General Relativity
Gravitation

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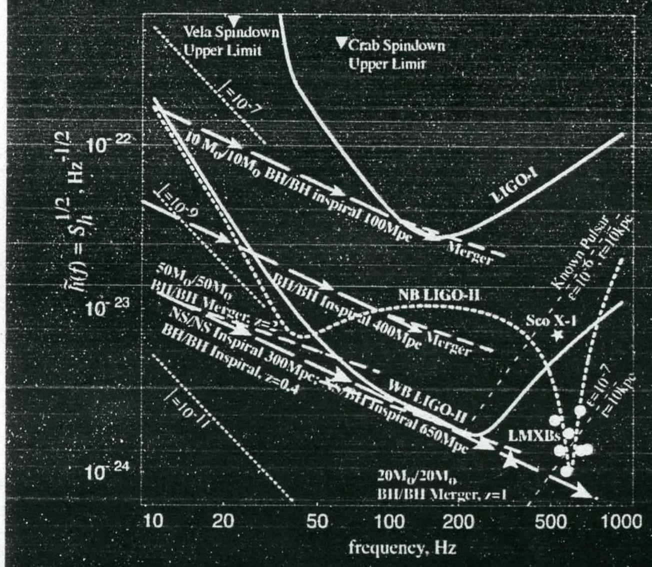


edited by

Nigel T. Bishop **Sunil D. Maharaj**

THE LIGHTER SIDE OF GRAVITY

JAYANT V. NARLIKAR

Inter-University Centre for Astronomy and Astrophysics, Post Bag 4,
Ganeshkhind, Pune 411 007, INDIA

This talk presents a light-hearted look at the phenomenon of gravity, the most enigmatic of all known natural interactions. The fact that a major international society is wholly devoted towards understanding this basic interaction of nature is ample testimony to its intellectual challenges. The GR-meetings are held once every three years to bring together workers in the field to share their ignorance as well as expertise in the field of gravity. It would be presumptuous on my part to attempt to tell anything new to the experts gathered here. This evening I will stay away from the complexities and take a light hearted look at some ideas and phenomena that make gravity so peculiar.

1 A (pseudo-)Historical Interlude

Perhaps, I should begin at the beginning. But where was the beginning? Much has been said and debated about the apple that fell on Newton's head, starting thereby a chain of thoughts that led him to the genesis of the law of gravitation. Although some argue that that particular event never happened, it certainly has added to the folklore on gravity.

However, a few years ago, one of our distinguished colleagues from India named Channapatna Venkataramaya Vishweshwara, whom the relativists not surprisingly prefer to address as 'Vishu', made a thought-discovery of historical importance (–if thought experiments are allowed in science, why not thought-discoveries in the history of science?–). He made this discovery at a gravity conference in the Indian coastal resort of Goa, and I can do no better than quote him verbatim on this topic:

> "*...Many were the reasons for selecting Goa as the venue for a conference on gravitation. For instance, the natural beauty of the land with its emerald sea, the azure sky and the vast stretches of the golden sand. The warm hospitality and open friendliness of the people. A fascinating culture in which the East and the West have mingled together. In addition to all these, there was a historical reason as well.*
>
> *"Legend has it that a sage belonging to this region discovered the universal law of gravitation some three hundred years before Isaac Newton. It so happens that there are hardly any apple trees in Goa, but one can find coconut groves all around. Consequently the discovery of the law of gravitation by our sage*

was occasioned by the fall of a coconut, as he sat in a contemplative mood. Needless to add, the world remained ignorant of his finding. This was indeed the first authentic case in unrecorded history of perishing without publishing."

This episode of unconfirmed historical authenticity will set the tone of my talk, which will end with another episode whose authenticity is also questioned by some historians.

Figure 1. The episode leading to the 'discovery' of the law of gravitation depicted by C.V. Vishveshwara.

2 The Experiment of Tweedledum and Tweedledee

Let us continue with another interesting thought experiment, this time in science, by two relativists, Hermann Bondi and William McCrea. The experiment concerns two remarkable creatures called Tweedledum and Tweedledee, so named after the famous characters in Lewis Carroll's Alice novel, *Through the Looking Glass.* In the Bondi-McCrea experiment, these characters are made of pliable material that allows them to change shape. Originally, they had identical spherical shapes and were set moving around each other in highly eccentric orbits under their mutual gravitational force. They were given an order that they must always move along these orbits. Let us assume further that both Tweedledum and Tweedledee always have shapes symmetrical about axes perpendicular to the plane of their orbits.

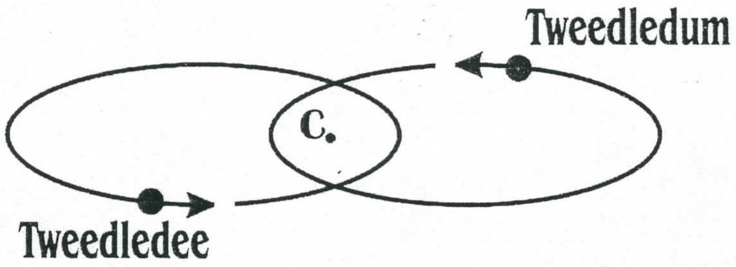


Figure 2. The highly eccentric elliptical orbits of Tweedledum and Tweedledee.

The orbits are identical, and the two move along their respective orbits in such a way that the point C midway between their centres is fixed. This is characteristic of the way any two objects move in each other's gravitational attraction. Even in the case of the Earth and the Sun, although we usually talk of the motion of the Earth only, the Sun should in principle also move under the Earth's gravitational force. However, in the Earth-Sun system, because the Sun's mass greatly exceeds that of the Earth, the Sun's motion is negligible. The centre of mass of the Earth and the Sun in fact lies within the Sun.

But to return to Tweedledum and Tweedledee: they would have no difficulty obeying the command to move along their assigned orbits if they were rigid creatures. Since they are pliable, their shapes get distorted by each other's tidal forces. Let us understand the tidal effect first.

In Figure 3, we have two initially spherical objects A and B. What happens to B if it is subject to A's gravitational force? Because of this force, in relation to B's centre, its part nearest to A will bulge in the direction of A, while its part away from A will bulge away from A. In fact it is because of this bulging tendency that the oceans rise and undergo tides under the

Moon's gravitational attraction on the Earth. Now, if B is also constrained to be symmetrical about an axis perpendicular to this direction (as Tweedledum and Tweedledee are), it will bulge all along its equator, as shown in Figure 3. The same happens to A under the tidal force of B.

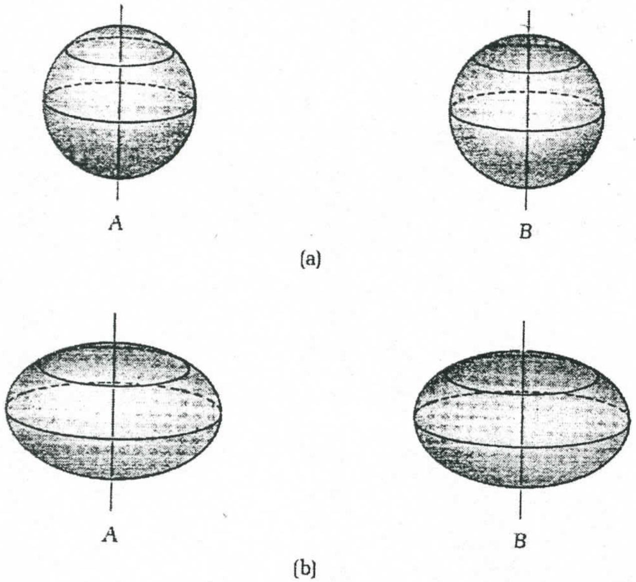


Figure 3. Initially, as in (a) the shapes of A and B are spherical. Because of their gravitational interaction both bulge out as in (b), attaining oblate spheroidal shapes.

When a sphere bulges along its equator as in Figure 3, it becomes an *oblate spheroid*. Had B instead been elongated at the poles, it would have become a *prolate spheroid*, as shown in Figure 4. An oblate spheroid is bun-shaped, and a prolate spheroid is egg-shaped, more like a rugby ball.

In the situation described in Figure 3, when the two spheres become oblate spheroids their mutual gravitational attraction *increases*. This is because A attracts B more powerfully as an oblate spheroid than as a sphere. This is the reason why the job of Tweedledum and Tweedledee is made more difficult - as they go around each other, their shapes tend to become oblate and the force between them increases, an effect which in turn tends to distort their orbits. However, remember that they are under strict instructions not to allow their

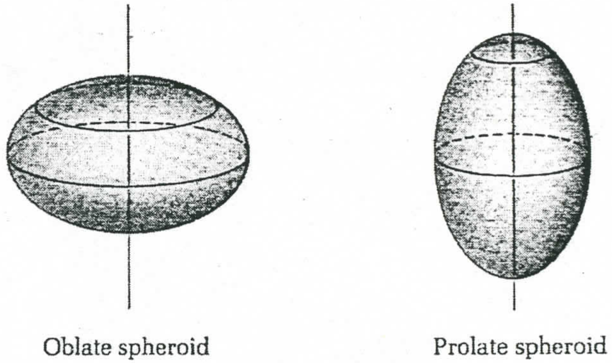


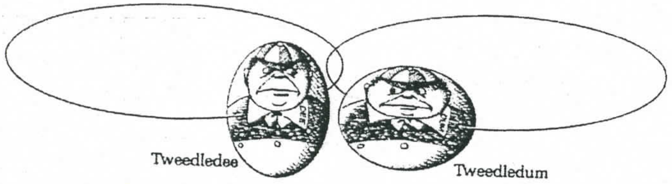
Figure 4. Typical oblate and prolate spheroids.

orbits to change. To overcome this difficulty, one course is open to them. If one of them becomes oblate, the other must become prolate, because the prolate spheroid exerts less force on its companion than a sphere. Thus, they can manage to keep their mutual force of attraction unchanged and thereby keep their orbits unchanged.

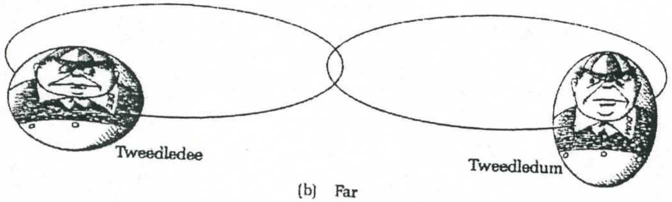
Now Tweedledum is clever and unscrupulous whereas Tweedledee is naive. Tweedledum uses his intelligence to capitalize on the situation in the following way. He makes Tweedledee sign an unfair agreement stating that Tweedledum will take the initiative in this shape-change operation: whenever Tweedledum becomes oblate, Tweedledee must become prolate, and vice versa. The exact shape that Tweedledee must acquire in order to keep their mutual gravitational foci unchanged, will be calculated and communicated to him by Tweedledum. The bottom line of this calculation is the criterion that their orbits must not change. Not knowing how to make this calculation himself, Tweedledee simply signs along the dotted line. This is a mistake for which he will have to pay dearly, as we will now see.

Moving in highly eccentric orbits, Tweedledum and Tweedledee alternately come close together and move farther apart. In Figure 5a, they are shown near each other. At this stage, there are huge tidal forces between them, and here Tweedledum allows himself to become oblate. To achieve, this, he of course does not have to do any work; as discussed earlier, the tidal force does the work of changing his shape. *And this work done by an out-*

side force increases Tweedledum's energy reservoir. What about Tweedledee? He must go into an appropriate prolate shape as per the agreement he has signed. To do this, he has to work against the tidal force, and spend energy. Consequently, his energy reservoir gets depleted.



(a) Near



(b) Far

Figure 5. The shape changes produced by Tweedledum and Tweedledee when they come close, as in (a) and move apart, as in (b).

Meanwhile, the two have started moving apart. When their separation is close to the maximum, as Figure 5b, Tweedledum changes himself to a prolate shape, thereby making Tweedledee go oblate. However, when the two are far apart, the tidal force between them is weak. Hence, even though Tweedledum does some work to become prolate, he has to spend very little energy doing so. Correspondingly, although Tweedledee gains some energy because this time the tidal forces *help* him change his shape, the energy gained by him is small.

We now see why this agreement is unfair. During each orbit, Tweedledum alternately gains a lot of energy and spends very little, while Tweedledee alternately loses a lot of energy and gains very little. What is in fact is happening, is that Tweedledum is cleverly using the tidal force to extort energy from poor Tweedledee, although the latter cannot, on the face of it, see where the unfairness of the agreement lies. You will readily see a parallel between this scenario and the occasional unfair trade agreements signed between countries!

3 Tidal Disruption

The crucial property of the tidal force that leads to the remarkable effects of the Tweedledum-Tweedledee experiment is that its strength diminishes with distance very rapidly. In fact, its strength diminishes in inverse proportion to the *cube* of the distance. Thus, if the farthest distance of separation between Tweedledum and Tweedledee is *ten* times the distance of their closest separation, the tidal force in the former case is *one-thousandth* of what it would be in the latter case. This is why Tweedledee had to work so much harder than Tweedledum in changing from oblate to prolate form.

The name 'tidal force' comes from its manifestation in the Earth-Moon system, where the Moon's gravity causes the Earth to bulge by the seas rising, especially at the Full and new Moon, when the effect of the Sun's gravity also contributes in the same direction as the Moon's. However, as mentioned before, the tidal force falls as the inverse third power of distance from the gravitating object, which is why the Moon, despite its lower mass is far more effective than the Sun in causing tides on the Earth, because it happens to be much closer to the Earth. We therefore expect the tidal force to be very powerful in circumstances where two astronomical objects are close to each other. How close can a planet be to its parent star? How close can a satellite come to the planet around which it revolves? The answers to these questions invariably involve calculations of the tidal force. If a satellite comes too close to a planet, the tidal force may become so enormous that it tears the satellite apart. The same consideration applies to a planet near its parent star. The limit beyond which the tidal forces become highly disruptive is known as the *Roche limit*, so named after the work of Eduard Roche. The rings around Saturn indicate a 'failed' satellite because of the strong tidal force of the planet.

Another circumstance in which the tidal force becomes significant is that of a binary star system. Like Tweedledum and Tweedledee, two stars in a binary system go around each other in elliptical orbits. A typical binary system is shown in Figure 6a. The stars A and B (which need not be and usually are not of identical mass) orbit around their common centre of mass. The dashed line shows the so-called *Roche lobe*. If either star becomes large enough to fill and overflow its Roche lobe, the tidal force of its companion will begin to make its disruptive presence felt.

Now, astrophysicists find that as a star like the Sun evolves, in due course it passes through the red-giant phase, when its physical size becomes very large. If one of the stars in our binary system becomes a red giant, its outer surface begins to spill over its Roche lobe, and the situation shown in Figure

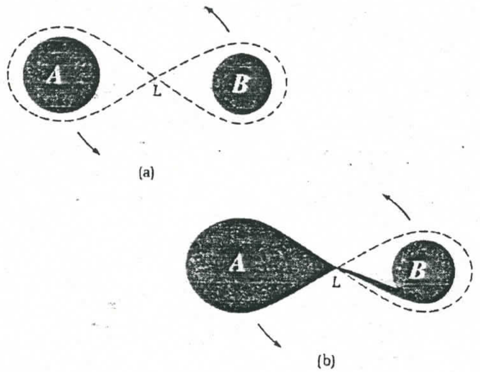


Figure 6. The dashed curve indicates the Roche Lobe of the binary system. At the Lagrangian point L the gravitational pulls of A and B balance each other. In (b) we see how star A expands and loses surface material to B which flows across the Roche Lobe towards B.

6b will occur. The companion star B now starts exerting a tidal force on A in such a way as to pull material from the surface of A that is closest to it. This surface, therefore, becomes distorted, and the material 'falls' towards B.

On an even grander scale, astronomers are now encountering examples of tidal interaction between galaxies, which leads to material being pulled out of one galaxy by another. This kind of interaction can lead to several interesting results like the birth of new stars, distortion of galactic shapes, emission of extra radiation by disturbed gas, etc. The 'toadstool' shown in Figure 7 is an example of two-galaxy interaction.

Having described the gravitational interaction between matter and matter, let us now see whether the interaction makes matter attract light.

4 The Bending of Light

While Issac Newton was working on issues related to light, he had conjectured as to whether light is attached towards matter by the latter's gravitational force. He asked the following important question :

Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action (caeteris paribus) strongest at the least distance?

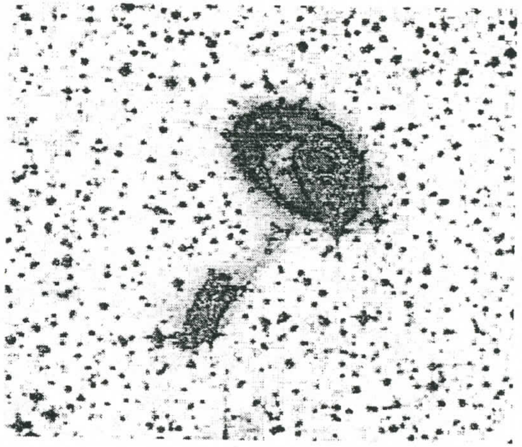


Figure 7. The 'toadstool' showing how one galaxy pulls material out of another when they are close enough.

— *Opticks, Query 1*

That the possibility of light being bent by gravity occurred to Newton was not surprising considering his genius, and also considering his belief that light is made of particles (which he called *corpuscles*). However, he had no experimental or observational means to settle his conjecture and so he left the issue unsettled.

4.1 A 'Newtonian' calculation

We can, however, use Newtonian ideas to work out how much, if any, bending light would suffer if it passed close to a massive body. Figure 8 illustrates the situation.

It shows the track of a typical particle coming from a great distance, with the speed of light. As it approaches the massive sphere, two possibilities arise. (i) It is immune to the force of gravity of the sphere and so continues along its original straight track. (ii) It *is* attracted by the spherical mass and bends round it and to emerge in another direction. The two possibilities are shown by (i) and (ii) in Figure 8.

We may consider (i) or (ii) as the possible outcome of Newton's conjecture about light. In the second alternative the bending can be calculated as the

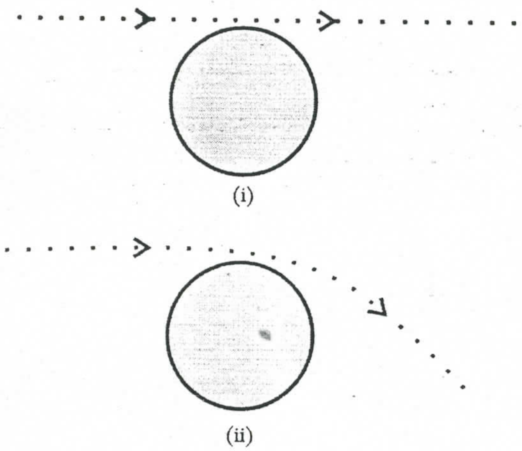


Figure 8. In (i) light is unaffected by the spherical mass, whereas in (ii) its direction is 'bent' by the gravitational pull of the mass. Which alternative represents reality?

angle between the two emerging directions (i) and (ii). The answer is the following : Multiply twice the value of Newton's gravitational constant by the mass and divide by the distance of closest approach by the ray to the centre of the sphere and also by the speed of light multiplied to itself. This gives the bending angle in radians.To express the angle in the conventionally better known unit of degrees, remember that π radians make 180 degrees. As we will shortly see, either the degree or the radian is too large a unit to measure bending of light. One needs to use the unit of an *arcsecond* which is the 3600th part of a degree. To convert radians into arcseconds a rough and ready rule is to multiply by 200,000.

If we work this out for a light ray grazing the surface of the Sun the answer is an angle as small as 0.87 seconds of arc. The smallness of this value is indicative of the rather weak effect gravity has on light, at least in the environment of our Solar System wherein the Sun is by far the strongest gravitating body.

I should also mention that even this effect has been obtained by extrapolating Newton's ideas somewhat. Thus if we take the modern concept of light as made of packets of energy, called *photons*, and assume that each photon is attracted by any mass as per Newton's law of gravitation, then we arrive at the result just described.

4.2 The bending of light in general relativity

How is the path of light affected by gravity according to Einstein's general theory of relativity?

Recall that in relativity gravitation is not looked upon as a force in the Newtonian sense. Rather, it is identified as an effect on spacetime geometry. So to solve the problem analogous to the Newtonian one which we just looked at, we first find out the non-Euclidean geometry in the vicinity of the gravitating sphere and then work out the path of a light ray in such a spacetime.

It may be worth mentioning for the benefit of the 'uninitiated' that the geometry we learn at school is that systematized by the Greek mathematician Euclid (*ca* 300 BC). If we change the basic assumptions of Euclid's geometry, we may get different *new* geometries, which as mathematical disciplines are every bit as respectable as the Euclidean geometry. But do they have any applications? Here Einstein had made the highly original suggestion that in the presence of gravitational influence, the geometry of space and time is different from Euclid's. His basic equations of general relativity tell us how to determine this non-Euclidean geometry in the presence of gravitating matter.

This was the problem solved by Karl Schwarzschild in 1916 when he showed how to determine the spacetime geometry outside a massive sphere. The second part of the problem is then straightforward. Notice that unlike the Newtonian case, there is no ambiguity here. We continue to assume that light travels in a straight line. However, travelling in a spacetime with geometry determined by gravity, *light has to modify its trajectory* from what it would have been if the geometry had been Euclidean. If we continue to use the Euclidean yardstick for 'straightness', then we have to conclude that light rays as per the non-Euclidean geometry determined by Schwarzschild, will appear to bend. A more correct statement is that given the prevalent non-Euclidean geometry, the straight line path followed by light as per its rules, will be different from the Euclidean path.

However, since we are comparing the relativistic result with Newton's alternative (ii) we will follow the rather loose but more commonly used phrase 'bending of light'.

How much does light bend? Having seen the Newtonian answer, the relativistic one is easy to state : *It is exactly double the Newtonian value.* In other words, the bending of light passing close to the Sun, will be by an angle 1.74 seconds of arc. Although the exact details of the spacetime geometry around a spherical mass became available in 1916 after the work of Schwarzschild, Einstein himself had worked out the relativistic bending of light in 1915, soon after formulating his equations of gravitation. In those early days very few scientists really understood what general relativity was all about. Most had found the notion of non-Euclidean geometry, actually applying to space and time, very bizarre and counter-intuitive.

A.S. Eddington, however, was one of those few who did grasp the essence of general relativity. Being an astronomer who had gone through the rigors of the Cambridge Mathematical Tripos to emerge as a Senior Wrangler, Eddington could not only appreciate the mathematical elegance of general relativity but also think of an astronomical test of the bending of light.

4.3 The 1919 eclipse expedition

Figure 9 is an adaptation of the second possibility of Figure 8. It shows a star A whose light grazes the surface of the Sun before coming towards the observer. The observer O therefore sees the star image at A' instead of at A; that is the star's image jumps from its regular position *if it happens to be just behind the eclipsed Sun.*

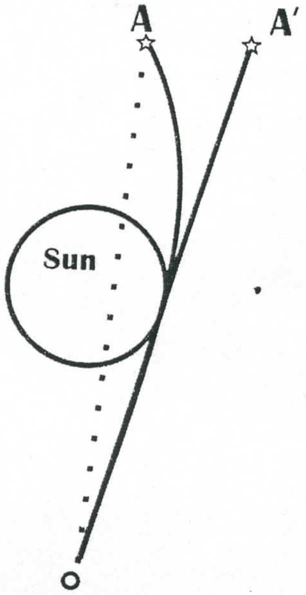


Figure 9. The 'bending' of light scenario. See text for details.

The expected shift in the direction of the star is no more than 1.74 seconds of arc. However, even to observe this shift we need a total solar eclipse. Otherwise, how can we see the star with the dazzlingly bright Sun in the forefront? Realizing this, Eddington proposed a measurement of this phenomenon at the time of the total solar eclipse of 29 May, 1919. Two teams set out, one consisting of Eddington himself and E.T. Cottingham to the island of Principe, in the Gulf of Guinea and the other of C.R. Davidson and A.C.D. Crommelin to Sobral in Brazil. A grant of £1000 obtained by the Astronomer Royal Sir Frank Dyson made this project possible.

In the end, (for the solar eclipse observation can be a chancy affair!) both teams were rewarded with adequate seeing conditions and measurements could be carried out.

The results of the observations were announced by the Astronomer Royal, Sir Frank Dyson on November 6, 1919, at a crowded joint meeting of the Royal Society and the Royal Astronomical Society. There had been great excitement as to what the findings would be. Would light show any bending at all? Or would it bend as calculated by the Newtonian methods? Or, would the answer favour relativity?

The results did favour general relativity. Within the estimated error bars, the bending of light was closer to the value 1.74 seconds of arc, rather than to half the value obtained from Newtonian gravity.

The success of the eclipse expedition made Einstein an instant celebrity. Although the concept of curved spacetime still remained beyond the common layperson, the results confirmed that nature did seem to follow these apparently crazy ideas.

And, of course, it was the first indication to the astronomer that because of bending of light by en-route masses, the observed positions of images in the sky may not represent reality.

But several decades had to pass for this indication to sink in.

4.4 A diversion

But there was another side to that historical expedition! The 1919 Solar Eclipse expedition that provided the first observational evidence for the bending of light by gravity also had a by-product : a problem in probability theory posed by Eddington.

Recall that four observers had been deputed to make the measurements : Davidson and Crommelin went to observe in Sobral in Brazil while Cottingham and Eddington went to the island of Principe in the Gulf of Guinea. A great deal depended on their results. Would light show any bending by gravity? Would the effect be as predicted by the (hybrid version of) Newtonian gravity or double that value as predicted by Einstein?

In an amusing after-dinner speech before they set out, Crommelin referred to the four observers C, C', D and E and hinted that a problem might arise as to the veracity of their claims with so much at stake and given the probability that each of them may be tempted to lie once in a while! The question was subsequently restated by Eddington in the following form :

A, B, C and D each speak the truth once in three times (independently). D makes a statement and A affirms that, B denies that, C declares that D is lying. What is the probability that D was speaking the truth?

This convoluted problem is solved by the use of arguments based on conditional probability. Try to solve it, if you like! The answer : the probability that D was telling the truth is 25/71. [For a solution see Eddington's article in the *Mathematical Gazette*, **19** ,256,(1935)]

5 Gravitational Lensing

Figure 10 shows an ordinary lens, the type of which is used in magnifying letters. The ray-diagram shows how the magnification occurs. The rays emerging from the object AB, appear to come from a much larger source $A'B'$ which is the 'virtual' image of AB.

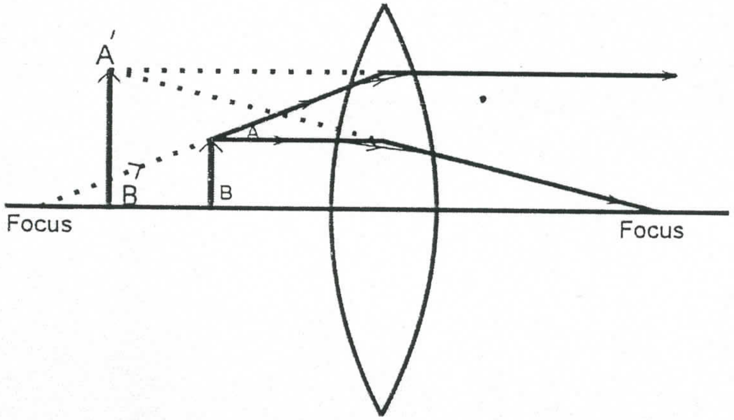


Figure 10. Image formation by a convex lens. The rays starting from A appear to emerge from A' when viewed from the other side and the size AB of the source appears magnified in the image $A'B'$.

Lenses are of various kinds. The one in Figure 10 has both its surfaces *convex*. There are others with both surfaces *concave* or with one surface convex, the other concave. All of them form images of real objects by bending light rays suitably. The cause of bending here is of course, *refraction* of light. It is the same phenomenon that leads to mirages in deserts.

Since gravitation can also bend rays of light, can we likewise encounter situations where the phenomenon produces lenses? This issue was first raised in the 1930s by the Caltech astronomer Fritz Zwicky. He wrote in 1937 :

Last summer Dr. V.K. Zworykin (to whom the same idea had been suggested by Mr. Mandl) mentioned to me the possibility of an image formation through the action of gravitational fields. As a consequence I made some calculations which show that extragalactic nebulae offer a much better chance than stars for the observation of gravitational lens effects.

There have been occasions, when a highly perceptive idea remains neglected because the scientific community is not ready for it. Zwicky's ideas were three to four decades ahead of their time and were forgotten. They were recalled and appreciated much later, when he himself was no more. Likewise the results obtained by S. Refsdal and Jeno Barmothy in the mid−1960s wherein working independently, these scientists explored the possibility of lensing by galactic masses and their effect on images of quasars, were considered interesting but hardly relevant to actual observations.

Then in 1978-79 the subject erupted all of a sudden, catapulting gravitational lensing onto the centre stage of astronomy. Zwicky's prophesy expressed in 1937 and reproduced below became realized :

Provided that our present estimates of the masses of cluster nebulae are correct, the probability that nebulae which act as gravitational lenses will be found becomes practically a certainty.

6 Cosmic Illusions

The example of a star's image shifting because of the bending of its light by the Sun's gravitation conjures up many more interesting possibilities.

Imagine, for example, a source of light and an observer on the Earth, with a massive object like a galaxy lying in between them. Figure 11 shows a possibility where there are *two* possible and different routes for light from the source to arrive at the observer. The light path is 'bent' by the galaxy in both cases, but the interesting result is that both alternative routes are made possible by the non-Euclidean geometry in the neighbourhood of the bending galaxy.

Why is it interesting? Because the observer will now see not one but two

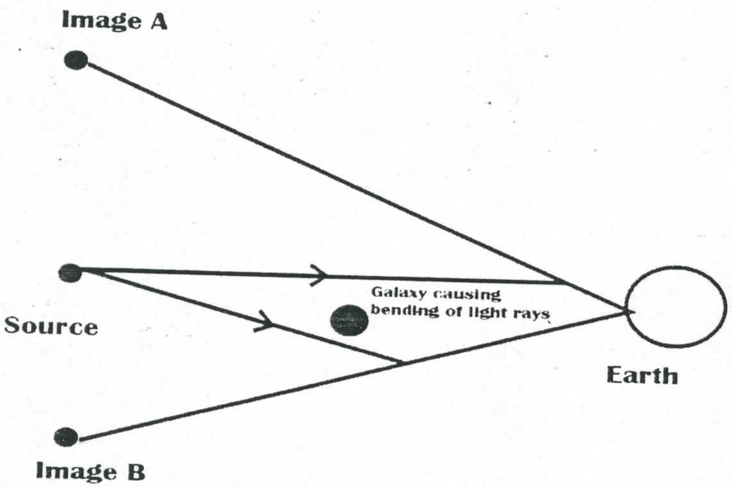


Figure 11. A single source is lensed and is seen as two images at A, B because of the bending of light rays by an intervening galaxy, as they reach the observer on the Earth.

displaced images shown by A and B in the figure)! And, of course, with more alternative light paths possible we might see even more images. In an idealized situation where the source, the gravitating mass, and the observer are exactly aligned, and the geometry has a symmetry about this axis, we should see *infinitely* many such images all distributed along a ring perpendicular to the axis. This ring is sometimes called the *Einstein ring.*

In 1979, a group of astronomers, D. Walsh, R.F. Carswell and R.J. Weymann, came up with a startling case precisely of this kind. The case concerned a pair of quasars with the catalogue names 0957+561 A & B.

Quasars are extremely powerful but very compact sources of light, so much so that before their significance was appreciated in the 1960s, a few bright quasars were mistaken for stars. Closer studies, however, revealed them to be much more powerful than typical stars and also considerably more distant from us than stars in our Milky Way Galaxy.

The quasars 0957+561 A & B were known to be such powerful and distant sources, but with the peculiarity that their directions as seen from here were very close to each other. Only a small angle of 6 arcseconds separated A from B. However, when Walsh, Carswell, and Weymann studied them more closely they found considerable similarity in their spectra and other features. While there is nothing to prevent two very similar looking objects from appearing

near each other, like human twins, one expects such quasar twins to be rather rare.

This is where the above gravitational lensing idea begins to assert itself. One could ask, Instead of there being two identical looking quasars in reality, are we seeing two images of only one real source? If so, where is the gravitating galaxy of Figure 11? Walsh et al. looked and found a galaxy that just about did the trick. Subsequently, it was noted that this galaxy belongs to a cluster which collectively also contributes to the bending of light, just as Zwicky had predicted.

The discovery demonstrated that gravitational bending of light can very subtly distort the astronomer's perception of reality. After 0957+561 A & B there were other cases of multiple quasars identified as gravitationally lensed images. In some cases three and even four images have been seen. One may see a single image, but in a distorted form. For example, in Figure 12 we see an arc extending across several galaxies. This may well be a distorted vision (like our own images seen reflected by curved mirrors!) produced by lensing. Another characteristic of lensing is that it may brighten one of the images by a large factor by concentrating a number of light rays together.

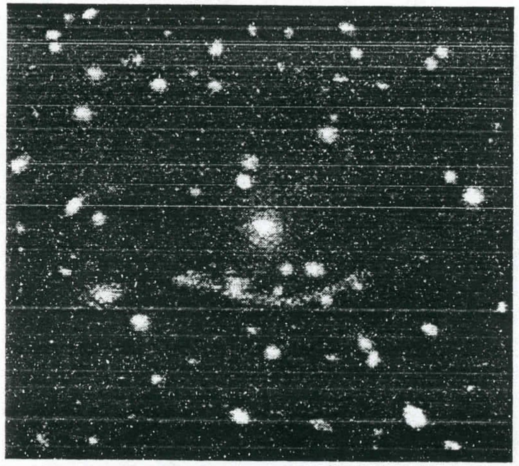


Figure 12. The arc in Abell Cluster 370 is a distorted image due to gravitational lensing.

Is there any way by which an astronomer can check whether two closely situated quasars are distinct real entities or images of one source? If the light from the quasars fluctuates with time then the answer is, 'yes, possibly'. For, even though the images are nearly identical, the lengths of their light paths are in general different. Thus, in Figure 11, the path which gave the image A may be longer than the path for the other image, in which case we are seeing in A an image of the source at an *earlier* epoch than in B. Thus, the light variations seen in A should be repeated in B after a specific gap, like a few weeks or a few moths or so. Hence, if we continuously monitor both A and B, we may be able to match their light fluctuation patterns by imposing a suitable time gap between the two.

Attempts like this are being made to discover whether the light variations of the two images 0957+561 A & B can be so matched. There are some indications that such matching can be done but it is still too early to say that the result is confirmed.

Whatever the outcome of these investigations, the mere possibility of gravitational lensing has cautioned the astronomer against the old adage 'Seeing is believing'.

7 The Black Hole of Calcutta

The bending of light is of course great in a very strong gravitational field. Can it be so much that in some cases, light is bent so much that it cannot escape the vicinity of the object at all? Such an object would remain invisible, even though it exerts gravitational influence on the surroundings. The notion of a *black hole* arose from this extreme limit. Astrophysicists believe that black holes form when a massive object finds itself unable to hold itself in equilibrium under its own force of gravity. Such an object would continue to shrink in size until it reaches a stage that the force of gravity on its surface becomes so strong as to hold in everything including light. Imagine an object ten times the mass of the Sun. When it becomes a black hole its diameter would be a mere sixty kilometres! Even the great Eddington found the notion of a black hole too bizarre to be realized in nature. However, today, despite its weird properties, the black hole has proved to be a very useful concept in astrophysics.

However, going back to history, if one were to ask the following quiz question:

Who talked of black holes first?

which of the four alternative answers would be the correct one?:
(A) John Wheeler in 1968
(B) Pierre-Simon de Laplace in 1799

(C) John Michell in 1784
(D) British Historians around 1757?

The correct answer is (D)!

The oldest mention of a black hole is found not in books of physics or astronomy but in books of history. In the summer of the year 1757, Nawab Siraj-Uddaula, the ruler of Bengal in eastern India, marched on Calcutta to settle a feud with the British East India Company. The small garrison stationed in Fort William at Calcutta was hardly a match for the Nawab's army of 50,000. In the four-day battle that ensued, the East India Company lost many lives, and a good many, including the company's governor, simply deserted. The survivors had to face the macabre incident now known as the *Black Hole of Calcutta*.

The infuriated Nawab, whose army had lost thousands of lives in the battle, ordered the survivors to be imprisoned in what came to be known as the Black Hole, a prison cell in Fort William. In a room 18 feet by 14 feet, normally used for housing three or four drunken soldiers, the 146 unfortunate survivors were imprisoned. The room had only two small windows. During the 10 hours of imprisonment, from 8 p.m. on 20 June to 6 a.m. on 21 June in the hottest part of the year, 123 prisoners died. Only 22 men and 1 woman lived to tell the tale.

Apart from its macabre aspect, the Black Hole of Calcutta did bear some similarity to its astronomical counterpart, involving as it did a large concentration of matter in a small space from which there was no escape. Indeed the incident is so macabre that most Indian historians discount it as fictitious, arguing that it was blown up by the British East India Company to find a reason to engage the Nawab in a battle and annex his state.

Whatever the real facts, I should mention that on the location of the notorious Black Hole of Calcutta, today there stands the General Post Office...which may perhaps explain the long postal delays!

I started on this light-hearted tour of gravity with a pseudo-historical interlude...I end the tour with this debatable historical incident.