ELEMENTS OF SIRIUS.

Period in years	50.17
Periastron passage	1894.25
Eccentricity	0.5938
Semi-axis Major	7."482
Inclination	42.°01
Position of Periastron	148.°38
Position of Nodal Point	44.°56

Hartford, Conn.

THE FRICTION OF THE GYROSCOPE: HOW TO ELIMINATE IT.

BY M. C. MOTT-SMITH.

In the ordinary text-books the theory of the gyroscope is developed on the assumptions that there are no frictions and that the supporting mechanism has no weight. The propositions so derived are then frequently illustrated by experiments in which the behavior of the gyroscope is described as though everything took place exactly in accordance with the theory. Only now and then is the reader warned, (oftentimes only in a foot-note), that friction may produce some slight modifications. If one repeats the experiments with an ordinary instrument, he will find not only slight modifications, but oftentimes behavior is so totally different from that called for by the theory, as to justify doubts as to the correctness or completeness of the latter. One must often wonder whether the authors of these texts really ever performed the experiments they describe. Where the divergency between theory and fact is so great, as in the case of the gyroscope, it certainly should not be dismissed with a vague remark or two about friction. While the theorist may care little about it, the practical man naturally wants to know why the actual gyroscope behaves as it does. His curiosity on this point should be satisfied—and that is what the present investigation aims to do.

We shall study the behavior of an actual instrument to find out its causes—what part is due to friction or other defects, what part to true gyroscopic causes. We shall then show methods by which the frictions and other defects may be removed or their effects annulled; the behavior of the actual gyroscope thus made to coincide with what theory tells us it really ought to do, but which it generally doesn't. So far as I know, this has not been done before. The matter is of importance in astronomy because the planets are gyroscopes, and are subject to tidal frictions.

Fig. 1 shows the kind of instrument that should be used. The wheel, *W*, is supported by three rings, which we shall call the x, y, and z rings as marked, the x ring being innermost. We accordingly have the x, y, and z axes, the x and x' bearings, etc., carried by the corresponding rings. The x axis is the spin axis or axle of the wheel. We also have the x, y, and z frictions respectively. The outermost or z ring is usually fixed in position by the clamp screw Z, so that it merely forms part of the frame of the instrument. Accordingly the z axis is vertical and fixed. It has no freedoms. The y axis is always

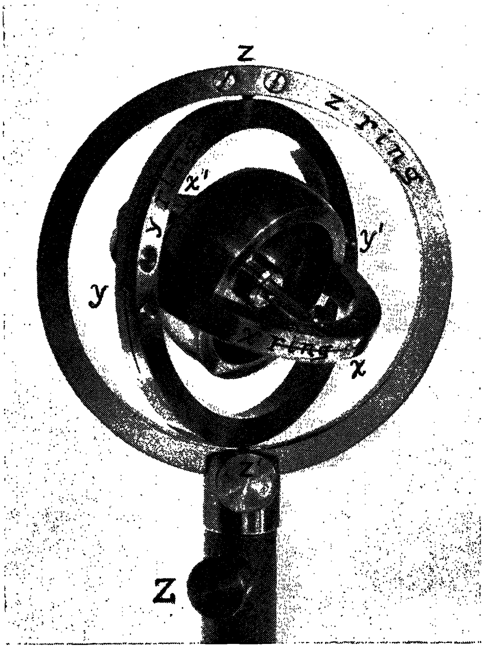

Fig. 1

horizontal, but can turn in azimuth, as the y ring turns in the z bearings. It therefore has one freedom. The x axis can turn in azimuth as the y ring is rotated, but it can also turn vertically about the y bearings. It can therefore be set in any direction, and has two freedoms. Finally the wheel of course has three freedoms. It is to be noted that the x, y, and z axes, as here described, are not the usual fixed coördinate axes. They have been chosen in this way merely for convenience of description. Since there will be no mathematical treatment, coördinate axes are not necessary.

Any change in direction of the axle, that takes place while the wheel is spinning, will be called a precession. It is to be noted that whatever the direction of such precession, the motions of the x and y rings, by construction of the instrument, show at once its vertical and horizontal components respectively, except when the axle is vertical. In the latter case the y ring may rotate rapidly, but shows no precession for there is none. It is merely dragged around by the x friction.

In common forms of gyroscope the outer or z ring is frequently omitted, and the y ring even reduced to a fork. The z bearings are then replaced by the vertical spindle at the lowest point of the y ring, which is allowed to turn in the socket at the top of the stand. In this form the z friction is excessive, and since this, as we shall see later, is the most important of the frictions, this form should be avoided.

The weight of the rings has two effects, which may be called inertial and static. The former occurs only when there is a change in the rate of a precessional motion, which requires a torque to produce it. In the weightless theory, only the inertia of the wheel is taken into account. We have merely to correct this by adding the inertia of the x ring, when the precession is vertical, and the inertias of the x and y rings, when the precession is horizontal. This is but a small correction to an effect already so small as to be seldom observable, and which moreover does not occur when the precession is steady. Hence it is truly negligible, and need not concern us at present.

The static effect occurs when a ring is out of balance. If one end of the x ring is heavier than the other, then when the wheel is stationary, the former end will sink, carrying with it the axle. When the wheel is spinning, this torque will cause a precession. To avoid this the ring must be balanced, either by attaching small weights to the lighter end, or by removing some of the metal from the heavier end. It is not sufficient however to balance so that the axle will stay in any position in which it is put. When that is accomplished, it simply means that the remaining unbalance is insufficient to overcome the static friction of the bearings. But kinetic friction is less than static. The final tests should be made by spinning the wheel with the axle horizontal, and correcting the balance until there is no precession during the whole course of the spin. The final stages should be watched particularly carefully, for the precessions increase when the spin is low. The wheel should stop in precisely the same position in which it started. To secure this may require some hours' labor, but it is of great importance in no-precession experiments.

So long as the z axis is strictly vertical, the y ring need not be balanced. But it is well to do so anyway, by turning the z axis horizontal, and balancing the y ring in the same manner as was done for the x ring.

We shall now by a series of experiments determine the effects of the three frictions. We shall take them up separately in the order z, y, x, which is the order of their importance.

THE z FRICTION.

Experiment 1. The Precession.

Give the wheel a counter-clockwise spin, with the axle horizontal and pointing toward the observer, as in Fig. 2. Attach a small weight *w*, by means of a bit of wax, to the nearer side of the *x* ring. This is better than suspending a weight, since the suspension would soon interfere with the ensuing motions.

As soon as the instrument is released, the near end of the axle instead of falling directly downward under the weight, as it would if there were no spin, moves horizontally to the right, as shown by the arrow in the figure. This is the well known precession. The frictionless theory tells us that whenever a torque is applied to a spinning wheel, precession occurs about an axis perpendicular to both the torque and spin axes, and the spin axis turns toward the torque axis, so that if the two ever came into coincidence, spin and torque would be in the same sense. Also when the spin is low the precession is greater. The *only* effect such a torque, when the steady state is reached, is to maintain this precession about the perpendicular axis.

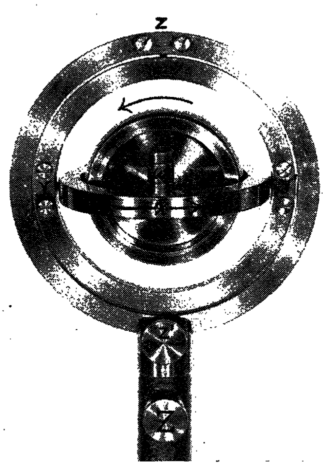

Fig. 2

In the present case then, according to the theory, the axle should continue to rotate in a horizontal plane. But observing carefully, we note that the weighted end of the axle is gradually sinking. As the spin diminishes both the precession and the sinking increase in speed, so that the end of the axle winds spirally inward and downward until it reaches the nadir. The final outcome is hence the same whether the wheel is spinning or not, only in the former case it takes a longer time and a more circuitous route to get there.

We have all witnessed similar phenomena when a fine pegged top is spun in an inclined position. The head of the top describes a horizontal circle. But as the spin diminishes, the top gradually sinks, until it finally strikes the ground.

It is natural to attribute this sinking of the axle to the dying out of the spin. Is it not the spin that holds the axle up? Would it not fall immediately if there were no spin? Does it not resist all the more sturdily, the greater the spin? What then more natural than to suppose that as the spin dies down it becomes less and less able to "overcome gravity"? This is in fact the popular conception. But it is entirely at variance with our frictionless theory. The latter asserts that the torque of the weight produces a *horizontal* rotation of the axle. Having produced this effect, it can produce no other, last of all a second rotation perpendicular to the first one. There is no provision in this theory for a steady downward motion of the axle, such as always occurs. To explain this gyroscopically requires a torque about the z axis, opposed to the horizontal precession. We have just such a torque in the z friction. According to our theory then the sinking of the axle is not a gradual succumbing to the force of gravity. It is a second precession induced by the torque of the z friction. It follows, that if z friction could be entirely removed, the axle would precess strictly horizontally despite the down pressure of the weight, *however low the spin*. The deduction seems incredible. Yet it is precisely what we intend to show.

The more usual methods of studying the effects of the z friction are three in number as follows:

EXPERIMENT 2. Application of a z Torque.

While the gyroscope is spinning and precessing as in experiment 1, lightly oppose the motion of the y ring with the finger. The downward motion of the axle at once increases, the more so the greater the opposition. Now press lightly on the y ring in the direction in which it is turning. The downward motion of the axle diminishes. With greater pressure, it ceases, and with still greater, the axle will rise. Hence we get the familiar rule: "Hurry the precession, and the top rises." The two experiments show that a torque about the z axis will produce the required vertical precession. Finally stick a pencil against the fixed z ring, in such a way that the y ring in turning will hit against it, and so be stopped completely. The axle falls at once, with the same alacrity as when there is no spin. Obviously it is not the spin that holds the axle up, but the precession. Prevent precession, and no possible spin will sustain the smallest weight. The so-called gyroscopic resistance vanishes completely. We have also seen that any opposition to the precession diminishes the gyroscopic resistance in proportion to the opposition. We may again draw the conclusion, that if the precession were completely unopposed, the axle would not sink at all.

EXPERIMENT 3. Increasing the z Friction.

Spin the gyroscope as before, but slightly tighten the z bearings so as to cause them to bind somewhat. It will be found that the sinking has increased. Since the rate of both precessions will depend upon the rate of the spin, and this cannot be exactly duplicated, it is the ratio of the two precessions that we must observe in this experiment, say the amount of horizontal turning accomplished, before w reaches the nadir. This will be found for the same w, to be fairly independent of the rate of spin.

Now tighten the z bearing somewhat more. The sinking will be further increased. Proceed in this way by gradual steps until finally the z bearing is clamped. The axle on being released now drops at once. It can in fact be turned over and over or spun vertically, with no more resistance than that offered by the friction of its bearings. The spin of the wheel causes no resistance. The effort to precess is however so great that unless the z bearings are very tight they may give way. There is always a groaning sound in this experiment. The popular notion that a gyroscope objects to having its spin axis turned is inexact. What the gyroscope decidedly objects to, is any interference with its precession. The axle may easily be turned in any desired direction by applying the proper torque. But stop the precession and the internal strains suffered are immediately evidenced by the groans emitted.

Experiment 4. Diminishing the z Friction.

If in experiment 3 we began with well oiled and adjusted bearings, so that they were already in the best possible condition, we cannot reduce friction by any further improvement of them. But we can easily do so in another way. Take the instrument out of the z bearings, and suspend it by a long thin untwisted fibre, the lower end attached to the top of the y ring, the upper end to a fixed support. It will require several hours to get all the twist out of the suspension, so that it is best to hang the instrument up the night before, and perform the experiments next morning. If now experiment 1 is repeated, it will be found that for a long time there is not the slightest perceptible sinking of the axle, while the whole instrument rotates continuously about the vertical axis. Finally a slight sag will appear, which once started increases much more rapidly than in experiment 1, so that the final descent to the nadir is fairly quick. But when this point is reached, it will be found that the wheel has either completely stopped spinning, or at most continues for but two or three turns more. Meanwhile the rotation of the whole instrument about the vertical continues by its momentum, but finally is brought to rest by the torsion of the suspension. Then it begins to rotate in the opposite direction as the fibre untwists. If it is desired to repeat the experiment, the number of turns made during the twisting up process should be counted, and the instrument stopped, when it has untwisted the same number. The equilibrium position of no twist can then be found in a few minutes by proper tests. Otherwise the instrument will go on and twist up in the opposite direction, nearly as many turns as the first twist, and so twisting and untwisting will again require several hours to come to complete rest.

In this experiment resistance to precession has been reduced to an extremely small amount, and we see that it *almost* accomplishes what the frictionless theory demands, namely, the axle remains horizontal *almost* to the end of the spin. We shall now in the next experiment, fully comply with the theoretical conditions entirely.

EXPERIMENT 5. Removal of *z* Friction.

Replace the instrument in its usual *z* bearings. Now so long as the *y* ring turns in these bearings, its motion will be resisted by their friction. If we could destroy the relative motion of the *y* and *z* rings there would be no friction between them. This can easily be done in the following manner. Loosen the lowermost screw *Z*, Fig. 2, which clamps the *z* ring. Now spin as before, starting with the *y* and *z* rings exactly in one plane. At the moment of releasing the axle grasp the *z* ring, being careful not to touch any other part of the instrument, and turn it smoothly and evenly so as to keep exact pace with the *y* ring, as the latter precesses. In the instrument shown in the figures, the rings being rectangular in section, this can be done with great nicety. It will now be found that the axle remains strictly horizontal thruout the *whole course of the spin*. At the end it drops suddenly, just as though it had rolled off the edge of a table. The spin will then be found to be completely dead.

So effective is this method, that even with the very slight spin that can be communicated to the wheel by means of the fingers, the axle will remain horizontal to the *end* of the spin, provided the much more rapid precession then occurring can be properly followed with the *z* ring.

In this way it is shown that the frictionless theory is strictly true, not only for planets and molecules that have no axles or bearings, but also for the ordinary gyroscope. If the theory breaks down anywhere, it is not until the last fraction of a turn.

There is another way in which precessional resistance might presumably be annulled, but the result is quite different from what might be expected.

EXPERIMENT 6. Back-Twisted Fibre.

The gyroscope is to be again suspended as in experiment 4, and that experiment repeated, counting the number of precessional turns made up to moment that *w* reaches the nadir. At this moment the twirling is to be stopped, the instrument allowed to untwist, and then twist up backwards, one half the number of turns, that were made forwards by the precession. At this point it is again stopped, the wheel given as nearly as possible the same spin as before, and the instrument released. It is obvious that if the same number of precessional turns are again made as before, during the first half of them, the fibre will be untwisting, and so aiding the precession, while during the last half, it will be twisting up and so hindering precession. The aid and the hindrance will be substantially of equal amounts, so that the net result should be zero. We might expect the axle to rise a bit during the first half, and then sink to its original level at the end of the second half. But instead an astonishing thing happens. For a long time nothing happens. The instrument precesses steadily, with no observable departure of the axle from the horizontal. But when about three-quarters of the turns are completed, the axle is seen to be *rising*. The motion slow at first, rapidly increases in speed, until w reaches the *zenith*. There it hesitates a moment until the spin is almost dead, when it falls to the nadir.

This behavior is in accord neither with popular conceptions, nor with the frictionless theory of the text books, nor with the z friction theory we have laid down. It is a striking illustration of the truth of the remark made at the beginning, that the frictions are not always mere slight disturbances. They are at times quite the determining factors. The explanation of this remarkable behavior must be deferred until after we have studied the other frictions.

Another line of investigation leads to the same conclusions concerning z friction, and yields some further information of importance concerning it.

Experiment 7. The Nutation.

The gyroscope is again to be suspended, so that precessional resistance is reduced to a minimum. Give the wheel a small spin, with horizontal axle, but no weight. Provide a rather large weight with a hook, and suddenly hook it on the end of the axle. If the spin is not too great, it will be noticed that the axle dips, and executes a series of vertical oscillations of diminishing amplitude, finally settling down at a somewhat lower level than that from which it started. Also the precession started immediately, but proceeded jerkily at first. But the jerks died out at the same time the vertical oscillations did, after which the precession proceeded steadily. Now suddenly remove the weight. The axle immediately rises above its original level, sinks again, and after a number of oscillations settles down at about the original level. The precession meanwhile, after a few concomitant jerks, stops. The experiment may perhaps be repeated two or three times before the spin is dead, and will show that the less the spin, the greater are these oscillations. If the spin is very low, the first dip may be so great that the axle cannot recover before the spin is dead. Thus a top must have a certain minimum spin in order to stand up at all. This is the speed at which the side of the top would just not strike the ground on the first dip. This dipping is called the nutation.

At ordinary speeds the nutation is too slight to be observed. It may be made visible however, if the spin is not too high, by allowing a beam of sunlight to fall upon the gyroscope. A number of curious reflections will be seen upon the walls of the room. By wiggling first the x, then the y rings, suitable spots or streaks derived from these rings may be selected for observation. Then when the weight is applied these spots will be seen to quiver as they move forward. With higher speeds the images will simply be blurred at first, and later become sharp.

The experiment may be varied by suspending the weight by a thin strip of rubber, or by a light spiral spring, and causing it to oscillate up and down. In this way are simulated the forced nutations, which the earth undergoes, because of the periodically varying torque, exerted by the attractions of the sun and moon upon her equatorial protuberance.

These nutations that occur when the speed of precession is changed, appear to contradict the principle already laid down that a torque produces a precession about a perpendicular axis. But it must be remembered that this is strictly true only when the precession is entirely unhindered. When the weight is first applied there is *no* precession. Therefore the axle starts straight downward, as in the latter part of experiment 3. Precession begins at once but is hindered by the inertia of the rings and wheel. Hence at this stage w moves slantingly as in the middle part of experiment 3. As the precession gathers speed, the inertial resistance diminishes, w moves more nearly horizontally, until finally the precession acquires a surplus speed and is carried forward by its momentum. Then the axle rises, for the precession is hurried. (See exper. 2.)

To start precession requires an expenditure of energy, and this is derived from the sinking weight. But like a pendulum it shoots beyond the equilibrium point, and has to return. There is therefore a flow of energy back and forth, until the precession settles down to the steady state, at a slightly lower level. The difference between the original and final levels of w, measures the energy represented by the steady precession. This state once attained requires, in the absence of frictions, no further expenditure of energy to maintain it. Hence the weight sinks no more, but continues to revolve steadily at the new level.

We may now see why when z friction is present the axle must sink steadily. Part of the energy which the dip puts into the precession is absorbed by the z friction. This consumption continues steadily, hence w must sink steadily to supply it, just as a locomotive must not only start a train, but must pull steadily to supply the energy consumed by friction. The sinking is hence in reality a continued dip.

We also see why in this experiment, z resistance must be reduced to a minimum, for otherwise, like a strongly damped pendulum, the oscillations will be unobservable, and may even be absent altogether.

EXPERIMENT 8. The Revolved Gyroscope and Planetary Inversion.

The gyroscope, replaced in its ordinary bearings is now to be fastened to the end of a rotating arm as in Fig. 3, spun with horizontal axle, and revolved. It will now be found, that even though perfectly balanced and no weight applied, one end of the axle slowly rises until the axle stands vertical, with the spin in the same sense as the revolution. Further turning produces no further effect, but if the revolution be reversed, the axle slowly turns over in the reverse sense until it again stands vertical with the up side down, and there remains as the revolution continues. This motion will be called the inversion. It will be noted that the gyroscope in this experiment simulates the situation and action of a planet revolving about the sun. We shall accordingly use the terms "direct" and "retrograde" in their usual astronomical sense.

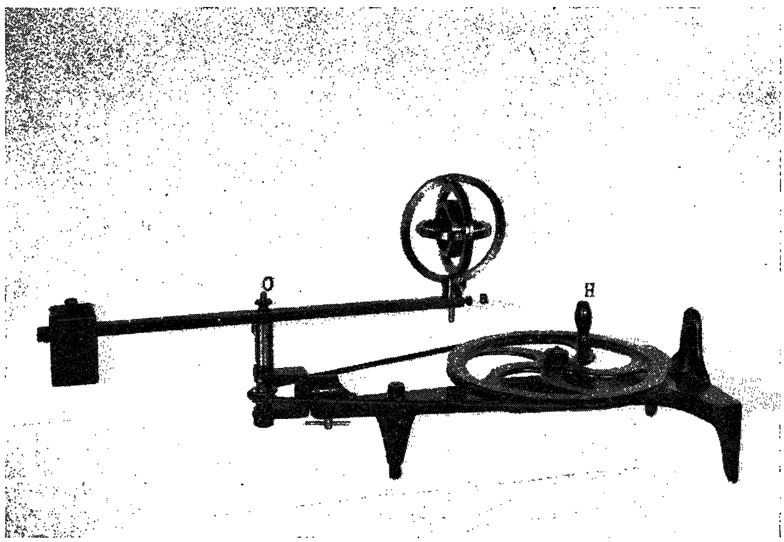

Fig. 3

It has been thought by Pickering[1] and others, that the planets have undergone a similar inversion—that originally they all had retrograde rotations, but that in the course of time the axes have gradually turned over until now nearly all have direct rotations.

Besides the inversion, there is also a horizontal precession to be observed in this experiment. The y ring at first maintains its plane substantially parallel to itself as it revolves. But gradually it turns slightly in the same sense as the revolution. When the axle finally stands vertical, the y ring may rotate rapidly, but this is no longer a precession, according to our definition, for there is then no change in direction of the axle. The y ring is then simply dragged around by the friction of the axle.

[1] "Astronomy and Astro-Physics," June and Sept. 1893.
"POPULAR ASTRONOMY," Oct. 1917.

The inversion of the gyroscope is correctly attributed by Pickering to z friction, and in the case of the planets he supposes a similar resistance to be offered by an "annual tide."[2] In fact we may note, that the z ring being securely fastened to the end of the revolving arm, is forced to rotate with it, at the same speed. It therefore exerts a frictional torque upon the inner parts of the apparatus, in the same sense as the revolution. In fact if the apparatus be revolved slowly and evenly without spin, the inner parts also rotate with the z ring as one piece, though there is no connection between them except through the z bearings. But if the arm be given a sudden twist, the inner parts remain behind, showing that it is really z friction that turned them in the first case. If now the wheel be spinning, the y ring maintains its direction in space but little altered, while the z ring rotates around it. But now, instead of dragging it with it, the frictional torque of the z ring produces a vertical precession in accordance with the principles already laid down.

We may imagine the gyroscope to be slid along the arm toward the center O (Fig. 3.), and fastened at various points. In every case the z rotation is equal to the revolution. But when the gyroscope is fastened at O, it is rotated only. By a series of experiments, with the gyroscope alternately at the end, and at the middle of the arm, we may show that the phenomena in the two cases are in every detail the same, and are due solely to the rotation of the z ring. That the inversion is really due to z friction can then be proved by methods similar to those of experiments 2, 3, 4, and 5. First, we may, with non-revolving instruments, push on the y ring in the direction in which it was previously revolved, and show that inversion can be thus produced, while a contrary push will produce an inverse inversion. Second, we may gradually tighten the z bearings, and show that at each stage inversion is more rapid, until at last when the bearings are clamped, it takes place at once upon attempting to rotate or revolve the instrument Third, we may suspend the gyroscope from the end of the revolving arm by a long fibre, and show that inversion is then much reduced. Fourth, we may eliminate z friction, in a manner to be described later.

THE y FRICTION.

The slight horizontal precession that takes place in these experiments looks as though the y ring were dragged to some extent by the z friction. But this is not so. It is a nutation, similar to the initial dip, and continued dip, that occurred in experiment 1, and due to similar causes. To produce this precession we require according to our principles a torque about the y axis opposed to the inversion. The y friction offers such a torque. In fact, if while inversion is proceeding, we place a small weight on the end of the axle which is rising, the horizontal precession will be increased. If we put the weight on

[2] Ibid.

the other end, the precession will be diminished, annulled, or even reversed, according to the size of the weight, while inversion continues in the same direction. On the other hand by gradually tightening the *z* bearing, we may show that the relative amounts of the horizontal and vertical precessions are unaffected by this tightening, even though the *z* bearing be clamped. In this latter case inversion takes place at once, but the amount of horizontal precession accompanying, say one-quarter of an inversional turn, is precisely the same as when the *z* bearing is entirely free. When clamped, the whole instrument must of course turn the required amount, with the *y* ring. The horizontal precession is therefore not affected by the *z* friction.

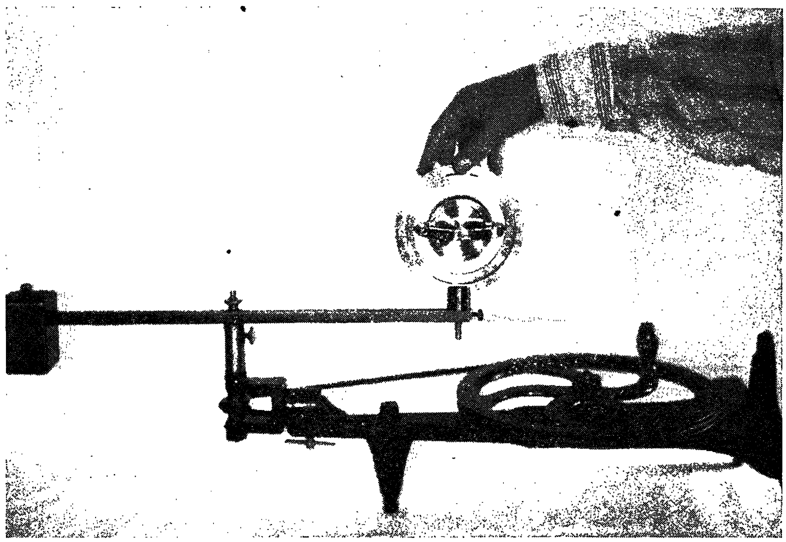

Fig. 4

On the other hand by gradually tightening the *y* bearings, we find at each stage, the precession for the same amount of inversion is increased, until at last when these bearings are clamped, the *y* ring turns as one piece with the *z* ring, precisely as though the *z* bearings were clamped.

In fact by properly adjusting the two sets of bearings we can get any desired ratio of the two precessions, limited only by the minimum friction attainable. To do this, we must always, so to speak, tighten the wrong bearings to get the right result.

Experiment 9. Removal of *z* Friction in the Revolved Gyroscope.

We have seen that the precessions of the revolved gyroscope are due to the rotation of the *z* ring, *z* friction producing the vertical, *y* friction the horizontal precession. Therefore if the *z* ring is prevented from rotating, while it revolves, both precessions should disappear. This might be accomplished by a mechanical device, but in practice it is found that the simple method shown in Fig. 4 is sufficient. The clamp screw at *a* is loosened, the wheel is spun with axle horizontal, and the *y* and *z* rings are set coplanar. Then instead of revolving by turning the handle, the *z* ring is grasped as shown in the figure, and the instrument pushed round and round, while the *z* ring is held so that its plane is always parallel to itself. In short it is revolved without rotating. It will now be found that whatever the ratio or direction of spin or of revolution, the direction of the axle shows no change throughout the whole course of the spin, or even thereafter. The *y* and *z* rings remain coplanar as at the start. In fact the instrument may be taken off the rotator, and moved about in any manner whatever, so long as the *z* ring is kept always parallel to itself, and the *z* axis vertical, without any change whatever in the direction of the axle. For the gyroscope such a motion does not differ from rest. But the moment the *z* ring is allowed to rotate, both precessions at once begin. They are therefore entirely due to this rotation.

THE *x* FRICTION.

In testing the balance, and in all the experiments so far described, it has always been specified that the axle should be set horizontal. This was to eliminate the effects of the *x* friction. It is obvious that this friction, besides diminishing the spin, tends to drag the *x* ring around in the direction of the spin. When the axle is vertical, as at the end of experiment 8, this friction in fact causes the *x* and *y* rings to rotate with the wheel. But when the axle is horizontal this rotation is prevented by the *y* bearings. The *x* friction then merely produces an upward pressure on one bearing and a downward pressure on the other. In any inclined position, the torque of the *x* friction can be resolved into two components, one horizontal the other vertical. The former will merely produce pressures in the *y* bearings, but the latter will coincide with the *z* axis, and produce precessions similar to those produced by the *z* friction. In fact, if in experiment 8 the axle is inclined upward, so that the spin is direct, but the apparatus is not revolved, both precessions will be found going on slowly by themselves, in the same direction as when the apparatus is given a direct revolution. If the axle is inclined downward, both precessions are reversed in the stationary gyroscope. Both precessions increase as the axle approaches the vertical, for the vertical component of the *x* frictional torque then increases.

With good bearings, these spontaneous precessions are very slight. Still they would entirely vitiate any no-precession experiment like number 9. That they are really due to *x* friction can be proved by the same methods as before. We may apply a torque to the *x* ring in the direction of the spin, or contrary, when the spontaneous precessions will be increased or diminished respectively. We may increase the friction by tightening the *x* bearings, but this is inadvisable, as these bearings are already subject to much wear. A better way is to provide a light paper brake as shown in Fig. 5. By varying the pressure of this brake, the spontaneous precessions will be found to vary in like manner. Naturally x friction cannot be very much increased, or the spin will die out so rapidly, that no observations can be made.

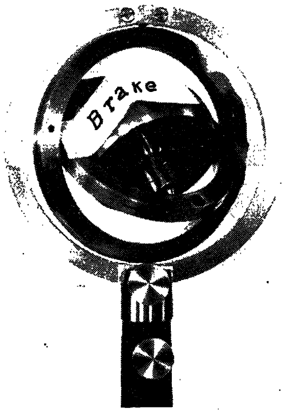

Fig. 5

It is interesting with this brake to repeat experiment 8, with the axle inclined sharply downward. If conditions are properly adjusted, then despite a forward revolution, the axle will precess downward, and retrograde, and stand vertical with the spin in the opposite sense to the revolution. This of course is directly opposite to the usual result of this experiment.

Finally we may annul x friction by driving the wheel with a motor attached to the x ring. Such a motor presses back on the x ring with a force precisely equal to that with which the friction of the axle tries to drag the x ring around, so long as the speed is constant. Of course when the motor is accelerating, the x ring must be held, or the axle set horizontal, since otherwise the x ring will be driven backwards. If one is so fortunate as to possess such a motor-driven gyroscope he may repeat with an inclined axle all the experiments for which we have here specified a horizontal axle and enjoy also the advantage of a higher and a constant spin.

When the axle is inclined upward, x friction carries it further upward, and when it is inclined downward, x friction carries it further downward. Hence the horizontal position is one of unstable equilibrium in this regard. If there is any slight displacement, x friction will increase the displacement. This explains the anomalous behavior of the suspended gyroscope in experiment 6, in which we endeavored to annul the precessional resistance,by twisting the fibre backwards half as many turns as we expected to be made forwards. In untwisting, the torsion of the fibre aided precession, and so raised the axle slightly, as we expected. But when the fibre began to twist up, instead of restoring the axle to its original level, x friction had already obtained a grip, and proved to be stronger than the very feeble torsion of the twisting fibre. As the axle rose, the z component increased, so that soon the fibre was completely out of the running, and the course of the experiment was exactly opposite to that expected. We had reckoned without x friction. With the gyroscope mounted in the usual way, the instability of the horizontal axle is not in evidence. But in this case, with z resistance reduced to an extreme minimum, it became quite the determining factor.

All this goes to show that we must take strict account of all the frictions, if we are successfully to predict, or correctly to understand, the behavior of an actual gyroscope under all circumstances. The behavior may be entirely different from, and even contradictory to, that deduced from the frictionless theory. The axle may go up, or it may go down, though theory says it should stay in the middle. In fact, the gyroscope has no manners. The only frictionless gyroscopes are planets and molecules, which are without axles and bearings. All others misbehave in various ways, for which we must learn to make the proper allowances. In the ordinary gyroscope the precessional effects of all the frictions may be removed by setting the axle horizontal, and destroying the relative motion of the y and z rings, either by moving the latter as in experiment 5, or by stopping its motion as in experiment 9. In the motor gyroscope, so long as the speed is constant, only the second condition is required. By observing these two simple rules, any ordinary gyroscope may be made to behave itself as it theoretically ought to.

AN OBSERVATORY ON THE EQUATOR.

By JAMES H. WORTHINGTON.

The study of Planetary Astronomy is prosecuted mainly by private enterprise. Most observers—situated as they are in comparatively high northern latitudes—have only been able to study the planets at locally favorable oppositions (or elongations). For example; Mars, during the opposition of the present year, is so far south as to be inaccessible to useful scrutiny from any observatory in Europe—and most of those in the United States.

And yet planets, being the only possible, probable or certain abodes of life, are more interesting to ordinary people than any other bodies in the heavens.

The planets move in the Zodiac, and zenith observations of them—which are best—have almost never been made, being only possible in the tropics.