nostrand Reinhold Company Inc., 1984.

shadow to within a 100 metres. This uncertainty translates to about 0.05 arcsecond which is about 35 km on the Sun. One could do the experiment from one total eclipse to the next and look for possible small changes in the solar diameter. The Dunham experiments seem to indicate a decrease in solar diameter by about 300 km from 1715 to 1979. However, due to the uncertainties in the exact limb profile of the moon the results are only tentative. Similar experiments were performed in India during the total eclipse of October 24, 1995 by N C Rana with an enthusiastic band of amateur astronomers. The experiment has to be repeated in future eclipses before one can draw definitive conclusions.

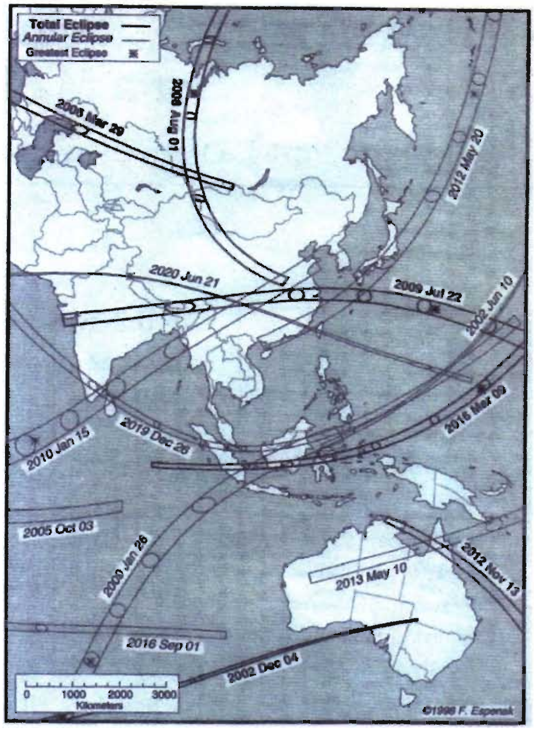

Figure 7. Central eclipses of the Sun (total + annular) in the Asia-Pacific region from 2000 to 2020. An annular eclipse over India will occur on 15th Jan 2010, 26th December 2019 and 21st June 2020. A total eclipse over India will occur on the morning of 22nd July 2009. Weather permitting it will be a great eclipse.

The Future

Total eclipses of the Sun will continue to occur with clocklike regularity for at least another 600 million years providing the earthbound eclipse chasers with changing views of the beautiful corona, as the Sun goes through its activity cycles. *Figure* 7 shows the paths of central (total or annular) eclipses of the Sun from AD 2000-2020 in the Asia-Australia region. The next major total solar eclipse over India will be on July 22, 2009. Weather conditions permitting, it will be a great eclipse to look forward to, as the path of totality cuts a swath through central India. After that we have a long wait till March 20, 2034 before another total eclipse occurs over India. Annular (not total) eclipses will occur over India on January 15, 2010, December 26, 2019 and June 21, 2020.

As each totality passes into history one is left recalling the immortal lines of John Keats in *Endymion*:

> *"A thing of beauty is a joy for ever :*
> *Its loveliness increases; it will never*
> *Pass into nothingness".*

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